Seismic Positioning, Grids and Binning

George Parr

ISBN: 978-629-99903-0-7.
Release: October 2024

Revisions

As new techniques or additional information become available, with respect to the contents of this publication, it will be revised to ensure it describes the best practices and current techniques. Revisions will be made to ensure the contents are as complete and up to date as possible. Contributions and comments from any subject matter expert will be welcome at any time and shall be submitted to the author for consideration. All diagrams and drawing in this document have been prepared by WX Geo Services Sdn Bhd.

Sponsors

To date this publication has received no sponsorship from any third-party company or organization. Any sponsorship that will improve the contents or distribution of this eBook will be welcome.

Contributors

The principal author of this publication is George Parr. Contributions are acknowledged from the company's geo-spatial team based in UK and Malaysia.

Preface

This publication is a collection of notes that have been assembled from our training materials entitled Seismic Positioning Data Management and extracted from our dedicated online training web site (https://geomatics-training.com). The general purpose of the publication is to introduce the role geo-spatial data plays in the upstream exploration cycle through the design of geometric grids used to manage the seismic trace data acquired.

The chapters present a logical progression of how a seismic grid is defined, the data it contains, how it is used to assist the design of a seismic survey to its role in managing the acquired data thus ensuring the final product meets the client's requirements. Further chapters cover how the International Oil and Gas Producers (IOGP) data formats are used for storing and exchanging seismic grid definitions. This is followed by computations explaining how seismic grid related data is converted and transformed between different associated coordinate reference systems, e.g., Derived CRS. The final sections are dedicated to examining seismic grid definitions and how they may change through the data life cycle in upstream activities and their role in the audit trail of a proposed well location.

Interspersed throughout this publication are notes and descriptions highlighting the importance of the link between geo-spatial data and the seismic trace data coveted by the geoscientists. It is important to stress this relationship as the successful completion of a seismic survey involves the triad of positioning, timing, and amplitude.

The book contents are a collective effort between the geo-spatial team of the publishing company. The principal author is George Parr with assistance from the Geomatics team in UK and Malaysia.

George Parr

Kuala Lumpur

Malaysia

October 2024

Figures

1 Introduction

Reflection seismic surveying has been the underlying technology used in hydrocarbon exploration stretching back over one hundred years. During that time, the geophysical community has very successfully improved the technique through the introduction of controlled geometric configurations (of sources and receivers), expanded spreads (2D to 3D) and advanced data processing methods. But where did it begin?

To determine the depth of a geological horizon from where reflected energy originated requires that two parameter values are known. The first is the time taken for the seismic wave to travel from the source, reflect off that geological interface, and be detected by the surface recorder. The second is to know the velocities with which the acoustic wave travelled through the inhomogeneous sub-surface.

Timing: By synchronizing zero time at the seismic source with zero time at the receivers the two-way travel time (TWT) is a direct measurement, i.e., the total travel time from generation to reception. This, along with recording the amplitude of the returning seismic energy are the two fundamental seismic observables.

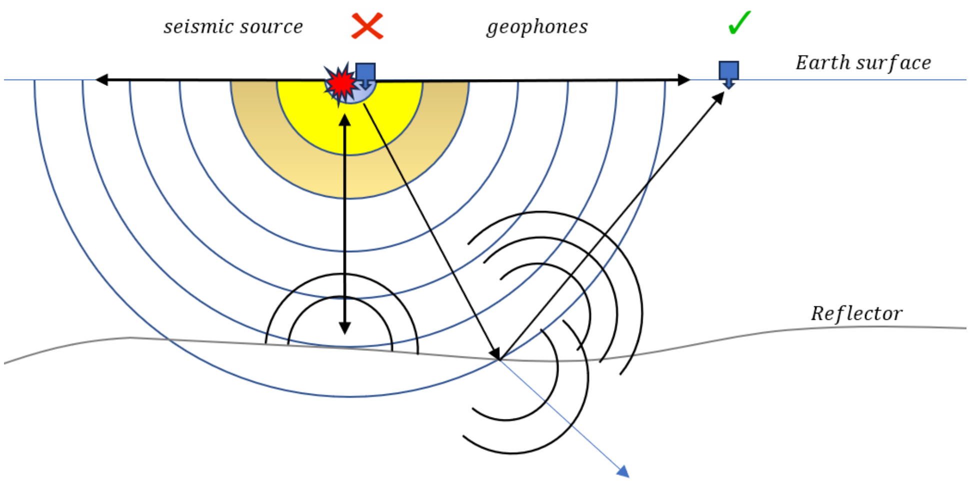


Figure 1: Energy ray paths from source to receivers

Velocity: The velocities with which the acoustic energy travels through the sub-surface is not a direct observation but one that must be computed from the recorded seismic trace data. Having a receiver co-located with zero lateral offset in relation to the source provides no real geophysical benefit to the derivation as shown on the left side of Figure 1. Instead, by introducing a lateral horizontal offset between the source and an array of receiver's the velocities can be determined. Naturally, this requires that the horizontal distance between the source and receiver is known, which necessitates precise positioning of both. This is called the source-receiver offset of which there will be a multiplicity at each shot point.

Because the Earth's strata comprises a collection of sequences, with each sequence comprising many beds or layers, the velocity of propagation will vary from one sequence to another because of differing rock properties (the interval velocities). Therefore, if the travel time and velocities are known the depth of the geological reflectors, below a selected reference surface, can be determined (depth conversion). It is the accumulation of thousands of such observations that enables the seismic processing geophysicists to determine a velocity profile and thus convert between the time and the depth domain (depth conversion). As such, velocity modelling is one of the most important tasks undertaken by seismic processors.

Mid-point: The acoustic wave is assumed to have reflected off the rock structures at the halfway point between the source and each receiver and this is known as the mid-point. Therefore, the depth the geological layer is assumed to be from the reference surface is along a perpendicular vertical line (red dashed line) to each mid-point.

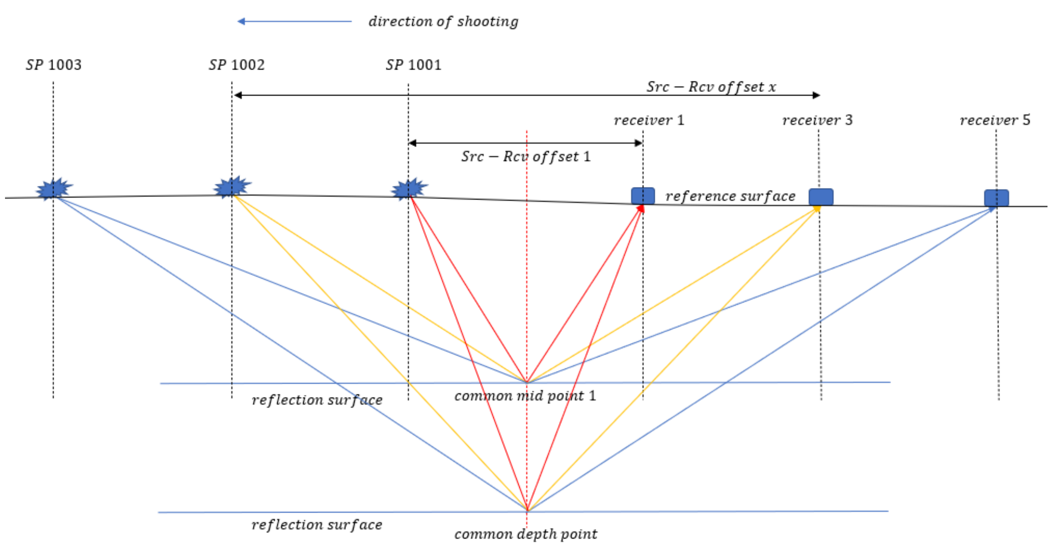


Figure 2: Basic seismic geometry

Where there are a collection of mid-points imaging the same rock structure this creates a common midpoint. Another term used is that of common depth point (CDP) which is applied to the collection of mid points associated with a reflection surface at a specified depth as shown in the lower part of Figure 2.

Noise: Early surveys were cursed by noise problems and the answer to its reduction was an increased awareness of the geometric relationship between source and receivers. The introduction of common mid points was one of the fundamental steps in improving signal to noise ratio. Sampling the same sub-surface points multiple time, using different source-receiver offset pairs (multiple mid-points), and 'stacking' together the seismic trace data provided the solution. Therefore, geometry became a decisive factor and the necessity of knowing the horizontal positions of all sources and receivers contributing to the stacked seismic trace data. This significantly influenced the offset distribution (in azimuth) of the seismic trace data contributing to each common mid-point.

Early seismic surveys were acquired along a single 'averaged' azimuth where multiple common mid-points, for various combinations of source-receivers, were observed. Therefore, the sub-surface was imaged along the same linear direction giving a 'picture' of the expected rock formation(s) along that azimuth only. This was later termed seismic 2D surveying to differentiate it from the future 3D surveys.

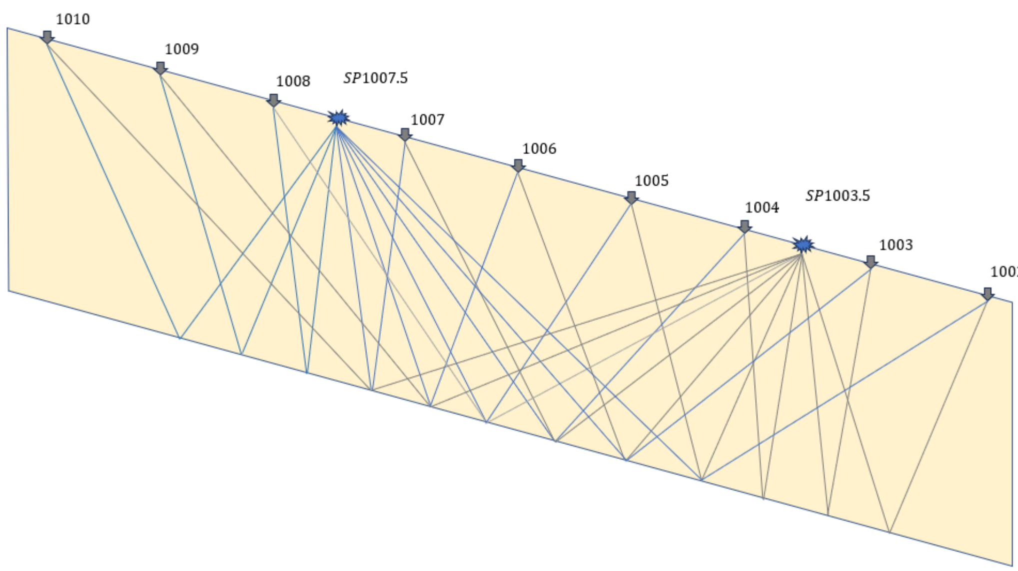


Figure 3: Multiple common mid-points

In the early 1960's trials were conducted to increase the size of the footprint over which the acquisition was simultaneously conducted in an effort to create better pictures of the sub-surface rock structures. This led to the receivers and sources being arranged in patterns other than the linear one shown in Figure 3. For example, orientating the source lines along a different azimuth or with a lateral horizontal offset to the receiver line (Figure 4). This meant common mid-points were acquired along a variety of azimuths, e.g., orthogonal to one another. In the 1960's land surveys were conducted by deploying 'out of plane' or 'cross-spread' geometries thus increasing the range of azimuths and footprint over which the sub-surface rock structures were imaged.

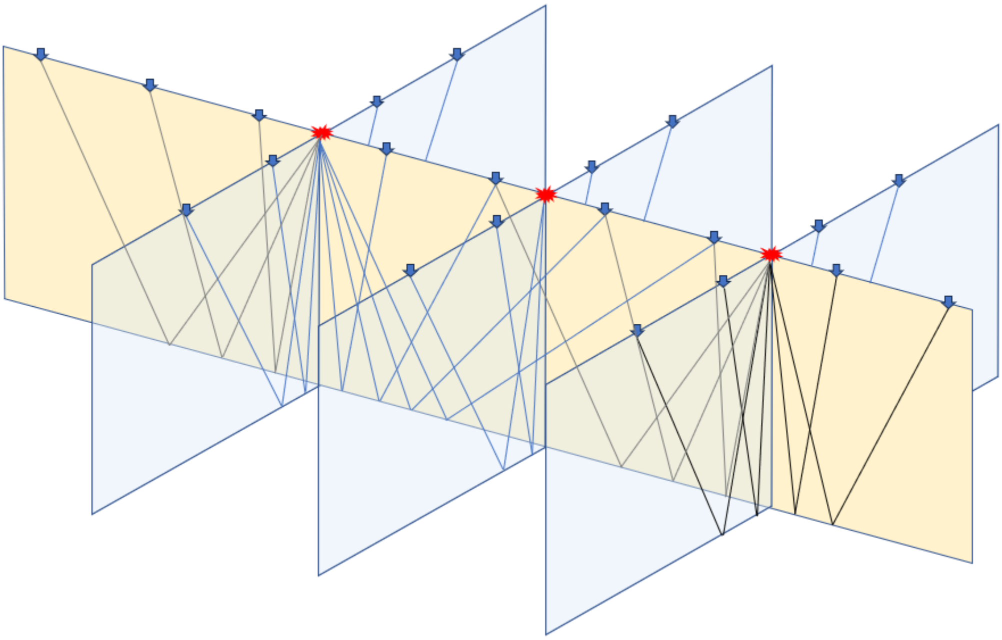


Figure 4: Out of plane concept

Signal quality: As the push for increased signal quality continued the concept of the seismic 3D survey was established with initial surveys being conducted in 1970s. In early field trials the pattern of receivers (blue squares, Figure 5) and shot locations (red circles) deployed were best achieved over a regular gridded area. Given the importance of geometry, the pattern of sources and receivers were designed such that multiple mid-points would image the same sub-surface points (black circles in Figure 5). With this configuration there was a marked improvement in the signal-noise ratio of the seismic trace data.

In the mid-1980s this approach was extended to performing 3D seismic surveys offshore. However, the task of making multiple seismic observations to image the same sub-surface points (from multiple source-receiver offsets) proved considerably more challenging than performing similar surveys on land. This was because of the dynamic nature of marine surveys (as opposed to static approach applied in land surveys) when data acquisition is conducted. Although the source is considered static at the time of firing, the receivers are in constant motion whilst 'listening' for the returning energy. Although continuously changing, only one coordinate is assigned to each receiver group to indicate its ‘fixed’ location at each shot point during acquisition. One major challenge was the technology available to determine the source and receiver positions of the in-water equipment and hence the precision of the mid-points used in the binning process. Positioning considerations are addressed in section 7.1.

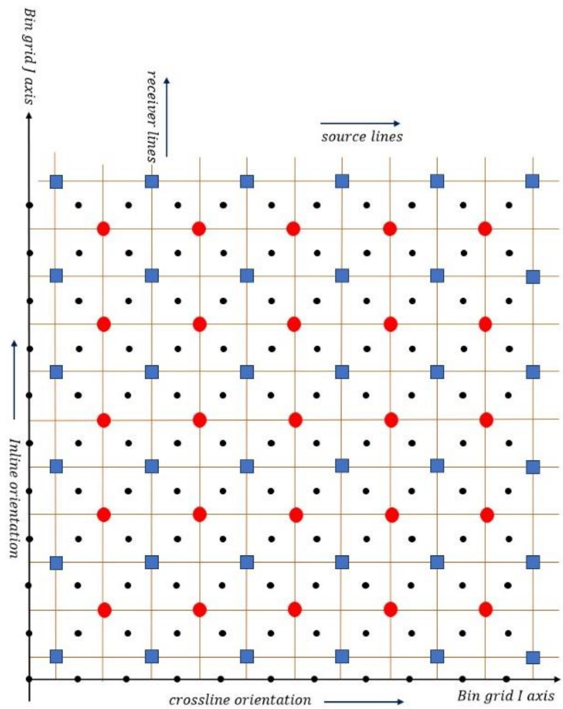


Figure 5: Offsets and azimuths contributing to a CMP

Environmental factors such as tides, currents and winds also disturb data acquisition to the extent of reducing the precision with which the source and receiver positions are derived. Towing the equipment several metres below the sea surface does place it below wave activity, even in moderate sea states, but this is still a harsh environment to make precise survey observations. Without such observation quality the precision of the final positions, and thus mid-points, is degraded.

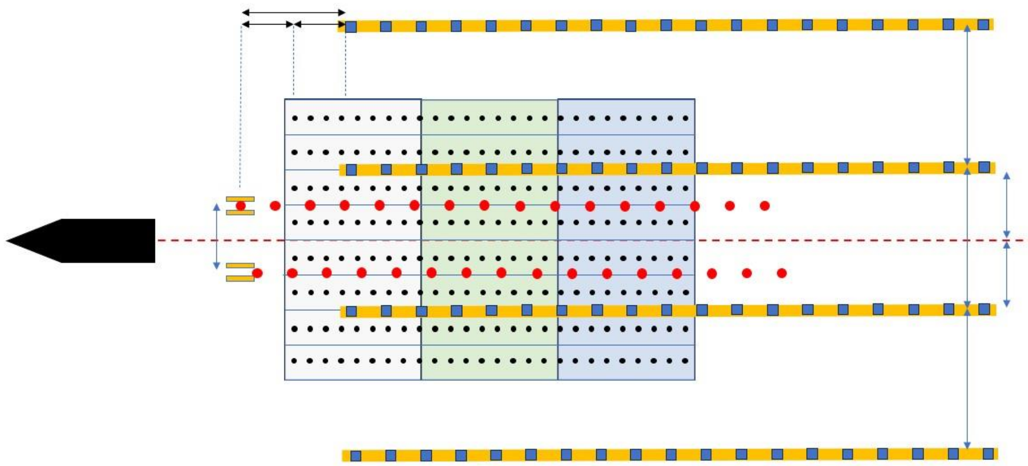


Figure 6: Marine seismic 3D survey geometry

In Figure 6, the same symbology is applied as Figure 5 with the blue squares representing the receiver groups located along each streamer. The red circles represent the location of the shot points (operating in flip-flop mode) and the black circles represent the geometric centre of each cell of the seismic grid over which the marine spread is currently navigating. The azimuth along which the shot points fire is the same as that of the receivers which is one of the limitations of this technique (see section 15).

Survey complexity: Over time, the complexity of surveys increased. The dimensions of the survey area grew significantly which increased the quantity of equipment deployed, e.g., multiple receivers and proposed source positions. This in turn led to considerably higher volumes of data being acquired and thus increased data processing requirements. The rapid improvements made in seismic data processing have perhaps been the biggest contributor to the improved images now generated, for example Full Wave Inversion. However, advances in the receiver technology generated greater signal clarity and the ability to make additional seismic observables, e.g., Shear waves observed in OBN surveys.

Survey types: Given the limitations of marine towed applications (see section 15) geoscientists began introducing more imaginative ways to acquire seismic trace data. For example, wide azimuth, rich azimuth, and circle shooting to name a few. Surveys using multiple vessels provided methods to increase offset range to image deeper geological targets. They also provided ways of imaging the sub-surface structures beneath static objects (platforms, reefs etc.) in what is known as undershooting.

Performing land style surveys in marine environments was introduced, first with ocean bottom seismic / cable (OBS / OBC) in the 1990s followed by ocean bottom nodes (OBN) in the 2000s. Here, the 'receiving' equipment is deployed on the seafloor rather than being towed through the water. The benefit is the creation of coupling between the node (the receiver) and the seabed thus enabling observations of shear waves (which cannot propagate through a liquid) in addition to primary waves using orthogonally mounted 3 or 4 component nodes.

4D surveys were introduced in 1990's where 'identical' surveys are performed over the same area separated by a lapse in time between acquisition, e.g., one to two years between surveys. Hence, they are also referred to a time lapse surveys. Their purpose was to increase knowledge of the physical reservoir and potential depletion rates through production over the fourth component of time.

Positioning: Regardless of the acquisition method employed, from a geo-spatial perspective the objectives remain common. Positioning techniques are required to ensure that precise coordinates are determined for the source and receiver locations at the time the acoustic energy is generated at each shot point. In this release of the book, there is a limited introduction to positioning techniques or in depth details of the different types of sources and receiver technology. What is included is found in section 7.1.

Design: To ensure the imaging of the sub-surface structures is conducted in accordance with the geophysical requirements set out by the project team, methods to optimize acquisition are performed. This includes a systematic survey design prior to data acquisition commencing and increased data management to administer the trace data acquired. An even and regular distribution of source-receiver offset pairs acquired at a desired horizontal geo-spatial resolution (imaging intervals) is pivotal in design considerations. Ensuring these goals are achievable is pivotal as is the compliant data management of the seismic trace data acquired. Equipping the seismic acquisition teams with functionality to perform such activity came in the form of a grid of regular shaped cells along two axes of a horizontal 2D coordinate system, the seismic grid.

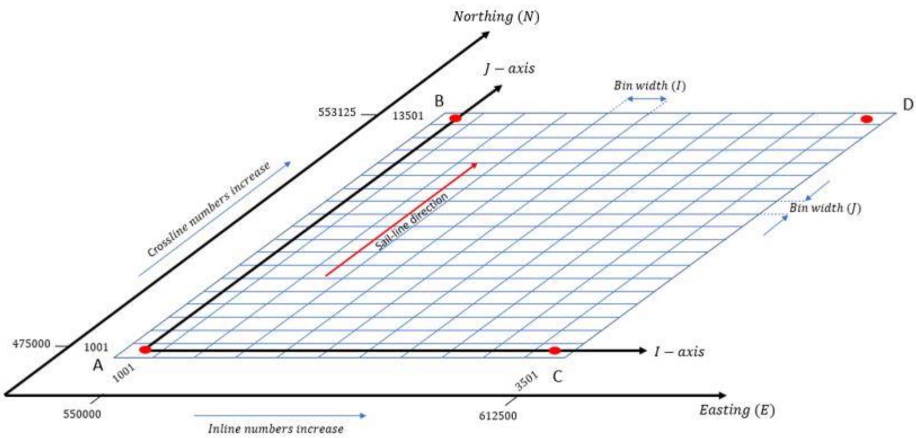


Figure 7: Grid representation

After precisely deriving positions for the seismic source and all receiver groups (at the time of shot), the mid-points are computed (the assumed position where the seismic trace data images the sub-surface structures) for all possible source-receiver offset pairs in the seismic spread. What remains (data management) is to determine into which cell of the seismic grid each mid-point position belongs for all source-receiver offset pairs acquired per shot point. This is a process known as 'binning' and when a source-receiver offset pair is attributed to a cell (also known as a 'hit') an increment of one is added to that cell's count. Over the course of the survey acquisition, each cell is required to have an even distribution of mid-points for all potential source-receiver offset pairs from the equipment deployed. The maximum number of possible offset pairs that can be attributed to each cell is known as the full fold coverage (the maximum count).

Seismic grids, for the design and management of seismic surveys, are not a new concept and have been around for decades (since the concept of seismic 3D surveys was introduced). However, the term 'bin grid' is deemed one that needs clarification and is a term that is used sparingly throughout this book. What follows is an introduction to how the seismic grid is designed and how it is used in acquisition, data processing, data loading and defining a proposed well location (PWL). Because of its importance it contributes to all steps of the exploration data cycle. Ensuring that correct coordinates, related to the designated coordinate reference system, are assigned to the PWL is an integral part of the audit trail that traces the history of the grid throughout each cycle stage (see chapter 14).

1.1 Usage

For narrative purposes, assume the general definition of the seismic grid remains unchanged throughout the life cycle of a project. For example, the corner points of the survey area remain the same as do the Coordinate Reference System(s) used. What does differ is the way information is captured and circulated between different stakeholders in the upstream cycle. Figure 9 illustrates some of the key stages of this process which are neatly separated into pre-survey and post-survey phases.

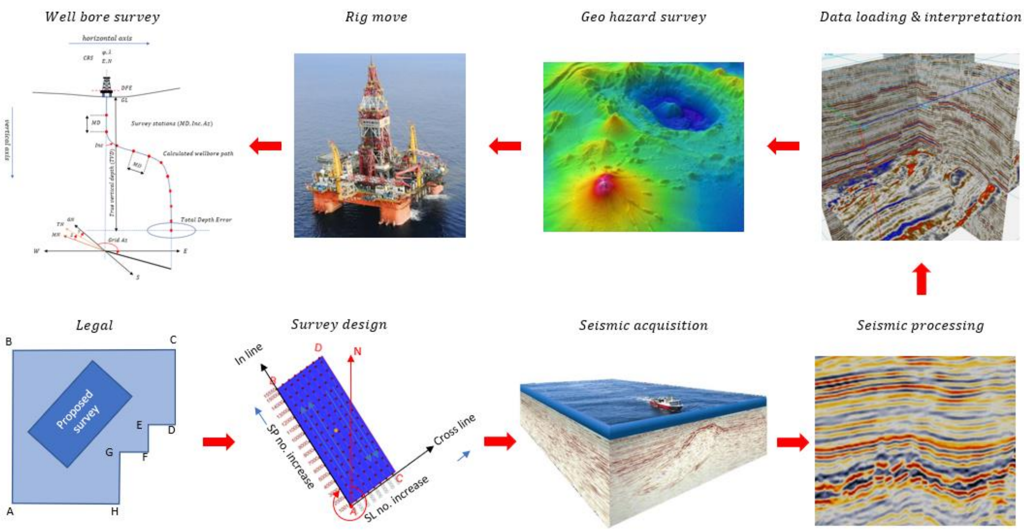


Figure 8: Data life cycle stages

Pre-survey: Stage one requires the project team specify their geophysical requirements, and the survey team specify the geo-spatial requirements, e.g., CRS parameters both of which are used in the initial survey design (see Figure 9). For example, what horizontal geo-spatial resolution and fold coverage are required when imaging the sub-surface rock structures. This directly impacts the geometry of the equipment deployed during acquisition and the theoretical population of source-receiver offset pairs in each cell of the seismic grid.

The resultant parameters and parameter values such as grid origin, cell widths, survey bearing, cell numbering (indexing) of the seismic grid comprise the conversion parameters defined in the Derived CRS. All these parameters are introduced in chapters 2 and 3. Also defined are the perimeters over which the survey can and cannot be conducted and these are introduced in chapter 4. The definition of the seismic grid conversion parameters are stored in one of several common exchange file formats which include the P6 and P1 file types, both published by International Oil and Gas Producers (IOGP) geomatics committee. These are utilized by the acquisition crew to ensure seismic trace data is acquired over the required perimeters to the tolerances specified.

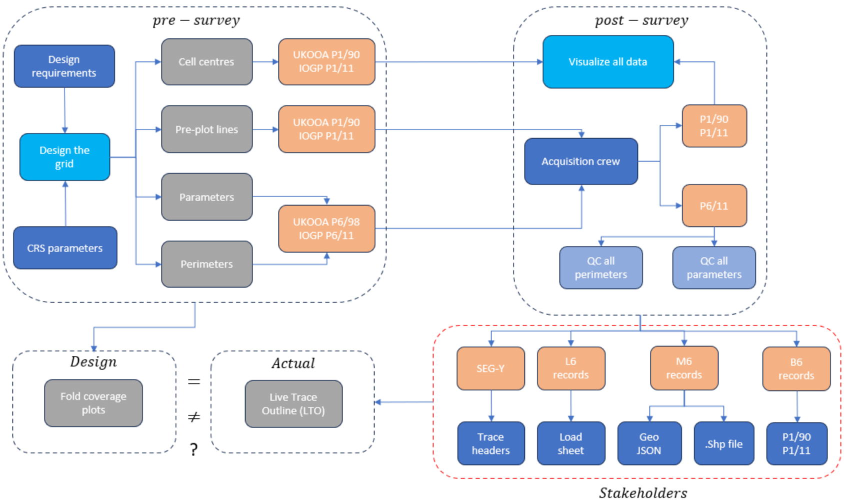


Figure 9: Generic dataflow

Post survey: The navigation and positioning data acquired on the survey will typically be delivered in P6 and either the P1, SPS or SEG-P1 data formats, depending on vintage and environment. The geo-spatial data contained therein is analysed by the survey / geomatics team both during and upon completion of data acquisition to ensure the navigation and positioning specifications have been achieved. Also supplied are the fold coverage plots created by the onboard binning module which illustrate the distribution of the source-receiver offset pairs acquired for the corresponding seismic trace data. Additionally, the cell centres of the full fold perimeters are captured in the trace headers of the SEG-Y file which forms an integral part of the post-survey checks.

Although the geo-spatial community recognizes the P6 and P1 formats they are not commonly used by other stakeholders in the exploration cycle. Therefore, it is important for the survey team to appreciate how the various stakeholders (geoscience teams) require definitions of the seismic grid and related perimeters to be presented for the work they perform. Some examples are shown in the blue box in the lower part of Figure 9. For example, .shp file, load sheet and GeoJSON formats. For further details of the file exchange formats, see section 9.

1.1.1 Geo-spatial / GIS teams

The P6/98 and P6/11 file formats are under the custodianship of International Oil and Gas Producers (IOGP) Geomatics committee and offer a comprehensive format architecture for storing the definition of the seismic grid and its associated perimeters. These formats provide real benefit to the geo-spatial team (Geomatics / Surveying) to ensure the integrity of the seismic grid (pre-plot and post-plot) with specific reference to the coordinate reference system(s), coordinate transformations, definition of the seismic grid metadata (e.g., origin, survey bearing, cell widths etc. that comprise the derived conversion parameters) and the extent of the perimeters over which the survey is acquired.

The GIS community do not need to know specific details of the seismic grid parameters other than the CRS to which the geo-spatial data is referenced, and the geographic extent of the perimeters assigned to that seismic grid, e.g., total coverage, full fold coverage, null coverage, and null fold coverage areas (see section 4.1.3). From a compliant P6 file the geo-spatial QC team can export shp files that represent the outline of the perimeters as polygons and points which can then be integrated into projects specifically designed to represent the survey outlines in relation to other available data types (e.g., culture data, satellite imagery etc.). Alternatively, for more ambitious users, refer to IOGP guidance note 483-6g that describes how data contained in the P6/11 file format can be employed in the bin grid GIS data model.

1.1.2 Seismic acquisition

Seismic crews operate software applications familiar (or should be) with the P6 and P1 exchange file formats which facilitates a seamless transition of the seismic grid, perimeters and pre-plot definitions from design to data acquisition. The deliverables expected from the completed survey will include, as a minimum, the post-processed positioning data (e.g., P1, SPS, SEG-P1) and the final definition of the extent(s) over which the survey was conducted (P6, .shp file). The extent is outlined by a collection of perimeters illustrating the geo-spatial area over which the seismic trace data was and was not acquired, for example, the total coverage area, null coverage areas and exclusion zones respectively.

1.1.3 Seismic processing

Seismic processing centres seldom recognize or use the P6 formats, instead preferring to store and extract positioning data from the trace headers of the SEG-Y files (see section 10). As such they have little reason to decode or encode the P6 format. Of more interest to them are the coordinates associated with the common mid-points or cell centres of the seismic grid which are hopefully stored in the appropriate byte locations of the SEG-Y trace headers. Data processing centres commonly modify the definition of the original acquisition grid to suite their in-house software applications. Such modifications include changing the origin of the seismic grid (used in acquisition) as well as renumbering, reprojecting, and merging of cells depending upon requirements specified by the client (see chapter 12).

Therefore, from the P6 file format the geo-spatial QC team are encouraged to create data files that contain the common mid-point coordinates associated with the cells of the seismic grid. One format used to exchange this data type is the P1/90 format, using the Q records (see section 9.4), or the P1/11 format using the P1 records, both usually in a decimated fashion. These data, when available can then be correlated to the coordinates captured in the SEG-Y trace headers. Upon QC checks being passed this results in the generation of a perimeter known as the Live Trace Outline (LTO) which describes the geographic extent over which all seismic trace data, regardless of fold coverage, was acquired (see section 8.2).

1.1.4 Data loading

Many of the popular interpretation software applications used by the geoscience teams do not recognise or decode the P6 format(s). Instead, the data loaders rely upon the load sheet (see section 9.5) or some equivalence that provides the basic details of the seismic grid perimeter definition to assist loading the seismic 3D volume from the SEG-Y file(s). For example, the coordinate reference system to which the projected coordinates of the trace headers belong.

Where a perimeter of the seismic grid requires specifying (as part of the loading process) it usually entails providing the coordinates of a minimum of three corner points, cell widths and increments along with the coordinate reference system to which these coordinates are related. It falls to the geo-spatial team to create the load sheet from the data contained in the P6 file delivered from seismic acquisition. An example of this illustrated in section 9.1 and how the latest version of the P6/11 format includes new data records to help facilitate this process.

1.1.5 Miscellaneous

Teams associated with the exploration cycle will typically include other stakeholders such as GIS, interpretation, reservoir, QI, Petrophysics etc. who use software applications that have little to zero understanding of the P6 and P1 exchange file formats. They are more likely to be familiar with formats such as

.shp files and GeoJSON (particularly with OSDU) to describe the area over which the seismic volume extends. The geo-spatial team should ensure such formats are generated from the P6 format once the original QC process has been finalized. Section 7 contains details and examples of these formats.

1.1.6 Other operations

During the data life cycle some additional coordinate operations may be performed on the seismic grid(s) for governance and data compliance purposes. These may include:

- Reprojecting a grid from a source Derived CRS to a target Derived CRS via conversion and or transformation
- Readjusting a grid after reprojection to ensure orthogonality
- Creating a master grid into which individual surveys are merged.

It is common practice for a survey to be acquired referenced to satellite datum but for the data to be delivered to authorities referenced to a local datum. This requires that data volumes are converted from the satellite to local datum to comply with project team or local governance matters. Details of these operations and processes are contained in section 12.1.

1.1.7 Disclaimer

Throughout this book reference is made to the International Oil and Gas Producers (IOGP), their geodetic parameter registry (epsg.org) and the guidance notes published by their Geomatics section which covers the treaty of 'the bin grid' thoroughly. The descriptions offered here are independent of IOGP and at times do differ from the definitions they provide. Here, a practical approach to the use of seismic grids for survey design and data management (binning process) is provided. These are solely the views of the publisher and not any regulatory or governance body.

2 Define the Seismic grid

Why is a seismic grid needed? What function does it perform and what benefits are derived from its use? To improve the signal to noise ratio of the seismic trace data (and thus the final images of the geological structures) multiple observations of the same sub-surface points (mid-points) are made. The sub-surface point is not actually a 'single' point, but a small rectangular area defined by two widths along the two horizontal axes of a local cartesian 2D / 3D coordinate system (see section 2.2.1). The cell widths (along axis 1 and axis 2) will determine the area of the rectangle as shown in Figure 10 (e.g., 25m x 12.5m = 312.5 sq. m.).

The horizontal plane comprises a structured arrangement along the two axes to create a blanket of cells that cover the geographic area over which the seismic survey is / was conducted, this is known as a perimeter. The widths selected for the cells have important ramifications to the imaging of the sub-surface structures and the geometric arrangement demanded of the seismic equipment deployed during acquisition. Both matters are addressed in section 3.

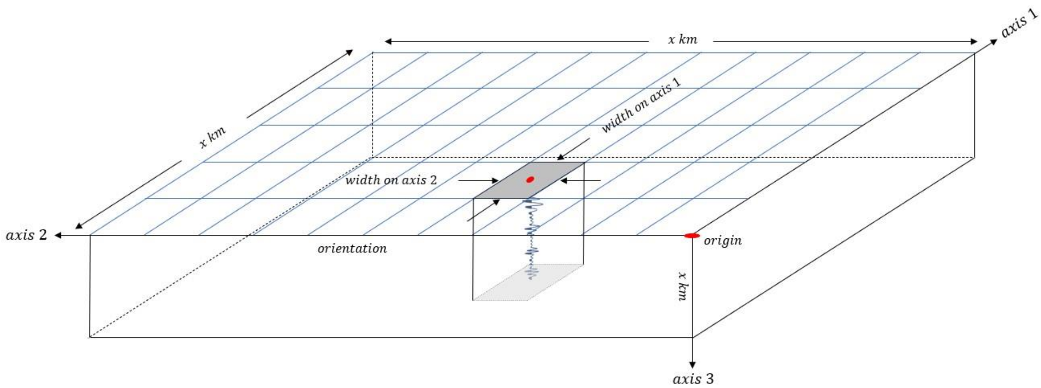


Figure 10: Generic grid with cartesian 3D coordinate system

For narrative purposes a seismic survey is acquired over a pre-defined geographic area (e.g., 30 x 20 km) and will image the geological strata to the depth (e.g., 6-7km, axis 3) of the intended target(s) and beyond. After the seismic 3D survey has been processed a cube of trace data is delivered at a spatial resolution specified in the initial survey design and or processing requests specified by the client. In the horizontal plane the geo-spatial resolution is specified by the size of the cells comprising the seismic grid and in the vertical plane by the sampling interval set in the seismic recording system (e.g., 2milliseconds). However, when designing the seismic grid only the geo-spatial horizontal component of the cube is considered. The design specifies what is required or expected to happen prior to the survey commencing. It is only when the survey is undertaken does the data bear out whether the design criteria has been honoured to the tolerances required. This is the quality assurance and quality control performed by the seismic crew in ensuring there is adherence to the contract specifications.

2.1 The concept of binning

As the survey is conducted all seismic trace data whose horizontal mid-point coordinates (correlating to a source-receiver offset pair) fall within the boundary of each individual cell are 'gathered'. The gathered / summed seismic trace data (in each cell of the grid) is assigned a horizontal coordinate equal to the common mid-point of that cell, e.g., cell centre. This is deemed to be the location where the sub-strata was imaged in a vertical plane below that point.

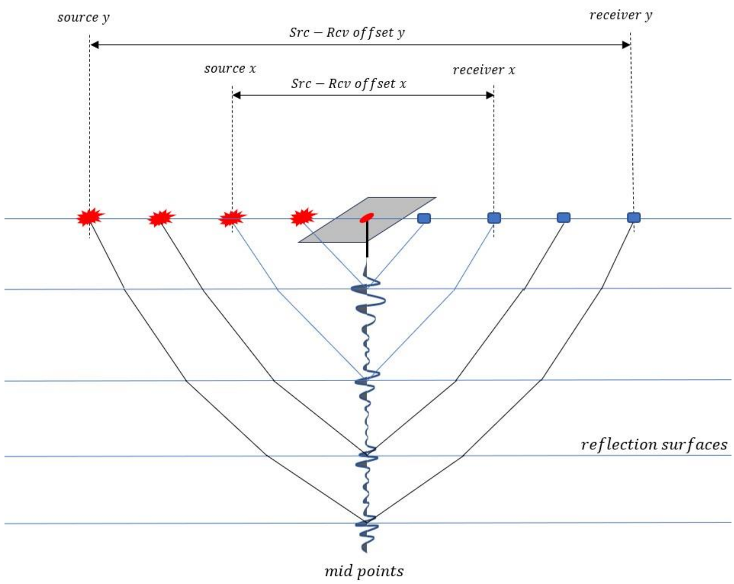


Figure 11: Source-receiver offsets

Here, a source-receiver pair is defined as the combination of the source array (that fired) and any of the receiver groups in the spread (e.g., port source array and receiver group 1 on streamer 4). Thus, the source-receiver offset is defined as the horizontal separation between the shot point (of the seismic source that fired) and the receiver listening for the returning reflected seismic data. The mid-point is defined as the halfway point between the two and there will be multiple mid-points from different source-receiver offset combinations (Figure 11). Each ensemble will be ‘gathered’ into a small, indexed area of the seismic grid known as a cell. The number of source-receiver offset pairs gathered into each cell is known as the fold coverage and the maximum number of pairs that it is possible to acquire per cell (with the deployed survey configuration) is known as the full-fold coverage. The entire seismic grid will comprise a juxtaposed collection of cells along the two horizontal axes of the 2D/3D grid coordinate system. The full fold perimeter specifies the extent of cells of the seismic grid into which seismic trace data is expected to be collected.

For the final product to be considered complete it is important to ensure that over the extremity of the survey area (full fold area) the sub-surface is imaged in a consistent manner. This requires uniformity of coverage in each cell of the full fold perimeter of the seismic grid, which should contain an identical number of range offsets from all possible source-receiver offset pairs (see section 7). Put another way, each common mid-point (e.g., cell centre) has the same number of source-receiver offsets contributing (regardless of environment or acquisition method).

Therefore, the main challenge in a seismic 3D survey is not the design of the seismic grid but one of how to manage the data that is acquired. This requires determining what observations, generated by the different shot points, and recorded by the different receiver groups, have mid-points that are common to each cell of the full fold perimeter of the seismic grid. From a data management perspective, it is essential to determine into which cell of the seismic grid perimeter each source-receiver offset shall be assigned and thus what trace data be gathered in seismic processing (see section 7).

The planning and management tool devised to address this matter is the seismic binning grid module which forms a key component of the software applications used on seismic 3D surveys. As such it provides the formal mechanism that:

- Acts as a design tool to define the common collective attributes for all the cells of the seismic grid that meet the azimuthal and geo-spatial resolution requirements set by the geoscience team.
- Acts as a data management tool to manage all the seismic trace and geo-spatial data acquired on the survey.
- Ensures that every source-receiver offset pair is assigned to the correct cell of the full fold perimeter of the seismic grid and that the positioning tolerances adhere to the thresholds specified in the contract specifications.

Consider a marine survey where the vessel tows multiple streamers and sources (Figure 12). This results in multiple common mid-point lines being acquired simultaneously for every vessel sail line. See section 5.4 for further details.

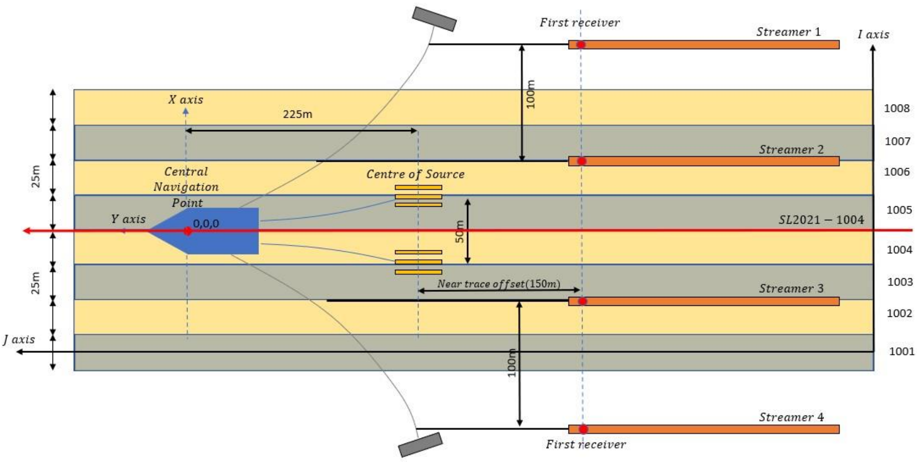


Figure 12: CMPs acquired from the spread deployed

The geometry of the acquisition spread will determine the dimensions of the common mid-point lines in the crossline direction (see section 5.4.1), i.e., along the $I\ axis$ of the grid. Alternatively, the crossline dimension of the common mid-point lines will determine the geometric spread used in acquisition. Either way, this influences the horizontal geo-spatial resolution with which the sub-surface structures are imaged by the seismic trace data (not to be confused with seismic resolution in the vertical and horizontal plane, see section 8.1.2.). Unlike a seismic 2D survey the juxtaposition of the common mid-point (CMP) lines in a 3D survey result in the sub-surface being imaged as a three dimensional cube.

2.2 Designing the seismic grid

The following attributes all contribute to characterizing of the seismic grid definition prior to it being incorporated into the definition of a coordinate reference system (see section 3):

- The coordinate axes and coordinate system
- The origin of the coordinate system
- The widths of the cells along the two axes of the coordinate system

- The increment of the cells along the two axes of the coordinate system.

How the attributes are defined and how they contribute to the definition of the seismic grid and the derived conversion parameters of the Derived CRS is addressed in the remainder of this section.

2.2.1 Coordinate axes and coordinate system

Start by defining the coordinate axes which comprise the horizontal plane of a Cartesian 3D coordinate system used in the definition of the seismic grid and thus the Derived CRS (see section 3.3).

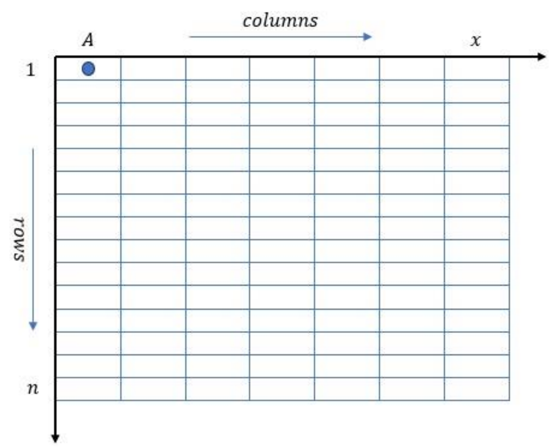


Figure 13: Grid of an excel spreadsheet

For those unfamiliar with a seismic grid consider the grid and indexing associated with an excel spreadsheet. The excel spreadsheet appears as a grid of cells, each of which can be uniquely indexed by establishing an 'address' for the cell. Here the indexing is given by Column and Row, e.g., A1 (blue circle in the upper left hand cell). Therefore, the grid has two axes named Columns and Rows which have an orthogonal relationship. They meet at the origin (first cell, A1) which is shown in the upper left hand corner of Figure 13. Along each axis the cells increment by a factor of 1: For Columns it is represented by letters (A, B, C etc.) and for Rows it is integers (1, 2, 3 etc.). The incrementation is positive along both the Columns (Column Positive) and Rows (Row Positive). For completeness, the orientation of the grid could be considered Column Positive, but this is irrelevant in this scenario.

2.2.1.1 Modify this grid

Take the grid illustrated in Figure 13 and rotate it 180^o around the Column Positive axis as shown in Figure 14.

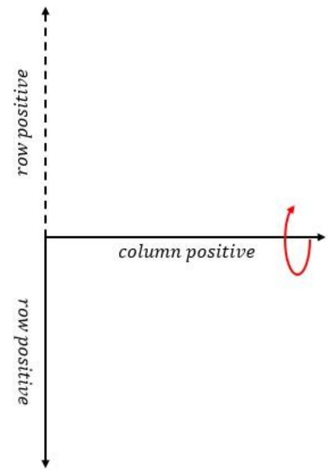


Figure 14: Rotate the grid through 180 degrees

Once rotated, a grid like the one shown in Figure 15 will result. Next, a modification is made to the indexing of the cells along the Column axis such that integers replace letters. Therefore, the index of the origin cell now becomes (1, 1). Because of the rotation the origin of the grid now appears in the lower left hand corner (blue circle).

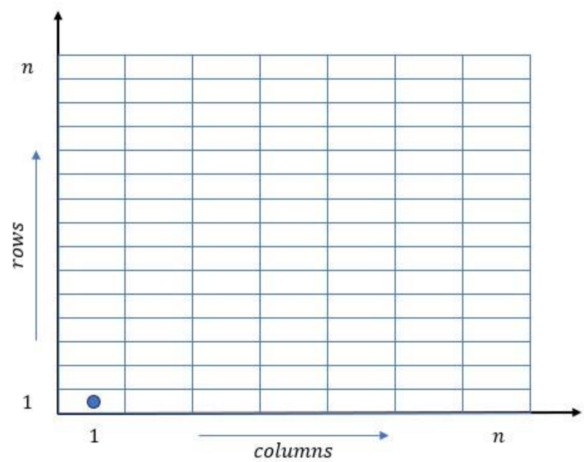


Figure 15: Grid after it has been rotated

2.2.1.2 Further modification

Take the grid shown in Figure 15 and re-label the two axes accordingly. Hence, the Row and Column axes become $Bin\,Grid\,I$ and $Bin\,Grid\,J$, which are abbreviated to I and J respectively. All other parameters remain the same. This is now metamorphosing into something that the more informed reader will recognise as a seismic 'binning' grid. Both axes have three attributes that describe the name, abbreviation, and orientation, as shown in Figure 16. Therefore, any cell in the grid space is uniquely referenced using the I and J numbering along the two axes, e.g., $P\ (I,J)$.

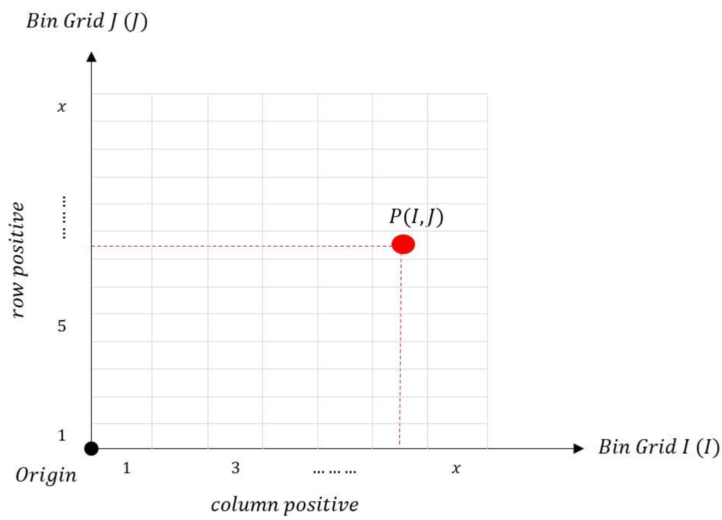


Figure 16: The grid after applying modifications

**The labels used on the diagrams from this point onwards are those adopted in the IOPG guidance note 483.6.1 (IOGP, 2017).*

Two different types of coordinate system known as the ordinal and affine require introducing as they impact the unit of measure (bin) used to the describe the magnitude of Point (P). The difference between the two is summarized as follows:

- The ordinal coordinate system has two axes which are orthogonal to one another and the unit of measure applied along each axis is the same which is counted as whole integers. Point (P) is specified by a pair of integer coordinates away from the origin.
- The affine coordinate system (describing affine space) comprises two axes which are independent from one another. They are not necessarily

orthogonal and do not have to share the same unit of measure but can. In Figure 17 the point (P) is shown as the place where the two perpendicular lines to the axes meet. Although affine space can be multi-dimensional the example shown here is for plane surface only.

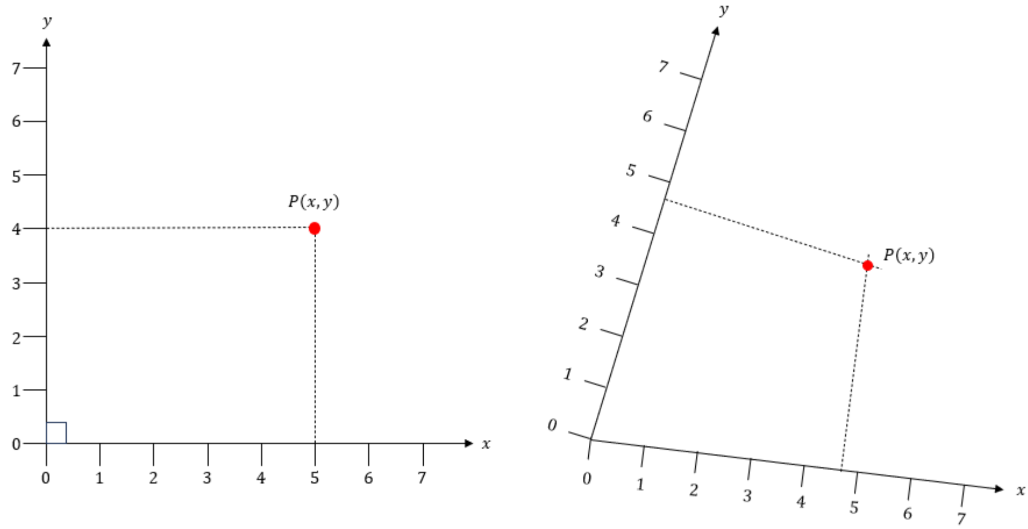


Figure 17: Ordinal versus affine coordinate systems

2.2.2 Magnitude along the axes

The magnitude that a point (P) lies away from the origin specifies its position in the coordinate system. However, to achieve this requires a decision be made on how the magnitude along each axis is described. This depends upon the type of coordinate system as described in section 2.2.1. which will either relate to the ordinal or affine coordinate system. Therefore:

- Magnitude is given as an integer number (e.g., 1, 2, 3, 4, 5 etc.)
- Magnitude is given as a real number (e.g., 312.5, 625.0 etc.)

This parameter is defined as being the data type. These are represented as follows:

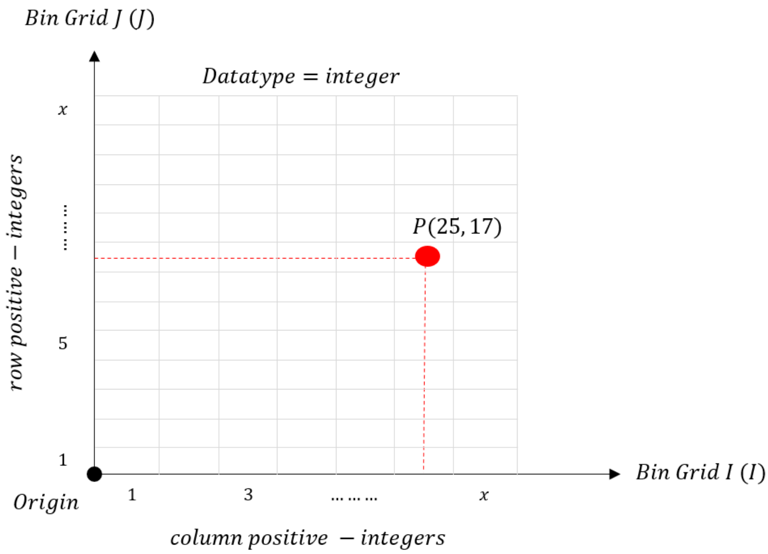


Figure 18: Right handed orientation – with integers

Figure 18 shows the ordinal coordinate system where the magnitude (ticks) along each axis is described using integers, i.e., a whole numbers of cells away from the origin. Therefore, the position of point P is given by the two integer numbers along the I and J $axes$ respectively (the coordinate tuple), e.g., P (25,17) is 25 units along the I $axis$ and 17 units along the J $axis$. Therefore, the data type used is Integer.

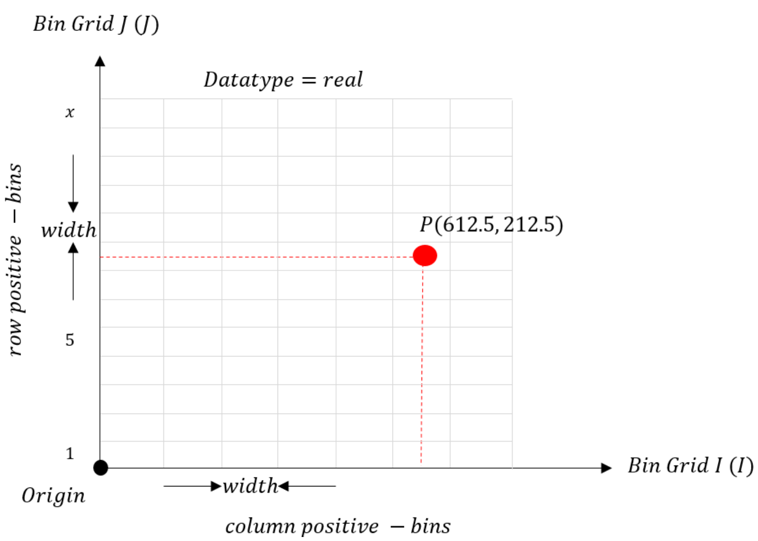


Figure 19: Right handed orientation – with reals

In Figure 19 is a 2D coordinate system where the magnitude (tick) along each axis is described using real numbers, i.e., a decimal number / distance away from the origin. Therefore, the position of point P is given by two decimal numbers along the I and J axes respectively, e.g., P (612.5, 212.5) is a distance of 612.5 metres along the $I\ axis$ and 212.5 metres along the $J\ axis$. Therefore, the data type used is real.

2.2.3 Orientation of the coordinate system

In the 2D cartesian coordinate system the relationship between $I\ axis$ and $J\ axis$ axes shall be orthogonal, i.e., right-angled. Therefore, rather than using $I\ axis$ and $J\ axis$, an alternative naming applied to the $I\ axis$ of the grid is:

- $J\ axis$ + 90°

Or

- $J\ axis$ - 90°

The orthogonal relationship implies that the $I\ axis$ will always be orientated 90^o to the $J\ axis$.

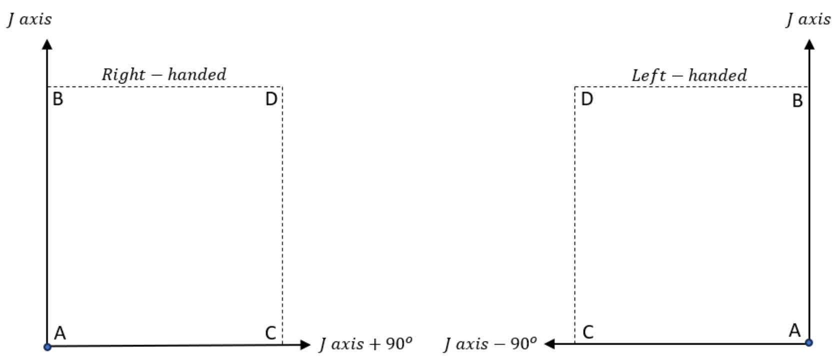


Figure 20: Alternative axis labelling

If the bearing of the $I\ axis$ is ($J\ axis$ + 90^o) the seismic grid is a Right-Handed, which is illustrated in both Figure 18 and Figure 19. However, if the bearing of the $I\ axis$ is $J\ axis$ - 90^o the seismic grid is Left-Handed as shown in Figure 21 and Figure 22.

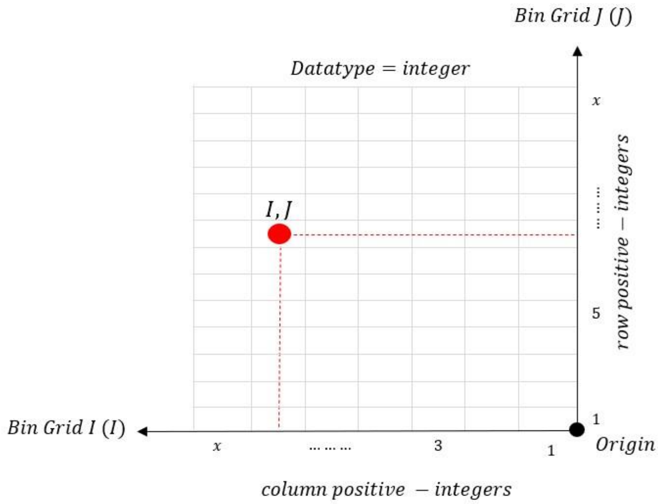


Figure 21: Left handed orientation - with integers

Following the convention used in the previous examples, the position of point (P) in left-handed seismic grids can also be described using either Integers and Reals in the same manner.

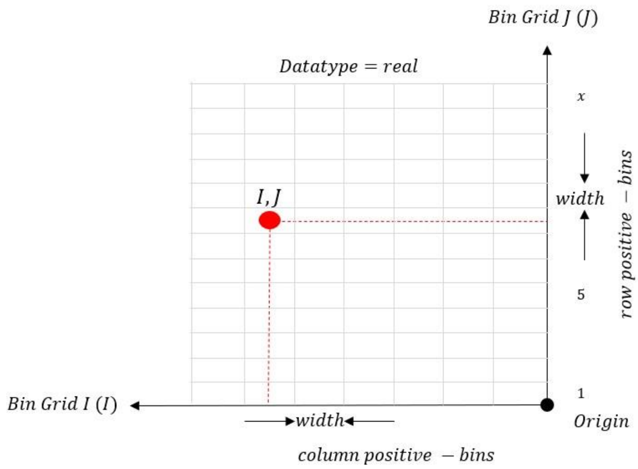


Figure 22: Left handed orientation - with reals

2.2.4 Alternative grid axes names

The seismic grid has two orthogonal axes which thus far have been labelled $Bin\ grid\ I$ and $Bin\ grid\ J$, abbreviated to I and J respectively (recommended by IOGP). More commonly, they are referred to as $I\ axis$ and $J\ axis$, or $J\ +/-\ 90^o$

and $J\ axis$. However, other combinations are applied with naming pairs that include:

- Inline and Crossline
- Track and Bin
- Sail-line and Shot point
- I and J

What convention is used is a matter of preference for an individual or organisation, it is a personal choice. However, the I and $J\ axes$ IOGP convention is recommended and will be used throughout this publication.

2.2.5 Grid attributes

Having defined the coordinate system, the next step is to define the basic attributes of the seismic grid, e.g., the cells that comprise the seismic grid and the area the grid will cover. The first parameters addressed are as follows:

- Origin: I_o, J_o
- Cell dimensions
- Increments
- Orientation
- Grid extents

2.2.5.1 Origin (Io, Jo)

The seismic grid origin is the point (black circle) where the two axes of the 2D cartesian coordinate system merge and is labelled Io, Jo as shown Figure 23. Note, the origin of the coordinate system is shown to coincide with the centre of the first cell of the grid (black circle) and not its lower left corner. This is deliberate and is the preferred association in the definition. This cell must also be assigned an address or indexing such that it can be uniquely identified.

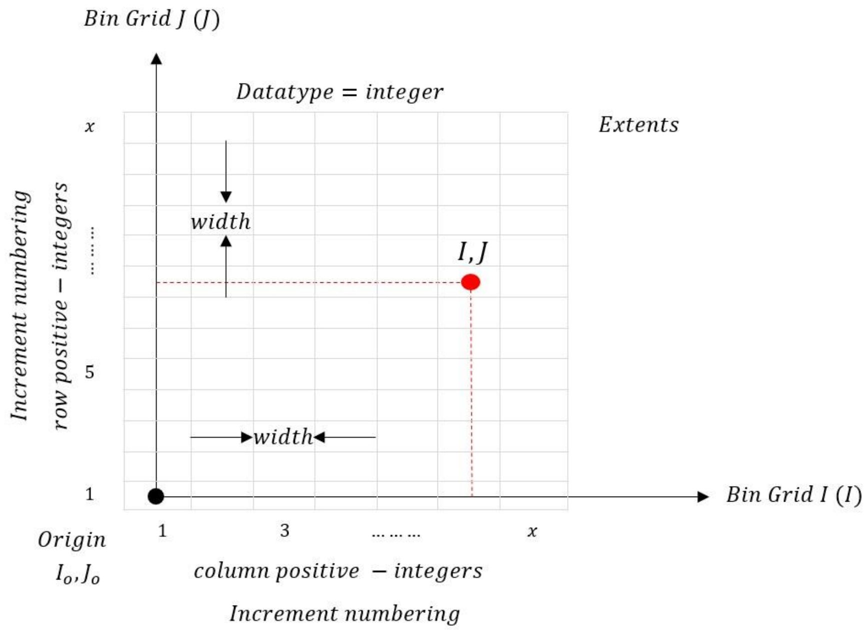


Figure 23: Parameters of the grid

This is the numbering applied at the origin for both the I and J *axes* of the coordinate system and in the example shown in Figure 23 the first cell is numbered 1 and 1 respectively. Along both axes these numbers will increase (increment) positively, e.g., column positive and row positive. In theory, it can take any number, either integer or decimal. However, for true ordinal coordinate system integers are used.

2.2.5.2 Cell widths

Two dimensions are specified to describe the width of the cells, one dimension along the I *axis* and one along the J *axis*. The values can differ between axes, but they must share the same units, e.g., data type and value. All cells along the I *axis* (width) must be the same size (e.g., 25 metres) and all cells along the J *axis* (length) must also be the same size (e.g., 12.5, or 6.25 metres). This is a condition of the similarity transform which (see section 11.2) demands uniformity in cell width and unit of measure along the two axes. Hence, the cells along the I *axis* are known as *Width on I axis*, and the cells along the J *axis*, as *Width on J axis*.

$$cell\ width\ (I) \napprox cell\ width\ (J)$$

The unit of measure assigned to the values of the cell widths must match the unit of measure used in the definition of the associated projected CRS (see section 3.3, Derived CRSs). This defines the horizontal geo-spatial resolution with which the rock structures are sampled as it delimits the footprint of the cells into which the seismic trace data, (associated with the source-receiver offset pairs), are 'gathered' (refer back to Figure 10). The smaller the cell widths the higher the geo-spatial resolution or the finer the sampling of the sub-surface structures. A typical geo-spatial resolution applied on a marine towed seismic survey include I = 25m and J = 12.5m, and I = 25m and J = 6.25m. Those used on land and OBN surveys are normally the same (e.g., 25m along both axes). However, with finer sampling comes a reduction in the fold coverage expected in each cell (see section 5).

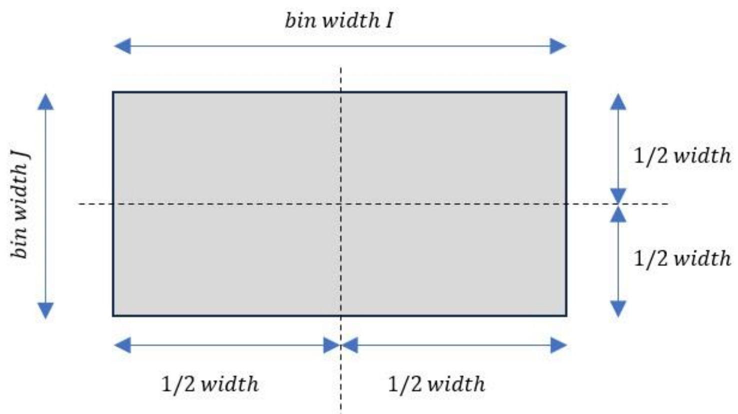


Figure 24: Widths of a cell along the two axes of the coordinate system

**The term resolution used in this capacity refers to the geo-spatial resolution of each cell of the seismic grid in the horizontal plane. It is not to be confused with seismic resolution (in the vertical plane) which describes the thickness or spacing between each reflector identified in the processed seismic volume.*

2.2.5.3 Increment

All cells in the seismic grid are uniquely identified by a number known as the cell index. The index of the first cell in the seismic grid has already been specified using I_o,J_o. What needs stipulating is by what value does the indexing of adjacent cells increase along the two axes when moving away from the origin? This is known as the increment and by default it is set to one on both I and J $axes$. The names applied to the increments are *Node Increment on I axis* and *Node Increment on J axis* respectively.

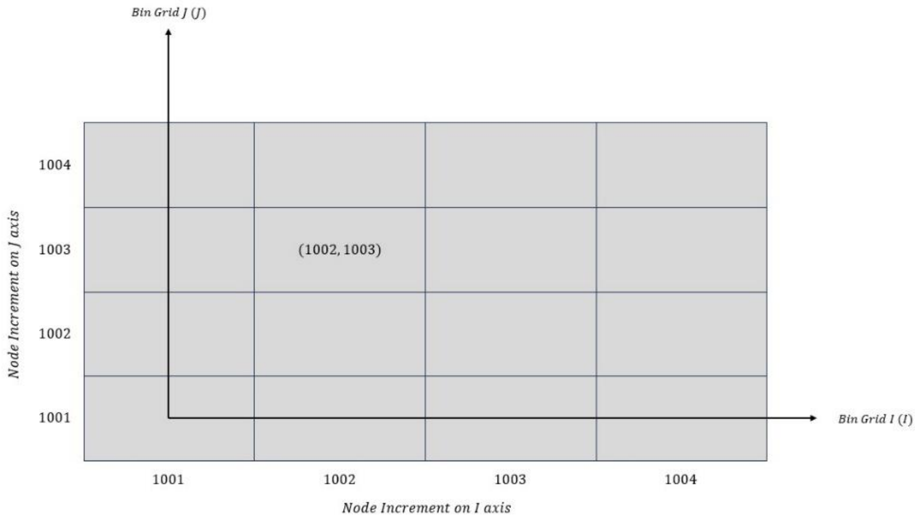


Figure 25: Increments along each axis

In Figure 25 the numbering (indexing) at the origin is specified as I 1001, $J = 1001$. The increment along each axis is given as 1 (Node increment on I and J $axes$) as shown and adjacent cells increase by that number away from the origin in a positive manner. However, the choice of numbers assigned to the origin (indexing) and the increment applied along each axis constitutes one of the unique features of the seismic grid definition. Theoretically, this can be either an integer or a real number.

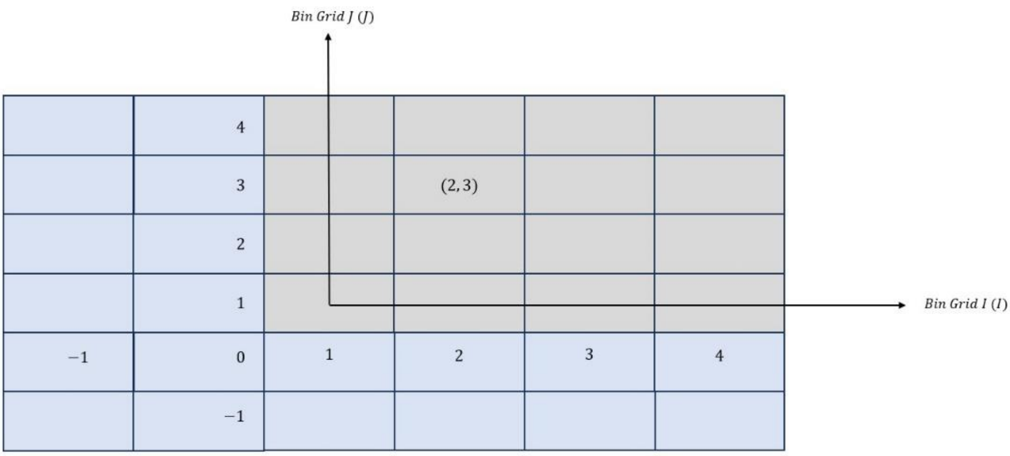


Figure 26: Inclusion of negative numbers

It is advised that the indexing assigned to the origin is not so small as to induce negative number in cells on the peripheral areas of the seismic grid as shown in Figure 26. Negative indexing has traditionally caused problems in processing the seismic trace data and to be removed requires the origin being moved and the cells renumbered.

2.2.5.4 Number of cells along each axis

What extent of cells are there along the I and J $axis$ of the seismic grid? The total number of cells along each axis must be sufficient to exceed the size of the survey area (plus a buffer). There is a strong argument that the number of cells does not need specifying here because it is addressed when the survey perimeters are defined (see sections 4 and 9.1.3). However, for narrative purposes the survey area has dimensions of 30km and 20km along the I and J $axes$, respectively.

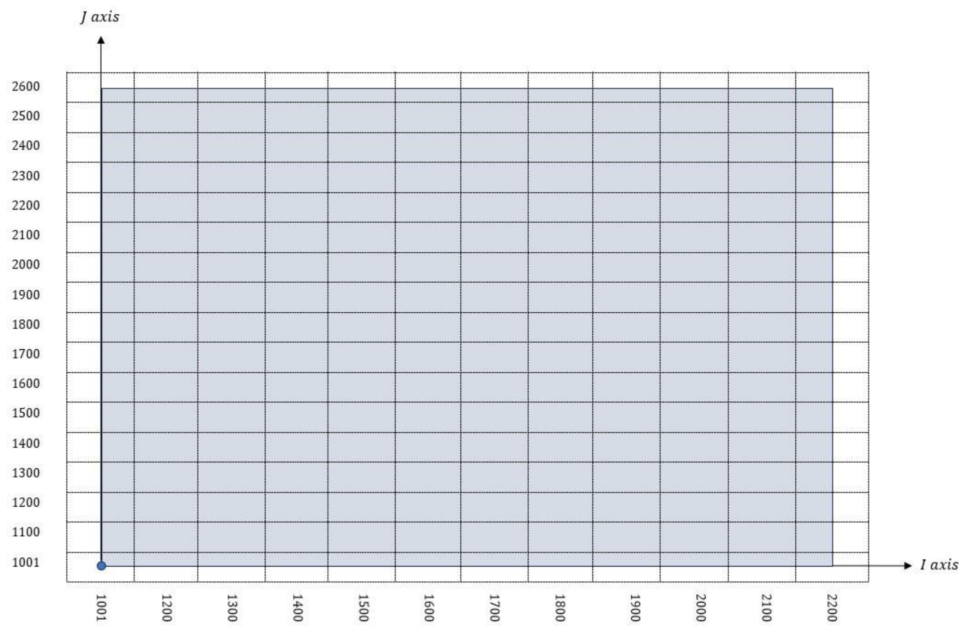


Figure 27: Cell ranges along each axis

Assume that the widths for the cells are 25m and 12.5m along the I and J $axes$ respectively. Therefore, the minimum number of cells required to cover the survey area will be as follows:

$$I_{Range} = \frac{30000}{25} = 1200$$

$$J_{Range} = \frac{20000}{12.5} = 1600$$

If the cell numbering applied at the origin, is $I = 1001$, $J = 1001$, the extent of the cells along the two axes is given by the four corner points as follows:

A	I_{min}	1001	J_{min}	1001
B	I_{min}	1001	J_{max}	2600
C	I_{max}	2200	J_{min}	1001
D	I_{max}	2200	J_{max}	2600

This is graphically represented in Figure 27 where the seismic grid is incremented to display of every 100th cell along the two axes of the grid coordinate system. The shaded area represents the extent of the proposed survey and is equivalent to defining the full fold perimeter shown in section 4.1.1.

2.2.5.5 Orientation

The orientation describes the directional relationship between the two orthogonal axes of the seismic grid and follows the same convention as that already described in section 2.2.3.

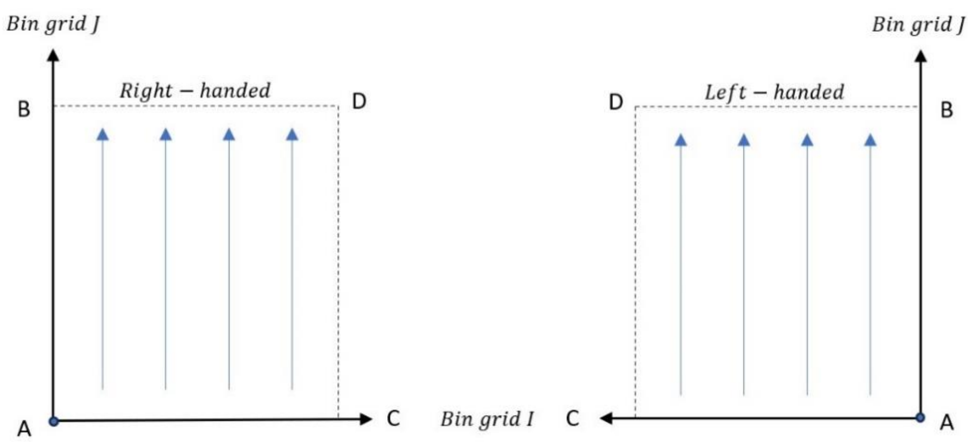


Figure 28: Right handed versus left handed orientation

Therefore, the seismic grid can take one of two conventions which are:

- Right-handed orientation ($J\ axis$ + 90°)

Or

- Left-handed orientation ($J\ axis$ - 90^{o})

By labelling the four corner points of the seismic grid with letters A, B, C and D the two possible orientations are illustrated in Figure 28. Note, corner point A coincides with the origin of the seismic grids shown in Figure 18 to Figure 22 regardless of their orientation.

Consequently:

- The right-handed orientation is one where point C lies to the right of line A-B.

And:

- The left-handed orientation is one where point C lies to the left of the line A-B.

With the palm of your right hand directed to your face the index finger shows the orientation of the Bin grid $J\ axis$ and the thumb shows the orientation of the Bin grid $I\ axis$. The Z axis is thus orientated along the middle finger. As the seismic grid is two dimensional the Z axis is not considered.

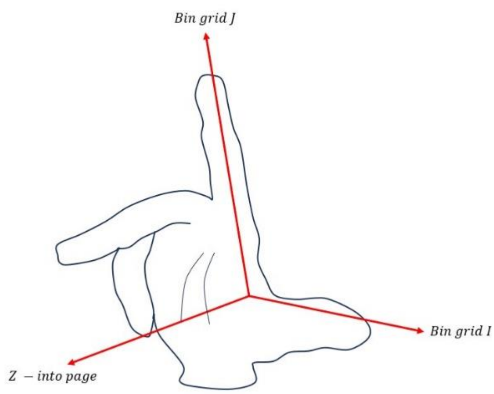


Figure 29: Right handed rule

2.3 Grid parameters and parameter values

The attributes thus far assigned to the seismic grid (the parameters and parameter values) are listed in Table 1. With respect to the unit of measure column, the unit assigned to the seismic grid origin and axis increments is the *bin*, which is the unit introduced by IOGP. The *bin* is effectively a scaling quantity applied to the two axes of the seismic grid to recognise the cell widths related to the affine transformation and the scale factor of the bin grid.

Table 1: Basic grid parameters

Parameter	Value	Unit of Measure
Grid origin I	1001	Bin
Grid origin J	1001	Bin
Width on I axis	25	metre
Width on J axis	12.5	metre
Increment on I axis	1	Bin
Increment of J axis	1	Bin
Number of cells along I axis	1500	Integer
Number of cells along J axis	4000	Integer

The current definition results in a simple grid which is graphically represented in Figure 30. It currently has no real world meaning (no geo-spatial attachment) because the seismic grid has no real world origin and survey bearing.

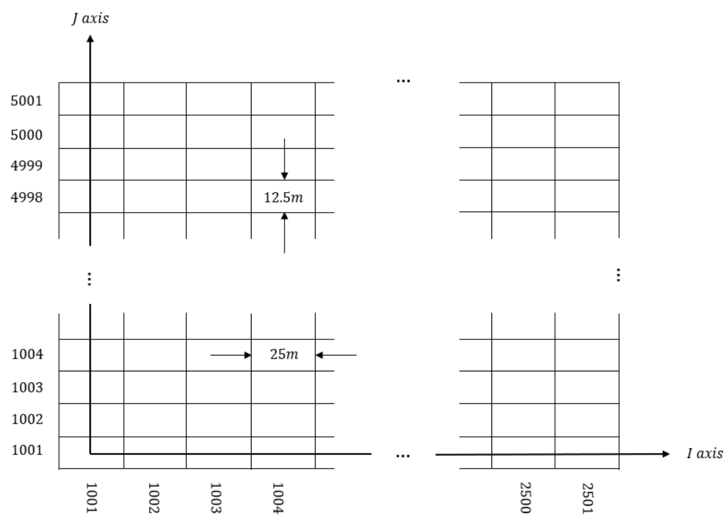


Figure 30: Basic grid design

Therefore, the seismic grid is ‘floating’ or arbitrary and for it to have any real use requires additional attributes be assigned which incorporates the coordinate system into the definition of a coordinate reference system. These are described in section 3.1.1.

3 CRSs associated with the grid

Geo-spatial referencing is formalized through the selection of an authorized Coordinate Reference System (CRS) against which the physical location of assets are specified to remove any positioning ambiguity. Here, an authorized CRS is described as one whose definition is either recognized as a pre-defined entry in the EPSG geodetic parameter registry or is a user-defined entry added to a localized version of the registry by the company's geo-spatial team.

Currently, the seismic grid defined in section 2 is considered arbitrary with no real world meaning as the cartesian 2D coordinate system is not tied to any specify body. This is achieved by assigning an origin and survey bearing in relation to an authorized CRS. In section 3.1.1.1 the coordinates of the physical origin (E_o, N_o) are introduced along with the survey bearing in section 3.1.1.2. which introduces the first CRS associated with the seismic grid, namely:

- Projected CRS (section 3.1.1)

Using all the parameters described in section 2 and section 3.1, there are two approaches by which a seismic grid CRS is defined. These methods are known as the following:

- Seismic grid of type: Engineering CRS (section 3.2)
- Seismic grid of type: Derived CRS (section 3.3)

The Engineering CRS was the original approach used as the seismic grid was considered best suited to this classification of CRS at the time. However, this is superseded with the introduction of the Derived CRSs which is a more logical approach, as will be demonstrated in section 3.3.

A fourth CRS, another Engineering CRS, is also introduced because of its use in defining the nominal offsets that describe the physical position of the seismic equipment in relation to the origin point and orientation of that CRS. This is applied to equipment both onboard the vessel and those towed behind and is known as:

- Moving platform CRS (section 3.4)

With the CRSs defined, coordinate operations of type: conversion and transformations are performed between them such that the position of vessel, sources, receivers and CMPs can be referenced to whichever CRS is required. These operations are paramount in the seismic binning process and examples are given in section 8.

3.1 Additional grid attributes

To give the seismic grid further context the following attributes require adding to the definition:

- The projected CRS and its base geographic 2D CRS
- The origin of the seismic grid related to the projected CRS, i.e., the Easting (E_o) and Northing (N_o) that correlate to the I_o and J_o grid origin
- Survey bearing with respect to Grid North, i.e., the grid bearing (θ) of $J\ axis$
- Extent: the geographic area over which the seismic survey will be conducted.

3.1.1 Projected CRS

To give the seismic grid definition real world meaning requires the selection of a projected CRS against which E_o, N_o and θ are referenced. The selection of CRS is important for the following four reasons:

- First, the CRS must have an extent (defined within the usage, see section 3.1.2) that sufficiently covers the geographic area over which the seismic survey is acquired. An example is shown in Figure 31.
- Second, the unit of measure used to define the cell widths of the seismic grid must match those used in the CRS definition.
- Third, the projected CRS is defined in relation to grid north and thus the survey bearing of the seismic grid must be given in relation to the same north reference.
- Fourth, the coordinate tuple defined in the CRS must be replicated when defining the coordinates of cell centres of the seismic grid.

Figure 31: Extent for Timbalai 1948 / UTM zone 49N

3.1.1.1 Origin (E_o, N_o)

In section 2.2.5.1., the origin of the seismic grid was specified by two coordinates labelled I_o and J_o whose parameter values reference the centre of the lowest indexed cell of the seismic grid (e.g., $I_o = 1001, J_o = 1001$). This is sometimes referred to as the lower left corner which can be very misleading when the survey bearing takes an oblique value. This terminology is not encouraged.

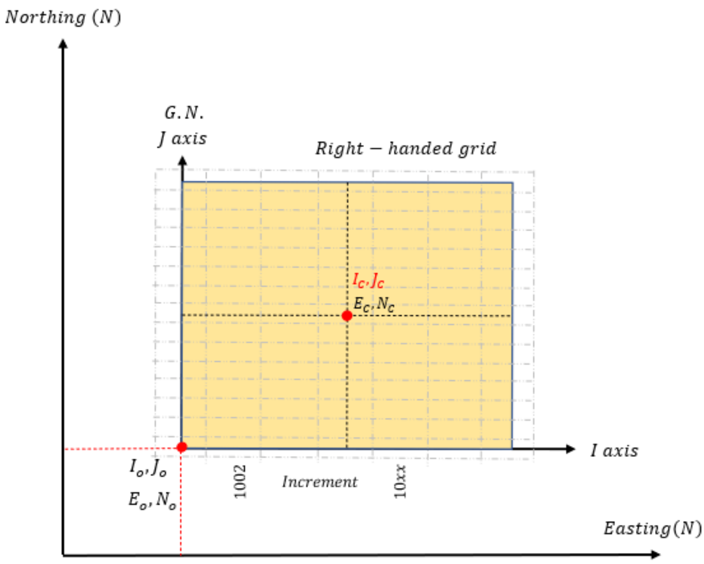


Figure 32: Origins of the grid

To remove the seismic grid's arbitrary definition requires the selection of a suitable CRS that meets the criteria specify in section 3.1.1. and assigning Easting and Northing coordinates (E_o *and* N_o) that correlate to the centre of cell 1001, 1001, e.g., I_o *and* J_o of the seismic grid. This anchors the seismic grid to the selected projected CRS at that point. Therefore, the origin of the grid (red circle, lower left in Figure 32) will comprise two corresponding sets of coordinates, one associated with seismic grid space, and one associated with the selected projected CRS. This is known as the grid pairing as shown in Figure 32.

3.1.1.2 Survey bearing

With the seismic grid now anchored to the Earth its definition is completed by assigning a survey bearing. Because only one anchor point was applied the seismic grid is rotated about that point to any desired bearing in relation to the reference north of the CRS (grid north). When assigning the survey bearing it describes an angular relationship between the J *axis* of the seismic grid and North direction (of the projected CRS), as shown by the bearing (θ) in Figure 33. It is measured in a positive clockwise sense from Grid North using the unit of measure: degree.

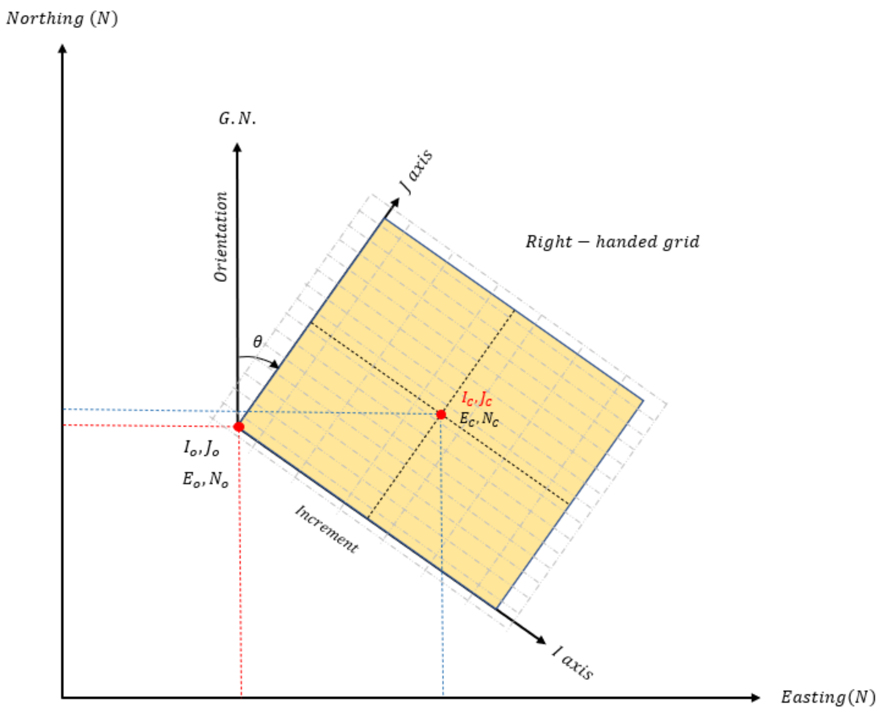


Figure 33: Orientation and survey bearing of the grid

Traditionally, the survey bearing (θ) of the seismic grid ($J\ axis$) is selected such that it will coincide with the geological objectives of imaging the rock structures (see section 5.2), i.e., along dip or strike direction. Consequently, it coincides with the direction along which the receivers are laid / towed, e.g., the direction of the pre-plot acquisition lines traversed by the vessel towing the streamers. The reflection seismic method is regarded to work optimally along the dip direction, although modern processing and imaging techniques now make this requirement somewhat obsolete.

3.1.1.3 Scale factor

The scale factor of the seismic grid will equal the scale factor of the projected CRS map projection (e.g., 0.9996 for UTM) and can be assigned to any point within the seismic grid, but typically the geometric centre of the bin grid is selected as specified by bin cell (Ic, Jc).

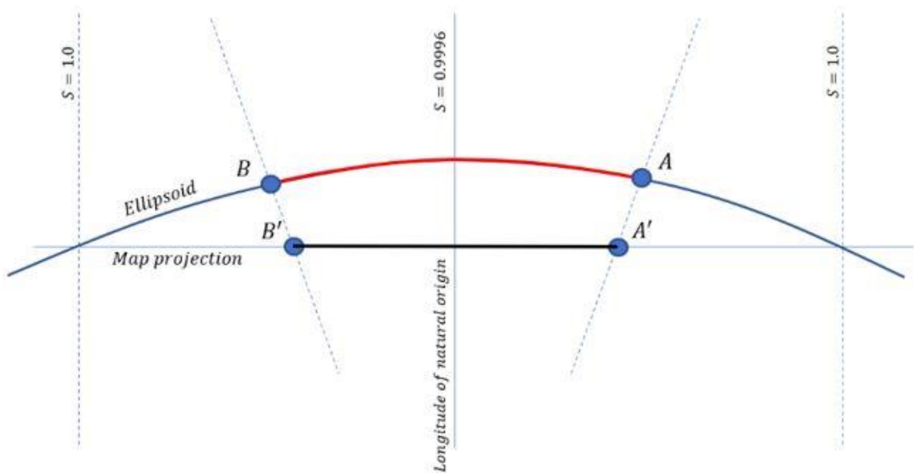


Figure 34: Scale factor

The scale factor (k_o) applied within some map projections better controls the amount of distortion experienced over the extent for which the projection is used. This is achieved by changing the value of scale from unity (1.0) to a lower nominal number along the central meridian defined for that map projection. Therefore, the two points of unity fall some distance away from the central meridian which is governed by the amount by which it is reduced. In Figure 34 a scale factor of 0.9996 is applied at the central meridian meaning the two points of unity occur either side, as indicated by the two vertical dashed black lines. The point scale factor describes the distortion of a distance measured on the Earth's terrestrial surface to what it would be when projected onto a selected map projection, e.g., the linear distortion at a single point only. Whereas it is usual to specify the scale factor at a given location like the central meridian.

3.1.2 Extent and Scope

Extent and scope are two sub-parameters which describe the usage of a geo-spatial object and was introduced to the EPSG geodetic parameter registry with the adoption of the ISO19111:2019 data model. Not all geodetic objects have usage defined as it is restricted to objects that have a controlled geographic area, for example: CRSs, transformations, and conversions, but not ellipsoids and prime meridians. The seismic grid coordinate system which forms part of the Derived CRS does include a usage definition.

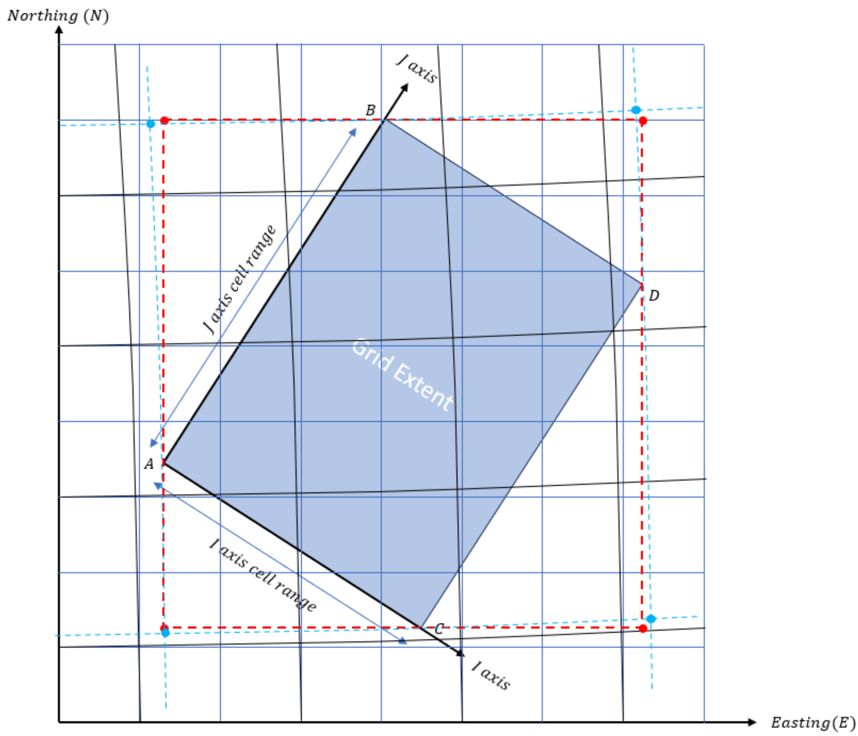


Figure 35: Geographic extent of the seismic grid

The extent describes the geographic area over which the CRS or coordinate operation should be used, and the scope describes for what it will be used. The extent is not to be confused with the specification of the maximum range of the cells along the two axes of the grid coordinate system, as shown in section 2.2.1. Instead, this parameter represents the geographic area over which the seismic survey is conducted by specifying the coordinates of a polygon / perimeter. The parameter was introduced and adopted by the IOGP in their EPSG geodetic registry from version 10.003 onwards.

The extent of the seismic grid footprint is illustrated by the blue polygon shown in Figure 35. It is defined by specifying the coordinates of the polygon using either a projected CRS and or a geographic 2D CRS. This is described numerically or through an extent polygon (represented by a .shp file) to illustrate the geographic area of the seismic grid's full fold coverage. The example shown in Figure 35 is for the definition given in Table 2.

- The red dash polygon represents an area known as the bounding box. The four corners of the bounding box describe the maximum and minimum coordinates associate with the extent of the full fold perimeter in relation to the projected CRS selected.
- The blue dash polygon represents another bounding box where the maximum and minimum limits of the box are defined in relation to the geographic 2D CRS, base geographic CRS of the projected CRS.

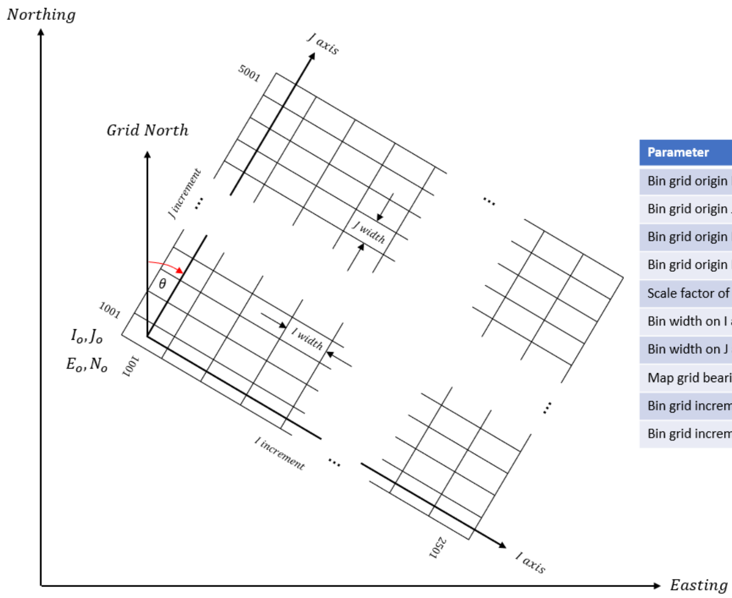
3.1.3 Collectively

The additional attributes described above, plus those given in section 2, are listed in Table 2. Those highlighted in orange are because they require additional metadata to be provided in the form of the projected CRS chosen (see section 3.1.1).

Table 2: Collective parameters of the grid

Parameter	Value	Unit of Measure
Grid origin I	1001	Bin
Grid origin J	1001	Bin
Grid origin Easting	462781	metre
Grid origin Northing	572946	metre
Scale factor of grid	1	unity
Width on I axis	25	metre
Width on J axis	12.5	metre
Map grid bearing of J axis	20	degree
Increment on I axis	1	Bin
Increment of J axis	1	Bin
Number of cells along I axis	1500	Integer
Number of cells along J axis	4000	Integer

The parameters highlighted in green are included in this definition but are not formally part of the seismic grid (conversion or transformation) definition published by the IOGP. The same parameters, using IOGP terminology, are shown in Figure 36. Notice the absence of the cell ranges in that parameter table.



Parameter	Symbol	Parameter value
Bin grid origin I (J + 90°)	I_o	1001
Bin grid origin J	J_o	1001
Bin grid origin Easting	E_o	462781
Bin grid origin Northing	N_o	572946
Scale factor of bin grid	SF	1
Bin width on I axis	I width	25
Bin width on J axis	J width	12.5
Map grid bearing of J axis	θ	20
Bin grid increment on I axis	I bin inc	1
Bin grid increment on J axis	J bin inc	1

Figure 36: Grid parameters

3.2 Seismic grid, CRS type: Engineering

An engineering datum is the integral element of an engineering coordinate reference system. This CRS type was originally designed for use with localized engineering projects, for example: plant work, e.g., Tombak LNG Plant in Iran. Such systems have been extensively defined with good examples included in EPSG geodetic parameter registry for Venezuela and North America. Their definitions have been for a variety of survey purposes, including seismic surveys and engineering plant operations.

Although a seismic grid definition, using an engineering CRS, is introduced here this approach is not encouraged for the definition of future seismic grids. It is included to illustrate how legacy seismic grids were originally defined in the eventuality that such an approach may be encountered with legacy seismic data. The definition of an engineering CRS is specified in the same way as those described in Reference surfaces and Coordinate Reference Systems book (Parr, 2024a) and comprises two components which are:

- Datum
- Coordinate System

3.2.1 Datum

This is a datum of type: Engineering and is not to be confused with the geodetic datum incorporated in a Geodetic CRS. There are no formal parameters or parameter values associated with the engineering datum as it comprises a text string into which a definition of the datum is described by the originator. For example, the text string may include details of coordinates describing the physical point on the Earth to which the coordinate system is tied. It may also include a statement about the survey bearing of one axis of the coordinate system, e.g., in relation to a specified CRS (and base geographic CRS by association). The downside of Engineering datum is that their definitions often lack sufficient metadata as to make their replication possible.

They have limited scope and are not encouraged when defining a seismic grid. However, in theory the engineering datum can be used to define the Easting / Northing (E_o, N_o) or Latitude / Longitude (φ_o, λ_o) parameters used to tie the seismic grid origin point (I_o, J_o) to the projected or geographic CRS selected. In choosing the CRS it is understood that its extent (defined as part of the CRS Usage) will coincide with the geographic area over which the seismic survey is being acquired.

3.2.2 Coordinate system

In sections 2.2.2 and 2.2.5.4 two different approaches were shown to defining the magnitude (unit of measure) of where a point (P) lies in relation to the origin of the coordinate system. One used integers related to an ordinal coordinate system and one used reals in relation to affine coordinate system. Additionally, two conventions were also defining for the orientation assigned to a coordinate system, namely: right-handed orientation and left-handed orientation. Hence, there are four variations of coordinate system that can be implemented in an Engineering CRS, namely:

- Right handed - integer value (Figure 18)
- Right handed - real value (Figure 19)

- Left handed - integer value (Figure 21)
- Left handed - real value (Figure 22)

For now, it is assumed that the cartesian 2D CS is right handed and that the unit of measure is metres.

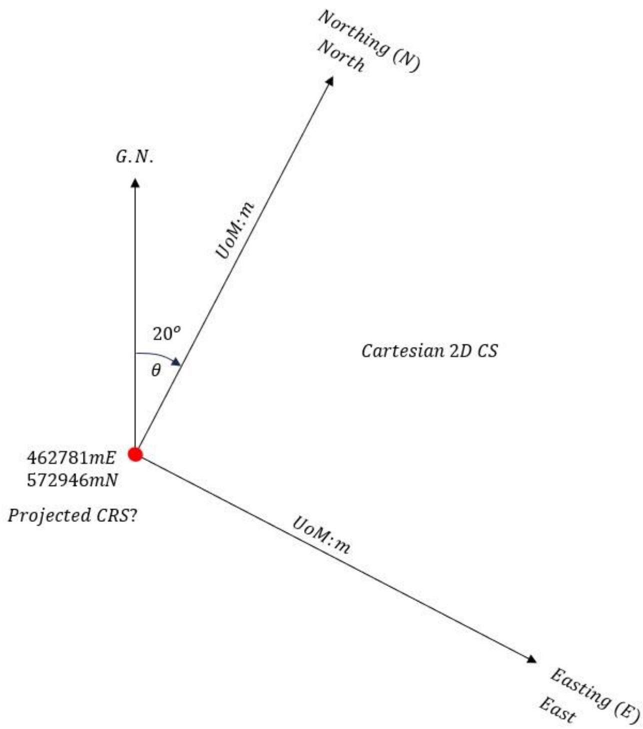


Figure 37: Engineering CRS

An example of the Engineering CRS is shown in Figure 37. The datum point is identified by the red circle and the coordinates to the left specify the origin of that point in relation to a projected CRS. Whether the description of the datum includes any details of the projected CRS is often potluck with many legacy definitions. The likelihood is that no details will be provided, rather a physical description of that point, e.g., the middle step of the main church in Oilsville. To complete its definition following parameters associated with its axes are required:

- Name
- Abbreviation

- Direction
- Unit of measure

Figure 38 illustrates their usage. The two axis names are given as $I\ axis$ and $J\ axis$, which are abbreviated to I and J respectively. The direction of the $J\ axis$ in relation to grid north is given by the survey bearing (θ) and $I = J + 90^o$. Finally, the unit of measure along both axes is the metre.

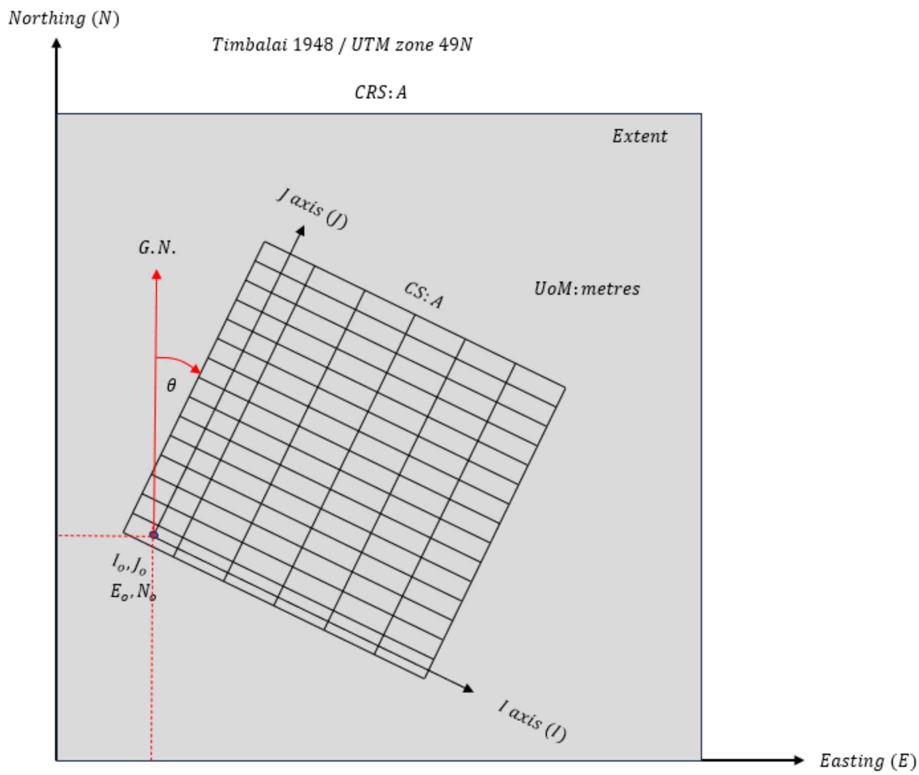


Figure 38: Coordinate system axes definition

3.2.3 Coordinate transformation

Neither of the two building blocks described above give any parameters or parameter values associated with the seismic grid definition (e.g., cell widths, increments etc.). Instead, these details are contained in an associated coordinate transformation that must accompany the Engineering CRS if any coordinate operations are required. As with other coordinate operation methods this coordinate transformation method comprises the following three components, namely:

- Parameter
- Parameter value
- Name

In the three columns of **Error! Reference source not found.** are the parameter names, parameter values and units of measure associated with this type of coordinate transformation (see chapter 11).

Table 3: Parameter and parameter values

Parameter	Value	Unit of measure
Bin grid origin I	1001	Integer
Bin grid origin J	1001	Integer
Bin grid origin Easting	456781	Metre
Bin grid origin Northing	572946	Metre
Scale factor of bin grid	1	Unity
Bin width on I axis	25	Metre
Bin width on J axis	12.5	Metre
Map grid bearing of J axis	20	Degree
Bin increment on I axis	1	Integer
Bin increment on J axis	1	Integer

With respect to the transformation method name: the name given to this method by IOGP in the EPSG geodetic parameter registry is as follows:

P6 I = J + 90^{o} seismic bin grid coordinate operation

It is treated as a coordinate transformation because the source datum and the target datum are considered different (e.g. engineering and geodetic). To perform the transformation three key parameter are required, namely:

- Source CRS (e.g., engineering CRS)
- Target CRS (e.g., projected CRS)

- Transformation method

In its pure form this is known as an Affine Transformation (see section 11.1). However when applied to the seismic grid a simplified version is used known as the Similarity Transformation (see section 11.2). Section 11.3 provides some worked examples of how this coordinate operation is performed. For those familiar with the concept of the Bound CRS (see section 3.6) this approach is similar because a coordinate transformation is tied to a CRS, albeit an Engineering CRS in this instance.

3.3 Seismic grid, CRS type: Derived

It is encouraged to define all future seismic grids as a component of the Derived CRS where the seismic grid coordinates (I, J) are derived from a sequence of controlled steps which are illustrated in Figure 39. For example, the projected CRS (E, N) coordinates are derived from the geographic 2D CRS (φ, λ) coordinates and the seismic grid coordinates (I, J) are derived from the projected CRS coordinates (E, N). Both coordinate operations are of type: conversion as the geodetic datum of each component is the same.

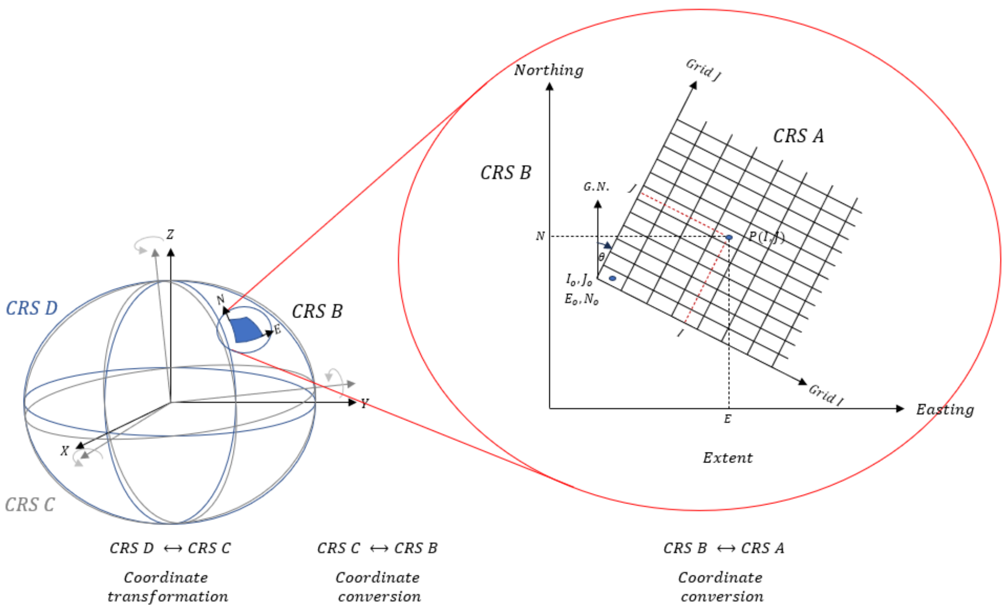


Figure 39: Different CRSs used in geo-spatial definition of the grid

In Figure 39 four coordinate reference systems are illustrated, namely:

- CRS A: Seismic grid
- CRS B: Timbalai 1948 / UTM zone 49N
- CRS C: Timbalai 1948 (geog 2D)
- CRS D: WGS 84

To illustrate the derived relationship start on the right side of Figure 39 and work to the left:

- The coordinate system (i.e., seismic grid) is defined using the parameters described in Figure 40 which constitutes CRS A, namely: GS45 grid (Seismic grid CRS name).
- The two rows named Grid origin easting (E_o) and Grid origin northing (N_o) are the easting and northing coordinates related to the projected CRS, i.e., CRS B**:** *Timbalai 1948 / UTM zone 49N*. Hence, CRS B is the base CRS of CRS A**,** and the seismic grid CRS coordinates (I, J) are derived from the projected CRS (E, N) coordinates (see section 11.3). This is a coordinate operation of type: conversion as both the source and target share the same geodetic datum.

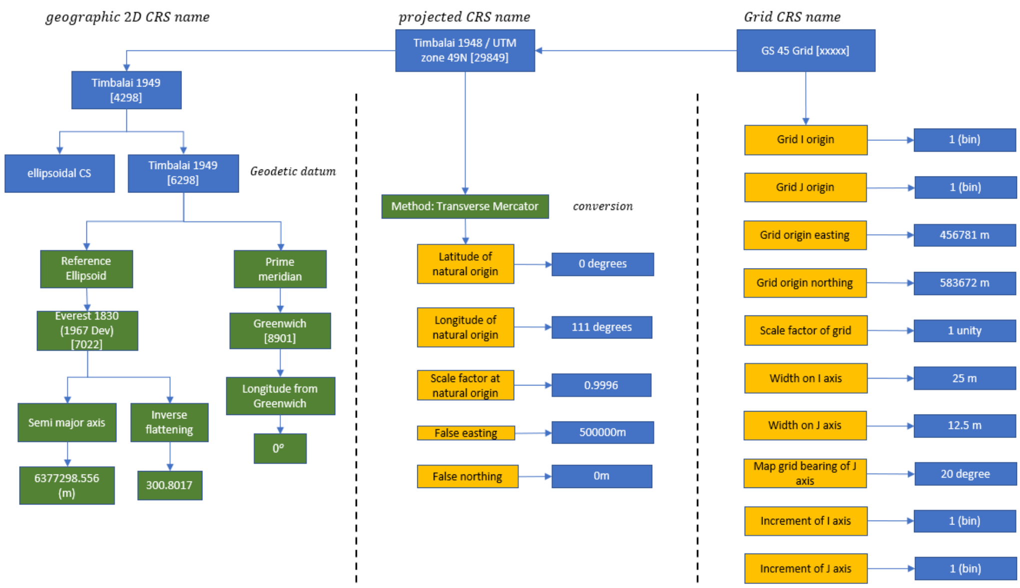


Figure 40: The component building blocks associated with grid CRS

Furthermore, in the definition of a projected CRS is a base geographic CRS which in the example of CRS B is CRS C. Hence, the base geographic 2D CRS of Timbalai 1948 / UTM zone 49N [29849] is Timbalai 1948 [4298].

The two rows highlighted in green in **Error! Reference source not found.** specify the number of cells that comprise the full fold perimeter along the two axes of the seismic grid coordinate system. These two rows are not formally part of the P6 bin grid definition published by IOGP and are not included in Figure 40. Further details can be found in section 7.2. Finally, CRS D is introduced as being a global CRS, for example: WGS 84. If CRS D and CRS C are different, then a coordinate transformation is required to transform positions between the two. This is not part of the derived CRS definition and should be treated as a separate coordinate operation (see section 9).

A Derived CRS is defined with the following three components are mandatory:

- Coordinate system: whose definition is identical to that already described earlier in this section. Refer to section 3.2.
- Base CRS: which represents the projected CRS associated with the coordinate conversion. For example: Timbalai 1948 / UTM zone 49N.
- Conversion: provides the grid parameters and parameter values used in the similarity transformation, which in IOGP terminology is the conversion between CRS B and CRS A.

Taking into consideration the two orientations of the coordinate system, there are four possible variations of the Derived CRS, namely:

- Right handed - integer value (Figure 15)
- Right handed - real value (Figure 16)
- Left handed - integer value (Figure 17)
- Left handed - real value (Figure 18)

Two use the data type: Integer and two use the data type: Real. Two are left-handed and two are right-handed. These only refer to the coordinate system associated with the seismic grid CRS and not the projected CRS, i.e., the ordinal and affine coordinate systems respectively. The former uses integers and the latter reals.

3.4 Moving platform CRS

A moving platform CRS is of type: Engineering and comprises two components, namely:

- Coordinate system
- Datum

It is used to determine the coordinates of key equipment nodes that change with time as a result of the platform upon which they reside moving (e.g., on a vessel, or being towed by a vessel). For example, a survey vessel traversing along a pre-plot acquisition line makes bathymetric observations from the echosounder. The vessel's primary position (GNSS) and heading (gyrocompass) are measured at positions on the moving platform that differ from that where the bathymetric observations are made, as shown in Figure 41. To compute the real world position of the echosounder (at the observation epoch) requires that the platform offsets (e.g., x_2, y_2) are applied from the origin position along the two axes of moving platform in relation to the azimuth reported by the gyrocompass at the same epoch as when the bathymetric observation was made.

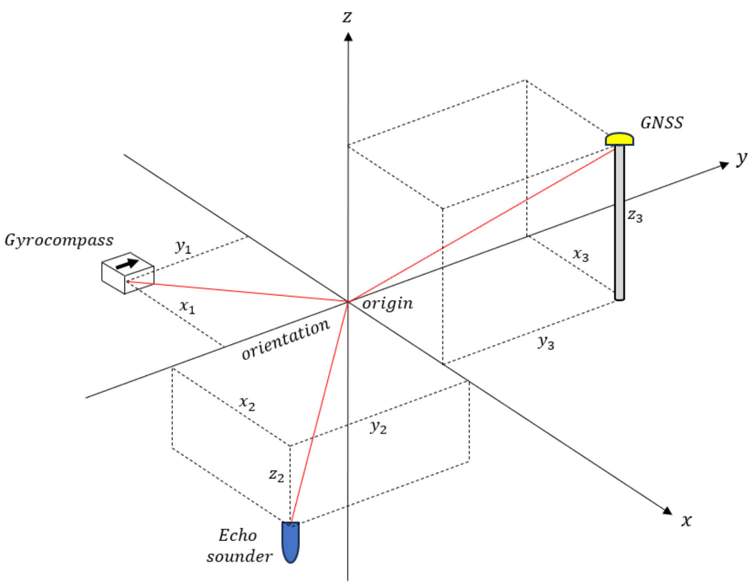


Figure 41: Offsets in moving platform CRS

Although the offsets between the equipment nodes do not change (with time) the platform as a whole moves and thus do the positions of every node on it with respect to a geodetic CRS. Therefore, the process of determining the node positions is repeated on an epoch by epoch basis with each one being time stamped as to when it occurred temporally. By computing the precise position of the nodes (making the observations) the maps and charts created for their data are representative of where the data sampling actually occurred.

3.4.1 Coordinate system

In line with all other coordinate system definitions this one comprises a collection of axes, where each axis is described by the following attributes: Name, abbreviation, and orientation. The number of axes required determines the dimension of the coordinate system and hence how many coordinates are required to describe the position of a point. For the moving platform CRS the coordinate system is of type: Cartesian 3D coordinate system (CS) and comprises three orthogonal axes, namely:

- Forward**,** abbreviated to (y) which is orientated along the centre line of the moving platform with the positive axis being forward of the platform.
- Starboard**,** abbreviated to (x) which is orthogonal to the y axis and orientated positively to Starboard.
- Platform Up**,** abbreviated to (z) which is perpendicular to the xy plane where it is positive upwards along the vertical plane.

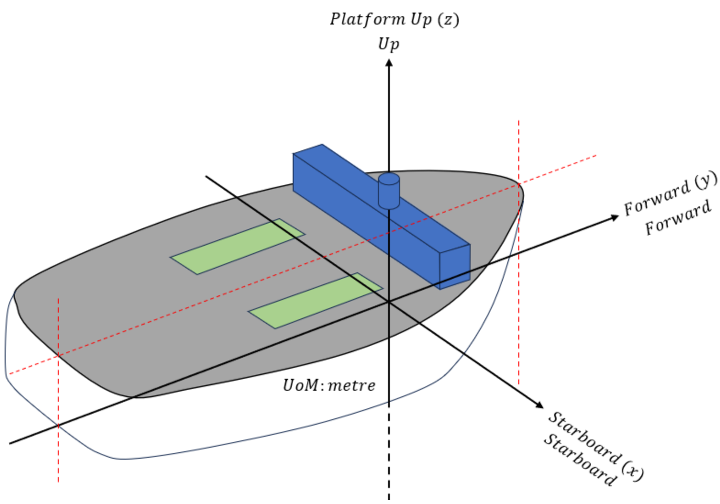


Figure 42: Moving platform coordinate system

The orientation of the Forward axis will coincide with the centre line of the platform from stern to bow (positive direction) as shown in Figure 42. This creates a right-handed coordinate system with your index finger pointing along the forward, your thumb pointing to starboard and your middle finger pointing upwards (see Figure 29). Collectively, the extended name of this coordinate system comprises the following components:

Cartesian 3D CS.

Axes: Starboard, Forward, Platform Up

Abbreviation:x, y, z,

Orientation: starboard, forward, up.

3.4.2 Datum

The datum is of type: Engineering and comprises a text description providing details of the datum. This may include aspects of the origin and orientation of where the coordinate system is tied to the moving platform. For example:

The coordinate system is tied to the platform, so its origin coincides with the primary navigation system, with the y axis orientated along the centre line of the platform from bow to stern.

Descriptions associated with Engineering datums are free text and vary in content significantly. Often, this makes their replication difficult when descriptions are inadequate.

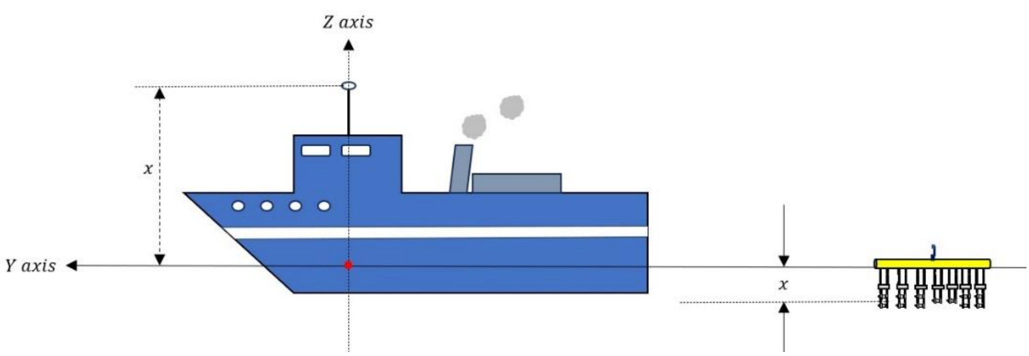


Figure 43: Offsets from side view

3.4.2.1 Realizing the datum

To realize the datum the coordinate system is tied to the moving platform such that scale and orientation are applied. As the origin is user-defined it can in theory be located at any physical point on the moving platform. A few popular options are firstly: to co-locate the horizontal component with the primary navigation system with the forward axis orientated along the central line of the vessel (the moving platform) and the vertical component co-located with mean sea level.

Secondly: co-locate the horizontal component at the centre stern of the moving platform and co-locate the vertical component with MSL. Regardless of origin point it is usual to assign it $(0, 0, 0)$ coordinate values. Names given to this point include Common Reference Point (CRP), Vessel Reference Point (VRP) and Central Navigation Point (CNP).

3.4.3 Create the CRS

To complete the definition of the coordinate reference system requires some additional information which includes:

- The unit of measure applied to each axis of the coordinate system, e.g., metre (m), feet (ft).
- The coordinate tuple to define the order in which the coordinates are specified when referencing a point. Here, the coordinate tuple is given as Starboard, Forward, Platform Up.

This completes the definition of the Moving Platform CRS.

3.5 Nominal offsets

For narrative purposes let the moving platform be a seismic acquisition vessel, onboard which are the standard navigation and positioning equipment, and behind which are towed multiple sources and streamers. Using the coordinate system of the Moving Platform CRS, nominal offsets describe the physical location of the key seismic objects by specifying their position as magnitudes along the three axes (of the coordinate system) in relation to the origin point (CNP). Each results in an x, y, z position for all navigation and positioning nodes used on the survey spread.

For example, in Figure 44 the offsets in the horizontal x, y plane are illustrated. The offsets shown are part of the initial survey design and indicate where each element of the in-water spread is required to be located relative to the origin of the

Moving Platform CRS such that the survey objectives (see section 5.4) are optimally achieved. Therefore, the seismic crew are required to realise these offsets to satisfy that the sampling requirements specified by the geoscience team (see section 5.3) are met. In Figure 44 notice that the $y\ axis$ of the moving platform CRS extends indefinitely to the stern of the vessel such that offsets can be described for all equipment being towed, i.e., the extent of this CRS. The offsets are described for the two components of the horizontal plane of the coordinate system which are known as the *inline offsets* (along the $y\ axis$) and the *crossline offsets* (along the $x\ axis$).

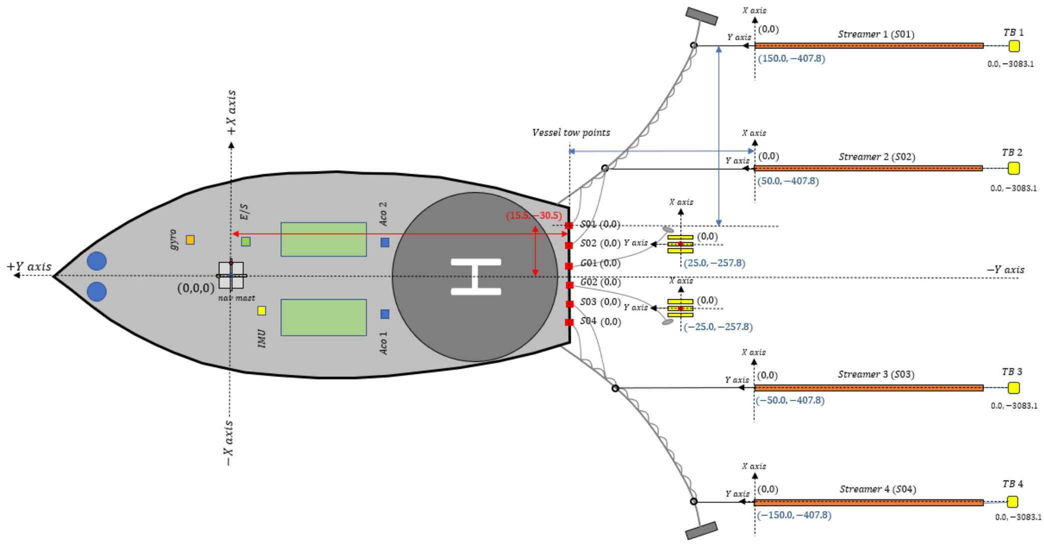


Figure 44: Tow point offsets

***Inline offsets**:* For example, both the port and starboard gun arrays are deployed such that the geometric centre of each array is 257.8 metres astern of the vessel CNP (227.3 metres from the towing points, assuming the distance from CNP to vessel stern is 30.5 metres). Similarly, the streamers are deployed such that the head of each streamer is 407.8 metres astern of the vessel CNP and 377.3 metres astern of their tow points.

Crossline offsets: The starboard gun array is deployed 25 metres along the +ve $x\ axis$ and the port gun array 25 metres along the -ve $x\ axis$, hence achieving a source separation of 50 metres. The streamers are deployed such that between each there is a lateral separation of 100 metres along the $x\ axis$. The outer starboard streamer will have a nominal offset of 150 metres and the inner starboard streamer an offset of 50 metres thus achieving the 100 metre separation. The same is repeated for the port streamers along the -ve $x\ axis$.

Vertical offsets (along the $z\ axis$): These are used to specify the height or depth at which equipment is located away from the vertical datum (e.g., MSL). For example, the sources and the receivers are towed at pre-selected depths in relation to the vessel's water line. For example, the sources are towed at a depth of 6 metres and the receivers at a depth of 7 metres (not addressing slanted streamers). The height of the primary navigation system has a positive value above the water line. The echosounder and hull mounted acoustic units have negative values below the water line.

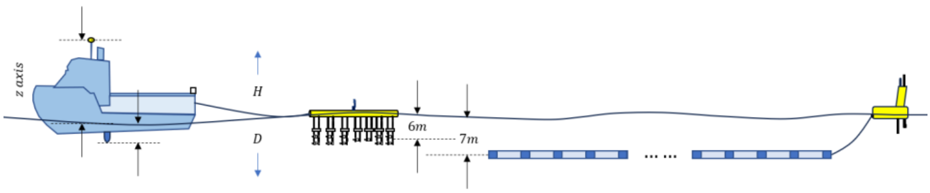


Figure 45: Vertical component offsets

Towing points: A towing point is a point on the vessel or on a deployed piece of equipment from which another piece of equipment is deployed. For example, the seismic equipment (gun arrays and streamers) is towed behind the vessel from a tow point on the vessel who's local x, y coordinates are known in relation to the CNP. A tailbuoy is towed by each streamer who's local x, y coordinates are known in relation to the streamer head.

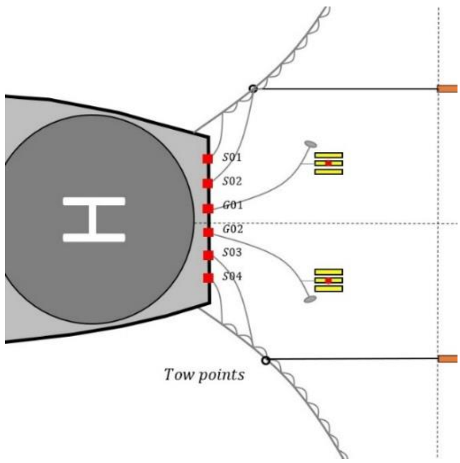


Figure 46: Tow points on the vessel

Therefore, each towing point has its own localize Moving Platform CRS (MPCRS) all of which have an interconnected relationship back the vessel's MPCRS. For example, the head of the outer streamer is the origin (0, 0) for the local MPCRS associated with that streamer. All offsets along that streamer are referenced to that systems origin. However, the origin of that streamers MPCRS has a known offset in relation to the towing point on the vessel, which in turn has a known offset to the CNP of the vessel. Hence the vessel CNP is the origin point of the vessels MPCRS which is orientated along the centre line of the vessel. It is assigned local coordinates (0,0,0).

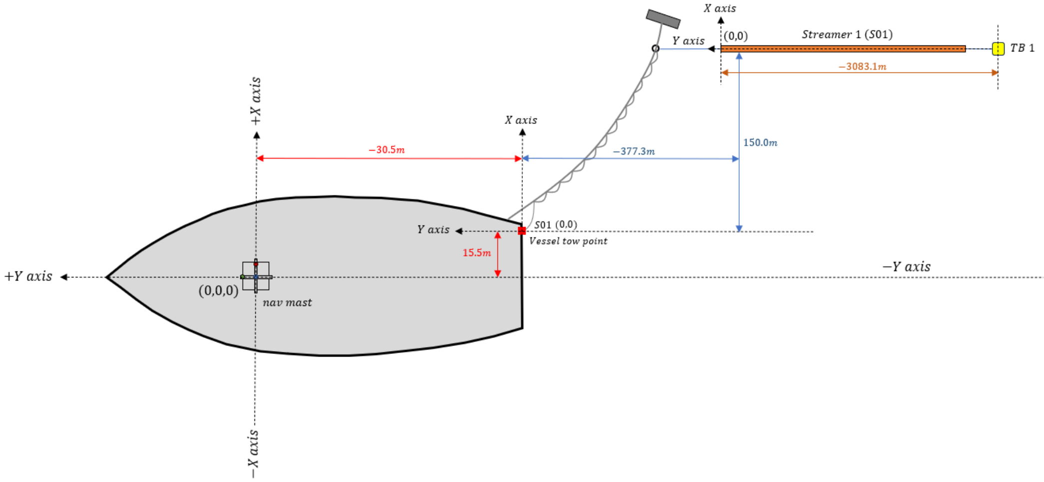


Figure 47: Offsets from CNP to TB1

From each relevant tow point (whose coordinates are (0,0)), the equipment is deployed. Consider the outer starboard streamer: To commence, the Tailbuoy (T01) enters the water followed by the active sections. To achieve the desired geometry (in this example), the streamer is deployed a distance of 377.5 metres to the aft of the stern and 150 metres to the starboard. As shown in Figure 47, the head of the streamer now becomes the origin for its localized MPCRS. The distance the Tailbuoy lies along the local $y\ axis$.

3.6 Bound CRS

There are two approaches to how a software application implements the selection of coordinate transformations which are referred to as late bound and early bound architecture. In the late bound architecture the user is required to select the coordinate transformation to apply at the time the operation is conducted. The user is normally presented with a list of coordinate transformation names and is required to select one to complete the operation. Although this architecture does offer flexibility it can prove daunting to an analyst not familiar with coordinate operations. In the early bound architecture the coordinate transformation is 'tied' to a coordinate reference system at the time of definition, i.e., a transformation is 'bound' to a coordinate reference system. This creating a new entity known as a Bound CRS which comprises two components, namely:

- Coordinate Reference System (either a geographic 2D CRS or a projected CRS).
- Coordinate Transformation

The advantage of the early bound architecture is that the user does not need to select a coordinate transformation from a list of candidates. This decision will have already been performed by the resident expert at the time the Bound CRS was defined.

How is the Bound CRS used? A project database has a base Bound CRS assigned, e.g., SAD69 / UTM zone 24S. Seismic data associated with a seismic grid is loaded to the database referenced to the Bound CRS Aratu / UTM zone 24S as shown in Figure 48. Because each are Bound CRSs they have an associated coordinate transformation that acts between the geographic CRS of that CRS and WGS 84, which is sometimes referred to as the Hub.

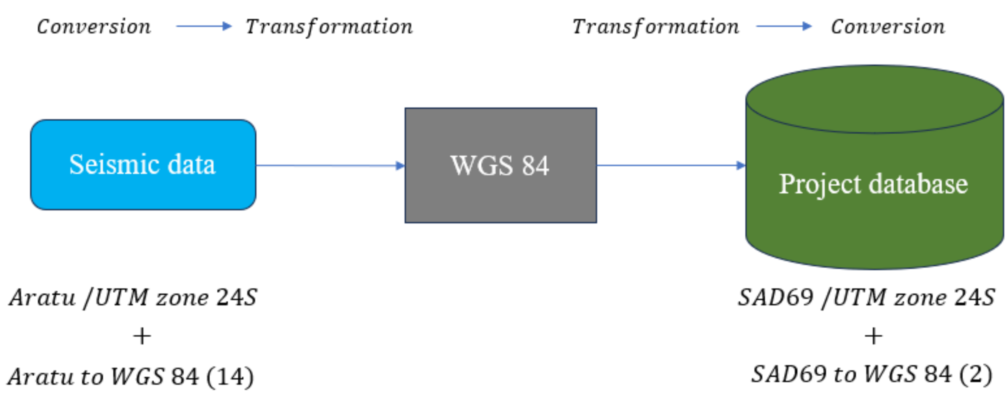


Figure 48: Bound CRS via WGS 84 Hub

As part of the input process the coordinates associated with the seismic data are converted and transformed to WGS 84 using the coordinate transformation specified in the import Bound CRS. Next, the Bound CRS acting as the project CRS is used to convert and transform the coordinates for the seismic data from WGS 84 to the database CRS, e.g., SAD69 / UTM zone 24S.

Although not officially recognized by the EPSG geodetic parameter registry this is an important CRS type implemented within the architecture of common interpretation software applications.

3.7 CRS relationships

All CRSs described (sections 3.2 to 3.4) have interlinked relationships which enable coordinate operations to be conducted between them. This is essential so the coordinates associated with the mid-points of every seismic trace source-receiver pair are binned into the correct cells of the seismic grid. There are a variety of ways to achieve this solution, and the one offered here is a very simplified generic version. At each shot point:

- Using the moving platform CRS the x, y coordinates of all each float, e.g., Headbuoys, Tailbuoys and source gun floats are determined in relation to the CNP. These comprise the fixed stations of the seismic network, a first order triangulation network if you like.
- Next, convert these positions to their equivalent Easting (E) and Northing (N) coordinates in relation to the selected projected CRS used for the survey.

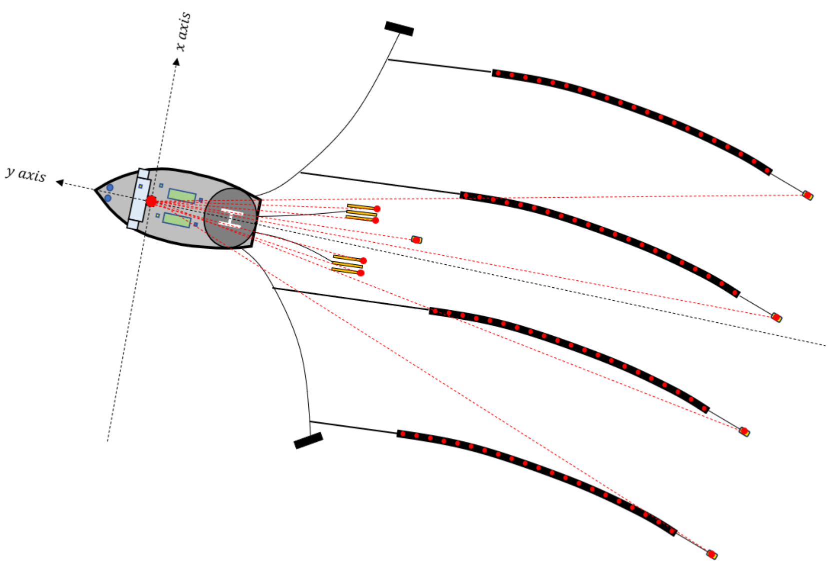


Figure 49: Buoy positioning

- Make the acoustic network observations between the fixed stations and all acoustic nodes attached to the streamers (see section 7.1).
- Input the coordinates of the fixed stations and all acoustic ranges into the unbiased estimator (e.g., least squares analysis / Kalman filter) to determine the coordinates for the source and every receiver group in relation to the MPCRS and projected CRS.
- Determine the mid-point coordinates for every source-receiver offset pairing in relation to the projected CRS.
- Using the similarity transform, convert the projected CRS coordinates of each mid-point to seismic bin grid (I, J) coordinates by applying the conversion of the Derived CRS.
- Determine into which cell of the seismic grid each mid-point belongs. Details of the source-receiver offset (e.g., source and receiver numbers) are captured and increase the count of that cell by one.

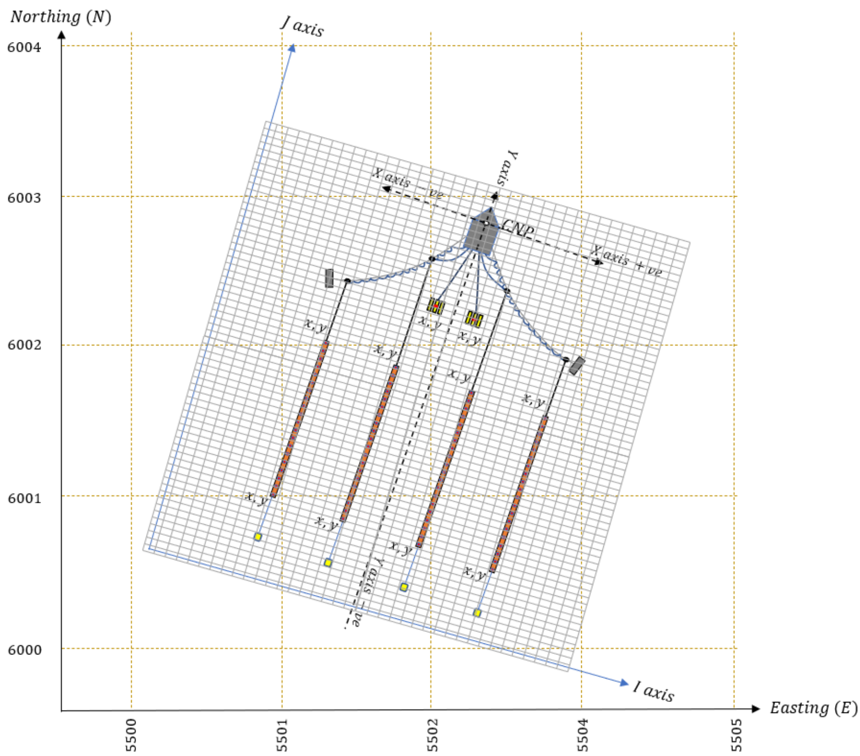


Figure 50: CRSs operating together

If the streamers experience zero feather and the vessel has zero crab angle, then the $y\ axis$ is aligned in the Inline direction ($J\ axis$) and the $x\ axis$ in the crossline direction (I axis) of the seismic grid as illustrated in Figure 50.

3.7.1 Navigation coordinate reference systems

Section 3.1.1. introduced the projected CRS whose definition incorporates the Cartesian 2D coordinate system. When determining the real-time position of the vessel using modern satellite technology the primary vessel position is originally referenced to a Cartesian 3D coordinate system of the Geocentric CRS, for example: WGS 84 [4978] which derives $Geocentric\ X$, $Geocentric\ Y$, $Geocentric\ Z$ coordinates for the CNP.

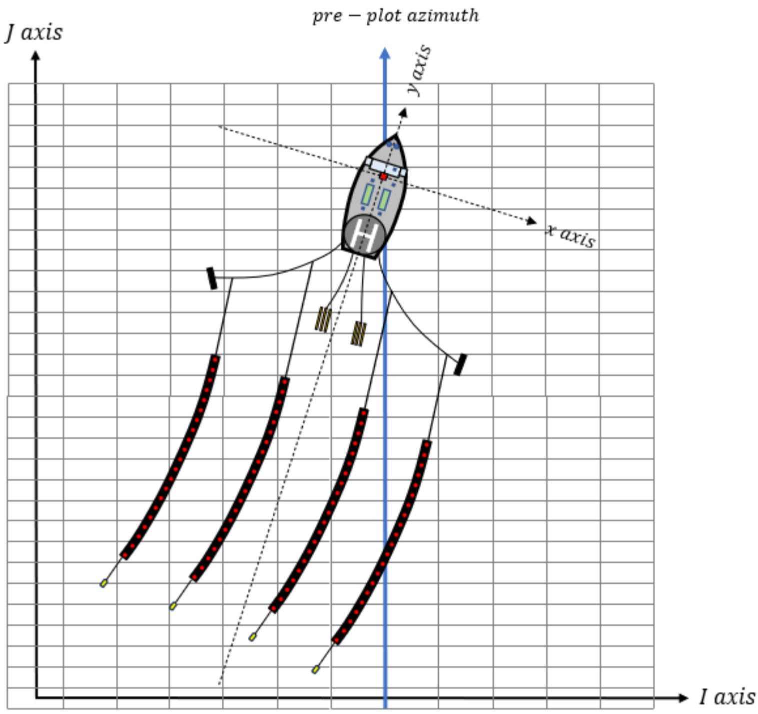


Figure 51: Moving Platform CRS skewed to the seismic grid

Next, it is converted to Geographic 3D CRS, WGS 84 [4979] deriving φ, λ, h coordinates and also to its horizontal component, i.e., φ, λ for the Geographic 2D CRS, WGS 84 [4326]. Finally, this is converted to a Projected CRS where the coordinates are given in E, N for the same CNP position. Therefore, for every shot point along the line the following coordinates are reported for the vessel position.

The choice of projected CRS is dependent on the area over which the seismic survey is conducted. This is equivalent to selecting CRS C as specified in section 3.3, where the CRS must comply with the conditions stated in section 3.1.1. Therefore, as the vessel traverses the sail line the real time positions of the CNP for the four CRSs are shown in Table 4, all of which are derived from the initial Geocentric CRS.

Table 4: Coordinate tuples of the CNP

	Code	Coordinate 1	Coordinate 2	Coordinate 3
Geocentric XYZ	4978	-2322292.252	5909785.079	599672.437
Geographic 3D CRS	4979	$5^o\ 25'\ 52.399"\ N$	$111^o\ 27'\ 09.719"\ E$	$0.00\ m$
Geographic 2D CRS	4326	$5^o\ 25'\ 52.399"\ N$	$111^o\ 27'\ 09.719"\ E$	
Projected CRS	32649	$550150\ mE$	$600350\ mN$	

This represents the coordinates for the red circle shown on the vessel in Figure 51 which is also the origin of the Moving Platform CRS. It is from this origin point and the alignment of the two axes of the Moving Platform CRS that the next stages of the positioning are conducted.

Knowing the vessel position is critical to ensuring it traverses the seismic line as required and that the shot points are fired in the correct pre-plot locations. However, the main challenge is to determine the positions of all the receivers being towed and the mid-point locations for every source-receiver offset pairing. The observations and computations performed are done so in relation to the Moving Platform CRS against which the x, y coordinates all the receiver groups are derived. This is complicated by the fact that the Moving Platform CRS will rarely align with the axes of the seismic grid because of the environmental factors effecting the vessel. Feathering of the streamers and vessel crabbing result which is illustrated in Figure 51.

3.8 Use of dynamic CRSs

A clear distinction is made between static and dynamic CRSs (IOGP, 2018). Dynamic CRSs are those that factor in minute changes in their definition (with respect to time) because of plate tectonic activity. Whether the definition of a seismic grid CRS should factor in these dynamic changes is a matter of opinion.

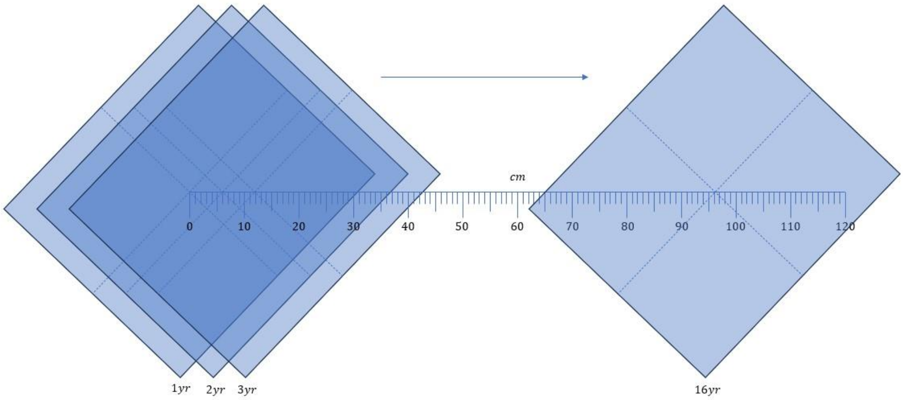


Figure 52: Plate motion effect on grid

To factor in such minute yearly changes (because of a dynamic CRS) has no geophysical significance, even over periods exceeding two or more decades. Even with horizontal plate tectonic motion(i rates of 6cm/yr it would take 16.6 years for the plate on which the seismic grid resided to move 1 metre. If a company considers this to have significance to the geophysical imaging, then a different mentality is required from that offered here. However, its relevance to engineering applications is a separate matter which are outside the scope of this book.

Why? Consider one aspect of how trace data is 'gathered' into each cell of the seismic grid.

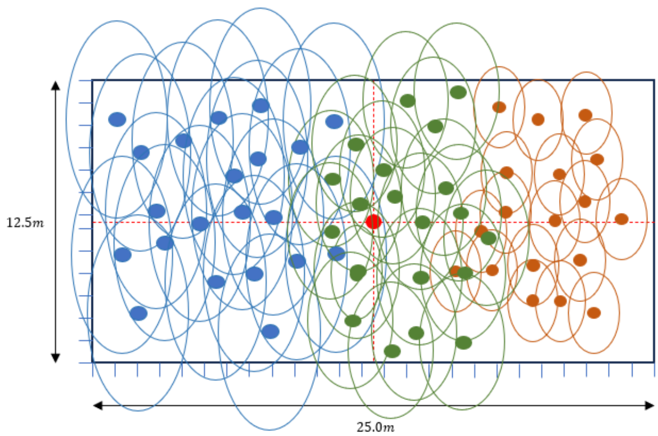


Figure 53: Mid points gathered from various source-receiver offset pairs

Each mid-point has a coordinate referenced to the projected CRS associated with the derived CRS of the seismic grid. Associated with each position is a horizontal error ellipse which describes the probability of the position being located within the ellipse at the one sigma (1σ) probability level which represents a 39.4% likelihood. However, this means this is a likelihood of 60.6% that the position will fall outside of the bounds of the ellipse. If the probability level is changed to two sigma (2σ) the dimensions of the error ellipses will increase significantly.

In 'gathering' the seismic trace data together every trace is assumed to be at the red circle, e.g., at the geometric center of the cell. Does this assumption introduction any geophysical issues? None whatsoever (see section 8.1.2). Geo-spatially what it means is that each contributing trace will have had its coordinates modified by as much as half a cell width along both the I and J $axes$ of the seismic grid. This introduces a potential error of up to 12.5m and 6.25m respectively into the original mid-point coordinates of each source-receiver pairing shown in Figure 53. The use of dynamic CRSs is not recommended for seismic acquisition or processing.

4 Perimeters associated with the seismic grid

Having defined the conversion parameters of the seismic grid (in relation to the Derived CRS) the next step is to define one or more perimeters (polygons) which when overlain on the seismic grid identify the geographic areas where seismic trace data is expected to be acquired (pre-survey) and where it was actually acquired (post-survey). There are four perimeters used for these purposes (Figure 54) which are named as follows:

- Full fold coverage perimeter
- Total coverage perimeter
- Null coverage perimeter
- Null fold coverage perimeter

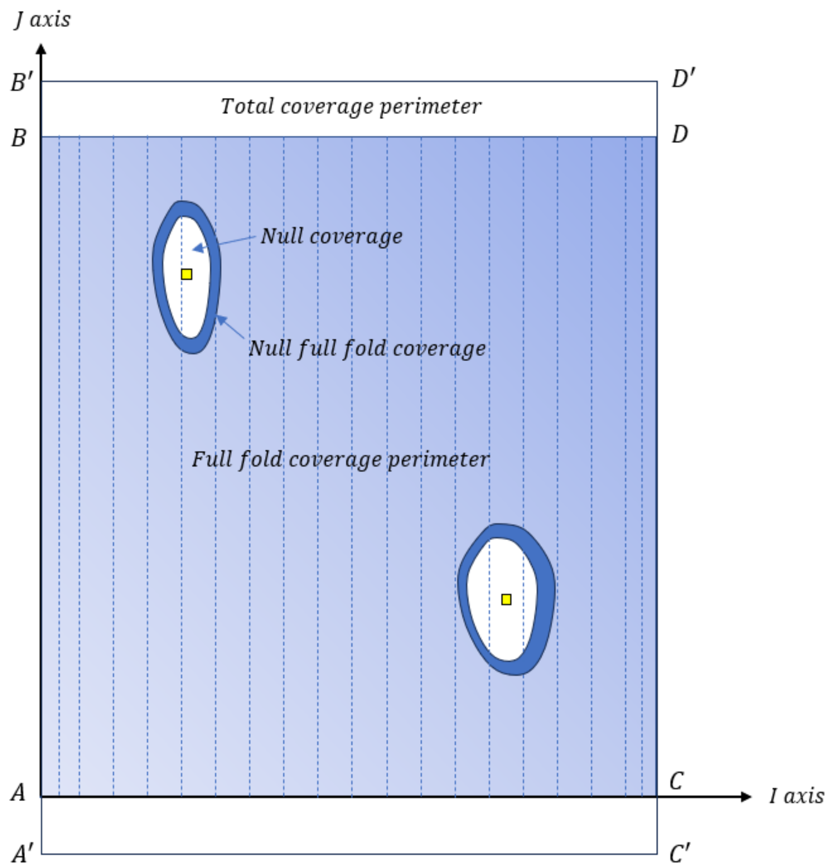


Figure 54: Full fold perimeter

4.1 Perimeter definitions

What follows are definitions of the four perimeters with some context of their usage which is further detailed in section 4.2.

4.1.1 Full Fold Coverage perimeter

Full Fold Coverage perimeter (points A, B, C, D) describes a geographic area of the seismic grid where all the cells therein require populating with a full complement of seismic trace data for all possible source-receiver offset pairs. The number of seismic traces required in each cell (the full fold) is decided by the geoscience team which in turn determines the geometric configuration of the seismic spread deployed during acquisition (see section 5.1).

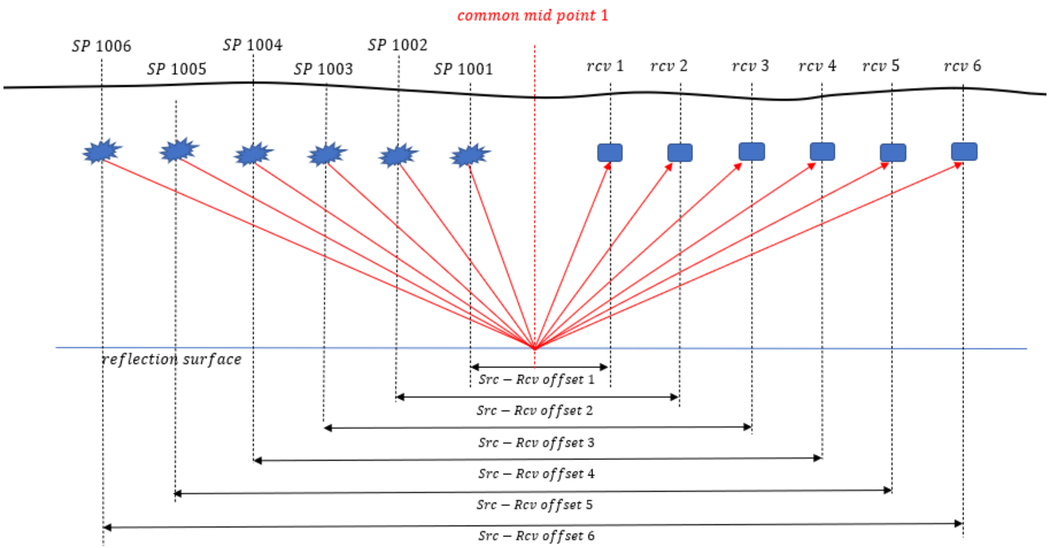


Figure 55: Source-receiver offsets converging at cell centre

4.1.2 Total Coverage perimeter

Total Coverage perimeter (points A', B', C', D') comprises the Full Fold Coverage perimeter plus an area known as the Taper Zone(s). The Taper Zone(s) defines an area of the seismic grid where the cells will not contain a full complement of source-receiver offset pairs because of the geometric relationship between the source and receivers. The size and shape of the taper zone depends upon the survey type and dimensions of the equipment spread deployed (e.g., streamer length).

For example, on a marine towed survey the taper zones results from the 'run in' and 'run out' performed by the vessel at the start and end of each primary seismic line respectively. Therefore, the total coverage perimeter represents the entire extent of where any seismic trace data is expected to be acquired regardless of the fold coverage achieved in each cell of the seismic grid. Figure 56 shows the relationship (boundary) between the Taper Zone and the Full Fold coverage area. Because the vessel is traversing to the left of the page the cells in the taper zone will never be populated to full fold capacity but will gradually ramp up from one to full fold at the boundary. This is further explained in section 6.2.

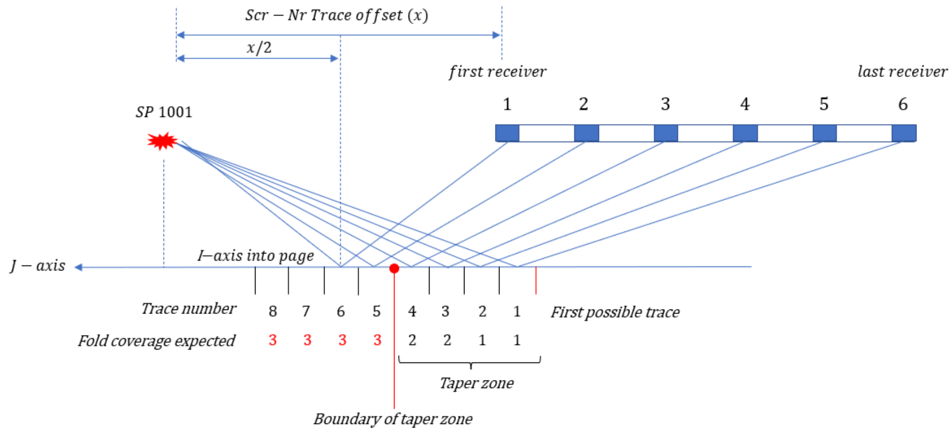


Figure 56: Full fold boundary and taper zone

4.1.3 Null full fold and null coverage perimeters

If there are obstructions in the survey area that are expected to impair data acquisition they require identifying. Consider an offshore production platform around which there is an exclusion zone of 500m radius centred on the platform's structure reference point. During acquisition the survey vessel nor any of the equipment being towed is permitted to enter the exclusion zone without prior authorization.

This will result in an inner area where no seismic trace data can be acquired (grey polygon in Figure 57) and an outer area where reduced fold coverage is expected (blue polygon). These two areas are known as the null coverage and null fold coverage perimeters (polygons) respectively. Because they represent areas where it is known (in advance) that zero or reduced seismic data is expected their usefulness in pre-planning cannot be underestimated. The expected size of the data voids are calculable from the exclusion zone radius, number of streamers, their length and separation. The cross line dimension is a factor of the streamer number and streamer separation whilst the inline dimension will be factor of the streamer length.

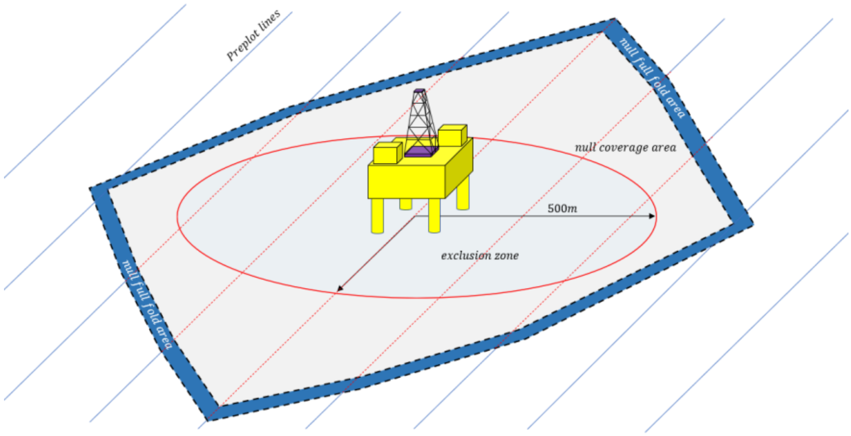


Figure 57: Expected (designed) Null coverage area

Whilst Figure 57 represents the expected void (pre-survey), Figure 58 illustrates an actual void caused by the vessel steering the equipment around the exclusion zone specified (post-survey). This results in no seismic trace imaging the sub-surface over that area shown by post-plot null coverage area represented by the grey polygon.

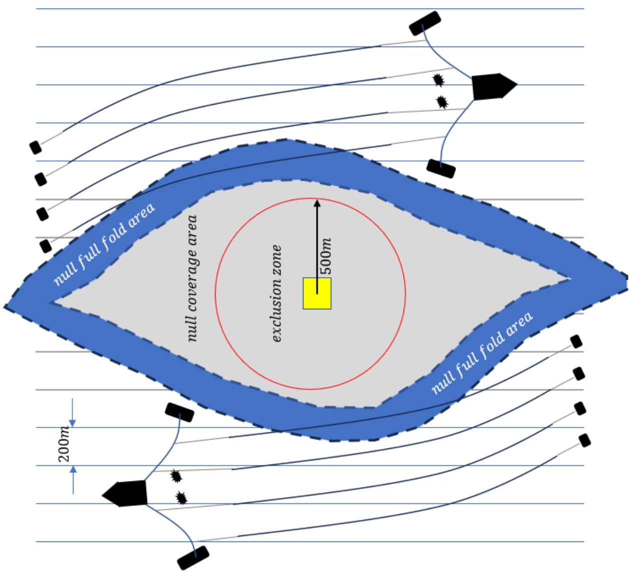


Figure 58: Steering to avoid the obstacle

4.1.3.1 Obstacles external to the perimeters

Additional logistical considerations are introduced by obstacles not located directly inside the survey area. For example, in Figure 59 a drilling rig is located outside of the western edge of the full fold perimeter and there is an area of shallow water caused by a sea mount south of the total coverage area. Although neither obstacle falls in the survey area, they both impact the data acquisition.

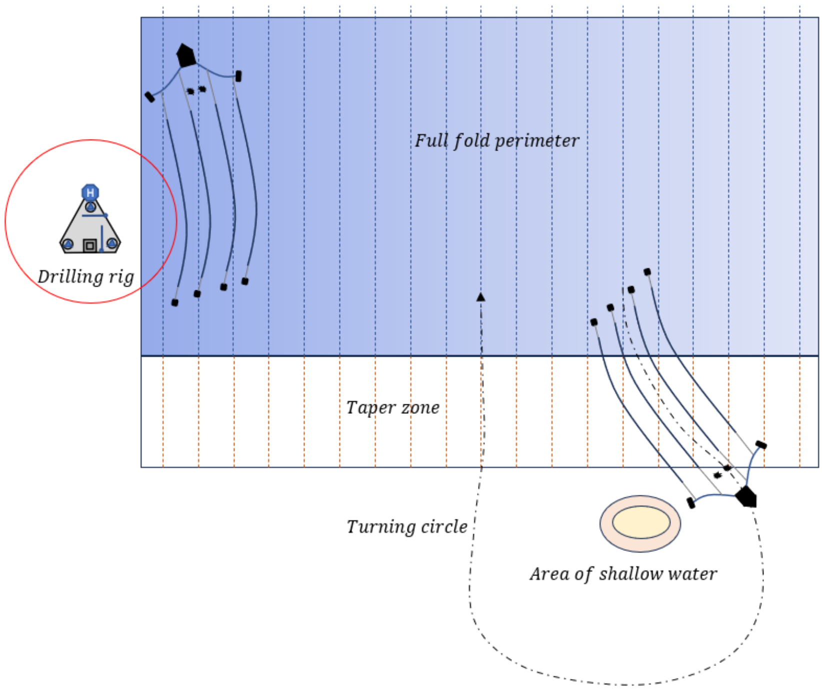


Figure 59: Obstructions outside survey area

For example, it is not possible for the vessel to traverse in the area close to the sea mount due to reduced water depth. Therefore, it cannot make a routine line change on the expected turning circle because of the deviation it must take around the obstacle. Similarly, the exclusion zone around the drilling rig requires the vessel to steer itself and all equipment to starboard or port accordingly. Such obstacles impact the survey in one of more ways, e.g., logistics and data deliverables.

- Time required to conduct line changes as such considerations will extend the duration of the survey due to increased off-line time.
- The potential reduction in the expected data coverage (fold coverage) as additional cells of the seismic grid will not contain their full complement of source-receiver offsets.

Obstacles create either permanent or temporary exclusion zones. The sea mount is permanent, whilst the drilling rig is temporary. Other examples include areas laying adjacent to or over international boundaries and designated military zones.

4.2 Pre and post survey considerations

The deliverables from the seismic survey (post-survey) will confirm if the objectives described in the initial survey design (pre-survey) have been achieved. Correlation of perimeters and coverage plots (see section 6) will provide that confirmation. This includes examination of the geographic areas over which the data was acquired, and the fold coverage reported for the cells of the full fold coverage area from the binning coverage plots (see section 7.2).

Therefore, using one or more of the four perimeter types in both survey design (pre-survey) and survey reporting (post-survey) proves very beneficial. The perimeters do not modify the definition of the seismic grid, they only highlight the extent of cells of the seismic grid where specific types of activity are expected to be conducted or have been conducted. The following application of the perimeters is described from a practical perspective and differs from the approach described in P6/11 definition document (IOGP, 2017). For an abbreviated description see section 7: P6/11 file format version 2.

4.2.1 Application of pre-survey perimeters

During survey design (pre-survey) the different perimeters are used to describe geographic areas over where it is and is not possible to acquire seismic trace data. For narrative purposes a pre-survey design is illustrated in Figure 60 to highlight the use of some of the perimeters described in section 4.1.

- The survey design must contain a minimum of one perimeter describing the full fold coverage area. Over what area of the seismic grid are the cells expected to contain seismic trace data for all source-receiver offsets. In Figure 60 the light green area represents this full fold perimeter. The light blue perimeter in the north-west corner defines an exclusion zone where no full fold data can be acquired by the seismic vessel.
- There are three known obstructions (production platforms) located in the vicinity of the full fold coverage perimeter and around each is drawn a null coverage perimeter (light brown) and a null fold perimeter (blue). The dimensions of each are selected such that the vessel and none of the equipment being towed will enter the 500 metre exclusion zone around each one. From this an estimate of what data loss is expected (sq.km. reduction) can be made.

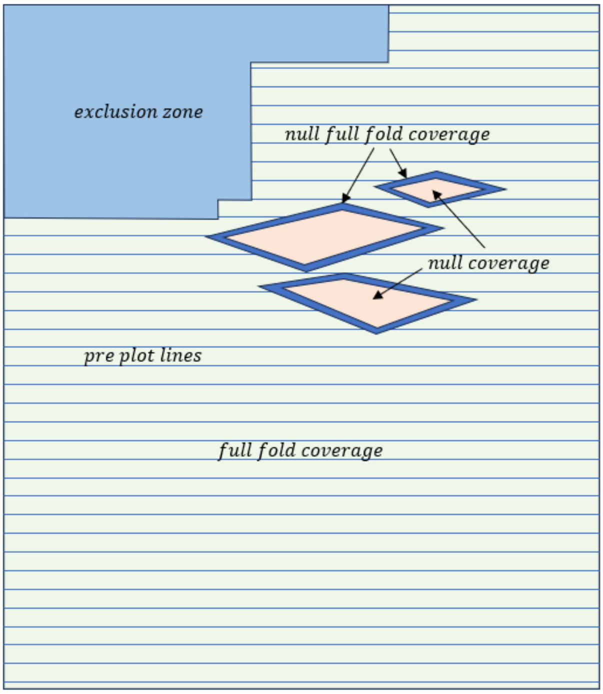


Figure 60: Pre-plot perimeters

- The data loss expected is not only a factor of the obstructions but also the acquisition technique being used, e.g., towed marine. Therefore, the use of other acquisition technologies can be considered to help reduce the expected loss. For example, conducting an undershoot or an OBN survey around the platforms (see section 15.1.4) and what budgetary impact such changes would introduce.
- All seismic grid parameters and perimeter definitions are stored in the P6 file format (P6/98 or P6/11) from the design stage (see section 9).
- Superimposed on the full fold coverage perimeter are the pre-plot lines along which the vessel is expected to traverse to optimize data acquisition (light blue lines Figure 60). The lateral separation between the pre-plot lines is based upon the geometry of the seismic equipment deployed as is described in section 6. All pre-plot lines are stored in one of the P1 exchange formats, e.g., P1/90 or P1/11.
- If required, it is possible from the definitions given to calculate the coordinates of every cell centre over the full fold coverage perimeter of the seismic grid prior to acquisition being conducted. If required, the cell coordinates are stored using the P1 file format where the line name and

event numbers are substituted for the I and J seismic grid coordinates (see section 9.4). The Q record identifier will also be used for P1/90 format.

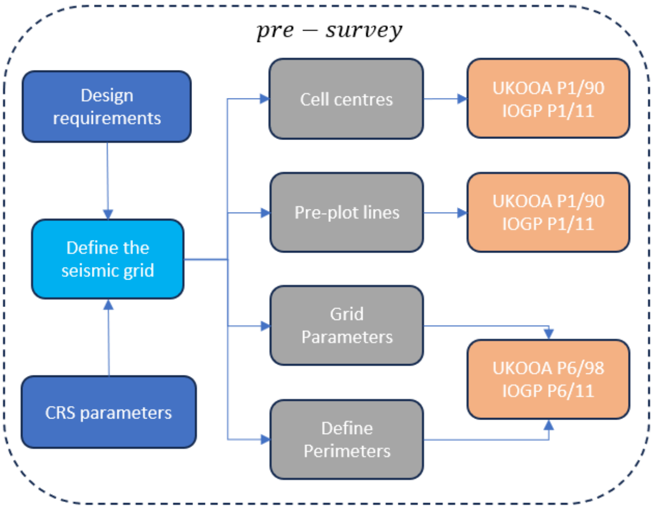


Figure 61: Pre-survey definitions

4.2.2 Application of post-survey perimeters

If the pre-survey perimeters are what are expected to happen on the survey, the post-survey perimeters are what actually happened. The volume of seismic trace data actually acquired during the survey depends upon several factors that include how successful were the seismic crew at navigating around the obstacles (both known and unknown) and how did they manage with the environmental conditions encountered. Their success in achieving the required coverage is reported in two forms: First, using the different perimeters created from the geo-spatial data acquired on the survey and second, from the coverage plots generated by the onboard binning system (see section 7.2 for an example).

4.2.2.1 Full fold and Total coverage perimeters

Figure 62 illustrates an example of the full fold coverage perimeter extracted from the post-survey P6/11 file format. This is shown by the solid blue polygon which represents an outline of all cells populated during the primary line acquisition between the expected first and last full fold cells. The red dashed line polygon represents the Full Fold Coverage perimeter created during the survey design. By overlaying the two perimeters clarifies the expected correlation required, i.e., the post-survey perimeter correlates directly to the pre-survey perimeter with no horizontal shifts resulting from different CRSs being used. The dashed blue perimeter represents the Total coverage perimeter extracted from the same P6/11 file format.

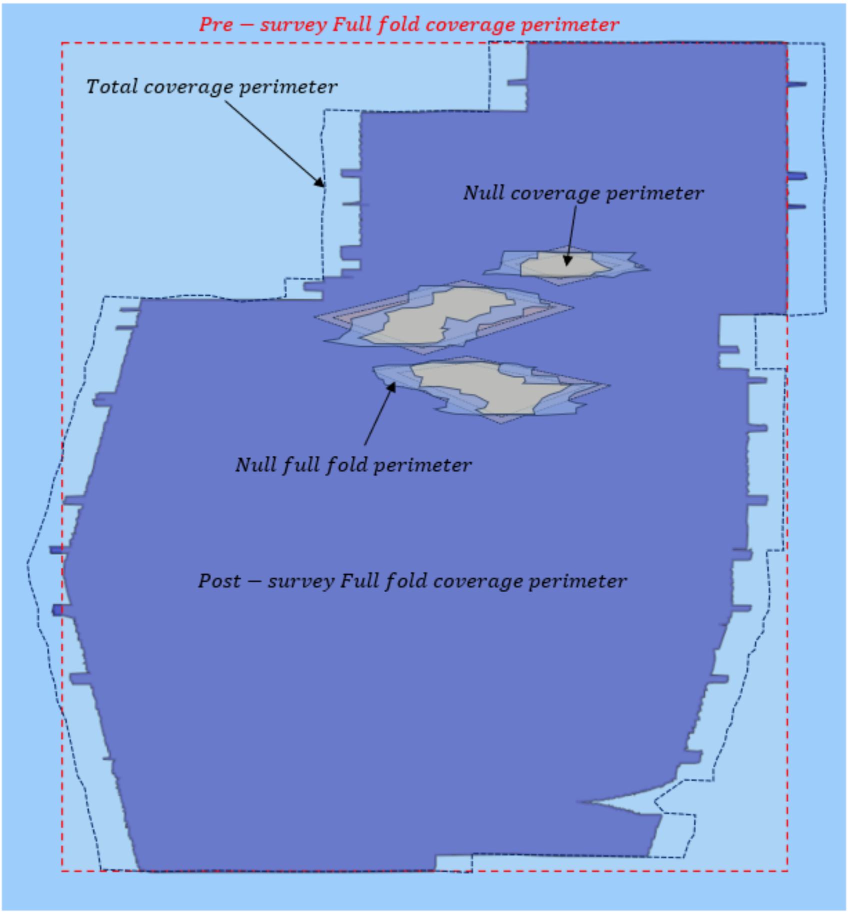
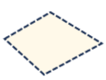
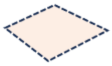


Figure 62: Post-survey full fold coverage perimeter

4.2.2.2 Null and null fold coverage perimeters

Where there are known obstacles in the full fold coverage perimeter the extent over which the seismic trace data is missing or much reduced are described by the null coverage and null full fold coverage perimeters respectively. By overlaying these on top of the perimeters estimated from the survey design will indicate if the data loss was more or less than expected. Figure 63 shows an expanded view of pre-plot and post-plot null full fold and null coverage areas displayed in Figure 62, where:

 The pre-survey null full fold perimeter

 The pre-survey null coverage perimeter

 The post-survey null full fold coverage perimeter extracted from the P6 file.

 The post-survey null coverage perimeter extracted from the P6 file.

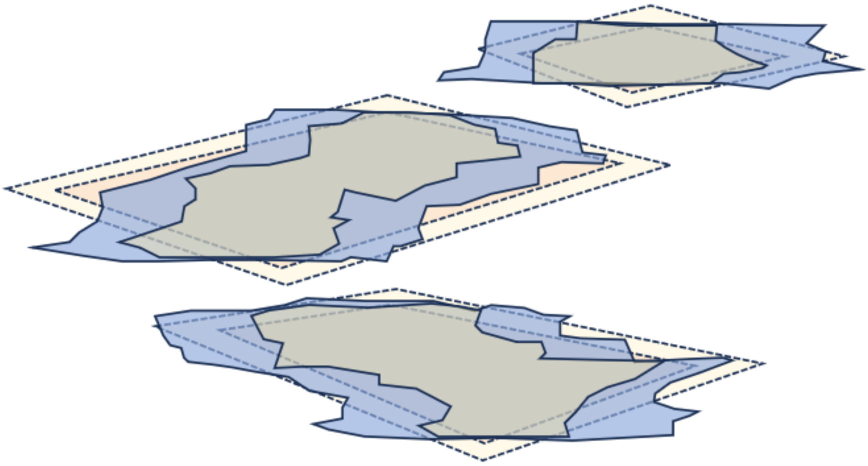


Figure 63: Post versus pre-survey perimeters

The perimeters contained in the post-survey P6/11 file describe the final acquired geo-spatial data extents using the multiple perimeters defined. Typically, the P6 file will contain one full fold, one total coverage and multiple null coverage and null full fold coverage perimeters to highlight areas of present and missing trace data.

- Delivery of the post-survey perimeters that define where trace data was acquired and where there were gaps and holes.
- Delivery of any post-survey perimeters modified by seismic processing. These are described by the M6 records contained in the data block of the P6/11 file format (see section 9.2).
- Delivery of the cell centre locations which are described by the B6 records in the P6/11 data block.
- Delivery of any files derived from the P6/11, e.g., GeoJSON, Shp Files, load sheets etc.

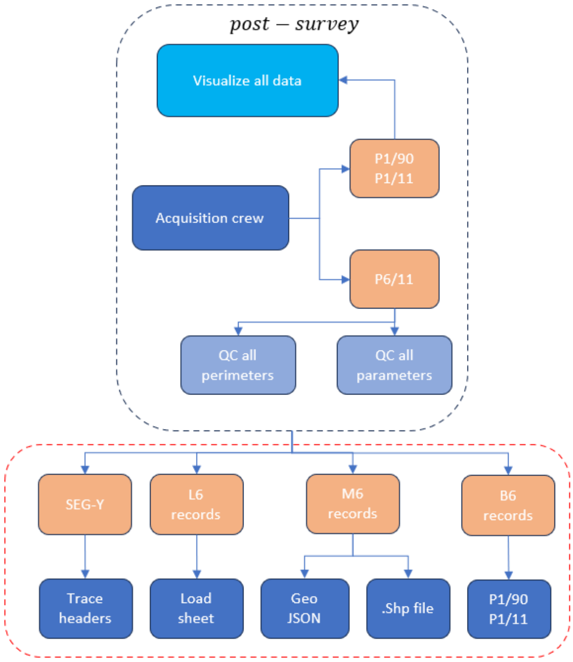


Figure 64: Post-survey definitions

4.2.2.3 Live Trace Outline

One final perimeter is generated to complete the three level correlation. This perimeter is created using the coordinates extracted from the trace headers of the SEG-Y file format.

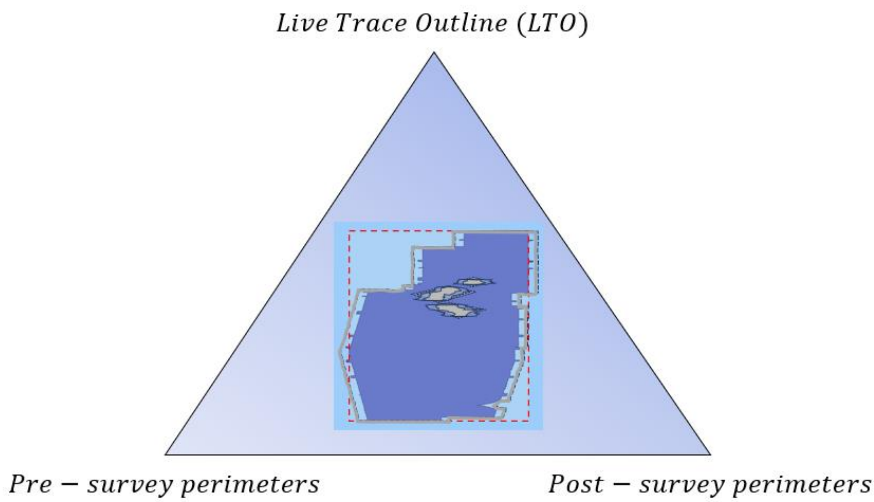


Figure 65: Correlating all perimeters

This perimeter, known as the Live Trace Outline (LTO) describes an area where all trace data is located regardless of fold-coverage or source-receiver offset pairs.

Trace Num...	Source_X	Source_Y	Group_X	Group_Y	CDP_X	CDP_Y	Inline	Crossline
1	9999	9999	9999	9999	443613	3125612	759	3000
2	9999	9999	9999	9999	443638	3125612	759	3001
3	9999	9999	9999	9999	443663	3125612	759	3002
4	9999	9999	9999	9999	443688	3125612	759	3003
5	9999	9999	9999	9999	443713	3125612	759	3004
6	9999	9999	9999	9999	443738	3125612	759	3005
7	9999	9999	9999	9999	443763	3125612	759	3006
8	9999	9999	9999	9999	443788	3125612	759	3007
9	9999	9999	9999	9999	443813	3125612	759	3008
10	9999	9999	9999	9999	443838	3125612	759	3009

Figure 66: Trace headers of SEG-Y file

In Figure 67 the LTO is superimposed on top of the pre-survey and post-survey perimeters such that all three are correlated to ensure there is no lateral shift that might lead to concerns of there being geo-spatial referencing errors at one or more stages of the data life cycle (see section 14).

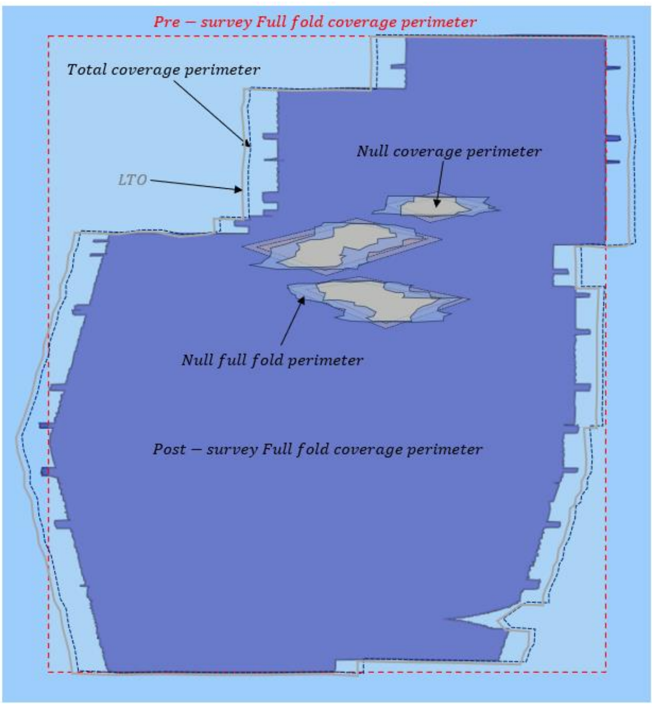


Figure 67: Live Trace Outline, total coverage perimeter

5 The seismic grid as a design tool

What are the best geometries to deploy in the field? What fold coverage can be expected? The design of the seismic survey raises a multitude of questions that require answers. Such matters include:

- The geophysical objectives of the survey
- Type of acquisition being conducted
- Type of target(s) expected to be imaged

Consideration is also given to target depth, noise suppression and signal strength. Imaging the same sub-surface points with seismic trace data acquired from multiple source-receiver offset pairs, leads to improved signal strength and the noise suppression needed. The collective number of traces required is known as the fold-coverage expected in each cell of the full-fold perimeter.

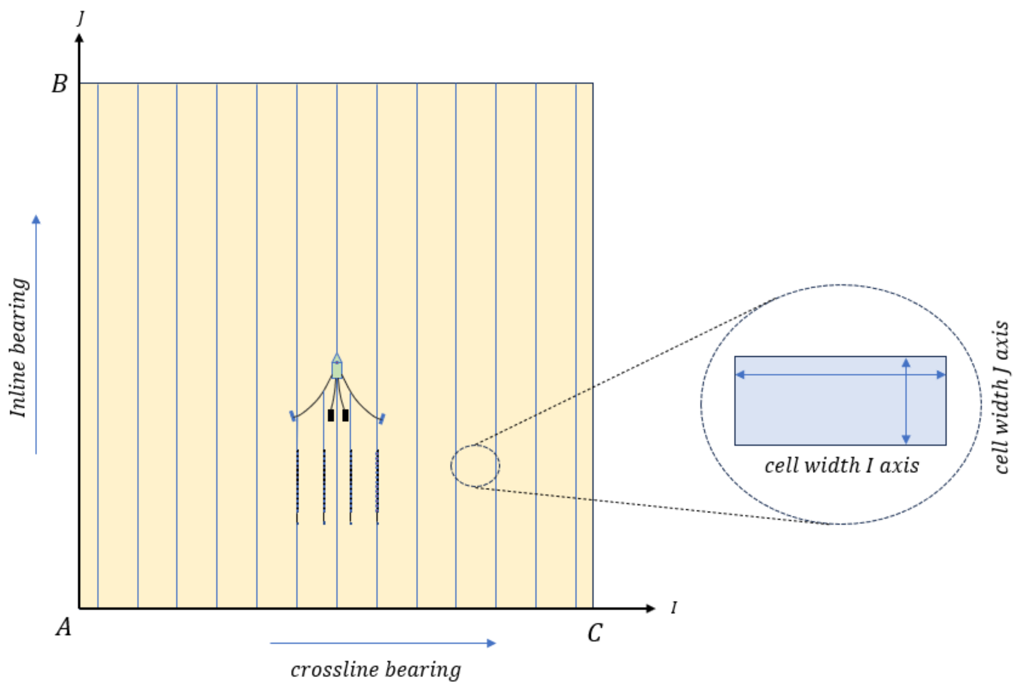


Figure 68: Area, azimuth, resolution, and geometry

The survey design ensures, theoretically, that the survey objectives can be achieved and conducting one is a must prior to the seismic acquisition commencing. The seismic grid parameters selected during the design will determine the sub-surface resolution and the source receiver geometry deployed in the field. In this section the design is considered with respect to the following:

- Area over which the survey is conducted
- Resolution with which the sub-surface is imaged
- Azimuth along which the survey lines are orientated
- Geometric layout of the sources and receivers deployed

This is described primarily for a marine towed 3D seismic survey with some additional comments related to Land surveys.

5.1 Area where survey is conducted

The geoscience team have selected an area over which the seismic 3D survey will be conducted. Their decision is based on existing local or regional seismic 2D data, previously acquired 3D survey(s) and any exploration wells drilled in the vicinity. For a new venture area, regional seismic 2D survey(s) are acquired ahead of any 3D survey to determine or reconfirm the fundamental geological structures of the sedimentary basin. If promising geological structures are identified it will give sufficient reason to garner a more detailed understanding of said structures by conducted a seismic 3D survey. The survey extent is defined by a multi-pointed polygon (perimeter) outlining where the sub-surface will be imaged. First, the polygon is plotted along with any available culture data and or satellite images. This will ensure the following:

- It falls in the geographic area expected
- The coordinate reference system supplied is correct
- It lies in an area that the company has rights to explore.

Checks are made to confirm the polygon does not stray into adjacent (un)license blocks or into other neighbouring territories by crossing international boundaries. If it does, is there permission to acquire data in these areas? Correlation is also made against all existing exploration data, including seismic 2D and 3D surveys and any wellbores surveys with associated geological logs.

Next, the size of the full fold area is computed and compared to the acreage expected by the project team. As a result, modifications may be made to the original definition that will either decrease or increase the polygon size to match any budgetary requirements or geophysical objectives of the survey.

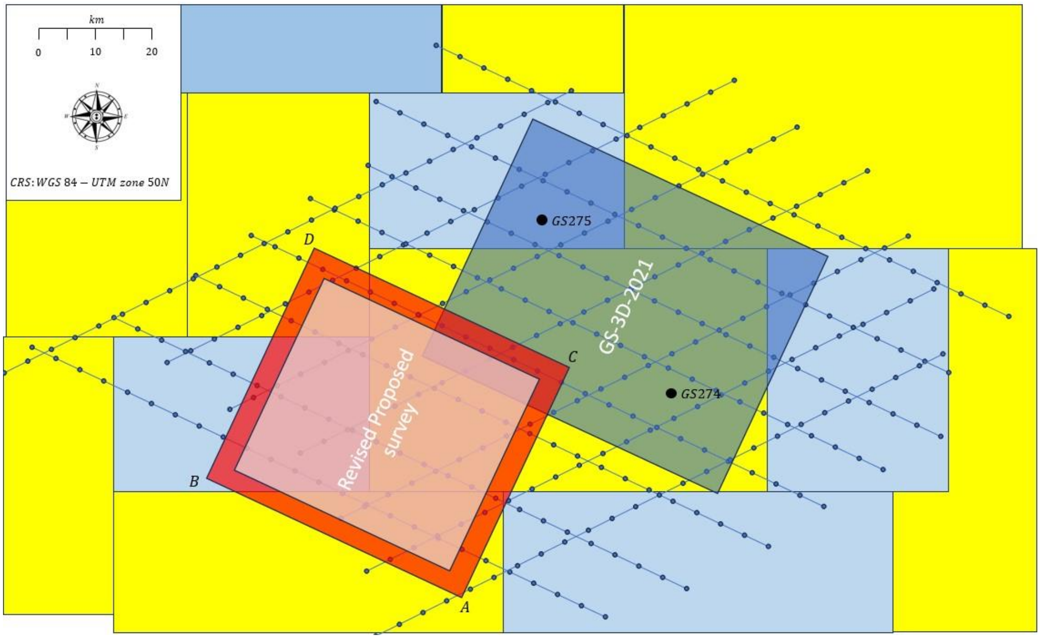


Figure 69: Original and modified survey areas

In Figure 70, the proposed operational survey area is represented by the blue polygon with the four corner points labelled A to D. This represents the full fold perimeter (see section 4) of the proposed survey. The perimeter has an origin designated by Point A which is where the two axes of the seismic grid coordinate system meet and a survey bearing along the line AB.

Superimposed on top of the blue polygon are a series of lines, and event numbers which (as will be discussed) represent the orientation of the pre-plot lines and shot point numbers along which the seismic acquisition will be conducted to ensure the objectives of the survey design are optimally achieved. The parameters and parameter values used in the seismic grid design are examined in this section. These are the parameters that describe the conversion component of the Derived CRS.

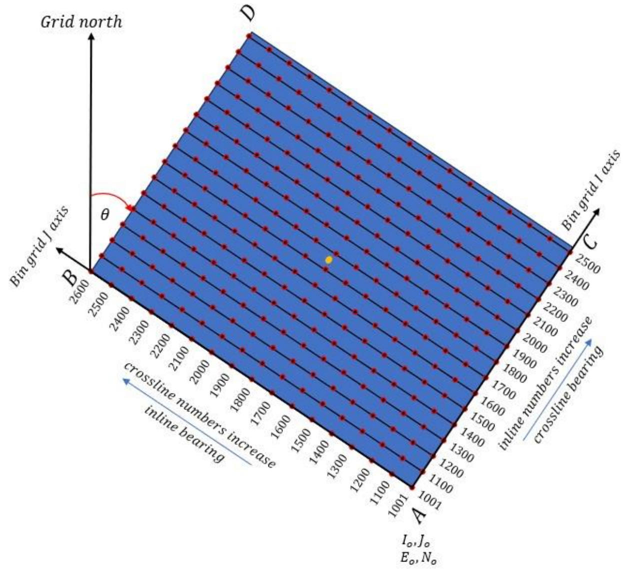


Figure 70: Basic parameters of the grid

5.2 Azimuth of the survey lines

The geoscience team will have a basic understanding of the rock structures from previous seismic data acquired, e.g., seismic 2D and 3D data. This will include knowing the general structural trends in terms of dip and strike. For a single seismic 2D line the orientation of the receivers will determine whether the seismic trace data predominately images the dip or strike direction, or a bit of both.

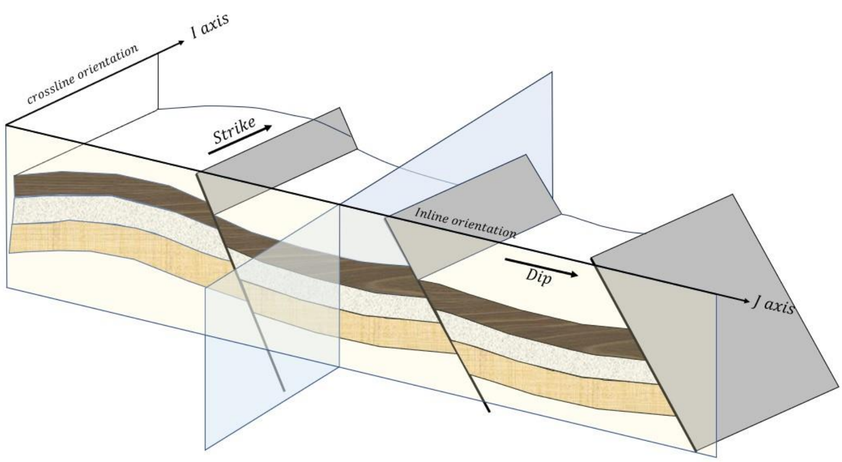


Figure 71: Dip and Strike versus azimuth

With a seismic 3D survey both dip and strike will be imaged as a cube of seismic trace data is acquired. What needs to be decided is which axis of the seismic grid is aligned along the dip direction. If this is chosen to be the $J\ axis$ of the seismic grid, the $I\ axis$ is orientated along the strike direction. These become the inline and crossline directions, respectively. This is the orientation shown in Figure 71. If the survey design is reversed then the two axes are also reversed such the $J\ axis$ is now aligned along strike and $I\ axis$ along dip.

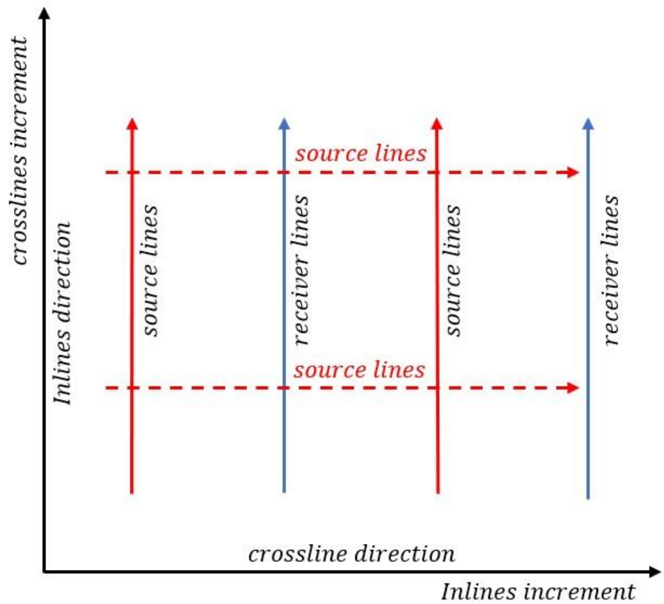


Figure 72: Inline and crossline directions

Figure 72 illustrates some basic azimuthal relationships between receivers and sources. In a towed marine survey, the receiver and source azimuths will be identical when pulled by the same seismic vessel. However, for OBN or land survey the sources line azimuth can be orthogonal to the receiver lines as shown by the dashed red lines. This is known as patch shooting. Alternatively, they can be in the same azimuth, which is known as swath shooting. The inline direction (bearing) is oriented between points A and B, as shown in Figure 73. Whilst the crossline direction (bearing) will be oriented between points A and C.

In Figure 73, the solid blue arrows superimposed on the lighter blue polygon indicate the direction in which the receivers will be towed and thus what direction the vessel will traverse. It is also the direction along which Shot Point (SP) numbers will increase from a minimum at point A to a maximum at point B (when sailing north south). As the vessel traverses up and down the survey area (along the pre-plot lines, see section 5.6), the line numbers (CMP line numbers) will increase along the bearing AC, from a minimum value at A to a maximum value at C. The shot point numbers will increase along the bearing AB, from a minimum at A to a maximum at B.

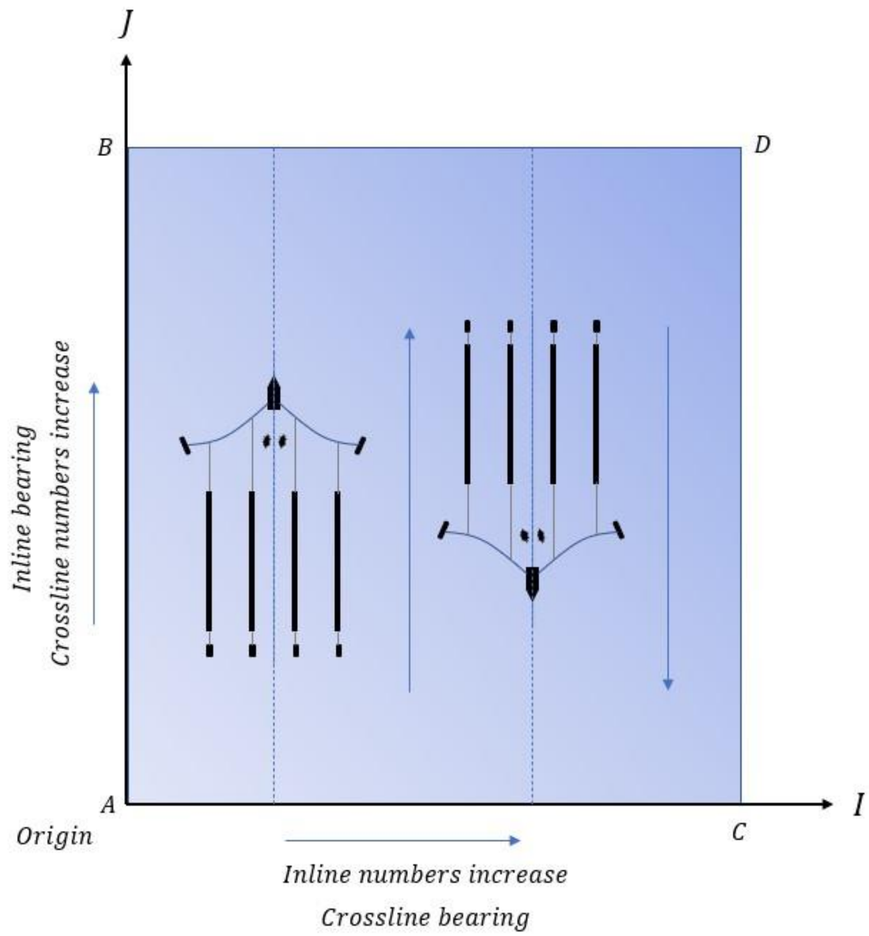


Figure 73: Source and receiver azimuth with marine towed survey

In either case, the bearing of the receiver lines will correlate to the bearing of the crossline axis ($J\ axis$ or Bin grid J) i.e., the direction along which the crossline numbers increase. The source azimuth will either match this or will correlate to the inline axis ($I\ axis$ or Bin grid I). Newer acquisition techniques do not have these limitations.

5.3 Geo-spatial resolution and fold coverage

The survey area has been selected and the geoscientists have formalized their survey objectives. Next, a basic survey design is performed to ensure the geophysical / geological objectives are feasible with respect to the desired sub-surface imaging. This requires the following matters are addressed:

- The geo-spatial horizontal resolution with which the sub-surface is sampled in both the horizontal inline and crossline directions of the survey area. This will determine the cell size of the seismic grid.
- The fold coverage required; the number of times the same sub-surface points are sampled to improve signal / noise ratio of the trace data. This will determine the receiver group interval and shot point interval.
- The depth to which the seismic trace data will penetrate the sub-strata to image the required geological target(s). This will determine how long the hydrophones / geophones listen for returning energy (or employ continuous listening).

All three have a direct impact on the geo-spatial deployment (geometry) of the seismic equipment used on the survey.

5.3.1 Geo-spatial resolution

The seismic grid extends over an area where the survey is being conducted, and it comprises an array of individual cells whose dimensions are given by two widths: One along the seismic grid *I axis* (*In-line axis*) and one along the seismic grid *J axis* (*Crossline axis*). These dimensions are common to all cells in the seismic grid. As indicated in section 3, typical widths are I = 25m and J = 12.5m.

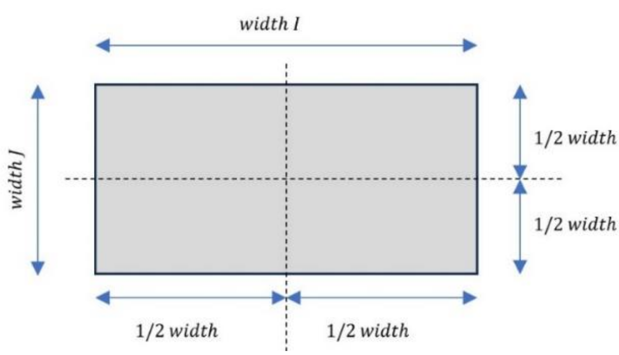


Figure 74: Cell dimensions specify the resolution

The cell represents a horizontal area into which the seismic trace data for the collection of source-receiver offset pairs will be ‘gathered’ (summed together) on the assumption that they are all imaging the same point of sub-surface strata.

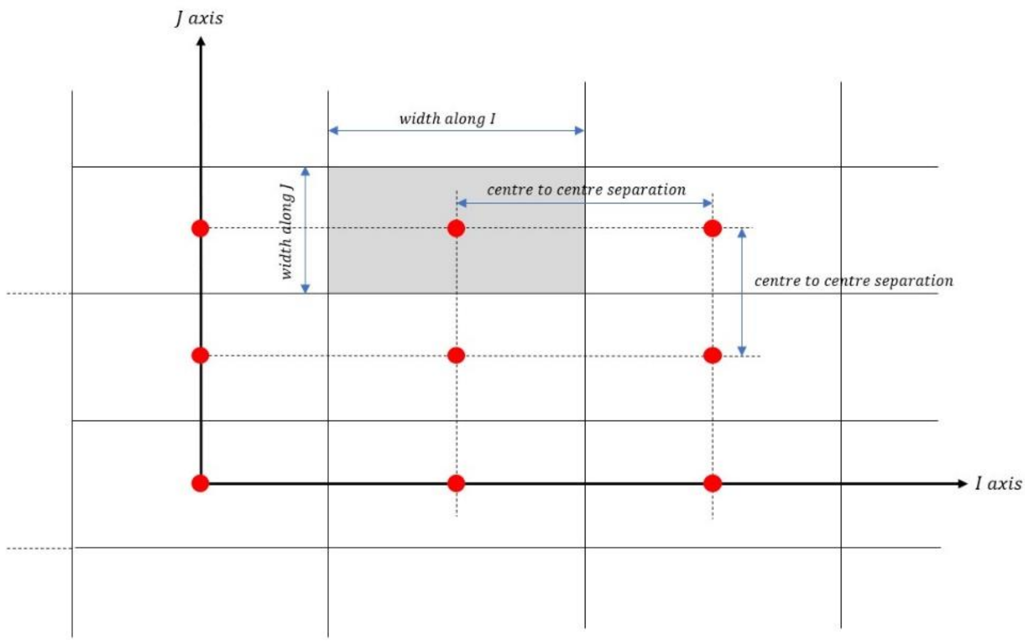


Figure 75: Centre to centre cell separation along both axes of the grid

The centre-to-centre separation between adjacent cells describes the horizontal geo-spatial resolution and is specified along both the I and J $axes$ of the seismic grids coordinate system. The higher their values the lower the geo-spatial resolution.

**Geo-spatial resolution is not to be confused with seismic resolution (in the vertical plane) which describes the thickness or spacing between each reflector identified in the processed seismic volume. See section 6.3 for further details.*

5.3.2 Extent of the seismic grid

For narrative purposes, there are 2500 cells along the seismic grid I $axis$ (widths) with each cell having a width of 25m and 12500 cells along the seismic grid J $axis$ (lengths) with each cell having a width of 12.5m. Therefore, the extent of the full-fold area has dimensions of 62.5km between corner points A and C and 78.125km between corner points A and B (see Figure 76). The survey bearing specifies the direction along which the receivers are towed. This is set to 0^o in relation to grid north which is the direction along which the vessel will traverse the pre-plot lines. Therefore, the J *axis* of the seismic grid will have the same bearing as the grid north of the projected CRS.

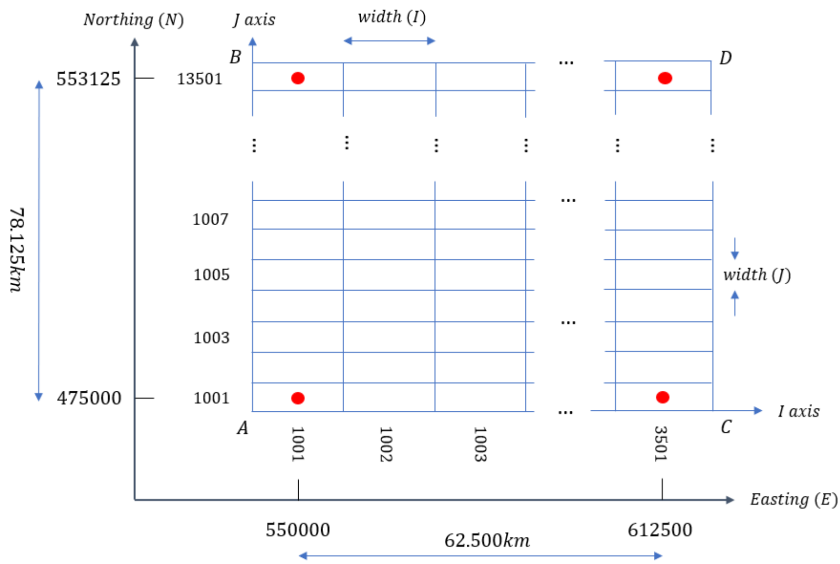


Figure 76: Seismic grid attributed

The grid corner points are specified using both the seismic grid coordinates and the selected projected CRS coordinates, which are reflected in what is contained in the P6/xx file. See sections 9.1 and 9.2 for an introduction to this file format.

Table 5: Corner points

Point	I	J	Easting	Northing
A	1001	1001	550000	475000
B	1001	13501	550000	553125
C	3501	13501	612500	553125
D	3501	1001	612500	475000

IOGP treatment of the seismic grid extent does vary from what is given here as their definition does not use parameters to specify the number of cells along the two axes, and hence there are no cell ranges. Instead, two other approaches are adopted depending upon how the seismic grid is stored. If its definition is stored in the EPSG geodetic parameter registry it is captured using the extent parameter in the usage details. This displays a rectangular area that corresponds to the dimensions of the full fold perimeter superimposed on the seismic grid. The coordinates shown on the upper, lower, left and right of the area represent the latitude and longitude limits of this perimeter. These are only given to two decimal places in EPSG geodetic parameter registry.

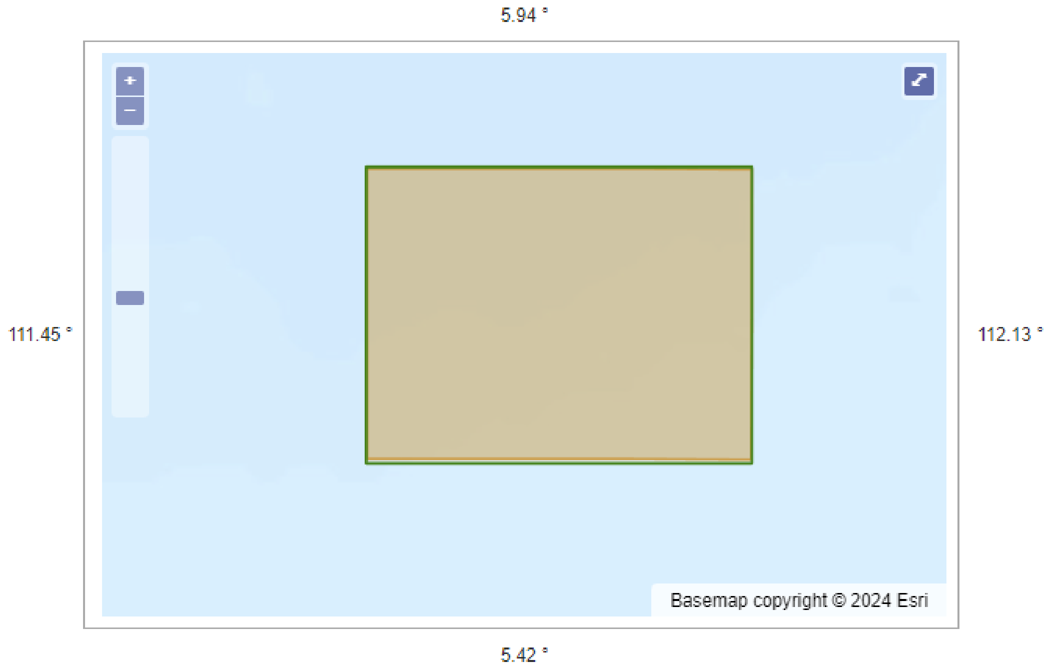


Figure 77: Extent of seismic grid, GeoRepository

Secondly, the perimeter(s) are captured in the P6/98 or P6/11 file formats using either the H3201 or M6 records, respectively. These formats do not show any graphical representation of the perimeters until they are plotted in a mapping package. Examples of this are given in section 9.2.

5.3.2.1 Cell coordinates

In Figure 76 and Table 5 only the coordinates of the corner cells are shown. However, the projected CRS coordinates of all other cells of the seismic grid can be computed once the design has been completed (i.e., the conversion parameters of the Derived CRS). In Figure 78 the coordinates of other cells along $J\ axis$ of crossline 1001 are displayed. See how the Northing coordinates remain the same, because of the 0^o bearing of the $J\ axis$, but the Easting coordinates increase by 25 metres for cells incrementing along the $I\ axis$ (inline numbers). This is the expected pattern as the distance between adjacent cells is set to 25 metres (width on $I\ axis$).

Moving north to the next crossline on the $J\ axis$, number 1002. The coordinates for the cell centre of the first Inline are shown (I = 1001, J = 1002). What the coordinates show in Figure 78 is one of the inadequacies of the P1/90 file (see section 7.4); that being because the projected coordinates are reported to only one decimal place, such that the 6.25 is rounded up to 6.3 as is reflected in the northing coordinate of that cell centre. This is not a problem when using the P1/11 file format (see section 9.4, cell centres) as there is no restriction to the geo-spatial resolution to which coordinates are stored.

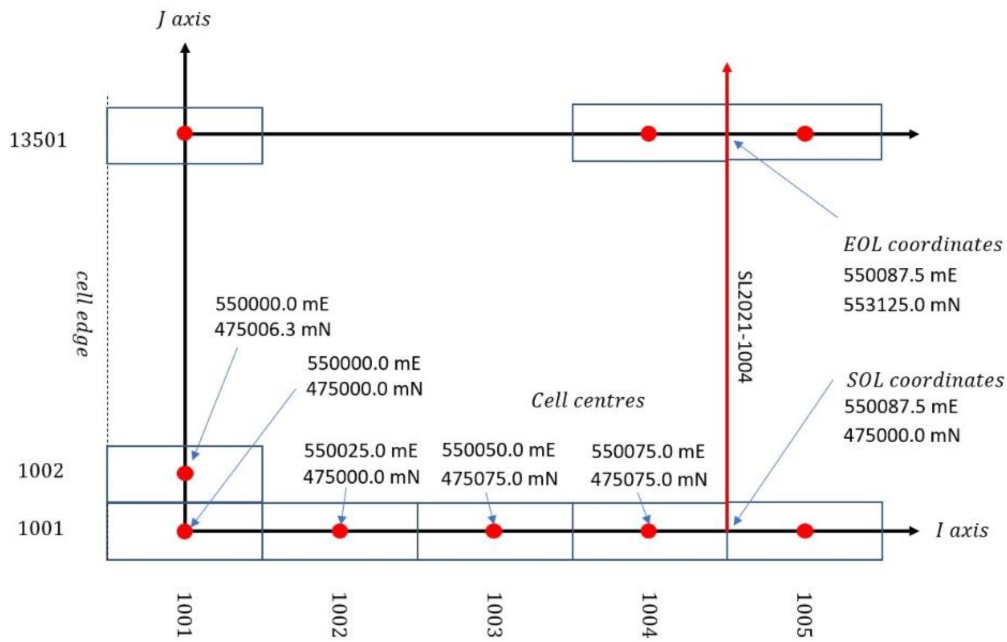


Figure 78: Bin centre coordinates

All the coordinates relating to the cells represent the cell centres and not an edge or a corner of the cell. If the coordinates are confused with either of these two it will invoke an error equivalent to half the cell width and length, respectively.

5.3.3 Fold coverage

The fold coverage is the number of times the geoscientists require the seismic trace data to image the same sub-surface points from the different source-receiver offset pairs available in the seismic spread. Multiple imaging enhances the signal quality of the trace data and thus the pictures generated from the processed trace data. Full fold coverage, as a variable is driven by the inline geometry deployed (see section

5.4.1.2), e.g., the number and interval between receiver groups (RGI) and the shot point interval (SPI). This is computed using:

$$Full\ fold\ coverage = \frac{\frac{RGI * No.of\ receivers}{2}}{SPI}$$

Given the importance of full fold coverage, and how fold accumulates because of equipment geometry, it is discussed in greater detail in sections 5.4.1.2 and 6.2. Refer to those sections for details on how the fold coverage builds up at the start of line and reduces at the end of line and remains constant for all cells in between.

5.3.4 Depth

A critical element of the survey design requires the geoscience team to specify the depth to which the sub-surface requires imaging, such that reflections (seismic trace data) are recorded for the geological targets of interest.

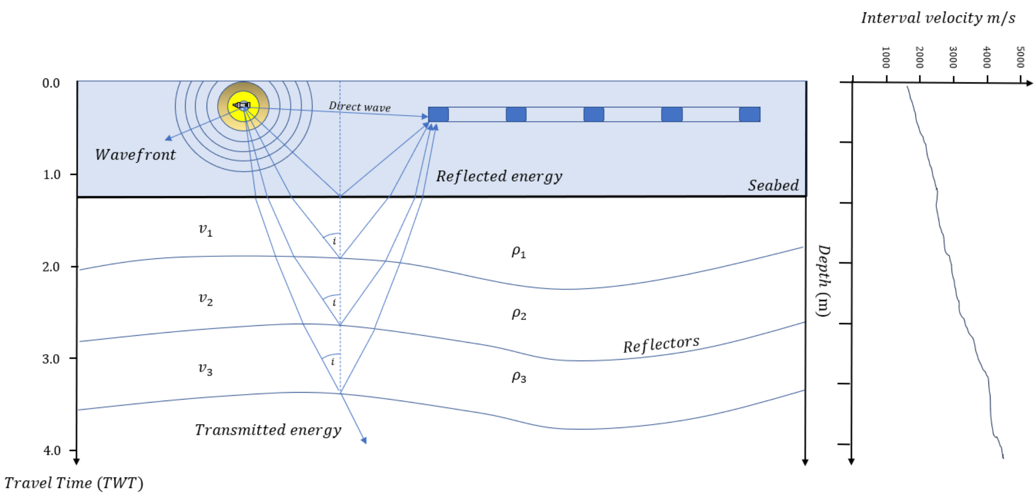


Figure 79: Depth and travel time

On a seismic survey depth relates to 'listening time,' i.e., the maximum time interval allowed for the seismic energy to penetrate the Earth, reflect off the numerous rock structure boundaries and be detected back at the surface receivers. This is known as Two Way Time (TWT) and is a parameter set in the seismic recording system. This is a measurable quantity whereas the physical depth of penetration is not. Hence, the original trace data is time related, or in the time domain. To convert the vertical axis of the trace data from time to depth requires knowledge of the interval velocities, i.e., the velocities with which the seismic energy propagates through the inhomogeneous rock layers of the sub-strata.

This quantity is unknown and therefore precise depths cannot be initially determined. Velocity modelling is the holy grail of seismic processing and precise velocity models are determined during data processing and seismic interpretation, especially with the contribution of well logs that complement the seismic trace data. This is required for true depth conversions and interpretation of the inhomogeneity of the sub-surface. The deeper the targets the further the acoustic energy must travel making the TWT of the journey lengthier. Therefore, the longer the receivers must remain open to listen for the returning energy. To image deeper targets often requires a larger cubic capacity of the seismic source, which in turn requires a longer time to recharge the airguns to the pressure at which they need to operate. Note, larger cubic capacity usually introduces larger amplitudes in the lower frequency portion of the frequency spectrum.

What role does this play in the field acquisition for marine towed surveys? By having a longer TWT means that the shot point interval can have a minimum distance value. For example, if the TWT required is 7 seconds and the vessel is moving at 4.5 knots, it will travel 16.2 metres whilst listening for the returning energy. Therefore, the next shot point cannot be any shorter than that distance, unless overlapping recording technology is applied. As such, a shot point interval of 12.5 metres would not be feasible and 18.75 or 25 metres used instead. Why must it be this? The shot point interval must have a geometric relationship to the receiver group interval (i.e., a multiple there of), i.e., a ratio that results in integers. If the RGI is 25 metres it will create an inline CMP every 12.5 metres, e.g., 1:2 ratio. Therefore, the SPI must have a similar ratio. For example, if the shot point is 50 metres it gives a ratio of 1:4 with the CMP and a ratio of 1:2 with the RGI.

5.4 Geo-spatial resolution and geometry

There is an intrinsic link between the geo-spatial resolution required and the geometric nominal offsets applied to the seismic equipment. This is a chicken and egg situation with one driving the other. For example:

- Specify the geo-spatial resolution and fold coverage to determine the survey geometry

Or

- Specify the survey geometry which will determine the geo-spatial resolution and fold coverage.

The former is the normal approach. However, the latter will apply if the seismic contractor has equipment limitations, i.e., can only operate with a specific geometry.

5.4.1 Specify resolution and fold coverage

For narrative purposes: the project team require the rock structures are sampled over the extent of a designated full fold coverage perimeter with each cell in the seismic grid having a width of 25 metres (*width on I axis*) and a length of 12.5 metres (*width on J axis*). A *survey bearing* of 0^o is chosen meaning the seismic grid is orientated in a north-south direction relative to Grid North. The geoscience team require a fold coverage of 60 for each cell in the full fold coverage perimeter. All other parameters associated with the seismic grid definition is given in Table 6.

Table 6: Seismic grid parameters

Parameter	Parameter value
Origin Easting, E_o	550000m
Origin Northing, N_o	475000m
CRS	WGS 84 / UTM zone 49N
Origin I_o	1001
Origin J_o	1001
Bin grid I width / Increment	25m / 1
Bin width J width / Increment	12.5m / 1
J bearing	(grid north) 0^o
Scale factor	1
Full fold coverage	60
I and J extents	2500 / 12500

The geo-spatial horizontal imaging requirements determine what equipment geometry must be deployed to achieve the design constraints. This is illustrated using a marine 3D towed seismic spread (Figure 80) in which the vessel tows multiple sources and streamers and therefore, multiple crossline CMPs are acquired per sail line. How many streamers and sources require deploying and what nominal offsets (see section 3.4.1) must apply to fulfil the survey objectives? For brevity (of drawing), the seismic vessel is towing four streamers and two sources.

Surveys are conducted with far more streamers deployed but this example is for narrative purposes only as the same principles apply.

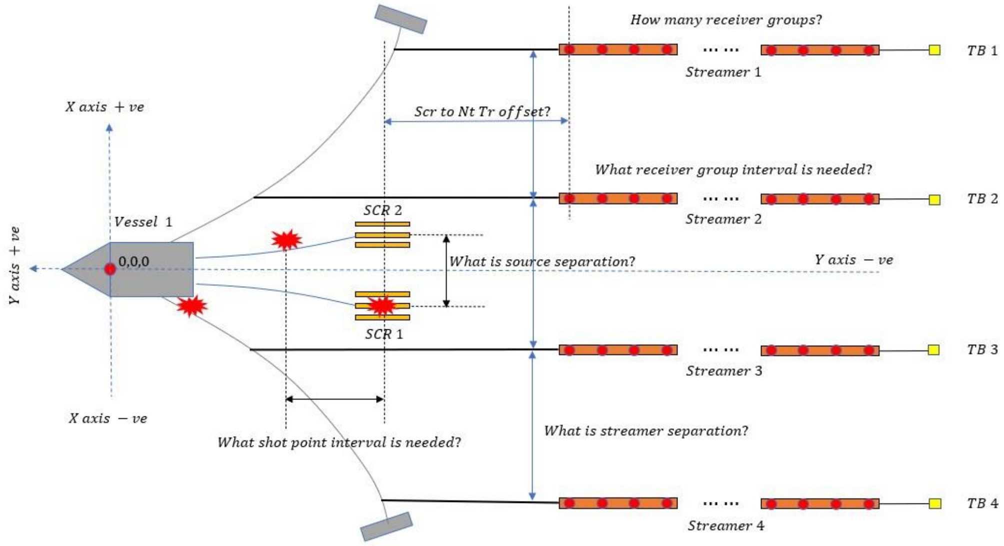


Figure 80: What offsets are required?

The geometric design is separated into two components, namely: the crossline and inline axes of the seismic grid definition. The crossline component is orientated along the $I\ axis$ of the seismic grid and is directly associated with source and streamer separations needed. Whereas the inline component is that along the $J\ axis$ bearing (vessel sail-line) and accounts for the number of receiver groups deployed, their group spacing, and thus the inline common midpoint interval. Although the shot point interval is a component of the $J\ axis$ its value only influences the fold coverage, and it is not linked to resolution required.

5.4.1.1 Crossline configuration

The crossline configuration must satisfy the requirement that a CMP line be acquired every 25 metres along the $I\ axis$ of the seismic gird because this is the cell width (sampling interval) defined. Two geometric factors that contribute to realizing this requirement are the separation between the port and starboard seismic sources (dual source) and the separation between each streamer towed. What nominal distances are required to ensure the $I\ axis$ CMP widths of 25 metres are met?

In Figure 81 the in-water spread is being viewed from behind the Tailbuoys with the vessel sailing into the page. The streamers are represented by the red circles and the sources by the blue stars. The grey lines represent the array paths generated between the port source and the receiver groups of the four streamers. Whilst the green lines represent the array paths generated between the starboard source and the receiver groups of the same four streamer.

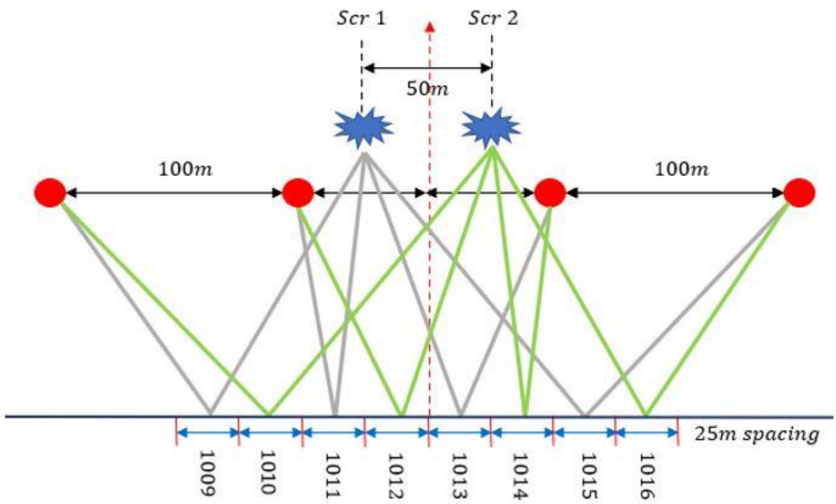


Figure 81: Crossline configuration of seismic spread

The $I\ axis$ CMP line numbers are shown along the base and range from 1009 to 1016. The sail line number is designated as 1012, indicated by the dashed red line.

$$Crossline\ CMP\ interval = \frac{\frac{Streamer\ separation}{2}}{2}$$

Each array path defines one common mid-point (CMP) located half-way between each source-streamer pairing. To satisfy the requirement of a 25 metre cell width the separation between the two sources must be half the separation between the streamers, with the streamer separation being 100 metres. If these criteria are not met there will not be equal spacing between the array paths that constitute the $I\ axis$ CMP separation required. With 4 streamers and 2 sources deployed, the number of $I\ axis$ CMP lines acquired per sail line is given by:

$$CMP\ lines = No.of\ streamers * No.of\ sources = 8$$

If the width of the cells along the $I\ axis$ is 25m then the swath acquired per sail-line will be 200 metres (8 x 25 metres) wide. This is shown by the outer-to-outer footprint of the CMP lines on the seabed (illustrated in Figure 81) and is not the outer-to-outer separation between the streamers (which is 300 metres).

5.4.1.2 Inline configuration

The in-water geometry must be deployed such that each cell of the seismic grid is populated at the regular spacing for the cell length specified, i.e., 12.5 metres along the $J\ axis$. Therefore, a CMP will be acquired every 12.5 metres along the in-line bearing (0^o). To honour cell widths along the $J\ axis$ the receiver group interval (RGI) must be double that size which is shown to be 25.0 metres in Figure 82. The $J\ axis$ cell dimension is not impacted by the shot point interval (SPI), only the full fold coverage achievable.

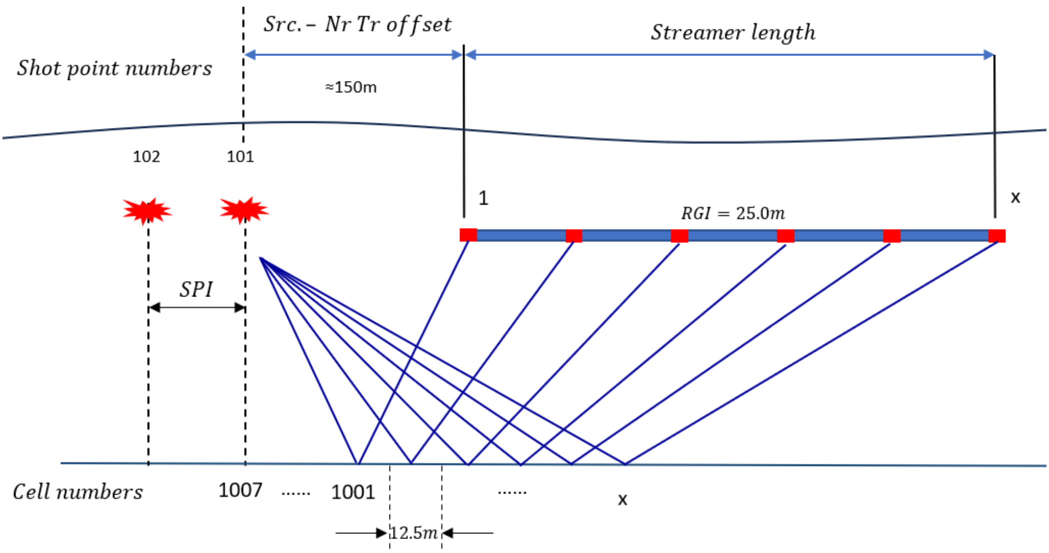


Figure 82: Inline configuration of the seismic spread

To increase the signal to noise ratio (of the seismic trace data) the sub-surface is imaged multiple times at each CMP location (along the $J\ axis$) by different source-receiver offset pairs. The number of times the sub-surface strata below each individual CMP cell is imaged is known as the fold coverage. Given the geometric relationship between the source and the receivers along each streamer, and the number of receivers housed in the streamer there will be a maximum number this parameter can achieve. This is known as the *full-fold coverage*, and as previously stated is computed using the following equation:

$$Full\ fold\ coverage = \frac{\frac{RGI * No.of\ receivers}{2}}{SPI}$$

Therefore, if the receiver group interval is 25.0 metres and the shot point interval is 25.0 metres how many receiver groups are required in each streamer to give a fold coverage of 60? By re-arranging the equation, we get:

$$\frac{2 * (fold\ coverage * SPI)}{RGI} = No.of\ receivers$$

By substituting in the values, the number required is given as:

$$\frac{2 * (60 * 50)}{25.0} = 240$$

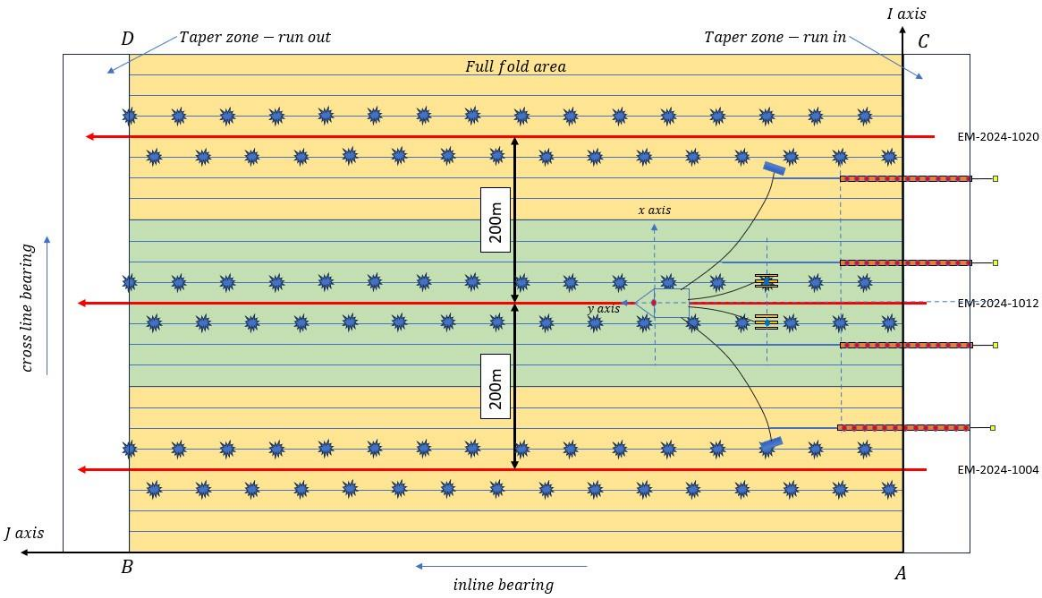


Figure 83: Generic design of marine towed 3D survey

As such, each streamer must have a total length of 6000 metres, comprising 240 receiver groups each with a spacing of 25.0 metres. Note, the shot point interval (SPI) is given as 50 metres in the equation above. This is because the sources are operating in flip-flip mode (dual sources) and thus fire alternately. Hence for each CMP line the fold coverage will be half what it would be if it were being acquired as a 2D seismic line. When two sources are deployed this is known as dual source (flip flop mode) comprising both port and starboard gun arrays. This arrangement has the upside of doubling the number of $I\ axis$ CMP lines acquired per sail line but has the downside of halving the fold coverage achievable versus its 2D geometric equivalent.

5.4.2 Fixed equipment geometry

The seismic contractor informs the client they can only acquire their seismic survey using one geometric configuration, which is specified as follows:

Six streamers:

Length: 4500 metres

Receiver groups: 180

Receiver group interval: 25m

Streamer separation: 75m

Two sources:

Source separation: 37.5m

Shot point interval: 18.75m

Given these parameters and parameter values what resolution and fold coverage can the client expect? The size of the cells along the $I\ axis$ is derived from the streamer separation and source separation:

x = Outer to outer separation of the streamers

y = Collective width of the CMP width

z = Total number of CMPs acquired per sail line

Therefore:

$$x = (No. of\ streamers - 1) * streamer\ sep. = (6 - 1) * 75 = 375m$$

$$y = (no. of\ strms - no. of\ srcs) * src\ separation = (6 - 2) * 37.5 = 150m$$

$$z = no. of\ streamers * no. of\ sources = 6 * 2 = 12$$

The cell width along the $I\ axis$ is computed as:

$$I\ width = \frac{x - y}{z} = \frac{375 - 150}{12} = 18.75m$$

The cell width along the $J\ axis$ is as follows, using the receiver group interval:

$$J\ width = \frac{receiver\ group\ interval}{2} = \frac{25}{2} = 12.5m$$

Maximum fold coverage possible:

$$fold = \frac{\frac{RGI * no.of\ receiver\ groups}{2}}{shot\ point\ interval * 2} = \frac{\frac{180 * 25}{2}}{37.5 * 2} = 30$$

Note, the fold coverage achievable is sensitive to two variables:

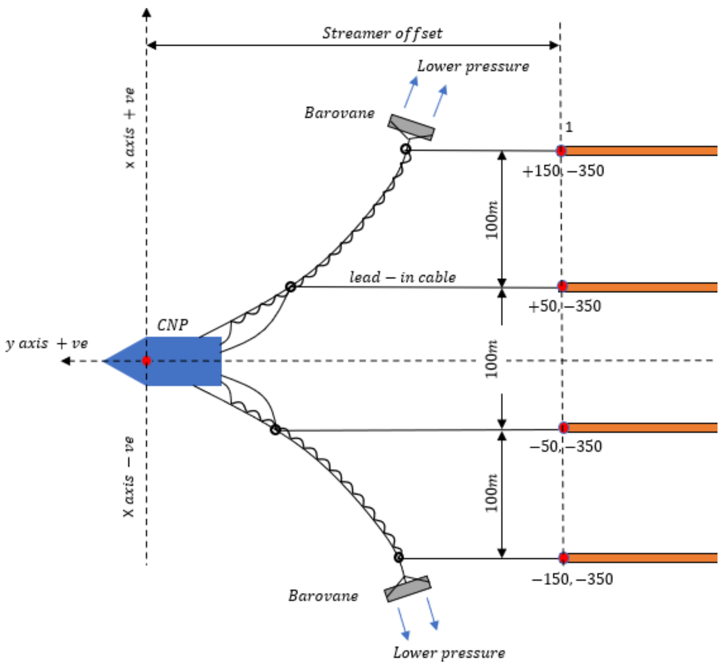


Figure 84: Layback to the streamer heads

First: the number of receiver groups being towed. The more receivers being towed the longer the streamer length? The fold coverage for a 4500m streamer comprising 360 receiver groups at 12.5m group interval is identical to a streamer comprising 180 receiver groups at 25m group interval.

Second: the shot point interval (SPI). The shorter the SPI the higher the fold coverage. However, a limiting factor on reducing the SPI is the two-way time length, refer to section 7.

5.4.3 Geometry deployment

First, consider the layback of the streamer heads (receiver group 1) from the vessel as the streamers are deployed first. The streamer layback (from vessel CNP) must be sufficient such that the desired streamer separation is achieved, e.g., 100 metres. The Barovanes, once deployed have a design that fights against the water flow which continually draws them away from the vessel (acts like a vertical airplane wing).

The lead-in cables (vessel side of the streamers) are attached by rings to the barovane tow wire (black circles) to achieve the streamer-to-streamer separation required. The length of each lead-in cable from the barovane tow-wire to the head of each streamer must be calculated such that the $y\ axis$ offset from the vessel results in an identical value, e.g., 350 metres in Figure 85.

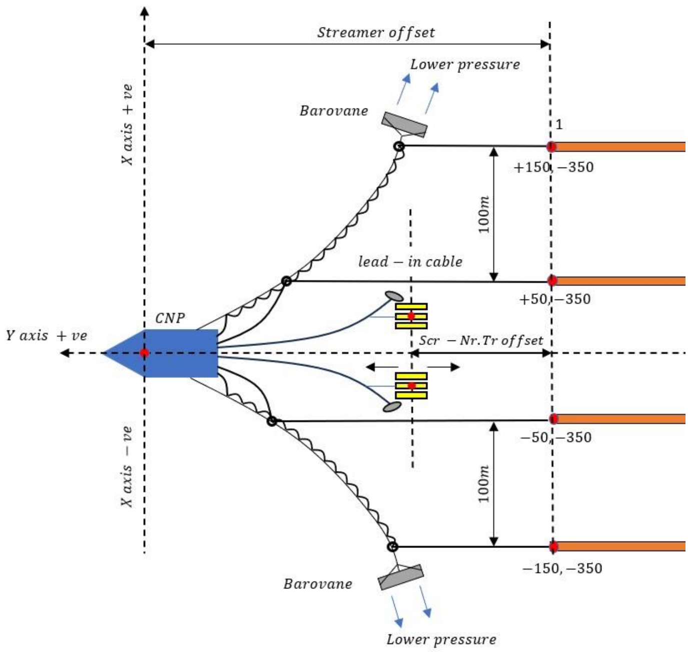


Figure 85: Source to near trace offset

5.4.3.1 Source layback

With the streamers arranged, the sources are deployed to a layback distance such that the source to near trace offset (required by the geophysicist) is achieved. Whilst this horizontal offset distance is required to be 'short' (e.g., approximately 120 to 150 metres) the water depth over the survey area will also influence this distance. Assume that a source to near trace offset of 125 metres is required and the distance between the CNP and head of the streamers is already set at 350m. Hence, the layback between the CNP and the centre of source will be 225m which requires source umbilical cables of at least this length to pump compressed air from the vessel's compressors to the airguns.

5.5 Increased resolution?

Assume that the geoscience team require the geo-spatial resolution to be increased. For example, the original grid design had cell widths of 25m x 12.5m in the inline and crossline directions respectively, with a fold coverage of 60. Now assume the geo-spatial resolution is increased to 25m x 6.25m. There are two possible outcomes:

- If the in-water geometry remains the same what will happen to the maximum fold coverage?
- If the fold coverage remains as originally selected, but with the increased geo-spatial resolution, what changes will be required to the in-water geometry?

5.5.1 In-water geometry stays the same

The geo-spatial resolution requirement changes such that the new cell size is reduced from 25m x 12.5m to 25m x 6.25m.

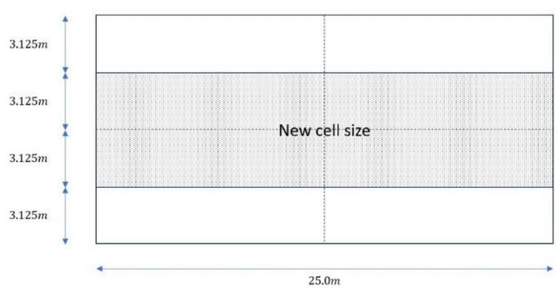


Figure 86: Change in cell resolution dimensions

If the in-water nominal offsets remain the same the computation of fold coverage will appear to remain the same. However, this will not be the case as the in-water geometry was not modified to accommodate the resolution requirements. Therefore, from a data management perspective, the expected fold coverage with the same configuration will be half that of the original geometry.

5.5.2 In-water geometry is modified

With the geo-spatial resolution of the cell widths modified, the in-water geometry requires modification if the fold coverage is to be maintained at the pre-modified level. If the cell size is modified to that shown in Figure 86 there is only a change required along the $J\ axis$ value and thus the in-line geometry. As such the fold coverage will be maintained by halving the receiver group interval for the new cell length selected. It is the relationship between the shot point (SPI) interval and receiver group interval (RGI) that affects the fold coverage achievable. Halving the receiver group interval changes the ratio to shot point interval, and whether it is operating in single or dual source mode.

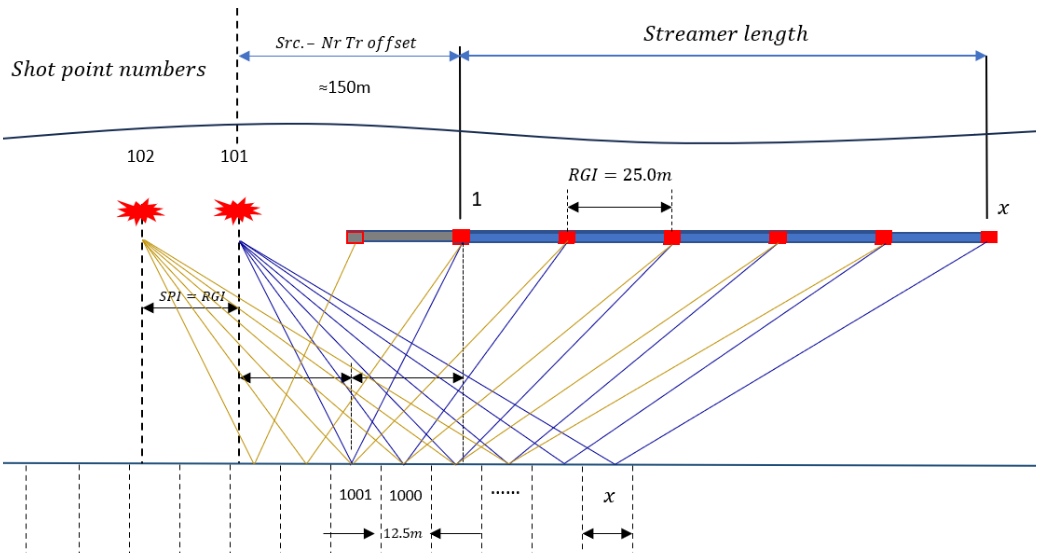


Figure 87: SPI is equal to RGI

In Figure 87 the SPI interval is equal to the RGI, which is a configuration popular when acquiring seismic 2D data. As such, when the source moves up to the next shot point position (SP102), it will have travelled 25m, which is equal to 2 CMP widths (12.5 x 2 = 25.0). Therefore, four of the CMP cells from SP101 will be populated with offset pairs from SP102 (e.g., 998 to 1001).

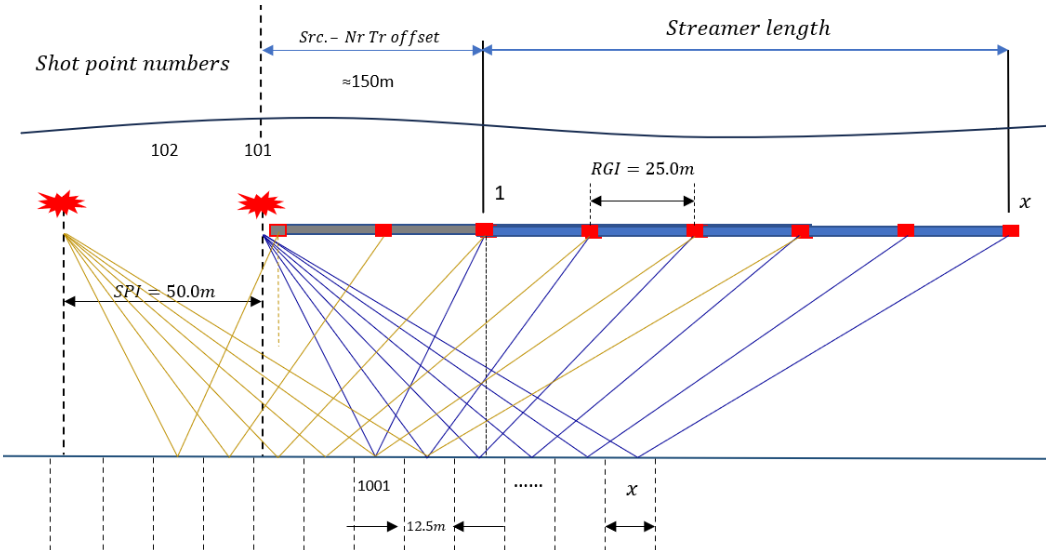


Figure 88: SPI is double to RGI

If the SPI interval is double the size of the RGI, the effect on the cell population is shown in Figure 88. As such, when the source moves up to the next shot point position (SP102), it will have travelled 50m, which is equal to 4 CMP widths (12.5 x 4 = 50.0). Therefore, only two of the CMP cells from SP101 will be populated with offset pairs from SP102. As the line progresses it means that the fold coverage from this configuration will yield a fold coverage half of that achievable when SPI is equal to RGI. This latter configuration would be typical of that deployed on a seismic 3D survey.

For seismic 2D surveys, understanding this relationship is important as it must be taken into consideration during the navigation merge, or Nav. Merge when the data is loaded to the workstation. This is the process of assigning coordinates to the common mid-points stored in the trace headers of the SEG-Y files. How many CMPs are there per Shot Point Interval and what CMP number matches closest to the first shot point of the line.

Data loaders will be familiar with this concept. The coordinates are known for each shot point along the line and the CMP coordinates can be interpolated accordingly. To perform this correctly the number of CMPs per shot point interval must be known (e.g., 2 or 4). One final configuration illustrated in Figure 89 is when the RGI interval is a quarter of the SPI, e.g., 12.5 metres versus 50.0m. This is another common configuration deployed on seismic 3D surveys when operating in dual source, flip-flop mode.

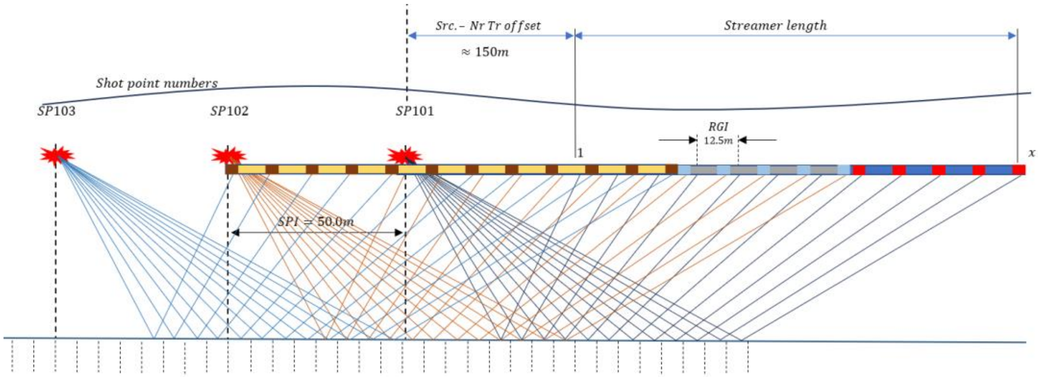


Figure 89: SPI is quadruple the RGI

Whilst this an efficient way to acquire the maximum number of CMPs per line is it also one that has the most detrimental effect on the fold coverage achievable. To ensure the fold coverage is sufficient longer streamers are recommended with a typical value of 8100m length being deployed which equates to there being 648 receiver groups per streamer.

6 Separation between pre-plot lines

The area over which the survey is conducted and the horizontal resolution with which the sub-surface is imaged (the seismic grid) have both been defined. Likewise, the seismic configuration to be deployed is confirmed. Next, an optimal series of pre-plot lines ($N1\ to\ N9, see\ section 9.2$) are designed to ensure all cells in the full fold area are theoretically populated with the maximum number of source-receiver offset pairs permissible without creating unnecessary overlap. Figure 90 shows a series of dashed pre-plot lines covering the full-fold area. But what must be the lateral separation between the pre-plot lines to optimize the acquisition program?

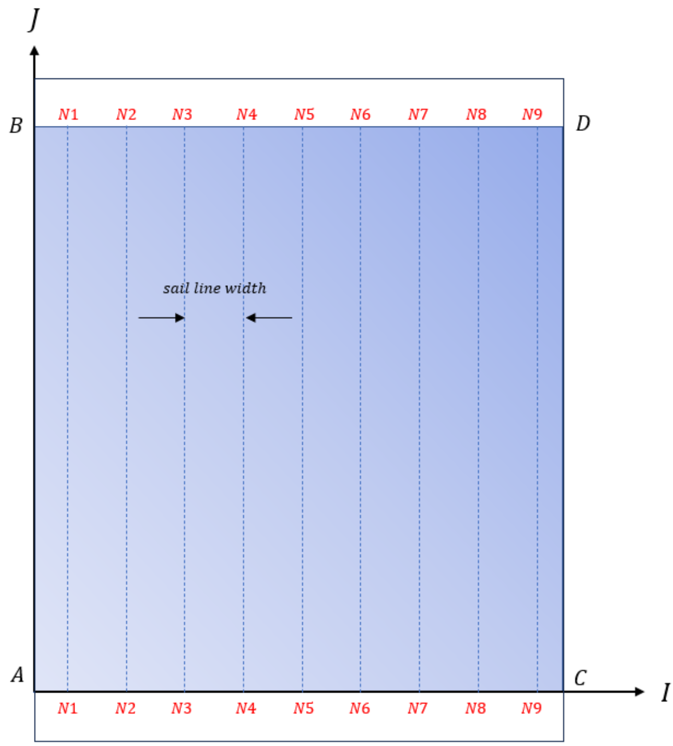


Figure 90: Generic pre-plot lines superimposed on bin grid

The spacing between the pre-plot lines is derived using the following variables:

- The number of streamers being towed
- The number of sources being towed
- The width of the bin cells along the $I\ axis$

The three parameter values enable the width of the CMP 'footprint' (or swath width) to be computed. For example:

- Number of streamers towed = 4
- Number of sources towed = 2
- Width of the cells along the $I\ axis$ = 25 metres

Therefore, for each sail line 8 CMP lines are acquired. With each having a width of being 25 metres the CMP footprint is 200 metres as shown in Figure 91.

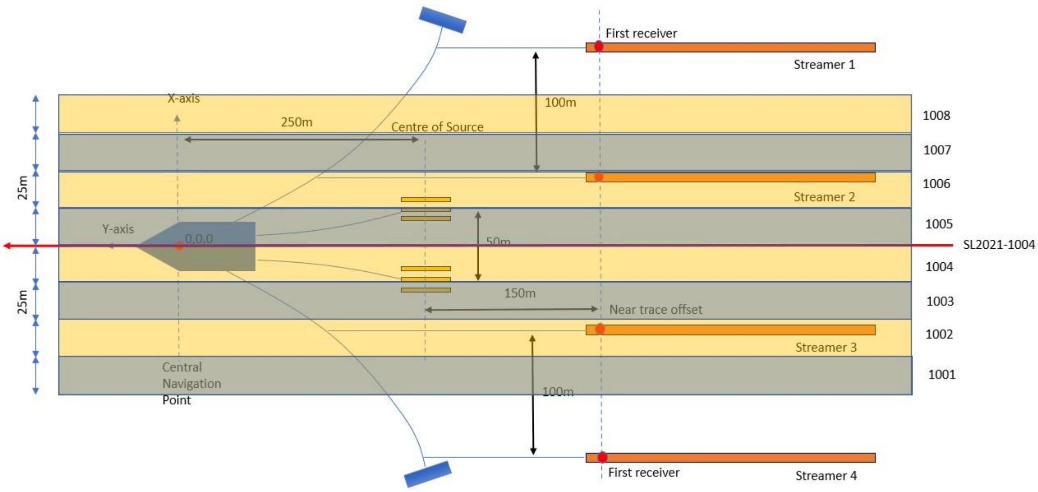


Figure 91: Swath width per sail line

To populate the cells of each CMP line in the swath the vessel must sail along a pre-determined path known as the pre-plot line. In this example it will lie along the boundary between the fourth and fifth CMP of the swath (red arrow). Therefore, four CMP's will fall to the port of the sail line and four to the starboard. The line name shown in Figure 91 is SL2021-1004. In the sail line name, 1004 indicates the CMP to which the sail line is correlated (the high side of CMP line 1004).

Hence, when traversing this sail line CMPs 1001 to 1008 are acquired. With this in-water configuration the distance 200m becomes significant as it specifies the separation between sail lines to acquire the CMP lines contained in the full-fold area. In Figure 92 the next swath (adjacent swath 2) will acquire CMP lines 1009 to 1016 if a sail line along the boundary of 1012 and 1013 to traversed. This will be named pre-plot SL2021-1012. Therefore, it will have a lateral offset of 200m further along the $I\ axis$ of the seismic grid from SL2021-1004.

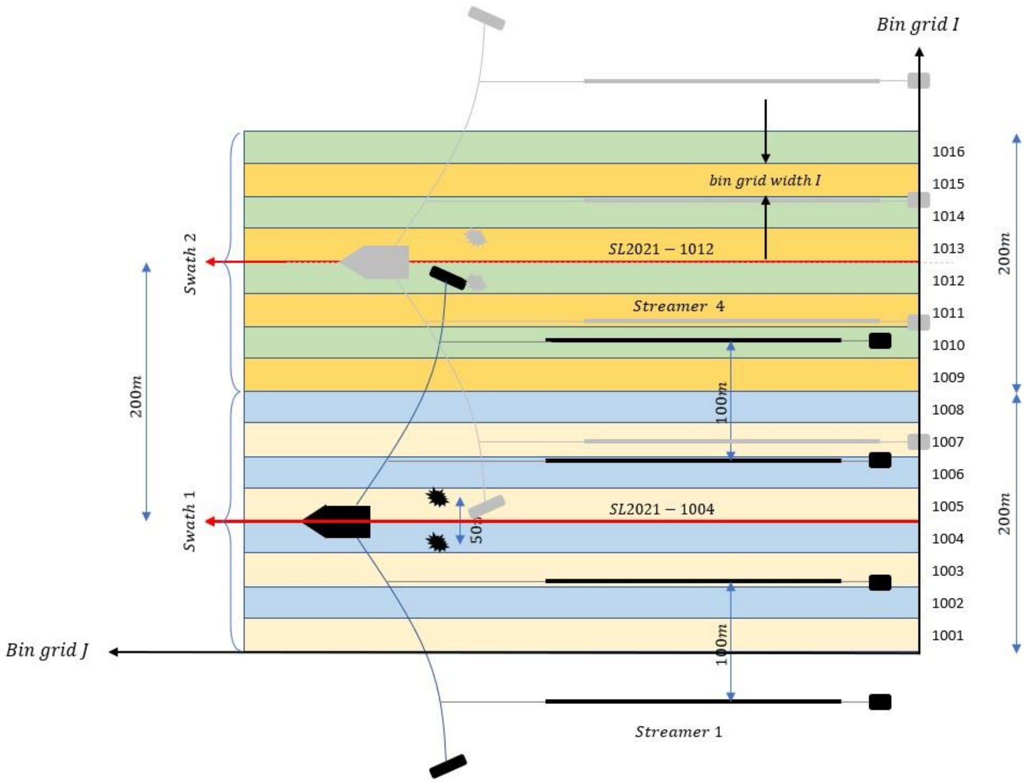


Figure 92: Separation of the sail lines

The same principle applies for all other combinations of streamers, sources, and CMP widths. On modern fleets up to 20 streamers may be towed simultaneously along with dual sources. Therefore, 40 CMP lines are acquired per sail line. With a streamer separation of 100 metres and a source separation of 50 metres the CMP width is 25 metres. With 40 CMPs per sail line the total CMP swath width is 1000m (1km). As such the lateral horizontal distance between sail lines (along the $I\ axis$ of the seismic grid) will be 1000m.

Reverting back to the initial example, the pre-plot separation is represented by a cross-section of adjacent swathes, and their respective array lines along the seismic grid $I\ axis$ are shown in Figure 93. This is viewed from the rear of the spread with the vessel sailing into the page. Notice how neatly the CMP lines fit together. This is the optimal method of acquisition provided the streamers a towed in a perfect straight line behind the vessel, which they are not.

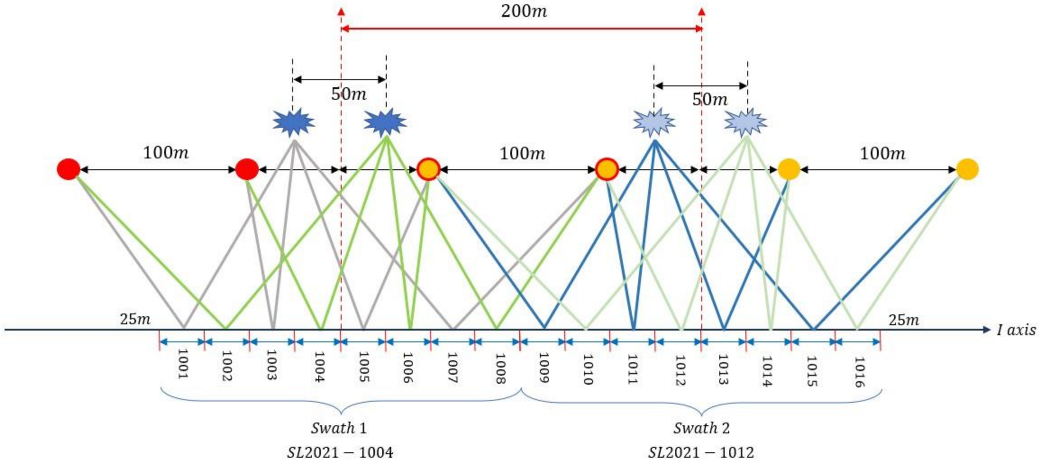


Figure 93: Crossline configuration - adjacent swaths

This pattern is repeated for all the pre-plot sail lines along the seismic grid I *axis* from point A to C. A collection of swathes is illustrated in Figure 94.

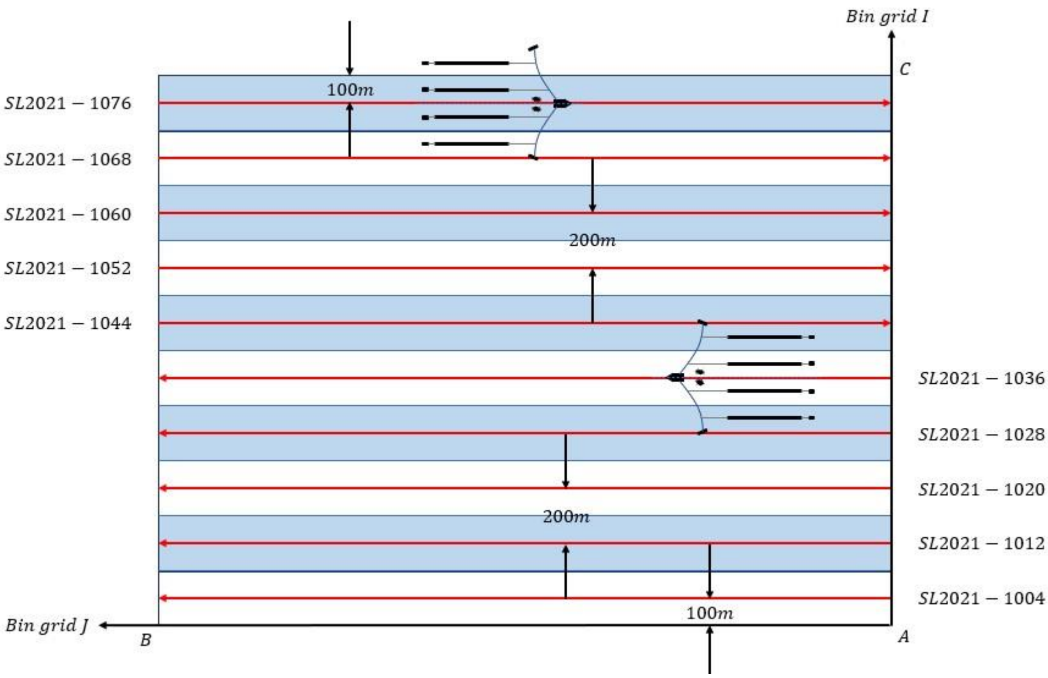


Figure 94: Sail line superimposed over survey area

The different colour bands in Figure 94 are shown to differentiate the different swathes acquired for the sail line names annotated.

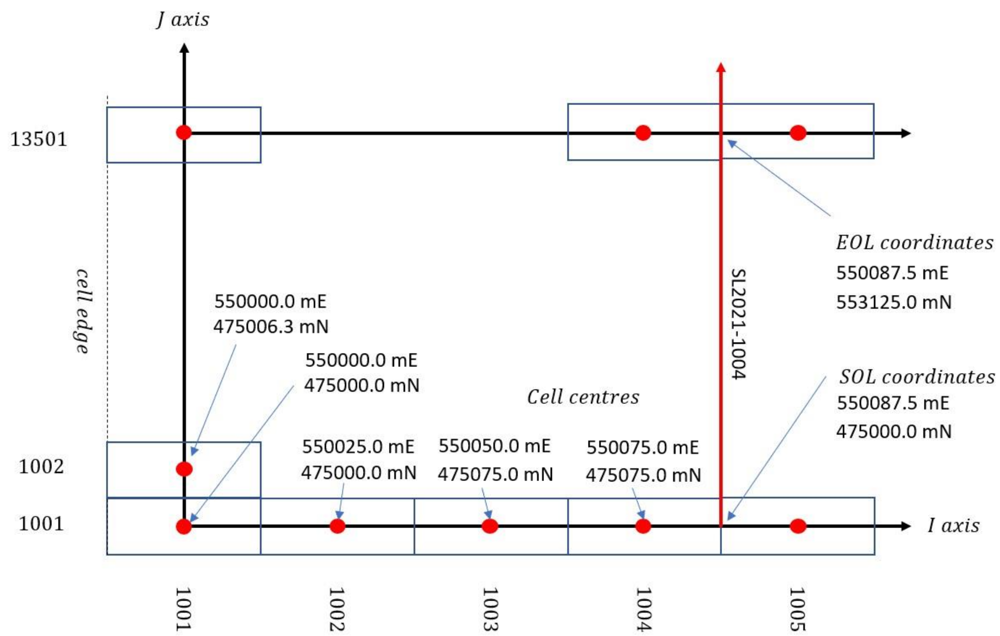


Figure 95: Sail line coordinates

The pre-plot lines used by the onboard navigators normally comprise the start-of-line (SOL) and end-of-line (EOL) coordinates only. These represent the two points where the pre-plot line crosses the border of the full-fold perimeter of the seismic grid. The seismic line, in terms of length, must contain an integer number of shot points and the full-fold area will be adjusted in length to accommodate this requirement. For example, if the origin length of the sail line (from point A to B) was given as 78.128km it equates to 3125.12 shot points. As such the line is slightly adjusted so a whole number of shot points fits that length. So, if this is reduced to an integer number of 3125 shot points the line length is shorted to 78.125km.

6.1.1 Interpolating shot point positions

As the vessel traverses the pre-plot line all shot point positions between the SOL and EOL are interpolated by the onboard Integrated Navigation System (INS). This is done using either projected or geographic coordinates with the latter resulting in a more precise solution, especially on longer line lengths. Figure 83 illustrates a very simple example using projected coordinates. Assume the shot interval is 25.0m and the sail line bearing is 38°. If the SOL coordinates (SP101) are given as:

500000mE

6000000mN

The port source will fire when the centre of that array reaches this position.

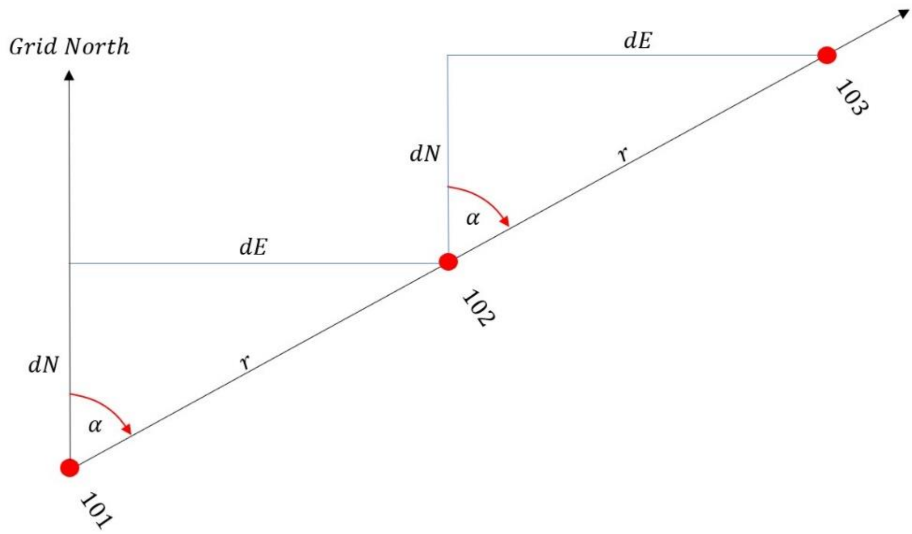


Figure 96: Interpolate shot point intervals on the grid

However, what will be the coordinates of SP102 when the starboard array fires? Using Pythagoras, the two distances dE and dN are computed which represent the distances along the two axes of the projected CRS for a radial separation of 25m (the SPI) on a bearing of 38^o.

$$dE_{102} = r \sin \alpha = 25 \sin(38) = 15.39m$$

$$dN_{102} = r \cos \alpha = 25 \cos(38) = 19.70m$$

The two components are used in the following equations to determine the coordinates of SP102.

$$E_{102} = E_{101} + dE_{102} = 500000 + 15.39 = 500015.39m$$

$$N_{102} = N_{101} + dN_{102} = 6000000 + 19.70 = 6000019.70m$$

This process is repeated until the EOL is reached. For details of how the same process applies on an ellipsoid surface see Parr (2024c).

6.1.1.1 Kalman Filter

The INS used onboard modern seismic vessels incorporates a Kalman Filter to perform line control and all positioning computations. This computational process is currently beyond the scope of the book, but details of the general working of the Kalman Filter can be found on https://geomatics-training.com.

6.1.2 Storing the pre-plot line coordinates

An example of a P1/90 file containing the pre-plot lines is shown in Figure 97. The record identifier is given as V (column 1) which indicates that the coordinates in each row refer to the Vessel position. This is followed by the CMP line number (columns 2 to 5), the shot point numbers (columns 22-25), latitude (columns 26-35), longitude (columns 36-46), easting (columns 47-56) and northing (columns 56-64). Further details of this format are given in section 9.4. The first two rows are displayed to show the column count for the P1/90 file format which comprises a maximum of 80 columns per row.

```
V1010               11   1001065536.14N0552442.05W 675480.6 765939.8   0.0   0 42235
V1010               11   2591071710.12N0552442.05W 675344.4 805689.6   0.0   0 42235
V1030               11   1001065536.14N0552425.77W 675980.6 765941.6   0.0   0 42235
V1030               11   2591071710.12N0552425.75W 675844.4 805691.3   0.0   0 42235
V1050               11   1001065536.14N0552409.48W 676480.6 765943.3   0.0   0 42235
V1050               11   2591071710.11N0552409.45W 676344.4 805693.0   0.0   0 42235
V1070               11   1001065536.14N0552353.19W 676980.6 765945.0   0.0   0 42235
V1070               11   2591071710.11N0552353.15W 676844.4 805694.7   0.0   0 42235
V1090               11   1001065536.14N0552336.90W 677480.6 765946.7   0.0   0 42235
V1090               11   2591071710.11N0552336.85W 677344.4 805696.5   0.0   0 42235
V1110               11   1001065536.15N0552320.61W 677980.6 765948.4   0.0   0 42235
V1110               11   2591071710.11N0552320.54W 677844.4 805698.2   0.0   0 42235
V1130               11   1001065536.15N0552304.33W 678480.6 765950.1   0.0   0 42235
V1130               11   2591071710.11N0552304.24W 678344.4 805699.9   0.0   0 42235
V1150               11   1001065536.15N0552248.04W 678980.6 765951.8   0.0   0 42235
V1150               11   2591071710.10N0552247.94W 678844.4 805701.6   0.0   0 42235
V1170               11   1001065536.14N0552231.75W 679480.6 765953.5   0.0   0 42235
V1170               11   2591071710.10N0552231.64W 679344.4 805703.3   0.0   0 42235
V1190               11   1001065536.15N0552215.46W 679980.6 765955.3   0.0   0 42235
V1190               11   2591071710.10N0552215.34W 679844.4 805705.0   0.0   0 42235
V1210               11   1001065536.15N0552159.17W 680480.6 765957.0   0.0   0 42235
V1210               11   2591071710.10N0552159.04W 680344.4 805706.7   0.0   0 42235
V1230               11   1001065536.15N0552142.89W 680980.6 765958.7   0.0   0 42235
V1230               11   2591071710.09N0552142.74W 680844.4 805708.5   0.0   0 42235
```

Figure 97: Pre-plot file example

6.1.3 Firing the fire shot of the line

As the vessel begins to traverse the pre-plot line (between the SOL and EOL**)** all towed equipment must be located as close to their required nominal offsets as possible prior to the first shot being fired. The coordinates shown in Figure 97 do not represent the positions where the source array will fire. They indicate the position of where the vessel will be at the time the source array fires. Therefore, consideration must be given to determine the source position in relationship to the cell(s) of the seismic grid such that they are populated with the designated source-receiver pairs. So, where must it (the vessel) and the source array be located when the first shot point on the line is fired with respect to the first cell of the full fold perimeter?

6.1.4 CMP layback

To complete the picture, the offset between the central navigation point (CNP) and the mid-point of the source and receiver group 1 is derived. This is computed as follows:

$$CMP\ layback = Source\ layback + \frac{source\ to\ near\ trace\ offset}{2}$$

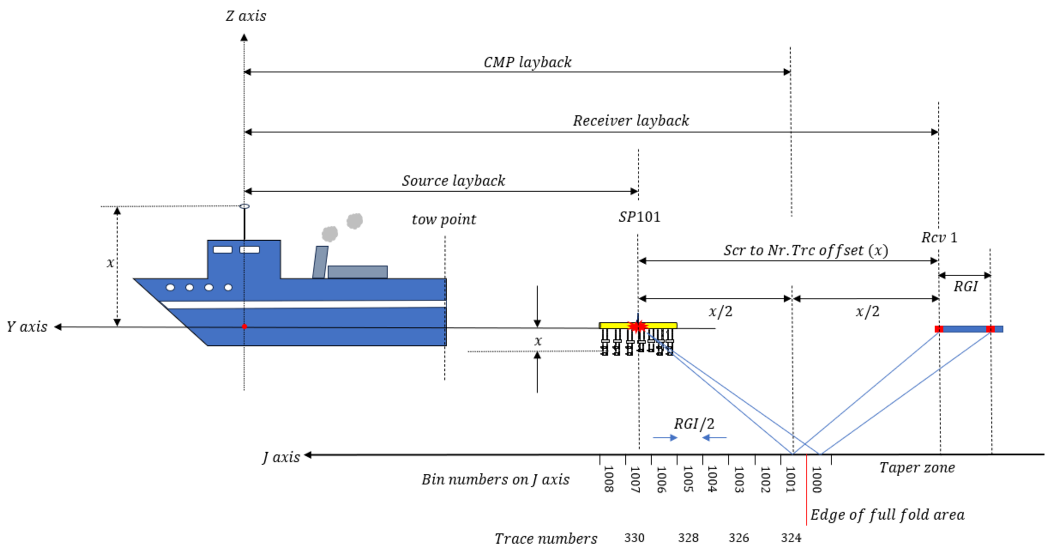


Figure 98: First shot offset from full fold boundary

Figure 98 illustrates this relationship for the side plan and Figure 99 the relationship in aerial view. In Figure 98 the edge of the full-fold perimeter is shown by the vertical red line between cell numbers 1001 and 1000 and in Figure 99 by the horizontal red line. This makes 1001 the first cell of the seismic grid along the $J\ axis$, with the $I\ axis$ going into the page in Figure 98. With the vessel traversing along the sail line this is the group of cells (in the inline direction) to be populated by the source-receiver offset pair SP101 and Rcv 1 in all four streamers and thus the first full fold cells in the full fold coverage perimeter (see section 4).

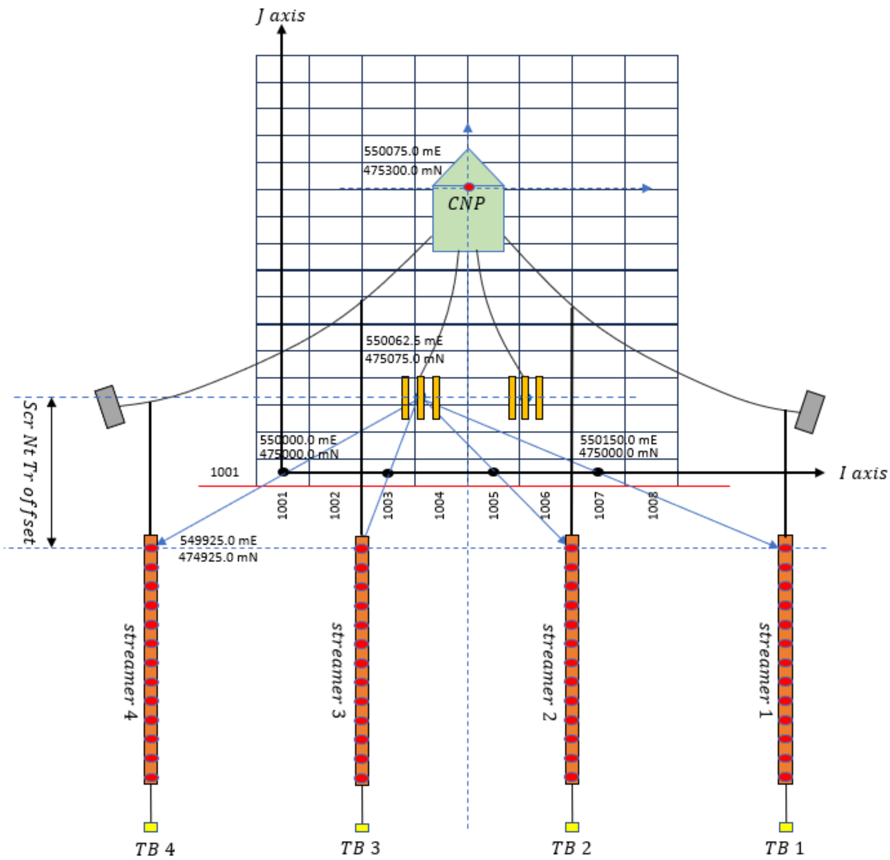


Figure 99: Coordinates at the first shot point

Figure 99 illustrates the mid-points acquired when the port source fires. These are indicated by the black circles for the four source-receiver offsets shown by the blue arrows. The coordinates of the cells (1001, 1001) and (1007, 1001) are annotated on the seismic grid for clarity.

6.2 Fold coverage – theoretical build up

The fold coverage is defined as the number of times the same sub-surface point is imaged by different source-receiver offset pairs as specified by the geoscience team (multiplicity). It plays a significant role in the streamer configuration deployed with respect to in-line configuration. Two questions need addressing:

- What controls the fold coverage?

and

- Given a specific configuration of source and receivers what is the maximum fold coverage achievable on a survey?

This is best illustrated using a seismic 2D configuration, with single source and single streamer. For simplicity, the streamer has six receiver groups with a receiver group interval of 25 metres. Regardless of the shot point interval a CMP is generated every 12.5 metres along the inline direction. Next, assume the single source fires at a shotpoint interval (SPI) of 25 metres. With these parameter values the maximum fold coverage achievable for this configuration is given by:

$$Fold\ coverage = \frac{\frac{25 * 6}{2}}{25} = 3$$

In the example shown, the streamer is towed directly behind the vessel in a straight line with zero feather angle.

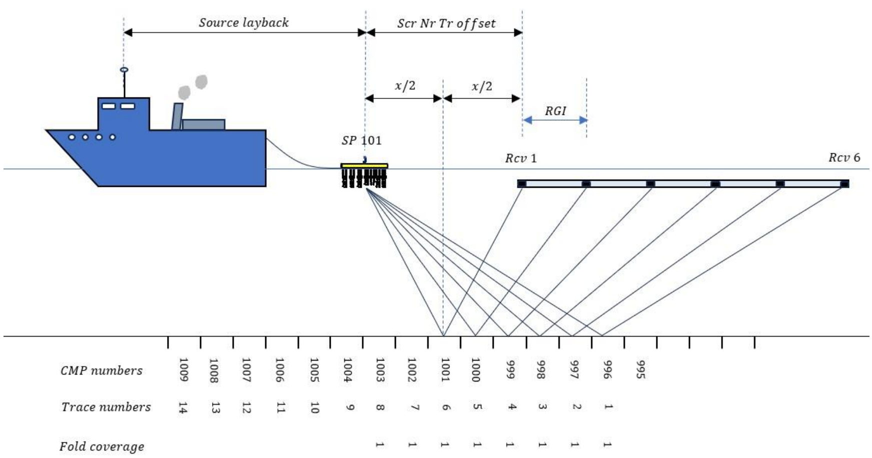


Figure 100: Fold coverage - first shot point on the line

The first shot point on the line is fired at location SP101. Six source-receiver offsets each create a mid-point as shown in Figure 100 which are the locations where the seismic trace is deemed to have sampled the sub-surface structures. Three sets of numbers are annotated at each mid-point, namely:

CMP numbers: Each Common Mid-Point (CMP) along the inline direction ($J\ axis$) represents a location where mid-points from consecutive shot points are gathered, and each one is given a unique identification number. From SP101 cells 996 to 1001 (right to left, in the inline direction) are populated with the first set of mid-points. Cell 1001 is the first one inside of the designated full-fold coverage perimeter. Cells 1000 and lower reside in the taper zone. CMP numbers are considered geo-spatial indexes.

Trace numbers: Trace numbers represent the locations where a minimum of one seismic trace was deemed to have been acquired. The first trace number on the line is identified as 1 which, in this configuration, is equal to CMP number 996. Trace numbers increase sequentially along the acquired line. Note, trace number 6 is co-located with CMP 1001. The trace number at the first full-fold cell will be equal to the number of receiver groups in the streamer.

Fold coverage number: This represents the current number of mid-points assigned to each CMP along the acquired line. At shot point 101 each cell will contain only one mid-point; hence, the numbering is shown as 1 in Figure 100.

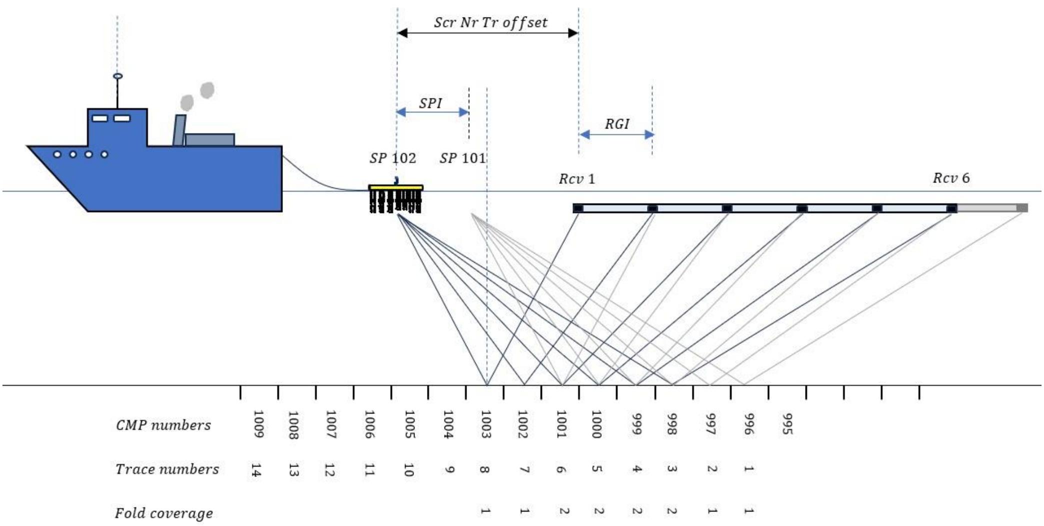


Figure 101: Fold coverage - second shot point on the line

The vessel traverses along the line to the second shot point (SP102) where another six source-receiver offsets are recorded, with each physical source-receiver offset being identical in horizontal distance to those acquired at SP101. The mid-points for this shot point are assigned to CMP cells 1003 to 998. The shot point interval between SP101 and SP102 is 25m, which is equivalent to two CMP intervals (12.5m * 2 = 25m). Because of this geometric relationship, and the assumption that it is maintained between adjacent shot points, there are four mid-points from SP102 that image the same sub-surface points as those imaged by SP101 (e.g., 1001 to 998). Therefore, the fold coverage at those four locations increases to two. However, because the vessel is sailing to the left of the page CMPs 996 and 997 will never be sampled again, hence their fold coverage will remain at 1.

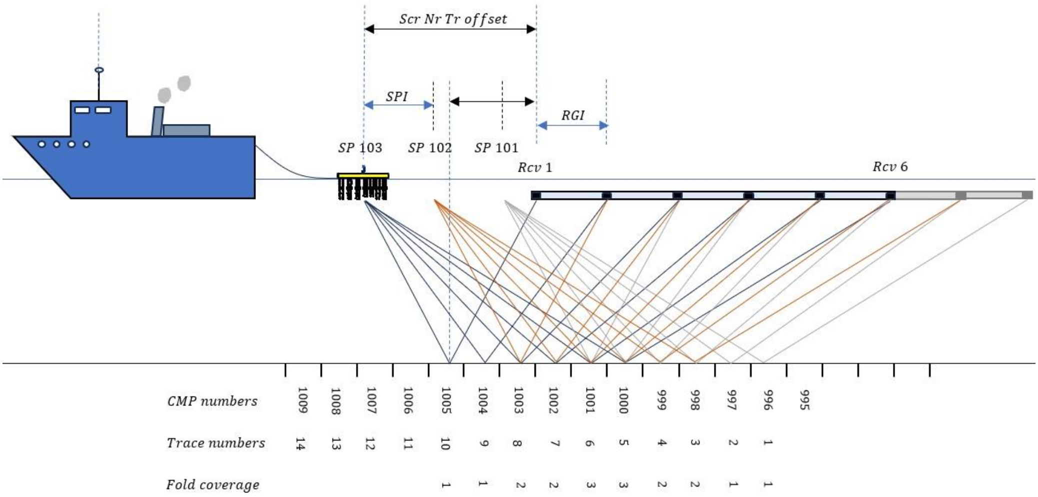


Figure 102: Fold coverage – third shot point on the line

Moving along the line to SP103 the same process is repeated as shown in Figure 102. The mid-points for this shot point occupy CMP locations labelled 1005 to 1000. Again, because of the SPI to CMP relationship and the inline geometry is maintained two CMP numbers (1001 and 1000) have now been imaged three times, once each from SP101, SP102 and SP103. However, notice how the fold coverage is increasing from its lowest value at CMP number 996 (trace 1) to a maximum number at 1000 (trace 6). Because the vessel is sailing to the left, the cells associated with the lower CMP numbers will have reduced samples (fold count) because the vessel is towing the equipment away from their locations. The portion of the line where the fold coverage gradually increases in this manner is known as the Taper zone.

From SP104 onwards this process is repeated with two more CMPs reaching full fold per shot point. One last observation from a design perspective: is to show that there is an even distribution of source-receiver offset contributions from receiver groups along the streamer. Consider CMP 1001: it contains three mid-point contributions which are populated from a receiver group at the front of the streamer, one from the middle of the streamer and one from the far portion of the streamer. Achieving this distribution is an important consideration for the seismic processors.

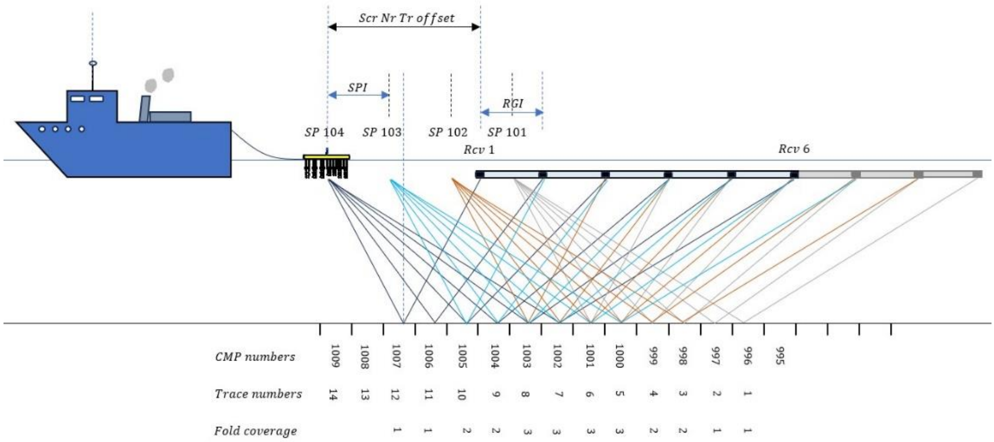


Figure 103: Fold coverage - fourth shot point on the line

6.2.1 Building fold coverage: example two

In this example, the shot point interval is reduced to half the receiver group interval. Therefore, twice the number of shot points are being fired into the same number of receiver groups. There are still six receiver groups with a group interval of 25 metres, i.e., there is no change to the streamer configuration. As such the CMP interval remains 12.5 metres. However, as the shot point interval (SPI) is reduced to 12.5 metres and is thus equal to the CMP interval. With this new configuration there is a change to the fold coverage, which is now calculated as follows:

$$Fold\ coverage = \frac{\frac{25 * 6}{2}}{12.5} = 6$$

The vessel traverses the line and shot points SP101 to SP107 are acquired. For simplicity, the shots are stacked in a vertical arrangement as shown in Figure 104. The same three numbers are shown at the base which have the same meaning as those shown in previous Figures. In this example, see how the fold coverage gradually accumulates as the shot points are acquired.

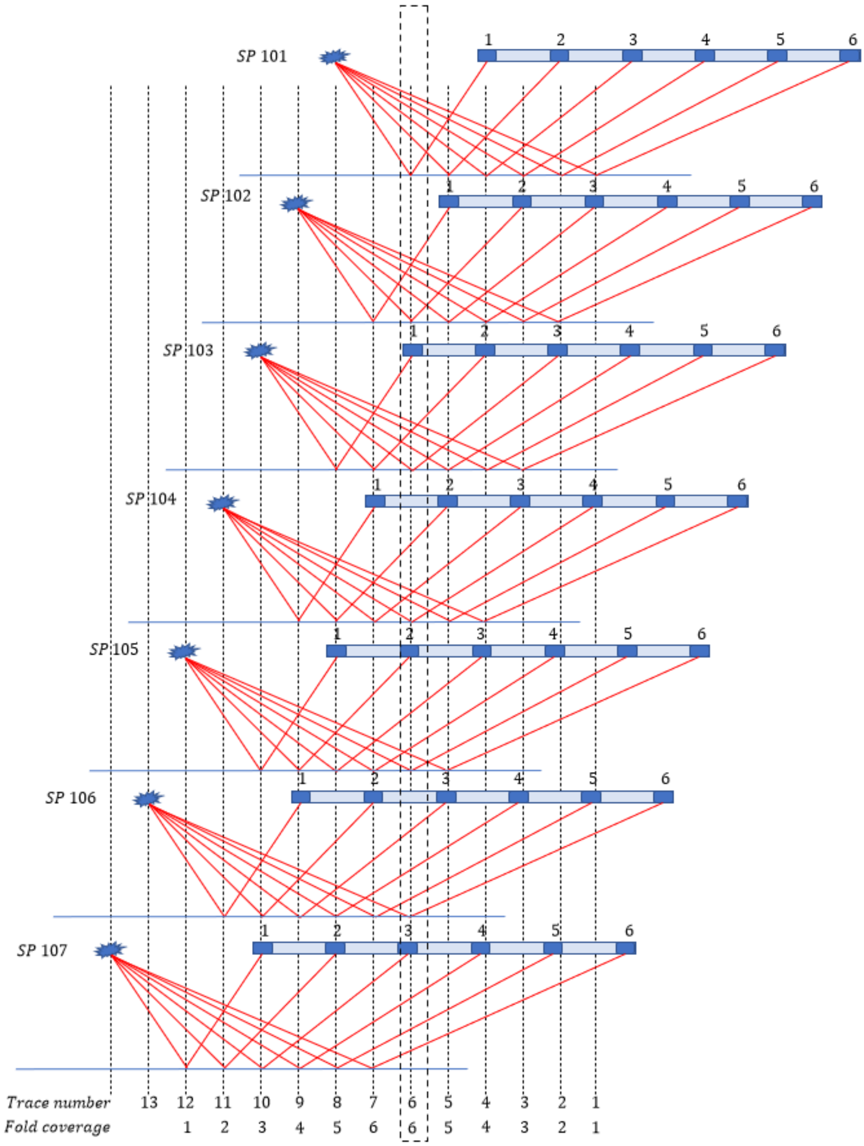


Figure 104: Fold coverage versus geometry

Start at trace number 1, which contains a trace hit from the source-receiver offset between the source SP101 and receiver group 6. As the vessel traverses to the left the sub-surface below this CMP will never be imaged again by any other source-receiver combination. Hence is fold coverage will always remain 1. Contrast this to the fold coverage at trace number 6, which is highlighted by the dashed black rectangle. For each of the shot points shown in Figure 104, count how often a different source-receiver pairs image the sub-surface below this location. These are listed in Table 7. The fold coverage at that CMP location reaches the maximum of 6 fold. Between trace numbers 1 and 6 notice how the number of contributing source-receiver offset pairs (fold) gradually increase from the minimum to the maximum number.

Table 7: Source-receiver pairs contributing to trace number 6

Source Number	Receiver Number
101	1
102	2
103	3
104	4
105	5
106	6

As the line continues, trace number 7 also contains the maximum full fold coverage. This pattern continues as the line progresses to the EOL shot point. The increase (ramp up) and decrease (ramp down) of fold coverage is represented graphically as shown in Figure 105.

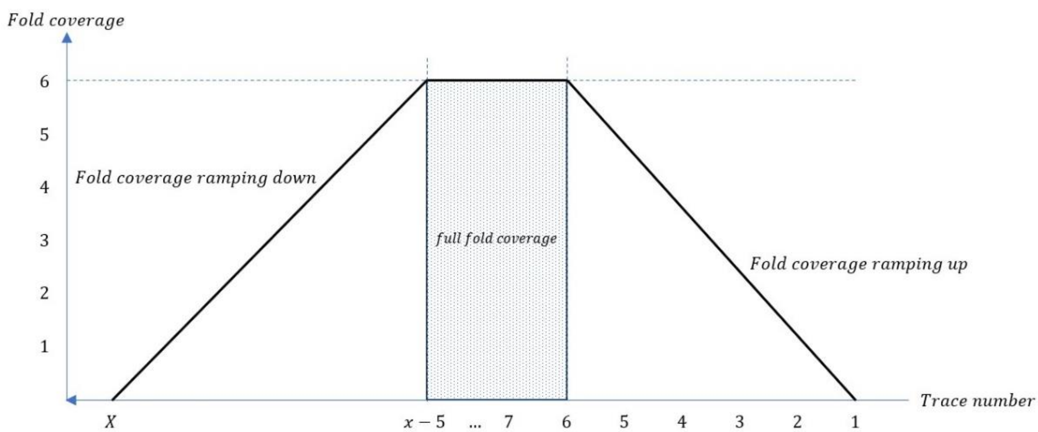


Figure 105: Fold coverage graph

6.2.2 Altering fold coverage

As demonstrated, one contributing factor to the full-fold value achievable is the frequency with which the seismic source(s) fires, i.e., the distance between adjacent shot points in relation to the distance between adjacent receiver groups. Using the fold coverage equation some other permutations are shown below. See how the full fold changes number by altering the shot point interval and receiver group interval parameter values:

1. SPI and RGI equal 12.5m with there being 480 receiver groups:

$$Full\ fold = \frac{\frac{12.5 * 480}{2}}{12.5} = 240$$

2. SPI is half that of the RGI. There are still 480 receiver groups:

$$Fold = \frac{\frac{25 * 480}{2}}{12.5} = 480$$

3. SPI is twice the size of the RGI. There are still 480 receiver groups:

$$Fold = \frac{\frac{12.5 * 480}{2}}{25} = 120$$

4. One final example with alternative distances. SPI is 37.5m and the RGI is 18.75m:

$$Fold = \frac{\frac{18.75 * 480}{2}}{37.5} = 120$$

CMP interval: From the scenarios presented the more shots that are fired the greater the fold coverage achievable. This is because of the reduction in the shot point interval. However, regardless of the shot point interval, it has no effect on the common mid-point interval along the $J\ axis$. CMP separation is always half the receiver group interval.

Shot point interval: There is a finite distance that can be traversed between adjacent shot points which is factor of the following:

- The ability of the vessels compressors to recharge the airguns to their required volume and pressure.

- The observation period of the receiver groups, or two-way time. If the TWT is set at 6 seconds, then the Δt between adjacent shot points must exceed this time.

These two factors have a controlling effect upon the speed which the survey vessel traverses the pre-plot line. In most instances vessel speed is restricted to between 4 and 4.5 knots, which is equivalent to just over 2 m/s. Therefore, with a shot point interval of 25 metres the source array is expected to fire every 10-12 seconds. This assumes speed over ground and not speed through the water.

6.2.3 Taper zone

The taper zone contains all the cells whose fold coverage is less than the full-fold value expected and falls external to the full-fold coverage polygon. The taper zone is required such that all the cells of the seismic grid inside the full-fold coverage area will, theoretically, be populated with all possible source-receiver offset pairs. To achieve this there must be a run-in and run-out portion to the sail lines the vessel traverses.

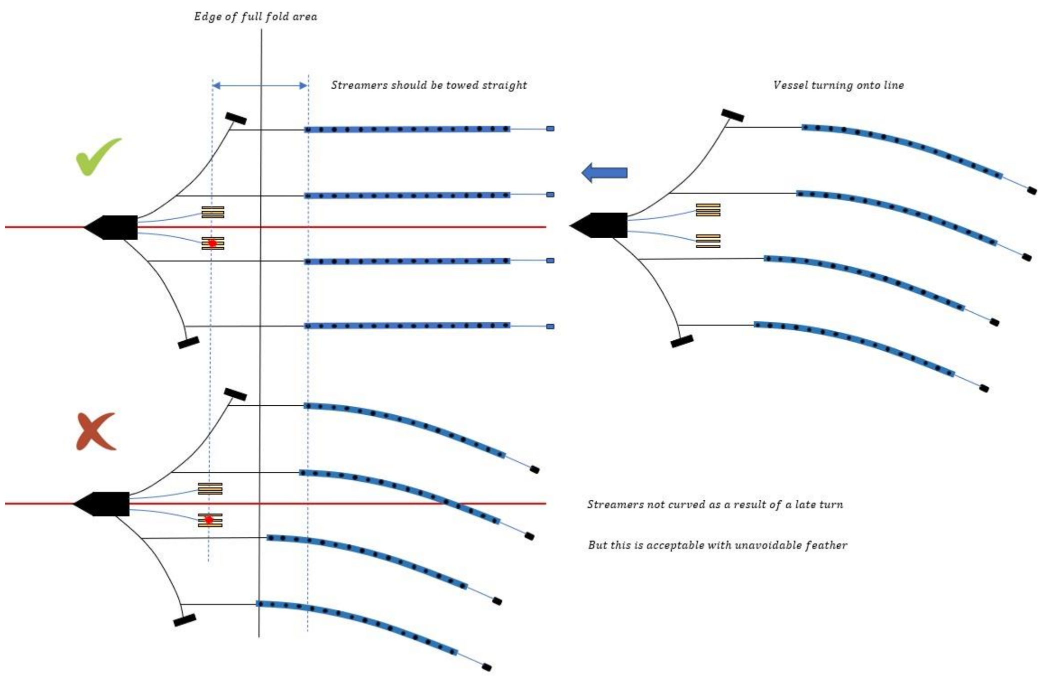


Figure 106: Run-in to the start of line

6.2.3.1 Run in

The vessel turns to commence its run-in to the next scheduled line. The run-in must be sufficiently long such that the streamers have no undesirable induced 'feathering' caused by the turn being too tight. The upper diagram in Figure 106 is the acceptable approach. In the upper right the vessel completes the turn to finalise the run-in ensuring the streamers are towed directly behind the vessel (upper left hand side). Whereas, in the lower one the helmsman has turned the vessel on to line too late or there are severe tides / currents causing unavoidable feather. In the latter circumstance the navigators will be required to feather match between adjacent lines (see section 8.1.1.1). The vessel is sailing to the left and the towed streamer has six receiver groups as shown in Figure 107. The first shot point is fired at a position such that the mid-point from source-receiver offset pair SP101-Receiver group 1 will populate the first cell at the edge of the full-fold area (e.g., 1001).

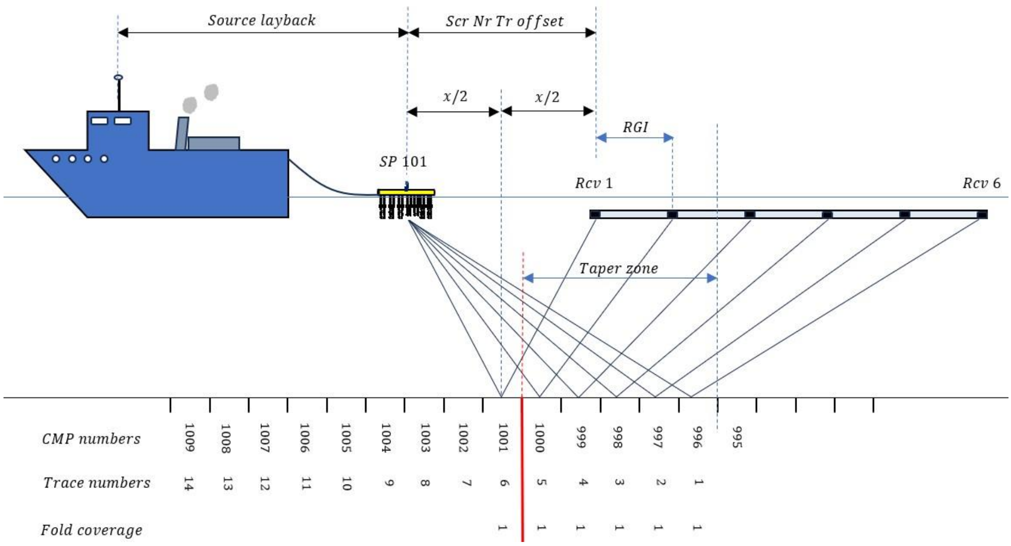


Figure 107: Run-in taper zone

As such the remainder of the source-receiver offset pairs will fall outside of the full-fold perimeter (e.g., CMP numbers 1001 to 995). Notice that the physical streamer is yet to enter the full-fold perimeter. As the vessel is sailing away from these cells, they will only be populated with a limit number of offset pairs, which increases in number the closer the cells are to the edge of the full-fold perimeter. The length of the taper zone along the $J\ axis$ of the seismic grid is derived using the following equation:

$$Taper\ zone\ length = \frac{Streamer\ length}{2} - \frac{RGI}{2}$$

Therefore, with this geometry:

$$Taper\ zone\ length = \frac{150}{2} - \frac{25}{2} = 62.5m$$

Which is equal to the cell width along $J\ axis$ (equal to half the receiver group interval) multiplied by the number of receiver groups minus one.

$$Length = J_{width} * (no. Rcv\ groups - 1)$$

6.2.3.2 Run out

A similar process also occurs at the end of the sail line. The vessel will fire the last shot point on the line at a position such that the last cell in the full fold perimeter of the seismic grid is populated to its full-fold coverage. This will include the source-receiver offset pair involving the last receiver group in the streamer. In Figure 108 the last cell with full fold perimeter is CMP number 1887, which when fired will constitute the End of Line (EOL). However, the cells relating to CMP numbers 1888 to 1892 will also contain seismic trace data, but the fold coverage in each will gradually reduce from full fold value down to one as illustrated in Figure 106. This is the reverse of the buildup described for the run in and this section of the taper zone relates to the line run out.

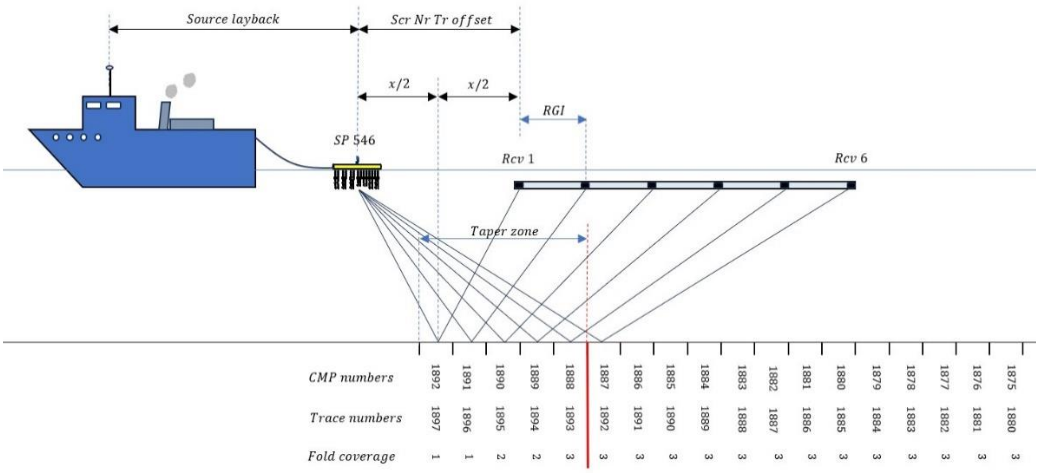


Figure 108: Taper zone on the run-out

The taper zone combined with the proposed full fold coverage perimeter constitute the proposed Total coverage perimeter. For further details see section 4.1. This is the perimeter illustrated by the blue dashed line in Figure 109, which connects the four points A', B', C' and D'.

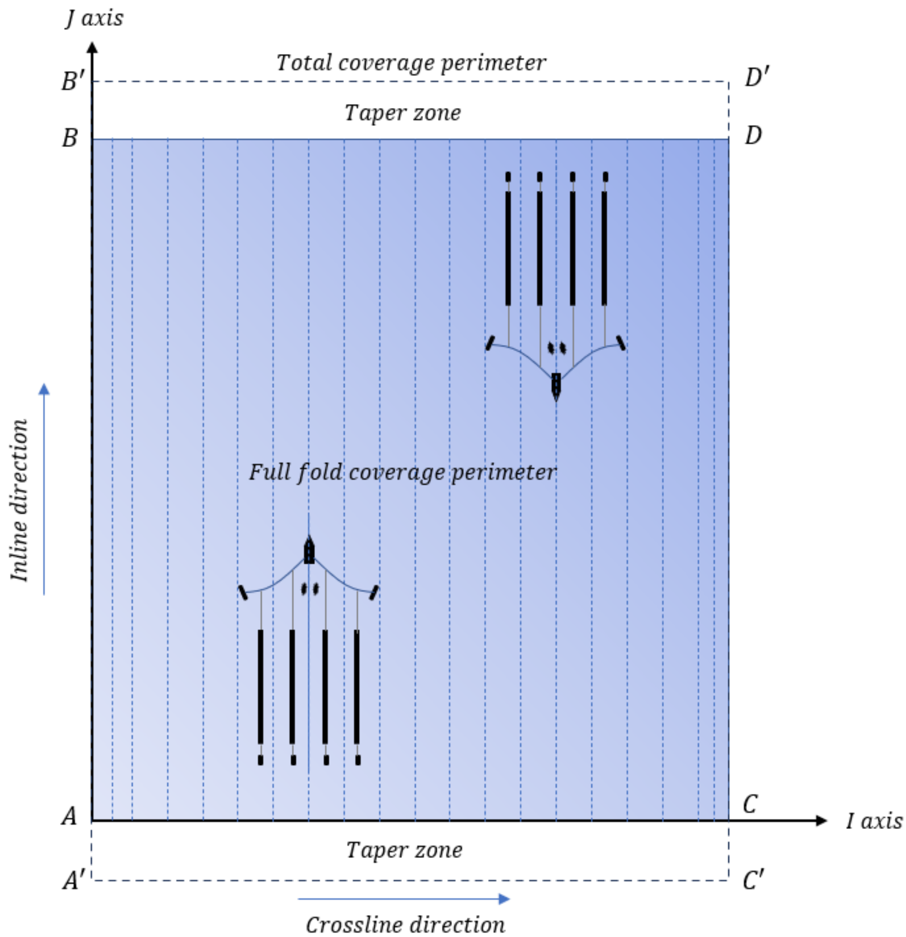


Figure 109: Total coverage area

6.2.4 Irregular full fold perimeters

Thus far all the full fold perimeters have been represented by 4 point polygon creating a regular rectangle. However, this will not always be the rule. Polygons comprising five or more corner points are common and for narrative purposes will be known as irregular polygons. Theoretically, there is no limit to the number of corner points that comprise the polygon.

6.3 Geometric footprint

Modern seismic vessels deploy ten or more streamers meaning the swath widths they acquire are considerably larger than the illustrations so far provided and Table 8 shows the swath widths for some of the larger spreads deployed. This assumes the use of dual sources in the configuration.

Table 8: Swath widths

No. of streamers	Streamer separation (m)	Outer to outer separation (m)	CMP width (m)	Swath width (m)
10	100	900	25	500
12	100	1100	25	600
14	100	1300	25	700
20	100	1900	25	1000

With a typical streamer length of 8.1 km and a CMP swath width of 1 km, the outer-to-outer streamer separation will be 1.9km when the streamer separation is 100m, which is a significant towed ‘structure’. With a line length of 60km it means 60 sq. km. of seismic data will be acquired per sail line. With an average speed of 4.5 knots the vessel can traverse a line of this length in around 7.2 hours. If a line turn of 4 hours is assumed the vessel will comfortably acquire two lines per day, equating to an acquisition of 120 sq.km. per day.

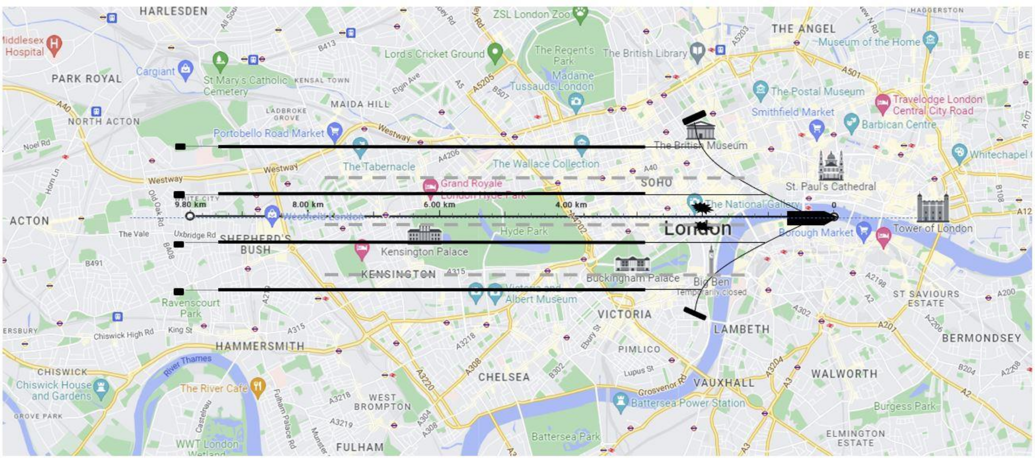


Figure 110: Putting size into perspective

To put the size of the seismic spread being towed in perspective, a scale representation of a spread containing 20 streamers (every 5th streamer drawn) is superimposed on a map of London city centre, United Kingdom, Figure 110. This stretches from St. Pauls Cathedral to White City and includes all active sections, stretch sections, lead-ins and Tailbuoys.

6.3.1 Survey planning logistics

When acquiring data the vessel will traverse a pattern known as a racetrack which is designed to optimize the acquisition program, see Figure 111. When following this pattern, the vessel is in one of two possible modes which are referred to as online and offline. The vessel is online when it is acquiring seismic data, and it is offline when conducting the turn (turning circle) between lines. The length of the streamers towed will directly impact the offline time and the size of turning circle the vessel must undertake. Typically, the run out and run in will be equal to the distance or one and half times the length of the streamers being towed. It is the desire of the acquisition company to be offline as short a time as possible, whilst at the same time ensuring that the turn is not made too tightly as it will unduly affect the fold coverage achievable during the run in.

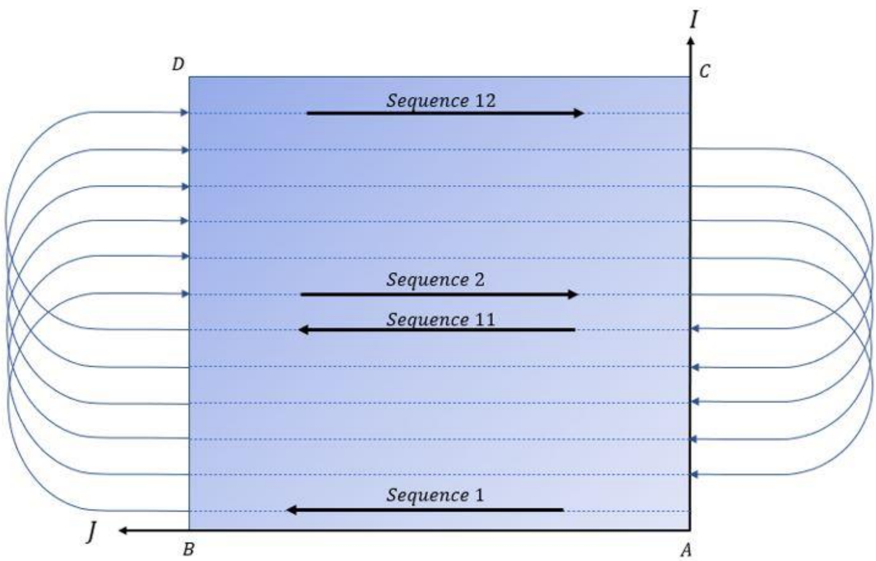


Figure 111: Racetrack acquisition pattern

Using the racetrack, the time it will take the vessel to conduct the survey is estimated. Using the survey area parameters described at the start of section 5.6 (i.e., 20km * 30km) and assuming the vessel maintains an average speed of 4.5 knots:

The vessel will traverse a linear distance at 8.334 km/hr.

Therefore, each sail line will take 2.399 hours (2 hours 23.94 minutes) to complete.

There are a total of 150 sail lines, giving a total online time of:

2.399 * 150 = 359.85 hours, which equates to 14.994 days (24 hour acquisition).

For narrative purposes, the vessel speed during offline activities will remain the same and the average line turn is assumed to be conducted in 4 hours. There will be 149 line turns required which adds another 596 hours to the survey time (24.833 days). Combined, this gives a duration of 39.827 days to conduct the survey. To complete the picture, 4 days are allotted to deploy the equipment and conduct pre-survey tests, with 2 days allotted to equipment recovery. This gives a total time of 46 days. However, this does not factor in any equipment downtime, weather downtime, time sharing or infill. If the infill of 20% estimated this will add another 8 days giving an estimated duration of 54 days.

6.4 Land seismic survey

On a land seismic survey, the receiver groups and shot points are both static at the time the shot point is fired. The pre-plot positions are staked out in advance of the acquisition commencing and during that time their locations remain fixed. Many different source and receiver patterns have been designed and deployed in attempts to optimize the geophysical objectives of the survey.

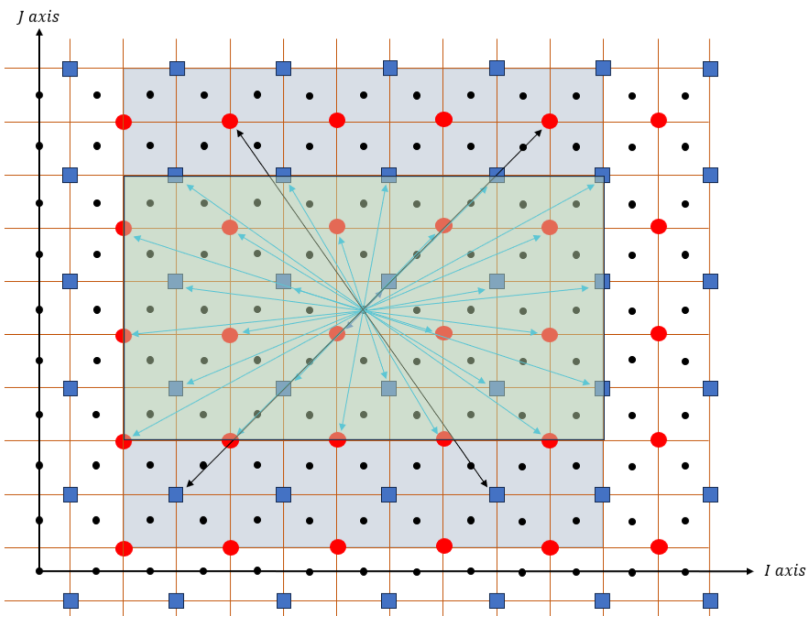


Figure 112: Land seismic source-receiver design

In Figure 112 a more traditional orthogonal relationship is illustrated with the receivers shown by the blue squares and the shot points by the red circles. The receiver lines are orientated in the north-south direction and the shot lines in the east-west direction. The black dots illustrate the geometric centre of the cells of the grid. Unlike a marine seismic survey, the cell widths of the grid are identical along both axes of the grid, for example, 25m x 25m.

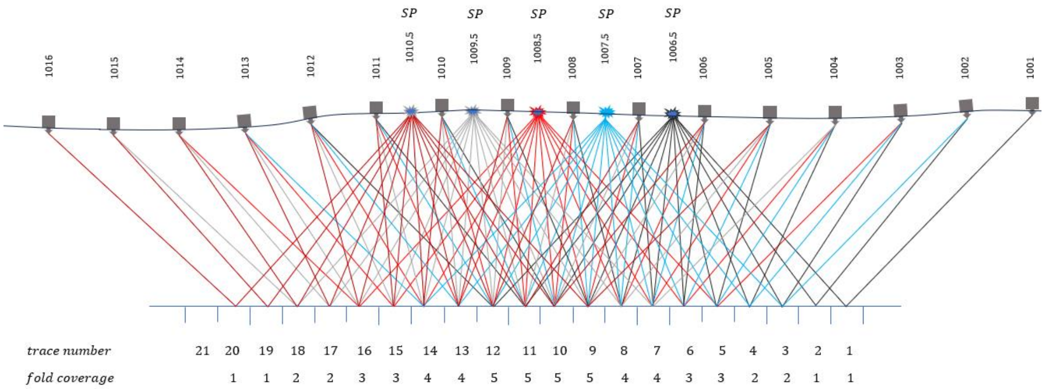


Figure 113: SP1001.5 to SP1005.5 of land seismic spread

The survey design will enable the expected full-fold coverage to be determined for each of the cells in the grid. For example, in Figure 112 the light blue arrow indicates the source-receiver offset pairs contributing to one of the cells of the grid which in this case is fifteen (covering the light grey footprint). As the footprint extends the fold coverage increases. Determining the rich array of azimuths contributing to the common mid-point also forms part of the design.

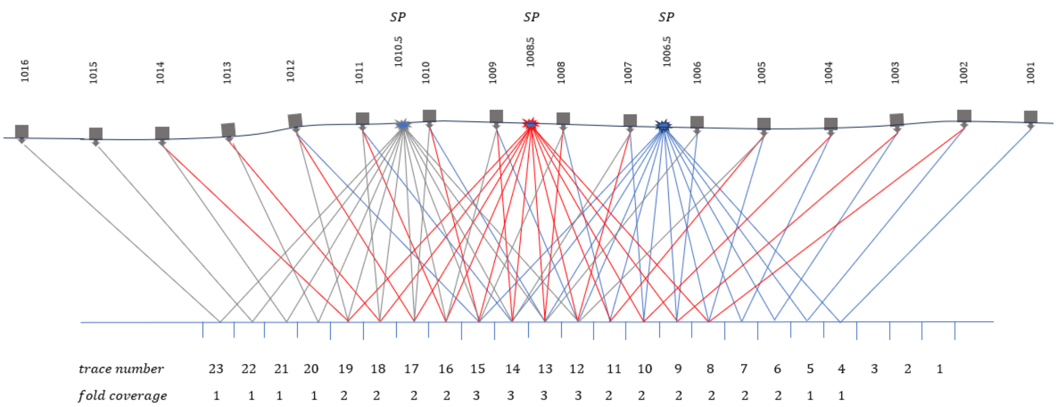


Figure 114: SP1001.5 to SP1003.5

The build-up of fold coverage on a land seismic survey differs from that of a marine towed survey because of the split spread geometry between each source and the geophones. First, consider a land seismic 2D configuration survey, except for the ends of the line, there will be geophones located either side of the shot point location as shown in Figure 113. Therefore, unlike a marine towed survey mid-points will be acquired in both forward and reverse azimuths. This means the fold coverage will build quicker on a 2D land survey. Figure 114 shows an example when the SPI and RGI are equidistant.

Note, the shot points are located halfway between the receiver group locations. This arrangement is deliberate for most land survey operations. The receiver groups are normally numbered with integers (e.g., 1001, 1002 etc.) and the shot point positions with decimals (e.g., 1001.5, 1003.5 etc.). The mid-point interval remains half the receiver group interval, and the trace numbers increase sequentially as they would for a marine survey.

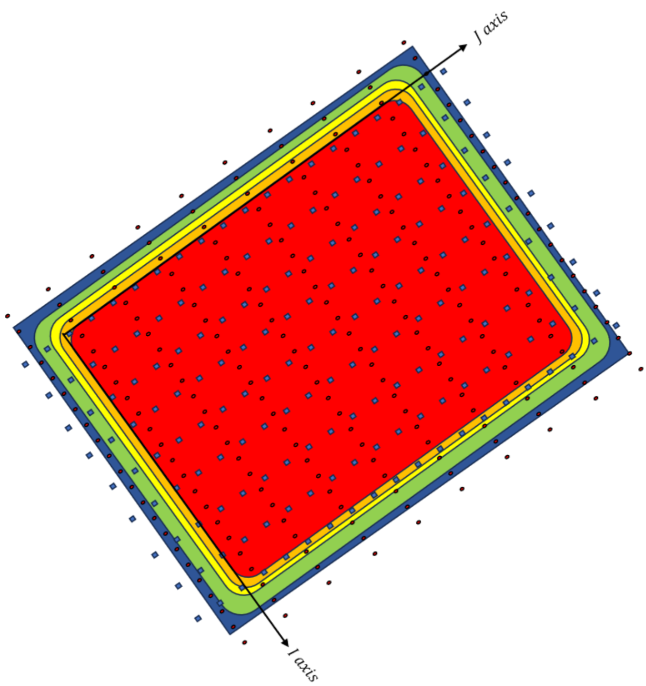


Figure 115: Survey design for a land seismic 3D survey

On the marine towed seismic 3D survey there are taper zones at either end of the full fold perimeter (run in and run out). However, on a land seismic 3D survey, the azimuthal relationship between shot points and receiver points offers more flexibility the taper zone can surround the full-fold perimeter as shown in Figure 115. The blue, green, and yellow bands represent the gradual build-up of the fold coverage with the red area denoting the full-fold coverage perimeter. This is not always the case and will depend upon the relationship between the source and receivers. The concentric nature of the fold-coverage zones represents the tapering experienced on a land survey. In this example, the orange zone representing the area where full-fold coverage is expected. The target the geophysicists are attempting to image shall be in the orange zone. The seismic grid will be defined to cover the area of where all fold coverage is expected.

7 The seismic grid in data management

A seismic grid is defined as per the attributes specified in section 3. Once the data acquisition commences it is now that the process of 'binning' is conducted. This is the procedure of determining into which cell of the seismic grid does the seismic trace data for each source-receiver offset pair belong and thus what trace data is gathered in each cell during seismic processing. Therefore, the seismic grid is used as a data management tool such that it:

- Ensures that the seismic trace data is acquired in the correct location and binned into the appropriate cell of the seismic grid.
- The required fold coverage is achieved in each cell of the full fold area.
- There are sufficient contributions from the various offset ranges, e.g., nears, mids and fars.
- Areas of infill are recognised and addressed.

On a marine seismic 3D survey this is performed by the onboard binning module in which the designed seismic grid definition is incorporated. The INS (Integrated Navigation System) computes the source and receiver positions in 'real-time' at every shot point. These coordinates are delivered to the binning module where the mid-point positions of every source-receiver offset pair are derived.

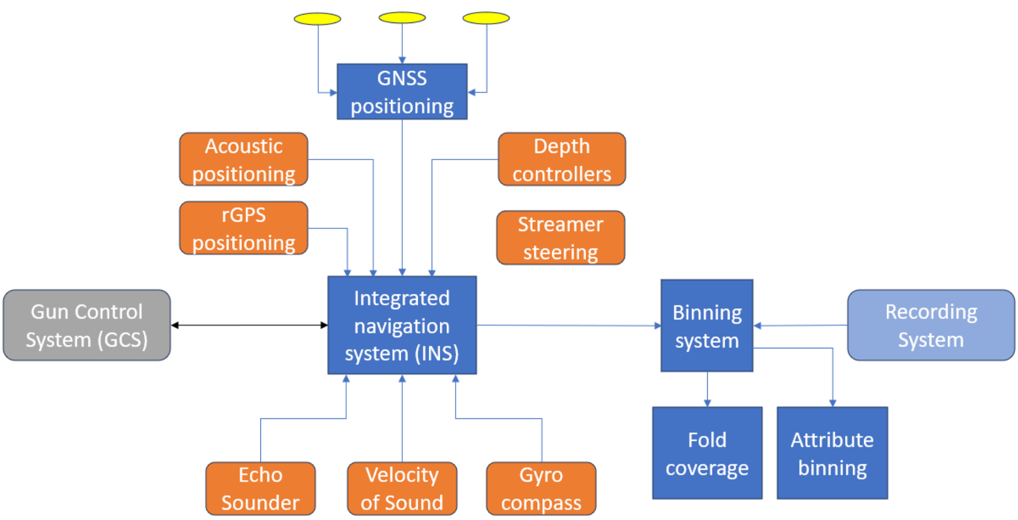


Figure 116: Navigation and Positioning - generic system configuration

The main functionality of the binning module is to determine into which cell of the seismic grid does each source-receiver offset pair belong (per shot point) and what collective number of different offset pairs (the fold coverage) are accumulated in each cell over the duration of the survey. Fold coverage plots generated from the data illustrate two key objectives:

- Is there a sufficient hit count in each cell, i.e., the fold coverage number.
- Is there an even distribution of source-receiver offset pairs contributing to each cell.

In this and the following sections three main topics are addressed, namely:

- High level details of how the sources, receivers and mid-points are computed.
- Binning the data: How fold coverage increases on a shot-by-shot basis from the data acquired.
- What problems effect the binning data coverage and what is done to correct and mitigate these issues.

7.1 Compute source, receiver, and mid-point positions

To assign the individual mid-points to the correct cells of the seismic grid (i.e., to perform the process of binning) requires their coordinates be precisely computed. This is achieved by initially positioning the seismic source and the individual receiver groups associated with each mid-point position. As there are many mid-points acquired at every shot point the computation is repeated for all combinations of source-receiver offset pairs across the seismic spread and on a shot-by-shot basis.

Historically, source and receiver coordinates have been determined using a variety of positioning systems. For example, on vintage marine surveys, this included streamer compasses, laser scanning and buoy tracking (using radio-positioning systems), and on modern surveys, fully braced acoustic networks and rGPS buoy tracking systems. On land surveys, traditional land survey techniques such as theodolites, precise levelling, and total stations, have been exclusively replaced by Real Time Kinematic (RTK), and Geoid models.

Towed marine 3D surveys are arguably the most challenging of the seismic operations to precisely determine source and receiver positions. Therefore, a description of the processes performed to achieve the precision levels specified are given along with the derivation of the coordinates of the associated mid-points. Marine towed seismic positioning presents a considerable challenge given the shear dimensions of the equipment spread involved and the environmental conditions in which the positioning equipment operates. Modern seismic vessels will tow ten or more streamers, often exceeding eight thousand metres in length. If there is a streamer separation of one hundred metres the dimensions of the spread will be a minimum of nine hundred metres crossline and approximately ten kilometres inline (see section 6.3).

Acquiring data offshore is often done in harsh environmental conditions where variable sea states play an important factor is the resulting product quality. Winds, tides, and currents all hamper the ability to maintain a regular equipment geometry, causing deviations from the desired nominal offset pattern. Regardless, the navigators rely upon their instrumentation to determine precise positions and make whatever steering adjustments are necessary to maintain the desired geometric spread in accordance with the nominal offsets.

Receiver groups are housed in each streamer at a fixed inline distance. The distance between receiver groups and the length of the streamer determines the number of receiver groups the streamer will contain. For example, if the streamer length is 8100 metres and the receiver group interval is 12.5 metres, there will be 648 receiver groups per streamer. Assuming ten streamers are towed this gives a total of 6480 receiver groups in the spread and the position of each receiver group must be determining to a required precision (specified in the contract specifications) at every shot point.

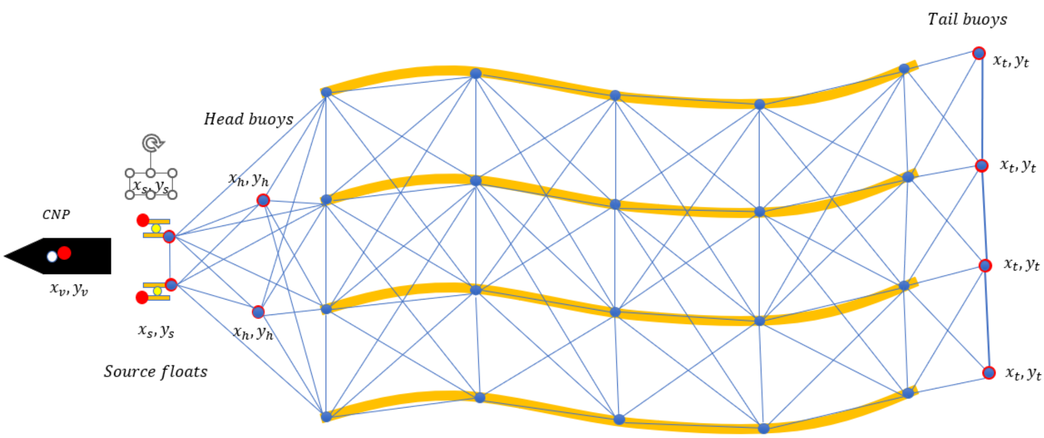


Figure 117: In-water positioning

In Figure 117, the red circles represent 'known' locations, whose positions are derived from space-based technologies e.g., primary positioning (GNSS) of the vessel, and rGPS tracking units used to derive the position of each towed buoy (Tailbuoys, Headbuoys and gun floats). The blue circles represent the location of the acoustic units deployed along each streamer and on each of the towed buoys. The nodes where both blue and red circles coincide represent the co-location of both rGPS and acoustic units. This is an important requirement when the acoustic network is processed to determine the unknown acoustic locations (step 4).

On modern fleets the use of rGPS buoy tracking and fully braced acoustic networks is common practice. How they contribute to determining source and receiver positions is described. For narrative purposes, this process is separated into the following key steps:

1. Position the CNP of the vessel e.g., PPP mode using GNSS (white circle).
2. Position each of the surface buoys, e.g., rGPS units on Tailbuoys, gun floats and Headbuoys (all red circles).
3. Make range observations between each of the acoustic nodes in the fully braced network located along each streamer (all blue circles).
4. Use the range observations and surface buoy locations (deemed 'fixed positions') to compute positions for each acoustic node.
5. Compute a 5th order polynomial curve through the acoustic nodes associated with each streamer as derived in step 4.
6. Interpolate the receiver group positions from the streamer shape and determine their coordinates referenced to a selected projected CRS.

7.1.1 Vessel positioning

Located onboard the seismic vessel are several positioning devices dedicated to determining the real time coordinates of the CNP, which is the origin point of the moving platform CRS (see section 3.4. These are referred to as the primary and secondary (and tertiary) satellite positioning systems. Today, they operate in Precise Point Positioning (PPP) mode using the hybrid Global Navigation Satellite Systems (GNSS), e.g., GPS + GLONASS as a minimum. Each solution deployed is required to have an element of uniqueness to provide the required redundancy. For example, what type of communication systems are used and what type of 'corrections' are distributed by the positioning vendor. The precision expected from PPP solutions is approximately 20 cm in the horizontal plane and 30 cm in the vertical plane (2 sigma probability). As such, the position of the CNP on the vessel can be considered the 'truth' because the error budget generated is so minimal.

7.1.2 Buoy positioning

Buoys are deployed to function as both navigation and positioning aids specifically with respect to the computations performed on the acoustic network. Buoys that are towed at the aft of each seismic streamer are known as Tailbuoys and those towed aft of the vessel and ahead of the streamers are known as Headbuoys. Gun floats, the floatation devices used in the source arrays, form the third category. Regardless of survey vintage Tailbuoys have always been used as a navigation aid to help identify where the end of each streamer is in relation to the vessel. On older surveys their positions were tracked using radio positioning systems (e.g., Syledis) and the vessel's radar, as they were fitted with aluminium cubic reflectors. Now, their positions are exclusively determined by rGPS or similar satellite based systems. Knowing their positions enabled the vessel and chase boat crews to warn nearby shipping to avoid them and the streamers between each buoy and the vessel. Streamer damage cause by vessels cutting across the tow path can be extremely costly and time consuming.

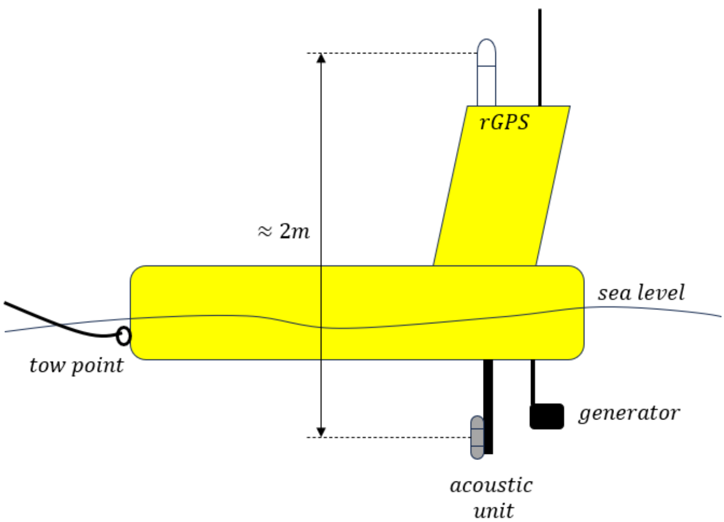


Figure 118: Tailbuoy unit

As a positioning aid their locations function as an integral part in determining coordinates for the seismic sources and every receiver group. Co-located in the horizontal component with the buoy positioning system is an acoustic transponder. Along the vertical axis there is a separation between the two of a few metres.

Because the position of the buoy unit is 'known' from the rGPS observations, it infers that that position of the co-located acoustic transponder is also known (in the horizontal component). See section 6.1.3 for further details on this integration.

7.1.2.1 Positioning the seismic source

Both port and starboard gun arrays comprise multiple sub-arrays (typically two or three) depending upon the size / volume of the array (the combined cubic capacity of all the airguns). The geometric centre of the seismic source is indicated by the red circle in Figure 119. This is the origin point (0, 0) of another local engineering 3D coordinate system which is used to describe the nominal offsets of each positioning aid and seismic gun. The orientation of the CS is along the centre line of the floats and assumes all floats are parallel. The numbers annotated on the floats indicate the nominal offsets (m) to the front and rear of each float in the array from the origin point.

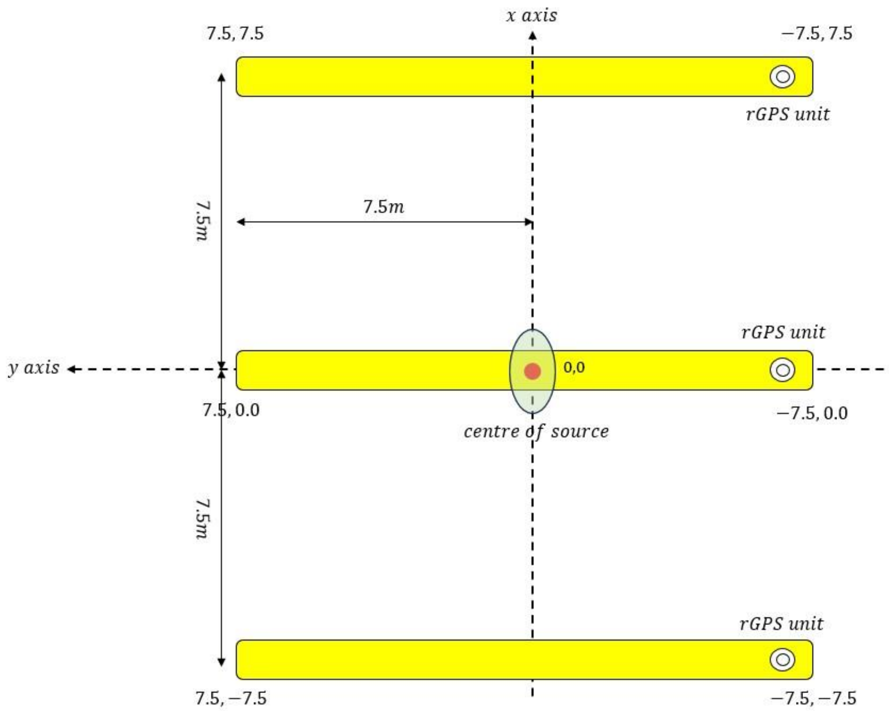


Figure 119: Determining centre of the seismic gun array

Below each floatation device (the gun float) are the airguns suspended by chains and to each is fitted a rGPS buoy tracking positioning system, which comprises two main components, a satellite antenna, and a comms link. It is common practice to deploy an rGPS unit on every gun float as illustrated in Figure 119 (white circles). The location at which each unit is placed will vary from contractor to contractor, for example, at the rear of each float or at float centre. But its distance to the origin point of the local CS is known.

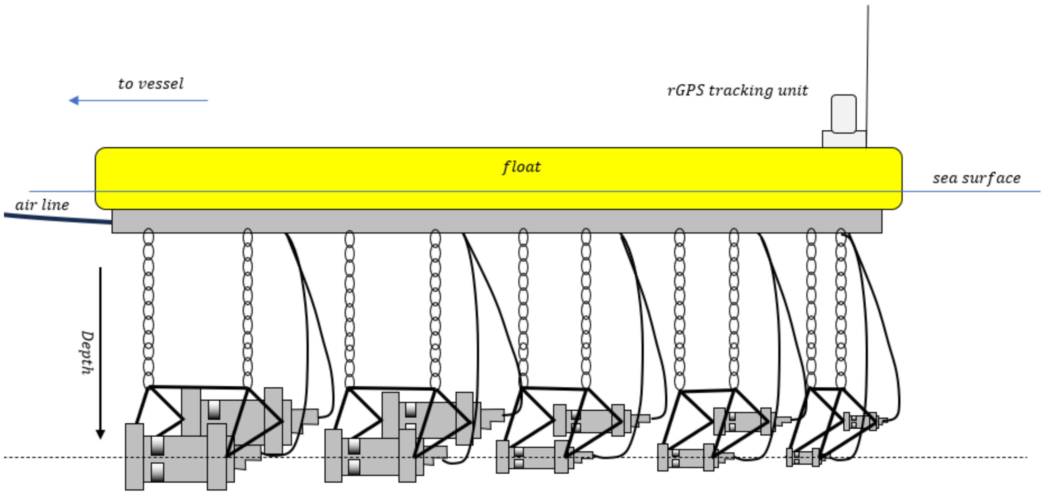


Figure 120: Airgun sub array with rGPS tracking unit

Located onboard the seismic vessel is the master rGPS control unit whilst the units deployed on each buoy are known as the slave or secondary units. Both master and slave units make code and phase observations to all common GPS / GNSS satellites in view. The observations made at each slave unit are transmitted back to the vessel via the dedicated comms link. The buoy tracking software uses all observations (master and slave) to determine the range and bearing between the vessel mounted rGPS antenna and each buoy. The observed quantities enable the horizontal position of each buoy to be determined in relation to the central navigation point (CNP) on the vessel.

The precision with which each buoy position is derived will depend upon distance from the vessel with the Tailbuoys being determined to approximately 1.5 metres (2σ, 95% probability). Depending upon the configuration of the tracking software buoy positions are computed at a minimum of 1Hz, although it is typical to compute it as a higher frequency (e.g., 10Hz). Once the position of each rGPS tracking unit is known the reverse offsets are applied to determine the origin point of the local coordinate system. This is centre of source and is the point at which the acoustic energy generated by the airguns at each shot point is deemed to have originated (see section 8.1.2.1). Around that point is drawn the horizontal error ellipse, see section 7.1.5.2 for further details.

The vertical component of the 3D coordinate system describes the depths at which the seismic guns are towed as shown in Figure 120. Typical depths will vary from 5 to 7 metres below water level. As mean sea level changes, the source depths must be adjusted from their actual depths below water line to MSL at every hour of every day for the duration of the survey. If not applied, it introduces an undesired static shift on the seismic trace data recorded.

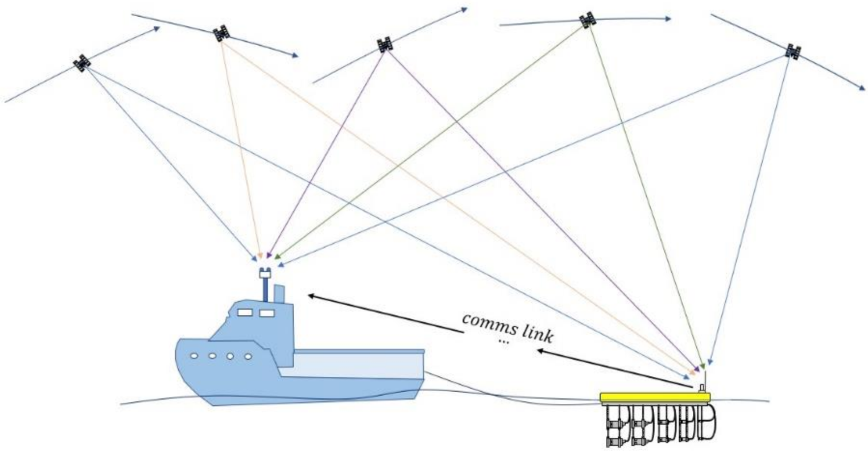


Figure 121: rGPS used to compute range and bearing

7.1.2.2 Use of acoustic units used on source arrays

Use of acoustic observations between the transponder(s) on the vessel and those located on seismic sources has been applied with limited success. Acoustic observations cannot travel through air and as the vessel's propellers create air bubbles this generates a medium through which the acoustic signals find it hard to propagate. So, unless the acoustic signals are transmitted along a more lateral path, (see Figure 123, light blue ranges) thus avoiding the cavitation created by the vessel's propulsion system, they will be largely corrupted. Similarly, when the airguns discharge it generates a sizeable oscillating air bubble which causes similar transmission problems around the sources.

7.1.3 Computing receiver positions

Along each streamer are deployed acoustic transponders / transceivers at lateral separations of around 300 metres (this will vary from contractor to contractor and on the technologies used, e.g., Q marine). Some units transmit and receive acoustic signals whilst others only receive and respond. Between the acoustic nodes a network of range observations is made in a sequence of 'individual' events, each transmitting acoustic node pings to other acoustic nodes in its close proximity.

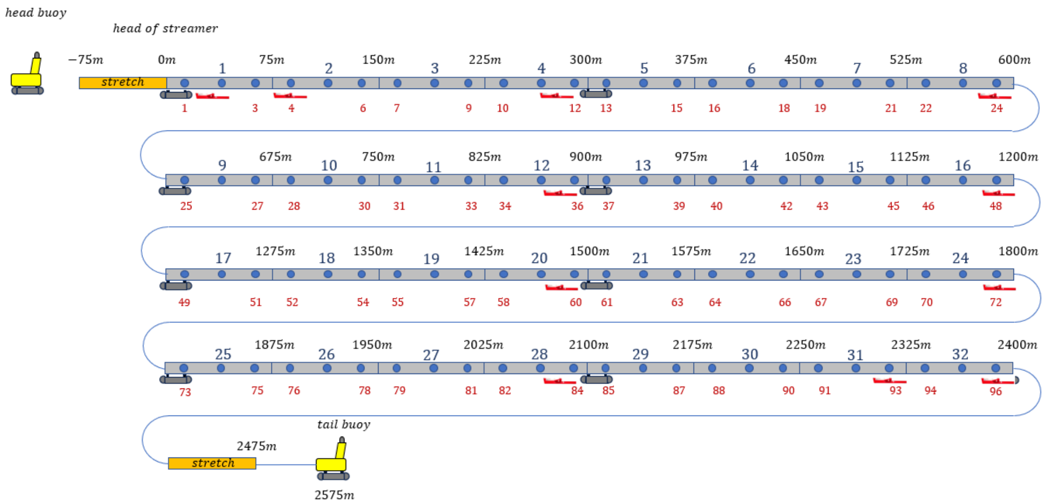


Figure 122: Example of streamer offsets

Therefore, acoustic observations are made up to a maximum radial range from each transmitting node (e.g., 1000 to 1200 metres) with a maximum number of observations made per ping. The different colours shown in Figure 123 tries to illustrate the observations made when an individual transmitting node pings. The travel time between transmission and reception is measured and using the velocity of sound in water (approximately 1520 m/s) the range observation is derived.

$$range = time * velocity\ of\ sound\ in\ seawater$$

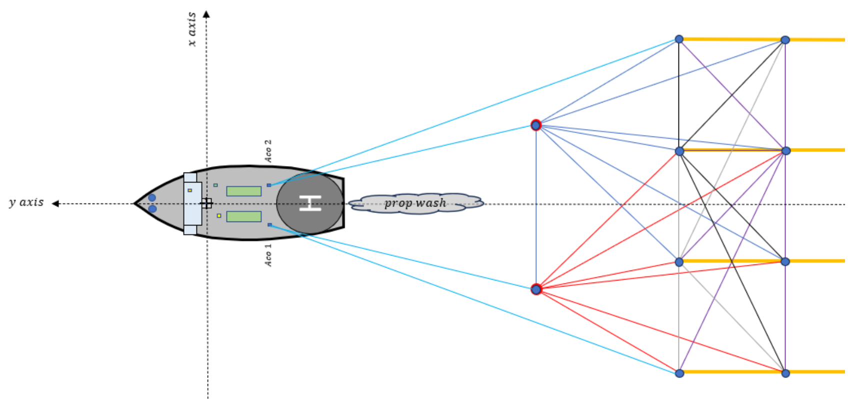


Figure 123: Acoustic ranges creating a network

The velocity of sound in seawater varies geographically and seasonally. Its value is determined by direct observation (e.g., TS Dip) or by indirect measurement where the transmission time between two nodes attached to the same streamer is determined. Values typically vary between 1480 m/s in colder climates to 1540 m/s in equatorial waters with seasonal trends. Therefore, thousands of range observations are made between the acoustic nodes extending the entire length of the streamers. This is known as a fully braced network or trilaterated network. Assuming there are 27 acoustic units attached to each streamer there will be a total of 270 acoustic units deployed on a ten streamer spread. Add to that the 10 units deployed on each Tailbuoy and two on the Headbuoys this gives a total of 282 acoustic nodes (12 known, 270 unknown). Next, assume there are 15 acoustic range observations made per node, it results in a total of 4230 observations made per shot point.

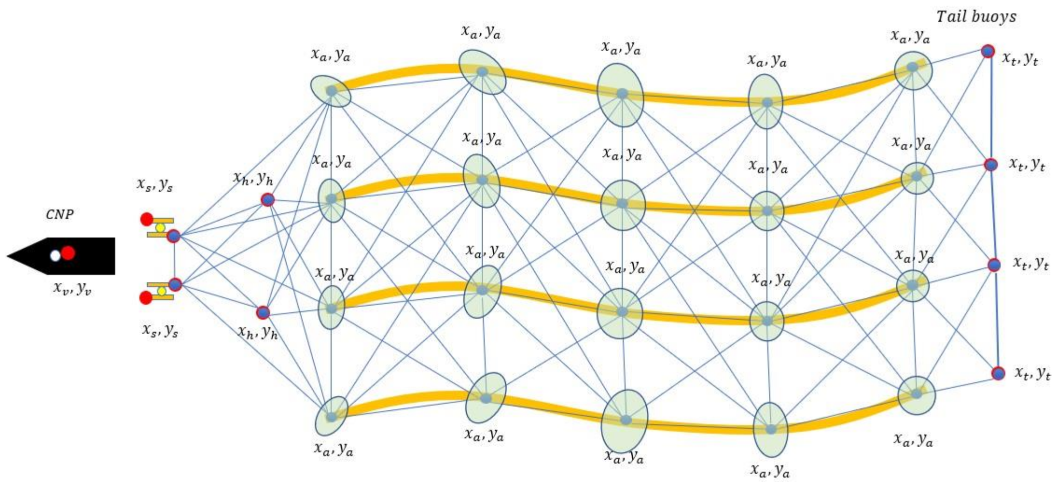


Figure 124: Network adjustment of acoustic observations

The acoustic nodes that are co-located with the rGPS units on the Head and Tailbuoys inherit their horizontal positions from the rGPS and are thus considered 'known' nodes (i.e., their positions are known). The network of acoustic ranges are input into a linear unbiased estimation technique (e.g., Least Squares Analysis) along with the 'known' fixed stations and a weighting strategy (stochastic model) to determine the coordinates of the acoustic nodes (unknown nodes) between which the observations were made and their quality measures (e.g., precision and reliability).

7.1.3.1 Network computation

A detailed analysis of computational processes used to derive coordinates for the acoustic nodes is beyond the scope of this book. For further details see Parr

(2024c) which includes a full description of the Least Squares Analysis, and all quality measures derived from that technique.

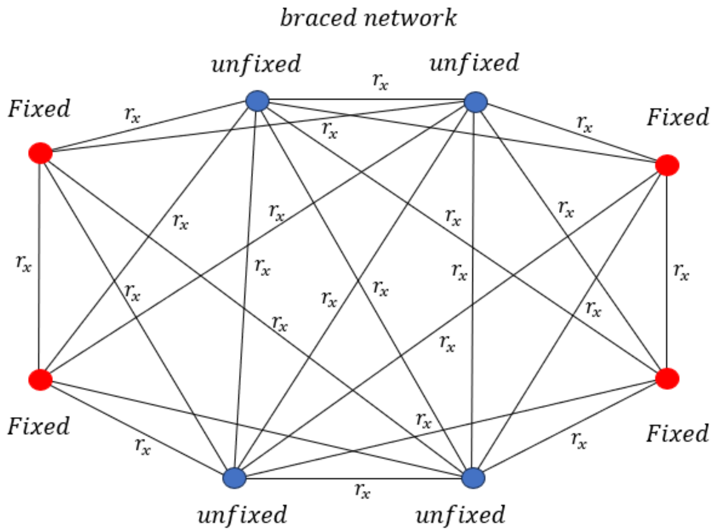


Figure 125: Range observations in a braced network

The fixed, or known, nodes are the red circles and the nodes whose positions require determination are the blue circles. In the survey community the least squares analysis (LSA) is the computational process of choice because of its unbiased nature. Range observations used to create the braced network shown in Figure 125 are input into the LSA along with the fixed nodes and an observation weighting strategy. These are used to derive the functional model (A), stochastic model (W) and observation vector (-b).

$$\hat{x} = [A^T W A]^{-1} A^T W b$$

Exported from the LSA are the best estimated coordinates of the unknown nodes ($\hat{x}$) and the residuals of the range observations ($\hat{v}$).

$$\hat{v} = A\hat{x} - b$$

Also computed are the covariance matrices from which the quality measures are computed. These are known as the covariance matrix of the unknown quantities $C_{\hat{x}}$, from which the horizontal error ellipses (precision measures) are derived and covariance matrix of the residuals $C_{\hat{v}}$ used in the reliability testing routines.

$$C_{\hat{x}} = [A^T W A]^{-1}$$

$$C_{\hat{v}} = W^{-1} - A[A^T W A]^{-1} A^T$$

The reason for showing these equations is to demonstrate that all are derived using the same input matrices. Finally, the unit variance (σ_o^2) is computed which is used in the automated statistical testing routines to confirm or deny the presence of outliers in the input observations. Further details for all these computations is found in the Positioning and Computations Book (Parr 2024c).

7.1.3.2 Curve fitting routine

There is a fixed relationship between each acoustic node attached to the streamer and its nearest co-located receiver group. Typically, a nominal offset diagram similar to the one shown in Figure 122 is created for each of the streamers being towed. It shows exactly where the acoustic nodes are deployed and therefore its position in the local 2D engineering coordinate system tied to each streamer head. Here, the streamer sections are 75m long (although 100m sections are commonplace) and there are three receiver groups per section with a group separation of 25m, the receiver group interval. Each section is given a unique number as are each receiver group in the sections (red numbers). The streamer illustrated is only 2400m long for brevity.

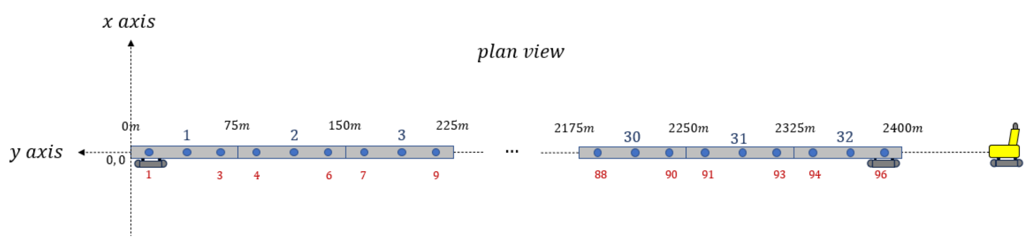


Figure 126: Local streamer CS in plan view

The distance along the streamer is given at the start of each section and this is the coordinate along the y $axis$ of the local 2D coordinate system associated with the streamer. The centre of the first receiver group is 12.5m from the head of the streamer and the centre of the last receiver group is 12.5m from the tail. This ensures all intermediate receiver group intervals are 25m apart.

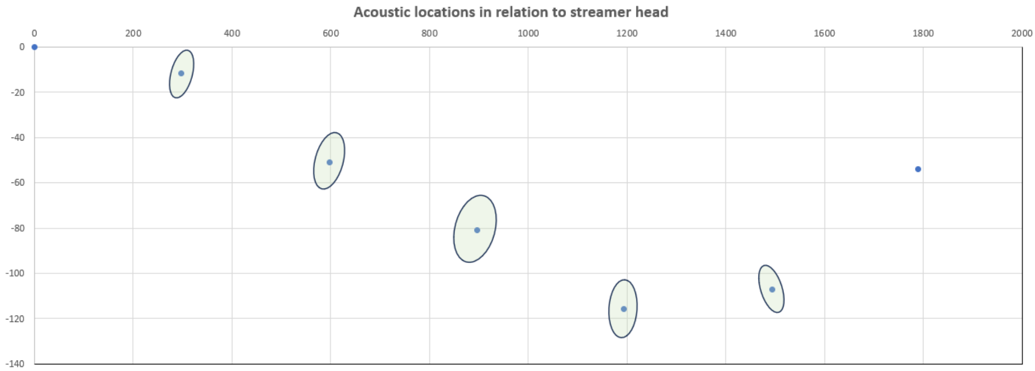


Figure 127: Acoustic unit locations derived from LSA

Exported from the Least Squares Analysis (LSA) are the estimated positions derived for each acoustic node attached to the streamers and this is shown for one streamer in Figure 127. The position of each node is referenced to the local 2D engineering coordinate system where the streamer head (0, 0) is the origin of the CS, and its orientation is parallel to the engineering CS attached to the vessel (see section 3.4). Around each derived acoustic position is a horizontal error ellipse which indicates the expected error each derived position is expected to contain to a specified level of probability.

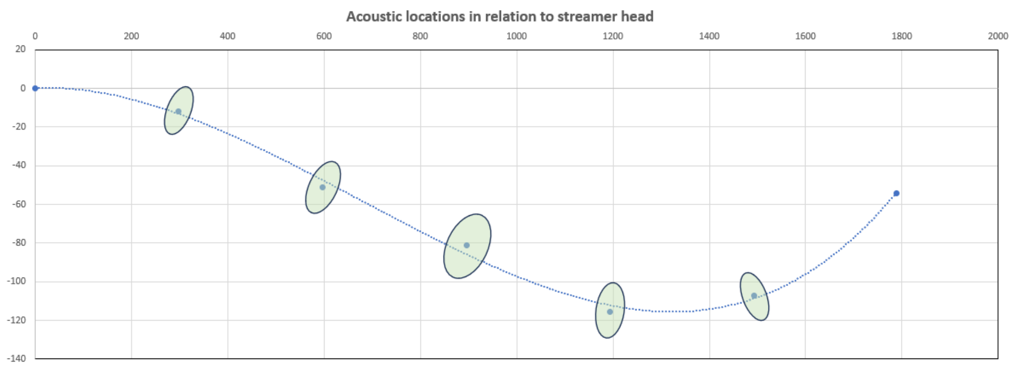


Figure 128: Acoustic units fitted with 5th order polynomial curve

By applying a curve fitting routine, such as a 5th order polynomial, to the x_a, y_a coordinates of each acoustic node a streamer shape like this one shown in Figure 128 is derived. It is on this curve that it is assumed each of the receiver groups belonging to that streamer will lay.

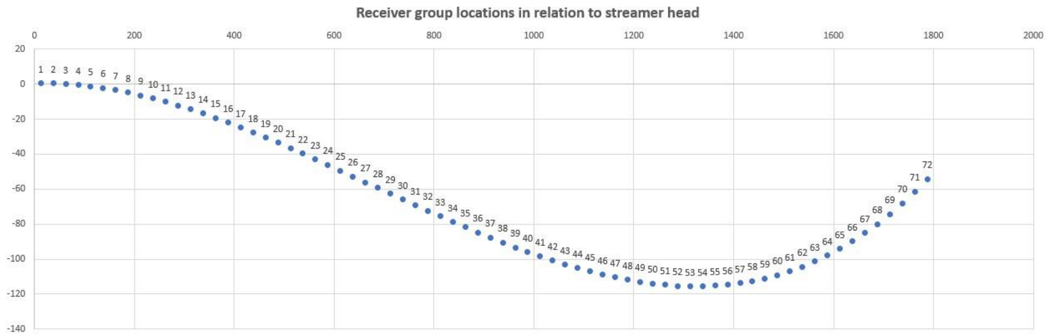


Figure 129: Receiver group locations derived from streamer shaping

As shown in Figure 122 there is a fixed linear relationship between the receiver groups as the interval between adjacent groups is identical along the entire length of the streamer. As it is linear, and the length of the streamer remains constant, each receiver group is plotted as shown in Figure 129, i.e., laying on the polynomial curve.

The fixed nodes have their coordinates derived in relation to the master rGPS unit on the vessel using the range and bearing computed to each slave unit. These horizontal coordinates are transferred to the co-located acoustic units and applied in the LSA which means the position of each receiver group can be reported in the same CRS. In Figure 130 an example is shown where the receiver group positions are reported referenced to a projected CRS and thus quoted in Easting and Northing.

Figure 130: Final receiver group coordinates

7.1.4 Nears, mids and fars

Consider a streamer that comprised 480 receiver groups with a receiver group interval of 12.5 metres, hence a streamer length of 6000m. Receiver group 1 is at the head of the streamer and 480 is at the tail of the streamer. As part of the contract specifications, it is required that within each cell of the full fold perimeter (of the seismic grid) there is an equal distribution of source-receiver pairing from all the possible offsets along the streamer. To monitor this, the receiver groups along the streamer are collected into a set of sub-assemblies known as the near groups**,** mid groups and far groups. As there is a mid-point associated with each receiver group, they too can be collected into nears, mids and fars and the footprint for all CMP lines acquired per sail line is shown in Figure 129 for one shot point.

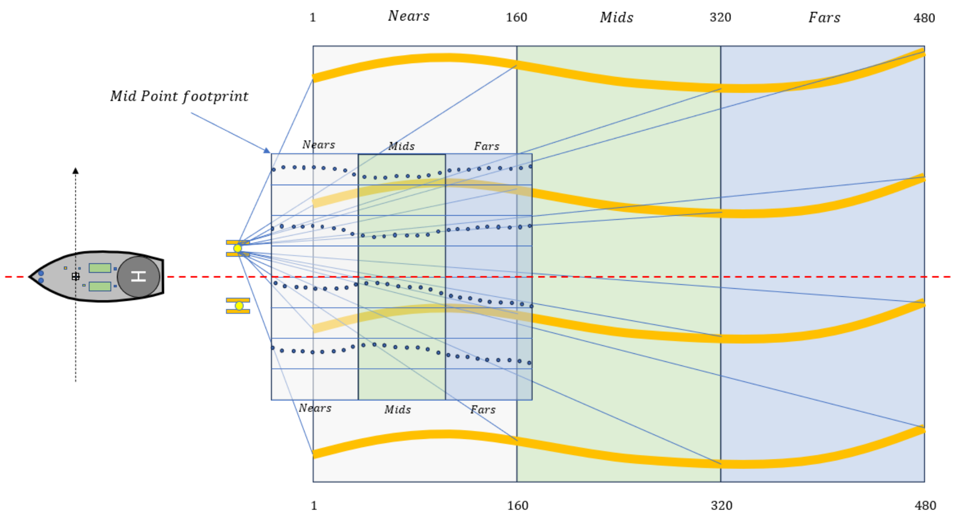


Figure 131: Mid-point footprint for Nears, Mids and Fars for one shot point

Therefore, each group is given a minimum and maximum offset range that is associated with their collective group distance along the streamer. These are shown in Table 9.

Table 9: Streamer offset groups

Group	Receiver group numbers	Offset range (m)
Nears	1 to 160	0 to 2000
Mids	161 to 320	2001 to 4000
Fars	321 to 480	4001 to 6000

In each cell of the seismic grid there must be an equal number of source-receiver offset pair contributions from the near, mid, and far receiver groups. Having an equal distribution is important to the seismic data processors and their determination of an optimal velocity model for the inhomogeneous sub-surface strata. The binning management module provides the mechanism of assessing whether this is being achieved by displaying the fold coverage contributed from the source-receiver pairs for each offset range. If the full fold coverage for all offset ranges is expected to be 120 fold, then the near, mid, and far groups are each expected to contribute 40 fold coverage to each cell in the full fold coverage perimeter. Therefore, plots are generated to show if the number of hits for each of the offset ranges is being achieved.

When longer streamers (>6000m) are used the number of receiver group assemblies are often extended to include two additional categories known as the near-mids and the mid-fars. Thus, there are five ensembles and hence five offset range categories. Consider a streamer with a length of 8100m and a total of 648 receiver groups. In this example each category would have 130 receiver groups, and the offset range would be reduced to 1620 metres per ensemble (0 to 1620, 1621 to 3240 etc.).

Table 10: Offsets groups on longer streamers

Group	Receiver group numbers	Offset range (m)
Nears	1 to 130	0 to 1620
Near-Mids	131 to 260	1621 to 3240
Mids	261 to 390	3241 to 4860
Mid-Fars	391 – 520	4861 to 6480
Fars	521 - 648	6481 to 8100

7.1.5 Computing the mid-point

Next, the mid-point coordinates for each source-receiver offset pair are derived using the coordinates for each contributing object. Figure 132 illustrates the mid-points associated with the source and receiver groups 1 and 3 respectively, along with their relevant coordinates. The mid-point for SP101 and Rcv 1 populates cell 1001 and with SP101 and Rcv 3 populating cell 999.

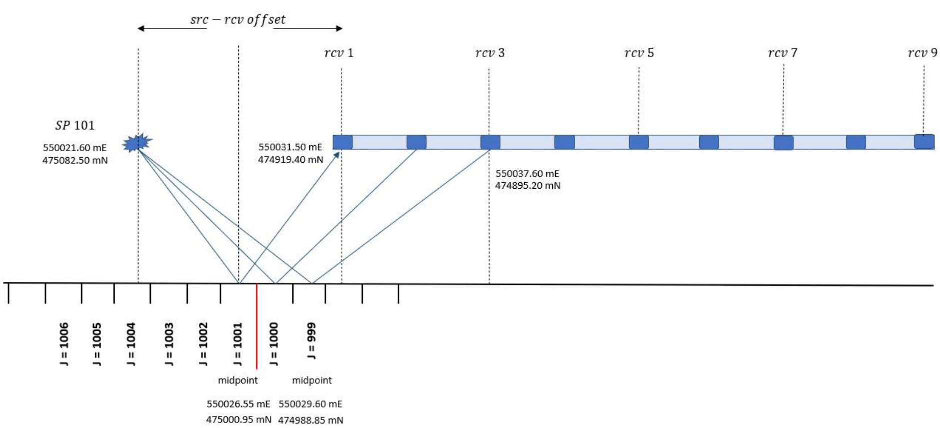


Figure 132: Calculate seismic trace mid-point positions

The coordinates for all positions associated with these two mid-points are shown in Table 11.

Table 11: Object coordinates for mid-point computation

	Source	Scr-Rcv 1 mid-point (1001)	Receiver 1	Scr-Rcv 3 mid-point (999)	Receiver 3
Easting	550021.60	550026.55	550031.50		550037.60
Northing	475082.50	475000.95	474919.40		474895.20
Easting	550021.60			550029.60	550037.60
Northing	475082.50			474988.85	474895.20

7.1.5.1 Horizontal mid-point error

From the computational process (LSA) a horizontal error ellipse can be derived for every estimated source and receiver group positions. This precision measure illustrates the error each position is expected to contain to a given confidence level, e.g., 1σ or 2σ which correspond to 39.4% and 95% probability levels, respectively. What is often of more interest is to determine the error ellipse for the mid-point position for each source-receiver offset pair. A method to compute this was proposed by Zinn (1991) who concluded that the increased performance of the positioning systems used decreased the errors at the target location, e.g., the mid-point error.

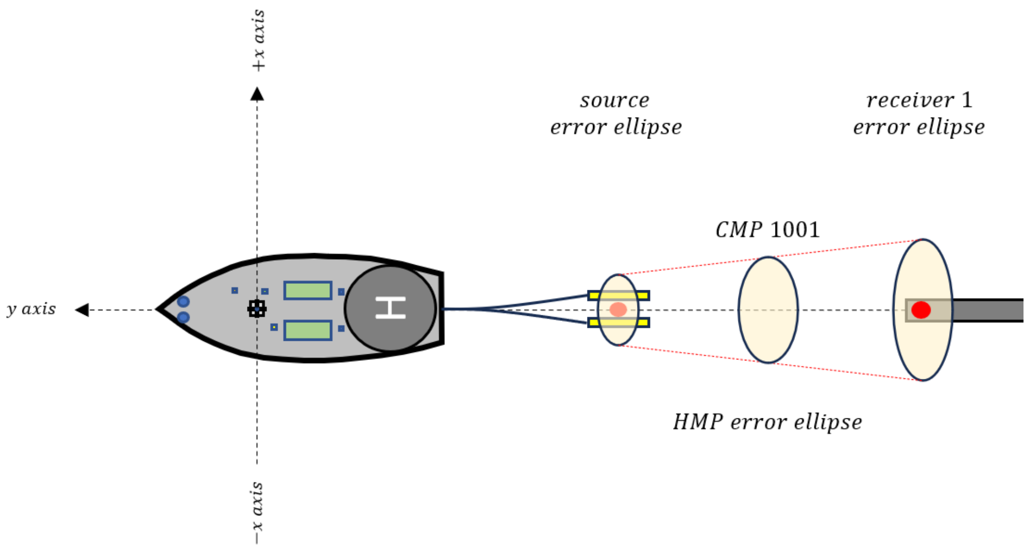


Figure 133: HMP error

Although the method does offer some insight to the errors associated with the mid-points its usage would appear limited given the significant improvement in positioning systems now employed.

7.1.5.2 Quality measures

Drawn around each of computed position (source centre and each acoustic node) is a figure known as the horizontal error ellipse. This is one of the precision quality measures and is a biproduct of the computation method used to determine the estimated coordinates of the unknown acoustic nodes. Anything other than a brief introduction to precision measures is beyond the scope of this book. For further details see Cross (1994), Parr (2024b). Their function is to describe an area or footprint that expresses the expected error each estimated position derived from the computational process is expected to contain to a specified probability (e.g., 95% probability, 2σ). The horizontal error ellipse has three key parameters, two of which describe the size along two axes and the other describes an orientation of one of the axes from a designated reference north.

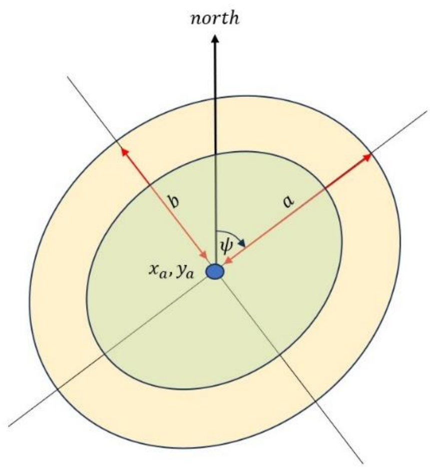


Figure 134: Horizontal error ellipse

The dimensions of the horizontal error ellipse are described by the semi-major axis (a) and the semi-minor axis (b). The former described the direction along the maximum expected error in the estimated position and its orientation is given by the angle ψ, in relation to a designated north reference. There are two error ellipses shown in Figure 134, green and orange. What they represent are two different footprints derived using two different confidence levels and hence probabilities. As the output from the computation process is an estimated horizontal 2D position the confidence level is by default one sigma (1σ), which represents a probability of 39.4%. It is more common to draw the horizontal error ellipses at a confidence level of two sigma (2σ), which represents a probability of 95%. Therefore, if the magnitude of the semi-major axis is 15.5m it is interpretated to mean that the potential error in the estimated position will be a maximum of this value with a 95% probability.

All positions derived from the computation process are estimated as the observations (acoustic ranges) used in the computation contain error which propagates from the observations into the estimated positions because of a process known as Gaussian Error Propagation. The amount of error each position contains will never be known, it can only be estimated, and the horizontal error ellipse is one formal mechanism of expressing the precision (other alternatives include Circle Error Probability and 2dRMS) of the estimated position.

7.2 Binning trace data

All that remains is to determine into which cell of the seismic grid do the mid-points belong for each source-receiver offset pairing. To commence, an example is shown of how this relates for data acquired when a 2D seismic CMP line is acquired. Although binning is not applied as per a 3D survey the same basic principles apply to the gathering of data and gradual increase in fold coverage.

7.2.1 Seismic 2D survey

On a seismic 2D survey only one CMP line is acquired per sail line as there is a single source and a single streamer, which for simplicity, contains only six receiver groups. The receiver group interval is 25m and the shot point interval is equal to the receiver group interval, see section 6.2. As such six source-receiver offset pairs will be acquired per shot point and thus six mid-points. In a seismic 2D survey a seismic grid is not used, but the same 'concept' of fold coverage build is identical.

In Figure 135 is the post-processed positioning data computed in real-time by the INS. In it are the S records representing the source positions and the R records for the six receiver positions. It is from these positions that the six mid-point positions are derived for each of the seven shot points. Figure 136 illustrates the single CMP line in planview for the seven consecutive shot points. These are labelled SP101 on the left hand side to SP107 to the right hand side. The vessel is traversing up the page and the individual 'cells' along the inline direction are represented by the rectangles whose numbers are annotated on the left hand side (ranging from 996 to 1015). The small red circles represent the centre point of each of cell along the inline bearing and are the common mid-point locations as defined from the pre-plot line attributes, e.g., interpolated between the Start of Line (SOL) and End of Line (EOL) coordinates assigned. The separation between the red circles is 12.5m because the receiver group interval is 25.0m.

```
V-05P1-029       1      101041759.90N1112704.57E 550075.0 475300.0  36.2096135608
S-05P1-029       11     101041753.39N1112704.56E 550075.0 475100.0  36.2096135608
R0001 550075.0 474950.0 9.10002 550075.0 474925.0 9.20003 550075.0 474900.0 9.21
R0004 550075.0 474875.0 9.30005 550075.0 475850.0 9.30006 550075.0 475825.0 9.31
V-05P1-029       1      102041800.72N1112704.57E 550075.0 475325.0  36.1096135618
S-05P1-029       11     102041754.21N1112704.56E 550075.0 475125.0  36.1096135618
R0001 550075.0 474975.0 9.10002 550075.0 474950.0 9.20003 550075.0 474925.0 9.21
R0004 550075.0 474900.0 9.30005 550075.0 474875.0 9.30006 550075.0 474850.0 9.31
V-05P1-029       1      103041801.53N1112704.57E 550075.0 475350.0  36.0096135628
S-05P1-029       11     103041755.02N1112704.56E 550075.0 475150.0  36.0096135628
R0001 550075.0 475000.0 9.10002 550075.0 474975.0 9.20003 550075.0 474950.0 9.21
R0004 550075.0 474925.0 9.30005 550075.0 474900.0 9.30006 550075.0 474875.0 9.31
V-05P1-029       1      104041802.35N1112704.57E 550075.0 475375.0  35.9096135638
S-05P1-029       11     104041755.83N1112704.56E 550075.0 475175.0  35.9096135638
R0001 550075.0 475025.0 9.10002 550075.0 475000.0 9.20003 550075.0 474975.0 9.21
R0004 550075.0 474950.0 9.30005 550075.0 474925.0 9.30006 550075.0 474900.0 9.31
V-05P1-029       1      105041803.16N1112704.57E 550075.0 475400.0  35.8096135648
S-05P1-029       11     105041756.65N1112704.56E 550075.0 475200.0  35.8096135648
R0001 550075.0 475050.0 9.10002 550075.0 475025.0 9.20003 550075.0 475000.0 9.21
R0004 550075.0 474975.0 9.30005 550075.0 474950.0 9.30006 550075.0 474925.0 9.31
V-05P1-029       1      106041803.98N1112704.57E 550075.0 475450.0  35.7096135658
S-05P1-029       11     106041757.46N1112704.56E 550075.0 475250.0  35.7096135658
R0001 550075.0 475075.0 9.10002 550075.0 475050.0 9.20003 550075.0 475025.0 9.21
R0004 550075.0 475000.0 9.30005 550075.0 474975.0 9.30006 550075.0 474950.0 9.31
V-05P1-029       1      107041804.79N1112704.57E 550075.0 475475.0  35.6096135708
S-05P1-029       11     107041758.28N1112704.56E 550075.0 475275.0  35.6096135708
R0001 550075.0 475100.0 9.10002 550075.0 475075.0 9.20003 550075.0 475050.0 9.21
R0004 550075.0 475025.0 9.30005 550075.0 475000.0 9.30006 550075.0 474975.0 9.31
```

Figure 135: P1/90 positions from INS

It is these locations that are populated into the trace headers of the SEG-Y file. They are generated from the processed trace data and are given as easting and northing coordinates related to a specified coordinate reference system. N.b. The SEG-Y file trace headers only permit the storage of projected coordinates. See section 10 for further details.

At SP101 a mid-point position (blue circle) is derived for each source-receiver offset pairing acquired at that shot point with each one annotated with its contributing source and receiver. Notice how the first cell populated by the source-receiver offset from SP101 and Rcv 1 is number 1001. Each blue circle represent the horizontal position of where the seismic trace data imaged the sub-surface along the vertical component (down). The current fold coverage is shown to the right of each cell which is one fold.

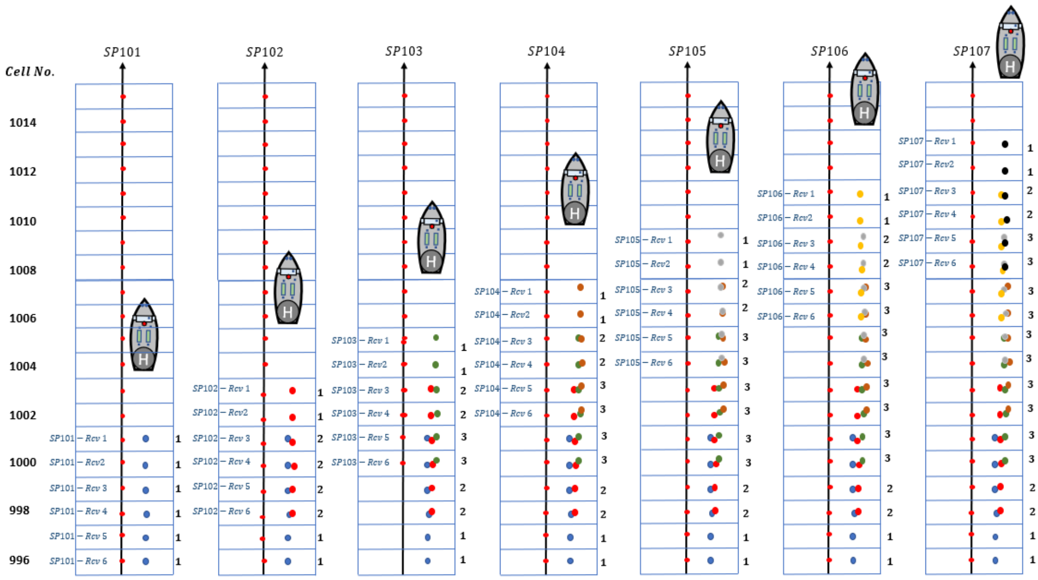


Figure 136: Fold coverage build up on a single CMP line

The vessel traversed along the line to the next shot point SP102 where the next six mid-points are acquired from the same source-receiver offset pairs. These are indicated by the six red circles drawn along with the mid-points from SP101. The gradual build in the fold coverage should start to become evident as four cells are now populated with offset pairs from both SP101 and SP102. This is expected because the source has progressed 25m along the line which is equal to two cell widths whose inline dimension are 12.5m.

This is repeated for the remaining five shots shown horizontally across Figure 136 where on the far right hand side is the total fold count in each cell after all seven shot points have been acquired. In Figure 136 fold coverage reaches a maximum value of three at SP103 for CMP numbers 1001 and 1002. This is the maximum value achievable with the equipment deployed and the geometric configuration between the source interval and receiver interval. As the line progresses each common mid-point, e.g., 1003 onwards, would each have three mid-points contributing to the common mid-point. As the end of the line is reached the fold coverage will taper back to 1 as the line terminates once the last full fold coverage point has been filled.

7.2.1.1 Streamer feathering on 2D survey

Ideally, the streamer is towed directly behind the vessel with zero angular offset in relation to the azimuth of the pre-plot line. With no feathering being experienced all the seismic trace data is acquired along the same azimuth as indicated in Figure 137.

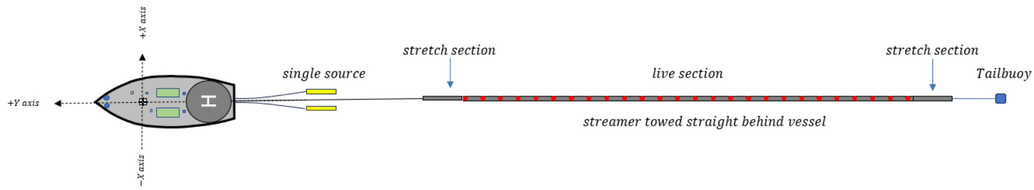


Figure 137: Seismic 2D streamer - no feather

Therefore, all source-receiver offset pairs are collected into the cells, as shown in Figure 136. Seldomly is this experienced, as tides and currents create an angular horizontal offset of the streamer to the pre-plot line meaning the mid and far receivers experience a lateral offset along the $x\ axis$.

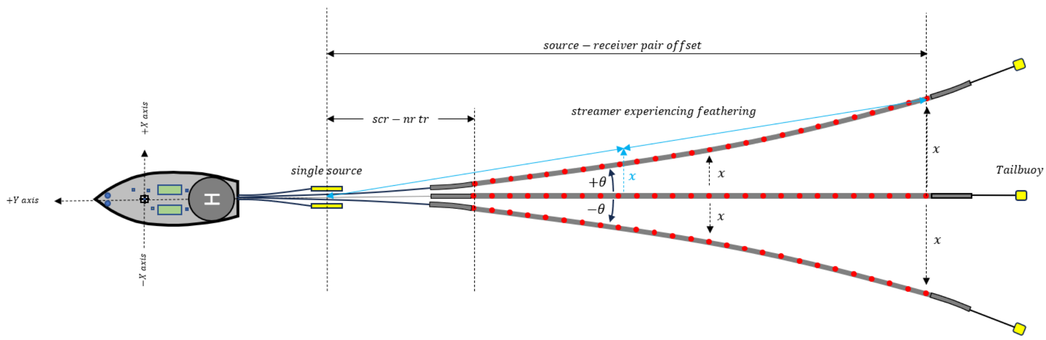


Figure 138: Streamer experiencing feathering

When the streamer experiences feathering to the starboard the angle is designated positive and when to port it is designated negative. The amount of lateral offset experienced by the mid and far receiver groups depends upon the size of the feather angle and the length of the streamer. Assume the streamer is 6000m long and the source to near trace offset is 150m, the source-receiver offset to the far trace is 6150m. Therefore, the mid-point distance is 3075m.

If the feather angle experienced is $+7^o$, the mid-point will fall +375m to the high side of the pre-plot line as shown by the light blue arrows in Figure 138. Despite this lateral offset the mid-point position is still assumed to be located as if the streamer is being towed directly behind the vessel. In this example, this is largest offset a mid-point would experience as this involved the source to last receiver group on the streamer as shown.

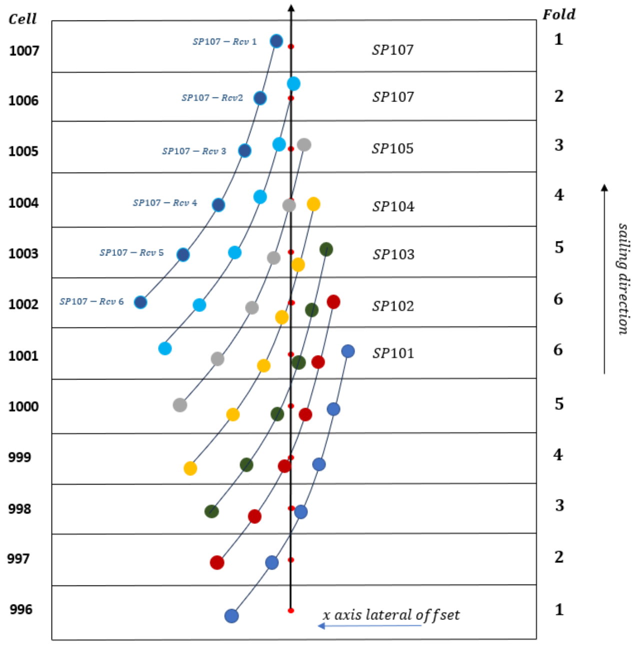


Figure 139: Mid-points 'gathered' with streamer feathering

One of the contract specifications set on a seismic 2D survey is the amount of feather angle that the streamer can experience before suspending acquisition with a typical value being between 10 and 15^o. The larger the feather angle, the less likelihood that the trace data will provide a proper representation of the rock structures trying to be imaged along the intended azimuth. However, leniency is given to the horizontal seismic resolution specified by the Fresnel zone (see section 8.1.2.5).

7.2.2 Seismic 3D survey

On a Seismic 3D survey, the vessel tows multiple sources which fire alternately, e.g., port fires at one shot point and starboard at the next. This is known as flip-flop shooting or dual source shooting. There is an extension of this where the vessel tows triple sources which also fire in a set sequence. This is known as flip-flop-flap shooting but has had limited commercial success. For the remainder of this section only the dual source configuration is considered.

When the pre-plot design specifies a 25m shot point interval it means the sources fire alternately every 25m. Therefore, the port and starboard gun arrays only fire every 50m, with the port guns firing at odd shot point numbers and the starboard guns firing at even shot point numbers (this is not fix and depends on the contractor).

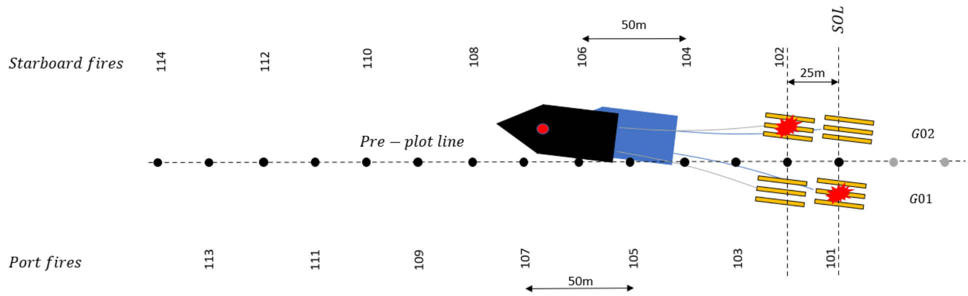


Figure 140: Dual Source shooting

On an ideal survey the streamers are towed directly behind the vessel with zero angular offset in relation to the azimuth of the pre-plot line (shown by the red line), e.g., the streamers are parallel to the pre-plot azimuth.

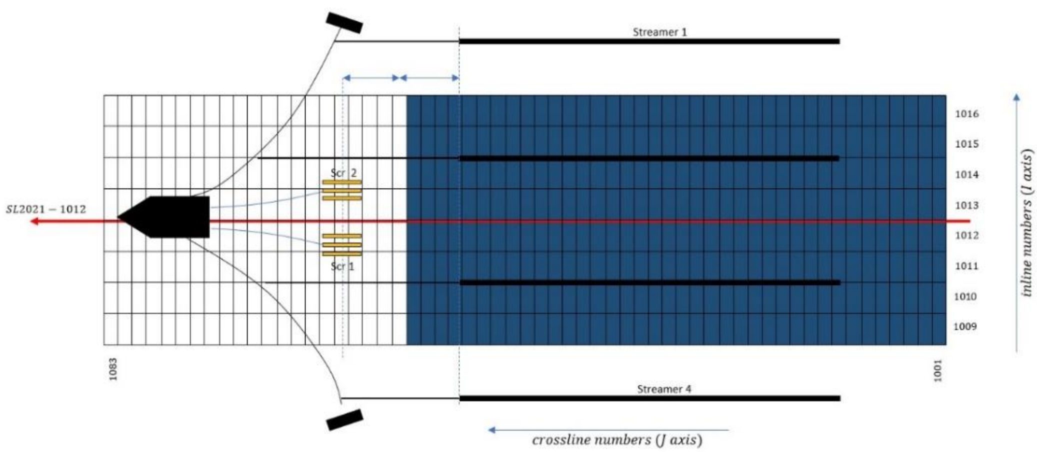


Figure 141: Fold coverage with zero feather

With zero rotational angular offset experienced, all the cells in the footprint of the current swath are populated as indicated in Figure 141. Provided all receiver groups are operational each cell is filled with the optimal number of traces from the source-receiver offset pairings designed to contribute to those CMP lines. For example, CMP line number 1009 (on the *I axis*) is populated by source-receiver pairs from source 1 and streamer 4 whilst CMP line number 1016 by source-receiver pairs from source 2 and streamer 1. The vessel is sailing along a pre-plot line named SL2021-1012 which includes 1012 in the naming syntax because that is its corresponding CMP line number. The sails lines are aligned along the $J\ axis$ of the seismic grid.

7.2.2.1 Binning example

A vessel is towing four streamers and two sources hence, eight CMP lines are acquired per sail line. For this example, the following equipment geometry is applied:

- Each streamer has 6 receiver groups at a group interval of 25m. Total length = 150m.
- The shot point interval (12.5m) is equal to half the receiver group interval (25m). * *This is for narrative purposes only*.
- The source separation (50m) is half the streamer separation (100m).
- There are six source-receiver offset pairs per streamer per shot point.
- The streamers are experiencing zero feather angle.

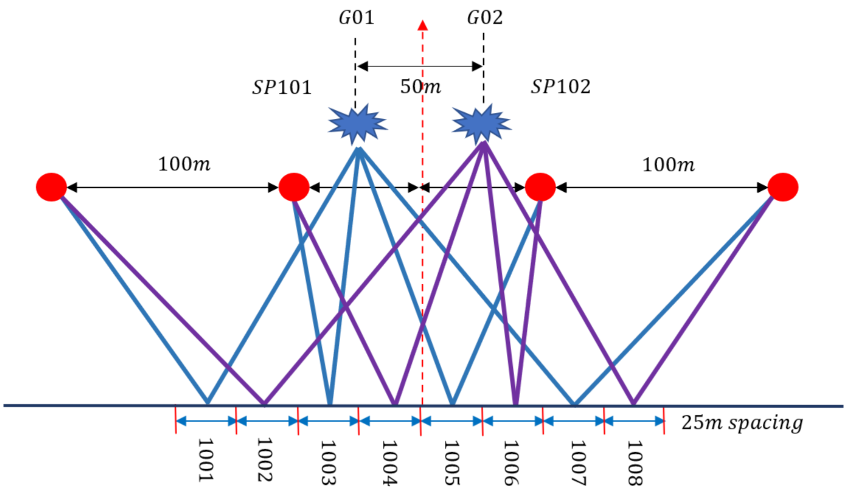


Figure 142: Populating the CMP lines from a cross section view

When the Port gun array (G01) fires at SP101 four CMP lines are populated represented by the blue lines shown in CMP lines 1001, 1003, 1005 and 1007. The vessel traverses to the next shot point where the Starboard gun array fires at SP102 which populates the remaining four CMP lines represented by the purple lines in CMP lines 1002, 1004, 1006 and 1008. The vessel is sailing into the page.

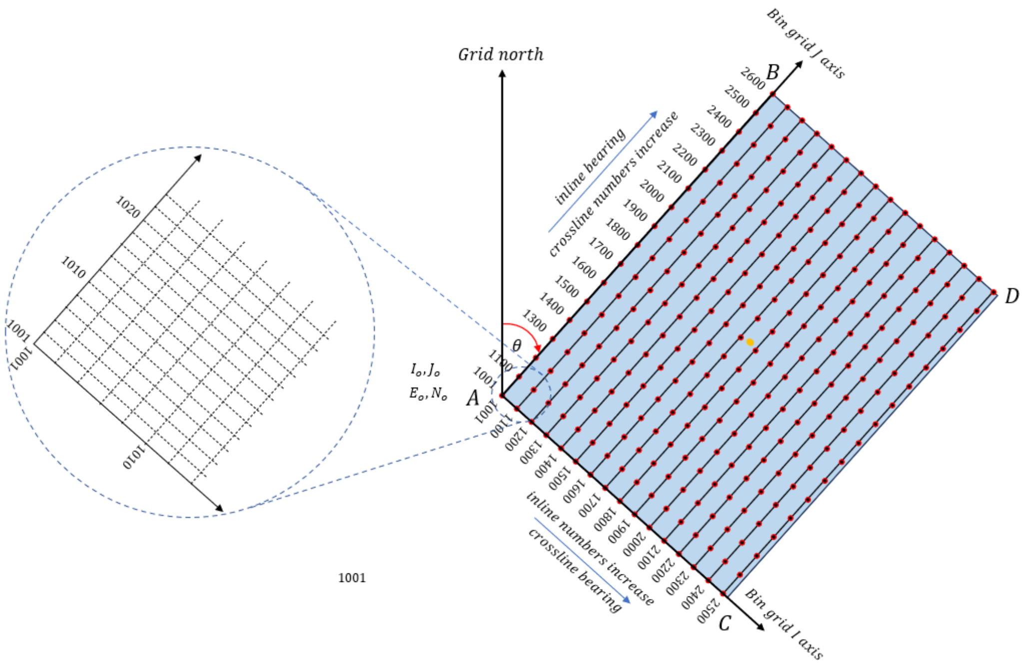


Figure 143: Binning the source-receiver offset data

On the right hand side of Figure 143 is the extent of the seismic grid full fold area (light blue rectangle). The lines and circles shown on the grid represent the direction and numbering of the CMP lines decimated to every 100th cell. On the left hand side is a sub-section of the seismic grid to show where the binning is performed in Figure 144 to Figure 146. This is illustrated for the first eight CMP lines for the first sail line SL-2021-1004.

Figure 144 illustrates how the cells of the seismic grid are populated in plan view. The cell numbers (and increments) for the J *axis* are shown on the vertical and those for the I *axis* are shown on the horizontal. The two axes of the seismic grid are superimposed on the grid cells, with the axes meeting at the origin of the seismic grid, e.g., (I = 1001, J = 1001). This correlates to the origin shown as point A in Figure 143. The red circles represent the cell centres as derived from the seismic grid design (see section 5.3). These are the locations where the seismic trace data for all source-receiver offset pairs gathered into each cell are deemed to have imaged the sub-surface vertically. The horizontal red line represents the boundary of the full fold perimeter along the I *axis*. The cells on the J *axis* that fall below this line belong to the Taper zone (see section 6.2.3).

Figure 144: Cells populated for SP101 and SP102

The port array (G01) fires at SP101 creating six mid-points per streamer which populate the first six cells (996 to 1001) of CMP lines 1001, 1003, 1005 and 1007. These positions are represented by the blue circles shown in Figure 144 against which are annotated the source-receiver offset pairs contributing to each mid-point. For example, cell (1001, 1001) is populated by the source-receiver offset pair from SP101 and receiver group 1 on Streamer 4 (SP101: Rcv1: St4). Whereas cell (1003, 998) was populated by the source-receiver offset pair from SP101 and receiver group 4 on Streamer 3. The logic continues throughout all the source-receiver offset pairs shown.

Next, the starboard array (G02) fires at SP102 creating a further six mid-points per streamer which populate cells 997 to 1002 of CMP lines 1002, 1004, 1006 and 1008. Their positions are represented by the purple circles in Figure 144. The same annotations are illustrated for SP102 to indicate which source and receivers are contributing to the mid-points for this shot point. Therefore, cell (1008, 1001) is populated by the mid-point between starboard gun array (GO2) and receiver group 2 on Streamer 1. After SP101 and SP102 are acquired, the fold coverage count for all the populated cells is incremented by 1 indicating they all have one contributing source-receiver offset pair**,** e.g., one hit in each.

Figure 145: Cells populated for SP103 and SP104

Next, the vessel traverses the pre-plot to SP103 where array G01 (port array) fires again. This is 25m along the pre-plot from where SP101 fired as the shot point interval is 12.5m and the arrays are operating in flip-flop mode. Because of the forward motion of the seismic source the cells populated by the six source-receiver offset pairs fall into cells 998 to 1003 as illustrated by the lighter blue circles in Figure 145. They do, however, populate the same CMP lines as SP101 as expected. At SP104 the starboard array (G02) fires again after the vessel has traversed a further 12.5 metres along the pre-plot. This populates cells 999 to 1004 of the same CMP lines filled by SP102. These are represented by the six light purple mid-points populating the same CMP lines as those populated by SP102.

On the right hand side of Figure 146 the fold coverage count is shown for each row of cells populated by the port and starboard arrays, respectively. Because of the geometric configuration between SPI and RGI and the number of receiver groups, four CMP lines are populated by source-receiver offset pairs from both the first and second round of shot points. This is shown by the increase fold count for those four cells.

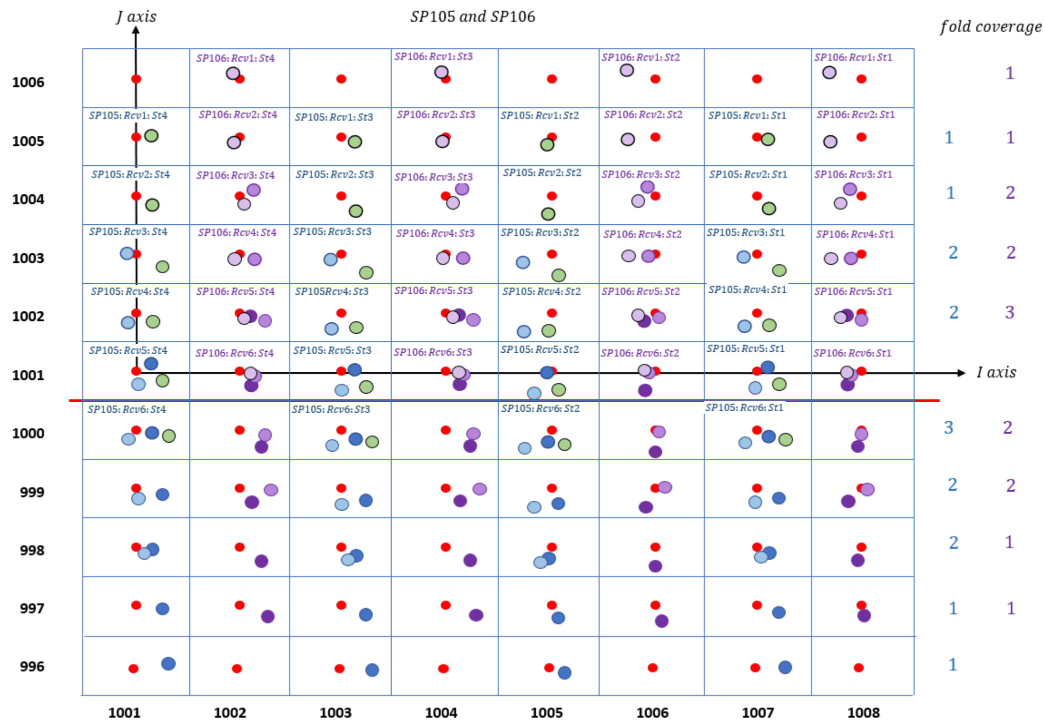


Figure 146: Cells populated for SP105 and SP106

As the acquisition continues for the next round of shot points (SP105 and SP106) the number of contributing offset pairs increases in each cell, as shown in Figure 146. Focus on the cells along the row J = 1001. Every cell in that row has three contributing source-receiver offset pairs. Given the geometric configuration specified at the section beginning this is the maximum number possible because:

$$full\ fold\ coverage = \frac{\frac{6 * 25}{2}}{25} = 3$$

Therefore, as the line progresses, each cell of the seismic grid will contain a maximum of three fold, which represents the full-fold coverage for this hypothetical configuration. The area over which all cells will have this accumulated number is represented by the full-fold perimeter.

7.2.2.2 Individual cells

In each cell of the seismic grid are gathered an ensemble of source-receiver offset pairs associated with the seismic trace data recorded. In Figure 146, three offsets contribute to cell J = 1001, I = 1001. An alternative way of illustrating this is shown in Figure 147. The seismic trace data belonging to the three different source-receiver offset pairs are all illustrated as imaging the same sub-surface point because in each case the source and receiver are equidistant from the common mid-point. With a streamer containing many receiver groups the number of source-receiver offset pairs of increased horizontal separation will theoretically contribute to the same cell. The collection of similar offsets is gathered into all the individual cells of the full fold perimeter of the grid.

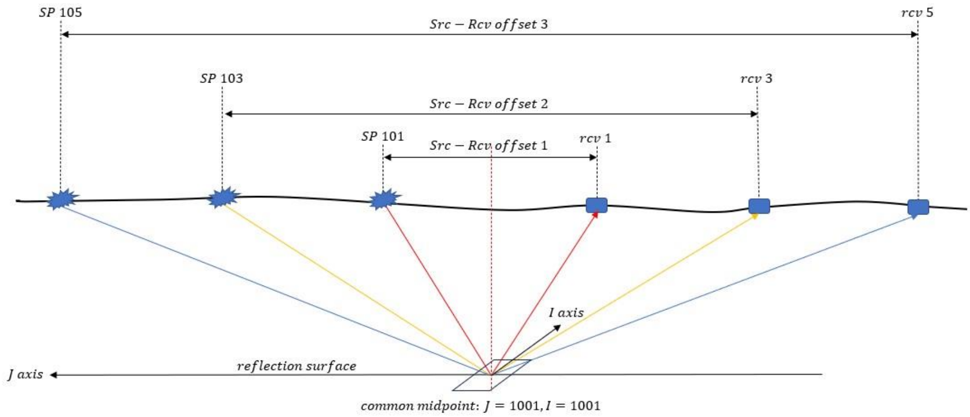


Figure 147: Offsets contributing the same cell

The locations of the mid-points for each source-receiver offset pair will be scattered over the extent of each individual cell. Figure 148 illustrates this concept for one cell of the seismic grid with each mid-point circle represents the location where the corresponding seismic trace data was computed to have imaged the sub-surface (from the source and corresponding receiver coordinates). The different colours represent mid-points from the nears (grey), mids (dark blue) and fars (light blue) and assumes the streamer is experiencing a slight feathering. The number of mid-points in the cell will depend upon the maximum fold coverage expected from the geometry of the seismic spread.

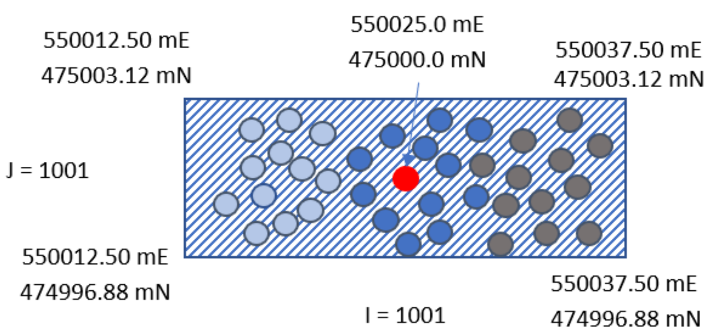


Figure 148: Source-receiver pairs contributing to one cell of the grid

The red circle represents the geometric centre of the cell whose coordinates are shown by the blue arrow. It is this point below which all the seismic trace data (for all source-receiver offset pairs) used in the gather is deemed to have imaged the sub-surface, e.g., the summation.

7.2.3 Data volume

The binning system has a database containing the location data for all the source and receiver positions at every shot point of the survey. The volume of points is correlated to the survey size and geometry used and needs careful data management. For example:

- Consider a survey area measuring 20km along the $J\ axis$ and 30km along the $I\ axis$ with cell widths of 12.5m and 25m respectively. Consequently, there are 1600 cells along the $J\ axis$ and 1200 cells along the $I\ axis$. Hence, the full-fold perimeter will comprise 1,920,000 cells.

- The SPI is 25 metres with gun arrays operating in flip-flop mode. There are 240 receiver groups in each of four streamers with RGI of 25 metres giving a total of 960 receiver groups in the spread.

- In the 20km line length ($J\ axis$) there are 800 shot points per sail line. There are 8 CMP lines per sail line, hence the interval between sail lines is 200m. Therefore, over a 30km there are a total of 150 sail lines.

- Over the Full Fold perimeter a total of 120,000 shot points will be fired whose positions all need computing and storing.

- At each shot point the position of all 960 receiver groups are computed. With 800 shot points per line there are a total of 768,000 receiver groups computed per sail line. Hence, a total of 768,000 mid-points per sail line.

- With 150 sail lines there are a total of 115,200,000 mid-points computed over the entire survey.

The fold coverage is calculated to be:

$$Fold = \frac{\frac{25 * 240}{2}}{50} = 60$$

Alternatively, it can be computed as follows:

$$Fold = \frac{115{,}200{,}000}{1920000} = 60$$

On larger spreads the numbers will rise accordingly. Assume there are ten streamers, 8100 metres in length with a receiver group interval of 12.5m. There are a total of 6480 receiver groups. However, there will only be 38 sail lines because of the swath width of 900 metres. There are still 800 shot points per sail line, given there are 6480 receiver group to be positioned per shot point means there are 5,184,000 receiver groups positioned per line. With a total of 38 lines this gives a total of 196,992,000 mid-points for the entire survey.

8 Overcoming fold contribution problems

To ensure the sub-surface is sampled correctly there needs to be an even regular distribution of seismic trace data from all possible source-receiver offset pairs across all cells of the seismic grid full fold perimeter. Seismic surveys are specifically designed to ensure a uniform geometric coverage is acquired (see section 5.3). However, on marine 3D towed surveys this presents a challenge given the dimensions of the equipment towed and the adverse environmental conditions in which the survey is performed. This frequently causes deviations from the required geometry which hampers the regularity of the fold coverage acquired.

What results is a divergence of the streamers from their intended tow pattern and a variation to their ideal streamer shape. Feathering and irregular cross line streamer separation means fold coverage is often reduced or missing altogether for some or all the source-receiver offset ranges. The effects are more evident for the mid and far group offset ranges because of the increased distance from their tow points. The size of the slithers / holes in the data coverage will vary significantly but data absence is damaging to the quality of the seismic product generated. Common environmental problems experienced include:

- Currents, tides, and rip tides hitting the streamers from a beam
- Strong currents experienced directly from ahead or astern
- Wave action experienced in moderate to poor sea states
- Wind causing increased sea state.

Deviations to streamer geometry are a major contributing factor to uneven fold coverage. Figure 149 illustrates a fold coverage plot for all offset ranges and highlights where the trace data was acquired and where it is missing. The blue colour indicates cells of the seismic grid where the desired full fold coverage was achieved, whereas the white colour indicate areas that are depleted of data, e.g., holes (null coverage areas). Other intermediate colours represent cells where the fold coverage tapers up from zero to the full fold number (null fold coverage areas). Typically, the count of fold coverage in each cell is represented by a colour coding scale defined in levels of count population, e.g. 0-10, 11-20, 21-30 coverage etc.

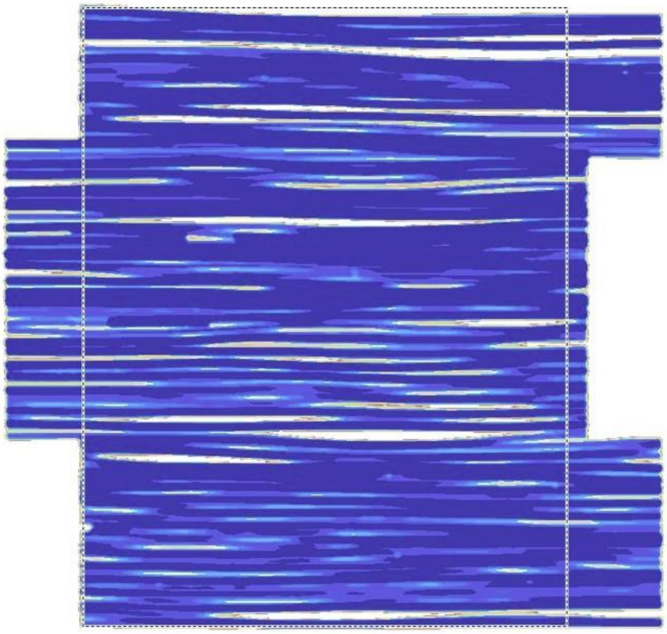


Figure 149: Fold coverage plot, all offset ranges

To achieve the finished product the areas of reduced fold coverage must be populated to fulfil the minimum required sub-surface sampling over the entire full fold perimeter (black dashed line). This requires the seismic crew to acquire additional data to make good any cells that are depleted of their full complement of hits and adhere to the contract specifications. 'Topping up' the cell count is an activity known as infill. Traditionally, this unpopular part of the survey activity can consume upwards of 20% of the survey campaign. The additional time and costs are often a bone of contention between the seismic party manager and the client's company man. However, alternative methods are available which are discussed in section 8.1.1.

The survey data shown in Figure 149 experienced prevailing currents from the north. As such it resulted in the streamers experiencing a negative feather angle on survey lines traversing along the 270^o bearing and a positive feather angle when traversing along the 90^o bearing. Figure 150 represented the vessel traversing along 270^o bearing with the streamers displaying a negative horizontal angular offset $(-\theta)$ between the azimuth of the pre-plot line (dashed blue line) and the azimuth of the deviated streamers. This results in cells belonging to the adjacent southerly swath being populated instead of those cells in the swath being acquired (see Figure 141).

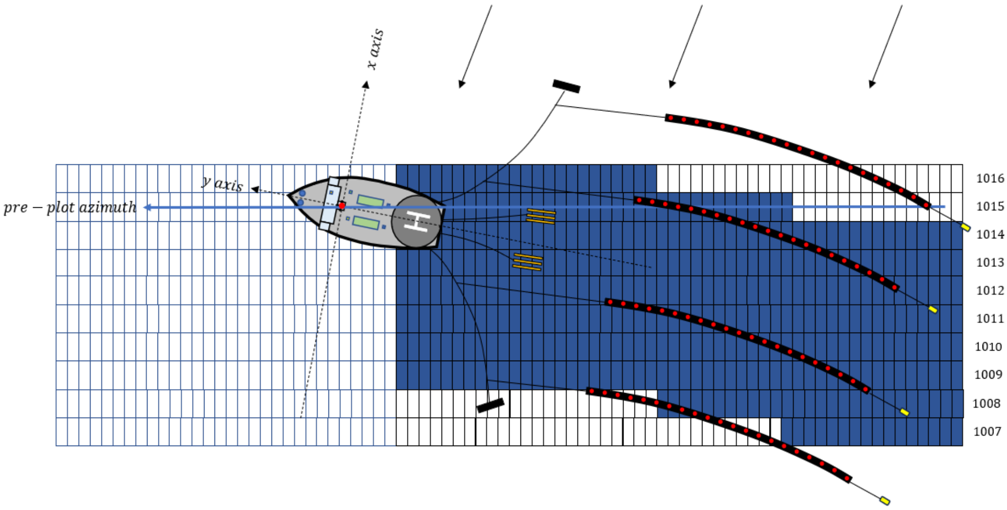


Figure 150: Feathering angle

Feathering is an occupational hazard but one that if managed correctly (see section 8.1.1.1) will have a minimal detrimental effect on the delivered product. However, if managed incorrectly, or environmental conditions make it too challenging, reduced fold coverage will result in an increase to the infill required. The decision on whether the null coverage areas are large enough to warrant an infill pass will depend upon what conditions are stipulated in the contract specification and the flexibility of the client's representative. Considerations will include factors such as:

How many adjacent CMP lines are depleted? If there is a single CMP that is missing hits in the cells it is unlikely that an infill pass will be conducted. However, where there a two / three / four or more adjacent CMP lines with missing data an infill pass will be required.

What offset ranges are missing? An assessment of what offset ranges are predominantly missing from the depleted cells is conducted from the bin coverage plots, e.g., the three receiver ensembles (nears, mids, and fars) are examined to determine the missing offset ranges. If the missing data is principally from the far offsets, it is unlikely additional data will be acquired as there are other ways to mitigate this problem (see section 8.1.1). However, if the missing offsets belong to the near or near-mid offsets an infill pass will invariably be conducted.

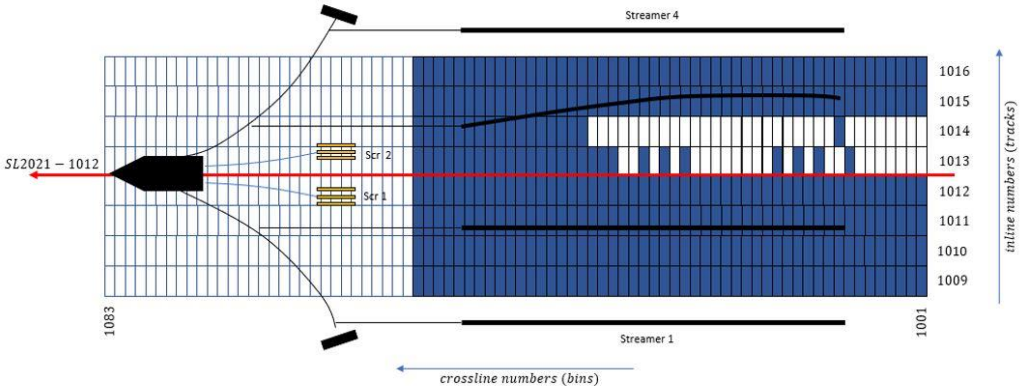


Figure 151: Streamer separation exceeding nominal geometry

Streamer deviations are not solely related to feathering. Because the streamers are towed, they often encounter unexpected events such as getting entangled with fishing nets or other marine debris. This affects the streamer(s) dynamics which may ultimately result in a convergence or divergence of lateral separation in relation to adjacent streamers. Figure 151 illustrates a separation problems with streamer 3 which has resulted in the fold coverage being diminished for CMP line 1013 and 1014.

8.1.1 Mitigating infill

There are operational procedures at the disposal of the seismic crew which are designed to enhance fold coverage and thus reduce the amount of infill experienced. The following are examples of such procedures:

- Feather matching
- Steering for coverage
- Streamer fanning and lateral streamer steering
- Flex binning

8.1.1.1 Feather matching

To counteract the issue of feathering requires the navigators to implement a process known as feather matching. This requires careful assessment of the currents and tides experienced in the vicinity of the survey area and their repeatability on consecutive days of the survey. This is monitored through the deployment of current metres within the survey area and to a lesser extent tide charts. These data establish a precise localized pattern of the daily and seasonal oceanographic variations which makes feather matching more achievable.

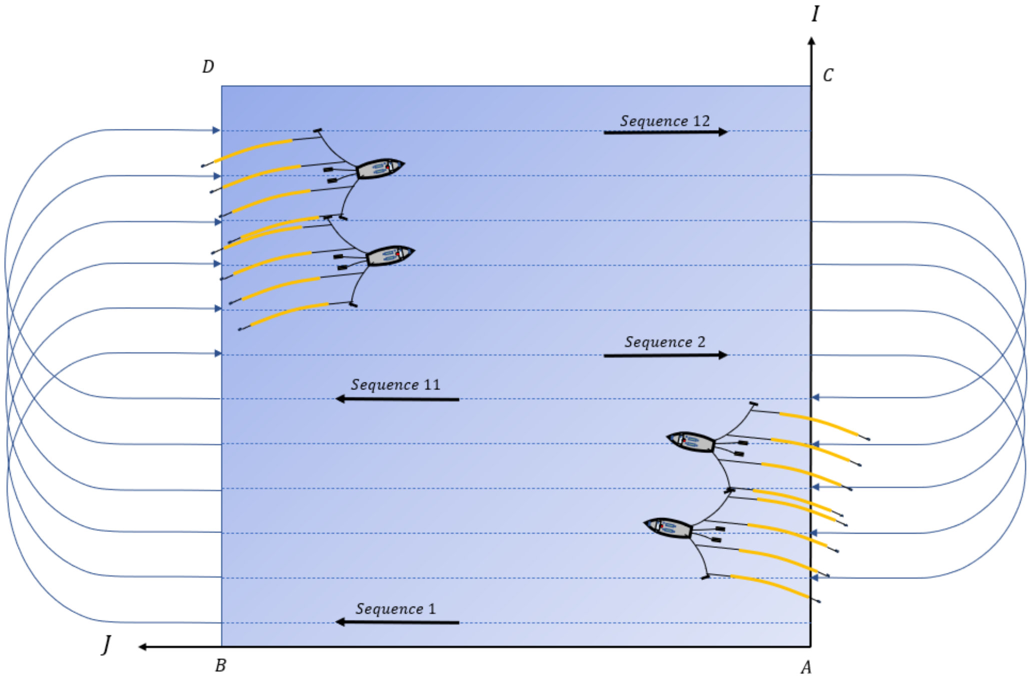


Figure 152: Feather matching, adjacent swaths

In the continued example illustrated (Figure 152), the predominant current is from the north. Therefore, the streamers feather to port (negative) when acquiring lines on the westerly orientation (270^o) and to starboard (positive) when acquiring lines on an easterly direction (90^o). For now, assume that the current is constant and the effect on the streamers is the same for all sequences. Consequently, the amount of feather experienced during sequence 1 should match that experienced on sequences 3 and 5 etc., and vice versa for sequences 2, 4 and 6 onwards. Hence the magnitude of feather angle experienced by each streamer should match and thus the amount the mid-points for the longer offsets intrude into the adjacent southerly swathes.

Performed correctly, the cells delinquent of certain source-receiver offset pairs from the previous swath will be populated from the next adjacent line acquired along the same azimuth. The navigators endeavour to repeat the pattern for all swathes acquired along the same orientation (e.g., P1, P3, P5 etc.) by applying the required lateral offset and have the vessel steered accordingly to match the pattern illustrated in Figure 153. This is feather matching and when properly executed will reduce the amount of infill the seismic crew are required to perform.

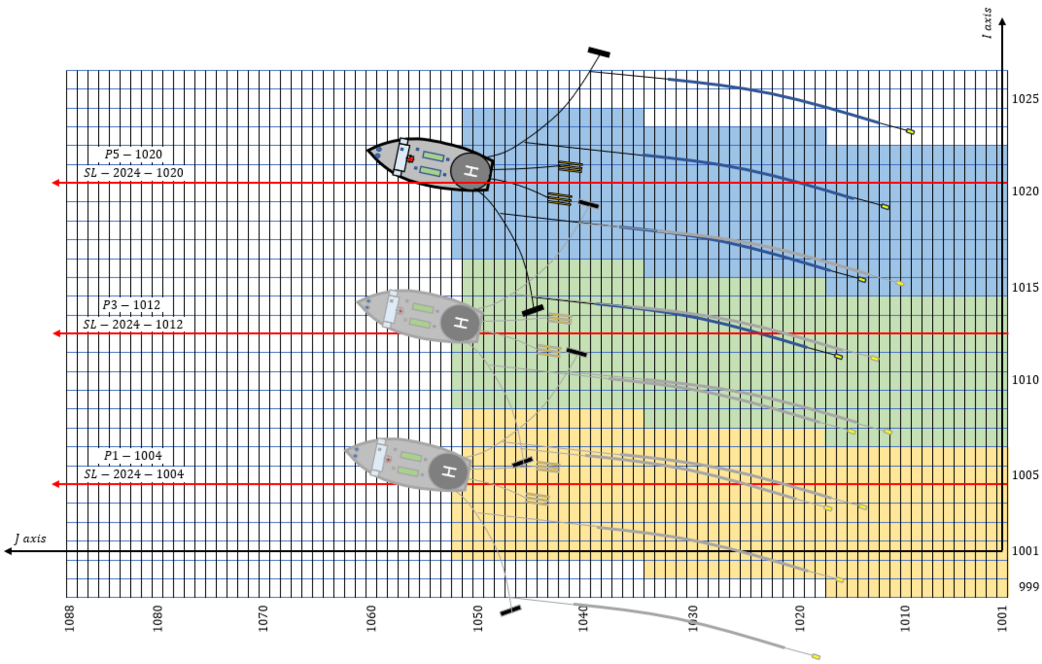


Figure 153: Feather matching between swathes

Sequence numbers indicate the order in which the seismic lines were acquired. The primary sequences (P10, P12 etc.) are those acquired along the original pre-plot lines. These numbers do not have any direct relationship to the names of the pre-plot lines. They are simply an integer to track their order within the acquisition program. Reshoot lines and infill lines are usually prefixed with R and I accordingly.

As an extreme example, feather matching could also be achieved by only acquiring lines along one azimuth (e.g., 270^o) at the same time of day when a similar current is most likely to the encountered. This is impractical because of the expense of having the vessel on standby without acquiring any data. Following the designed pre-planned racetrack optimizes acquisition but can result in slithers of missing data between swaths. This is a trade-off between time versus reduced fold-coverage levels.

8.1.1.2 Steering for coverage

This is a bit of a misnomer because if feather matching is applied then this concept, in theory, becomes absorbed in that procedure. From a geophysical perspective the approach is this: The target depth is such that the predominant returning signals will be recorded by the mid groups. With the streamers experiencing feather the helmsman is requested to steer a course such that the source-receiver offset pairs involving the mid groups are acquired along the CMP lines to which they would belong assuming the streamers were experiencing zero feather.

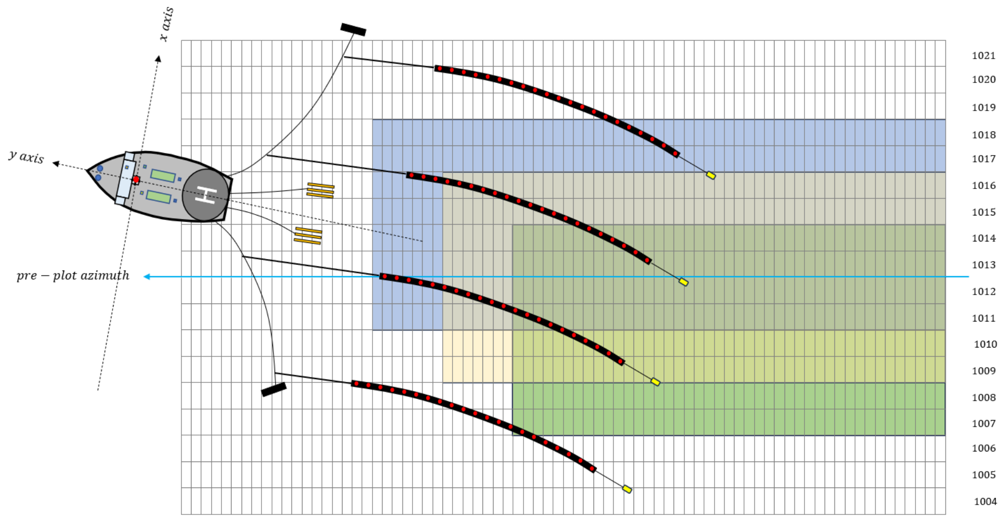


Figure 154: Steering for coverage

In Figure 154 these mid-points are shown in the yellow rectangle. If steered correctly they will populate the CMP lines equally spread either side of the pre-plot line shown in light blue. By steering this way, the mid-points recorded for the nears will be acquired in the CMP lines to the north (blue cells) of their intended track and those associated with the far groups to the south (green lines).

8.1.1.3 Crabbing

When streamers experience feathering the helmsman compensates by steering the bow of the vessel into the prevailing current. This creates an angular difference between the heading reported by the vessel's gyrocompass and the bearing of the pre-plot line. This is known as the crab angle, so called because the vessel appears to have a slight sideways motion as it traverses along the sail line. The crab angle is positive when the vessel bow is steered to starboard and negative when steered to port. Figure 155 illustrates a positive crab angle. One effect of a positive crab angle is that the starboard paravane (diverter) will increase its y offset in relation to the vessel, whilst the port paravane will decrease its y offset. Therefore, the y offset of streamers 3 and 4 will increase and the y offsets of streamers 1 and 2 will decrease. This has a slight skew effect on the cells of the seismic grid being populated. This is highlighted in Figure 154.

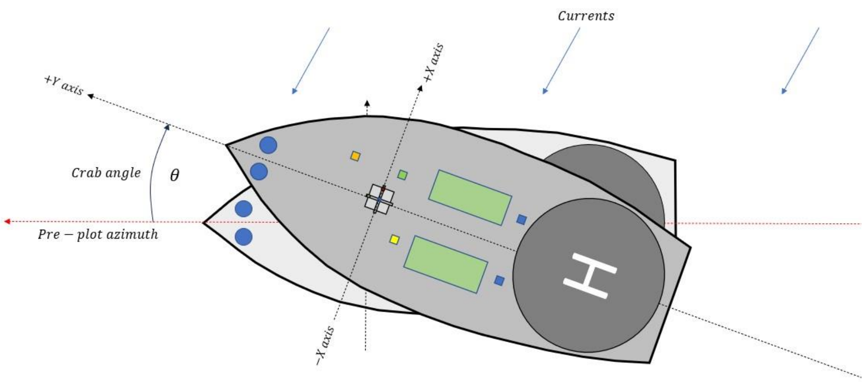


Figure 155: Crab angle of vessel

8.1.2 Trace data frequency characteristics

The final three processes (fanning, steering, and flexing) were devised to be sympathetic to the signal bandwidth and wavelength characteristics of the recorded returning energy at the far receiver groups. Without side tracking too much into the geophysics it is important into introduce four concepts because of their link to these procedures. Namely:

- The characteristics of the source signature
- Frequency attenuation due to the inhomogeneity of the Earth
- Vertical seismic resolution
- Horizontal seismic resolution

8.1.2.1 Source signature characteristics

The most popular seismic source operated on marine seismic surveys is known as the airgun. Over time many other devices have been developed, but the airgun remains the most popular and reliable. It comprises two main chambers, an upper chamber and a lower discharge chamber between which is a shuttle assembly (light green) as shown in Figure 156. At the top are two external connectors. The left hand one is an air hose which feeds the airgun with compressed air generated by compressors located on-board the seismic vessel. The right-hand one is an electrical cable down which is sent an electric pulse to a device called the solenoid which triggers the airgun to discharge its compressed air at a designated geo-spatial position (shot point).

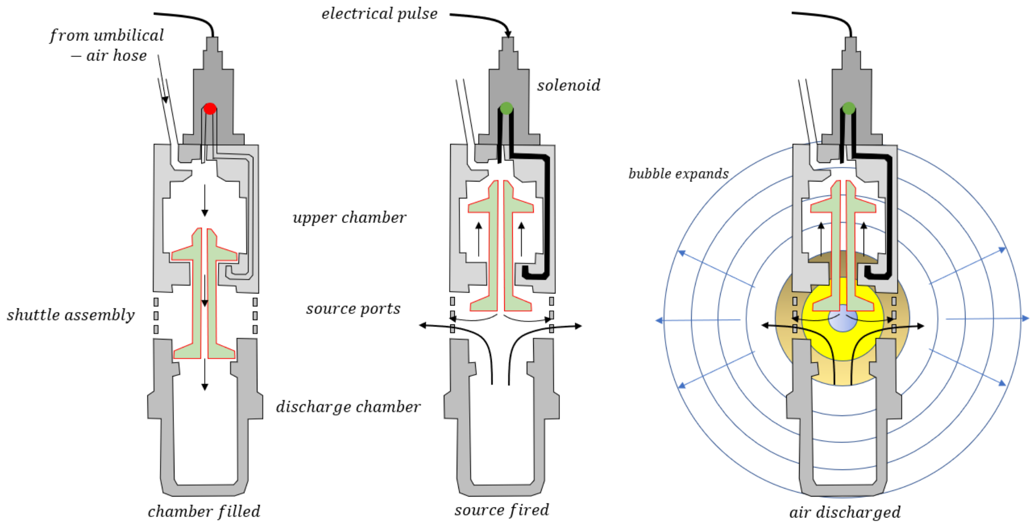


Figure 156: Marine source firing

How does this device generate the acoustic signal?

- First*: The airgun is charged with compressed air, usually to a pressure of 2000 pounds per square inch (psi or 138 bar). Initially the upper chamber is filled and then the lower discharge chamber through a conduit in the shuttle assembly. The black vertical arrows in the left-hand side of Figure 156 show the basic flow of the compressed air.

  **The seismic array (see section 7.1.2.1.) comprises multiple airguns that discharge their energy simultaneously which creates a combined air bubble.*

- Second: Once the airgun is fully charged an electrical pulse is sent to the solenoid from the gun control system when the source array reaches the next pre-plot position. This opens a port which allows the compressed air to flow to the underside of the shuttle assembly through the black conduit illustrated in the middle diagram.

- Third: As the shuttle assembly is violently forced upwards the compressed air in the discharge chamber escapes through the source ports. This process takes approximately 2 milliseconds to complete allowing the air to escape very rapidly.

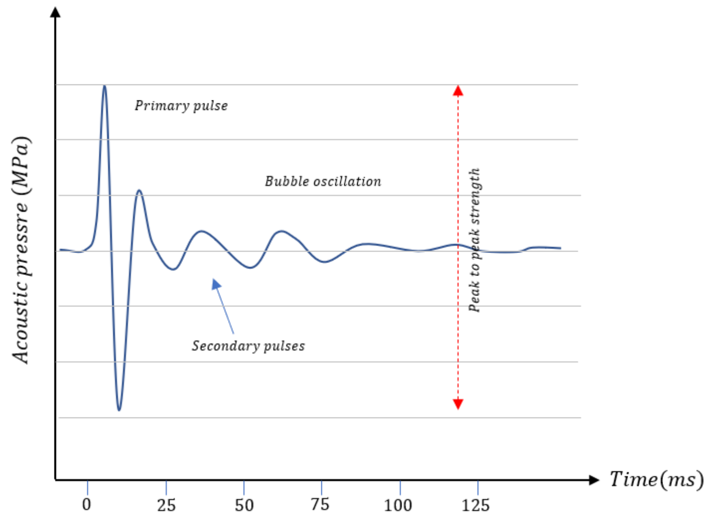


Figure 157: Source signature - air gun array

- Fourth: As the air escapes into the surrounding water column, it creates a bubble which rapidly expands outwards until it reaches and exceeds the pressure equilibrium of the surrounding environment. When the internal bubble pressure exceeds equilibrium with the adjacent water pressure it collapses to create the acoustic spike (Figure 157), which in its perfect form resembles a Dirac function. The bubble size dramatically shrinks until its internal pressure again becomes far higher than its surroundings and the expansion process repeats. The later iterations are heavily dampened which is shown by the gentle ripples after the main spike. This oscillation continues until the bubbles frictional forces deplete sufficiently.

- Fifth: The acoustic wave moves omni-directionally away from the seismic source predominantly in a downward direction. The wave front that propagates upwards is reflected off the sea surface and then begins its downward path but with a reversed polarity. This results in the reflected wavefront destructively interfering with the wavefront that was originally propagated downwards. This is known as source ghosting with the resulting interference creating a notch frequency in the frequency spectrum of the source signature.

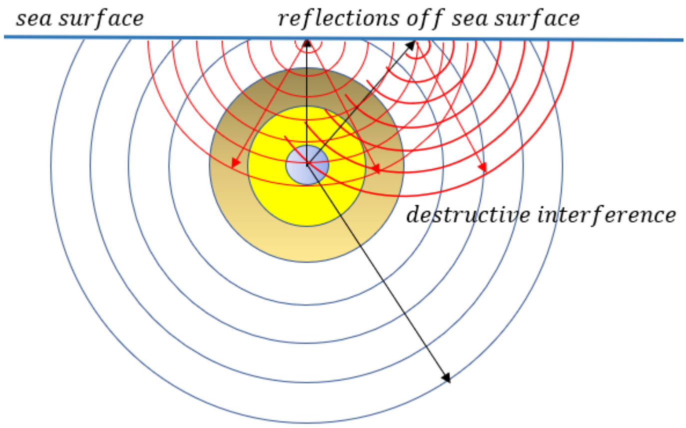


Figure 158: Source ghosting

Associated with the source signature is a frequency spectrum which illustrates the range of frequencies contained in the signal. Typically, frequencies range from 1 Hz to approximately 225 Hz but is dependent on towing depth and the design of the tuned array. Shown in the spectrum is the notch caused by the source ghosting effect.

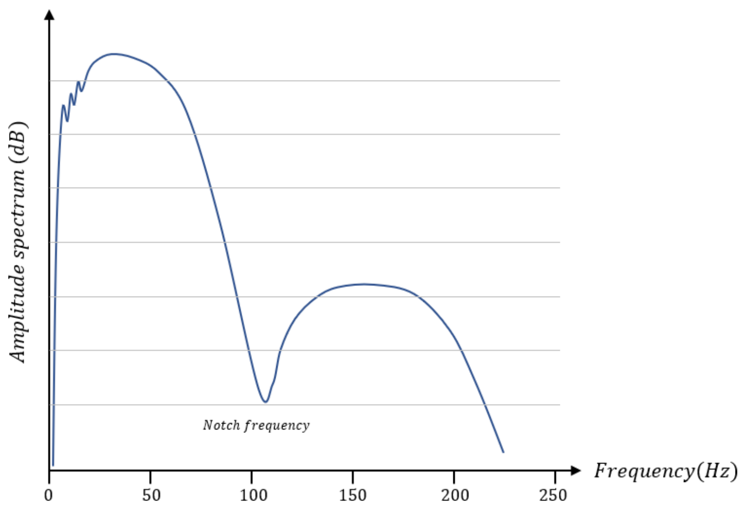


Figure 159: Frequency spectrum

The location of the notch frequency in the spectrum is also a function of the source depth. The shallower the depth is towed the higher the notch frequency. This is why high resolution seismic surveys tow their sources at a much shallower depth (approx. 2-3 metres) compared to deep seismic. The useful 'seismic' frequencies of the spectrum are those prior to the notch frequency and in recent decades source array designs have advanced to help eliminate the notch frequency and increase the bandwidth of the signal with higher frequencies. When the source signal is generated, it has maximum signal amplitude (strength), kinetic energy, and bandwidth plus minimum wavefront and wavelength. The general characteristics of the seismic wavelet include the following attributes: Amplitude, period and wavelength.

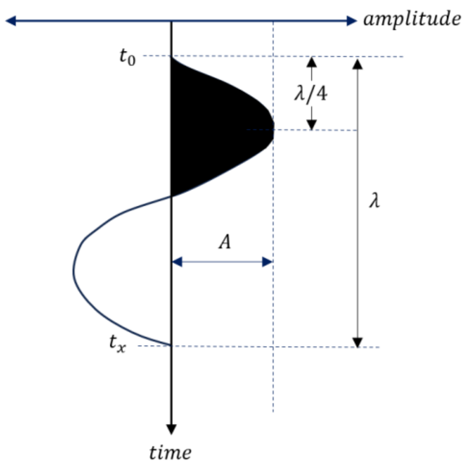


Figure 160: Wavelet attributes

The period (P) is the time taken for the wave to complete one full cycle $(t_x - t_0)$ from which the signal frequency is calculated:

$$f = \frac{1}{P}$$

The pulse length or wavelength is computed from the following where the velocities are those values taken from Table 12.

$$\lambda = \frac{V}{f}$$

Finally, the equation associated with depth is given by:

$$distance\ (depth) = \frac{V * T}{2}$$

These represent the three basic equations applied throughout the remainder of this section.

8.1.2.2 Earth characteristics

The sub-surface comprises multiple inhomogeneous rock strata which when associated with hydrocarbon exploration typically belong to a sedimentary basin. Each rock type has specific properties such as density, fluid content, porosity, texture and grain size that determine at what rate an acoustic signal will propagate (velocity) through that layer. Some typical examples of rock type densities (Sharma, 1997) and their velocities include:

Table 12: Sample rock characteristics

Type	**Density (kg/m^3)**	**Velocities (m/s)**
Sand	1.6 - 2.0	1800 – 2000
Sandstone	2.2 - 2.55	2000 – 3500
Limestone	2.5 - 2.8	3500 – 6000
Shale	2.2 - 2.5	1100 – 1800
Compacted shales	2.65 - 2.75	1700 - 2500

One physical characteristic (derived from the rock type properties) of specific importance to the seismic reflection technique is known as acoustic impedance (I) which is computed using the rock density (ρ) and the propagation velocity (V):

$$I = \rho V$$

For example, the acoustic impedance for a limestone layer, with a velocity of 3500m/s, will range between 6.250 to 9.8 $Pa.s/m^3$. Velocity of propagation is normally higher for greater compaction (usually with depth) and density. However, the texture of the rock and grain size (porosity) also contribute. Texture relates to the mineral content (e.g. quartz, silica etc) and grain size relates to rock type, e.g., sandstones have larger grain size than shales, thus the friction the wave experiences during propagation. At each layer boundary there is likely to be an acoustic impedance discontinuity caused by a density contrast between the strata above and below that boundary. The contrast is described using a variable known as the reflection coefficient (R) which for a compressional wave is computed as follows:

$$R = \frac{I_2 - I_1}{I_2 + I_1} = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

Because of the density contrast it impacts the transmission of the acoustic seismic wave such that at each boundary a percentage of the wave energy is reflected back to the surface and the remainder propagated through to the layer below (Figure 161). *This is the basic principle behind the reflection seismic technique*. The greater the contrast in acoustic impedance the greater the reflection coefficient and thus the more energy is reflected off the boundary. This is also treated as a resistivity or a ratio of resistivities. The value of the reflection coefficient can be negative or positive depending on the density and velocity of the rocks straddling the boundary. When negative it creates a phase inversion in the seismic wave.

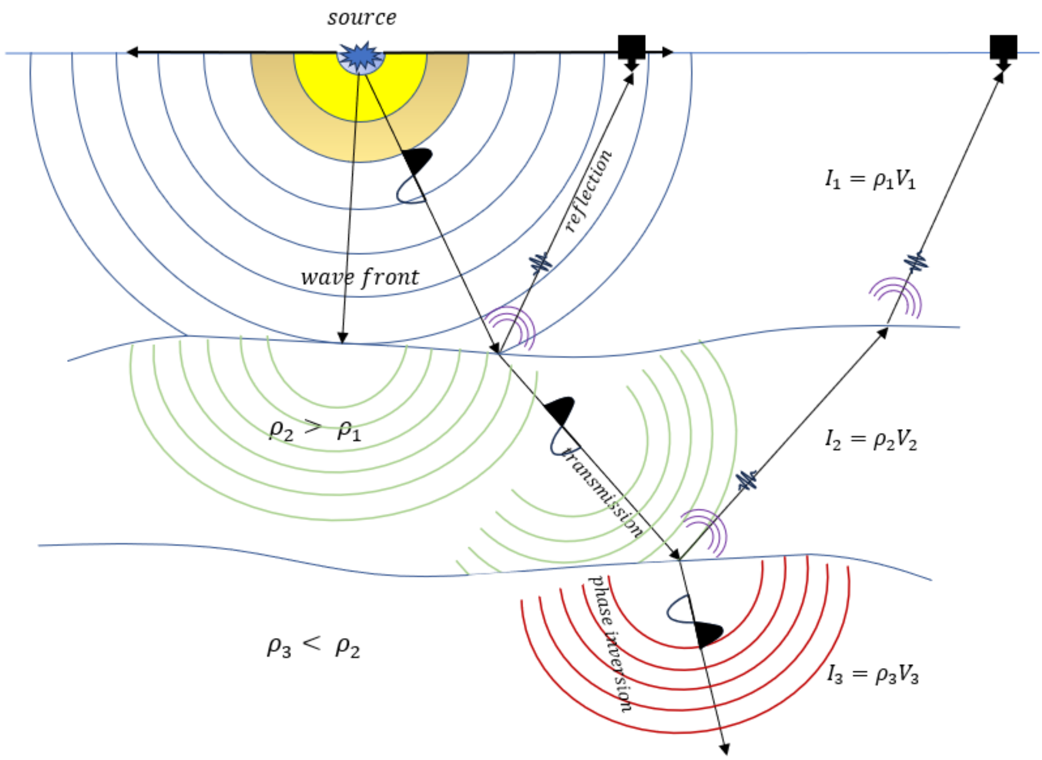


Figure 161: Acoustic impedance and reflection coefficient

In Figure 162 four rock layers are shown with their respective acoustic impedance values which are also illustrated in the vertical step graph immediately to the right. At each of the three boundaries the reflection coefficient is calculated as shown. For narrative purposes (only) at the first boundary this is interpreted as 0.148% of the wave energy is reflected back to the surface whilst 99.852% of the energy is transmitted to the next layer. The relatively small amount of reflected energy enables the signal to penetrate thousands of feet into the sub-surface before friction fully absorbs the wave energy. This allows deep targets to be imaged by the reflection seismic method.

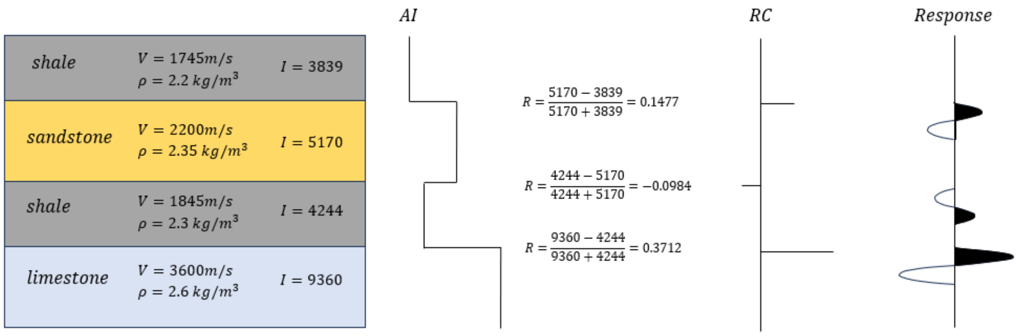


Figure 162: Impedance, reflection coefficient and response (minimum phase)

On the right hand side of Figure 162 is the seismic response, which is generated by a process called convolution, where the seismic wavelet is multiplied with the reflection coefficient. In its natural form it is a minimum phase wave which is the physical response from the Earth. It comprises two distinct parts known as the peak (black area) and trough (white area), where the maximum amplitude of the peak occurs $\lambda/4$ of the wavelength after the energy reaches the interface (first break). If the reflection coefficient is positive the peak occurs before the tough whilst for a negative value, the polarity is reversed with the trough occurring before the peak.

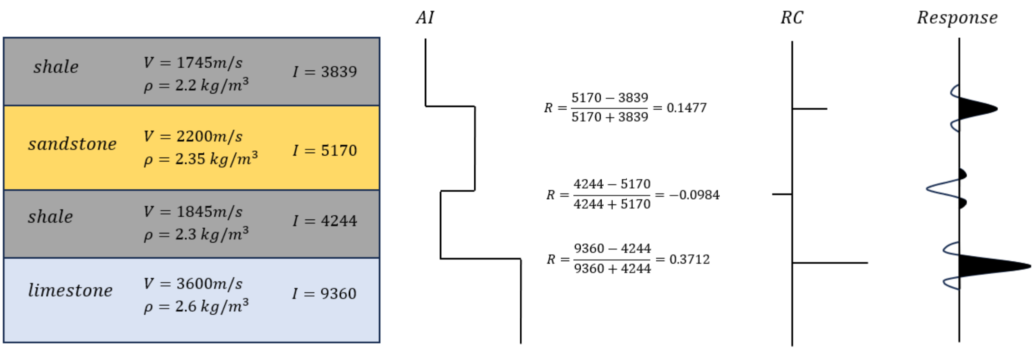


Figure 163: Impedance, reflection coefficient and response (zero phase)

An alternative convention of representing the wave is as a zero phase wavelet as represented in Figure 163 which is generated by performing a Fourier transformation on the minimum phase wavelet during seismic processing. The characteristics of the zero phase wavelet are the pre and post cursors either side of the black peak to create a symmetrical wavelet. For further details on the pulse duration, wavelength and bandwidth of the wavelets see section 8.1.2.4 where its effects on the vertical resolution and the ability to resolve the tops and bases of individual geological layers is described.

8.1.2.3 Signal attenuation

As the acoustic seismic wave propagates into the sub-surface its properties begin to change. Notably, modifications occur to the spreading of the wavefront, pulse broadening (pulse duration), loss of signal amplitude and frequencies (band width) through the process of absorption. Although the water column, regardless of depth, absorbs little of the acoustic energy the same cannot be said of the seabed and geological rock strata below. Collectively, energy dissipated with increased depth is known as signal attenuation and it is broadly divided into three categories. The first two are known as elastic and anelastic attenuation which result from signal scattering and signal absorption respectively. The third is known as geometric spreading of the seismic wavefront as it propagates downwards.

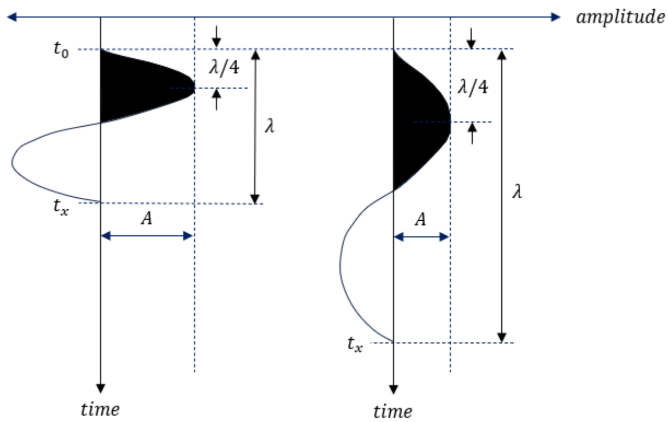


Figure 164: Changes to seismic wavelet

In general:

- Frequencies (bandwidth) are mainly lost by the scattering of the seismic energy due to the inhomogeneous nature of the Earth and also the presence of liquids in the rock formations. This is known as elastic attenuation.
- Amplitudes are reduced due to internal friction as the wave propagates through the rock formations. Energy is converted to heat owing to friction which is attributed to grain size. This causes the seismic pulse to broaden and amplitudes to be reduced. In is known as anelastic attenuation.

- As the wave propagates the wavefront naturally increases as a result of geometric spreading. As each part of the wavefront contacts a boundary another it created in accordance with Huygen's principle. Therefore, its kinetic energy becomes thinned out across the dimensions of the wavefront and thus becomes more susceptible to energy absorption at each boundary.

Attenuation is measured using the Q factor (rock quality factor) which is a unitless quantity measuring the ratio between the amount of energy stored by a rock to that which is dispersed and is thus a measure of energy loss. In essence the amount of energy lost is a factor of the frequency (wave cycles) and the amount of energy lost per cycle is described by:

$$Q = \frac{2\pi E}{\Delta E}$$

Where:

Q = Amount of attenuation

E = Energy dissipated

Therefore, signal attenuation is a measure of how much the amplitude, frequency content (bandwidth), pulse duration and wavelength of the returning energy has decayed during propagation due to the seismic pulse(s) being broadened, scattered and dispersed. These effects are intrinsically linked to the depth of the reflecting boundaries, two way travel time, and rock types (within the frequency spectrum) of the returning energy.

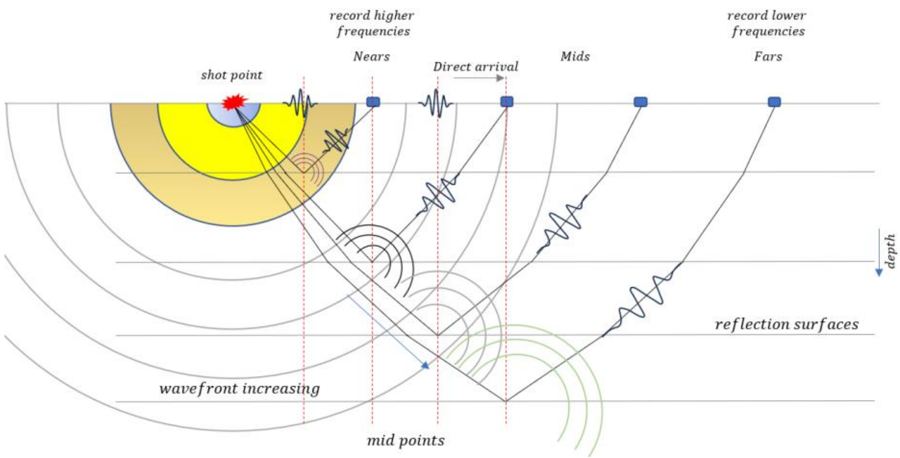


Figure 165: Frequency attenuation

Consequently (see Figure 165):

- Energy reflected from shallower geological boundaries has a shorter two-way travel time and experience less seismic attenuation. They have shorter wavelengths (pulse duration) and are richer in higher frequencies (higher bandwidth) and are observed by receivers located closer to the shot point. In this form they more closely resemble their original spike appearance.
- Energy reflected from deeper geological boundaries has a longer two-way travel time and therefore experiences more seismic attenuation. They have increased wavelengths (pulse duration) are richer in lower frequencies (lower bandwidth) and are observed at receivers located further away from the shot point. The returning pulse does not resemble the origin spike.
- Because of lost energy, increased wavefront, reduced bandwidth and amplitude, leniency can be applied with respect to the geometry and cell dimensions associated with the longer source-receiver pairs.

8.1.2.4 Vertical seismic resolution

The perfect seismic response is where all geological strata down to a few metres in thickness have their tops and bases identified by the recorded seismic trace data. If the seismic pulse retained a high bandwidth and short duration period it would always resemble a spike and the tops and bottom of all formations, regardless of thickness, would be imaged. In reality this never happens because of seismic attenuation the seismic pulse experiences which reduces its bandwidth, whilst increasing the pulse duration and wavelength.

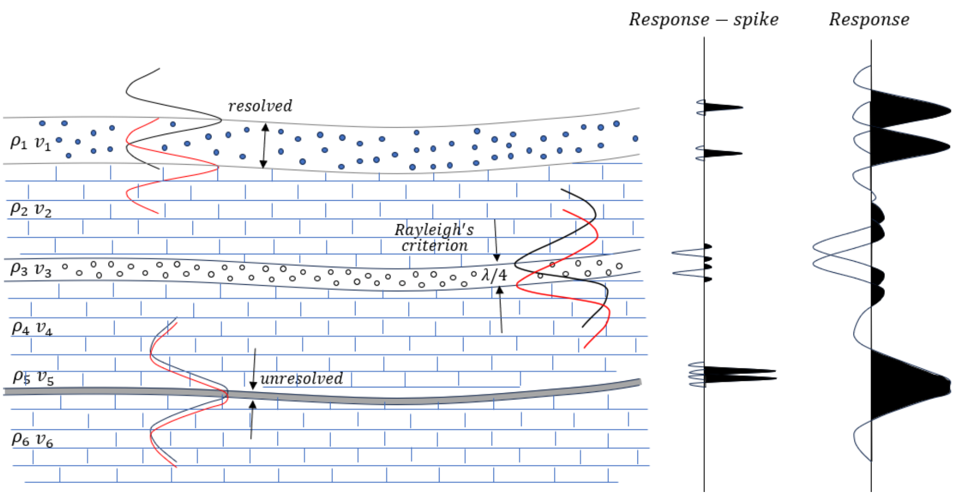


Figure 166: Resolved and unresolved boundaries

These modifications remove the ability of the pulse to identify the top and bottom boundaries of thinner geological layers. As such there is a limit to the thickness a geological layer must reach (dz) before both its top and bottom reflections are distinguishable in the recorded trace data. This property, which changes with travel time (depth) is known as the vertical seismic resolution. It is not only influenced by the wave characteristics but also the wave shape, i.e., whether it is minimum phase or zero phase where the latter has a smaller wavelength.

For the bespectacled amongst us it is akin to taking an eye test at the optician. The larger letters on the upper part of the wall chart are easy to identify. But as the letters become progressively smaller you reach a cutoff point where it is no longer possible to distinguish between the smaller font letters. Take this one step further by increasing the distance between yourself and the wall chart (increasing depth). The further back you stand the higher the cutoff point.

Figure 166 illustrates the seismic pulse reflecting off geological layers of varying thickness. Given the modifications to the seismic pulse (with depth), can two reflections, one off the top and one of the bottom of the layer be distinguished such that thickness of the layer be determined during interpretation? What thinness must the layer reach (at the depth it occurs) before it becomes indistinguishable? Hence, the vertical resolution (dz) describes the level of detail with which the sub-surface can be imaged. When the two recorded reflections do not overlap, i.e., their two way travel time has sufficient separation to distinguish between the top and bottom reflectors which is known as being resolved. However, when the travel time of the reflections start overlapping, interference occurs (both constructive and destructive) resulting in top and bottom signals blending and taking on the appearance of one reflection with an unresolved thickness. For the top and bottom reflections to be identified individually the recorded data it must comply to the Rayleigh Criterion which states that in order to distinguish between two reflecting surfaces their separation (dz) must be greater than ¼ of the wavelength of the pulse at the depth of observation.

$$dz = \frac{\lambda}{4}$$

This is a function of the bandwidth of the signal and the amount of attenuation the acoustic wave has experienced up to that reflection interface (depth). As the wavefront of the signal gets larger (with depth) signal wavelength (λ) increases and bandwidth decreases leading to a decrease in the resolution with which rock sequences can be determined. Consequently, as travel time and depth increase the thickness of the rock strata must increase before it complies with the Rayleigh Criteria. A layer 20 metres thick at a shallow depth can be resolved but the deeper the layer the chances of it being unresolved significantly increase. This is illustrated in Figure 167 with the resolution in the shallows being considerably better than that experienced with increased depth.

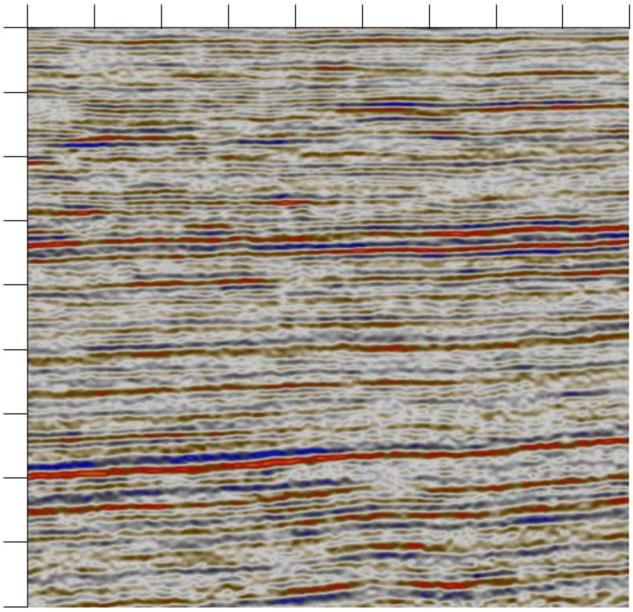


Figure 167: Resolution change with depth

Some examples of the thickness a layer must attain before it can be resolved is shown for two different depths. Entering parameter values into the equations given previously provides an indication of the Rayleigh Criteria at these depths, which are distinguished by the velocity of propagation and dominant frequency bandwidth.

Velocity = 1600 m/s

Bandwidth = 40 Hz

$$\lambda = \frac{1600}{40} = 40.0m$$

$$dz_{min} = \frac{40.00}{4} = 10.00m$$

Velocity = 2500 m/s

Bandwidth = 20 Hz

$$\lambda = \frac{2500}{20} = 125.00m$$

$$dz_{min} = \frac{125.00}{4} = 31.25m$$

Therefore, there must be a minimum separation of approximately 31m between the peak of the two reflectors ($\lambda/4$ wavelength) before they can be individually distinguished from the seismic trace data. What is clearly shown though is that as depth increases so must the thickness of the strata sequence before its top and base can be resolved by the seismic trace data.

8.1.2.5 Horizontal seismic resolution

When the main wavefront contacts a boundary, a new wavefront is created for each sample interval following Huygens principle as illustrated in Figure 168. This means multiple reflections are returned off the reflecting surface which are detected back at the surface.

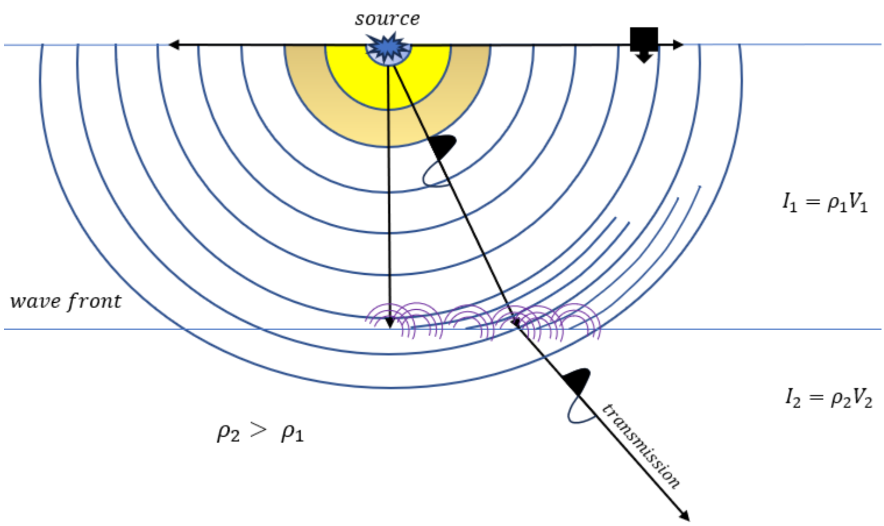


Figure 168: Huygens principle applied to main wave front

Provided the arrive time of the reflected energies is less than half a wavelength different ($D\ to\ D + \lambda/4$) they will constructively interfere and appear as one coherent single arrival. Therefore, the energy does not belong to a single point but from an area or zone which is known as the Fresnel zone. When determining the size of the Fresnel zone the horizontal seismic resolution is being defined. Reflections from outside the zone will interfere in repeated destructive and constructive bands.

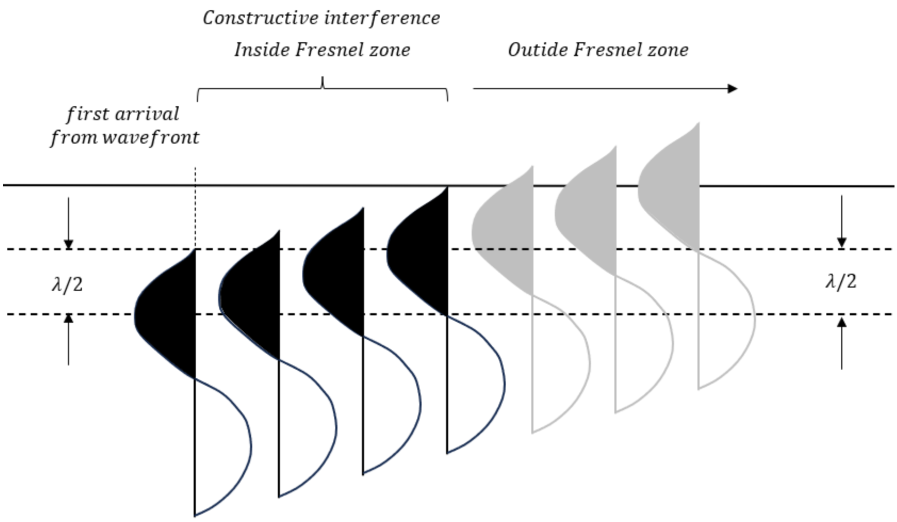


Figure 169: Coherent interference of the returning energy

Figure 170 shows the Fresnel zone footprint for a simplified version where there is zero offset and homogeneous layer. This approach has no real practical purpose other than to illustrate the relationship between depth, wavelength, time and footprint size (zone). The larger the wavelength of the pulse the larger the zone from which the constructive coherent reflected energy are returned and the lower the horizontal seismic resolution. Therefore, the dimension of the Fresnel zone will increase with depth and the pulse wavelength as it is a function of frequency and velocity.

Using Pythagoras:

$$D^2 + r_Z^2 = (D + \frac{\lambda}{4})^2$$

$$r_Z^2 = (D + \frac{\lambda}{4})^2 - D^2$$

$$r_Z = \sqrt{(D + \frac{\lambda}{4})^2 - D^2}$$

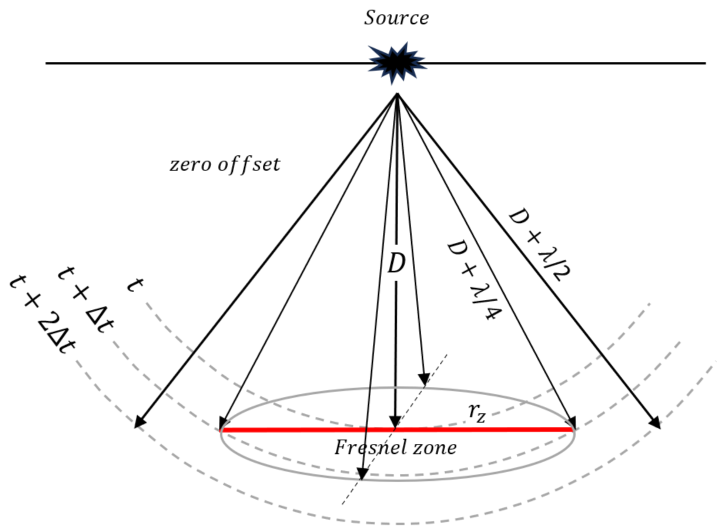


Figure 170: Fresnel zone footprint

If the velocity of travel is 2500m/s and the bandwidth is 20 Hz when the wavefront encounters a reflecting surface at depth of 3000m, the radius of the Fresnel zone will be:

$$\lambda = \frac{2500}{20} = 125m$$

$$r_Z = \left(3000 + \frac{125}{4}\right)^2 - 3000^2 \approx 435m$$

Although these dimensions appear large, they are significantly reduced in seismic processing through the application of the migration algorithm which has the effect of lowering the hydrophones though the Earth to coincide with the reflector. The Fresnel zones become reduced to small circles provided there is sufficient data from a similar sized zone on the surface, i.e., the geo-spatial distribution of receivers on the surface must be equal to the minimum of the Fresnel zone in order to reduce the reflected data to a point feature off the reflecting event.

8.1.3 Fanning and flexing

Energy reflected from deeper geological boundaries are observed at the mid-far and far receiver groups which are located furthest away from the shot point. As their two-way travel time is longer the trace data experiences more seismic attenuation resulting in increased wavelengths (pulse duration) and reduced bandwidth. To digitally preserve waves with lower frequencies requires a lower sampling rate to still meet the condition of the Nyquist frequency thus preventing aliasing.

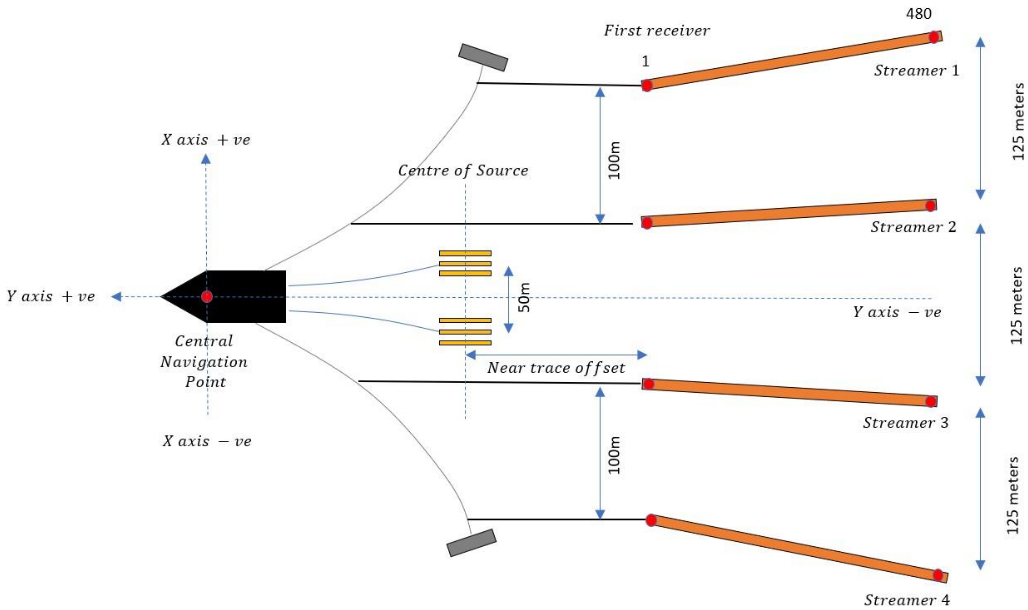


Figure 171: Fanning the streamers

Relaxing the geometric separation between the receivers at the far groups will have no detrimental effect on the trace data given the wavelength and bandwidth in the signal expected. Consider the arrangement shown in Figure 171 which is known as streamer fanning where the horizontal crossline separation between the streamers at the mid-fars and fars is increased from that of the nears, hence creating the appearance of a fan. If the streamer separation is one hundred metres at the near traces this gradually increases to a percentage value of the near trace separations, e.g., 125% or 150% at the far offsets.

Devices fitted along the length of each streamer provide a mechanism of manoeuvring the streamers to this desired offset during acquisition. This makes the streamers steerable, which offers the following advantages:

- To ensure that the streamers geometry is as close to the nominal offsets are possible when deployed normally

- Streamers do not naturally fan and when operated in fan mode they are required to maintain a gradual increase in lateral horizontal separation from near to far trace
- When the streamer depth is deliberately varied from near trace to far trace to be towed with an increased slant.

As these devices are equipped with motors that drive the birds' wings (to affect the movement), they do create noise that can interfere with the seismic trace data. Therefore, it is undesirable to have them working overtime to ensure the interference is kept to a minimum.

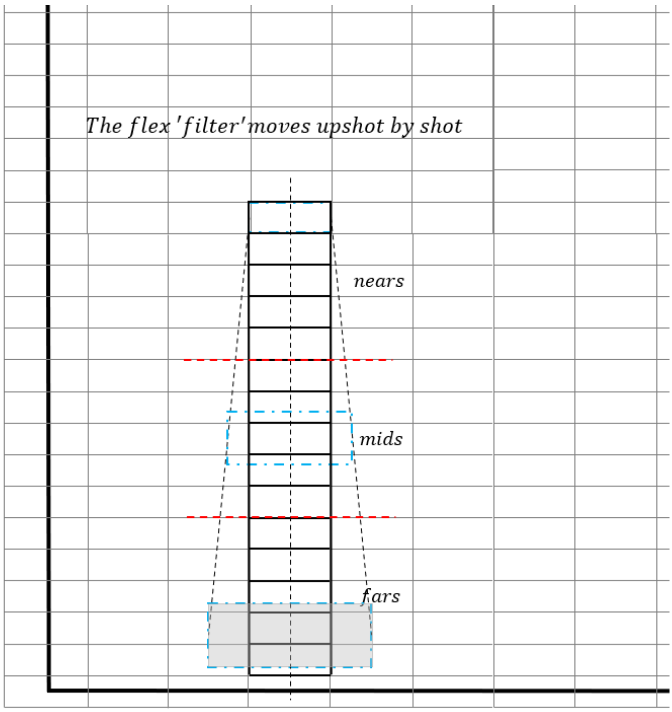


Figure 172: Flexible binning

With the streamers operating in fan mode it is natural to assume it would have an adverse effect on the fold coverage acquired for the far offsets. To overcome this another procedure is applied known as flex binning (flexible binning) which counteracts the problem. It is sympathetic to the fan mode geometry and bolsters the fold contributions of mid-fars and far receiver groups. This requires a deliberate increase in the nominal dimensions of the cells, typically along both the I and J $axes$ of the seismic grid. For example, cell widths that were set to a width of twenty-five metres would be extended by the same percentage increase applied in fan mode to increase their sizes (e.g. by half a cell width to 37.5 metres). As a new larger footprint has been created it automatically increases the fold coverage for the far offset ranges by including all source-receiver offset pairs that would otherwise be restricted to adjacent cells of the seismic grid.

If the dark blue area represents the dimensions of the original cell size (e.g., I = 25m and J = 12.5) the fold coverage contributed by the far receiver groups is eighteen. However, by increasing the dimensions by 50% in both the $I\ axis$ and the $J\ axis$ the cell size is amplified (e.g., I = 37.5m and J = 18.75m) and the fold contributions are increased to thirty-six, which represents a rise of 100%. Obviously, as the dimensions of the cells are further increased the fold coverage will also grow. It is by this mechanism that the fold coverage can be improved such that the number approaches the desired full-fold coverage required.

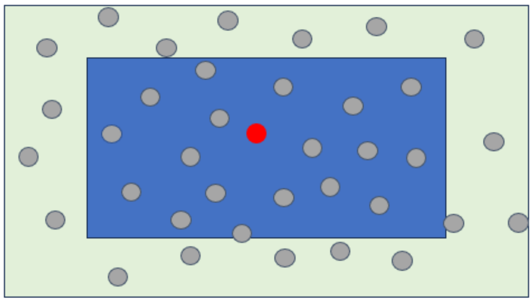


Figure 173: Flexing cell size to increase fold count

This process will improve the signal-to-noise ratio of the final seismic trace, as there are significantly more traces contributing to the gather. This is despite the traces being gathered from a more lenient geometric footprint. However, given the dimensions described for the Fresnel zone these cell dimension increases are very modest. In a later addition of this chapter the process concerning Fresnel Zone Binning will be introduced which will fully justify the leniency which can be applied to the positioning precision of the sources and receivers without having a detrimental effect on the seismic trace quality.

If the flex binning is not applied the fold coverage can still be improved by acquiring more infill lines using the standard lateral offsets. Either way, more cells of the seismic grid are displayed in the colour reflecting that the minimum level of fold coverage has been reached. An example of this is illustrated in Figure 174 for the same survey shown in Figure 149. However, there are cost implications of acquiring further data using the traditional infill approach versus flexing the cells.

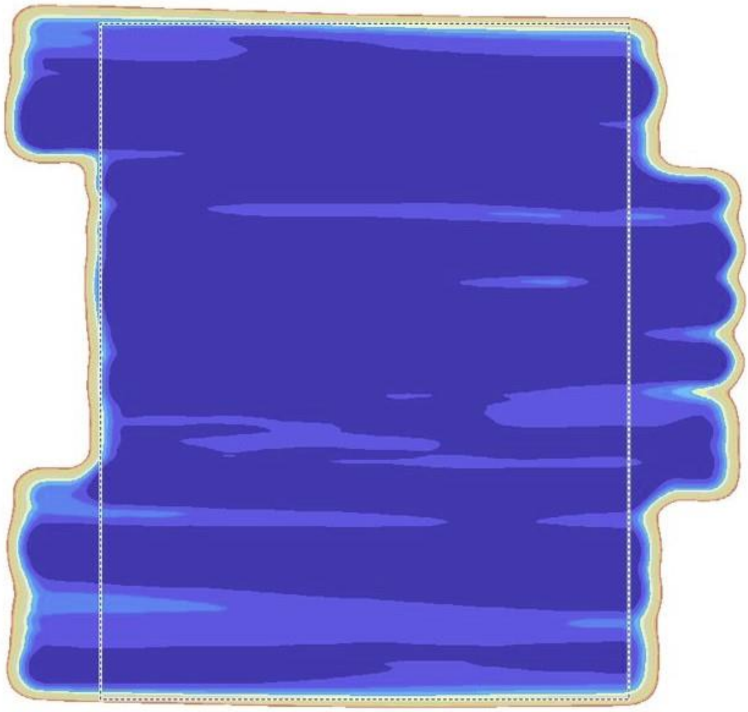


Figure 174: Fold coverage plot - after infill

The binning module generates coverage plot used by the QC geophysicist to examine the contribution to fold coverage from the different offset ranges, e.g., Nears, Mids and Fars. For example, with the streamer containing 480 groups, the first 160 will belong to the Nears, the next 160 to the Mids and the latter 160 belonging to the Fars. With the sources operating in flip-flop mode and a shot point interval of 25 metres (port source firing every 50 metres) the maximum fold coverage contribution from the Nears will be 20, which is mirrored by the Mids and Fars, giving a maximum total fold of 60. Coverage plots that illustrate the fold coverage from the different offset groups will provide sufficient evidence the required levels have been achieved.

8.2 Live Trace Outline

As described in section 4, one perimeter generated upon completion of data processing, is the Live Trace Outline (LTO) of which an example is illustrated by the blue polygon in Figure 175. It describes a perimeter showing the area where all trace data was acquired, regardless of the number of traces contained within an individual cell (from one fold to full fold). Because of environmental factors affecting the acquisition process (e.g., feather angles), the perimeter will extend beyond the boundaries of the pre-plot bin grid definition.

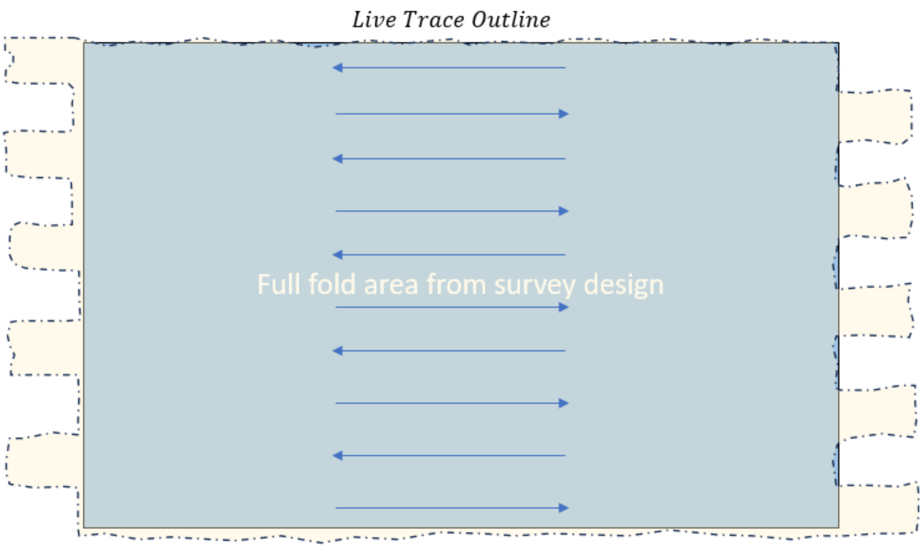


Figure 175: Live trace outline (LTO)

As trace data is deemed to fall outside of the pre-plot bin grid it is often sensible to increase the size of the bin grid to exceed the actual size of the pre-plot full fold area in the crossline direction. Therefore, all traces associated with the LTO will be assigned to a designated seismic grid, within the extended seismic grid definition.

9 Exchange file formats

Historically, the seismic user community has exchanged positioning data and grid definitions in many home grown formats, often providing insufficient metadata to properly replicate their original description. However, since the 1970's the United Kingdom Offshore Operators Associated (UKOOA), as it was then, began publishing a series of documents describing a more formal mechanism by which geo-spatial data associated with seismic activities could be captured, stored and exchanged. The documents, or guidance notes classified the seismic geo-spatial data into three categories as follows:

- P1 format: Describing the capture and storage of post-processing positioning data acquired on a seismic survey.
- P2 format: Describing the capture and storage of raw positioning observations used to derive the post-processed positioning data (P1 format).
- P6 format: Describing the definition of the seismic grid.

Both P1 and P2 file formats comprise two sections known as the header and data block. Into the header is stored all the attributes and metadata associated with the navigation and positioning data contained in the data block. In a slight departure, the P6 format comprises just a header block into which the seismic grid attributes, metadata and data perimeter(s) are stored.

Over time updates to these formats were released as acquisition technologies improved and data volumes increases. This resulted in the following publications:

Table 13: History of exchange file formats

Format	**1978**	**1984**	**1986**	**1990**	**1994**	**1998**	**2011**
P1	P1/78	P1/84		P1/90			P1/11
P2			P2/86		P2/94		P2/11
P6						P6/98	P6/11

Similar positioning formats were also published by Society of Exploration Geophysicists (SEG) of which the most commonly used is the SEG-P1 format released in 1983, and the Shell Processing Support (SPS) format published by Shell International in 2007 (rev 2.1).

Today, all these formats are under the custodianship of International Oil and Gas Producers (IOGP) geomatics section with all elements of each vintage format supported under the latest Px/11 series. One major modification to the Px/11 formats was the introduction of a common header which contains project details and geodetic parameter definitions that are common to each format when they related to the same survey. A brief introduction to each of the formats relating to the seismic grid and its exports is given in the remainder of this section. For more detailed descriptions refer to the IOGP guidance notes (5, 6, 7, 8).

9.1 P6 file format

An example of the original P6/98 format is shown in Figure 176. The first two rows are not part of the header and are included to illustrate that each row is limited to a maximum of 80 columns with specific column ranges being reserved to store particular variable names and their values.

```
12345678901234567890123456789012345678901234567890123456789012345678901234567890
         1         2         3         4         5         6         7         8

H0100 3D SURVEY NAME                             Manual Bin Grid
H0300 GEODETIC DATUM NAME        WGS 84
H0400 ELLIPSOID-AXIS-INV FLAT    WGS 84       6378137.000 298.2572236
H0500 PROJECTION METHOD          001   Transverse Mercator
H0510 PROJECTION ZONE NAME       UTM zone 21N
H0540 MAP GRID ORIGIN (DMS N/E)     0 0 0.000N   57 0 0.000W
H0550 MAP GRID ORIGIN (E,N)         500000.00E         0.00S
H0560 MAP GRID SCALE FACTOR      0.9996000000
H0600 DESCR OF LINEAR UNITS      1 metre                     1.000000000000
H0700 DESCR OF ANGULAR UNITS     1  Sexagesimal degrees
H0800 BIN GRID ORIGIN (IO, JO)     2000.0000   3000.0000
H0900 BIN GRID ORIGIN (E, N)        525000.00E   6025000.00N
H1000 SCALE FACTOR AT I, J       1.0000000000   2000.0000   3000.0000
H1100 NOM BIN WIDTH ON I AXIS     25.0000
H1150 NOM BIN WIDTH ON J AXIS     12.5000
H1200 GRID BEAR J AXIS (DMS)        0 0 0.000
H1210 GRID BEAR I AXIS (DMS)       90 0 0.000
H1300 BIN NODE INCREMENT I AXIS      1.000
H1350 BIN NODE INCREMENT J AXIS      1.000
H1400 Coords (I,J,E,N) Fst Node    1000.0       1000.0        500000.00  6000000.00
H1401 Lat,Lon (dms) First Node     540853.18N   570000.000
H1410 Coords (I,J,E,N) Sec Node    1000.0       5000.0        500000.00  6050000.00
H1420 Coords (I,J,E,N) Gen Pnt     2000.0       3000.0        525000.00  6025000.00
H2100 Comments                   This bin grid has been specifically created for
H2100 Comments                   the user manual.  Please add any comments that a
H2100 Comments                   re required.
H2300 Data Extent Bin Grid         5000.0000   1000.0000   3000.0000   1000.0000
H2400 Data Extent Map Extents      6050000.00  6000000.00   500000.00   550000.00
H2700 Number of perimeters        2
H2801 Total Coverage # of Nodes     5
H2901 Total Coverage (i,j,E,N)     1000.0000    500.0000      500000.00  5993750.00
H2901 Total Coverage (i,j,E,N)     1000.0000   5500.0000      500000.00  6056250.00
H2901 Total Coverage (i,j,E,N)     3000.0000    500.0000      550000.00  5993750.00
H2901 Total Coverage (i,j,E,N)     3000.0000   5500.0000      550000.00  6056250.00
H2901 Total Coverage (i,j,E,N)     1000.0000    500.0000      500000.00  5993750.00
H3101 Full Fold Cov # of Nodes      6
H3201 Full Fold Cov (i,j,E,N)      1000.0000   5000.0000      500000.00  6050000.00
H3201 Full Fold Cov (i,j,E,N)      3000.0000   5000.0000      550000.00  6050000.00
H3201 Full Fold Cov (i,j,E,N)      3000.0000   1000.0000      550000.00  6000000.00
H3201 Full Fold Cov (i,j,E,N)      1500.0000   1000.0000      512500.00  6000000.00
H3201 Full Fold Cov (i,j,E,N)      1500.0000   2100.0000      512500.00  6013750.00
H3201 Full Fold Cov (i,j,E,N)      1000.0000   2100.0000      500000.00  6013750.00
H3201 Full Fold Cov (i,j,E,N)      1000.0000   5000.0000      500000.00  6050000.00
```

Figure 176: Bin grid exchange format - P6/98

Letter H always appears in column 1 and specifies that the contents of that row belong to the header block in common with all other UKOOA/IOGP formats (note, the newer version use HC to designate Common Header records). Columns 2 to 5 are reserved for a series of codes that uniquely identify each of the parameters relating to the seismic grid definition.

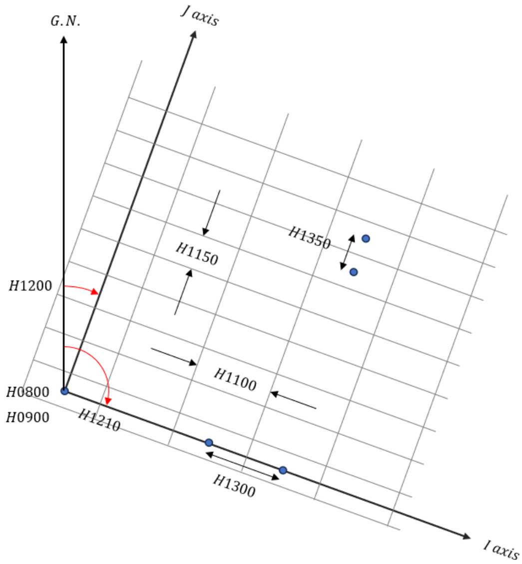


Figure 177: P6 object identities

Figure 177 displays some of these record codes as they relate to the seismic grid parameters. Refer back to Figure 176 to see what variable name corresponds to the H records illustrated in Figure 177. For example, H1200 refers to the grid bearing of the $J\ axis$ in relation to grid north, which for our example is the survey orientated on a north-south direction. The parameters of the header block fall into three basic categories which are:

- CRS details
- Grid parameters
- Perimeter definitions

9.1.1 CRS details

CRS details are stored both implicitly, by name only, and explicitly by describing all the salient geodetic parameters used in their definition. These are contained in records H0300 to H0700. For example:

- H0300 – Geodetic datum
- H0400 – Reference ellipsoid parameters
- H0500 – Coordinate conversion technique
- H0510 – Projection zone name
- H0540 – Projected coordinates of the grid origin (E_o, N_o).
- H0600 / H0700 – Units of measure

The P6/98 version makes no reference to any EPSG codes, or the newer adopted variable names associated with the IOGP geodetic parameter registry (see sections 2 and 3). However, some minor revisions were made with the inclusion of the H80xx records. For further details on the definition of these parameters see Reference surface and Coordinate Reference Systems Book (Parr 2024) and OGP Coordinate Conversions and Transformations including formulas (IOGP 2020).

9.1.1.1 Coordinate transformation related matters

The P6/98 does not cater for the storage of parameters and parameter values associated with a coordinate transformation. Whilst it does permit the definition of all common map projection parameters, grids, and perimeters it is limited in scope such that only one CRS can be defined per file. Should definitions of the seismic grid require referencing to multiple CRSs then multiple P6/98 files are necessary, one referenced to each CRS.

9.1.1.2 Affine transformation

Because of the vintage of the P6/98 it treated seismic grids as being of type: Engineering CRS and thus comprising a datum of type: engineering. To convert coordinates between the projected CRS and the seismic grid (or vice versa) requires the use of a special case of the affine transformation, known as the similarity transformation. It is deemed a transformation because there are two geodetic datums involved, one relating to the Source CRS and one to the Target CRS. For example, when the seismic grid is of type Engineering CRS:

Source: Datum is an engineering datum included in an engineering CRS.

Target: Datum is a geodetic datum included in the projected CRS.

The P6/11 considers the seismic grid to be of type: Derived CRS where the geodetic datum used by both Source and Target CRSs are identical. Therefore, strictly speaking it is not a transformation as there is no change in geodetic datum between the two. Therefore, it is classified as a coordinate operation of type: conversion. The algorithm (filter) used to perform this operation (as either a transformation or conversion) uses the parameters and parameter values specified in the header block as shown in Figure 176, see section 9.1.2. Details of the algorithm are given in section 11.2 with worked examples given in section 11.3.

9.1.2 Grid parameters

The grid parameter variables store the parameter values that uniquely define the seismic grid as described in sections 2 and 3. For example, in the P6/98:

- H0800 – Grid origin in relation to engineering CS (I_o, J_o)
- H0900 – Grid origin in relation to projected CRS (E_o, N_o)
- H1100 – Bin widths on $I\ axis$
- H1150 – Bin widths on $J\ axis$
- H1300 – Cell increments on $I\ axis$
- H1350 – Cell increments on $J\ axis$
- H1200 – Axis bearing of $J\ axis$

Refer to Figure 177 to see the codes superimposed on the grid diagram. These also represent the parameters and parameter values used within the similarity transformation to convert between projected CRS and binning grid Engineering CRS.

9.1.2.1 Test point

Record types are also provided to store the coordinates of a test point(s) which show the value of a point P in both the projected CRS and the seismic grid (H14xx records). Test points (if correct) act as a guidance to ensure the coordinate operation can be repeated which will indicate that sign conventions and rotations have been correctly applied. In Figure 176, identify the record ID H1420 which is reiterated below:

```
H1420 Coords (I,J,E,N) Gen Pnt    2000.0      3000.0        525000.00  6025000.00
```

The test point is used to determine whether the transformation applied in a software application correctly performed the coordinate operation between the seismic grid and the projected CRS. Therefore, if the coordinates of point P in the seismic grid:

$$I = 2000$$

$$J = 3000$$

What will be the reciprocal coordinates for point P be referenced to the Projected CRS after it passes through the similarity transformation:

$$\mathrm{E} = 525000.00$$

$$\mathrm{N} = 6025000.00$$

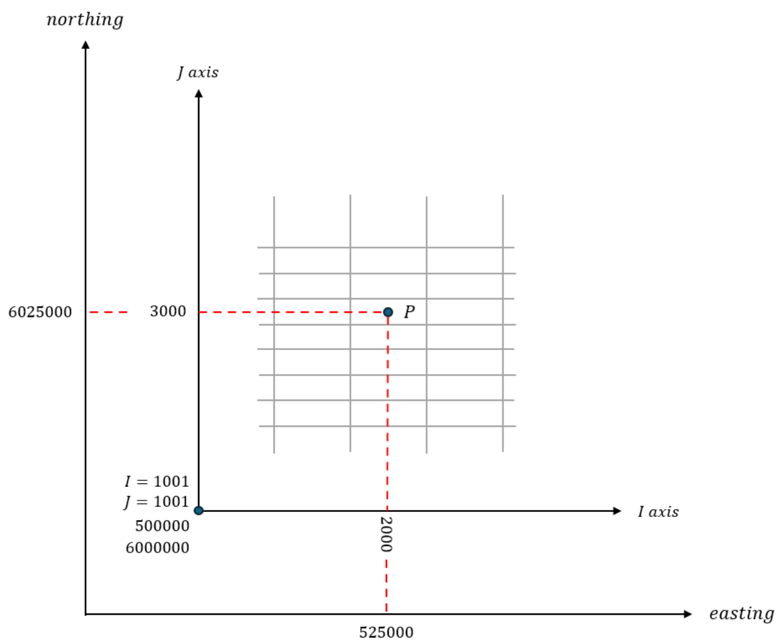


Figure 178: Test point shown graphically

The input and output associated with the test point is only valid for the parameter values associated with the seismic grid definition, for example as described in section 9.1.2.1, as it is unique to each grid.

9.1.3 Perimeter definitions

The perimeter definitions that overlay the grid are described in section 4. In Figure 179 an extended grid is shown. This is deliberate to emphasize the concept that the range of cells along the I and J $axes$ of the seismic grid do not need specifying at the time of definition (as per IOGP approach). The grid can be considered to extend indefinitely along the two axes of its cartesian coordinate system. These have been capped at 5750 and 9000 along I and J $axes$ for display purposes. Superimposed on top of the seismic grid are the extents of the various perimeters that the P6/98 format recognizes, namely:

- Total coverage (H28xx, H29xx)
- Full fold coverage (H31xx, H32xx)
- Null fold coverage (H34xx, H35xx)
- Null coverage (H37xx, H38xx)

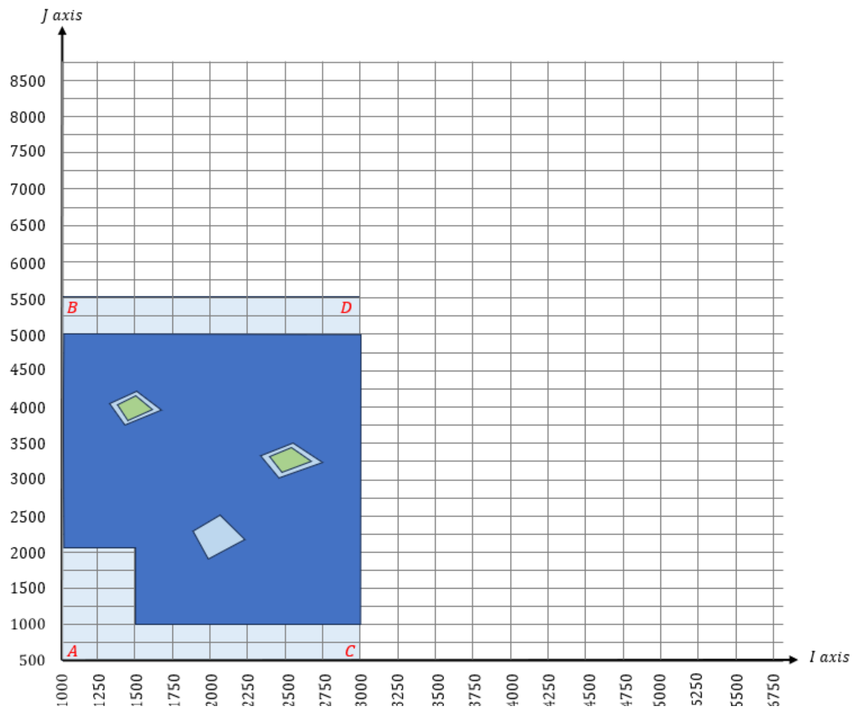


Figure 179: Perimeters defined in P6 file

In this example seven polygons (or perimeter) are illustrated (one is the minimum required) as shown in Figure 179. Their definitions all follow the same format, which comprises:

H2700 – specifies the total number of perimeters contained in the file, e.g., 7. In this example it comprises the following:

- 1 Total coverage,
- 1 Full fold coverage,
- 2 Null fold coverage
- 3 Null coverage.

An example of how these are captured in the P6/98 format is shown in Figure 180. The codes that identify the type of perimeter are shown in columns 1 to 5 which replicate the codes specified at the beginning of this section. In Figure 179 the Total coverage perimeter is described by points A to D (red letters). Using the H2801 perimeter (Figure 180) the number of nodes used to describe the perimeter is given. The number is 5 because the first point is repeated to close the loop.

```
H2700 Number of perimeters       7
H2801 Total Coverage # of Nodes    5
H2901 Total Coverage (i,j,E,N)    1000.0000    500.0000     500000.00  5993750.00
H2901 Total Coverage (i,j,E,N)    1000.0000   5500.0000     500000.00  6056250.00
H2901 Total Coverage (i,j,E,N)    3000.0000    500.0000     550000.00  5993750.00
H2901 Total Coverage (i,j,E,N)    3000.0000   5500.0000     550000.00  6056250.00
H2901 Total Coverage (i,j,E,N)    1000.0000    500.0000     500000.00  5993750.00
H3101 Full Fold Cov # of Nodes     6
H3201 Full Fold Cov (i,j,E,N)     1000.0000   5000.0000     500000.00  6050000.00
H3201 Full Fold Cov (i,j,E,N)     3000.0000   5000.0000     550000.00  6050000.00
H3201 Full Fold Cov (i,j,E,N)     3000.0000   1000.0000     550000.00  6000000.00
H3201 Full Fold Cov (i,j,E,N)     1500.0000   1000.0000     512500.00  6000000.00
H3201 Full Fold Cov (i,j,E,N)     1500.0000   2100.0000     512500.00  6013750.00
H3201 Full Fold Cov (i,j,E,N)     1000.0000   2100.0000     500000.00  6013750.00
H3201 Full Fold Cov (i,j,E,N)     1000.0000   5000.0000     500000.00  6050000.00
H3401 Null Full Fold # of Nodes    5
H3501 Null Full Fold (i,j,E,N)    2382.0000   2851.0000     534542.00  6023143.00
H3501 Null Full Fold (i,j,E,N)    2284.0000   3240.0000     532095.00  6027997.00
H3501 Null Full Fold (i,j,E,N)    2453.0000   3666.0000     536332.00  6033324.00
H3501 Null Full Fold (i,j,E,N)    2604.0000   3230.0000     540095.00  6027874.00
H3501 Null Full Fold (i,j,E,N)    2382.0000   2851.0000     534542.00  6023143.00
```

Figure 180: Perimeters contained in P6/98 format

The coordinates of the Total coverage perimeter nodes are captured by repeating the H2901 records that immediately follow. The two coordinates relating to the seismic grid are followed by the two coordinates relating to the Projected CRS. For example, in the first H2901 record the seismic grid coordinates are given as I = 1000.0000 and J = 500.0000, and the Projected coordinates are given as E = 500000.00 and N = 5993750.00. Theoretically, there are no limit to the number of perimeters that the file can contain.

9.2 Revised P6 format: P6/11

The survey and positioning section of UKOOA became absorbed into the International Association of Oil and Gas Producers (IOGP) Geomatics section, who are the current custodians for all navigation and positioning formats and associated guidance notes. The legacy seismic related file formats are still recognized but have been superseded by later revisions, which are commonly known as the Px/11 formats. The x refers to a member of the positioning format family, for example: P2, P1 or P6 formats where 11 refers to the year (2011) the formats were originally released.

Hence, the P6/98 is replaced by the latest revision which is known as the P6/11 file format. This format significantly differs from the P6/98 in many ways with the major change being the replacement of the column delimited format with a comma delimiter format. An example of the P6/11 format is shown in Figure 181 and Figure 184.

```
OGP,OGP P6,6,1.1,1,2022:06:29,11:45:34,20220629.p611,GeoSuite
HC,0,1,0,Project Name                               ,20220629,WXGGeoSuite,2022:06:29,2022:07:30
HC,0,3,0,Geographic Extent                          ,0.673,1.502,55.104,56.513
HC,0,4,0,Client                                     ,Geomatic Solutions
HC,1,0,0,Reference Systems Summary                  ,6,1,3,1
HC,1,1,0,Unit of Measure                            ,1,  metre, length, 2, ,,,,, SI base unit of length,9001,       EPSG Dataset,7.6,9001
HC,1,1,0,Unit of Measure                            ,2, radian,  angle, 2, ,,,,,SI angular measure unit,9101,       EPSG Dataset,7.6,9101
HC,1,1,0,Unit of Measure                            ,3, degree,  angle, 2,2,0.00,3.14159265358979,180,0.0, Measure of plane angle,9102,
HC,1,1,0,Unit of Measure                            ,4,  unity,  scale, 2,,,,,,For unitless entities,9201,       EPSG Dataset,7.6,9201
HC,1,1,0,Unit of Measure                            ,5,    bin,counter, 2,,,,,,            Bin count,1024,       EPSG Dataset,7.6,1024
HC,1,1,0,Unit of Measure                            ,6,SI time,   time,11,,,,,, SI base unit of time,    ,POSC UOM Dictionary,2.2,   s
HC,1,1,1,Example Unit Conversion                    ,3,3,180,2,3.14159265358979
HC,1,2,0,Time Reference System                      ,1,1,0,UTC,0,,6
HC,1,3,0,CRS Number/EPSG Code/Name/Source           ,1,4230,ED50,,,,
HC,1,3,0,CRS Number/EPSG Code/Name/Source           ,2,23034,ED50/UTM zone 34N,,,,
HC,1,3,0,CRS Number/EPSG Code/Name/Source           ,3,32764,Seismic bin grid datum,,,,
HC,1,4,0,CRS Number/EPSG Code/Type/Name             ,1,4230,2,geographic 2D,ED50
HC,1,4,4,Geodetic Datum                             ,1,6230,European Datum 1950,
HC,1,4,5,Prime Meridian                             ,1,8901,Greenwich,0.000000,3,degree
HC,1,4,6,Ellipsoid                                  ,1,7022,International 1924,6378388.000,1, metre,297.000000000
HC,1,6,0,Coordinate System                          ,1,,Ellipsoidal 2D CS,3,Ellipsoidal,2
HC,1,6,1,Coordinate System Axis 1                   ,1,1,106,  Geodetic Latitude,north, Lat,3,degree
HC,1,6,1,Coordinate System Axis 2                   ,1,2,107, Geodetic Longitude, east,Long,3,degree
HC,1,4,0,CRS Number/EPSG Code/Type/Name             ,2,23034,1,projected,UTM zone 34N
HC,1,4,3,Base Geographic CRS                        ,2,1,4230,ED50
HC,1,4,4,Geodetic Datum                             ,2,6230,European Datum 1950,
HC,1,4,5,Prime Meridian                             ,2,8901,Greenwich,0.000000,3,degree
HC,1,4,6,Ellipsoid                                  ,2,7022,International 1924,6378388.000,1, metre,297.000000000
HC,1,5,0,Map Projection                             ,2,16031,UTM zone 34N
HC,1,5,1,Projection Method                          ,2,9807,Transverse Mercator,5
HC,1,5,2,Latitude of natural origin                 ,2,8801, 0.000000000,3,degree
HC,1,5,2,Longitude of natural origin                ,2,8802,21.000000000,3,degree
HC,1,5,2,Scale factor at natural origin             ,2,8805, 0.999600000,4, unity
HC,1,5,2,False easting                              ,2,8806,500000.000000000,1,metre
HC,1,5,2,False northing                             ,2,8807,0.000000000,1,metre
HC,1,6,0,Coordinate System                          ,2,,Cartesian 2D CS,2,Cartesian,2
HC,1,6,1,Coordinate System Axis 1                   ,2,1,1,Easting,east,E,1, metre
HC,1,6,1,Coordinate System Axis 2                   ,2,2,2,Northing,north,N,1, metre
HC,1,4,0,CRS Number/EPSG Code/Type/Name             ,3,32764,6,engineering,Seismic bin grid datum
HC,1,4,8,Engineering Datum                          ,3,,Seismic bin grid datum
HC,1,6,0,Coordinate System                          ,3,,Cartesian 2D CS,2,Cartesian,2
HC,1,6,1,Coordinate System Axis 1                   ,3,1,1428,Bin grid I,  J-axis plus 90 degrees,I,5,bin
HC,1,6,1,Coordinate System Axis 2                   ,3,2,1429,Bin grid J,See associated operation,J,5,bin
```

Figure 181: P6/11 file format example

This example captures the seismic grid definition for an Engineering CRS (see section 3.2) approach. Make a comparison of the way in which the geodetic datum name is represented between the two formats. In the P6/98 it uses the H0300 record, where in columns 33 onwards the text states WGS 84. In the P6/11 format this is replaced with the HC,1,4,4 record where the name is given in the eighth field as World Geodetic System 1984. Prior to that, in field seven is given the EPSG code of that geodetic object. All the later formats are closely aligned to the IOGP geodetic parameter registry, https://epsg.org specifically the with extensive use of the EPSG objects codes.

In the P6/98 format all header records are specified by H appearing in column 1, and in P6/11, with the introduction of the Common Header it is specified using HC. The common header is part of the new architecture where certain parameters, including the general survey and geodetic parameters are shared between P1, P2, and P6 formats as they are common to all for the same survey. All those records shown in Figure 181 are part of the Common Header.

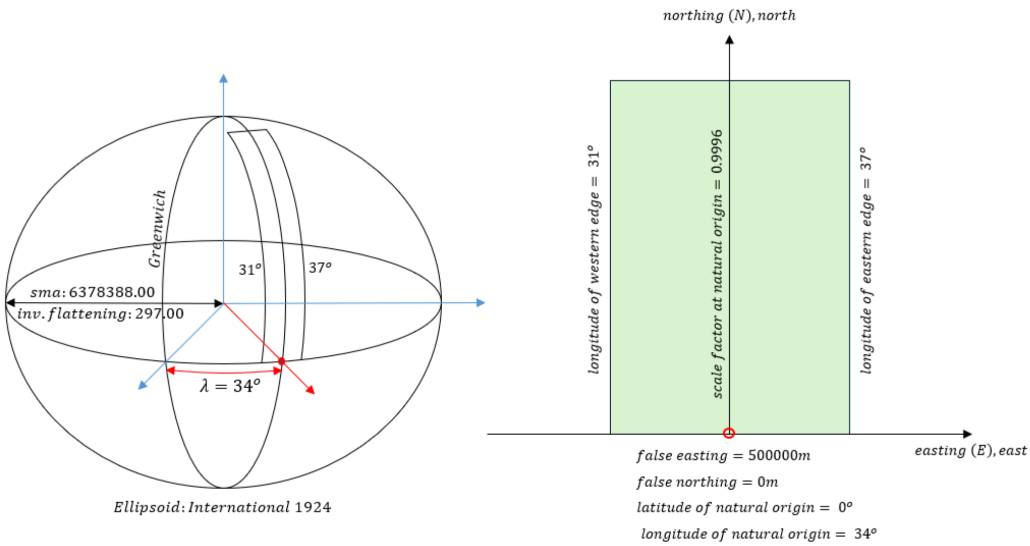


Figure 182: CRS explicit details

One significant design change from P6/98 is the provision to define and store multiple CRSs and multiple coordinate transformations between those CRSs. As a minimum there must be two CRSs contained in the file, namely:

- Engineering CRS (to describe the seismic grid)
- Projected CRS

In Figure 181 three CRSs are listed, namely:

Table 14: Components of Derived CRS

CRS number	Name	EPSG code
1	ED50	4230
2	ED50 / UTM zone 34N	23034
3	Seismic bin grid	32764

The implicit definition is specified in the HC,1,4,0 record, which is followed by the explicit definition. The following is an example for CRS 2 in the table above. The CRS is of type: Projected with the given name of ED50 / UTM zone 34N. Its base geographic CRS is ED50 [4230], comprising the international 1924 ellipsoid and Greenwich prime meridian. The grid parameters associated with the Projected CRS definition include all those required of the Transverse Mercator conversion method, namely:

- Latitude of natural origin
- Longitude of natural origin
- Scale factor at natural origin
- False easting
- False northing

Figure 183 illustrates all the parameters associated with the projected CRS in an alternative way. Included here are the EPSG codes that are an integral part of the new Common Header format.

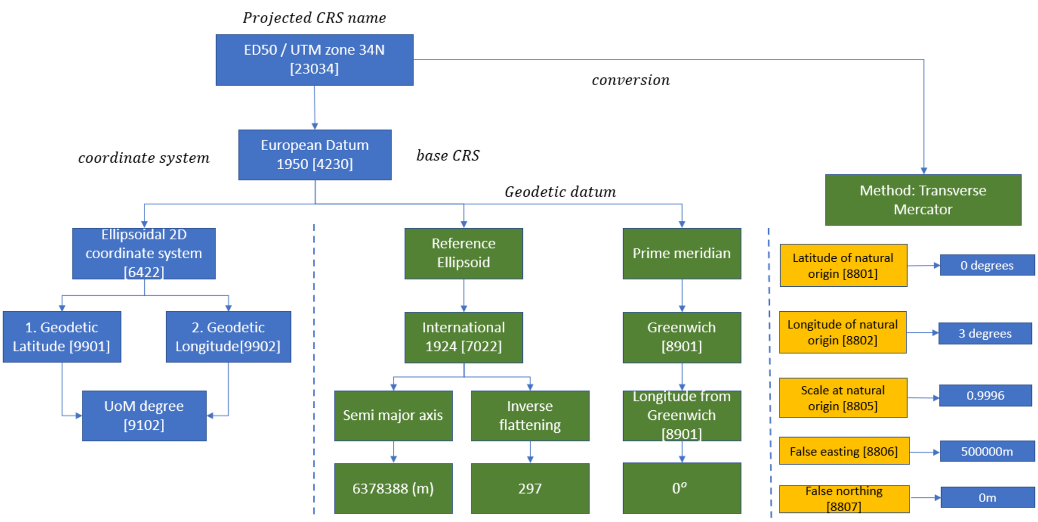


Figure 183: CRS parameters

As the P6/11 format allows for the specification of coordinate transformations between any two of the CRSs listed in the common header, how are these parameters and parameter values stored? Figure 184 shows these for a coordinate transformation between the projected CRS and the Engineering CRS, as specified in HC,1,7,0. After which the transformation method (HC,1,8,2), parameters and parameter values (repeated HC,1,8,4) associated with the transformation are given. The transformation method is defined by coordinate operation code 9666 which designates the method the P6 ($I = J + 90^o$) seismic bin grid transformation. Also recognised is the coordinate operation method, 9667: P6 ($I = J - 90^o$) seismic bin grid transformation. This first is used with right handed grids and the latter with left handed grids.

```
HC,1,7,0,Transformation Number/EPSG Code/Name/Source       ,1,,Transverse Mercator to OGP P6 seismic bin grid,,,,
HC,1,8,0,Transformation Number/EPSG Code/Name              ,1,,Transverse Mercator to OGP P6 seismic bin grid,
HC,1,8,1,Source CRS/Target CRS/Version                     ,1,2,,Transverse Mercator,3,,OGP P6 seismic bin grid,
HC,1,8,2,Transformation Method                             ,1,9666,P6 (I = J+90degrees) seismic bin grid transformation,1,10
HC,1,8,4,Bin grid origin I                                 ,1,8733,   1001.000,5,   bin,0
HC,1,8,4,Bin grid origin J                                 ,1,8734,   1001.000,5,   bin,0
HC,1,8,4,Bin grid origin Easting                           ,1,8735, 500000.000,1, metre,0
HC,1,8,4,Bin grid origin Northing                          ,1,8736,6000000.000,1, metre,0
HC,1,8,4,Scale factor of bin grid                          ,1,8737,      1.000,3,degree,0
HC,1,8,4,Bin width on I-axis                               ,1,8738,     25.000,1, metre,0
HC,1,8,4,Bin width on J-axis                               ,1,8739,     12.500,1, metre,0
HC,1,8,4,Map grid bearing of bin grid J-axis               ,1,8740,    000.000,3,degree,0
HC,1,8,4,Bin node increment on I-axis                      ,1,8741,      1.000,5,   bin,0
HC,1,8,4,Bin node increment on J-axis                      ,1,8742,      1.000,5,   bin,0
```

Figure 184: Transformation parameters

The codes (field 7) are directly linked to the EPSG geodetic parameter registry with respect to the parameter names (field 5) and the parameter values (field 8) for all parameters included in the CRS and coordinate operation definitions.

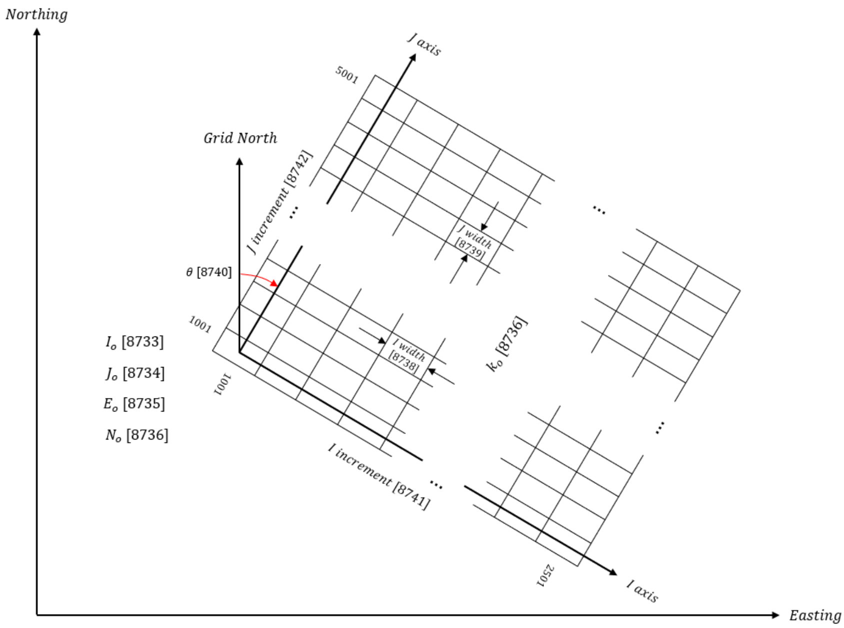


Figure 185: EPSG codes associated with grid parameters

The general take up and usage of the P6/98 file was not extensive, and seismic grids defined in this format are not common. The P6/11 has so far followed a similar trend but is gaining more popularity as it is promoted by the IOGP and its membership. The latest v2 revision of this format is soon to be released (Mid 2024).

9.3 EPSG geodetic parameter registry

The EPSG geodetic parameter registry provides a facility where user-defined seismic bin grid definitions can be stored directly in a local version of the database. An example is shown here for the Derived CRS (see section 3.3) Figure 186 shows a user-defined entry in a localized version of the registry.

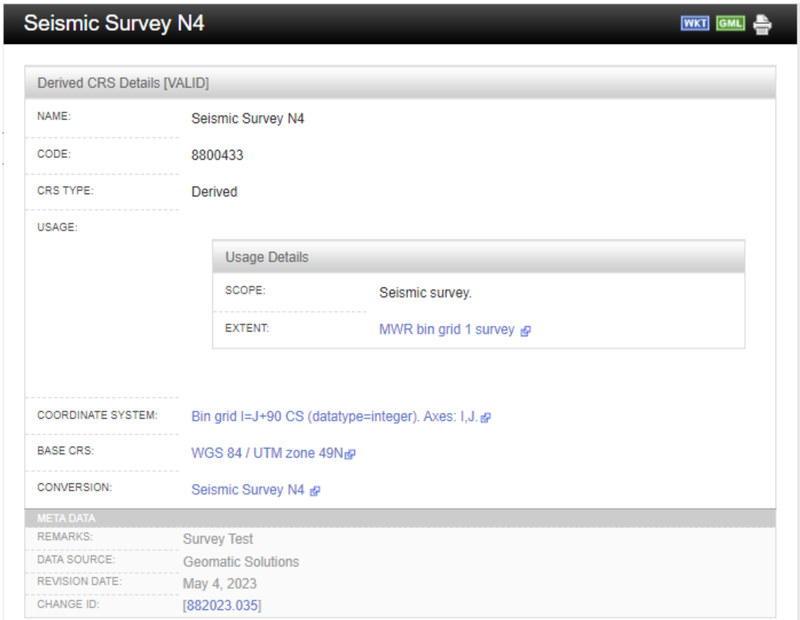


Figure 186: Seismic bin grid stored in EPSG registry

The three main elements of the definition are shown as:

- Coordinate system
- Base CRS
- Conversion

All of which are discussed in section 3.3. With respect to the Derived CRS this is stored as a conversion and not a transformation because there is no change in geodetic datum during any part of the operation. The parameters and parameter values associated with this entry are shown in Figure 161.

CONVERSION METHOD: P6 I=J+90 seismic bin grid coordinate operation

CONVERSION PARAMETERS:

Parameter	Value	Unit	Reversible
Bin grid origin I	1001	(bin)	No
Bin grid origin J	1001	(bin)	No
Bin grid origin Easting	550000	metre	No
Bin grid origin Northing	600000	metre	No
Scale factor of bin grid	1	unity	No
Bin width on I-axis	25	metre	No
Bin width on J-axis	12.5	metre	No
Map grid bearing of bin grid J-axis	0	degree	No
Bin node increment on I-axis	1	(bin)	No
Bin node increment on J-axis	1	(bin)	No

Figure 187: Conversion parameters and parameter values

The names applied to the parameters are replicated from the definitions provided in other sections, namely section 2 and section 3 where the same parameter values are applied.

9.4 Cell centres

In section 11.2 (with a worked example given in section 11.3), it is shown that coordinates for the geometric cell centre of every cell of the seismic grid can be calculated from the parameters and parameter values of the seismic grid definition (the conversion). Consequently, this enables the coordinates of the gathered seismic trace data to be determined prior to the acquisition of the seismic survey commencing.

Cell centre coordinates are useful to certain stakeholders in the data life cycle including seismic processing and GIS and the P1 exchange format lends itself nicely to storing the metadata and positioning data. Although not specifically designed for this purpose, the column ranges used from line name and event number are readily adopted to suite this requirement. The two latest versions of the P1 format are the P1/90 (released by UKOOA) and P1/11 (released by IOGP) and both contain a header block and data block. The header block stores the project geodetic metadata, whilst the data block the coordinates for all of the cell centres exported.

```
H1500POST PLOT DATUM           WGS84      WGS 84      6378137.000 298.2572236
H1800PROJECTION                001 Transverse Mercator
H1900PROJECTION ZONE           UTM zone 49N
H2000GRID UNITS                1 INTERNATIONALMETRE     1.000000000000
H2002ANGULAR UNITS             1 DEGREES
H2301GRID ORIGIN                 0  0 0.000N111  0 0.000E
H2302GRID ORIGIN (E,N)           500000.00E       0.00N
H2401SCALE FACTOR              0.9996000000
H2600 FOLLOWING RECORDS COVERS 3D GRID DEFINITION
H2600 ORIGIN DESCRIPTION       GRID ORIGIN (I,X) (I=2251, X=7251)
H2600 EASTING AT (I,X)         581250.00m
H2600 NORTHING AT (I,X)        514062.50m
H2600 INLINE DIRECTION         0.000000 DEGS (CLOCKWISE FROM GRID NORTH)
H2600 CROSSLINE DIRECTION      90.000000 DEGS (CLOCKWISE FROM GRID NORTH)
H2600 BIN SIZE INLINE/XLINE    25.00 m / 6.25 m
H2600 BIN INCR.INLINE/XLINE    1 / 1
H2600 ALL INLINES              INLINE 1001 TO INLINE 3501
H2600 ALL XLINES               XLINE 1001 TO XLINE 13501
H2600 FOLLOWING RECORDS DESCRIBES RECTANGLE FOR MIN/MAX INLINE/XLINE
H2600                   Point#  INLINE ID XLINE ID MAP PROJ.E MAP PROJ.N
H2600                       1   1001      1001     550000.00  475000.00
H2600                       2   1001      13501    550000.00  553125.00
H2600                       3   3501      1001     612500.00  475000.00
H2600                       4   3501      13501    612500.00  553125.00
H2600 EXPORTED TO UKOOA P1/90 FORMAT BY GEO SUITE v5.0.11025.9835, 2021:05:09
H8000EPSG Geographic CS Name    WGS 84
H8001EPSG Geographic CS Code    4326
H8002EPSG Projected CS Name     WGS 84 / UTM zone 49N
H8003EPSG Projected CS Code     32649
```

Figure 188: P1/90 bin centre header block

Extensive use of the H2600, comment records, is common as it enables relevant details of the seismic grid definition to be captured as shown in the Figure 188 example.

9.4.1 Header block

There are three key record types that are contained in the P1/90 file format, namely:

- Project details
- CRS details
- Comment records

9.4.1.1 Project details

The project detail records are used to capture the main salient details of the survey, which include the following:

- H0100 – Description of survey area
- H0200 – Date of survey
- H0300 – Details of client
- H0400 – Details of geophysical contractor
- H0500 – Details of positioning contractor
- H0600 – Details of positioning processing contractor

```
H0100SURVEY AREA                Melaka basin, Melaka Strait
H0200DATE OF SURVEY             11 May 2024
H0300CLIENT                     Melaka Energy Bhd
H0400GEOPHYSICAL CONTRACTOR     Geomatic Solutions
H0500POSITIONING CONTRACTOR     Geomatic Solutions
H0600POSITIONING PROCESSING     Geomatic Solutions
H0700POSITIONING SYSTEM         GeoSuite Toolkit
H0800SHOTPOINT POSITION         MEAN CMP
H0900OFFSET V1 TO SHOTPOINT        1   2    0.00 -216.00
H2600SHOOTING POINT V1 MEAN CMP AT (0.0, 0.0)
H0901OFFSET V1 TO G1               1   2    0.00 -147.50
H0902OFFSET V1 TO S01              1   2    0.00 -284.50
H0903OFFSET V1 TO GPS V1G1         1   2    0.00    0.66
H0904OFFSET V1 TO GPS V1G2         1   2   -0.05    0.14
H0905OFFSET V1 TO GPS V1G3         1   2    0.87   -0.21
H0906OFFSET V1 TO GPS V1R1         1   2    0.40   -0.17
```

Figure 189: P1/90 project details records

For full details of all the project record types recognized in the P1/90 file format see (UKOOA, 1990).

9.4.1.2 CRS details

The metadata is stored in the header block of the file of which an abbreviated example is shown in Figure 188. This illustrates some of the fields used to capture the geo-spatial parameter values of the CRS.

- H1500 – Geodetic datum
- H1900 - Projection Zone
- H2301 – Map grid origin

Note, compare the record codes used in the P6/98 header to those used for similar parameters in the P1/90. The P1/90 H1900 record contains the same record as the

H0510 record in the P6/98, and the P1/90 H2301 is the same as the H0540 record in the P6/98. This historical approach was not ideal, and a new approach was introduced using the Common Header (HC) of the Px/11 formats. Also included are the H8 records that are used to store the CRS details in an implicit manner, e.g.,

H8000 – Geographic CRS Name

H8002 – Projected CRS Name

9.4.1.3 Comment records

The P1/90 format is not designed to store any parameters associated with the seismic grid definition. Therefore, use of the H2600 record type is encouraged (the user-defined comment) to capture any relevant parameters and parameter vales of the seismic grid. An example is illustrated in Figure 188 where all the salient parameters associated with the seismic grid are included in the header block. The text shown in these records is not formally part of any format and is at the discretion of the file originator. Another approach has been the creation of a hybrid solution where the header of a P6/98 file is merged with the P1/90 data block. Although not a recognised solution, it is a combination that does make sense.

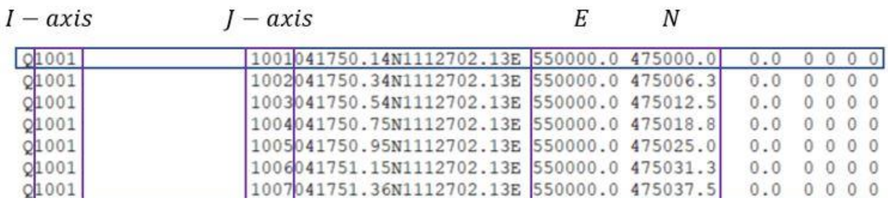
9.4.2 Data block

An example of the data block of the P1/90 format is shown in Figure 190. In column 1 of the data block is the letter Q, which in the P1/90 format signifies that the data contained in that row represents the details of the cell centre.

- In the P1/90 format columns 2 to 12 are reserved for the line name. Instead, these columns are used to accommodate the cell indexing along the I axis.
- Whereas columns 20 to 25 are reserved for the event number (e.g., shot point number). These columns are used to accommodate the cell indexing along the J axis.
- From columns 26 to 80 the P1/90 format remains the same and used to store the geographic coordinates (columns 26 to 46) and the projected coordinates (columns 47 to 64).

- The remaining columns will remain empty as no depth or timing related information requires capturing.

In Figure 190, four relevant data columns are labelled to show where the I, J seismic grid coordinates and Easting, Northing projected CRS coordinates are stored for each cell centre of the seismic grid.



$I - axis$	$J - axis$		E	N		
Q1001	1001	041750.14N1112702.13E	550000.0	475000.0	0.0	0 0 0 0
Q1001	1002	041750.34N1112702.13E	550000.0	475006.3	0.0	0 0 0 0
Q1001	1003	041750.54N1112702.13E	550000.0	475012.5	0.0	0 0 0 0
Q1001	1004	041750.75N1112702.13E	550000.0	475018.8	0.0	0 0 0 0
Q1001	1005	041750.95N1112702.13E	550000.0	475025.0	0.0	0 0 0 0
Q1001	1006	041751.15N1112702.13E	550000.0	475031.3	0.0	0 0 0 0
Q1001	1007	041751.36N1112702.13E	550000.0	475037.5	0.0	0 0 0 0

Figure 190: P1/90 bin centres - data block

The first row highlighted at the top of Figure 190 is for $I\ axis$ = 1001 and $J\ axis$ = 1001. They correspond exactly with the cell centre shown in the lower left of Figure 191 (red circle). Subsequent rows show the indexing and coordinates of the next six cells along the $J\ axis$ of CMP line 1001.

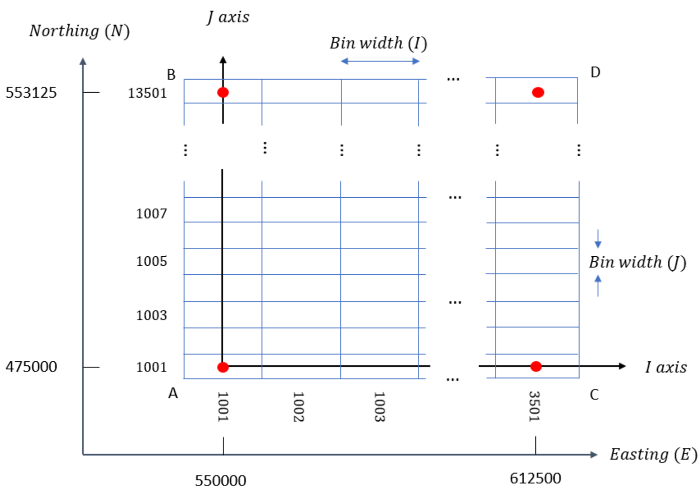


Figure 191: Cell centre indexing of the grid

Between the column containing the $J\ axis$ index and the column containing the Easting coordinate are the latitude and longitude equivalent for the base geographic 2D CRS of the projected CRS coordinates. Therefore, the coordinates of each of the three steps of the Derived CRS are collectively stored.

9.4.2.1 Reducing data export

Exporting the coordinates of every cell in the seismic grid can be prohibitively large and often unnecessary. For a seismic grid of 30km x 20km with cell sizes of 25m x 12.5m there are 1,920,000 cells. Therefore, decimating the exported file is common practice, e.g., every 10th inline and 10th crossline. As the seismic grid is linear (along both axes of the coordinate system) interpolation can be applied to determine the coordinates of the cell centres not included in the exported file.

9.5 Load sheets

The load sheet is not a formal file format published by any of the organisations such as IOGP or SEG. It is data sheet created out of convenience to provide data loaders with the relevant geo-spatial details associated with the SEG-Y file being input to a software application.

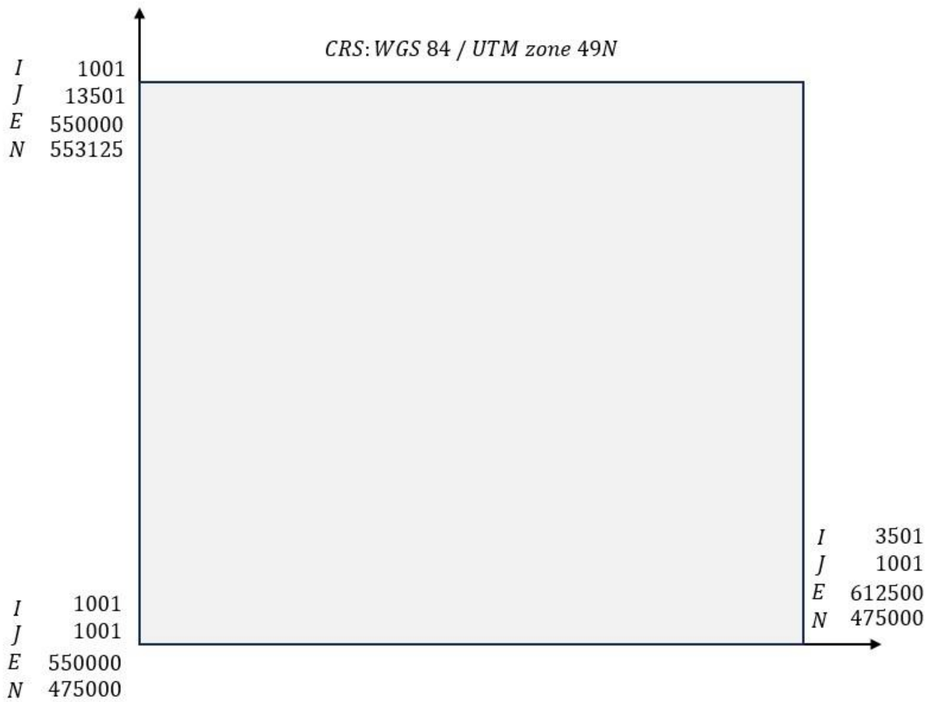


Figure 192: Corner points of the SEG-Y data volume

When importing 3D seismic volumes to a software application one common practice to specify the coordinates of three corner points of the seismic grid of which an example is given in Figure 192, e.g., points A, B and C. How the load sheet parameters and parameter values are presented to the data loader will depend upon the data source and any application that is capable of creating such a document. An example on one is shown in Figure 193 which correlates to the seismic grid illustrated in Figure 192. The coordinates and CRS details shown in this example are replicated in the user interface of the software to which the SEG-Y is being imported.

```
Bin grid name:
Date:  Thursday, 21 March, 2024

Point:      B                                         Point:      D
I:          1001.00                                   I:          3501.00
J:          13501.00                                  J:          13501.00
Easting:    550000.00                                 Easting:    612500.00
Northing:   553125.00                                 Northing:   553125.00

Point:      A                                         Point:      C
I:          1001.00                                   I:          3501.00
J:          1001.00                                   J:          1001.00
Easting:    550000.00                                 Easting:    612500.00
Northing:   475000.00                                 Northing:   475000.00

Corners:

Point     I         J         Easting      Northing       Latitude          Longitude
A      1001.00   1001.00   550000.00    475000.00    04°17'50.136"N  111°27'02.128"E
B      1001.00   13501.00  550000.00    553125.00    05°00'14.445"N  111°27'03.746"E
C      3501.00   1001.00   612500.00    475000.00    04°17'48.187"N  112°00'49.633"E
D      3501.00   13501.00  612500.00    553125.00    05°00'12.174"N  112°00'53.272"E

Bin grid details:

       Projected CRS:   WGS 84 / UTM zone 49N [32649]
       Units:           metre
       I width:        25.000000
       I increment:    1.00
       I bearing:      090° 00' 00.00" (90.000000)
       J width:        6.250000
       J increment:    1.00
       J bearing:      000° 00' 00.00" (0.000000)
```

Figure 193: Load sheet example

In the latest version (version 2) of the P6/11 file format is a new data record known as the L6 record. Details of this format are currently beyond the scope of this version of the book other than to illustrate how coordinates belonging to different CRSs are stored. In this example, the following CRSs are defined, which correlate to the CRSs labelled in Figure 194.

CRS A – Seismic grid coordinates (I, J)

CRS B – Projected CRS coordinates (E, N)

CRS C – Base geographic 2D coordinates of CRS B (φ, λ)

CRS D – Global geographic 2D CRS coordinates (φ, λ)

CRS A *CRS B* *CRS C* *CRS D*

L6, 0, 1, 2, 1, 1001, 1001, 550000.00, 475000.00, 4.2975898, 111.4506506, 4.2680040, 111.4541069, origin

L6, 0, 1, 2, 2, 1001, 13501, 550000.00, 553125.00, 5.0043866, 111.4511001, 5.0035559, 111.4545586, upper left corner

Figure 194: Example of L6 records from P6/11 version 2.0 format

9.6 Shp files

The shp file format is extensively used by the Geo-spatial community in a variety of GIS applications. The shp file format comprises four file types including one known as the .prj file in which the geodetic parameters belong to the CRS are stored.

```
PROJCS["Aratu_UTM_Zone_24S",
  GEOGCS["GCS_Aratu",
    DATUM["D_Aratu",
      SPHEROID["International_1924",6378388.0,297.0]],
      PRIMEM["Greenwich",0.0],UNIT["Degree",0.0174532925199433]],
  PROJECTION["Transverse_Mercator"],
    PARAMETER["False_Easting",500000.0],
    PARAMETER["False_Northing",10000000.0],
    PARAMETER["Central_Meridian",-39.0],
    PARAMETER["Scale_Factor",0.9996],
    PARAMETER["Latitude_Of_Origin",0.0],
    UNIT["Meter",1.0],
AUTHORITY["EPSG",20824]]
```

Figure 195: The .prj file

An example is shown in Figure 195 for projected CRS named: Aratu / UTM zone 24S. This file format is known as the Well Known Text, abbreviated to WKT. There are many variants of the WKT or which the one shown in Figure 195 is WKT version 2.0. The shp file is used to describe the geographic Extent of the grid with respect to the full fold perimeter. In Figure 196 the survey area and the corner points are displayed together.

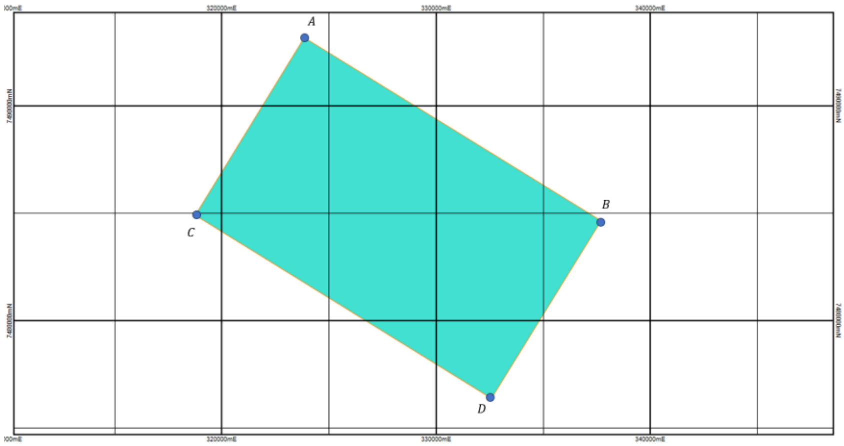


Figure 196: Shp file Extent

9.7 Geo JSON

The Geo JSON format provides the ability to export a variety of topographic features, e.g., polygons, lines, points, text etc.

```
{
  "coordinates": [
    [550000, 475000],
    [550000, 553125],
    [612500, 475000],
    [612500, 553125]
  ],
  "type": "Full fold perimeter projected"
}
{
  "coordinates": [
    [1001, 1001],
    [1001, 13501],
    [3501, 1001],
    [3501, 13501]
  ],
  "type": "Full fold perimeter grid"
}
```

Figure 197: Geo JSON example for full fold perimeter

Despite its lightweight nature the perimeters of the seismic grid are readily captured using this open notation language. An example of this is shown in Figure 197.

9.8 Pre plot line format

The file format that lends itself conveniently to the storage of the pre-plot line data is the P1 file format, whether it be the latest release (P1/11) or any of its predecessors (P1/90, P1/84). The P1 file was introduced in section 9.4 to illustrate how the coordinates of the seismic grid cell centres can be stored. Here an example of how the P1/90 file format uses the data block to store the pre-plot lines is shown.

```
H0100SURVEY AREA                Offshore South America
H0101SURVEY DETAILS             3D marine survey
H0200Survey Date                31/07/2023
H0201POST PLOT TAPE DATE        31/07/2023
H0203LINE PREFIX                GS-
H0300CLIENT DETAILS             Big Oil
H0400GEOPHYSICAL CONTRACTOR     Geomatic Solutions
H0500POSITIONING CONTRACTOR     Geomatic Solutions
H0600POSITIONING PROCESSING     Geomatic Solutions
H1000CLOCK OFFSET               -4
H1500POST PLOT DATUM            WGS84       WGS 84       6378137.000 298.2572236
H1800PROJECTION                 001 Transverse Mercator
H1900PROJECTION ZONE            UTM zone 21N
H2000GRID UNITS                 1 INTERNATIONALMETRE      1.000000000000
H2002ANGULAR UNITS              1 DEGREES
H2301GRID ORIGIN                  0 0 0.000N 57 0 0.000W
H2302GRID ORIGIN (E,N)            500000.00E       0.00N
H2401SCALE FACTOR               0.9996000000
H2600 NUMBER OF SOURCES         2
H2600 SOURCE DEPTH              -6.00 m
H2600 SOURCE SEPERATION         50.00 m
H2600 SOURCE OFFSET             150.00 m
H2600 NUMBER OF STREAMERS       10
H2600 STREAMER DEPTH            -7.00 m
H2600 STREAMER SEPERATION       100.00 m
H2600 STREAMER OFFSET           300.00 m
H2600 CMP LINE INTERVAL         25.00 m
H2600 SAIL LINE INTERVAL        500.00 m
H2600 SHOT POINT INTERVAL       25.00 m
H2600 LINE GENERATION MODE      Preplot lines have been generated on a grid
H2600 TOTAL AREA SURVEYED       1763.74 square kilometres
H2600 NUMBER OF SAILLINES       91
H2600 FF SAIL LENGTH            3513.53 kilometres
H2600 AVG. FF SAIL LENGTH       38.61 kilometres
H2600 EXPORTED TO UKOOA P1/90 FORMAT BY GEO SUITE v5.0.11025.9835, 02/05/2023
H2600 EXPORTED TO UKOOA P1/90 FORMAT BY GEO SUITE v6.0.5.3807, 09/05/2023
H8000EPSG Geographic CS Name    WGS 84
H8001EPSG Geographic CS Code    4326
H8002EPSG Projected CS Name     WGS 84 / UTM zone 21N
H8003EPSG Projected CS Code     32621
```

Figure 198: Header of P1/90 pre-plot file

9.8.1 Header block

As with the previous example the header block contains the general header records (H0100 to H0600) and the geo-spatial records for the CRS definition, e.g., H1800, H1900 etc. In Figure 198 the CRS details are as follows:

- CRS name: WGS 84 / UTM zone 21N
- Projection: 001 Transverse Mercator
- Grid origin: $0^o\ 0'\ 0.000''\ N,\ 57^o\ 0'\ 0.000''\ E$
- Grid origin: $500000.00E, 0.00N$
- Scale factor: 0.9996

In the example shown (Figure 198), again there is extensive use of the H2600 records in which some of the geometric configurations of the in-water equipment are described. The parameters and parameter values captured in the H2600 record types are user-defined and not formally part of the UKOOA file format. As such there are no restrictions as to what information can be stored. This is at the discretion of the file originator.

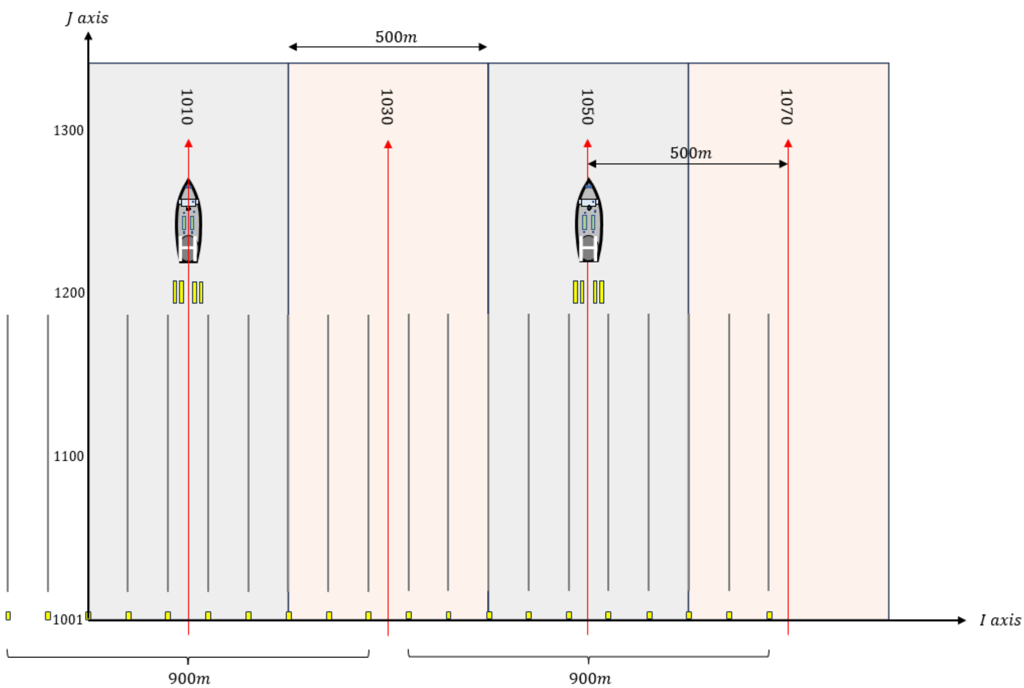


Figure 199: Line numbering

9.8.2 Data block

An example is shown in Figure 200 for the P1/90 file format as it is easier to comprehend the basic concept of the format than its P1/11 successor. Indexing numbers for each cell of the grid and the coordinates of the cell centre are contained in each row of the data block. The coordinates are given in both geographic coordinates referenced against the geographic 2D CRS (WGS 84) and the projected CRS (WGS 84 / UTM zone 49N).

Here, the survey vessel is towing 10 streamers and two sources. With a streamer separation of 100 metres and source separation of 50 metres each CMP line width will be 25 metres along the I axis. As there are 20 CMP lines per sail line the swath width is 500 metres. On the first swath CMP lines acquired are 1001 to 1020, with the vessel sail line being labelled 1010 as shown in Figure 199. The next sail line will be labelled 1030 and the one after that 1050 etc., always incrementing by values of 20. Therefore, each sail line will fall 500 metres to the east of the previous sail line.

The CMP line number along which the vessel traverses will form either all or part of the line name stored in the P1 file. In Figure 185, the former is applied (e.g. 1010). The column range reserved for the event numbers (shot point numbers) is used in the same fashion described in the P1/90 document with no modification required. Because of the linear nature of the shot point interval, it is not necessary to store the details of every event and typically, only the start of line (SOL) and end of line (EOL) events are captured. For line 1010 in Figure 185 the SOL takes event number 1001 and EOL 2591. One caveat here is that the event numbers on a towed marine survey must take integer values. The remaining columns for each row specify the latitude and longitude coordinates followed by easting and northing coordinates for the given event number.

```
V1010          11   1001065536.14N0552442.05W 675480.6 765939.8   0.0  0 00000
V1010          11   2591071710.12N0552442.05W 675344.4 805689.6   0.0  0 00000
V1030          11   1001065536.14N0552425.77W 675980.6 765941.6   0.0  0 00000
V1030          11   2591071710.12N0552425.75W 675844.4 805691.3   0.0  0 00000
V1050          11   1001065536.14N0552409.48W 676480.6 765943.3   0.0  0 00000
V1050          11   2591071710.11N0552409.45W 676344.4 805693.0   0.0  0 00000
V1070          11   1001065536.14N0552353.19W 676980.6 765945.0   0.0  0 00000
V1070          11   2591071710.11N0552353.15W 676844.4 805694.7   0.0  0 00000
V1090          11   1001065536.14N0552336.90W 677480.6 765946.7   0.0  0 00000
V1090          11   2591071710.11N0552336.85W 677344.4 805696.5   0.0  0 00000
V1110          11   1001065536.15N0552320.61W 677980.6 765948.4   0.0  0 00000
V1110          11   2591071710.11N0552320.54W 677844.4 805698.2   0.0  0 00000
V1130          11   1001065536.15N0552304.33W 678480.6 765950.1   0.0  0 00000
V1130          11   2591071710.11N0552304.24W 678344.4 805699.9   0.0  0 00000
V1150          11   1001065536.15N0552248.04W 678980.6 765951.8   0.0  0 00000
V1150          11   2591071710.10N0552247.94W 678844.4 805701.6   0.0  0 00000
V1170          11   1001065536.14N0552231.75W 679480.6 765953.5   0.0  0 00000
V1170          11   2591071710.10N0552231.64W 679344.4 805703.3   0.0  0 00000
```

Figure 200: Pre-plot lines in P1/90 format

10 SEG-Y file format

The SEG-Y file format is unique in so much that it contains both positioning data and seismic trace data. It is a format used to export seismic data at any stage of seismic data processing, from basic QC of shot and receiver gathers to intermediate stages of near trace gathers, brute stacks to final migrated sections. Two parts of the SEG-Y format that are of interest geo-spatially are:

- The EBCDIC header

- The trace headers

```
C01  ----------------------------------------------------------------------------------
C02  CLIENT        : WX GEO            CREATED      : JULY 2018
C03  AREA          : SOUTH CHINA       DATA TYPE    : FINAL MIGRATED STACK
C04  PROJECT NO.   : 6289              INLINE RANGE      :  14 - 178, I1
C05  SURVEY NAME   : WX-2018           CROSSLINE RANGE  : 196 - 942, I1
C06  ACQUIRED BY   : GEOMATICS         PROCESSED BY: GEOMATICS
C07  OUTPUT FILE NAME  : WX-2018-NS.sgy
C08 ----------------------ACQUISITION PARAMETERS----------------------------
C09 INSTRUMENT     : SEAL 428        GAIN TYPE      : FIXED
C10 REC. FORMAT    : SEGD8036        SAMPLE CODE    : 4 BYTE FLOATING POINT
C11 SAMPLE INT.    : 2MS             SAMPLES/TRACE  : 1001
C12 DATA TRACES    : 2 X 96          AUX. TRACES    : 0
C13 LC FILTER      : 10HZ 6DB/OCT    HC FILTER      : 180HZ 24 DB/OCT
C14 SOURCE TYPE    : 2 X 4350 CUIN   SP INTERVAL    : 6.25M FLIP FLOP
C15 CABLE TYPE     : SOLID SEAL      REC. INTERVAL  : 12.5M
C16 FOLD           : 168             OFFSET         : 25M
C17 ------------------------PROCESSING SEQUENCE-----------------------------
C18 01. TAPE TRANSCRIPTION              02. -50MS RECORDER DELAY CORRECTION
C19 03. GEOMETRY APPLICATION            04. SWELL NOISE AND SI REMOVAL
C20 05. ZERO PHASE CONVERSION           06. SRME, SRWEMA
C21 07. FAR TRACE NOISE REMOVAL         08. 3D NAVIGATION MERGE
C22 09. TIDAL CORRECTION                10. REGULARISATION
C23 11. 1ST ROUND VELOCITIES (250X250M) 12. KIRCHHOFF PSTM
C24 13. 2ND ROUND VELOCITIES (250X250M) 15. KIRCHHOFF PSTM
C25 16. TRACE MUTING FOR FAR STACK      17. STACK
C26 18. GAIN CORRECTION                 19. BANDPASS FILTER
C27 20. GUN AND CABLE STATIC            21. OUTPUT TO SEGY
C28  ---------------------------PROCESSING GRID-------------------------------
C29  BIN SIZE : 6.25M X 6.25M
C30             ILINE    XLINE     X          Y
C31             14       196    441603.23  503800.28
C32             14       942    446254.38  503475.15
C33             178      196    441531.76  502777.78
C34             178      942    446182.91  502452.65
C35  Survey Datum   TIMBALAI 1948; Projection UTM ZONE 49N;
C36  Central Meridian 111deg E
C37  ------------------------SEGY TRACE HEADER INFO----------------------------
C38  SEGY TRACE HEADER INFO:
C39        3D ILINE NB : BYTE 189-192           3D XLINE NB : BYTE  193-196
C40        CDP X       : BYTE 181-184           CDP Y       : BYTE  185-191
```

Figure 201: EBCDIC header

10.1.1 EBCDIC header

The EBCDIC (Extended Binary Coded Decimal Interchange Code) header is an encoding method introduced by IBM (1964). It is an 8-bit encoding method used to represent numbers, alphabetical characters, and grammatical syntax. This format is still used in SEG-Y file format but not in other formats where the ASCII format is preferred. An example of the EBCDIC header in number and character form is shown in Figure 201. The header comprises 40 rows of free format alphanumeric text. Each row in the header commences with the header record C which is immediately followed by the row number (e.g., C30). After that the publisher has the remaining column widths to enter any text comments that are relevant to the data contained in the data block. In Figure 201, notice how the first 16 lines contain general text information about client, survey area and some byte location details. Whilst rows 18 to 36 contain details concerning the processing flow applied in seismic processing to the trace data. However, as this format is free text there is no published format that the file generators need to follow during the header creation.

From a geo-spatial perspective, it is important to check whether the EBCDIC header contains any details relating to the coordinate reference system to which the positions stored in the trace header are related. As will be demonstrated, the byte locations in the trace header allocated to store geo-spatial data can only accommodate coordinates referenced to a projected CRS. Therefore, knowing details of the CRS are important to ensure the integrity of the seismic trace data is retained.

10.1.2 Trace header

Associated with each seismic trace is a trace header which comprises 240-byte block of metadata. Unlike the EBCDIC header, the trace header is structured, and the 240-byte locations are designated to storing specified data. An example of some of the byte definitions is shown in Figure 202. For a full definition see the SEG-Y format document.

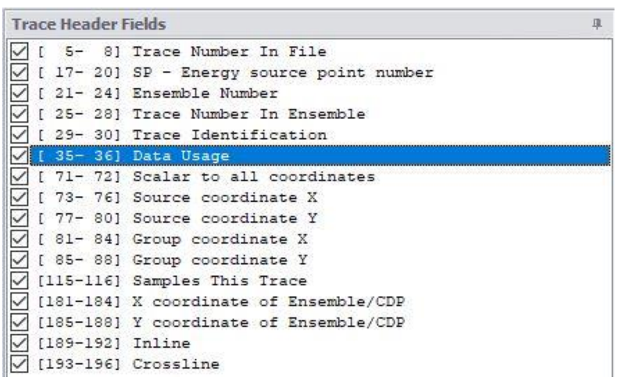


Figure 202: Example byte locations of the SEG-Y trace header

This depends upon what seismic data the SEG-Y file contains. Typically, three types of seismic gathers will be stored in SEG-Y file. These being:

- Shot gathers
- Receiver gathers
- Trace gathers

The type of gather will depend upon what byte locations are used and how. Three examples will follow in the order given:

10.1.2.1 Shot gather

A shot gather comprises the seismic data recorded at different receiver groups for a single shot point. An example of a shot gather for a marine seismic is shown in Figure 203.

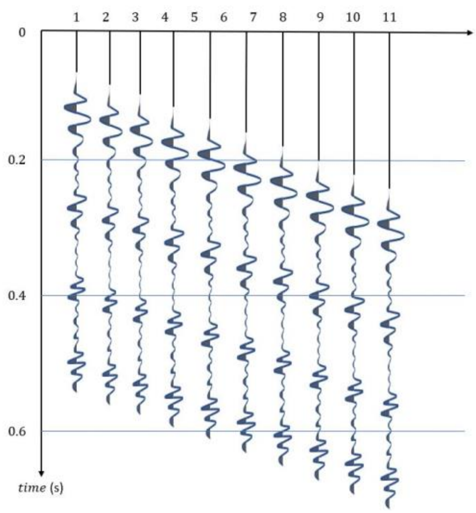


Figure 203: Shot gather

Along the vertical axis is the two way time which represents the travel time between the acoustic energy leaving the source and being detected at each receiver (hydrophone). Along the horizontal axis are the receiver group numbers in the streamer. This is shown diagrammatically in Figure 204 which represents the rays traveling between the source and receiver groups 1 through to group 11. With each receiver group, the first arrival is the direct arrival which is the wave that travels along the surface from the source to each receiver group.

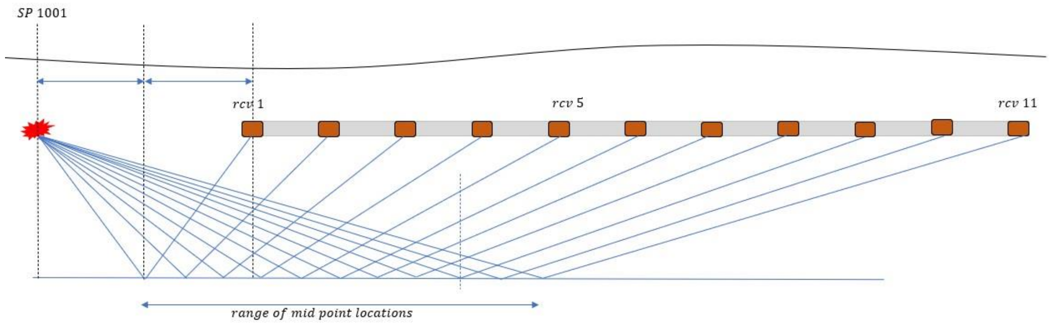


Figure 204: Representation of the shot gather

Therefore, in the source gather there is one shot point location and multiple receiver locations. As such, the byte locations in the trace header of the SEG-Y will resemble what is shown in Figure 205.

Trace No.	Ensemble No.	Source_X	Source_Y	Group_X	Group_Y
1	14899	442682	6303743	441859	6303800
2	14900	442682	6303743	441865	6303800
3	14901	442682	6303743	441871	6303799
4	14902	442682	6303743	441877	6303799
5	14903	442682	6303743	441884	6303799
6	14904	442682	6303743	441890	6303798
7	14905	442682	6303743	441896	6303798
8	14906	442682	6303743	441902	6303797
9	14907	442682	6303743	441909	6303797
10	14908	442682	6303743	441915	6303796
11	14909	442682	6303743	441921	6303796
12	14910	442682	6303743	441927	6303795
13	14911	442682	6303743	441934	6303795
14	14912	442682	6303743	441940	6303795
15	14913	442682	6303743	441946	6303794
16	14914	442682	6303743	441952	6303794
17	14915	442682	6303743	441958	6303793
18	14916	442682	6303743	441965	6303793
19	14917	442682	6303743	441971	6303792
20	14918	442682	6303743	441977	6303792
21	14919	442682	6303743	441983	6303792
22	14920	442682	6303743	441990	6303791
23	14921	442682	6303743	441996	6303791
24	14922	442682	6303743	442002	6303790
25	14923	442682	6303743	442008	6303790
26	14924	442682	6303743	442015	6303789
27	14925	442682	6303743	442021	6303789
28	14926	442682	6303743	442027	6303789

Figure 205: Example of the coordinates in a shot gather

- Source X coordinate is stored in Byte locations 73 to 76
- Source Y coordinate in Byte locations 77 to 80
- Group X coordinate in Byte locations 81 to 84

- Group Y coordinates in Byte locations 85 to 88

In Figure 205 notice that the source coordinates are identical for each trace number, but the receiver coordinates are different. This is what is expected from a geo-spatial data contained in the SEG-Y trace headers for a source gather. The byte locations reserved for the CDP_X and CDP_Y should be empty as no geo-spatial data associated with the trace gathers is stored.

10.1.3 Receiver gather

The receiver gather comprises all the seismic data acquired at a single receiver group from multiple shot points.

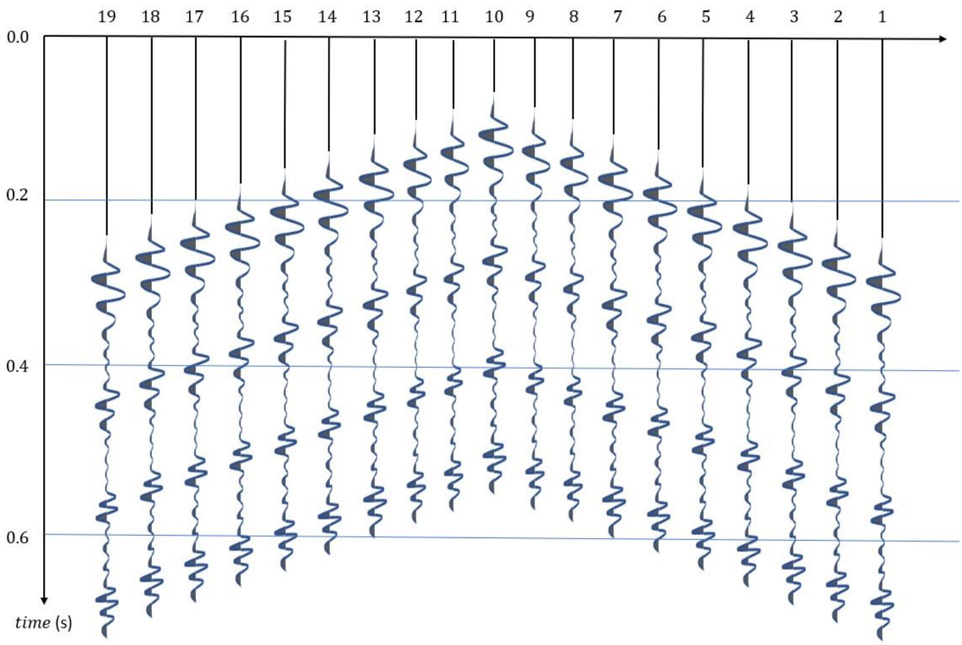


Figure 206: Receiver gather

This is shown diagrammatically in Figure 207. One receiver records returning seismic energy from multiple shot points at varying horizontal offsets from the receiver. In this example the receiver is located at the centre of the diagram with shot point 10 being the closest approaching source position.

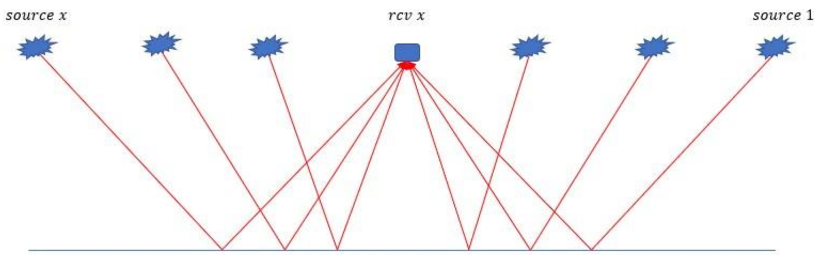


Figure 207: One receiver recording data from multiple sources

Again:

The Source X coordinate is stored in Byte locations 73 to 76

Source Y coordinate in Byte locations 77 to 80

Group X coordinate in Byte locations 81 to 84

Group Y coordinates in Byte locations 85 to 88

Trace No.	Ensemble No.	Source_X	Source_Y	Group_X	Group_Y
1	14899	441859	6303800	442682	6303743
2	14900	441865	6303800	442682	6303743
3	14901	441871	6303799	442682	6303743
4	14902	441877	6303799	442682	6303743
5	14903	441884	6303799	442682	6303743
6	14904	441890	6303798	442682	6303743
7	14905	441896	6303798	442682	6303743
8	14906	441902	6303797	442682	6303743
9	14907	441909	6303797	442682	6303743
10	14908	441915	6303796	442682	6303743
11	14909	441921	6303796	442682	6303743
12	14910	441927	6303795	442682	6303743
13	14911	441934	6303795	442682	6303743
14	14912	441940	6303795	442682	6303743
15	14913	441946	6303794	442682	6303743
16	14914	441952	6303794	442682	6303743
17	14915	441958	6303793	442682	6303743
18	14916	441965	6303793	442682	6303743
19	14917	441971	6303792	442682	6303743
20	14918	441977	6303792	442682	6303743
21	14919	441983	6303792	442682	6303743
22	14920	441990	6303791	442682	6303743
23	14921	441996	6303791	442682	6303743
24	14922	442002	6303790	442682	6303743
25	14923	442008	6303790	442682	6303743

Figure 208: Trace header coordinates for a receive gather

In Figure 208 notice that the receiver coordinates are identical for each trace number, but the source coordinates are different. This is what is expected from a geo-spatial data contained in the SEG-Y trace headers for a receiver gather. The byte locations reserved for the CDP_X and CDP_Y should be empty as no geo-spatial data associated with the trace gathers is stored.

10.1.4 Trace gathers

Source and receiver gathers are considered pre-stack data. The trace gather is post-stack data, indicating that the seismic data has undergone some element of processing which involves all the trace data gathered into each cell of the binning grid.

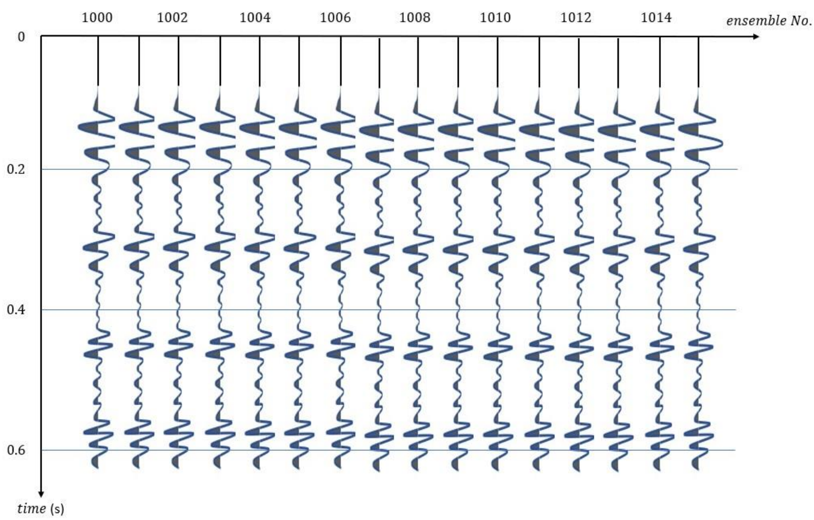


Figure 209: Trace gather

Each vertical wiggle represents a single location where seismic trace data is gathered together. This is known as a common mid-point on the CMP line and the coordinates of every individual location are stored in the trace header and should be in byte locations 181-184 and 185-188 for the X and Y coordinates respectively. However, it is not unusual to find them in other byte locations such as those dedicated to the source X and source Y or some other arbitrarily designed byte locations, which may or may not be specified in the EBCDIC header.

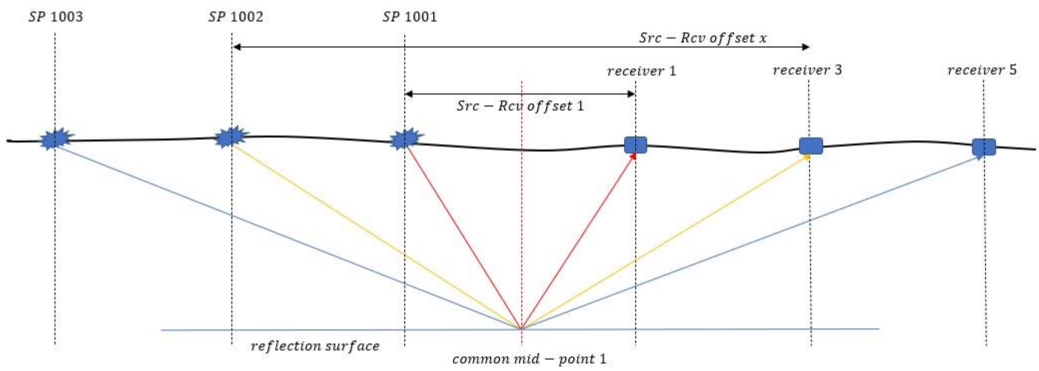


Figure 210: Common mid-point gather

An example of the coordinates stored in the CDP byte locations is shown in Figure 211. The coordinates are stored in the correct byte locations and are shown under the CDP_X and CDP_Y columns which correlate to the trace numbers shown in the left hand column. As this is a 3D seismic survey the inline and crossline numbers shown on the right indicate to which cell of the seismic binning grid the coordinates belong. These coordinates represent the center of each cell indexed.

Trace Num...	Source_X	Source_Y	Group_X	Group_Y	CDP_X	CDP_Y	Inline	Crossline
1	9999	9999	9999	9999	443613	3125612	759	3000
2	9999	9999	9999	9999	443638	3125612	759	3001
3	9999	9999	9999	9999	443663	3125612	759	3002
4	9999	9999	9999	9999	443688	3125612	759	3003
5	9999	9999	9999	9999	443713	3125612	759	3004
6	9999	9999	9999	9999	443738	3125612	759	3005
7	9999	9999	9999	9999	443763	3125612	759	3006
8	9999	9999	9999	9999	443788	3125612	759	3007
9	9999	9999	9999	9999	443813	3125612	759	3008
10	9999	9999	9999	9999	443838	3125612	759	3009
11	9999	9999	9999	9999	443863	3125612	759	3010
12	9999	9999	9999	9999	443888	3125612	759	3011
13	9999	9999	9999	9999	443913	3125612	759	3012
14	9999	9999	9999	9999	443938	3125612	759	3013
15	9999	9999	9999	9999	443963	3125612	759	3014
16	9999	9999	9999	9999	443988	3125612	759	3015
17	9999	9999	9999	9999	444013	3125612	759	3016
18	9999	9999	9999	9999	444038	3125612	759	3017
19	9999	9999	9999	9999	444063	3125612	759	3018
20	9999	9999	9999	9999	444088	3125612	759	3019
21	9999	9999	9999	9999	444113	3125612	759	3020

Figure 211: CDP / CMP byte locations

10.1.5 The data block

The data block or trace block contains the seismic trace data extracted from the SEG-Y file. An example of this is shown in Figure 212.

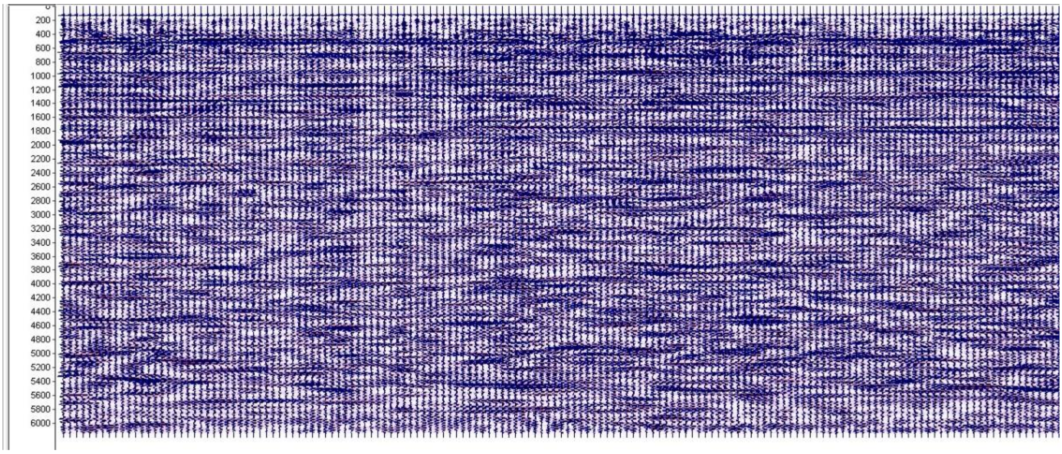


Figure 212: Example seismic section from data block

Each trace is shown by an individual vertical wiggle and associated with each wiggle is a trace header which contains the horizontal position of that trace (see section 10.1.4). What processing steps have been applied to the seismic trace data will normally be described in the EBCDIC header to indicate through what part of the processing cycle this section belongs (e.g., final migrated stack).

Down the left-hand side is shown the Two-Way Time (TWT) which is the length of time it took the acoustic energy to travel from the seismic source, reflect off the geological boundary and be detected by the hydrophones in the seismic streamer. Therefore, this is a time related section (time domain). One modification made to this is to convert the vertical component from the post-stack time domain to the post-stack depth domain by the application of the velocity model generated for the seismic data.

11 Euler rotations and the similarity transform

A coordinate operation is described that converts the coordinates of a point P between two independently defined coordinate systems about a single rotation point. In its full form this is called the affine transformation of which there are several variants. A simplified version of it is known as the similarity transformation which is the one applied when a coordinate operation between two cartesian coordinate systems is conducted, e.g., between seismic bin grid and a projected CRS. This is a special case of the Affine transformation as will be demonstrated. Prior to introducing the simplified version, it is prudent to start with the affine transformation and describe the unique complexities involved in its definition. Details of this are given in here along with a 3D expansion of the technique. This is followed by some worked examples in its application to the seismic bin grid.

11.1 Affine transformation

The affine transformation has several variants and that described here is known as the geometric version because it is the one applied when the conversion (of the Derived CRS) between the coordinate system of the seismic grid and that of the projected CRS is conducted.

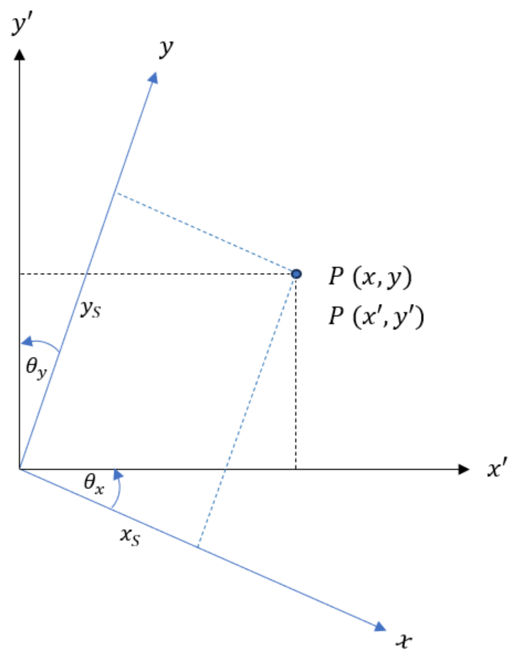


Figure 213: Affine space and coordinate system

In affine space, the two axes of the affine coordinate system are treated individually such that they can experience different amounts of rotation and different levels of scaling and magnitude when the transformation is applied. Refer to Figure 213 where the two different rotations are shown by θ_X and θ_Y. The cartesian coordinate system and affine coordinate system share the same origin point. The coordinate operation is reversible and therefore consideration is given to both the forward and reverse methods.

11.1.1 Forward transformation

The input coordinates of point P, X_S and Y_S are given in relation to the X and Y axis of the input affine coordinate system (the source) and the output coordinates, X_T and Y_T in relation to the axes of the cartesian coordinate system (the target). This is illustrated in Figure 214 where the input coordinates are represented by the blue lettering and the output as the black lettering.

$$X_S, Y_S \Leftrightarrow Transform \Leftrightarrow X_T, Y_T$$

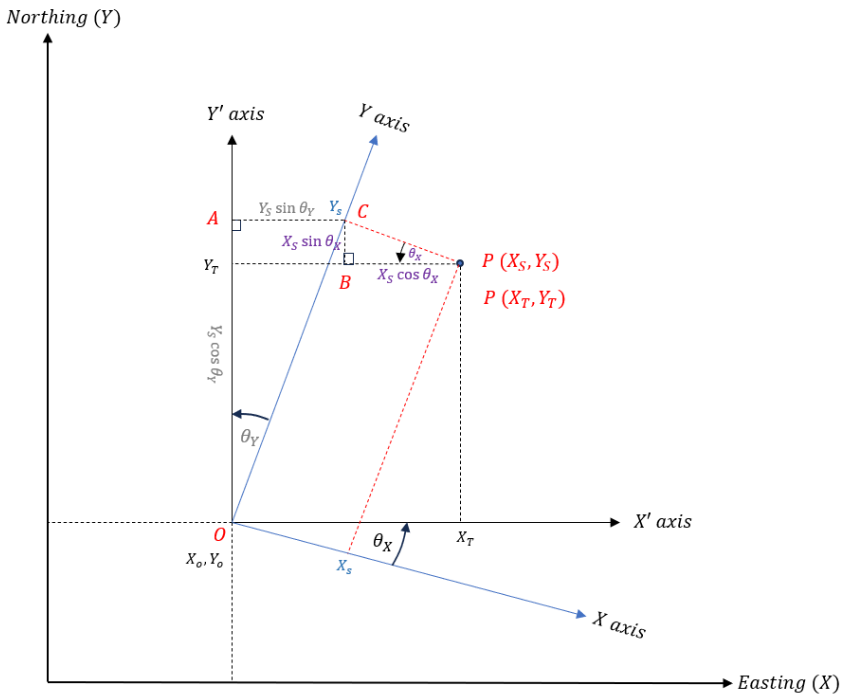


Figure 214: Affine transformation

The transformation is derived as follows. Consider triangle ΔOAC and take the trigonometric functions of the triangle, namely:

$$\sin\theta_Y = \frac{AC}{OC} \qquad \cos\theta_Y = \frac{OA}{OC}$$

$$\therefore OC\sin\theta_Y = AC \qquad \therefore OC\cos\theta_Y = OA$$

Note, the rotation is given by the angle θ_Y.

Next, consider triangle ΔPBC where its trigonometric relationships are given by:

$$\sin\theta_X = \frac{BC}{PC} \qquad \cos\theta_X = \frac{PB}{PC}$$

$$\therefore PC\sin\theta_X = BC \qquad \therefore PC\cos\theta_X = PB$$

Where the rotation is given by the angle θ_X.

Prior to applying these trigonometric relationships, the input and output coordinates are represented as follows:

$$X_S = PC \qquad \Leftrightarrow \qquad X_T = PB + AC$$

$$Y_S = OC \qquad \qquad Y_T = OA - BC$$

First, substitute the alternative input coordinates into trigonometric functions, e.g., $X_S \; and \; Y_S$ to give:

$$Y_S\sin\theta_Y = AC \qquad Y_S\cos\theta_Y = OA$$

$$X_S\sin\theta_X = BC \qquad X_S\cos\theta_X = PB$$

Next, substitute the trigonometric relationships into the two equations of the output coordinates to give the following:

$$X_T = X_S\cos\theta_X + \; Y_S\sin\theta_Y$$

$$Y_T = Y_S\cos\theta_Y - X_S\sin\theta_X$$

Put these two equations into matrix form with a slight rearrangement of the terms to give:

$$\begin{bmatrix} X_T \\ Y_T \end{bmatrix} = \begin{bmatrix} \cos\theta_X & \sin\theta_Y \\ -\sin\theta_X & \cos\theta_Y \end{bmatrix} \begin{bmatrix} X_S \\ Y_S \end{bmatrix}$$

Which is simplified to:

$$\begin{bmatrix} X_T \\ Y_T \end{bmatrix} = R \begin{bmatrix} X_S \\ Y_S \end{bmatrix}$$

Where:

$$R = \begin{bmatrix} \cos\theta_X & \sin\theta_Y \\ -\sin\theta_X & \cos\theta_Y \end{bmatrix}$$

Next, factor in the linear offset between the origin of the affine coordinates system (seismic grid) and the origin of the cartesian coordinate system (projected CRS), which is given by X_o and Y_o. This results in the following:

$$\begin{bmatrix} X_T \\ Y_T \end{bmatrix} = \begin{bmatrix} X_o \\ Y_o \end{bmatrix} + \begin{bmatrix} \cos\theta_X & \sin\theta_Y \\ -\sin\theta_X & \cos\theta_Y \end{bmatrix} \begin{bmatrix} X_S \\ Y_S \end{bmatrix}$$

Finally, the magnitude of point P, with respect to the axes along both affine and cartesian coordinate systems (X_S, Y_S & X_T, Y_T), needs further quantification in order that scaling can be applied to each axis independently, as required. This is a condition of the affine transformation, and the scaling applied to the two axes (of the input coordinate system) is represented by the two terms ($I_S \ and \ J_S$). These are included as multiplication factors to the two axes $X_S \ and \ Y_S$ in the above equation accordingly.

$$\begin{bmatrix} X_T \\ Y_T \end{bmatrix} = \begin{bmatrix} X_o \\ Y_o \end{bmatrix} + \begin{bmatrix} \cos\theta_X & \sin\theta_Y \\ -\sin\theta_X & \sin\theta_Y \end{bmatrix} * k * \begin{bmatrix} I_S & 0 \\ 0 & J_S \end{bmatrix} * \begin{bmatrix} X_S \\ Y_S \end{bmatrix}$$

Provision is also given to applying a scaling factor (k) to the output coordinate system (e.g., map projection). This is known as the point scale factor and is represented by the term k in the equation above. Only one term is required here as the unit of measure applied to the two axes of the output coordinate system (map projection) must be the same by definition.

11.1.2 Reverse computation

In this derivation the input coordinates of point P (X_T and Y_T) are given in relation to the X and Y axis of the input cartesian coordinate system (the source) and the output coordinates, X_S and Y_S in relation to the X' and Y' axes of the affine coordinate system (the target). This is illustrated in Figure 215 where the input coordinates are represented by the black lettering and the output as the blue lettering.

$$X_S, Y_S \Leftrightarrow Transform \Leftrightarrow X_T, Y_T$$

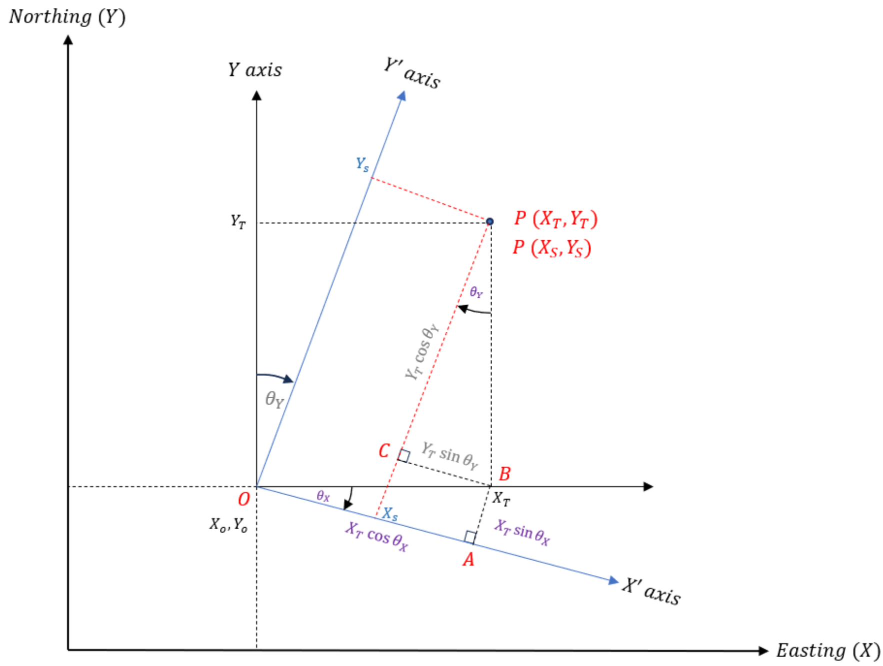


Figure 215: Affine transformation - reverse method

The transformation is derived as follows. Consider the triangle ΔPCB and take its trigonometric functions, namely:

$$\sin\theta_Y = \frac{BC}{BP} \qquad \cos\theta_Y = \frac{PC}{BP}$$

$$\therefore BP\sin\theta_Y = BC \qquad \therefore BP\cos\theta_Y = PC$$

Note, the rotation is given by the angle θ_Y.

The second triangle is ΔOAB and its trigonometric functions are given by:

$$\sin\theta_X = \frac{AB}{OB} \qquad\qquad \cos\theta_X = \frac{OA}{OB}$$

$$\therefore OB\sin\theta_X = AB \qquad\qquad \therefore OB\cos\theta_X = OA$$

Where the rotation is given by the angle θ_X.

Prior to applying these trigonometric relationships, the input and output coordinates are represented as follows:

$$X_T = OB \qquad\qquad X_S = OA - BC$$

$$Y_T = BP \qquad \Leftrightarrow \qquad Y_T = AB + PC$$

First, substitute the alternative input coordinates into the trigonometric functions, e.g., $X_T\ and\ Y_T$ to give:

$$Y_T\sin\theta_Y = BC \qquad\qquad Y_T\cos\theta_Y = PC$$

$$X_T\sin\theta_X = AB \qquad\qquad X_T\cos\theta_X = OA$$

Next, substitute in the trigonometric relationships into the two equations of the output coordinates gives the following:

$$X_S = X_T\cos\theta_X - Y_T\sin\theta_Y$$

$$Y_S = Y_T\sin\theta_Y + X_T\cos\theta_X$$

Put these two equations into matrix form with a slight rearrangement of the terms:

$$\begin{bmatrix} X_S \\ Y_S \end{bmatrix} = \begin{bmatrix} \cos\theta_X & -\sin\theta_Y \\ \sin\theta_X & \cos\theta_Y \end{bmatrix} \begin{bmatrix} X_T \\ Y_T \end{bmatrix}$$

Which can be simplified to:

$$\begin{bmatrix} X_S \\ Y_S \end{bmatrix} = R\begin{bmatrix} X_T \\ Y_T \end{bmatrix}$$

Where:

$$R = \begin{bmatrix} \cos\theta_X & -\sin\theta_Y \\ \sin\theta_X & \cos\theta_Y \end{bmatrix}$$

Therefore, the rotation matrix of the reverse method is the inverse matrix of the forward method.

$$\begin{bmatrix} X_S \\ Y_S \end{bmatrix} = \begin{bmatrix} X_o \\ Y_o \end{bmatrix} + \begin{bmatrix} \cos\theta_X & -\sin\theta_Y \\ \sin\theta_X & \sin\theta_Y \end{bmatrix} * k * \begin{bmatrix} \frac{1}{I_S} & 0 \\ 0 & \frac{1}{J_S} \end{bmatrix} * \begin{bmatrix} X_T \\ Y_T \end{bmatrix}$$

In the reverse method the scaling related to the axes is the inverse of that applied in the forward method.

11.2 Similarity transformation

The simplification applied to the affine transformation to give the special case known as the similarity transform is done through the following four rules to ensure a space equivalence:

- There is an orthogonal relationship between the coordinate axes of the cartesian 2D coordinate system used in the grid definition.
- The angular rotation applied to the two axes is the same. Hence:

$$\theta_X = \theta_Y$$

- The scale factor is the same along both axes of the grid.
- The unit of measure is the same along both axes of the grid.

Therefore, the similarity transformation is named such that the properties of the coordinate system are the same for both axes.

$$\begin{bmatrix} X_T \\ Y_T \end{bmatrix} = \begin{bmatrix} X_o \\ Y_o \end{bmatrix} + \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \sin\theta \end{bmatrix} * k * \begin{bmatrix} I_S & 0 \\ 0 & J_S \end{bmatrix} * \begin{bmatrix} X_S \\ Y_S \end{bmatrix}$$

In this matrix equation, notice that the same rotation (θ) is applied to both axes of the cartesian coordinate system.

11.2.1 Cartesian 3D model

Thus far the cartesian coordinate system has been treated as a 2D model. When expanded to include a third axis, the $Z\ axis$, it creates a cartesian 3D coordinate system with the three axes as shown in Figure 216. The introduction of the third axis creates three-dimensional space about three axes. Rotations can be applied around any of the three axes to create a displacement of the shape / objects described which introduces Euler's Theorem and the basic concept of the Euler rotation. This theorem has many uses in geo-spatial data which include the representation of the geocentric global CRS about which rotations are performed to change the data such that it is referenced to another target CRS.

Therefore, apply a rotation about the $Z\ axis$ of the cartesian 3D model. Here, the axes of one coordinate system (black) are labelled X, Y and Z with the alternative coordinate system (red) being labelled X', Y' and Z. This converts the points defining the shape from the source coordinate system (X, Y, Z) to a Target coordinate system (X', Y', Z) by some angle θ_Z, which is known as the Euler angle. Notice that Z axis is common to both, the rotation axis.

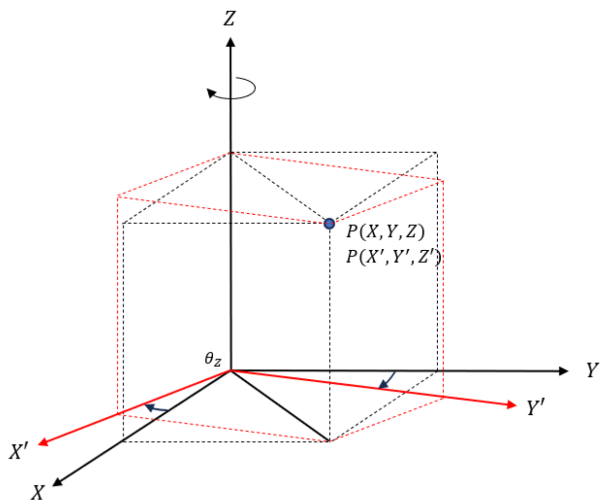


Figure 216: Rotation about the Z axis

If the rotation is applied about the $Z\ axis$ of the black coordinate system this will only affect data in the X-Y plane. The angular relationship between the two coordinate systems is described by θ_Z. The rotation about $Z\ axis$ can be applied in both a positive and a negative sense, where:

1. Where (X, Y) is the Source and (X', Y') the Target.
2. Where (X', Y') is the Source and (X, Y) the Target.

These are shown in Figure 217 where the $Z\ axis$ is perpendicular to the page (coming out of the page). Viewing it from this perspective (outside looking in) a positive rotation is in the clockwise direction (left side) and the negative rotation (right side) is in the counterclockwise direction. Therefore, the rotation only affects the X-Y plane. The matrix representation of the transformation can be extended to include the third axis as shown:

$$\begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} = \begin{bmatrix} X_O \\ Y_O \\ Z_O \end{bmatrix} + \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} * k * \begin{bmatrix} I_S & 0 & 0 \\ 0 & I_J & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix}$$

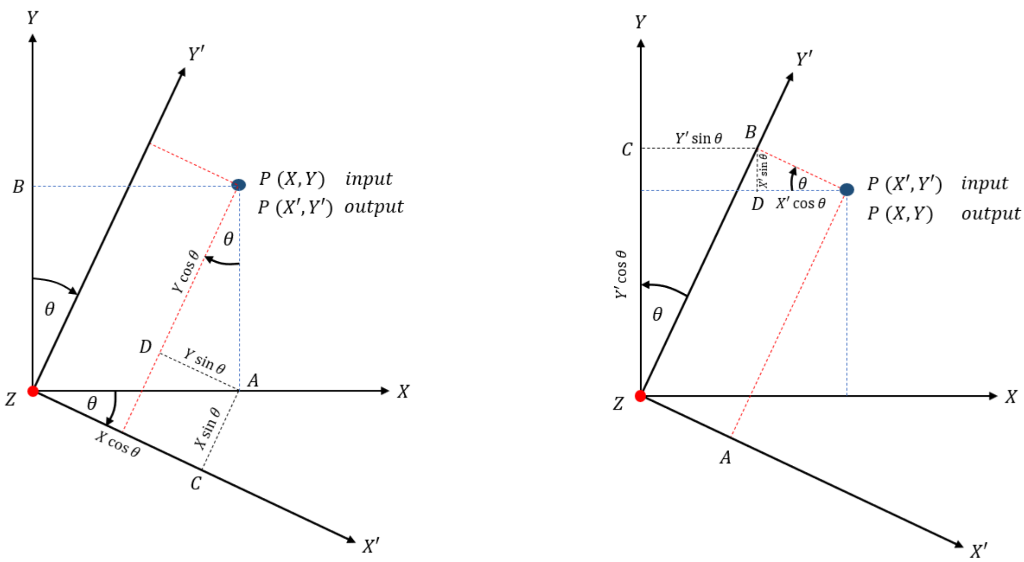


Figure 217: Positive and negative Euler rotations

11.2.2 Model specific to seismic grid

Before any worked examples are discussed the similarity transformation is described as operating between the seismic grid and the projected CRS for the two cases laid out in section 3. Namely, when the seismic grid is of type: Engineering CRS and Derived CRS.

For the seismic grid of type: Engineering CRS the coordinate operation is treated as a transformation, as it assumes the datum of the Source and the base datum of the Target CRS differ. For example:

Source CRS: Engineering CRS (integer or real values)

Target CRS: Projected CRS (real values)

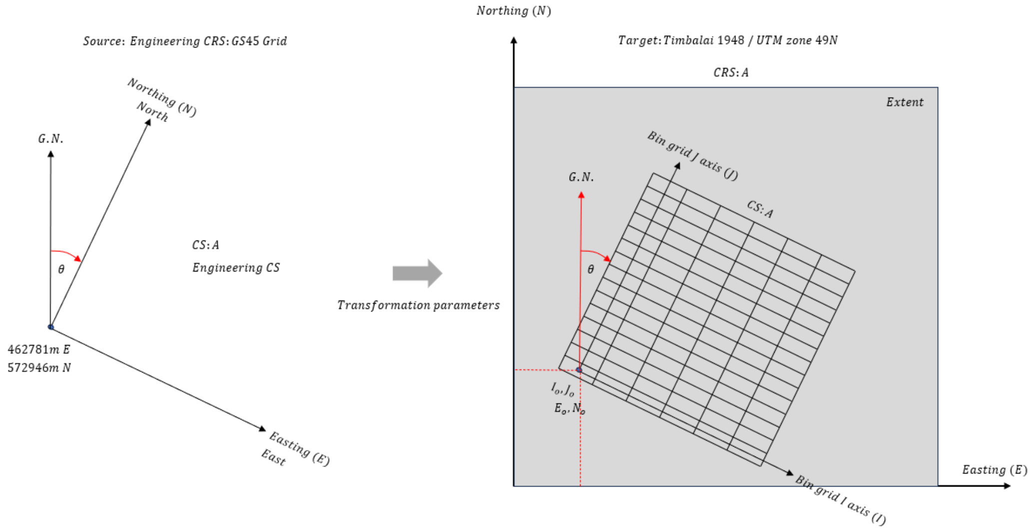


Figure 218: Transforming from grid to projection

As such the datum of the engineering CRS is of type: engineering and the datum of the projected CRS is of type: geodetic and thus there is a change in datum type.

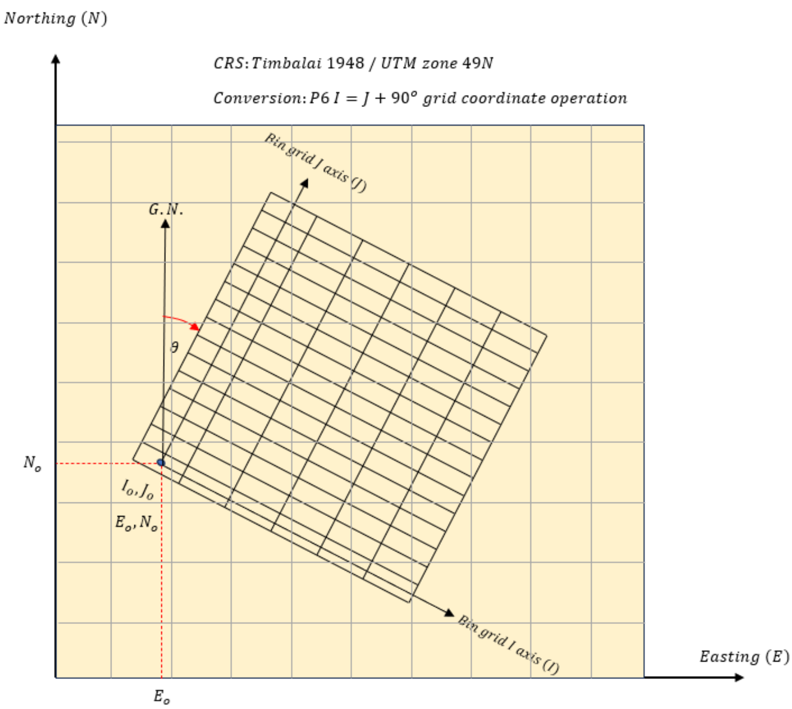


Figure 219: Grid derived conversion

For the seismic grid of type: Derived CRS this is coordinate operation of type: conversion as the base geodetic datum associated with each CRS remains consistent throughout the operation. As there is no change in geodetic datum the operation is treated as a conversion.

Seismic grid: CRS A (Figure 219)

Projected base CRS of seismic grid: Timbalai 1948 / UTM zone 49N

Base geographic CRS of projected CRS: Timbalai 1948

Regardless of operation type, the parameters applied are shown in Table 15. Therefore, the parameters and parameter values for the Engineering CRS are applied to the associated transformation, whilst they are applied as a conversion for the Derived CRS.

Table 15: Transformation parameters from Engineering CRS

Parameter	Value	Symbol	Unit of Measure
Grid origin I	1001	I_o	Bin
Grid origin J	1001	J_o	Bin
Grid origin Easting	462781	E_o	metre
Grid origin Northing	572946	N_o	metre
Scale factor of grid	1	k or SF	unity
Width on I axis	25	I_{width}	metre
Width on J axis	12.5	J_{width}	metre
Map grid bearing of J axis	20	θ	degree
Increment on I axis	1	I_{inc}	Bin
Increment of J axis	1	J_{inc}	Bin

The algorithms used in the forward and reverse application appears identical for both cases as the worked examples will demonstrate.

11.3 Computations and worked examples

Diagrammatically, the operations between the seismic grid and either the Engineering CRS (transformation) or Derived CRS (conversion) is shown in Figure 220. When converting points between the seismic grid (I, J) and the projected CRS (E, N).

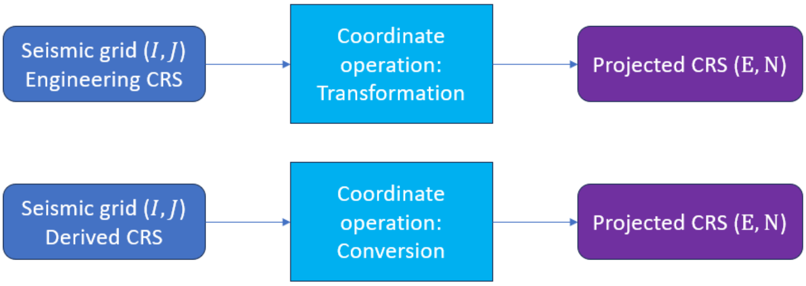


Figure 220: Coordinate operation type

What follows are three coordinate operation computation examples which involve different rotation angles and different grid orientations. As the computations are reversible (both forward and reverse) it enables the following:

- Input: I and J coordinate of the cell centre of the seismic grid. The output is the E and N referenced to the projected CRS.
- Input: E and N coordinate of the cell centre in relation to a projected CRS. The output is the I and J coordinate referenced to the seismic grid.

The three examples shown are as follows:

- Where the $J\ axis$ of the seismic grid is aligned in the same orientation as the projected CRS grid north. The seismic grid has a right handed orientation.
- Where the $J\ axis$ of the seismic grid is at an oblique angle to the projected CRS grid north. The seismic grid has a right handed orientation.
- Same as above but the seismic grid has a left handed orientation.

All of which will use all or part of the general similarity transform equation applied to the forward and reverse computations. For the forward computation the general similarity transform is given by:

$$\begin{bmatrix} E \\ N \end{bmatrix} = \begin{bmatrix} E_o \\ N_o \end{bmatrix} + \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} SF \begin{bmatrix} I_{width} & 0 \\ 0 & J_{width} \end{bmatrix} \begin{bmatrix} I - I_o \\ J - J_o \end{bmatrix}$$

Where the reverse computations is given by:

$$\begin{bmatrix} I \\ J \end{bmatrix} = \begin{bmatrix} I_O \\ J_O \end{bmatrix} + \begin{bmatrix} E - E_O \\ N - N_O \end{bmatrix} * \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} * \begin{bmatrix} \frac{1}{SF * I_{width}} & 0 \\ 0 & \frac{1}{SF * J_{width}} \end{bmatrix}$$

Therefore, if the axes of the seismic grid coordinate system are aligned to those of the projected CRS the rotation matrix is removed giving:

$$\begin{bmatrix} E \\ N \end{bmatrix} = \begin{bmatrix} E_O \\ N_O \end{bmatrix} + SF \begin{bmatrix} I_{width} & 0 \\ 0 & J_{width} \end{bmatrix} \begin{bmatrix} I - I_O \\ J - J_O \end{bmatrix}$$

And for the reverse:

$$\begin{bmatrix} I \\ J \end{bmatrix} = \begin{bmatrix} I_O \\ J_O \end{bmatrix} + \begin{bmatrix} E - E_O \\ N - N_O \end{bmatrix} * \begin{bmatrix} \frac{1}{SF * I_{width}} & 0 \\ 0 & \frac{1}{SF * J_{width}} \end{bmatrix}$$

Both versions are shown in sections 8.3.1. and 8.3.2. respectively.

11.3.1 J axis aligned to grid north

This is the simplest case and a good one with which to introduce the computation. The parameters of the seismic binning grid are shown in Table 15.

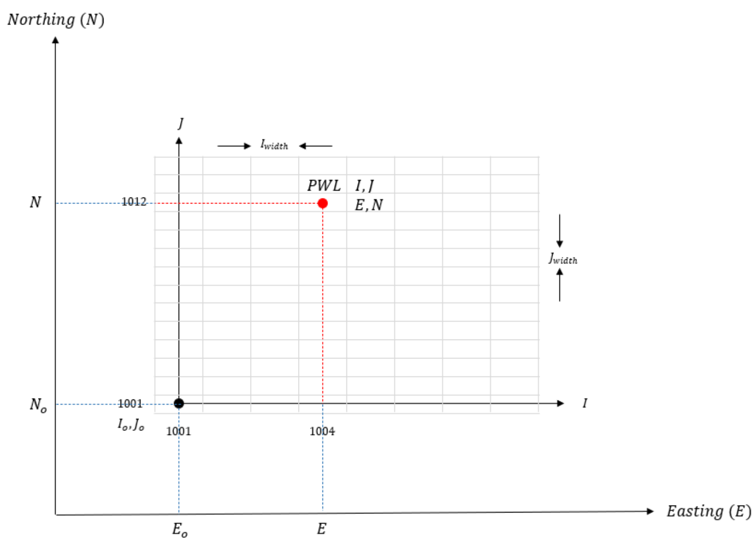


Figure 221: With seismic grid aligned to grid north

A Proposed Well Location (PWL) is chosen whose coordinates when referenced to the seismic grid are given as I = 1004 and J = 1012 in relation to the seismic grid origin of I = 1001 and J = 1001. What is required is to express the same physical position but now referenced to a selected projected CRS. Therefore, the I, J coordinates related to the seismic grid form the input and the E, N coordinates of the projected CRS form the output. If the projected CRS is Timbalai 1948 / UTM zone 49N what values are derived for the PWL referenced to this CRS? Note, the orientation of the $J\ axis$ of the binning grid 0^o in relation to grid north. Therefore, no rotations are required, e.g., matrix R is redundant.

11.3.1.1 Forward computation

As no rotation is required the simpler form of the similarity transformation is applied which when its matrix form is expanded gives:

$$\begin{bmatrix} E \\ N \end{bmatrix} = \begin{bmatrix} E_o \\ N_o \end{bmatrix} + SF \begin{bmatrix} I_{width} & 0 \\ 0 & J_{width} \end{bmatrix} \begin{bmatrix} I - I_o \\ J - J_o \end{bmatrix}$$

$$E = E_o + SF * I_{width} * (I - I_o)$$

$$N = N_o + SF * J_{width} * (J - J_o)$$

First, the distance of the point P along the two axes of the seismic grid is derived as follows:

$$I_{width} * (I - I_o) = I_{width} * \Delta I = I_{distance}$$

$$J_{width} * (J - J_o) = J_{width} * \Delta J = J_{distance}$$

Where:

I_o is the origin of the grid along the $I\ axis$

I_{width} is the real width of each cell along the $I\ axis$ (e.g., one unit along the $I\ axis$)

I is the coordinate of point P along the $I\ axis$

J_o is the origin of the grid along the $J\ axis$

J is the real width of each cell along the $J\ axis$ (e.g., one unit along the $J\ axis$)

J is the coordinate of point P along the $J\ axis$

Therefore, the offsets of the point (PWL) in relation to the seismic grid origin are given as:

$$I\ axis = I - I_o = 1004 - 1001 = 3$$

$$J\ axis = J - J_o = 1012 - 1001 = 11$$

Multiply the cell offsets by the width of the cells along the two axes of the coordinate system, which are given by $I_{width} = 25m$ and $J_{width} = 12.5m$:

$$I\ axis = I_{width}(I - I_o) = 25 * 3 = 75m$$

$$J\ axis = J_{width}(J - J_o) = 12.5 * 11 = 137.5m$$

The scale factor along the two axes is given as one which requires no further action on the expressions shown above:

The origin of the seismic binning grid in reference to the projected CRS is given as:

$$462781.00\ mE$$

$$572946.00\ mN$$

Substitute in the parameter values to compute the projected CRS of the proposed bin grid location.

$$Easting = 462781 + 1 * 25 * (1004 - 1001) = 462856.00m$$

$$Northing = 572946 + 1 * 12.5 * (1012 - 1001) = 573083.50m$$

11.3.1.2 Reverse process

If the easting and northing coordinates are known (for the proposed drilling location) the conversion is reversed to determine into which cell of the seismic grid the location belongs.

$$\begin{bmatrix} I \\ J \end{bmatrix} = \begin{bmatrix} I_o \\ J_o \end{bmatrix} + \begin{bmatrix} E - E_o \\ N - N_o \end{bmatrix} * \begin{bmatrix} \frac{1}{SF * I_{width}} & 0 \\ 0 & \frac{1}{SF * J_{width}} \end{bmatrix}$$

Multiple out the matrix form to get the two equation, which are the forward computations rearranged thus:

$$I = \frac{(E - E_o)}{SF * \ I_{width}} + I_o$$

$$J = \frac{(N - N_o)}{SF * \ J_{width}} + J_o$$

Therefore:

$$I = \frac{(462856 - 462781)}{25} + 1001 = 1004$$

$$J = \frac{(573083.5 - 572946)}{12.5} + 1001 = 1012$$

11.3.2 Seismic grids with oblique angles

Next, consider a seismic grid whose survey bearing is oblique, i.e., not 0° in relation to grid north, for example, the $J\ axis$ has a bearing of 30° in relation to grid north. Therefore, the grid will appear as is shown in Figure 222.

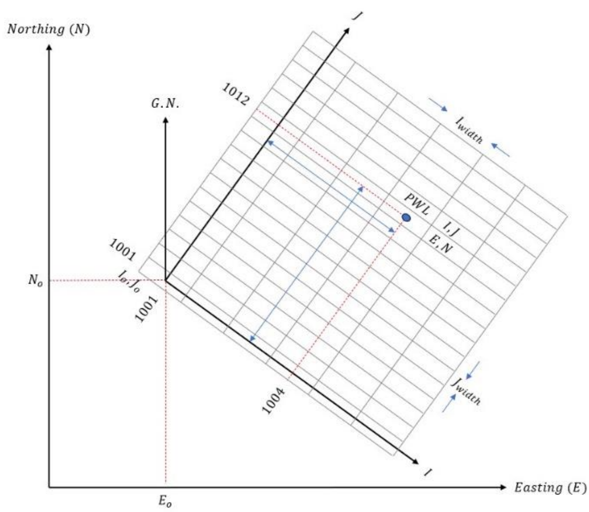


Figure 222: Rotated bin grid related to grid north

The seismic grid is defined using the same parameters as previous, with the exception that the survey bearing has changed from 0° to 30°. This is the angle between grid north and the $J\ axis$ of the seismic grid. Just to mix things up the other grid parameters have been modified but are still referenced to the same projected CRS.

Table 16: Grid parameters used in the computation

Parameter	Symbol	Parameter value
Grid origin I	I_o	1001
Grid origin J	J_o	1001
Grid origin Easting	E_o	550000
Grid origin Northing	N_o	475000
Scale factor of grid	SF	1
Width on I axis	I width	25
Width on J axis	J width	6.25
Map grid bearing of J axis	θ	30
Grid increment on I axis	I inc	1
Grid increment on J axis	J inc	1

11.3.2.1 Forward process – right handed orientation

With an oblique angle, the coordinate conversion between the seismic grid (I, J) and projected CRS (E, N) must use the full form of the equation and thus contain the term of the rotation matrix to account for the angular difference in the X Y plane. Therefore, the equation is given as follows:

$$\begin{bmatrix} E \\ N \end{bmatrix} = \begin{bmatrix} E_o \\ N_o \end{bmatrix} + \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} SF \begin{bmatrix} I_{width} & 0 \\ 0 & J_{width} \end{bmatrix} \begin{bmatrix} I - I_o \\ J - J_o \end{bmatrix}$$

Assuming SF = 1 and multiplying out the equation produces the following:

$$E = E_o + \big(\cos\theta * SF * I_{width} * (I - I_o)\big) + (\sin\theta * SF * J_{width} * (J - J_o))$$

And:

$$N = N_o + \big(-\sin\theta * SF * I_{width} * (I - I_o)\big) + (\cos\theta * SF * J_{width} * (J - J_o))$$

Enter the parameter values into the second and third terms of the Easting equation yields:

$$\cos\theta * SF * I_{width} * (I - I_o) = \cos(30) * 1 * 25 * (1004 - 1001) = 64.95$$

And:

$$\sin\theta * SF * J_{width} * (J - J_o) = \sin(30) * 1 * 6.25 * (1012 - 1001) = 34.37$$

Next, enter the parameter values into the second and third terms of the Northing equation yields:

$$-\sin\theta * SF * I_{width} * (I - I_o) = -\sin(30) * 1 * 25 * (1004 - 1001) = -37.50$$

And:

$$\cos\theta * SF * J_{width} * (J - J_o) = \cos(30) * 1 * 6.25 * (1012 - 1001) = 59.54$$

Finally, substitute all elements into the easting and northing equations to determine the coordinates of point P in relation to the projected CRS:

$$Easting = 550000 + 64.95 + 34.37 = 550099.33m$$

$$Northing = 475000 - 37.50 + 59.54 = 475022.04m$$

11.3.2.2 Reverse process – right handed orientation

The reverse process of computing the I and J coordinates of the seismic binning grid from the easting and northing coordinates of the projected CRS is achieved using the following equation:

$$\begin{bmatrix} I \\ J \end{bmatrix} = \begin{bmatrix} I_o \\ J_o \end{bmatrix} + \begin{bmatrix} E - E_o \\ N - N_o \end{bmatrix} * \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} * \begin{bmatrix} \frac{1}{SF * I_{width}} & 0 \\ 0 & \frac{1}{SF * J_{width}} \end{bmatrix}$$

Multiplying out this matrix expression results in the follow for I:

$$I = I_o + ((E - E_o) * \cos\theta) - ((N - N_o) * \sin\theta) * \frac{1}{SF * I_{width}}$$

And:

$$J = J_o + ((E - E_o) * \sin\theta) - ((N - N_o) * \cos\theta) * \frac{1}{SF * J_{width}}$$

Enter the parameter values into the second and third terms of the I equation yield:

$$(E - E_o) * \cos\theta = (550099.33 - 550000) * \cos(30) = 86.02m$$

$$(N - N_o) * \sin\theta = (475022.07 - 475000) * \sin(30) = 11.03m$$

Repeat the following by entering the parameter values into the second and third terms of the J equation:

$$(E - E_o) * \sin\theta = (550099.33 - 550000) * \sin(30) = 49.67m$$

$$(N - N_o) * \cos\theta = (475022.07 - 475000) * \cos(30) = 19.09m$$

Finally, substitute all the parameter values into the expressions for I and J to get:

$$I = 1001 + (86.02 - 11.03) * \frac{1}{25} = 1004$$

$$J = 1001 + (49.67 - 19.09) * \frac{1}{6.25} = 1012$$

11.3.2.3 Forward process – left handed orientation

The final example shows a seismic binning grid which has a left handed orientation. Theoretically, this is identical to the reverse process of the right-handed orientated grid. To confirm this a separate example is performed.

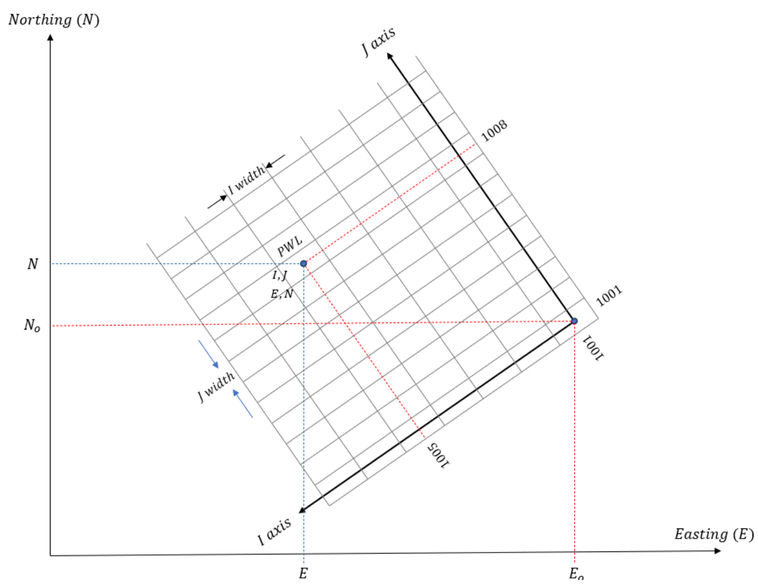


Figure 223: Left handed orientation

The input is the (I, J) of the seismic binning grid and the output is the (E, N) referenced to the projected CRS.

$$\begin{bmatrix} E \\ N \end{bmatrix} = \begin{bmatrix} E_o \\ N_o \end{bmatrix} + \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} SF \begin{bmatrix} I_{width} & 0 \\ 0 & J_{width} \end{bmatrix} \begin{bmatrix} I - I_o \\ J - J_o \end{bmatrix}$$

Multiplying out the upper equation gives:

$$E = E_o + \left(\cos\theta * SF * I_{width} * (I - I_o)\right) + (\sin\theta * SF * J_{width} * (J - J_o))$$

And:

$$N = N_o + \left(-\sin\theta * SF * I_{width} * (I - I_o)\right) + (\cos\theta * SF * J_{width} * (J - J_o))$$

Origin:

$$E_o = 550000m$$

$$N_o = 475000\text{m}$$

Survey bearing:

$\theta = 330^o$ (clockwise), -30^o (counterclockwise)

Enter the parameter values into the second and third terms of the Easting equation yields:

$$\cos\theta * SF * I_{width} * (I - I_o) = \cos(330) * 1 * 25 * (1005 - 1001) = 86.60$$

And:

$$\sin\theta * SF * J_{width} * (J - J_o) = \sin(330) * 1 * 12.25 * (1008 - 1001) = 43.75$$

Next, enter the parameter values into the second and third terms of the Northing equation yields:

$$-\sin\theta * SF * I_{width} * (I - I_o) = -\sin(330) * 1 * 25 * (1005 - 1001) = -50.00$$

And:

$$\cos\theta * SF * J_{width} * (J - J_o) = \cos(330) * 1 * 12.50 * (1008 - 1001) = 59.54$$

Finally, substitute all elements into the easting and northing equations to determine the coordinates of point P in relation to the projected CRS:

$$Easting = 550000 - (86.60 + 43.75) = 549869.65m$$

$$Northing = 475000 + (-50.00 + 75.78) = 475025.77m$$

The negative sign introduced into the easting coordinate takes into consideration the quadrant in which point P falls in relation to the origin of the seismic binning grid.

11.4 3D-rotational model

As described in section 11.2.1 the rotational model is best described as belonging to a Cartesian 3D coordinate system where the origin point shared by the two coordinate systems will be considered the point at which the $Z\ axis$ meets that plane. However, for completeness the rotations about the X and Y axes are described here to develop a three dimensional rotational model.

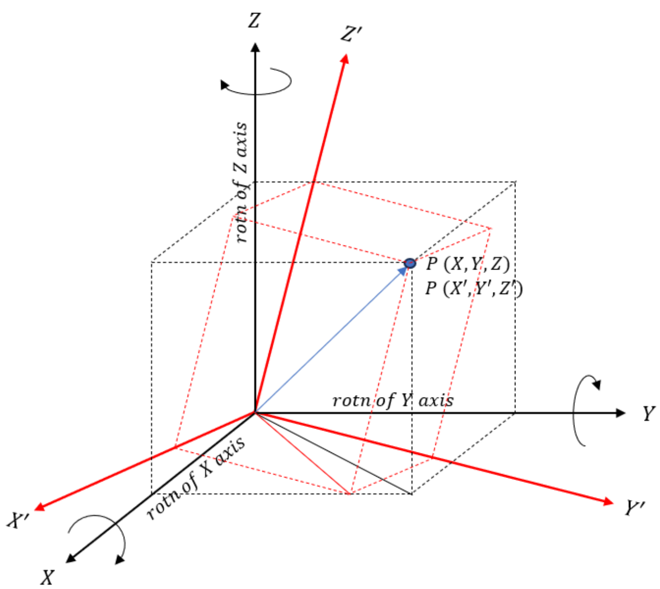


Figure 224: Three rotations about the three axes

Geo-spatial data works in a 3D world and thus any discussions on transformations should be three dimensional. Such rotations occur in several key aspects of geo-spatial work, of which the following two may be more familiar to readers rather than the application to a seismic binning grid:

- The Helmert 7-parameter transformations, when applying the three rotation parameters, $rX, rY\ and\ rZ$. Refer to The Coordinate Operations Book for further details (Parr 2024a).
- Computing vessel attitude from observations of Heave, Pitch and Roll.

The transformation is shown three dimensionally in Figure 224 which comprises three separate rotations about the X, Y and Z axes of the Cartesian 3D coordinate system as follows:

- Rotation about $Z\ axis$ (θ_Z): Change of P in the X Y plane (already shown)
- Rotation about $X\ axis$ (θ_X): Change of P in the Y Z plane
- Rotation about the $Y\ axis$ (θ_Y): Change of P in the X Z plane

11.4.1 Rotation about X axis

In similar fashion, the rotation is conducted about $X\ axis$ where the rotation is conducted in the Y Z plane. This is illustrated in Figure 225. To prevent repetition, the same triangular relations are described in the previous section apply.

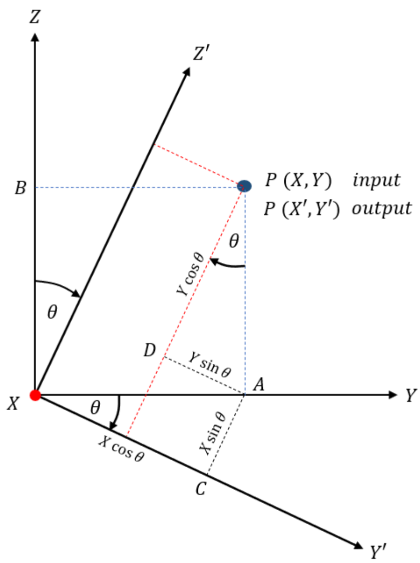


Figure 225: Rotation about X axis

Therefore, by substituting in the same triangular relationships gives:

$$Y' = Y\cos\theta - Z\sin\theta$$

$$Z' = Y\sin\theta + Z\cos\theta$$

Which again is expressed more neatly in matrix form, as follows:

$$\begin{bmatrix} Y' \\ Z' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} Y \\ Z \end{bmatrix}$$

By introducing the third axes ($X\ axis$), as previously shown for the $Z\ axis$, the matrix expression is expanded thus:

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

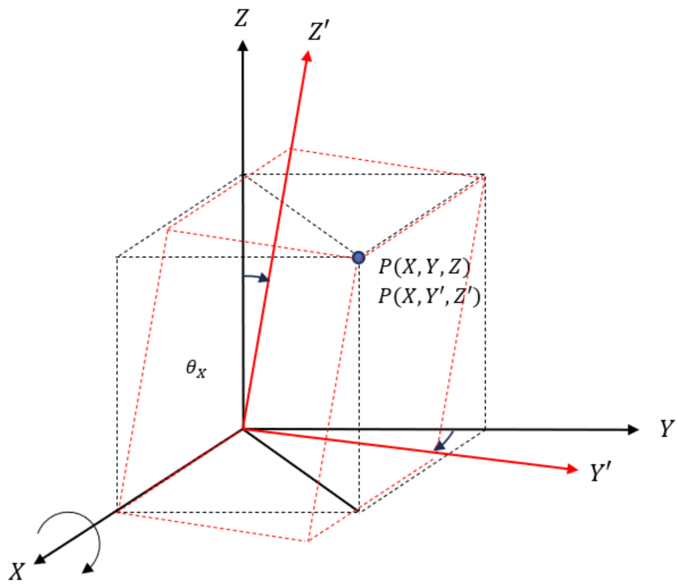


Figure 226: Rotation about X axis

11.4.2 Rotation about the Y axis

Finally, Figure 227 illustrates the rotation about the $Y\ axis$ in the X Z plane.

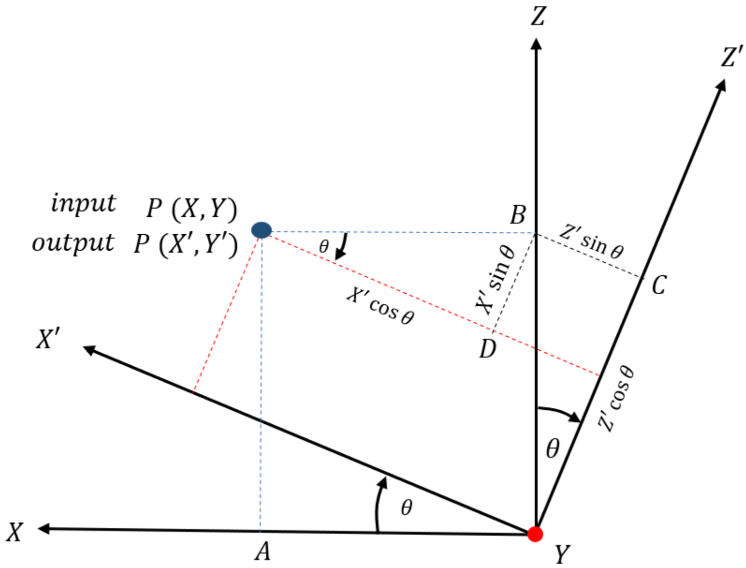


Figure 227: Rotation about the Y axis

The rotation about the Y axis appears to have a reversed perspective compared to the two previous rotations. However, the same triangular relationships apply to derive the rotation matrix.

First, consider Δ YBC and the two trigonometric relationships:

$$\sin\theta = \frac{BC}{BY} \qquad \cos\theta = \frac{CY}{BY}$$

$$\therefore\ BY\sin\theta = BC \qquad \therefore\ BY\cos\theta = CY$$

Second, consider Δ PBD and its two trigonometric relationships:

$$\sin\theta = \frac{BD}{PB} \qquad \cos\theta = \frac{PD}{PB}$$

$$\therefore\ PB\sin\theta = BD \qquad \therefore\ AP\cos\theta = PD$$

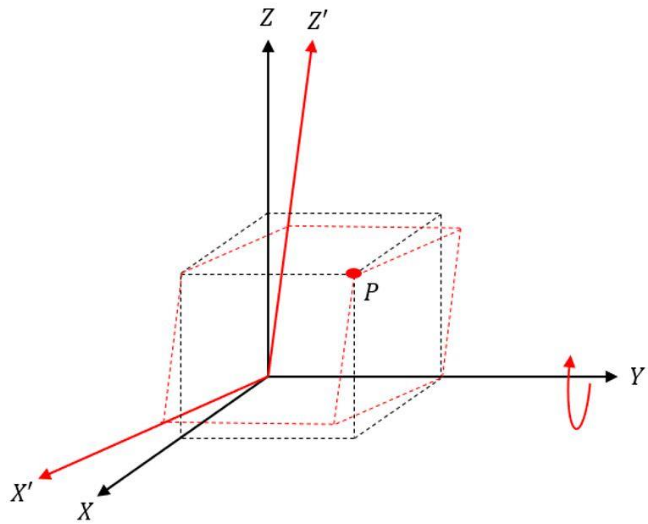


Figure 228: Rotation about the Y axis

Therefore, substitute in the four triangular relationship to give:

$$X' = X\cos\theta - Z\sin\theta$$

$$Z' = X\sin\theta + Z\cos\theta$$

Again, this is expressed more neatly in matrix form as follows:

$$\begin{bmatrix} X' \\ Z' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} X \\ Z \end{bmatrix}$$

Likewise, by introducing the third axes ($Y\ axis$) as previously shown the matrix expression is expanded thus:

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

When the angles of rotation are very small it is convenient to write the three rotation matrices as follows:

$$R_z = \begin{bmatrix} \theta_z & -\theta_z & 0 \\ \theta_z & \theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \theta_x & -\theta_x \\ 0 & \theta_x & \theta_x \end{bmatrix} \quad R_y = \begin{bmatrix} \theta_y & 0 & -\theta_y \\ 0 & 1 & 0 \\ \theta_y & 0 & \theta_y \end{bmatrix}$$

Where the values assigned to each of the three rotations are given in arc seconds. A true three-dimensional rotation matrix will describe the rotations about all three axes in the same model. This is formed by multiplying together the three individual matrices to give:

$$R = \begin{bmatrix} 1 & -\theta_z & \theta_y \\ \theta_z & 1 & -\theta_x \\ -\theta_y & \theta_x & 1 \end{bmatrix}$$

When the angles are larger this assumption will not apply, and the respective trigonometric functions must be included in the rotation matrix.

11.4.3 Positive rotation worked example

Consider a rotation applied about the $Z\ axis$, i.e., in X Y plane. In Figure 229 the red circle represents the origin of both coordinate systems and represents the vertical plane through which the $Z\ axis$ passes. It is point about which the rotation is conducted by some value (θ_Z). This creates the angular separation between the two axes of the coordinate systems about the same origin point.

Point P is considered 'fixed', and the purpose of the transformation is to have a formal mechanism whereby the coordinates of point P can be referenced to either of the two coordinate systems.

$$\begin{bmatrix} X' \\ Y' \end{bmatrix} = R \begin{bmatrix} X \\ Y \end{bmatrix}$$

If the coordinates of point P is (X, Y) in relation to the X Y coordinate system, what will its equivalents be (X', Y') in the X' Y' coordinate system. The angular rotation between the two coordinate systems is a positive rotation (clockwise positive) of 20^o.

Assume the coordinates of point P related to the X Y coordinate system are:

X = 1000m

Y = 1000m

This constitutes the input.

The rotation about the $Z\ axis$ is given as:

$\theta = 20^o$

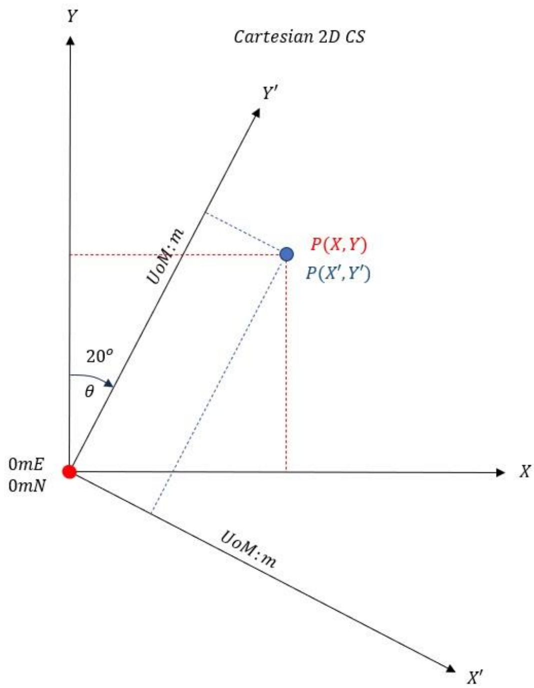


Figure 229: Positive rotation about Z axis

The parameter values are put into the following matrix expression (the function):

$$\begin{bmatrix} X' \\ Y' \end{bmatrix} = \begin{bmatrix} \cos(20) & -\sin(20) \\ \sin(20) & \cos(20) \end{bmatrix} \begin{bmatrix} 1000 \\ 1000 \end{bmatrix}$$

Which is expanded to:

$$X' = 1000\cos(20) - 1000\sin(20) = 597.67$$

$$Y' = 1000\sin(20) + 1000\cos(20) = 1281.71$$

Therefore, the coordinates of point P related to the X’ Y’ coordinate system are:

X’ = 597.67m

Y’ = 1281.71m

This constitutes the output.

11.5 Negative rotation

Source coordinate system is (X', Y') and the target coordinate system is (X, Y). With this designation, the rotational relationship between the two Cartesian axes is derived thus:

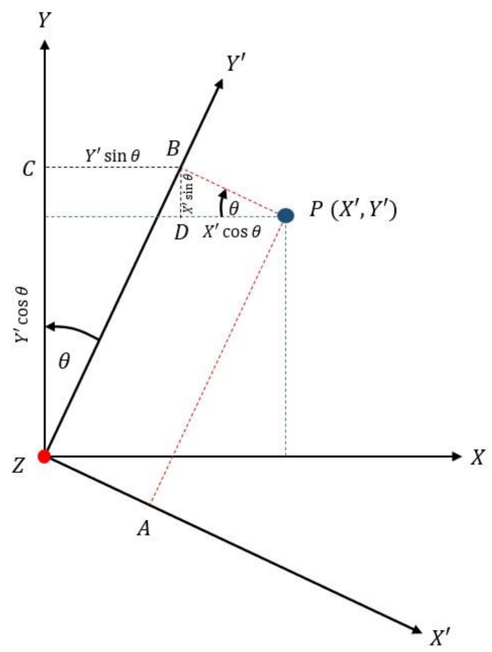


Figure 230: Negative or reverse rotation angle

First, consider the Δ ZCB:

$$\sin\theta = \frac{CB}{ZB} \qquad \cos\theta = \frac{CZ}{ZB}$$

$$ZB\sin\theta = CB \qquad ZB\cos\theta = CZ$$

Second, consider the Δ PBD:

$$\sin\theta = \frac{BD}{BP} \qquad\qquad \cos\theta = \frac{PD}{BP}$$

$$BP\sin\theta = BD \qquad\qquad BP\cos\theta = PD$$

In the (X', Y') Cartesian 2D coordinate system, point P is described by:

$$X' = ZA = BP$$

$$Y = ZB$$

And in the (X, Y) Cartesian 2D coordinate system, point P is described by:

$$X = CB + PD$$

$$Y = CZ - BD$$

Therefore:

$$X = X'\cos\theta + Y'\sin\theta$$

$$Y = -X'\sin\theta + Y'\cos\theta$$

These two expressions are more neatly written in the following matrix form:

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} X' \\ Y' \end{bmatrix}$$

Conceptually, the vertical component (Z) creates the third axis, or the axis about which the rotation is performed. Therefore, the matrix expression can be expanded to include the third dimension thus:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix}$$

This is repeated for the other two axes (X and Y) which results in the following 3D matrices:

About the $X\ axis$:

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

About the $Y\ axis$:

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

When the angles of rotation are very small it is convenient to write the three rotation matrices as:

$$R_z = \begin{bmatrix} \theta_z & \theta_z & 0 \\ -\theta_z & \theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \theta_x & \theta_x \\ 0 & -\theta_x & \theta_x \end{bmatrix} \quad R_y = \begin{bmatrix} \theta_y & 0 & \theta_y \\ 0 & 1 & 0 \\ -\theta_y & 0 & \theta_y \end{bmatrix}$$

Where the values assigned to the rotations are given in arc seconds. A true three-dimensional rotation matrix will describe the rotations about all three axes in the same model. This is formed by multiplying together the three individual matrices to give:

$$R = \begin{bmatrix} 1 & \theta_z & -\theta_y \\ -\theta_z & 1 & \theta_x \\ \theta_y & -\theta_x & 1 \end{bmatrix}$$

Note, the matrix appears the same as that for the positive rotation, except for the sign reversals.

11.5.1 Negative rotation worked example

To apply the rotation in the opposite direction means converting the coordinates of point *P* from the input (X', Y') coordinate system to the output (X, Y) coordinate system. Notice that the rotation angle is in the opposite direction.

$$\begin{bmatrix} X \\ Y \end{bmatrix} = R^{-1} \begin{bmatrix} X' \\ Y' \end{bmatrix}$$

The same logic applies to the development of the rotation matrices of this scenario. Again, a rotation applied about the $Z\ axis$, i.e., in X' Y' coordinate system. The red circle represents the origin of the two coordinate systems and also the vertical plane through which the $Z\ axis$ passes.

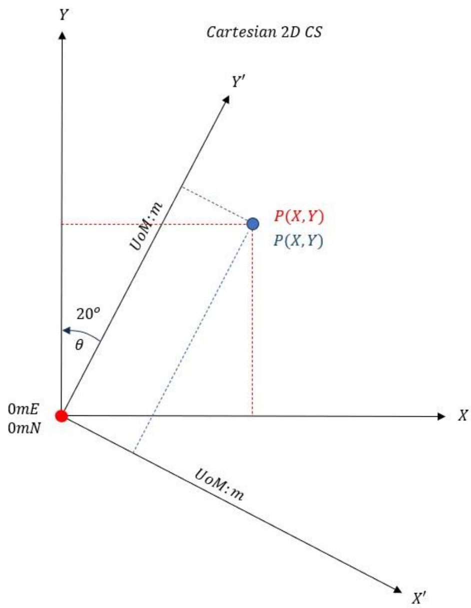


Figure 231: Negative rotation about Z axis

Like the positive rotation, the rotation about the $Z\ axis$ creates the angular different between the two coordinate systems sharing the same origin point.

Point P is again considered 'fixed'. If the coordinates of point (P) are (X', Y') in relation to the X' Y' coordinate system, what will their equivalents be (X, Y) in the X Y coordinate system. The angular rotation between the two coordinate systems is a negative rotation (clockwise positive) of 20^o.

If the input coordinates are:

X' = 597.67m

Y' = 1281.71m

The rotation about the $Z\ axis$ is given as:

$$\theta = 20^o$$

The parameter values are entered into the following matrix expression (the function):

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \cos(20) & \sin(20) \\ -\sin(20) & \cos(20) \end{bmatrix} \begin{bmatrix} 597.67 \\ 1281.71 \end{bmatrix}$$

Which expands to:

$$X = 597.67\,cos\,(20) + 1281.71\sin(20) = 1000$$

$$Y = -597.67\,sin\,(20) + 1281.71\cos(20) = 1000$$

Therefore, the output coordinates are calculated to be:

X = 1000m

Y = 1000m

12 Modifications performed to a seismic grid

Some common operations that are performed on seismic grids include:

- Re-projecting the seismic grid from one Derived CRS to another.
- Re-adjusting the seismic grid after it has been reprojected.
- Creating a master grid into which other seismic grids are merged.

12.1 Reprojecting the grid

In the Derived CRS (see section 3.3) the I and J coordinates of the seismic grid are derived from the base CRS (E, N) contained in its definition, e.g., a projected CRS, by means of performing a conversion that applies the similarity transformation (see section 11.2). However, it is common practice to modify the base CRS to which the coordinates of the seismic grid are derived which implies that an alternative Derived CRS has been selected. For example, the acquisition was performed referenced to a global datum, e.g. WGS 84 / UTM zone 49N. But the project team required the seismic grid perimeter(s) is delivered to the processing house referenced to a local datum e.g., Timbalai 1948 / RSO Borneo (ftSe). As such the target Derived CRS is modified from the source Derived CRS as shown in Table 17.

Table 17: Change in Derived CRS

	Source	Target
Coordinate System	$I = J + 90^o$	$I = J + 90^o$
Base CRS	WGS 84 / UTM zone 49N	Timbalai 1948 / RSO Borneo (ftSe)
Conversion	Deriving conversion (S)	Deriving conversion (T)

In theory there are two ways in which the coordinate operations can be conducted:

- The corner points of the perimeter(s) are converted from the source to target Derived CRS. With the new corner point coordinates the conversion parameters of the seismic grid are recomputed which will modify the cell widths along both I and J axes and the survey bearing in relation to the grid north of the target CRS (see example that follows).

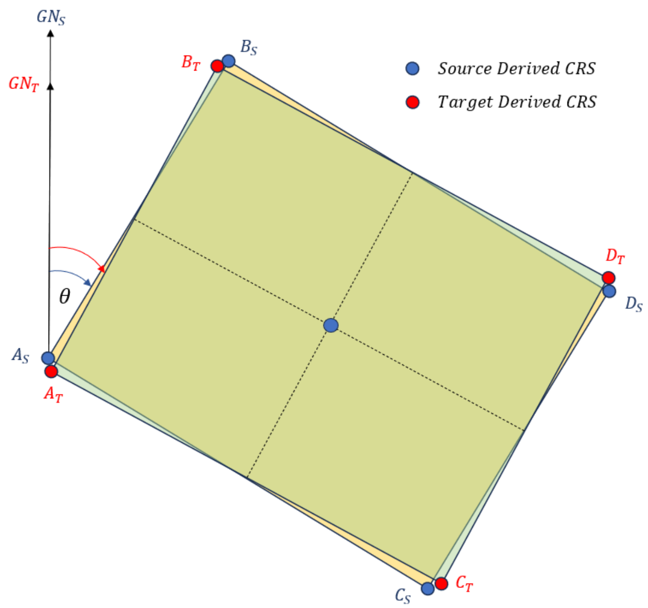


Figure 232: Recompute the four corner points

- The origin point (point A) is computed relative to the target Derived CRS. With original the conversion parameters the corner points of the perimeter(s) are computed.

The first approach yields the preferred result as it better preserves the integrity of the seismic grid cell relationship. The second method is not recommended. Either way, the change from Source to Target Derived CRS is loosely known as the Re-Projection and there are three possible solutions depending upon the source and target Derived CRSs selected, namely:

- A change in datum with no change in map projection

  WGS 84 / UTM zone 49N to Timbalai 1948 / UTM zone 49N

- A change in datum and a change in map projection (Figure 233)

  WGS 84 / UTM zone 49N to Timbalai 1948 / RSO Borneo (ftSe)

- A change in map projection with no change in datum

  Timbalai 1948 / UTM zone 49N to Timbalai 1948 / RSO Borneo (ftSe)

Hence, a collection of coordinate operations are required depending upon the selections made. An introduction to some common coordinate operation methods is provided in chapter 13. However, for a more in depth treatment refer to IOGP (2020) or for a lesser one then Parr (2024a).

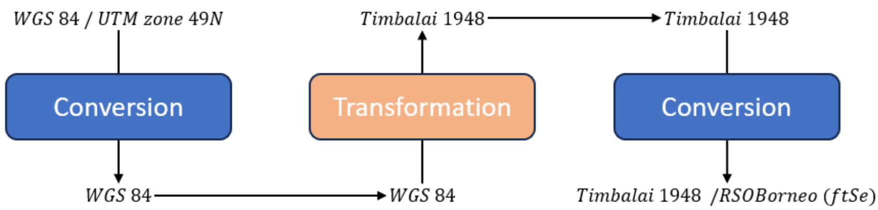


Figure 233: Coordinate operations in the reprojection

Although reprojecting the seismic grid definition is common practice it is one that is often done unnecessarily and usually because of historical reasons, e.g., the "we have always done it this way" play book. Unless there is a specific reason why the seismic grid needs to be reprojected it is recommended not to perform this type of operation. Legitimate reasons include sharing this information with partner companies or reporting the data to government agencies.

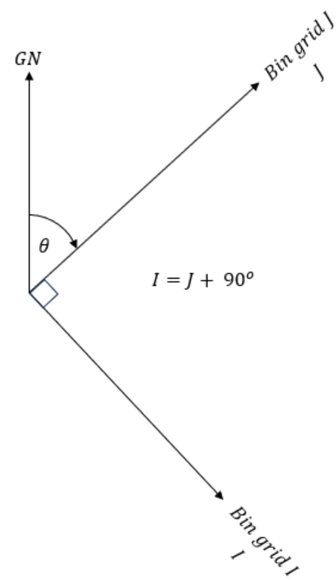


Figure 234: Derived CRS coordinate system

Consider the following example where the source Derived CRS comprises the following:

Coordinate system: Ordinal coordinate system as illustrated in Figure 234.

Base CRS is referenced to WGS 84 / UTM zone 49N:

The conversion parameters contained in the Derived CRS definition include the following parameter values:

Table 18: Deriving conversion parameters

Parameter	Parameter value
Bin grid origin I	1001
Bin grid origin J	1001
Bin grid origin Easting	550000
Bin grid origin Northing	475000
Scale factor of bin grid	1
Bin width on I axis	25
Bin width on J axis	12.5
Map grid bearing of J axis	45
Bin node increment on I axis	1
Bin grid increment on J axis	1

This is also known as the deriving conversion, and it is from these deriving parameters that the I and J coordinates of cells in the seismic grid are computed from their Easting and Northing equivalents. The full fold perimeter associated with the seismic grid has four corner points ($A\ to\ D$) whose coordinates are shown in Table 19 and are given with respect to the seismic grid (I, J) and the base CRS (E, N) of the Derived CRS definition.,

Table 19: Original seismic grid

	I	J	Easting	Northing
A	1001	1001	550000.00	475000.00
B	1001	7001	603033.01	528033.01
C	4001	1001	603033.01	421966.99
D	4001	7001	656066.02	475000.00

Next, the reprojection of the four corner points of the full fold perimeter is performed as illustrated in Figure 233. This converts the coordinates between the base CRS of the source Derived CRS to the base CRS of the target Derived CRS, which is Timbalai 1948 / RSO Borneo (ftSe). This yields the values shown in Table 19.

Table 20: Target CRS coordinates

	I	J	Easting	Northing
A	1001	1001	642923.76	1559339.49
B	1001	7001	817301.24	1733313.29
C	4001	1001	816906.18	1385058.75
D	4001	7001	991173.13	1558948.35

As the coordinate operation involved a coordinate transformation these details must be captured as part of the audit trail as there are multiple options to transform between Timbalai 1948 and WGS 84 with each yielding a different answer. In this instance the coordinate transformation applied was Timbalai 1948 to WGS 84 (4), EPSG code [1852].

12.1.1 Change in derived conversion parameters

A seismic grid designed in relation to the original Derived CRS is done such that it inherits the property of orthogonality, i.e., all internal angles of the full fold perimeter are 90^o as shown on the left hand side of Figure 235. This property is intrinsically tied to the datum and mapping surface of the base CRS of the Derived CRS upon which the design was performed. However, when the full fold perimeter is reprojected to the base CRS of the target Derived CRS it is likely that the property of orthogonality will be lost. This depends upon the difference in map projection between source and target and also the size of the full fold perimeter.

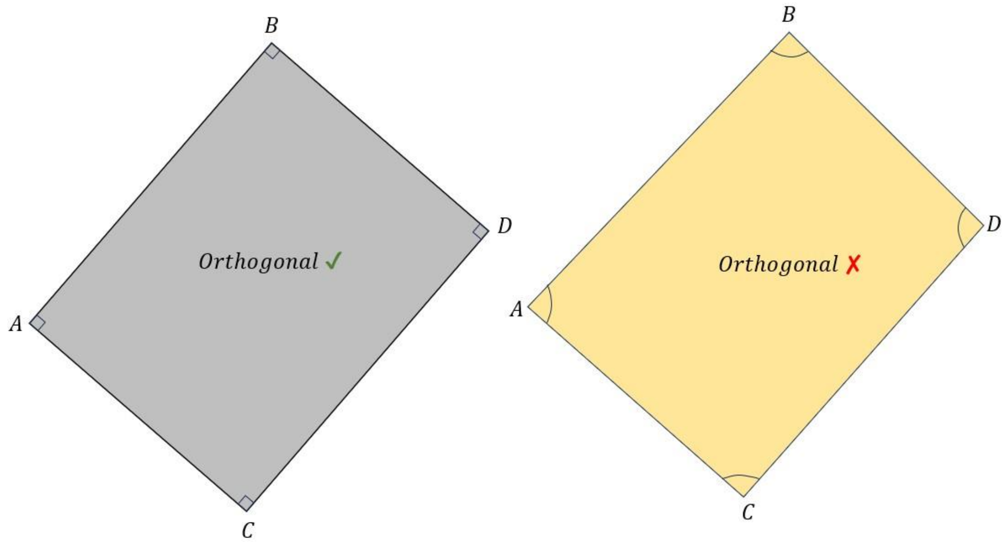


Figure 235: Effect of reprojecting perimeter between CRSs

Of the three coordinate operation scenarios listed above this is more likely to happen when the process involves both a change in datum and map projection type (the conversion).

All that remains is to determine the derived conversion parameters associated with the target Derived CRS. These include changes to the bin grid origin related to the base CRS, bin widths along the two axes and the map grid bearing of the $J\ axis$.

Bin grid origin

The Easting and Northing of the bin grid origin are assigned the coordinates for Point A related to the base CRS of the Derived CRS, e.g. Timbalai 1948 / RSO Borneo (ftSe). Therefore:

Bin grid origin Easting = 642923.76 ftSe

Bin grid origin Northing = 1559339.49 ftSe

Widths along the I and J axes

compute the distance between points A and B using the coordinates in table 19. Because the coordinates are projected this is done using Pythagoras as follows:

$$r = ((dE)^2 + (dN)^2)^{1/2}$$

$$r = ((174377.48)^2 + (173973.80)^2)^{1/2}$$

Therefore:

$$r = 246321.72\ ftSe$$

Next, the cell range between point A (1001) and B (7001) is derived to be 6000 cells and divide the range by the number of cells, which gives a cell size along the J axis of:

$$Bin\ width\ on\ J\ axis = 41.054\ ftSe$$

The same approach is applied along the $I\ axis$ between point A and C which yields the following bin width:

$$r = 246259.33\ ftSe$$

$$Bin\ width\ on\ I\ axis = 82.086\ ftSe$$

The widths of the cells along the two axes of the seismic grid prior to the reprojection being apply were I = 25m and J = 12.5m. The widths of the cells after applying the coordinate operations are given in a different unit of measure because of the definition of that CRS. However, these can be converted from ftSe to metres to illustrate that the cell widths have changed. This is achieved by applying the conversion factor between the two as given by:

$$British\ forr\ (Sears\ 1922)\ to\ metre = 0.30479947153868$$

When applied it yields the following dimensions:

Bin width on I axis equivalent	*25.0199 m*
Bin width on J axis equivalent	*12.5131 m*

Although the differences are small ($\Delta I = 0.0199m$ and $\Delta J = 0.0131m$) they are significant when applied across the extent of the full fold perimeter. However, it does illustrate the point that some form of distortion is inevitable.

Map grid bearing of J axis

Next, the survey bearing along the $J\ axis$ needs to be computed using:

$$\theta = \arctan\frac{dE}{dN} = \frac{174377.48}{173973.80}$$

Which yields:

$$\theta = 45.06639605$$

Or

$$\theta = 45^{o}\ 3'\ 59.026''$$

Using these parameter values it is now possible to create the definition of the target Derived CRS.

The coordinate system definition remains the same as the source Derived CRS:

The base CRS is given as: Timbalai 1948 / RSO Borneo (ftSe)

The deriving conversion parameters are given in Table 20.

Table 21: Deriving parameters Target Derived CRS

Parameter	Parameter value	Unit
Bin grid origin I	1001	Bin
Bin grid origin J	1001	Bin
Bin grid origin Easting	642923.76	ftSe
Bin grid origin Northing	1559339.49	ftSe
Scale factor of bin grid	1	Unity
Bin width on I axis	82.086	ftSe
Bin width on J axis	41.054	ftSe
Map grid bearing of J axis	$45^{o}\ 3'\ 59.026''$	Degree
Bin node increment on I axis	1	Bin
Bin grid increment on J axis	1	Bin

In this instance the bin is defined as an integer meaning the coordinate system is of type: ordinal.

12.2 Readjusting a seismic grid

After a full fold perimeter has been reprojected one potential consequence is that the new definition loses its property of orthogonality. To regain this property the perimeter is readjusted so as to change the corner points to regain internal 90° angles (in the case of a four-point grid). The two conventional methods of achieving this are:

- Squaring method
- Averaging method

12.2.1 Squaring method

The squaring method operates in the following manner: Start at point A, the seismic grid origin. First, determine the bearing between points A and B. This is achieved prior to, or after the grid is re-projected.

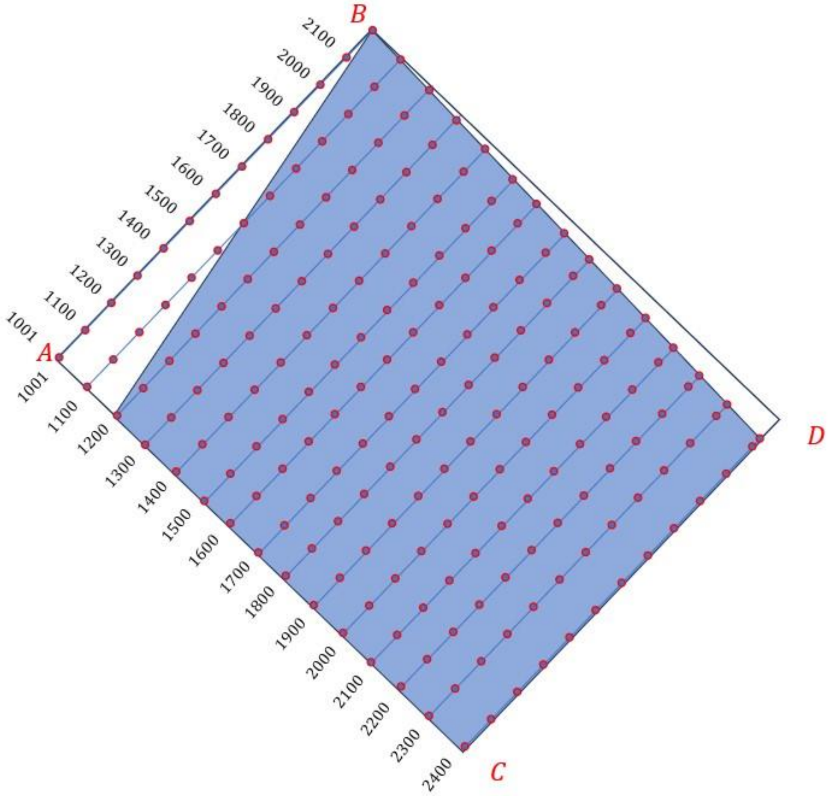


Figure 236: Readjusting the bin grid

If the perimeter has not been re-projected, it assumes that both points A and B are intrinsically correct and thus the bearing between the two can be computed (checking for the correct quadrant). It cannot contain an error in either point as is shown in Figure 236, as this will have a dramatic effect on the end results of points D and C. User is required to check the integrity of points A and B prior to conducting the squaring method.

If the perimeter has been re-projected, it will take the bearing between points A and B as the survey bearing along the $J\ axis$ as is shown in Figure 237. However, this assumes that all corner points that were used to define the perimeter prior to it being re-projected had their integrity checked, as any significant errors in such points will have a detrimental effect to the average bearing for $J\ axis$ as shown in Figure 237.

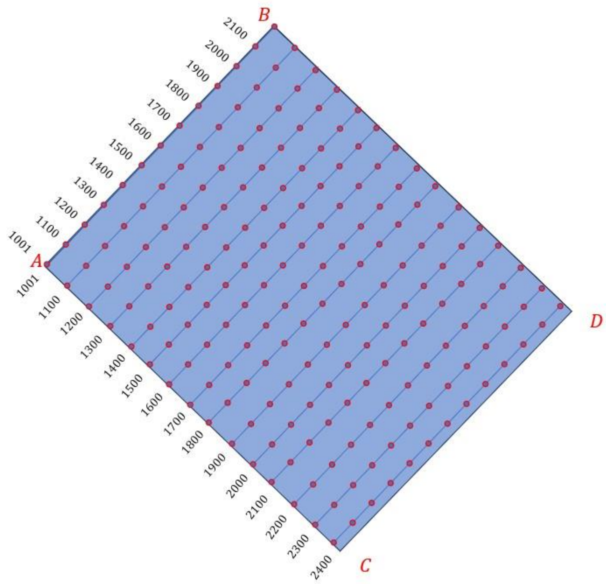


Figure 237: Bin grid after readjustment

Next, the internal angle A-B-D must be 90° for the squaring condition to be met. Therefore, this is checked first, using these three corner points. If this angle does not equal 90°, then changes are made to the coordinates of point D. This is achieved in the following manner:

- First, compute what the distance between points B and D should be by multiplying the in-line range ($I_{MAX} - I_{MIN}$) by the cell size along the $I\ axis$ as is shown in Figure 237.
- Next, compute the bearing between points B and D by adding 90° to the bearing between points A and B, when the seismic grid is right-handed, or subtracting 90° to the bearing between points A and B, when the seismic grid is left-handed.
- Using the range and bearing, and a starting point of point B, the coordinates that point D must take (to observe the squaring rule) can be derived. However, the I and J grid values will be retained for this point. These cannot change.

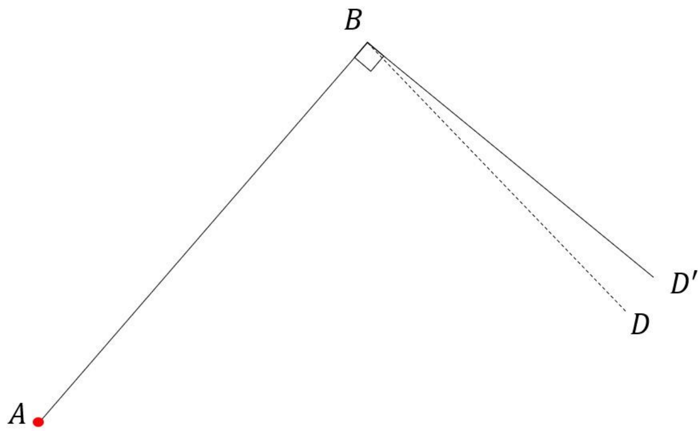


Figure 238: Squaring function to obtain point D

Next, the exercise is repeated to determine point C which is achieved in the following manner:

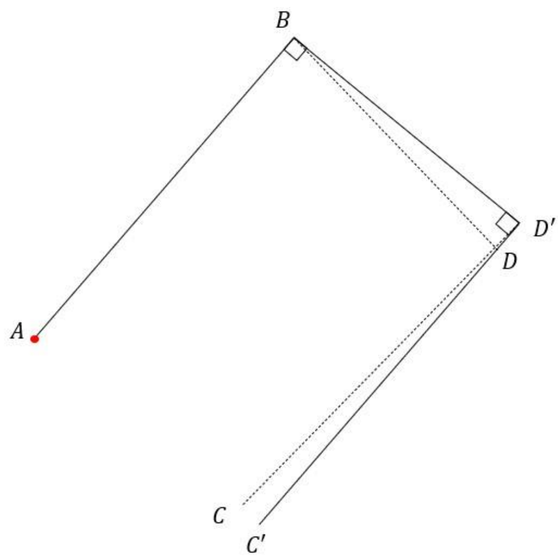


Figure 239: Squaring method, final leg

Check if the internal angle B-D-C is 90° for the squaring condition to be satisfied which is determined using these three corner points. If this angle does not equal 90° then changes to the coordinates of point C are needed. This is achieved in the following manner:

- First, compute what the distance between points D and C should be by multiplying the crossline range $(J_{MAX} - J_{MIN})$ by the cell size along the

$J\ axis$. Compare the answer to the actual distance between points A and B computed using the corner point coordinates. The difference must not exceed ½ cell width along the $J\ axis$ direction. If it does, revert to using the distance between points A and B.

- Next, compute the bearing between points D and C by adding 90° to the bearing between points B and D, when the seismic grid is right-handed, or subtracting 90° to the bearing between points B and D, when the seismic grid is left-handed.
- Using the range and bearing, and a starting point of point D, the coordinates point C must take to observe the squaring rule are derived. However, the I and J grid coordinates will be retained for this point. These cannot change.

Finally, test the angle D-C-A for orthogonality. If the internal angle equals 90° then point C is in the correct place.

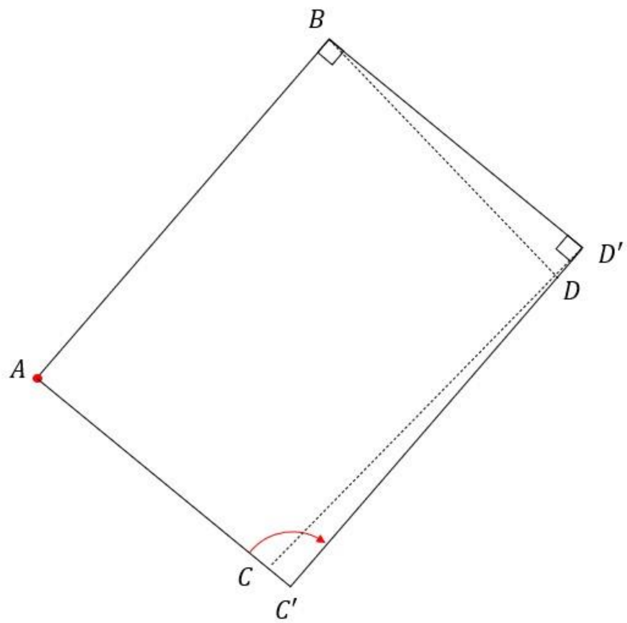


Figure 240: Test the angle DCA

If the angle does not equal 90° then point C must be re-computed. However, this must meet the condition that the point can only be moved along the bearing of DC. If not, this will compromise the internal angle B-D-C. In doing this it prevents any adjustment having to be made to point A, which if moved will compromise the starting point of the test.

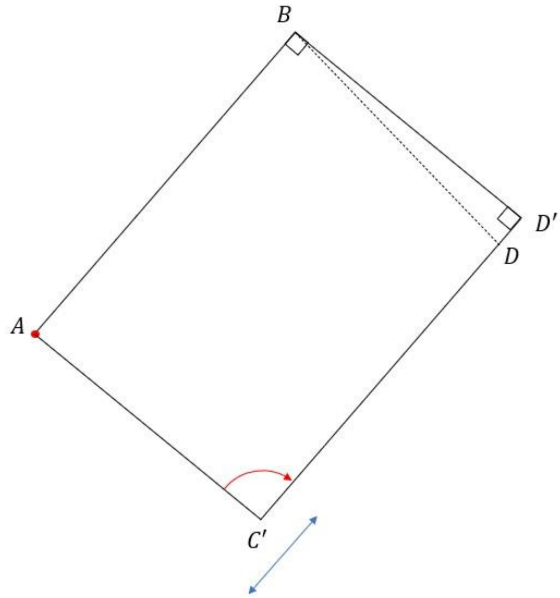


Figure 241: Re-adjust point C (inline)

12.2.2 Averaging Method

The averaging method only works with a four corner point perimeter. First step is to calculate the survey origin, which is defined by the geometric center determined from the four corner points as shown in Figure 242.

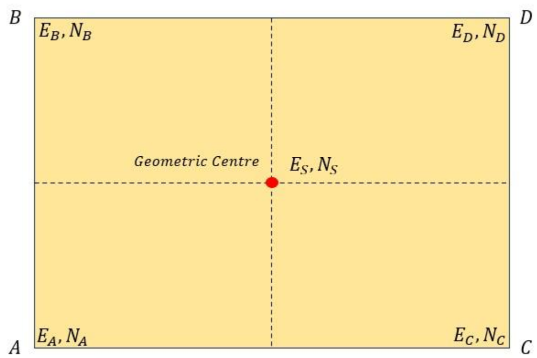


Figure 242: Compute the survey origin from four corner points

The Easting and Northing of the survey origin (E_S, N_S) are computed by summing together the Easting and Northing coordinates of the corner points and dividing by the number of corner points, i.e., four. Next, the cell width (Bin width) along the inline direction ($J\ axis$) is determined by calculating the distance A-B using the base CRS coordinates and dividing that distance by the number of cells along the J axis of the seismic grid ($J_{MAX} - J_{MIN}$). This is the same process applied when computing the derived parameter values as shown in the previous section.

$$AB = [(E_B - E_A)^2 + (N_B - N_A)^2]^{1/2}$$

Cell width:

$$Cell\ width\ on\ J\ axis = \frac{AB}{(J_{MAX} - J_{MIN})}$$

This is repeated for the side C-D, which is considered parallel to side A-B.

$$CD = [(E_D - E_C)^2 + (N_D - N_C)^2]^{1/2}$$

Cell width:

$$Cell\ width\ on\ J\ axis = \frac{CD}{(J_{MAX} - J_{MIN})}$$

The final distance along the $J\ axis$ is the average of these two figures.

$$Av. cell\ width = \frac{width\ AB + width\ CD}{2}$$

The cell width along the crossline direction ($I\ axis$) is calculated in the same fashion as that described above. First, the cell widths along the side A-C are determined.

$$AC = [(E_C - E_A)^2 + (N_C - N_A)^2]^{1/2}$$

Cell width:

$$Cell\ width\ on\ I\ axis = \frac{AC}{(I_{MIN} - I_{MIN})}$$

Next, this is repeated along the side D-B:

$$DB = [(E_D - E_B)^2 + (N_D - N_B)^2]^{1/2}$$

Cell width:

$$Cell\ width\ on\ I\ axis = \frac{DB}{(I_{MAX} - I_{MIN})}$$

The final distance along the $I\ axis$ is the average of these two values:

$$Av.width = \frac{width\ AC + width\ BD}{2}$$

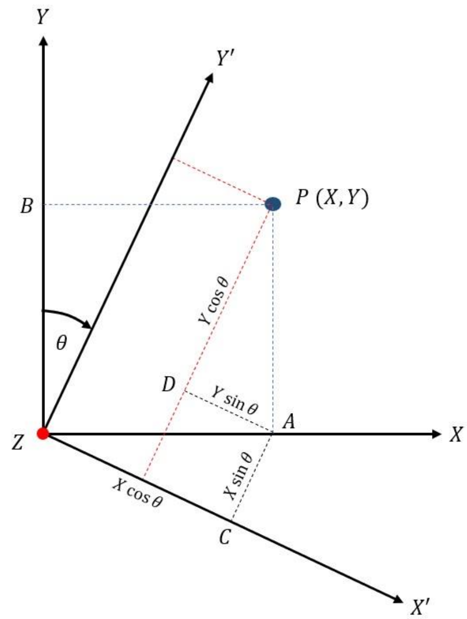


Figure 243: Similarity transform shown diagrammatically

Finally, the survey bearing for the perimeter is calculated by averaging the bearing along the sides A-B and C-D.

$$\theta_{AB} = tan^{-1}\frac{(E_B - E_A)}{(N_B - N_A)}$$

$$\theta_{CD} = tan^{-1}\frac{(E_D - E_C)}{(N_D - N_C)}$$

$$Bearing = \frac{\theta_{AB} - \theta_{CD}}{2}$$

All the derived conversion parameters of the new perimeter seismic grid required for the input to the similarity transformation (bin grid origin, widths, bearing and the scale is assumed to be 1) are now available. The similarity transformation is used to calculate the coordinates for the four corner points as defined by the min and max in-line and crossline values.

12.3 Creating a Master Grid

It is common that over the same geographic area numerous seismic 3D surveys will have been acquired over time. This is specifically true over more mature producing basins / fields. Rather than working with the seismic trace data on a survey by survey basis it is more advantageous to combine all the trace data into one master seismic grid so a more regional picture of the structural geology can be obtained.

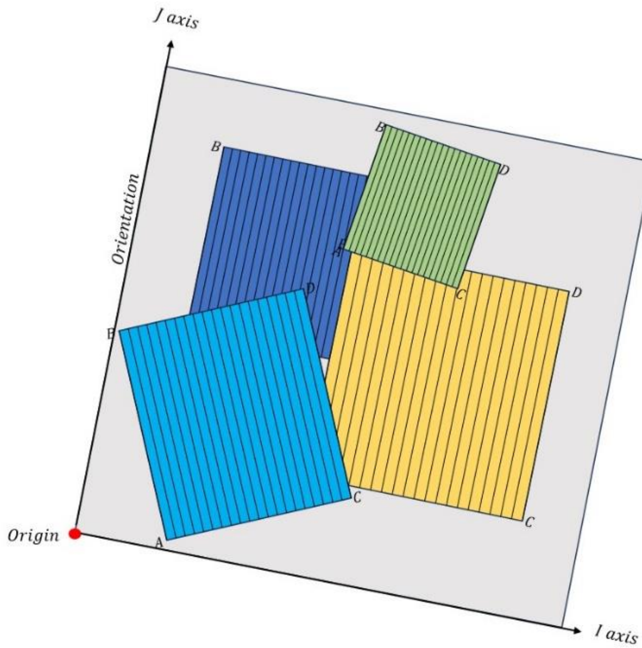


Figure 244: Master seismic grid

The design of the master seismic grid is performed such that it will take into consideration the following:

1. What is the collective extent of all the existing seismic grids to be merged which is established by plotting each seismic grid on a general map.

2. Determine if there is a common azimuth of the I and J $axes$ between the collection of individual grids.

3. Determine if there are common cell sizes along the I and J $axes$ between the collection of individual grids.

4. Are there any specific issues relating to the cell incrementations that need consideration.

5. What overlap is there on the existing seismic 3D survey.

What seismic trace data is re-binned into the new master grid? That in the full fold perimeter or all data in the total coverage area. It is advantageous to collate the data from all the individual 3D surveys into one master survey to derive a more comprehensive understanding to the geological environment over a wider area. Applied over a regional area, this is often done to facilitate coordinate reference systems associated with Play Based Exploration (PBE).

13 Coordinate operations

The coordinate operation used in the Derived CRS (see section 3.3) describes the conversion between the seismic bin grid (I, J) and the base projected CRS (E, N) and is specific to this coordinate pairing of the seismic bin grid. This operation is just one of many others all of which are defined to perform identifiable tasks, e.g., NADCO. In this chapter an introduction is given to those that are strictly involve with Source CRS and Target CRS both of which involve a geodetic datum. Although the EPSG geodetic parameter registry does not distinct between categories of coordinate operations they are broadly separated into three types that comprise:

- Conversions are methods where the geodetic datum of the source CRS and target CRS remain the same. Those shown between the vertical arrows in Figure 245, e.g., UTM zone 49N.

- Transformations are methods where the geodetic datum changed between source CRS and target CRS. Those shown between the horizontal arrow in Figure 245, e.g., Timbalai 1948 to WGS 84 (variant number).

- Point motion methods are those where the source and target CRS share the same geodetic datum and are used to update the coordinates of a point between two time epochs (Δt) resulting from tectonic movement, e.g., Point motion (ellipsoidal).

Figure 245 illustrates the coordinate tuples associated with a well header for six different CRSs. The well header does not change its physical position, the only change is to the coordinates used to describe that position.

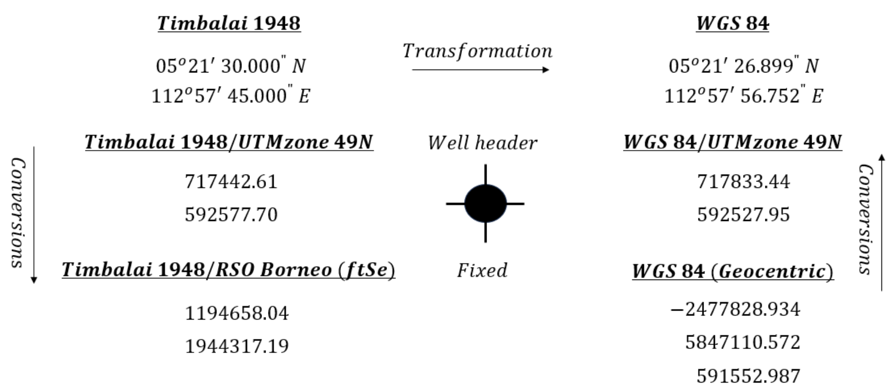


Figure 245: Coordinates of same well header

Regardless of the method or category the hierarchy of operation definition is similar in that each has:

- Operation method
- Operation method parameters
- Operation method parameter values

Their purpose is the facilitate the conversion or transformation of the coordinates of a physical point (P) from one CRS to another CRS who definition includes a geodetic datum. It is a common practice to perform such operations as the geo-spatial data passes through the exploration life cycle from acquisition to processing to data loading. This chapter introduces some of the basic concepts of these operation types.

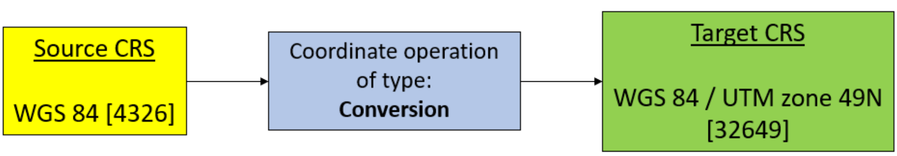
13.1.1 Coordinate conversions

The coordinate conversion is a coordinate operation where Source CRS and Target CRS share the same geodetic datum (IOGP, 2020). An example of this type of operation is where the geodetic latitude (φ) and geodetic longitude (λ) associated with a geodetic CRS (geographic 2D CRS) are converted to Easting (E) and Northing (N) associated with a projected CRS, e.g., UTM zone 31N.

An exhaustive list of conversion methods have been published which far exceeds the scope of this book. So, two common examples of conversions are described that involve the use of the following map projections: Transverse Mercator and the Lambert Conic Conformal. Further details can be found in IOGP (2020) and Parr (2024).

13.1.1.1 WGS 84 / UTM zone 49N

The input, geodetic latitude (φ) and geodetic longitude (λ) coordinates, are related to WGS 84, and the output, Easting (E) and Northing (N), are related to WGS 84 / UTM zone 49N. The filter is the conversion, e.g., the algorithm and the parameter values applied to convert from (φ, λ) to (E, N) and vice versa. The coordinate operation is a one step process between the source and target CRSs as illustrated. For details on the algorithm see IOGP (2020).



Step one: The conversion method, also known as the map projection by many, is a Transverse Mercator and the five parameters used by this conversion method are listed in the following table, along with examples of the parameter values and their associated unit of measure:

Table 22: Parameters of Transverse Mercator

UTM zone 49N		
Parameter	**Parameter value**	**Unit of measure**
Latitude of natural origin	0^o	degree
Longitude of natural origin	111^o	degree
Scale at natural origin	0.9996	unity
False easting	500000	metres
False northing	0	metres

This collection of operation method, parameters and parameter values are collectively named as UTM zone 49N. Applying different parameter values to the same parameters will result in an alternative name being applied. For example, if the Longitude of natural origin was $3^o E$, whilst the other parameter values remained the same, the collective name is UTM zone 31N.

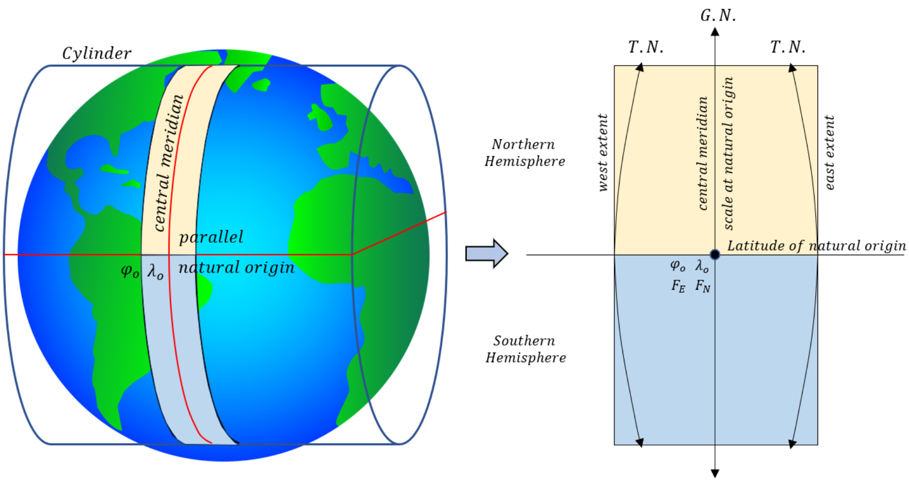


Figure 246: Transverse Mercator projection

To add some clarity to the parameters: The map zone (extent) is separated into two hemispheres, northern (light brown) and southern (light blue) which applies to all zones of the special case of the Universal Transverse Mercator (UTM). Northern zones map features of the Earth north of the equator and southern zones map features south of the equator. The only difference between the parameter values of the different hemispheres is with respect to the False northing parameter value. Whilst it is 0 metres in the Northern hemisphere it takes a value of 10000000m (ten million) in the Southern hemisphere. For example:

Table 23: Different parameter values for different zones

Parameter	UTM zone 49N	UTM zone 49S
Latitude of natural origin	0^o	0^o
Longitude of natural origin	111^o	111^o
Scale at natural origin	0.9996	0.9996
False easting	500000m	500000m
False northing	0m	10000000m

This pattern repeats for all 60 UTM zones around the Earth making a total of 120 zones when both the northern and southern hemispheres are taken into consideration.

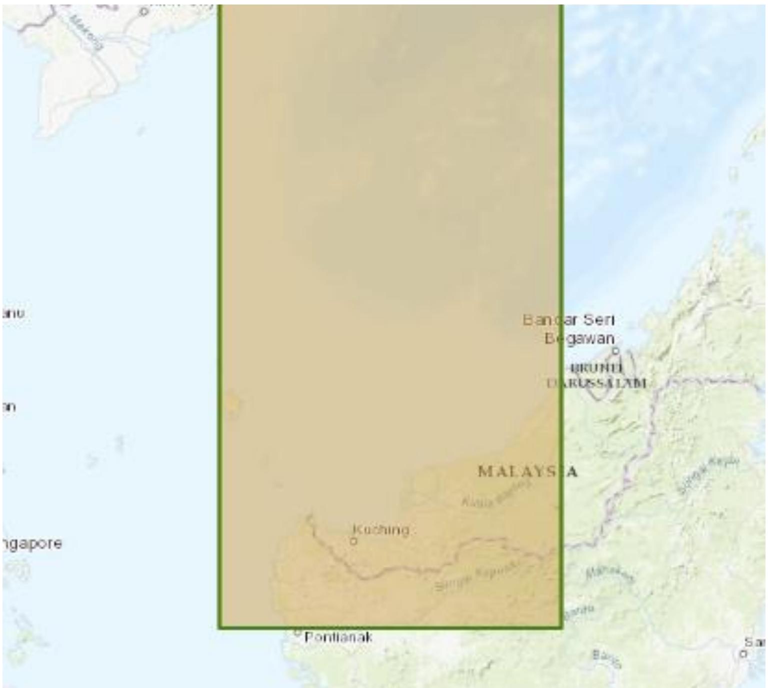


Figure 247: WGS 84 / UTM zone 49N extent

Example:

Source CRS: WGS 84, EPSG [4326]

Target CRS: WGS 84 / UTM zone 49N, EPSG [32649]

Conversion: UTM zone 49N, EPSG [16049]

Conversion method: Transverse Mercator, EPSG [9807]

Extents: Describes the geographic area over which the conversion can be applied.

The input point is supplied for coordinates belonging to the geographic 2D CRS:

$$04^{o}\ 30'\ 00.000''\ N$$

$$112^{o}\ 30'\ 00.000''\ E$$

Because this is a one-step operation the output coordinates are computed referenced to the projected CRS:

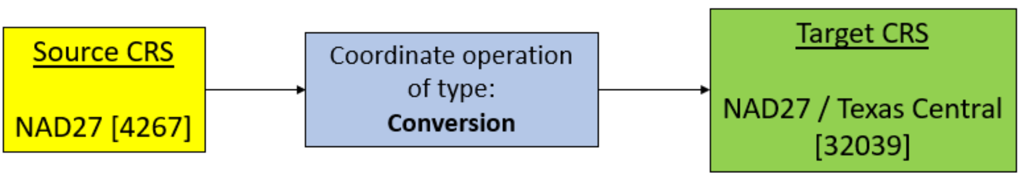
$$666420.24\ mE$$

$$497566.41\ mN$$

End of the coordinate operation.

13.1.1.2 NAD27 / Texas Central

The input geodetic latitude (φ) and geodetic longitude (λ) coordinates are referenced to NAD27, and the output Easting (E) and Northing (N) are referenced to NAD27 / Texas Central. The filter is the conversion applied.



Both the source and target CRSs share the same geodetic datum (NAD 27) making it a conversion. The conversion parameters used in the conversion method are those defined in Table 24, which are collectively known as Texas CS27 Central zone:

Table 24: Texas CS27 central zone parameters

Parameter	Parameter value	Unit of measure
Latitude of false origin	$29^o\ 40'\ 00''\ N$	degree
Longitude of false origin	$100^o\ 20'\ 00''\ N$	degree
Latitude of 1st standard parallel	$30^o\ 07'\ 00''\ N$	degree
Latitude of 2nd standard parallel	$31^o\ 53'\ 00''\ N$	degree
Easting at false origin	2000000	ftUS
Northing at false origin	0	ftUS

Example:

Source CRS: NAD27, EPSG [4267]

Target CRS: NAD27 / Texas Central, EPSG [32039]

Conversion: Texas CS27 Central zone, EPSG [14203]

Conversion method: Lambert Conic Conformal (2SP), EPSG [9802]

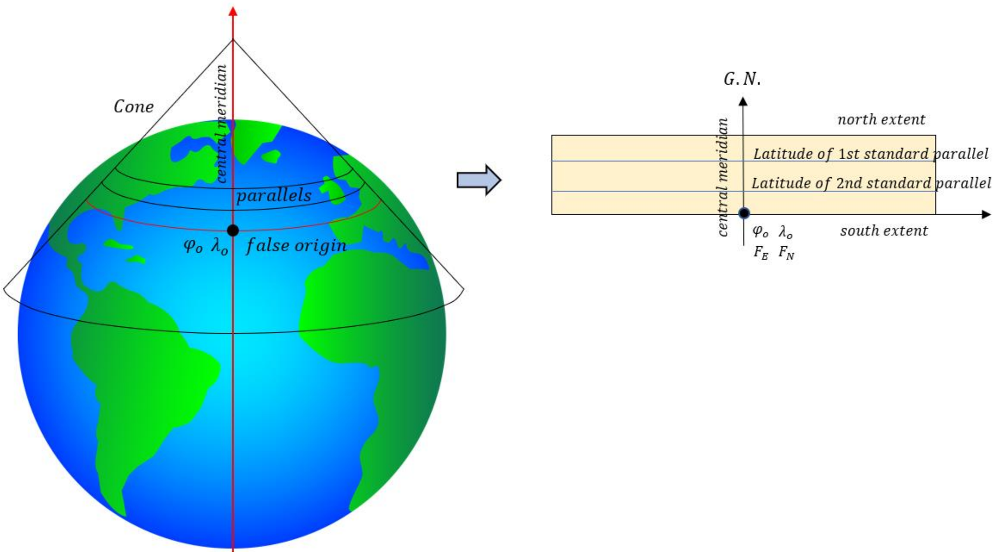


Figure 248: Lambert conic conformal (2SP) projection

Extents:

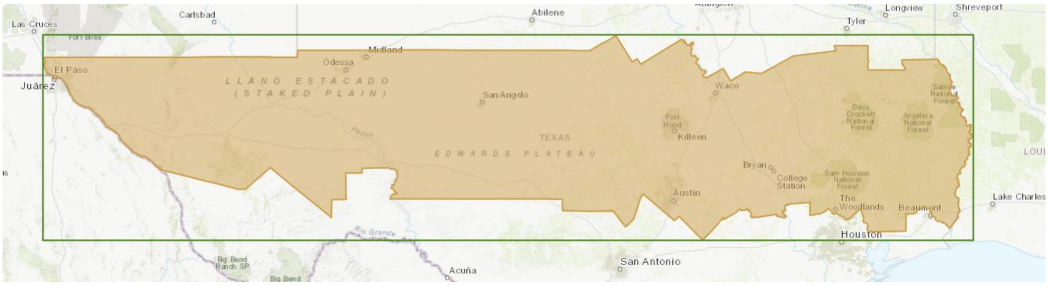


Figure 249: NAD27 / Texas Central extent

The input point is supplied for coordinates belonging to the geographic 2D CRS:

$$30^o\ 50'\ 00.000''\ N$$

$$103^o\ 30'\ 00.000''\ W$$

Because this is a one-step operation the output coordinates are computed referenced to the projected CRS:

$$1006282.52\ ftUS\ E$$

$$438442.40\ ftUS\ N$$

13.1.2 Coordinate transformations

The coordinate transformation is a coordinate operation performed when the two geodetic CRSs do not share the same geodetic datum. What follows is a general introduction to some of the more common operation methods used with geo-spatial exploration data. For a more detailed description see IOGP (2020) and The Coordinate Operations Book (Parr, 2024b).

Of the many types of coordinate transformation methods documented some of the more common ones used with exploration data sets are:

- Geocentric translation
- Helmert 7 parameter transformation
- Interpolated gridded transforms

Regardless of the method the coordinate operations all comprise sets of parameters and parameter values. The number of parameters used is dependent upon the operation method.

13.1.2.1 Geocentric translation

The geocentric translation method shifts the origin of the Cartesian 3D coordinates system of the source CRS to match the origin of the target CRS. This is achieved using three translation parameters (tX, tY, tZ) which are shown in the following equation.

$$\begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} = \begin{bmatrix} tX \\ tY \\ tZ \end{bmatrix} + \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix}$$

Therefore, the input coordinates (X_S, Y_S, Z_S) are transformed to the output coordinates (X_T, Y_T, Z_T) by the application of the translation parameters (tX, tY, tZ). This is graphically shown in Figure 250.

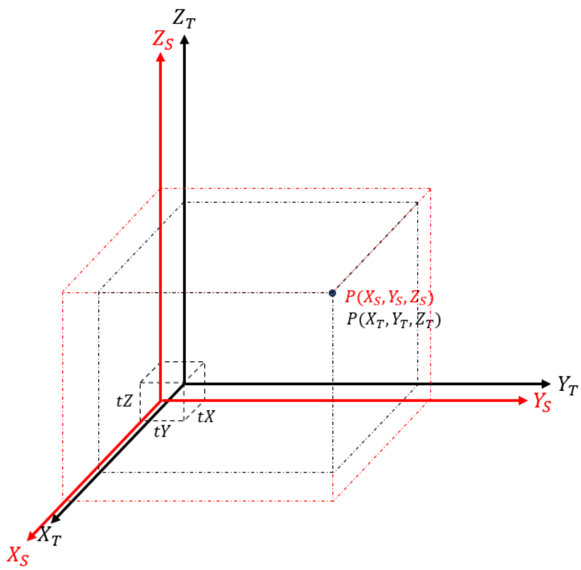


Figure 250: Geocentric translation parameters

The transformation method commences when a user supplying the input coordinates related to the type of geodetic CRS and coordinate system. This can take one of three forms, which relate to the input domain, namely:

- Geographic 2D CRS: Where a user enters geodetic latitude (φ) and geodetic longitude (λ), (geog 2D domain).
- Geographic 3D CRS: Where a user enters geodetic latitude (φ), geodetic longitude (λ) and ellipsoidal height (h), (geog 3D domain).

- Geocentric CRS: Where a user enters Geocentric X, Geocentric Y and Geocentric Z, (geocentric domain).

For narrative purposes, assume that the coordinates are supplied in the geographic 2D CRS (geog 2D domain) as shown in Figure 251. To complete the coordinate transformation involves the five concatenated steps shown, at the core of which is EPSG coordinate operation [9603]. To begin, this involves two coordinate operations known as follows:

- Step one: Geographic 3D to Geographic 2D conversion

$$\varphi, \lambda \leftrightarrow \varphi, \lambda, h$$

- Step two: Geographic 3D to Geocentric conversion

$$\varphi, \lambda, h \leftrightarrow X, Y, Z$$

The first two steps convert the coordinates such that they are conditioned for input to the Geocentric transformation in the Geocentric domain (X, Y, Z). Both operations are reversible and are thus used to convert:

   - Geographic 2D to Geographic 3D (step 1 and step 5)
   - Geocentric to Geographic 3D (step 2 and step 4)

- Step three: Geocentric translation transformation

In step three (in the Geocentric domain), the coordinate transformation is performed using the parameters specified for the Geocentric translation method:

Table 25: Geocentric Translation parameters

Geocentric Translation		
Parameter	Parameter Value	Unit
tX	-87	m
tY	-98	m
tZ	-121	m

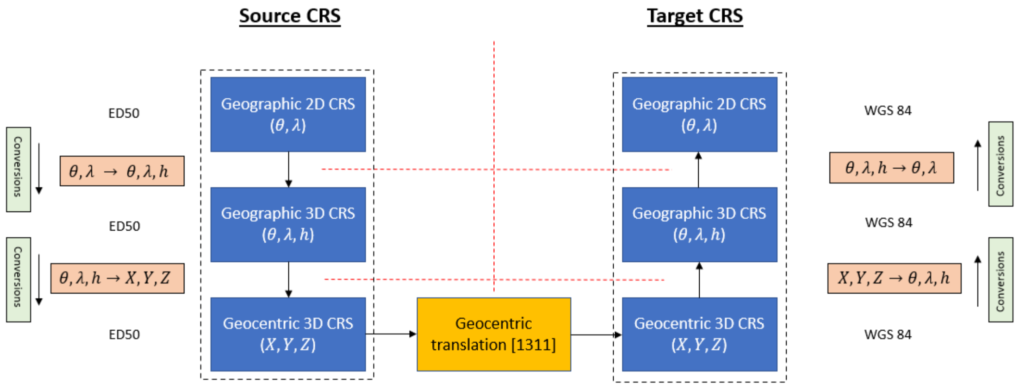


Figure 251: Coordinate operation flow [9603]

Multiplying out the matrix expression shown at the start of this section yields three equations, one for each of the three axes of the Geocentric cartesian 3D coordinate system. It is here that the three translation parameter values shown in Table 24 are applied.

$$X_T = tX + X_S$$

$$Y_T = tY + Y_S$$

$$Z_T = tZ + Z_S$$

- Step four: Geocentric CRS to Geographic 3D CRS
- Step five: Geographic 3D CRS to Geographic 2D CRS

In steps four and five the reverse operations conducted in steps two, and one are performed but with respect to the Target CRS.

Example:

Source CRS: ED50, EPSG [4230]

Target CRS: WGS 84, EPSG [4326]

Transformation method: Geocentric translation (geog2D domain), EPSG [9603]

Transformation variant: ED50 to WGS 84 (1): EPSG [1133]

Extent:

Figure 252: ED50 to WGS 84 (1) extent

The input position is supplied for coordinates related to the geographic 2D CRS (geog 2D domain):

$$55^{o}\ 30'\ 00.000''\ N$$

$$02^{o}\ 30'\ 00.000''\ E$$

As per step one, these are converted to geographic 3D domain by introducing the pseudo vertical coordinate for the ellipsoidal height:

$$55^{o}\ 30'\ 00.000''\ N$$

$$02^{o}\ 30'\ 00.000''\ E$$

$$0\ m$$

Next, the geographic 3D coordinates are converted to the Geocentric coordinates as per step two, which yields:

$$X = 3617588.475$$

$$Y = 157947.323$$

$$Z = 5233219.153$$

In step three the Geocentric translation coordinate transformation is performed. This converts the cartesian coordinates from source CRS to Target CRS, e.g., WGS 84 [4978] by applying the three translation shifts along the three axes:

$$X = 3617501.475 = -87 + 3617588.475$$

$$Y = 157849.323 = -98 + 157947.323$$

$$Z = 5233098.152 = -121 + 5233219.153$$

In step four the Geocentric coordinates are converting back to the Geographic 3D coordinates, WGS 84 [4979] giving the following values:

$$55^{o}\ 29'\ 57.452^{"}\ N$$

$$02^{o}\ 29'\ 54.639^{"}\ E$$

$$-151.37m$$

Finally, in step five the coordinates are converted to geographic 2D CRS, e.g., WGS 84 [4326] by dropping the ellipsoidal height as follows:

$$55^{o}\ 29'\ 57.452^{"}\ N$$

$$02^{o}\ 29'\ 54.639^{"}\ E$$

This completes the coordinate operation.

13.1.2.2 Helmert 7 parameter transformation

The Helmert 7 parameter transformation applies three types of parameters to modify the coordinates from the Source CRS to the Target CRS. These are:

- Three translation parameters (tX, tY, tZ) that perform the same function as those described for the Geocentric translation method.

- Three rotation parameters (rX, rY, rZ) that align the coordinate systems axes from the Source CRS to those of the Target CRS.
- Scale parameter (s) that corrects the distances computed on the source reference ellipsoid to what they would be computed on the target reference ellipsoid.

Collectively these parameters are shown in the following equation:

$$\begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} = \begin{bmatrix} tX \\ tY \\ tZ \end{bmatrix} + (1 + s)[M] \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix}$$

Therefore, the input coordinates (X_S, Y_S, Z_S) are transformed to the output coordinates (X_T, Y_T, Z_T) by the application of the three translation, three rotation and one scale parameters. This is graphically shown in Figure 253.

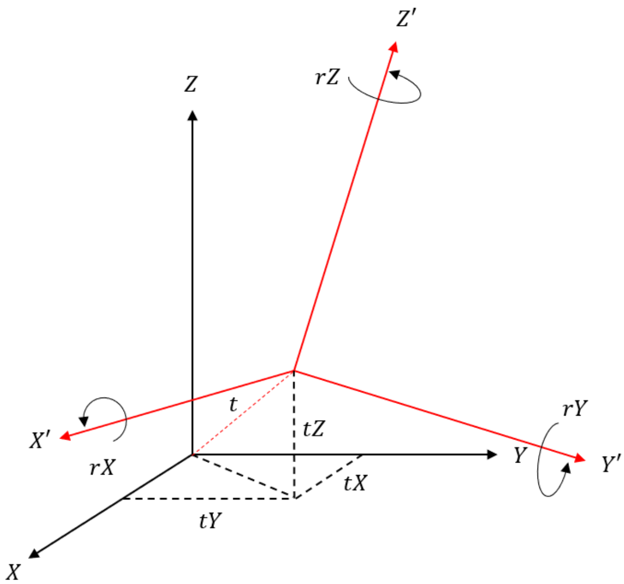


Figure 253: Helmert 7 parameter transformation

There are two variants of this method known as:

- Coordinate Frame rotation (CF)
- Position Vector transformation (PV)

The difference between the two variants relates to the sign convention used in the rotation matrix $[M]$. The coordinate frame rotation applies a positive counterclockwise convention whilst the position vector transform applies a positive clockwise convention. Full details of these two variants are described in the Parr (2024a). However, the difference between the two is illustrated with two examples given in this section.

Regardless of variant the method it commences when the user provides the input coordinates that will take one of the three forms described in section 13.1.2., namely:

- Geographic 2D domain (φ, λ)
- Geographic 3D domain (φ, λ, h)
- Geocentric domain (X, Y, Z)

Following the similar example shown for the Geocentric translation the input coordinates are supplied in the geographic 2D domain. Therefore, the same five concatenated steps (one to five) are required to complete the coordinate operation.

<u>Coordinate Frame rotation (geog2D domain)</u>

Using the rotation convention of positive counterclockwise the equation of the Coordinate Frame rotation is given as:

$$\begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} = \begin{bmatrix} tX \\ tY \\ tZ \end{bmatrix} + (1+s) \begin{bmatrix} 1 & \theta_Z & -\theta_Y \\ -\theta_Z & 1 & \theta_X \\ \theta_Y & -\theta_X & 1 \end{bmatrix} \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix}$$

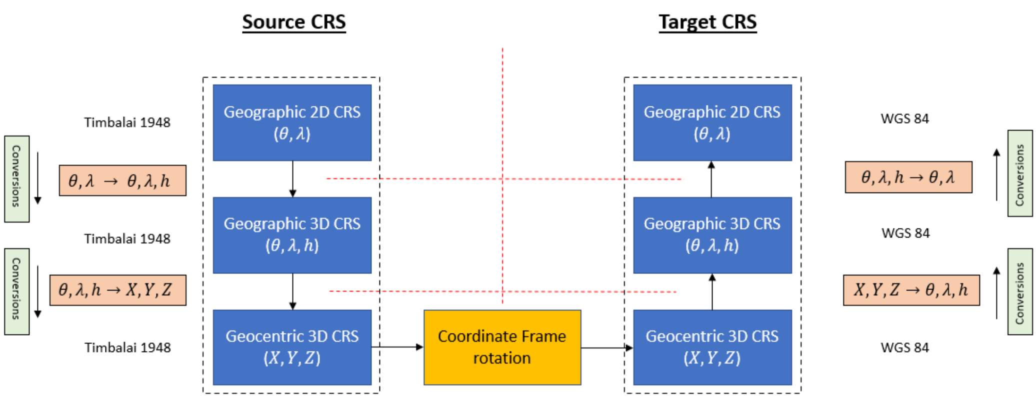


Figure 254: Coordinate operation flow [9607]

The five steps associated with the coordinate operation are as follows:

- Step one: Geographic 3D to Geographic 2D conversion

$$\varphi, \lambda \leftrightarrow \varphi, \lambda, h$$

- Step two: Geographic 3D to Geocentric conversion

$$\varphi, \lambda, h \leftrightarrow X, Y, Z$$

The first two steps are applied to convert the coordinates such that they are conditioned for input to the Geocentric transformation in the Geocentric domain (X, Y, Z).

- Step three: Coordinate Frame rotation is conducted in the Geocentric domain using the parameters and parameter values specified for the Coordinate Frame rotation:

Table 26: Parameter of the Coordinate Frame rotation

Parameter	Parameter Value	Unit
tX	-689.5937	m
tY	623.84046	m
tZ	-65.93566	m
rX	0.02331	arcsec
rY	-1.17094	arcsec
rZ	0.80054	arcsec
s	5.88536	ppm

Multiplying out the matrix expression shown above yield three equations, one for each of the Geocentric coordinates associated with the coordinate system.

$$X_T = tX + (1 + s)[X_S + Y_S\theta_Z + Z_S(-\theta_Y)]$$

$$Y_T = tY + (1 + s)[X_S(-\theta_Z) + Y_S + Z_S\theta_X]$$

$$Z_T = tZ + (1 + s)[X_S\theta_Y + Y_S(-\theta_X) + Z_S]$$

- Step four: Geocentric CRS to Geographic 3D CRS

- Step five: Geographic 3D CRS to Geographic 2D CRS

In steps four and five the reverse operations conducted in steps two, and one are performed but with respect to the Target CRS.

Example:

Source CRS: Timbalai 1948, EPSG [4298]

Target CRS: WGS 84, EPSG [4326]

Transformation method: Coordinate frame rotation, EPSG [9607]

Transformation variant: Timbalai 1948 to WGS 84 (5)

Extent:

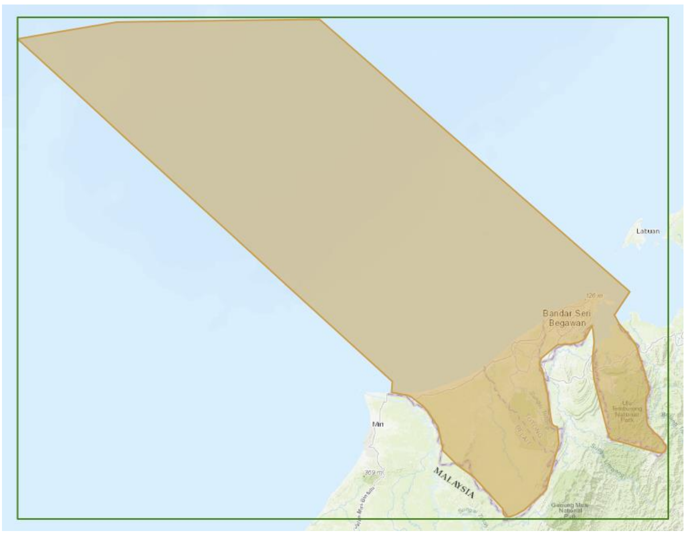


Figure 255: Timbalai 1948 to WGS 84 (5) extent

The input point is supplied for coordinates belonging to the geographic 2D domain:

$$05^{o}\ 40'\ 00.000''\ N$$

$$113^{o}\ 50'\ 00.000''\ E$$

As per step one, the coordinates are converted to geographic 3D domain with the pseudo vertical coordinate for the ellipsoidal height:

$$05^{o}\ 40'\ 00.000''\ N$$

$$113^o\ 50'\ 00.000''\ E$$

$$0m$$

Next, the geographic 3D coordinates are converted to the Geocentric coordinates as per step two, which yields:

$$X = -2564413.080$$

$$Y = 5805153.502$$

$$Z = 625540.162$$

Enter all the coordinates and parameter values into the equation to obtain:

$$\begin{bmatrix} -2565091.688 \\ 5805821.530 \\ 625491.810 \end{bmatrix} = \begin{bmatrix} -689.5937 \\ 623.84046 \\ -65.93566 \end{bmatrix} + (1 + 5.88536 * 10^{-6})[M] \begin{bmatrix} -2564413.080 \\ 5805153.502 \\ 625540.162 \end{bmatrix}$$

Where:

$$M = \begin{bmatrix} 1 & 0.00000388 & 0.00000568 \\ -0.00000388 & 1 & 0.000000113 \\ -0.00000568 & -0.000000113 & 1 \end{bmatrix}$$

In step four the Geocentric coordinate are converted to geographic 3D coordinates, WGS [4979] which yields the follow values:

$$05^o\ 39'\ 56.759''\ N$$

$$113^o\ 50'\ 11.400''\ E$$

$$-151.45m$$

Converting these back to the Geographic 2D domain yields coordinates referenced to WGS 84 [4326]:

$$05^o\ 39'\ 56.759''\ N$$

$$113^o\ 50'\ 11.400''\ E$$

This completes the coordinate operation.

Position Vector transform (geog2d domain)

Using the rotation convention of positive clockwise the equation of the Position Vector transform is given as:

$$\begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} = \begin{bmatrix} tX \\ tY \\ tZ \end{bmatrix} + (1+s)\begin{bmatrix} 1 & -\theta_Z & \theta_Y \\ \theta_Z & 1 & -\theta_X \\ -\theta_Y & \theta_X & 1 \end{bmatrix}\begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix}$$

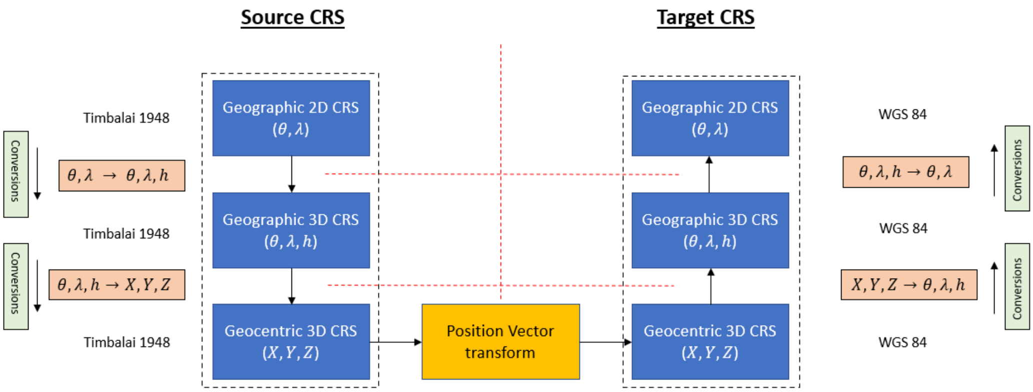


Figure 256: Coordinate operation flow [9606]

- Step three: Position Vector transform is conducted in the Geocentric domain using the parameters and parameter values specified for the Position Vector transform. The parameter values assigned to the parameters of the operation method are given as follows:

Table 27: Parameter values of Position Vector transform

Parameter	Parameter Value	Unit
tX	-533.4	m
tY	669.2	m
tZ	-52.5	m
rX	0	arcsec
rY	0	arcsec
rZ	4.28	arcsec
s	9.4	ppm

Multiplying out the matrix expression shown above yield three equations, one for each of the Geocentric coordinates associated with the coordinate system.

$$X_T = tX + (1+s)[X_S + Y_S(-\theta_Z) + Z_S\theta_Y]$$

$$Y_T = tY + (1+s)[X_S\theta_Z + Y_S + Z_S(-\theta_X)]$$

$$Z_T = tZ + (1+s)[X_S(-\theta_Y) + Y_S\theta_X + Z_S]$$

Notice how the rotations have reversed signs from those given for the Coordinate Frame rotation method. This reflects the clockwise versus counterclockwise variants of the Helmert 7-parameter method. The input coordinates are geodetic latitude (φ) and geodetic longitude (λ) which must undergo the same conditioning operations to arrive at coordinates in the Geocentric domain (X, Y, Z).

Example:

Source CRS: Timbalai 1948

Target CRS: WGS 84

Transformation method: Position vector transform

Transformation variant: Timbalai 1948 to WGS 84 (4)

Extent:

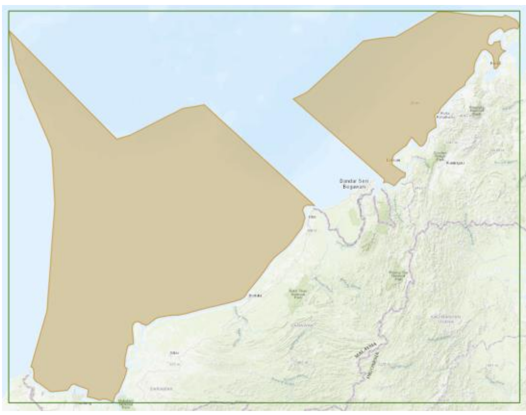


Figure 257: Timbalai 1948 to WGS 84 (4) extent

Input coordinates:

$$05^o\ 40'\ 00.000''\ N$$

$$113^o\ 50'\ 00.000''\ E$$

$$0m$$

The Geocentric coordinates become:

$$X = -2564413.080$$

$$Y = 5805153.502$$

$$Z = 625540.162$$

Enter all the coordinates and parameter values into the equation to obtain:

$$\begin{bmatrix} -2565091.043 \\ 5805824.059 \\ 625493.541 \end{bmatrix} = \begin{bmatrix} -533.400 \\ 669.200 \\ -52.500 \end{bmatrix} + (1 + 9.4 * 10^{-6})[M] \begin{bmatrix} -2564413.080 \\ 5805153.502 \\ 625540.162 \end{bmatrix}$$

Where:

$$M = \begin{bmatrix} 1 & 0.00000208 & 0.00000000 \\ -0.00000208 & 1 & 0.00000000 \\ 0.00000000 & 0.00000000 & 1 \end{bmatrix}$$

In step four the Geocentric coordinate are converted to geographic 3D coordinates, WGS [4979] which yields the follow values:

$$05^{o}\ 39'\ 56.809''\ N$$

$$113^{o}\ 50'\ 11.348''\ E$$

$$-151.45m$$

Converting these back to the Geographic 2D domain yields coordinates referenced to WGS 84 [4326]:

$$05^{o}\ 39'\ 56.809''\ N$$

$$113^{o}\ 50'\ 11.348''\ E$$

As with the Geocentric example this operation is separated into the same five steps as mentioned.

This ends the coordinate operation.

13.1.2.3 Interpolated gridded methods

The interpolated gridded methods comprises the determination of geographic offsets which are added to the input coordinates to compute the output coordinates using the following equation:

$$\begin{bmatrix}\varphi_T\\ \lambda_T\end{bmatrix} = \begin{bmatrix}\Delta\varphi\\ \Delta\lambda\end{bmatrix} + \begin{bmatrix}\varphi_S\\ \lambda_S\end{bmatrix}$$

The parameters associated with this method are given as follows:

$$d\varphi$$

$$d\lambda$$

These are known as the latitude and longitude geographic offsets respectively. The parameter values they take are obtained from associated gridded data files that act as a ‘look up table’.

Example:

Source CRS: NAD27

Target CRS: NAD83

Transformation method: NADCON

Latitude and longitude offsets – derived by interpolation within the gridded data.

Parameter values are extracted from the following files:

Conus.las

Conus.los

The first contains the latitude offsets and the latter the longitude offsets.

Extent:

Figure 258: Extent for NADCON

14 Proposed well location audit

The coordinates assigned to a proposed well locationare the result of a culmination of concatenated activities involving numerous geoscience disciplines. This commences with the design of the seismic survey and concludes with the selection of coordinates computed by the algorithms and geodetic libraries implemented in the seismic interpretation workstation software. The key activities in the data lifecycle include design, seismic data acquisition, seismic data processing, data loading and interpretation with each activity being the responsibility of different stakeholders in the exploration team. The two principal data sets used are the seismic trace data and the geo-spatial data describing the geographic location where the rock structures were imaged by the trace data.

The geo-spatial data is described by a tuple of coordinates referenced to an authorized coordinate reference system (CRS). During each activity multiple CRS' may be used simultaneously with each describing the position of the seismic trace data related to a different coordinate system (e.g., ellipsoidal or cartesian). For example, geographic coordinates (φ, λ), projected coordinates (E, N) or coordinates belonging to a seismic binning grid (I, J). When the coordinate tuples are related to the same base geodetic datum, they are grouped together to form a Derived CRS (see section 3.3). The term 'derived' infers that one set of coordinates stems from a computation performed on a related base CRS. For example, projected CRS coordinates (E, N) are derived from their base geographic 2D CRS coordinates (φ, λ) through the coordinate operation of type: conversion (see section 13.1.1). Whilst the coordinates of a cell centre in the seismic grid (I, J) are computed by another conversion directly related to the projected 2D CRS (E, N). Hence, one set is derived from another. For further details of these coordinate operations refer to IOGP Guidance Note 373-07-2 (IOGP 2020).

During the life cycle of the seismic trace data, it is common practice to apply coordinate operations of type: conversion and transformation to its geo-spatial component and thus change from an original source CRS to a new target CRS. Where transformations are conducted it means the source and target CRS do not share the same geodetic datum, e.g., European Datum 1950 to World Geodetic System 1984. Coordinate operations are further complicated because multiple methods can exist over a similar geographic area to process coordinates between the same source CRS and target CRS. Each method will apply different parameters and parameter values (see section 13) resulting in different answers being calculated. Additional considerations include knowing how different software applications implement the same coordinate operations. This can only be ascertained by a thorough understanding of the geodetic algorithms and geodetic inventories used by each application.

Managing changes to the geo-spatial component of the seismic trace data requires meticulous housekeeping that chronicles all modifications made to the data based on the application of coordinate operations. This becomes the most critical undertaking of the quality process when verifying the surface position of a proposed well location. This chapter describes some recommended considerations for a QA/QC process where each step requires extracting key data from specific file types used throughout the data life cycle. It focuses on identifying the different Coordinate Reference Systems contained (including Derived and Bound CRS) in the data files such as the P series (P1 and P6) and SEG-Y file and explicit record types they contain. This must be coupled with detailing what coordinate operations (if any) were conducted between each stage and what methods and parameter values were used. A high level description of how the QA/QC workflow implements these checks is given with respect to the geo-spatial component of the seismic trace data. Although, it is common practice for the geoscientists to select the proposed well location from seismic 3D data volumes it is recognised this is also conducted using seismic 2D data volumes. There are nuances to the workflow where 2D versus 3D seismic data is used and these are described.

14.1 Geo spatial referencing and file types

The different stages of the data life cycle involved in the selection of a proposed well location were identified in the introduction and are shown by the light blue boxes in Figure 259. The grey boxes indicate the different key data types associated with each activity and the orange boxes the file types into which they are stored. At the top are listed the coordinate reference systems used throughout the processes which are labelled CRS A to CRS E. Each file type contain coordinates and the CRSs to which these are referenced is annotated next to each of the relevant boxes. The final step is described by the red box where the perimeters contained in the seismic grid definitions are graphically overlaid and correlated. This includes the Live Trace Outline extracted from the trace data contained in the final migrated SEG-Y file.

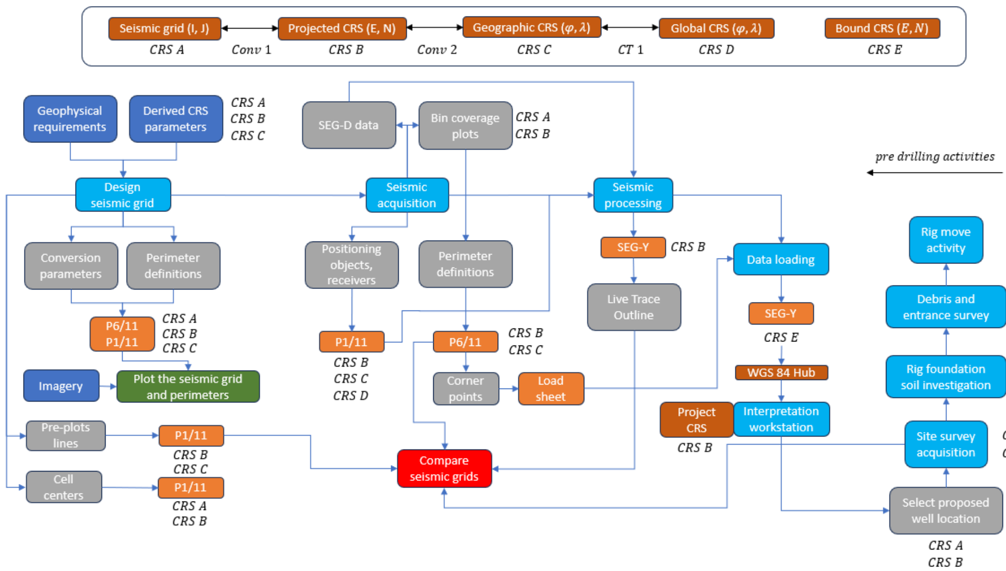


Figure 259: Stages of the proposed well location audit

14.1.1 Data and file types

The success of the proposed well location audit is largely dependent on the availability of the necessary data files, containing the data types required. This includes any associated reports being obtained for each stage of the quality process. The absence of these files and reports will degrade the audit process with analysts resorting to assumptions. An introduction to the different file types was given in chapter 9 and what key information is required from each file type is highlighted as follows:

Design seismic grid

The project team provide the geophysical requirements the seismic survey is required to achieve, and the surveying team the geo-spatial referencing requirements. The survey design is conducted, and all related metadata (conversion parameters) and attributes (CRS definitions) are captured in the P6 file format. The P6 must also contain a perimeter definition for the full fold extent. It may also contain null fold and null coverage (see section 4) perimeters where there are known obstructions in the full fold extent. Collectively, they describe the areas where the seismic trace data can and cannot be acquired (e.g., M6 records of the P1/11 file). Additionally, two other data types may also be created, namely:

- *Coordinates of the seismic grid cell centres*. The coordinates for the cell centres can be generated from the survey design as required and stored in the P1/90 file format as Q records or in the P1/11 format as P1 records. Alternatively, they can be stored as B6 records in the P6/11 format.
- *The pre-plot acquisition lines*. The P1 file format is also used to store the start and end of line coordinates of the pre-plot acquisition lines. Using the P1/90 file format they are normally represented by the V records and in the P1/11 by the N1 records.

Further representations of the seismic bin grid can also be distributed to different stakeholders in the project team using the following formats:

- ESRI .shp file format
- GeoJSON format

As each file type is generated from the same seismic grid definition there will be consistency in all the metadata and extent of the full fold perimeter.

Seismic acquisition

After the acquisition has been completed the seismic crew will deliver the geo-spatial data in four different formats:

- P1 file format contains the processed positioning data for all the positioning objects in the seismic spread, e.g. sources and receivers.
- P6 file format containing the all the perimeter definitions where seismic trace data was acquired. It must also include the total coverage perimeter along with all null fold and null coverage perimeters describing areas of reduced or missing trace data coverage.
- Binning grid coverage plots that describe the fold coverage acquired in each cell of the seismic grid. Various plots are generated to illustrate the fold coverage for specific offset ranges (nears, mids and fars) as well as the total coverage.
- SEG-D file format containing the raw seismic data, the CRS stanzas and associated auxiliary navigation files (P1, P2).

If the P6/11 and P1/11 versions are used they are expected to apply the same common header expressed by the HC records in the header block.

Seismic processing

Using the SEG-D raw seismic data and the associated navigation files the trace data is processed and stored in a general purpose SEG-Y file format. In the SEG-Y file format are trace headers associated with every seismic trace. This comprises 240 bytes with dedicated byte locations to store the projected coordinates for source, receiver and CMP positions depending upon the type of data stored, e.g. shot gathers, receivers gathers or trace gathers. With the latter, if the byte locations are populated the coordinates can be extracted to generate a Live Trace Outline (LTO) from which a polygon / perimeter is created defining the area over which all seismic trace data was acquired, regardless of fold coverage.

N.b. The P6 file format is seldom if ever used in seismic processing as an input or an output.

Data loading

From the P6 file a load sheet can be created provided there is sufficient data contained therein. The purpose of the load sheet is to assist the data loader in ensuring the seismic trace data contained in the SEG-Y file is imported into the interpretation workstation correctly. For example, was the correct CRS selected and did the corner points of the seismic 3D cube correlate to those expected. This brings into play CRS E as stated in Figure 255, otherwise known as the Bound CRS, which is the CRS selected by the data loader when importing the seismic trace data. Note, the load sheet is not a formal file format, more a concept. However, in the latest version of the P6/11 format are L6 records used to populate the load sheet.

Interpretation

The seismic trace data, once in the interpretation software project will be referenced to the base CRS of the project and may or may not have undergone a coordinate operation during input. There is no formal output file generated from the interpretation. The coordinates of the proposed well location are extracted directly from the software user interface.

14.2 QC audit – some considerations

The quality assurance procedure will comprise a series of steps using the data files exported from the survey design, data acquisition, data processing and data loading. Between each stage understanding the referencing applied to the geo-spatial components of the data remains the main purpose of the QC process.

14.2.1 Coordinate reference systems

Two questions that require addressing: First, to what coordinate reference system(s) is the geo-spatial component of the data referenced at each stage of the QC process? Second, if the CRS has been modified between consecutive steps of the audit what coordinate operations were conducted? This includes determining the coordinate operation name, the operation parameters and the operation parameter values.

For example, the CRS used in acquisition was WGS 84 / UTM zone 31N. However, that applied in data processing was ED50 / TM 0 N. Changes to both geodetic datum and map projection mean that a coordinate transformation and coordinate conversion(s) have been applied to the positions of the seismic trace data. What the audit trail must document is how the coordinate operations were conducted, using what method, method parameters and parameters values.

For this example the following steps are required:

- WGS 84 / UTM zone 31N (E, N) is converted to WGS 84 (φ, λ)
- WGS 84 (φ, λ) is transformation to ED50 (φ, λ)
- ED50 (φ, λ) is converted to ED50 / TM 0 N (E, N)

It is what methods and parameter values that are applied at each stage that require documentation. On the right hand side of Figure 260 are the parameters and parameter values applied in the Transverse Mercator operation method of step 1. Including the EPSG codes in the audit trail confirms the implicit definition. Documenting the parameter and parameter values confirms the explicit definition.

Next, the coordinate transformation is applied to convert the coordinates from WGS 84 to ED50 geographic 2D CRS. Again, the operation method and parameter values require documenting as shown in the lower middle portion of Figure 260. The coordinate operation method is specified as the Position Vector Transformation which applies the seven parameters shown. Different operation methods yield different results, hence the importance of documenting the method applied. The provision of test points in the audit trail improves the transparency of the computations involved. Check the coordinate transformation against the test points.

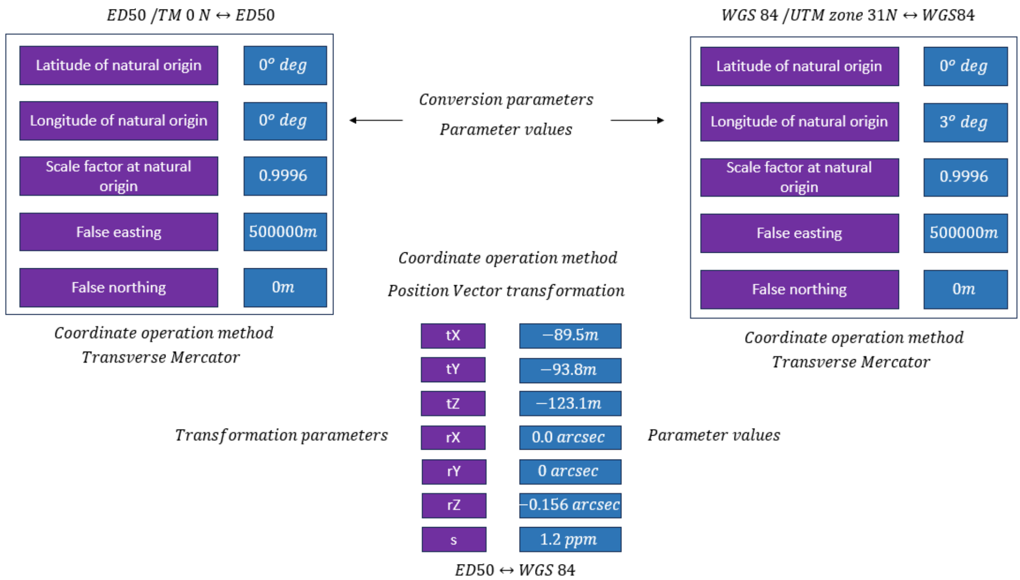


Figure 260: Coordinate operations documented in audit trail

Finally, in step three the geographic coordinates (φ, λ) are re-projected on to the target map projection (E, N) using another coordinate conversion. Again, the parameter method and parameters values used in the conversion (E, N) are shown on the left hand side of Figure 260.

The documentation should state who performed the coordinate operations and what software was used. For example, the requested deliverables from the seismic acquisition may include multiple P6 and P1 files referenced to different coordinate reference systems, e.g., satellite datum and survey datum. This would indicate the seismic contractor was responsible for the conversions which is common given that the early stages of seismic data processing are often conducted whilst the data acquisition is being performed.

Pinch points that arise during data loading often relate to the inexperience of the analyst to select the appropriate CRS (for the seismic data volume) at the time of loading. Given the daunting nature with which some of the more common interpretation packages present their inventory of CRSs (to the user) this is not surprising. Selecting the wrong CRS does not always create significant horizontal errors that become obvious when mapped. Errors that are tens to hundreds of metres is size are more difficult to isolate and normally result from the wrong geographic CRS being selected, e.g., WGS 84 / UTM zone 31N selected instead of ED50 / UTM zone 31N. The map projection is the same, only the geodetic datum differs.

Making provision for a load sheet will help prevent selection errors being made by instructing the analyst as to which CRS they are required to select for each dataset being loaded to the project. The load sheet must be associated with individual datasets as there are no guarantees that the same CRS will apply to all data being loaded to the same project. For an example of the load sheet refer to section 9.5 and Figure 193.

Another related to this common scenario: the interpretation project to which the seismic data volume(s) is imported is assigned a base CRS usually chosen because of historical matters (or hysterical matters), i.e., the project team has always worked in that CRS. Typically, this will differ from the CRS to which the data was referenced during data acquisition and perhaps data processing (e.g. data CRS) When the base CRS and data CRS differ there is a tendency to request a coordinate operation is applied prior to data loading to ensure parity, i.e., data CRS now matches the base CRS of the interpretation project.

However, in practice some of the more commonly used interpretation software applications provide functionality to perform coordinate operations at the time data is loaded. If the CRS selected for the seismic data volume being imported differs from that chosen for the base CRS of the project coordinate operations are automatically applied. This is known as an 'on-the-fly' coordinate operation. This prevents the necessity of these operations having to be conducted at a different stage as ideally there is no need to make a CRS change until the point of data loading.

For example: The CRS of the seismic trace data being loaded is WGS 84 / UTM zone 31N (source) and the base CRS of the interpretation project is ED50 / TM 0 N (target). Because the interpretation software applies the Bound CRS (see section 3.6) the coordinate operations required to convert the geo-spatial data contained in the SEG-Y from source to target CRS are conducted at the time of loading. Hence it prevents the need to perform any coordinate operations on the geo-spatial at any earlier stages. The less changes there are to the CRSs of the data throughout the data life cycle the better. This will help preserve the integrity of the geo-spatial data. It is worth remembering that when a coordinate transformation is conducted it introduces error to the data.

14.2.2 Survey design

Only necessary if the audit trail can trace the process back to this stage. It is assumed that the Derived CRS is used in the definition of the seismic grid. As described in section 3.3 the three components of the Derived CRS are:

- Projected CRS: WGS 84 / UTM zone 49N
- Coordinate System: $I = J + 90^o$ coordinate system, Axes: $I \; and \; J$
- Conversion: Seismic grid conversion where $I = J + 90^o$

The last element is the conversion which describes the attributes assigned to the seismic grid, e.g., origin, survey bearing, increments and cell widths. These are selected by the project team and describe the geophysical objectives of the survey in terms of geo-spatial horizontal data resolution. They have a direct bearing on the geometry of the seismic equipment deployed during data acquisition and governs the optimal pattern of pre-plot lines along which the survey crew perform the acquisition. The data and metadata associated with the survey design will be stored in the P6 and P1 formats. Therefore, the recommended checks performed at this stage will include:

- Confirm the implicit and explicit parameters and parameter values specified in the Derived CRS.
- Check that the conversion parameters in the derived CRS are identical to those specified in the seismic grid design.
- Check the test points for coordinate operations between the geographic CRS, projected CRS and seismic grid CRS (using the appropriate conversion method) of the derived CRS.

Next, check the perimeter definitions that describe where and where not the seismic trace data is expected to be acquired. The checks shall involve the corner points and extent of the full fold, and the null fold and null coverage perimeters should they be available. To check the perimeters, extract the H6,2,0,0 records for all the perimeters defined in the Header Block and the corresponding M6 records from the data block.

```
H6,2,0,0,Survey Perimeter Definition       , 1,     Full Fold,3,2,3,     Full Fold Coverage,0,
H6,2,0,0,Survey Perimeter Definition       , 2,       Null FF,3,2,4,Null Full Fold Coverage,0,
H6,2,0,0,Survey Perimeter Definition       , 3,    Total Fold,3,2,2,         Total Coverage,0,
H6,2,0,0,Survey Perimeter Definition       , 4,       Null CF,3,2,5,          Null Coverage,0,
```

Ensure, there are M6 records corresponding to all the perimeters defined in the Header Block. For example, below are the M6 records corresponding to the Full Fold perimeter specified in the first line above.

```
M6,0,1,1,1,1,1001,1001,,550000.00,475000.00,,
M6,0,1,1,2,1,1001,13501,,550000.00,553125.00,,
M6,0,1,1,3,1,3501,13501,,612500.00,553125.00,,
M6,0,1,1,4,1,3501,10019,,612500.00,475000.00,,
```

If coordinates are required for any of the cell centres of the seismic grid check that the associated B6 records are present in the P6 file or the Q records of the P1/90. An example of the B6 records is shown below:

```
B6,0,1,1001,1001,,500000.00,600000.00,,
B6,0,1,1001,1002,,500000.00,600012.50,,
B6,0,1,1001,1003,,500000.00,600025.00,,
B6,0,1,1001,1004,,500000.00,600037.50,,
B6,0,1,1001,1005,,500000.00,600050.00,,
B6,0,1,1001,1006,,500000.00,600062.50,,
B6,0,1,1001,1007,,500000.00,600075.00,,
B6,0,1,1001,1008,,500000.00,600087.50,,
B6,0,1,1001,1009,,500000.00,600100.00,,
B6,0,1,1001,1010,,500000.00,600112.50,,
B6,0,1,1001,1011,,500000.00,600125.00,,
B6,0,1,1001,1012,,500000.00,600137.50,,
B6,0,1,1001,1013,,500000.00,600150.00,,
B6,0,1,1001,1014,,500000.00,600162.50,,
B6,0,1,1001,1015,,500000.00,600175.00,,
B6,0,1,1001,1016,,500000.00,600187.50,,
B6,0,1,1001,1017,,500000.00,600200.00,,
B6,0,1,1001,1018,,500000.00,600212.50,,
B6,0,1,1001,1019,,500000.00,600225.00,,
```

The numbers in the red rectangle represent to cell indexes related to I and J, whereas the numbers in the blue rectangle represent their equivalent projected CRS coordinates (E, N).

Finally, verify that the pre-plot lines overlay the full fold perimeter as expected. All the pre-plot lines must overlap the full fold perimeter with no lateral offset being observed (see Figure 261). There must also be equal spacing between the pre-plot line along the crossline direction.

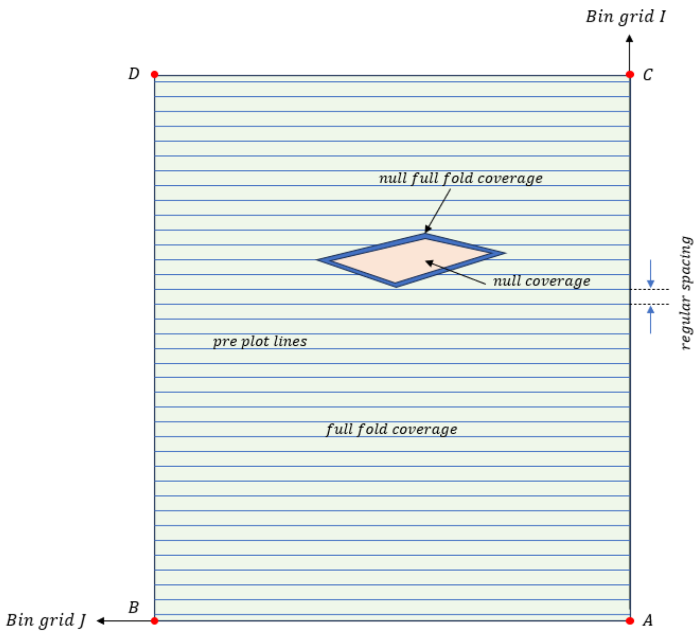


Figure 261: Corner points, perimeters and pre-plot lines

14.2.3 Data acquisition

The seismic crew acquire seismic trace data over the extent of the full fold perimeter, originally along the primary pre-plot lines and then to conduct any re-shoot or infill lines. The geometry of the deployed seismic equipment must be such that the geophysical objectives of the survey are achieved with respect to inline and crossline cell widths associated with the horizontal geo-spatial resolution chosen. The navigation data contained in the P1 files will be plotted and displayed on top of the pre-plot lines as shown in Figure 262. Typically, the V records (of the P1/90) will be used or the equivalent positioning object (OBJTYPEREF) from the P1/11 file for a marine survey.

Where land seismic or OBN / OBC data is acquired the preferred file format is the SPS format which comprises three inter-related files. One for storing the source records, one for storing the receiver records and one relational file describing what receivers were awake at each shot point. For these survey types the SPS file format is more commonly used that the P1 format.

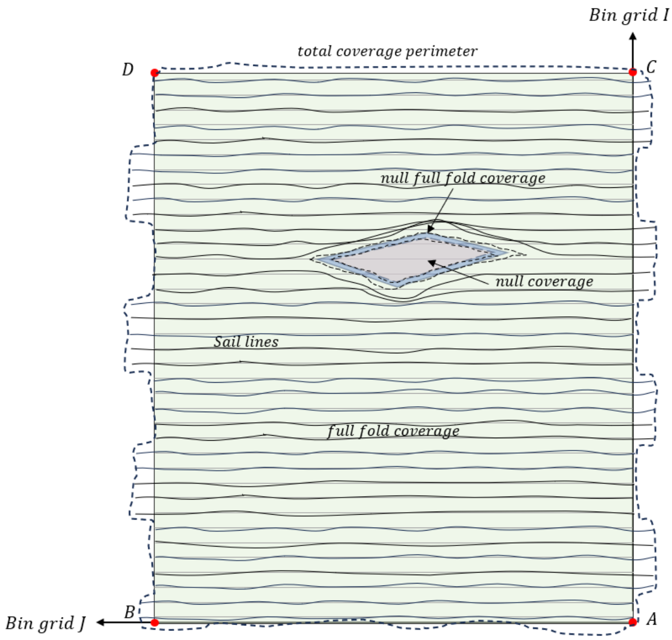


Figure 262: Vessel sail lines superimposed on pre-plots

From the post-survey P6/11 file extract and plot the M6 records that describe the various perimeters contained of which an example is shown in Figure 262. Ensure that there is no lateral shift between the total coverage perimeter and the full fold perimeter (or survey design) indicative of a coordinate transformation problem.

Next, verify that the P1 and P6 files are populated with all the correct geo-spatial metadata in their header block. Where the files belong to the Px series they are expected to share the same HC records of the common header. An example of the HC records is shown below for a sample of the geodetic records available.

```
HC,1,3,0,CRS Number/EPSG Code/Name/Source          ,1,5818,Bin Grid I = J+90°,,2022:08:17,IOGP,
HC,1,3,0,CRS Number/EPSG Code/Name/Source          ,2,32648,WGS 84 / UTM zone 48N,,2022:08:17,IOGP,
HC,1,4,0,CRS Number/EPSG Code/Type/Name            ,1,5818,6,engineering,Bin Grid I = J+90°
HC,1,4,8,Engineering Datum                         ,1,9315,Seismic bin grid datum
HC,1,4,0,CRS Number/EPSG Code/Type/Name            ,2,32648,1,projected,WGS 84 / UTM zone 48N
HC,1,4,3,Base Geographic CRS Details               ,2,2,4326
HC,1,4,4,Geodetic Datum                            ,2,6326,World Geodetic System 1984
HC,1,4,5,Prime Meridian                            ,2,8901,Greenwich,0,4,degree
HC,1,4,6,Ellipsoid                                 ,2,7030,WGS 84,6378137,2,metre,298.257223563
HC,1,5,0,Projection                                ,2,16048,UTM zone 48N
HC,1,5,1,Projection Method                         ,2,9807,Transverse Mercator,8
HC,1,5,2,Latitude of natural origin                ,2,8801,0,4,degree
HC,1,5,2,Longitude of natural origin               ,2,8802,105,4,degree
HC,1,5,2,Scale factor at natural origin            ,2,8805,0.9996,5,unity
HC,1,5,2,False easting                             ,2,8806,500000,2,metre
HC,1,5,2,False northing                            ,2,8807,0,2,metre
HC,1,5,2,semi_major_axis                           ,2,100,6378137,2,metre
HC,1,5,2,semi_minor_axis                           ,2,101,0,2,metre
HC,1,5,2,inverse_flattening                        ,2,102,298.257223563,5,unity
HC,1,6,0,Coordinate System                         ,2,4400,Cartesian 2D CS,1,projected,2
HC,1,6,1,Coordinate System Axis 1                  ,2,1,1,Easting,east,E,2,metre
HC,1,6,1,Coordinate System Axis 2                  ,2,2,2,Northing,north,N,2,metre
```

Coverage plots are generated by the onboard binning system to report the fold coverage in each cell of the seismic grid from all source-receiver offsets pairs or from a specified range group (nears, mids or fars). The binning grid plots are assigned a CRS by virtue of the coordinates computed for the source and also receiver groups at every and thus the mid points which are binned into the cells of the seismic grid. As the binning software is fed coordinates from the integrated navigation system it will operate in the same CRS.

14.2.4 Data processing

Data processing centres are unlikely to decode the P6 file(s), instead they obtain coordinates from one of two places, the SEG-D file containing the raw seismic trace data and the associated P1 file containing the processed source and receiver positions on a shot by shot bases. The latter are also referred to as the navigation backup files.

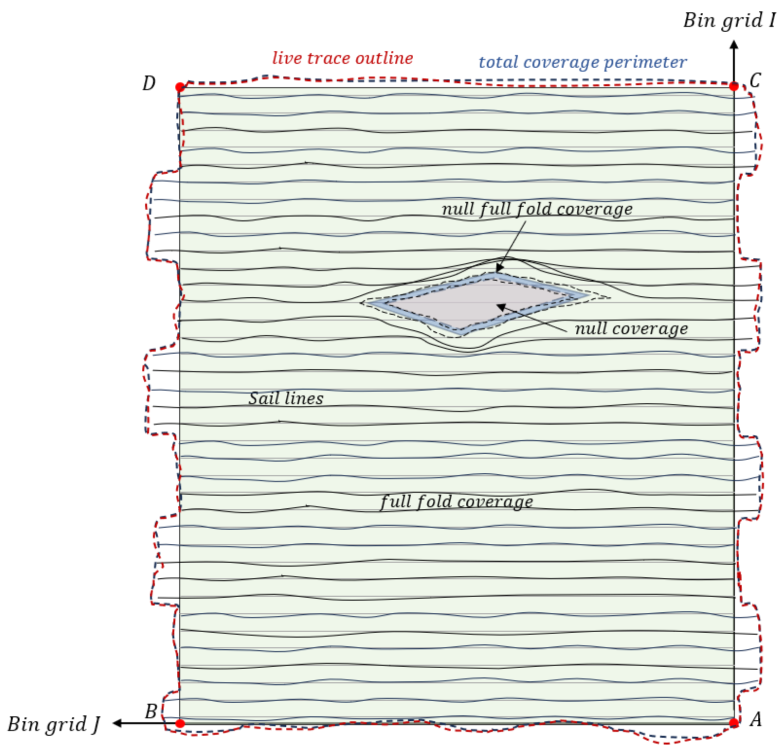


Figure 263: Live trace outline superimposed on acquisition data

The processed seismic trace data is stored in the general purpose SEG-Y data file. In this file are two locations where geo-spatial parameters and data values may or may not be available. The first is in the header block, known as the EBCDIC header in which free format text is stored in repeated 40 line blocks. The second is in the trace headers of the data block.

First, examine the EBCDIC header to determine if any of the text refers to the CRS to which the coordinates in the trace header are referenced and or the corner points of the seismic trace volume. If text is present are the details of the CRS correct? If no details are provided is there an accompanying acquisition or processing report with details of CRS and the corner points of the data.

Check the Trace Headers of the SEG-Y file to determine if the projected CRS coordinates are contained in the correct byte locations, or whether an alternative location is specified in the EBCDIC header. The populated byte locations will depend on the type of seismic data contained in the file. For example, if the trace data are common midpoints then byte location 181-184 and 185-189 should contain the projected Easting and Northing coordinates respectively.

Export the Live Trace Outline (LTO) from the SEG-Y file trace headers. The format is not important, but the file must contain the projected coordinates along with some numbering, e.g., inline and crossline numbers to which the coordinates belong. Next, plot the LTO using the correct CRS (as specified in the EBCDIC header) and correlate it to the total coverage perimeter extracted from the P6 file. Check to ensure there is no lateral offset between the two datasets.

The seismic grid definition used in processing may have undergone some modifications to that used during acquisition. Check to see if any such modifications have been introduced by the processors such as origin point, survey bearing, cell widths and increments. Further modifications may include merging adjacent cells to reduce the volume of data that has been processed. Provided the modifications are recognised it should not hamper the correlation of the extent of the LTO to that of the total coverage perimeter.

14.2.5 Data loading

From the survey design, the coordinates of the cell centres can be exported in a number of way which includes:

- Q records of the P1/90 format

- P1 records of the P1/11 format
- B6 records of the P6/11 format

An example of the P1/90 format is shown in Figure 264 using the Q records, where Q indicates that the information provided in that row relates to a cell centre (bin centre) of the seismic grid. The indexing of each cell centre is represented as follows: The columns reserved for the line name (e.g. columns 2 to 14) are used to store the inline numbers (along $I\ axis$) and the columns reserved for the event number (e.g., columns 17-25) are used to store the crossline numbers (along the $J\ axis$). What follows are the latitude (φ) and longitude (λ) of the cell centre referenced to the geographic 2D CRS (specified in the header block) followed by the easting (E) and northing (N) referenced to the projected CRS. In Figure 264 only the first thirteen crossline cells (1001 to 1013) on the first inline (1001) are shown to illustrate how the format is used to store the bin centres. If the columns reserved for the latitude and longitude are not populated the check can still proceed just using the projected coordinates.

```
Q1001                 1001540844.42N0034555.67E 550000.06000000.0  0.0  0 0 0 0
Q1001                 1002540844.82N0034555.68E 550000.06000012.5  0.0  0 0 0 0
Q1001                 1003540845.22N0034555.68E 550000.06000025.0  0.0  0 0 0 0
Q1001                 1004540845.63N0034555.69E 550000.06000037.5  0.0  0 0 0 0
Q1001                 1005540846.03N0034555.70E 550000.06000050.0  0.0  0 0 0 0
Q1001                 1006540846.44N0034555.71E 550000.06000062.5  0.0  0 0 0 0
Q1001                 1007540846.84N0034555.71E 550000.06000075.0  0.0  0 0 0 0
Q1001                 1008540847.25N0034555.72E 550000.06000087.5  0.0  0 0 0 0
Q1001                 1009540847.65N0034555.73E 550000.06000100.0  0.0  0 0 0 0
Q1001                 1010540848.06N0034555.74E 550000.06000112.5  0.0  0 0 0 0
Q1001                 1011540848.46N0034555.74E 550000.06000125.0  0.0  0 0 0 0
Q1001                 1012540848.86N0034555.75E 550000.06000137.5  0.0  0 0 0 0
Q1001                 1013540849.27N0034555.76E 550000.06000150.0  0.0  0 0 0 0
```

Figure 264: Coordinates of the cell centres

Therefore, from left to right:

- Blue rectangle – inline numbers
- Red rectangle – cross line numbers
- Green rectangle – geographic coordinates
- Azure rectangle – projected coordinates

From the SEG-Y file are extracted the projected coordinates from the trace headers which should correlate to the same cell indexing as that contained in the P1 file, provided the processing house did not apply any renumbering. The coordinates extracted from the P1/90 files are superimposed over the coordinates extracted from the SEG-Y file as shown in Figure 265. Consider this check to be a more detailed version of the correlation between the LTO and the total fold coverage perimeter.

Figure 265: Comparing cell centres

Assume that there has been a change in CRS between data acquisition and data processing: provided that the different CRSs were honoured as part of the check the correlation between datasets should reveal a result similar to the one shown in Figure 265. Any small differences normally arise as a result of the coordinate transformation parameters used. This can be eliminated if the accompanying acquisition or processing reports provide details of the transformation method and parameter values applied.

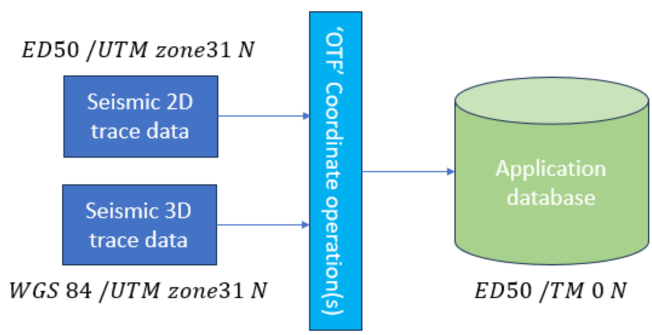


Figure 266: Data loading CRS selection

Prior to commencing data loading it is advised to verify the base coordinate reference system of the project to which the file is being imported. This will establish whether the bound CRS to which the data is referenced sufficiently overlaps with the extent of the project CRS and the extent of the coordinate transformation used in the bound CRS. All three must overlap for the loading to commence.

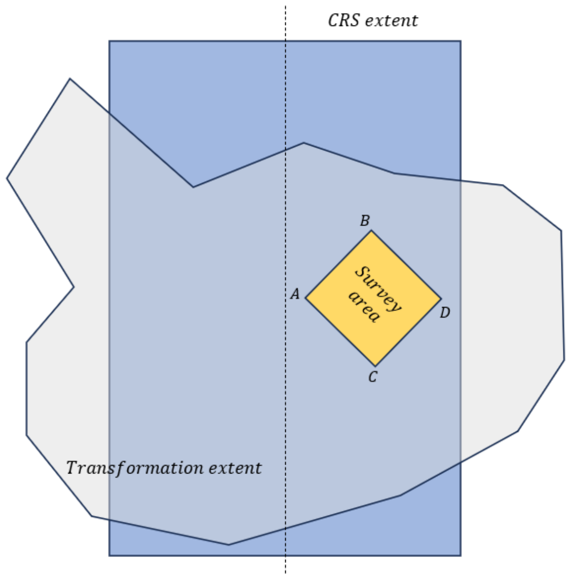


Figure 267: Extent of bound CRS overlaid with survey area

The survey area perimeter can be generated in several will be generated from the L6 records contained in the P6/11 file created from the data acquisition.

14.2.6 Interpretation

The proposed surface and target well locations selected by the interpreter (from the project data) are given in terms of two sets of coordinates: one related to a projected CRS (E, N) and one related to the derived coordinates for the seismic grid (I, J e.g., inline and crossline) as shown in Figure 268. The terms inline and crossline and the abbreviations I and J are applied in this example but different pairs of terms also commonly used. For example, synonymous with I and J are track and bin or line and trace. The choice of labelling is company dependent and there is no problem with using any pair provided there is consistency in their usage throughout the audit process. However, I and J is preferred and used throughout previous chapters.

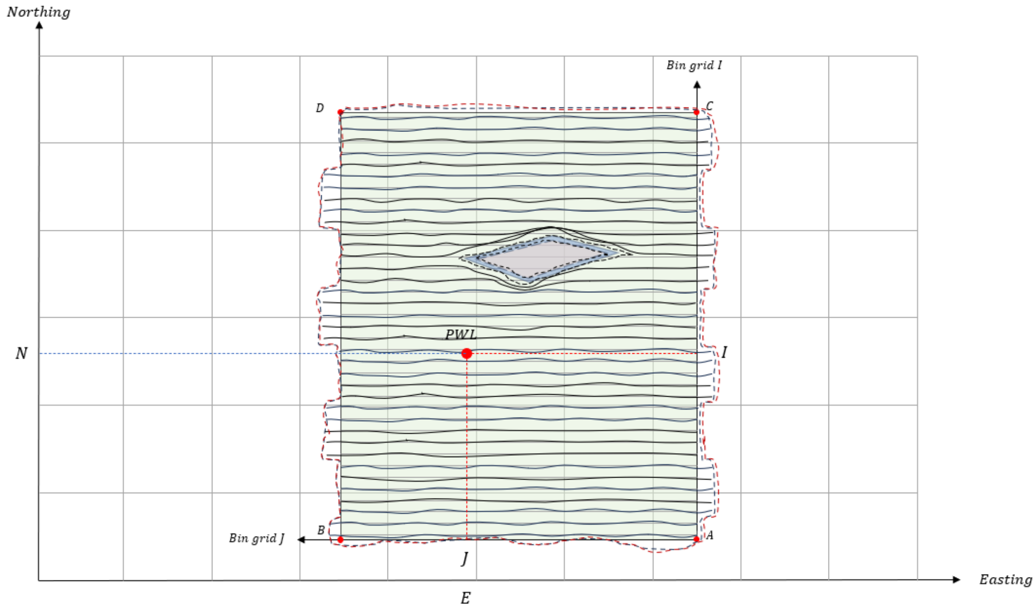


Figure 268: Coordinates selected for proposed well location

The coordinates of the target location (I_T, J_T) will differ from the surface position (I_S, J_S) for a deviated wellbore path as shown in Figure 269. As with the surface position, the target position will also be assigned the equivalent projected CRS coordinates (E_T, N_T).

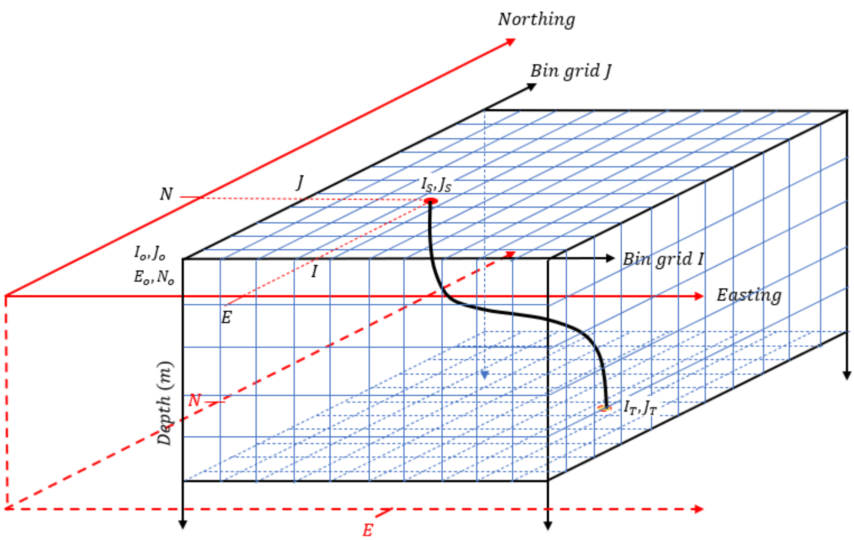


Figure 269: Surface and target wellbore coordinates

The wellbore audit must also confirm the target depth in relation to a vertical datum which will be given in relation to mean sea level as this is the common reference surface applied to the seismic trace data.

14.2.7 Reporting

The audit trail is the formal mechanism of collating the geo-spatial data along with the implicit CRS definitions to which the coordinates are referenced. For a proposed well location (selected from seismic 3D volume) it shall include a geo-spatial template similar to the one shown in Table 28. Clearly labelled data will help prevent any horizontal and vertical errors from occurring.

Table 28: Proposed Well Location template

Well Name: Trillion-1			
Country:	Malaysia	Block:	JTR
Seismic grid name	GS-Trillion 3D	I: 1756 J: 2841	
Projected CRS	ED50 / TM 0 N	Easting: 568841.31m Northing: 6480948.65m	
EPSG code	23090		
Geographic 2D CRS	ED50	Latitude: $58^o 27' 44.762"\ N$ Longitude: $001^o 10' 47.550"\ E$	
EPSG code	4230		
Vertical CRS	MSL	Target depth	
EPSG code	5715	D: 2251m	
I: 1846 J: 2889	Easting: 569893.89m Northing: 6481568.39m	Latitude: $58^o 28' 04.193"\ N$ Longitude: $001^o 11' 53.160"\ E$	
Radial precision:	15m	Probability:	95%
Comments:	Add in any comments that might be necessary		

It is recommended that the projected CRS specified on the form is that used by the interpretation software application. The conversion between the seismic grid (I, J) and the projected CRS (E, N) must also be checked to ensure the interpretation software has generated the correct equivalent values. The same applies when converting to the geographic 2D CRS (φ, λ) coordinates.

Converting coordinate back to a CRS used during an earlier stage of the data life cycle is advantageous for further stages of field operations such as geo-hazard site surveys and rig move activity and is recommended. For example: the coordinates of the proposed well location are converted from the project CRS to CRS used during seismic data acquisition. Table 29 shows the conversion of the proposed surface well location back to the original CRS used in data acquisition.

Table 29: Coordinate conversion

Coordinate Set 1		Coord op	Coordinate Set 2	
Projected CRS	ED50 / TM 0 N	Coordinate Transformation [1133]	Projected CRS	WGS 84 / UTM zone 31N
EPSG code	23090		EPSG code	32631
Easting	568841.31		Easting	393714.46
Northing	6480948.65		Northing	6481567.56
Geographic CRS	ED50		Geographic CRS	WGS 84
EPSG code	4230		EPSG code	4326
Latitude	$58^{o}27'44.762"\ N$		Latitude	$58^{o}27'42.531"\ N$
Longitude	$001^{o}10'47.550"\ E$		Longitude	$001^{o}10'41.618"\ E$

Any form or template is not complete without names, dates and signatures of the analysts who conducted the audit and those who authorized the results presented. This related purely to the geo-spatial element of the proposed well and does not cover any geological matters.

14.2.8 Issues specific to seismic 2D data

For a proposed well locations based on seismic 2D data the surface location will be quoted using the following: the projected CRS (E, N) coordinates and also line name and trace number as illustrated in Figure 272. The audit is conducted using both the SEG-Y file(s) and the associated P1 navigation file(s) and involves the following checks.

Ensuring the nav merge was conducted correctly is an important first step which confirms the relationship between shot point position and CMP position, e.g., what shot point numbers coincide with what trace numbers. The purpose of this is to confirm the coordinates of the CMP positions stored in the SEG-Y trace headers by matching shot points to CMP / trace numbers. In Figure 270 a generic relationship is illustrated to show how many trace numbers there are per shot point which is determined from the geometry used during data acquisition. For example, if the shot point interval is equal to receiver group interval there will be two traces per shot point. However, if the shot point interval is double the receiver group interval there will be four traces per shot point. This is because the trace (or CMP) interval is always half the receiver group interval. Therefore, in this example SP1001 coincides with trace number 1 and SP1002 with trace number 5. The coordinates of CMP / trace numbers 2, 3 and 4 are interpolated at it is known there are four traces per shot point.

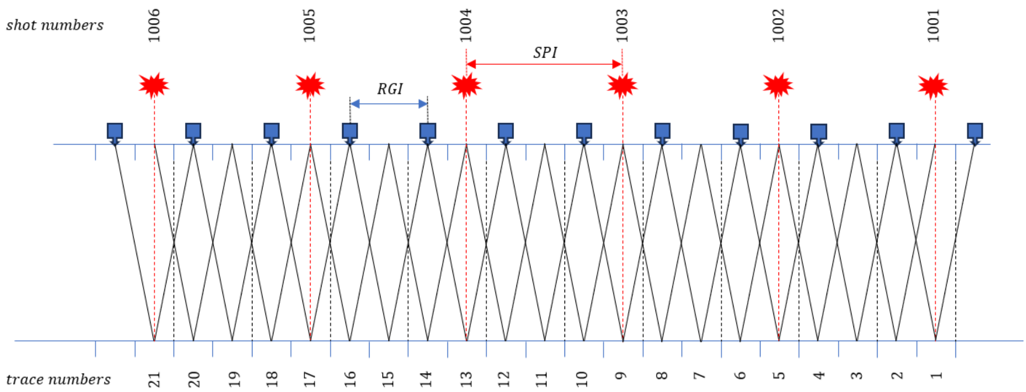


Figure 270: Shot to trace number relationship

This relationship is simple to resolve when all the relevant data is contained in the SEG-Y and P1 files. However, when data is missing it will require some deeper analysis with the common problems experienced being:

- The trace numbers or CMP numbers will only appear in the P1 file if the C record identifier is being used to represent the common midpoint positions in each row. Trace numbers are not used with other seismic objects, but instead shot point numbers.
- Although the SEG-Y trace header provides a byte location for the inclusion of the shot point number this is often empty.
- SPs may have been renumbered (relative to acquisition P1 data) due to limitations in with seismic processing software.
- Land seismic data is often acquired in multiple segments for logistical reasons and the segments are stitched together to create a seamless final migrated line. Hence, the need to check the event numbers applied to the CMP's and are they correctly stated in the SEG-Y file?

Data correlation

Figure 271 illustrates another common problem when data from the SEG-Y and SPS / P1 files are correlated. Extract the coordinates contained in the trace headers of the SEG-Y file for all the available seismic traces are plotted against the shot point and receiver coordinates extracted from the SPS / P1 navigation file. Next, plot the two data sets as shown in Figure 271 to determine the correlation. In this example, the coordinates extracted from the SEG-Y file are represented by the blue circles and plot as a perfectly straight line with regularly spaced CMP intervals. Whereas the coordinates extracted from the SPS / P1 plot in the valley to the east. The blue triangles represent to source positions and the red circles the receiver positions. The CMP / trace positions extracted from the trace headers do not appear representative of where the seismic trace data was acquired, and any decisions made using the SEG-Y trace header positions would induce both a horizontal and vertical error component on any proposed well location.

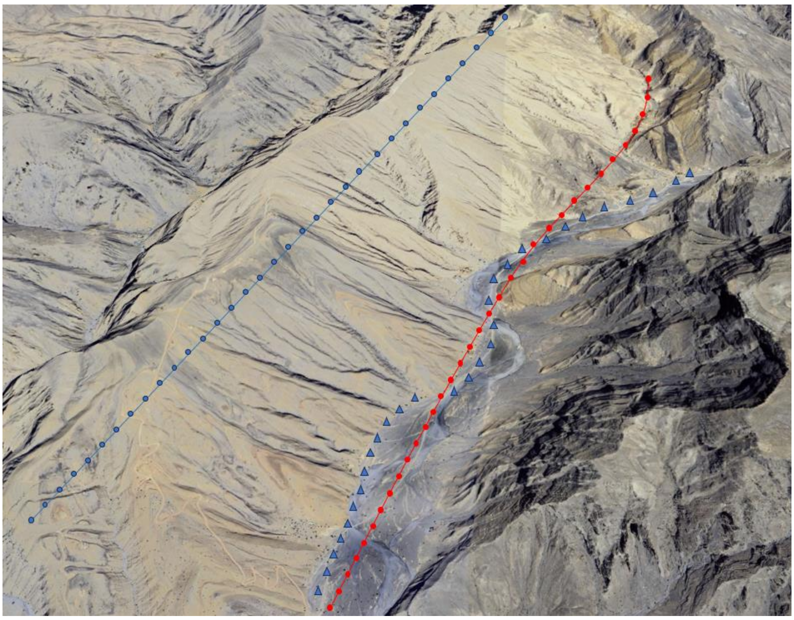


Figure 271: SEG-Y coordinates versus P1 coordinates

Common data issues

Some other common data issues to be considered during the audit trail include:

- EBCDIC headers, especially on legacy data, often contain zero CRS details or are created by copy and paste.

- The lateral offset problem highlighted in Figure 271 was caused because the CRS details in the EBCDIC header were wrong and a coordinate transformation was performed unnecessarily.
- Trace headers only accommodate for the storage of projected coordinates there is no way of cross correlating their values with their geographic equivalents and thus determine the possible CRS and geodetic datum to which the data belongs.
- The coordinates contained in the SEG-Y file are interpolated from start of line to end of line along a fixed bearing. This results in the perfect regularity of the trace spacing along the line as shown in Figure 271. It is also common practice to extrapolate the coordinates for the seismic traces in the taper zones of the line(s). When crooked line processing is used this will not be performed.

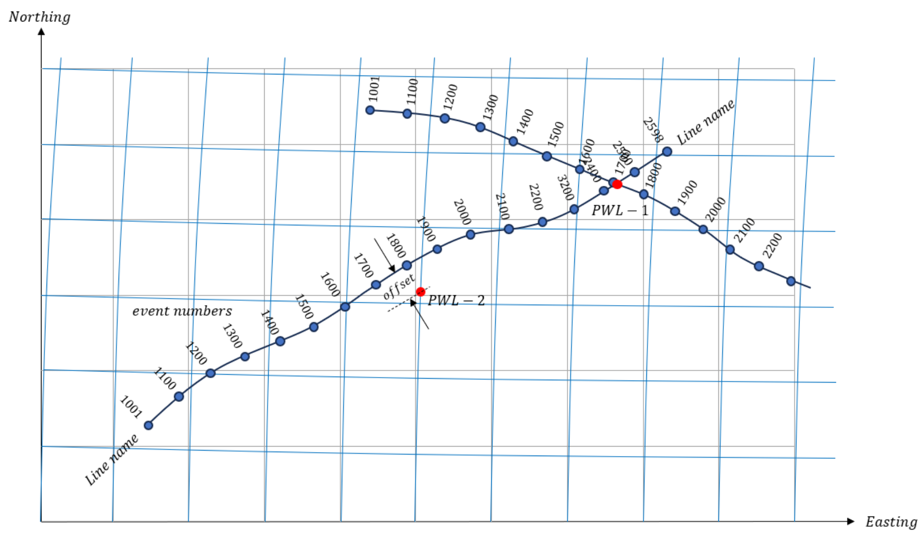


Figure 272: Coordinates selected from seismic 2D data

- When the navigation file is a UKOOA/IOGP P1 format it is important to ensure that the record identifier contained in column 1 is representative of the expected seismic objects contained in the data block. When the seismic objects are plotted their inter-event distances will provide some clues to help determine or confirm to what type of record identifier the positions belong, e.g., are they source, vessel or CMP positions? This process is mandatory when there is no record identifier such as with SEG-P1 format. This check is important to help remove any along line errors being introduced as these are considerably harder to identify and eliminate than crossline errors.

15 Marine towed streamer technique, limitations

The popularity of marine towed 3D streamer surveys is not what it once was, and the technology is being gradually replaced in favour of node surveys which despite their added expense do offer significant benefits to the products delivered to the geoscientists. Because of the nature of its geometric configuration, marine towed seismic surveys have two characteristics that have long hindered this technology:

1. The imaging of the sub-surface has different horizontal geo-spatial sampling rates along the two axes of the seismic grid with the $J\ axis$ having a higher sampling rate than the $I\ axis$. This creates an irregular sampling pattern. This does not refer to the sampling rate applied to recording the seismic trace data in the vertical plane but the geo-spatial component in the horizontal plane.

2. Horizontal geo-spatial sampling is limited to the azimuth along which the vessel traverses and the receivers are towed.

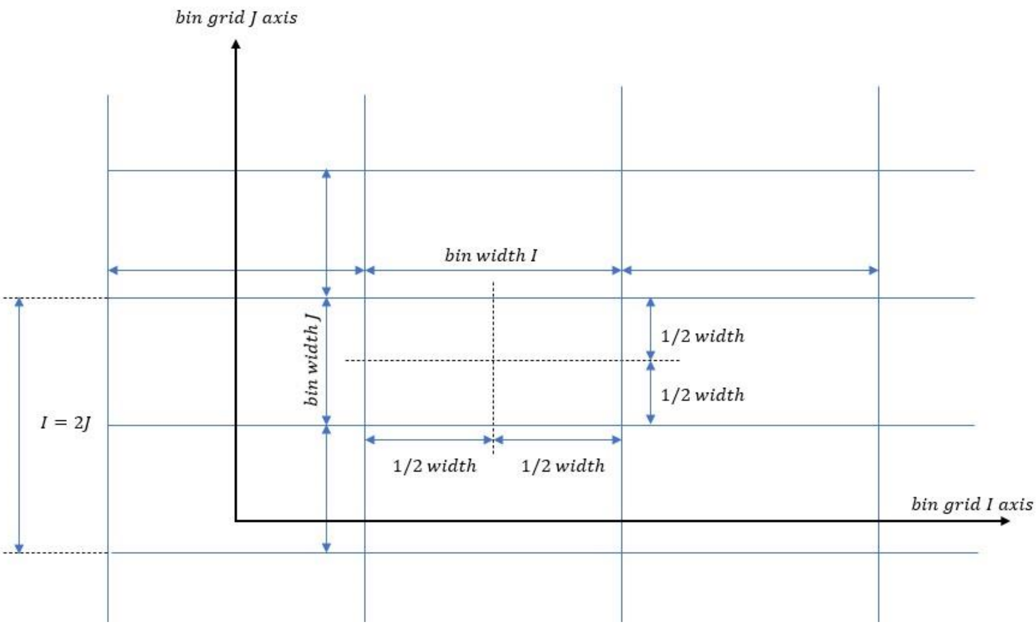


Figure 273: I width double J width

In Figure 273 the width of the cells on the $J\ axis$ is half that of the $I\ axis$. Therefore, the sub-surface is sampled twice as often along $J\ axis$. Another example is shown in Figure 274.

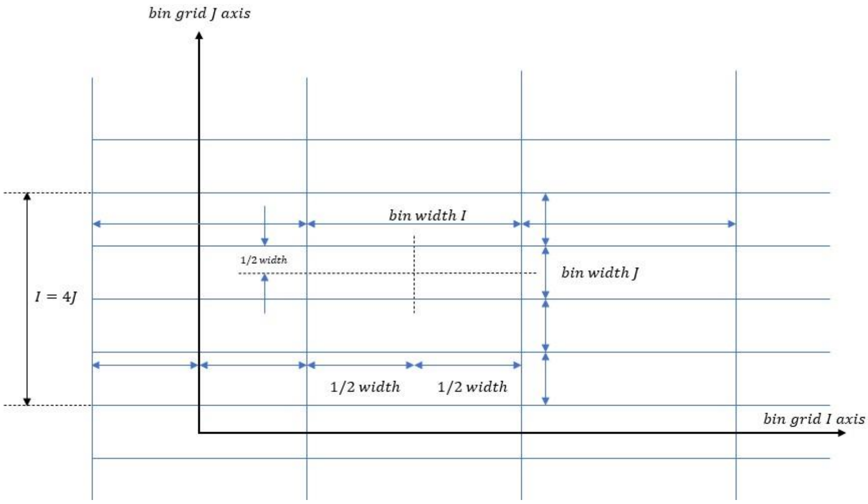


Figure 274: I width quadruple J width

The cell widths along the $I\ axis$ is four times larger than along the $J\ axis$ (e.g., 25 metres x 6.25 metres). Hence, the sub-surface is sampled four time more along the $J\ axis$.

15.1.1 Marine surveys are dynamic operation

In a towed marine seismic operation, the source and receivers are always dynamic, as their physical locations are constantly changing. Without this they would sink.

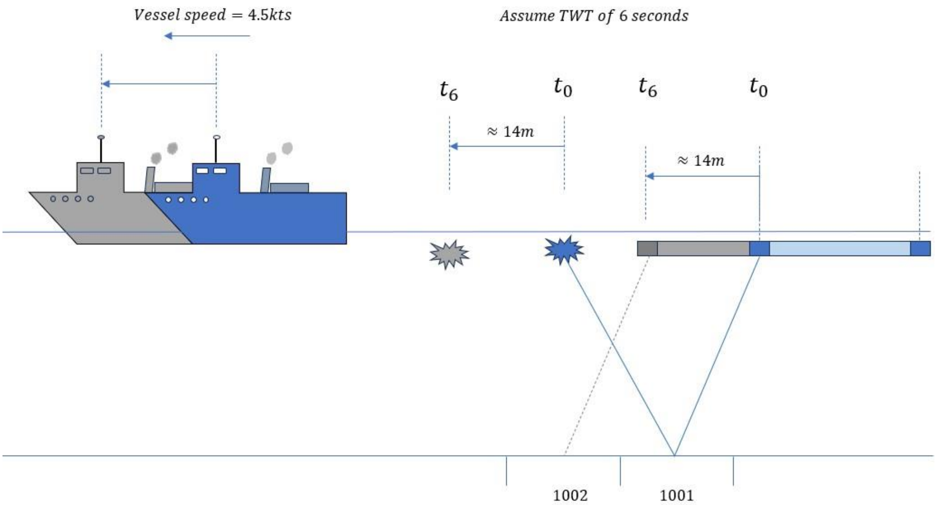


Figure 275: Receiver groups moving during recording

The source fires and the receivers start 'listening' at time t_0. The acoustic energy from the source is dissipated instantly, so is assumed to have happened at t_0. The receiver groups start listening but are in motion all the time they are recording. Assume that the vessel is traversing at 4.5 knots and the required Two Way Time (TWT) is 6 seconds. Between t_0 and t_6 the receiver groups will have moved approximately 14 metres in the inline direction. Geophysically, this is not deemed problematic, but from a geo-spatial perspective the receivers will have traversed several cells along the $J\ axis$ in this time interval. Into which cell does the returning energy belong?

15.1.2 Maintaining geometry

On land surveys, the geometric relationship between the sources and receivers is a 'fixed' pattern between successive shots, e.g., in relation to offsets. However, when acquiring a marine survey, the environmental conditions (tides, currents, winds etc.,) affect the geometry of the equipment being towed. For 3D surveys this matter can be overcome provided the horizontal positions of the source and receivers are determined with sufficient precision. It is then a matter of determining into which cell does each source-receiver offset trace belong.

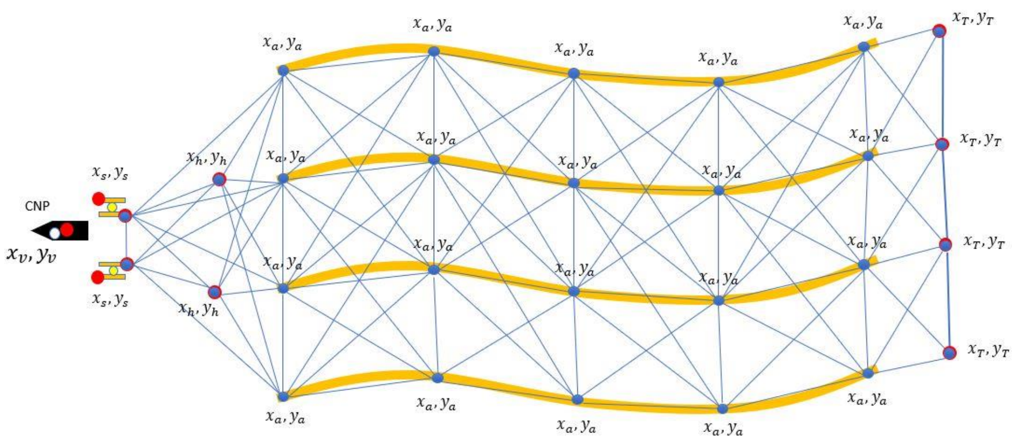


Figure 276: Observations are used to determine the source and receiver positions

15.1.3 Precision

To what precision can the source and receiver positions can be derived? Unlike land seismic surveys, the position of the source and receiver cannot be determined by placing a precise positioning device directly at each node. Instead, their positions are indirectly determined by making observations between 'known' fixed surface locations and sub-sea devices (acoustics and compasses) towed close to the equipment whose positions require computing. With land surveys the source and receiver locations are known very precisely. However, with marine towed surveys the source and receiver positions contain more error and thus have lower precision.

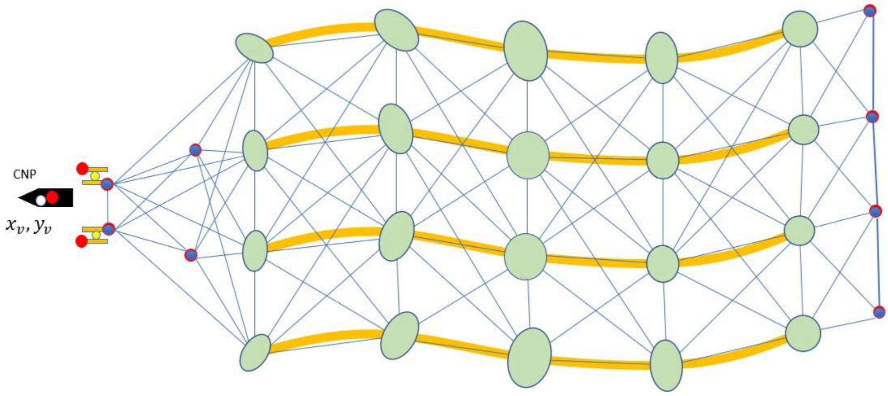


Figure 277: Inline precision measures

All observations contain, as a minimum, random error which will increase when measurements are made in harsher environments, e.g., higher sea states. As the observations are used to compute the position of the unknown nodes (e.g., the receiver groups) the error propagates from the observation domain to the position domain. Therefore, all final best estimated positions will contain error. The amount of error cannot be physically determined, it can only be estimated to a given probability.

This indicates the quality of the position with respect to random error and the most frequently used quality measure is the horizontal error ellipse. The dimensions of the horizontal error ellipse, given by the semi-major axis will be far larger on marine surveys than they will on land seismic surveys. A general rule of thumb is that the precision measures for mid receiver groups will be approximately half a cell width along the I and J $axes$.

15.1.4 Limitation in the azimuth

On a towed marine survey, the vessel traverses along pre-plot lines with a single reversed azimuth (e.g., 90^o and 270^o). Therefore, the sub-surface is only imaged along this fixed azimuth. This is regardless of the number of sources and streamers being towed. It is factor of the azimuth along which the seismic vessel sails.

Despite this being a restricting factor geophysically, it is the most efficient manner to acquiring the data volume over the extent of the survey area.

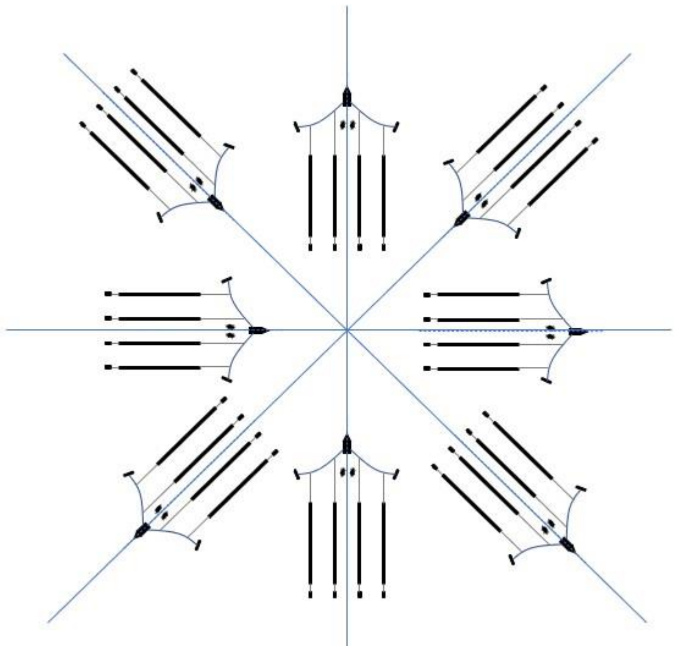


Figure 278: Rich azimuth survey

However, all CMP lines will have this azimuth in common. Compare this to a land 3D seismic survey where each CMP in the full fold area of the grid will gather source-receiver offset pairs from a variety of azimuths which results in a more detailed image of the rock structures. Enhanced seismic processing techniques have helped overcome this limitation to improve the 3D pictures produced. But this was not always the case which resulted in more exotic varieties of marine towed surveys being introduced to overcome such limitations. Two common techniques were known as rich azimuth and wide azimuth surveys.

To acquire trace data along additional azimuths requires the vessel to traverse sail-lines with alternative bearings. This is known as rich azimuth as shown in Figure 278. This illustrates seismic lines being acquired along 4 different azimuths all crossing at one common point. Such an approach is beneficial when the geological target is associated with salt domes. Wide azimuth surveys are ones where there is a lateral horizontal offset between the source vessel and the recording vessel. The location of the source vessel in relation to the streamers can vary with a couple of options depending upon where the sources are located in relation to the streamers. In Figure 279 the sources are located perpendicular to the head of the streamers. However, they could equally have been located perpendicular to the mid receiver groups.

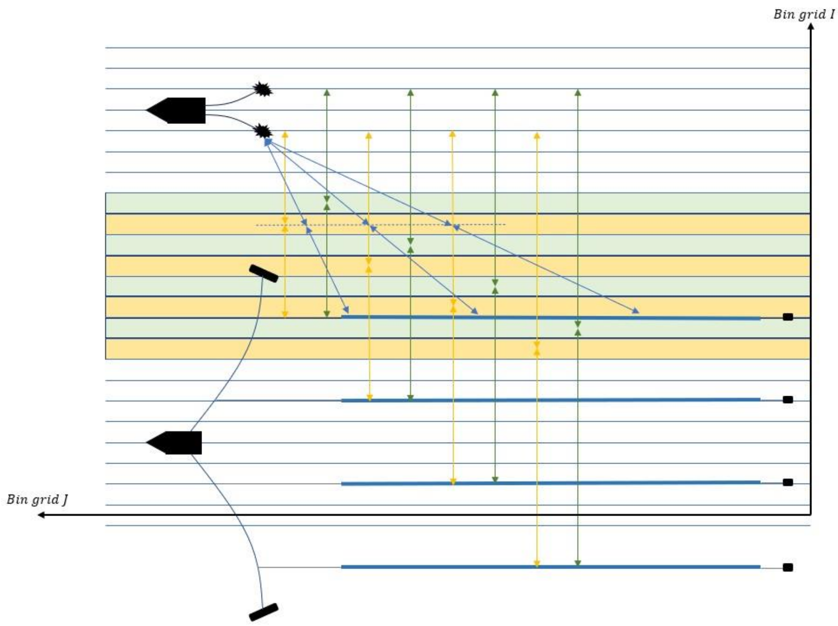


Figure 279: Lateral offset between shooting vessel and receiver vessel

Where an obstruction prevents the vessel from towing the equipment over the survey area required one solution to image the sub-surface is to perform an undershoot.

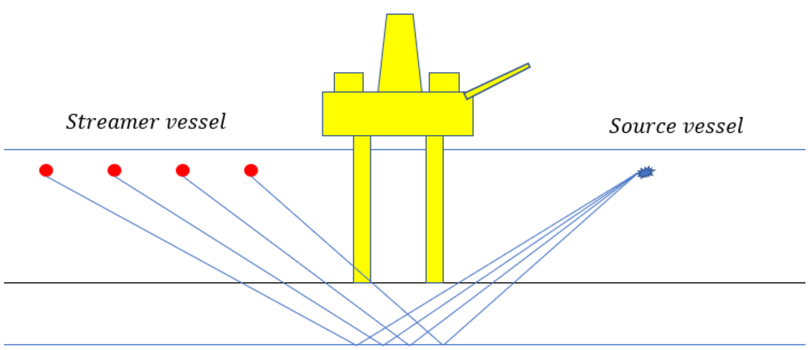


Figure 280: Undershoot geometry

In an undershoot, the two vessels operate simultaneously either side of the obstruction (e.g., fixed production platform). One vessel tows the seismic source, called the source vessel and one tows the streamers, called the streamer vessel. Such an acquisition spread will result in the CMPs being sampled under the obstruction itself as these positions fall halfway between the source(s) and streamer receiver groups being towed. However, it is usual to expect source-receiver offset pairs involving near receiver groups will not contribute to the post stack sections due to the offset between the two vessels being too great to observe these seismic traces for shorter two-way times.

15.1.5 Long Offset

On a towed marine survey there is an offset range limit dictated by the length of the streamer being towed. To achieve longer offsets requires a modification to the configuration, with one solution being the introduction of a second vessel which tows additional streamers as shown in Figure 281. The lead vessel is considered the master vessel and the trailing vessel the slave vessel. Very careful synchronization between both vessels is required to ensure recording is commenced simultaneously once a shot is fired.

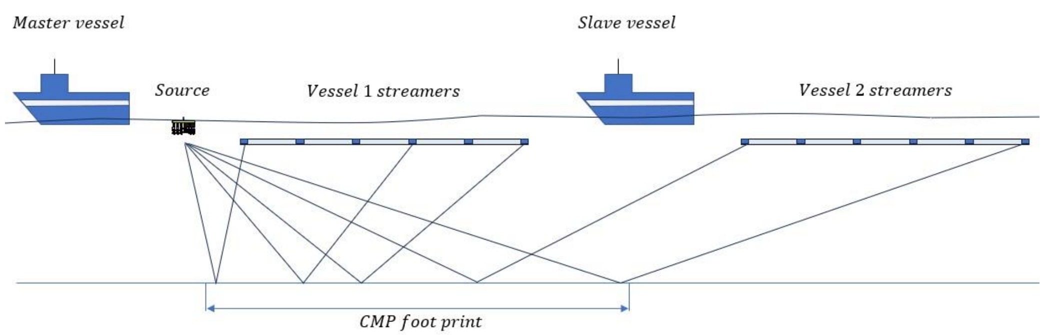


Figure 281: Long offset configuration

Seismic trace data is now acquired for all offsets including between the source and receiver groups towed by the slave vessel. This has the effect of doubling the source-receiver offsets and thus the ability to image deeper geological structures.

Index

W

Z

References

1. Bakker, G., J.C. de Munck, G.L. Strang van Hees. *Radio positioning at sea*. Delft University Press, Delft, revised edition 1995.
2. Bowring, B.R. *Transformation from spatial to geographic coordinates*. Survey Review, 181, 1976, pp 323-327.
3. Cross. P.A. *The computation of position at sea*. Hydrographic Journal, 20, 1981, pp 7-16.
4. Cross. P.A. *Working Paper No. 6, Advanced least squares applied to position-fixing*. University of East London, 1994.
5. IOGP. *OGP Surveying and Positioning Guidance note 1, Geodetic awareness*. Report 373-01. 2008.
6. IOGP. *OGP P1/11 Geophysical position data exchange format*. Report 483-1. 2015.
7. IOGP. *OGP P6/11 Seismic bin grid data exchange format*. Report 483-6.1. 2017.
8. IOGP. *Geomatics Guidance Note 25, Dynamic versus static CRSs and use of the ITRF*. Report 373-25. 2018.
9. IOGP. *OGP Coordinate Conversions and Transformations including formulas*. Report 373-07-2. 2020.
10. Kalman, R.E. *A new approach to linear filtering and prediction problems*. Journal of Basic Engineering, 82, 1960, pp 35-45.
11. Monk. D.J. Reducing infill requirements using Fresnel zone binning and steerable streamers. SEG Technical Program 3802-2806. 2010.
12. Parr. G. *Reference surfaces and Coordinate Reference Systems*. In print, 2024.
13. Parr. G. *Coordinate Operations*. In print, 2024.

14. Sharma. P.V. *Environmental and Engineering Geophysics*. Cambridge University Press. 1997.
15. SEG. *SEG standard exchange formats for positional data*. SEG Subcommittee. 1983
16. SEG. *SEG-Y rev 2.0 Data Exchange format*. Technical Standards Committee. Release 2.0, 2017.
17. Shell International Petroleum Maatschappij B.V. *Shell processing support format for 3D surveys*. Revision 2.1. 2006.
18. Sheriff. R.E. *Encyclopaedia Dictionary of Applied Geophysics*. SEG. 2002.
19. UKOOA. *P6/98 definition of 3D seismic binning grids*. Revision 3.0. 2000
20. UKOOA. *P1/90 post plot data exchange tape 1990 format*. Version 28-06-1990. 1990
21. Vincenty, T. *Direct and inverse solutions of geodesics on the ellipsoid*. Survey Review XXII, 176, 1975, pp 88-93.
22. WX Geo Services Sdn Bhd. *Seismic positioning data management*. Class notes, revised edition 2022.
23. Zinn, N. *Horizontal Midpoint (HMP) Accuracy in Marine Seismic*. SEG Annual Meeting, Houston, Texas. 1991.

Seismic Positioning, Grids and Binning

Definition of the seismic grid, edits and modifications.

Coordinate reference systems associated with the seismic grid, e.g., projected and moving platform.

Perimeter definitions related to the seismic grid, full-fold coverage, total fold coverage etc.

Survey design considerations, area of acquisition, obstructions and restrictions. Relationship between design and acquisition geometry.

Seismic grids and data management. Use of the grid definitions in the binning process and the assessment of survey completion.

Introduction to common exchange file formats used with seismic grids to store metadata, perimeters and bin centre coordinates.

Introduction to the coordinate operations applied to the seismic grid

Modifications made to the seismic grid related to reprojecting, readjusting and merging multiple grids to a new master grid.