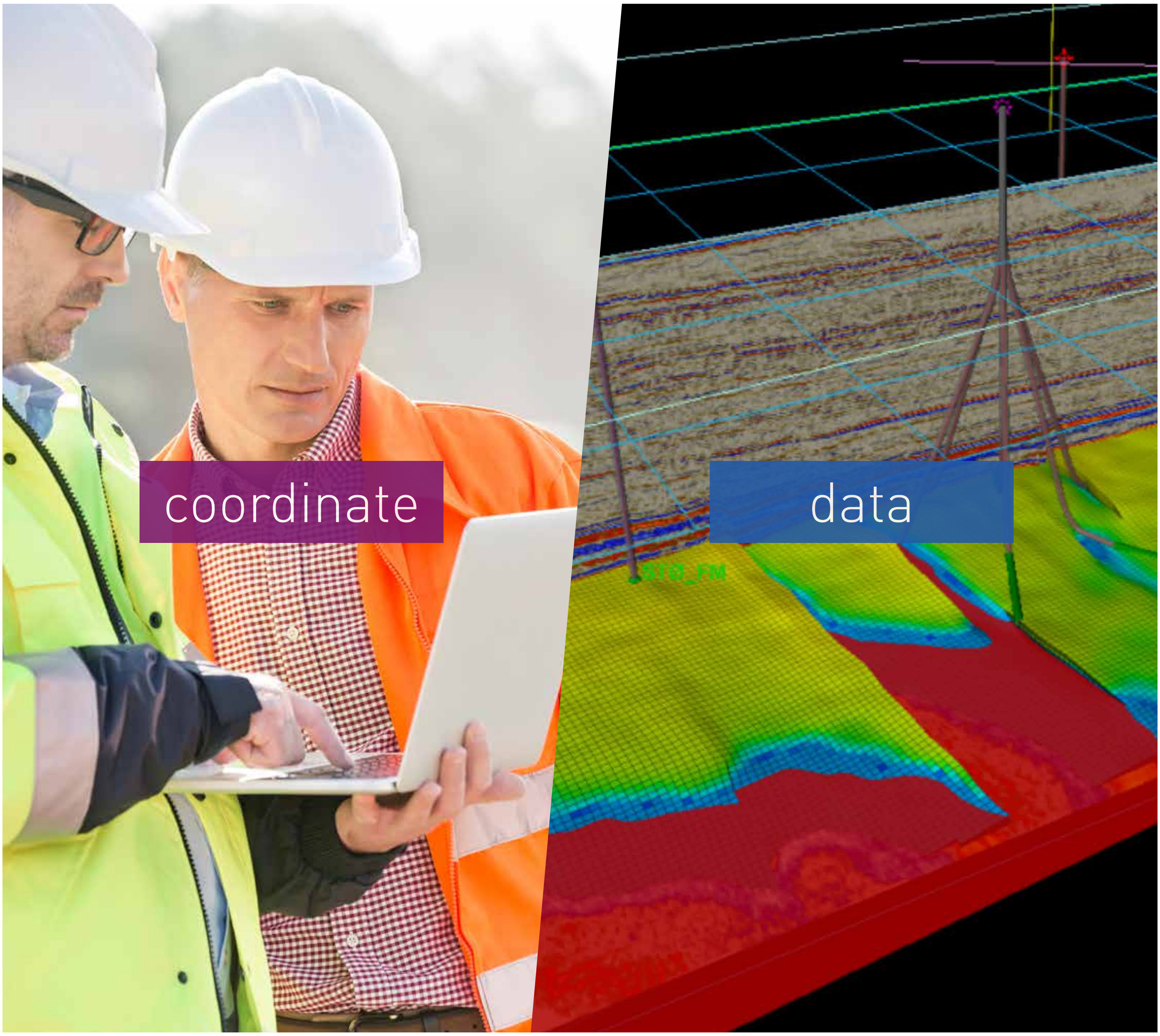
International Association of Oil & Gas Producers

REPORT 373-24 | NOVEMBER 2017

Geomatics Guidance Note 24
Vertical data in oil and gas applications



Acknowledgements

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REPORT
373-24

NOVEMBER
2017

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Revision history

VERSION	DATE	AMENDMENTS
1.0	November 2017	First release

Contents

Introduction

This guidance note discusses issues associated with vertical Coordinate Reference Systems (CRSs), in particular those related to coordinate operations (coordinate conversions and coordinate transformations) and metadata. It is aimed at geoscientists, data managers and software developers.

Horizontal and vertical data are equally important in oil and gas exploration and development processes, and incomplete attention to either can impact the integrity, resolution and accuracy of the resultant datasets. Typically, vertical data is not worked to the same level of detail as horizontal data, and the perceived accuracy of the vertical data is often higher than reality. There is generally insufficient attention to reference surfaces and inconsistent use of terminology which can result in erroneous offsets being introduced to datasets. Axis directions (heights and depths) are frequently interchanged without an appropriate audit trail. These errors are often the result of transferring data between applications, either through software exchanges or common data exchange formats without the transfer of the associated metadata, including an explicit definition of the vertical geodetic datum and CRS.

This guidance note describes the basic concepts of vertical CRSs and reference surfaces used with vertical data. The importance of recording data operations and associated metadata to ensure the unambiguous referencing of vertical data and preservation of data accuracy is stressed. The following sections address two key groups of stakeholders: those that use and/or manage vertical data; and those involved in software development. In each case, guidance is provided to understand, use and implement the recommendations.

Background

Vertical data (height and depth) are inherently important data used in oil and gas exploration and production activities. The vertical component of seismic profiles, 3D volumes, well, pipeline and other infrastructure data are fundamental to oil and gas activities, and form the basis for the creation of subsequent datasets used for engineering in the subsurface environment and also in well planning, modelling, and integrity and flow management.

All coordinate reference systems are built upon a datum. Three different datum types are used in the EPSG data model: geodetic, vertical and engineering. Vertical and engineering datums are most relevant to the discussion of the vertical references used for subsurface data in the oil and gas industry. See Ref. [2] and Ref. [3] for more information.

Vertical CRS

A vertical reference surface is the basis for recording heights or depths. Vertical CRSs comprise a 1 dimensional coordinate system which consists of a defined axis orientation and unit of measure, and a vertical datum. The vertical datum defines the relationship of a gravity related vertical reference surface to the earth. In geodesy, the vertical datum is often chosen as mean sea level at one or more points and the reference surface extended across the continents from this datum point. The vertical CRS is used to unambiguously reference data in either a height or depth system (defined by the axis direction), as illustrated in Figure 1. The structure of a vertical CRS is discussed in more detail in section 4 of Ref. [4] (hereafter called GN 7.1).

Acronym	Full Term
h	Ellipsoidal height (positive up)
H	Gravity related height (positive up)
N	Geoid height (positive up)
WD	Water Depth (positive down)

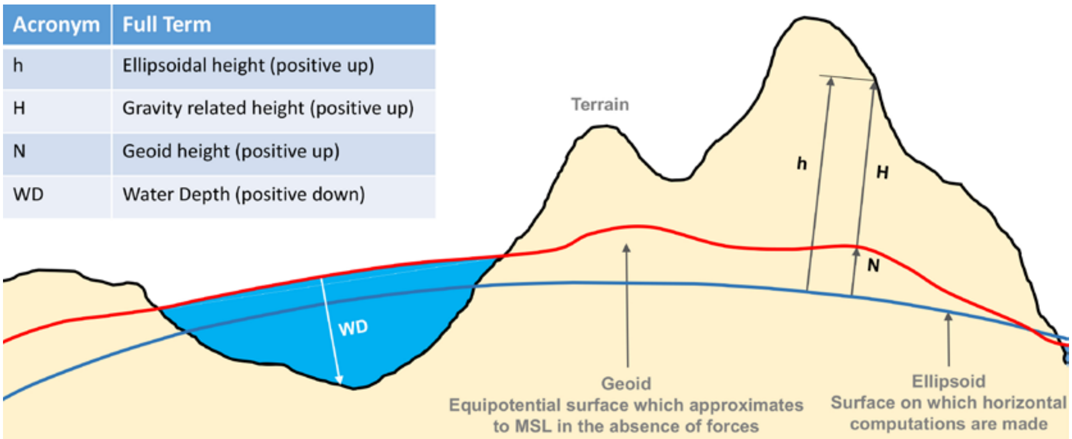


Figure 1: Different vertical surfaces

A new vertical CRS must be defined if either the unit of measure or the axis direction is changed, because these are part of the definition of a CRS. Two common vertical CRSs that are particularly relevant to this guidance note, and illustrate the dependency on axis direction, are:

- MSL height (height above Mean Sea Level), defined in metres with a positive up direction (EPSG CRS code 5714)
- MSL depth (depth below Mean Sea Level), defined in metres with a positive down direction (EPSG CRS code 5715).

Global Navigation Satellite Systems (GNSS) measure heights in a geographic 3D CRS. The height component is referred to as an ellipsoidal height. Geoid height models provide the separation from the ellipsoid to the reference surface of a given vertical CRS (see Figure 1). There are multiple geoidal models defined in the EPSG dataset. The definition and implementation of these models are described in Ref. [5]. See Appendix B for an example which starts with a GNSS position in a geographic 3D CRS.

Vertical CRS for Geoscientists and Data Managers

Vertical references used in subsurface data

Seismic

Seismic data is typically the first data type acquired in the subsurface domain. This can often be the starting point for establishing and/or selecting reference systems used in handling other data with a vertical component, for the same area. During seismic acquisition, the fundamental seismic measurements are time and amplitude, thus the vertical aspect (depth) of the observed geological features is from the outset expressed in time. Nonetheless, the time reference is linked to the surveyed height or depth of the sources and receivers.

When processing seismic data, it is necessary to reference all the data to a common vertical reference surface. In marine seismic, vertical reference surfaces such as MSL in the project area are used for this purpose, and the variation of the instantaneous sea surface relative to MSL is often neglected given that it is insignificant in relation to other much larger uncertainties in the seismic process. Terrestrial seismic acquisition requires corrections for variations in topography, and a vertical reference surface often called 'seismic datum' is defined prior to processing (illustrated in Figure 2). The seismic datum generally represents the average elevation in the local or national height reference system over the whole license block or the prospect area to be explored. In some cases, to make merging of other seismic datasets simpler, operators might choose to select a seismic datum used on other seismic projects in the vicinity. In areas where the topography is relatively close to sea level, the national height reference surface (defined with respect to MSL) might be chosen as the seismic datum which will aid integration with seismic data acquired offshore.

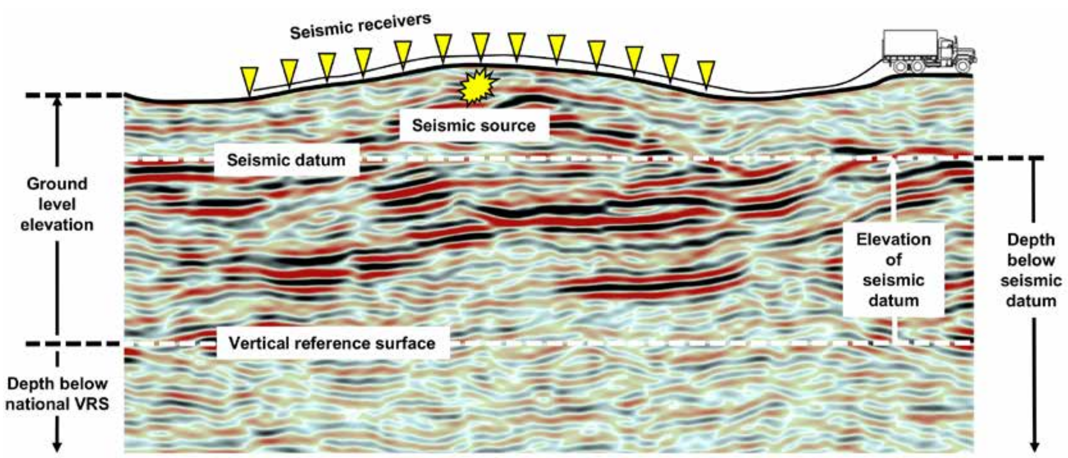


Figure 2: Land seismic – Vertical reference surfaces

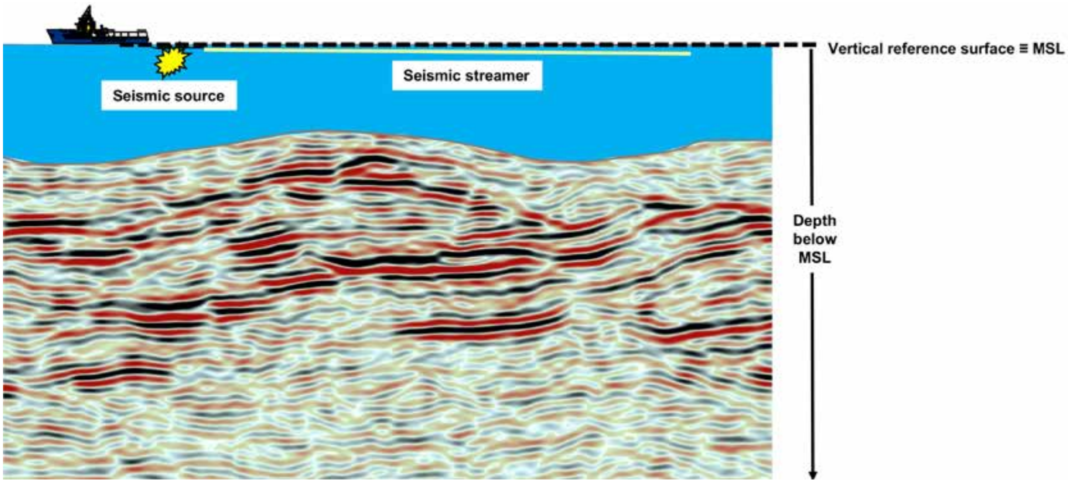


Figure 3: Marine seismic – Vertical reference surfaces

Regardless of whether 2D or 3D seismic is acquired, the same principle applies when it comes to the vertical aspect and time. Processing of 2D data, however, will produce vertical profiles which later are gridded and contoured to produce a 3D subsurface model. For 3D seismic the model is more directly related to seismic acquisition and processing, and is a much more accurate representation of the true subsurface, than the model obtained from 2D seismic.

Wells

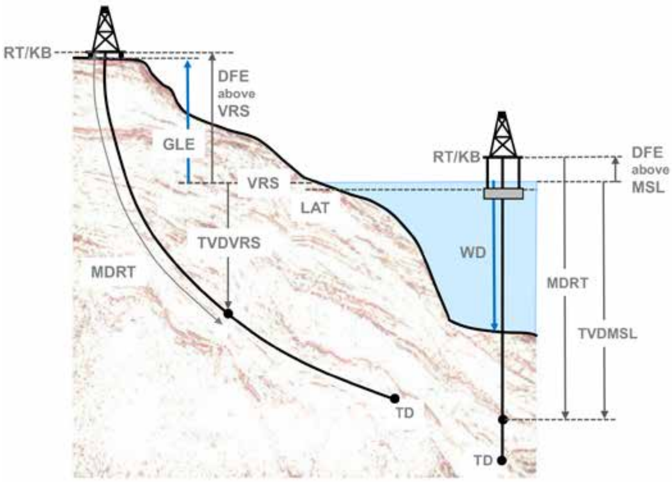
Wellbore survey data are fundamentally referenced to an engineering CRS with its origin at a reference point on the drilling rig. A number of different surface reference points are commonly used throughout the industry (Kelly Bushing (KB), Drill Floor (DF), Rotary Table (RT), Ground Level (GL), well casing flange, top of 36" conductor housing, etc.). It is recommended to standardize on one of these within a company and/or application. The downhole data is generally expressed relative to this surface reference point. Hence, it is critical that the coordinates of the reference point are known in absolute 3D geodetic space. The vertical reference used with well data can often be implied (e.g. MSL) or records of the reference (metadata or audit trail) may simply be missing. Recommendations for the metadata content that should accompany well coordinate data are provided in Ref. [6]

The basic observables for the determination of the well track are:

- MD – Measured depth (along hole)
- AZ – Azimuth
- INC – Inclination.

These basic observables are later transformed to relative coordinates in the chosen projected CRS and the vertical aspect is expressed as TVD – True Vertical Depth as illustrated in Figure 4. Errors are often introduced in this transformation process by oversimplifications.

When referencing geological information to the measured well tracks the use of Driller's depth and Logger's depth may introduce inconsistencies and need to be accounted for: Cores and drill cutting interpretations are referenced to depth observations measured along the drill string, the so-called 'Driller's depth'. On the other hand, all data generated by logging runs have depth measured along the wireline used for logging, the so-called 'Logger's depth'. The latter are generally more accurate given that the drill string is subject to much more tension than a wireline used for logging. Both options are effectively versions of Measured Depth Rotary Table (MDRT), illustrated in Figure 4.



Note: In this offshore example, MSL is used as the VRS, but the VRS but could also have been LAT or any other vertical reference surface.

Acronym	Full Term
DFE	Drill Floor Elevation
GLE	Ground Level Elevation
KB	Kelly Bushing
LAT	Lowest Astronomical Tide
MDRT	Measured Depth Rotary Table
MSL	Mean Sea Level
RT	Rotary Table
TD	Total Depth
TVDMSL	True Vertical Depth from MSL
TVDSS	True Vertical Depth Sub Surface (also referred to as Sub Sea)
TVDVRS	True Vertical Depth from VRS
VRS	Vertical Reference Surface
WD	Water Depth

Note: TVDSS is a commonly used alternative to TVDMSL and TVDVRS.

Figure 4: Vertical reference surfaces for well data – Measurements and terms

Subsurface Data Integration

Geological interpretations are often made on seismic time volumes but, in order for these products to be useful in reservoir modelling and drilling, the vertical aspect of seismic models and interpretations have to be converted from time to depth. This is done by applying assumptions of the velocity of the signal as it travels through geological formations and where applicable through the water column. This time to depth conversion is normally carried out by specialists, and can be a significant source of vertical error if not done correctly. For projects with complex subsurface, this time to depth conversion is often an integral part of the seismic processing.

If different seismic projects are merged, any possible differences in the seismic datum used for the individual projects have to be corrected. If the projects have lateral overlap it is common to merge them by re-processing.

Software systems and applications used for geological interpretation and reservoir modelling generally have no explicit reference to the vertical reference surface used for the data. The reference is implicit in the data model and all data in a project is assumed referenced to the same reference surface. When loading discrete datasets most applications have functionality that makes it possible to apply the necessary vertical offset to move the data to a common reference surface, whether that common reference surface is explicitly stated or not. Hence, the relative vertical relationship between the datasets is important. If discrete datasets are loaded using different vertical axis direction conventions (for example OpenWorks uses positive down, whereas Petrel uses negative down), most applications also have an option to apply a transformation (simple sign reversal) upon data loading, essentially applying data conversions on the fly. An example 3D environment with several integrated datasets is shown in Figure 5.

One of the main challenges for subsurface teams working with seismic and well data is establishing the correct context for well operations by extracting the necessary CRS information from the reservoir model. Given that the vertical data for a well are initially referenced to a local CRS with its origin at a reference point on the rig, the generation of the absolute vertical reference (usually MSL) has to take into account a number of offsets with their correct signs. Conversely, the same challenges are encountered when the results from well operations are merged back into a reservoir model. It is not uncommon for incorrect offsets to be applied to discrete data sets, and then further corrective offsets need to be applied later to 'make the data fit'.

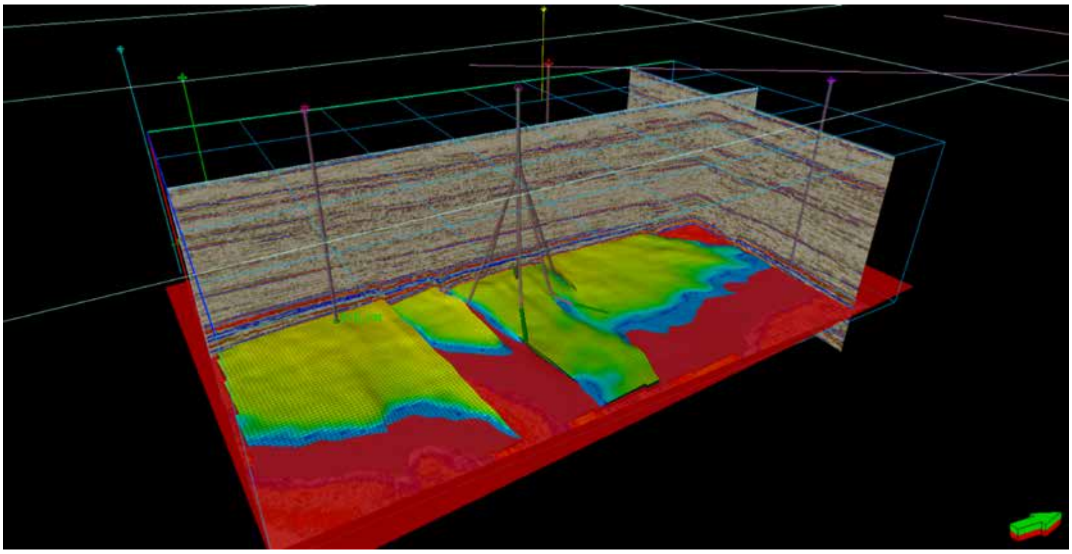


Figure 5: Successful 3D integration of seismic, reservoir model and well data (tophole, trajectory, logs) in a single project environment. Credit: Schlumberger

Vertical dimension used in engineering activities

Gathering data for engineering activities is central to many operations throughout a project life cycle in the oil and gas industry. From initial concept design to decommissioning activities, establishing a detailed understanding of the environment in 3 dimensions is crucial to ensure problems are avoided throughout. As for other oil and gas applications, the vertical dimension is just as important as the horizontal in mapping, charting and data integration activities, with a fundamental understanding of water depth or ground elevation being paramount.

The safety of operations in many engineering project activities relies on the ability to accurately position assets and communicate, visualize and integrate this position information correctly. Vertical data is a crucial element of this integration. As an example, 3D monitoring of anchor line positions during an offshore semi-submersible rig move, is crucial to appropriately control the clearance of mooring lines over seabed infrastructure (illustrated in Figure 6). Vertical references must be unambiguously defined to ensure the correct integration of data, which can then be appropriately represented in real-time during anchor deployment/recovery, tensioning and rig skidding operations.

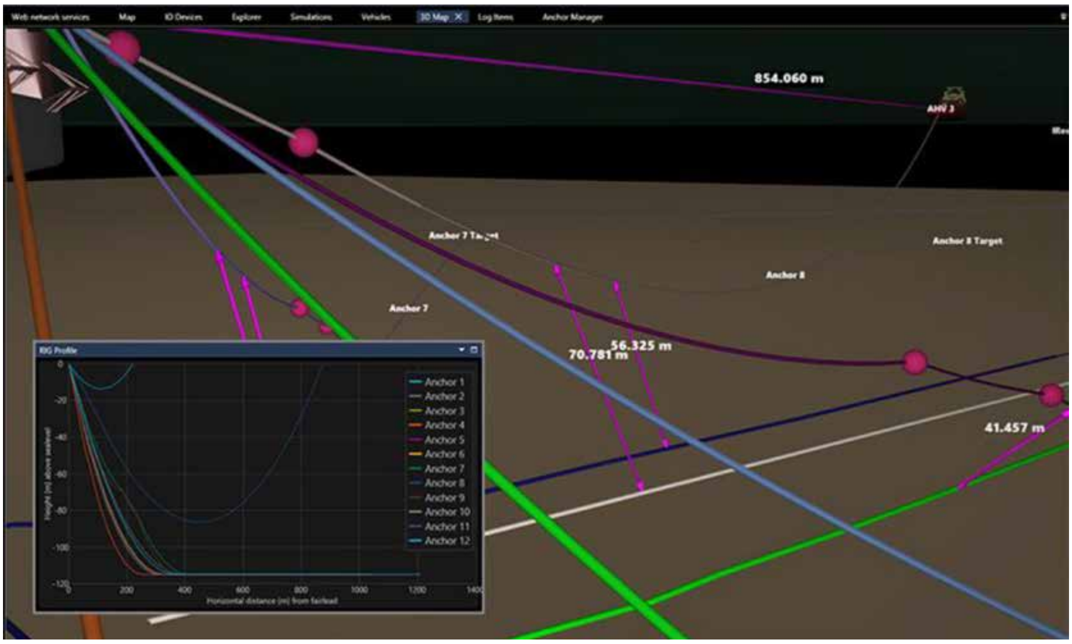


Figure 6: Critical vertical accuracy of data during 3D visualization of live anchor line clearance over subsea infrastructure. Credit: 4D Nav

For some construction and engineering activities objects are positioned relative to another object using a well-defined fixed point as a reference (e.g. a flange or interface point). This reference point is typically used as a local vertical datum and measurements of relative heights/depths can be used as vertical control in such operations.

In operations where the absolute depth/height is less relevant, the seabed (or ground elevation) may be used as a relative vertical reference. The absolute depth/height of this local vertical reference can be determined later and then used to link the datasets to a vertical reference in a real-world coordinate reference system, enabling integration with other datasets. However, the variation in topography of the chosen local reference may then become a source of error. The same issues are prevalent for this type of data as for other subsurface data types – establishing the various offsets to the absolute vertical reference, and ensuring they are applied correctly (including sign conventions).

A good example of this would be the acquisition of a detailed bathymetry dataset as part of a site survey or engineering study. This provides a detailed picture of the seabed and water depth across a survey area. This information can then be used with pipeline data, for example, linking pipeline locations (2D coordinates) and the pipeline height/depth relative to seabed, to convert the pipeline positions to absolute 3D position (2D coordinates and true vertical height/depth – presumably referenced to MSL in this example).

Data environments – Offshore/onshore

There are some subtle differences between data acquired onshore and data acquired offshore.

In offshore seismic acquisition, the data is time referenced to the instantaneous sea surface when the data was acquired. However, in certain operations where a higher accuracy is required, such as 4D seismic acquisition, tidal corrections may become significant. In these cases, the decision to reduce to MSL will depend on the tidal characteristics of the work site and the relative accuracy requirements. Lowest Astronomical Tide (LAT) is sometimes used in the offshore environment as the vertical reference (for example, charting and rig move operations). LAT is offset from MSL and this offset varies by location (the variability and magnitude of the offset is dependent upon the tidal regime in the area). In other locations, such as inland seas (e.g. the Caspian), another datum may be used.

Onshore seismic data, on the other hand, is typically referenced back to the national vertical reference surface, with varying degrees of accuracy (in many applications an approximately defined MSL is used as a reference for the vertical data instead of the national vertical reference surface). The EPSG dataset contains several national height systems defined as a vertical CRS. Typically, there is no need for depth versions of these national height systems, as generally they are not used for wells and reservoir models. The population strategy for the EPSG dataset is described in the next section of the document.

Vertical reference surfaces are often critical for pipeline, cable, and other landfall or transition zone operations, where the onshore vertical reference surface is typically different from the offshore vertical reference surface. Account needs to be taken of this difference, to avoid mismatching issues between pipeline/cable heights/depths, excavation volume calculations and earthworks, cofferdam or trenching design, etc.

Vertical CRS for software developers

The full implementation and support of vertical CRSs requires the ability to transform/convert between different vertical CRSs. The EPSG data model (which is compliant with the ISO 19111 standard Ref. [9]) supports coordinate operations (transformations) between CRSs and not datums. The EPSG dataset contains several coordinate operation methods applicable to vertical CRSs, which can be implemented to transform/convert between different source and target vertical CRSs:

1) Geographic 3D to Gravity Related Height (various methods)
2) Vertical Offset by Interpolation of Gridded Data (various methods)
3) Vertical Offset (method code 9616)
4) Vertical Offset and Slope (method code 1046)
5) Change of Vertical Unit (method code 1069)
6) Height Depth Reversal (method code 1068).

Methods one to four are only used between vertical CRSs when the positive direction of the axis and the unit of measure of the source and target CRS are the same, described in full in Ref. [5]. If this is not the case, then the last two methods (Change of Vertical Unit and Height Depth Reversal) may be used either in isolation, or where required, in a concatenated approach with any of the other methods to provide a transformation/conversion path between the source and target CRSs, as illustrated by the example shown in Figure 7 (through intermediary vertical CRSs, MSL height and MSL depth to the target CRS, which is MSL depth (ft[1])).

A pragmatic and recommended approach to managing vertical data in subsurface software (and other applications), is to apply simple conversions (e.g. EPSG method codes 1068 and 1069) to the vertical coordinates on the fly. Where any of these conversions are used (which may already be routinely applied in many applications), it is vital that a record is maintained to track all such coordinate operations on the data. The original vertical reference information should be retained with the underlying data, in addition to a vertical reference representing the working environment (on-the-fly coordinate operations). It is imperative that the CRS reference information is always complete and accurate for the data (using EPSG codes where available, or alternate explicit definitions). With this approach (and if the application allows it), the user may want to export data in either the original CRS (in which the data was loaded) or the working CRS.

An audit trail should be kept with each dataset to record all coordinate operations that have been applied to each dataset. Under no circumstances should a CRS definition remain unchanged after a coordinate operation has been applied to make changes to a CRS. An audit trail is a record that can enable a user

[1] ft – International foot, ftUS – US Survey foot (both as per EPSG convention)

to return to the original or any intermediate dataset by undoing or reversing operations previously applied. Such an audit trail is often maintained in subsurface applications for the handling of 2D horizontal coordinates, and functionality this should be extended to cover the vertical component of the data (or developed where this functionality does not currently exist in spatially aware applications). The use of the 2D horizontal CRS + 1D vertical CRS approach therefore provides the required flexibility, whilst retaining a full and unambiguous CRS definition.

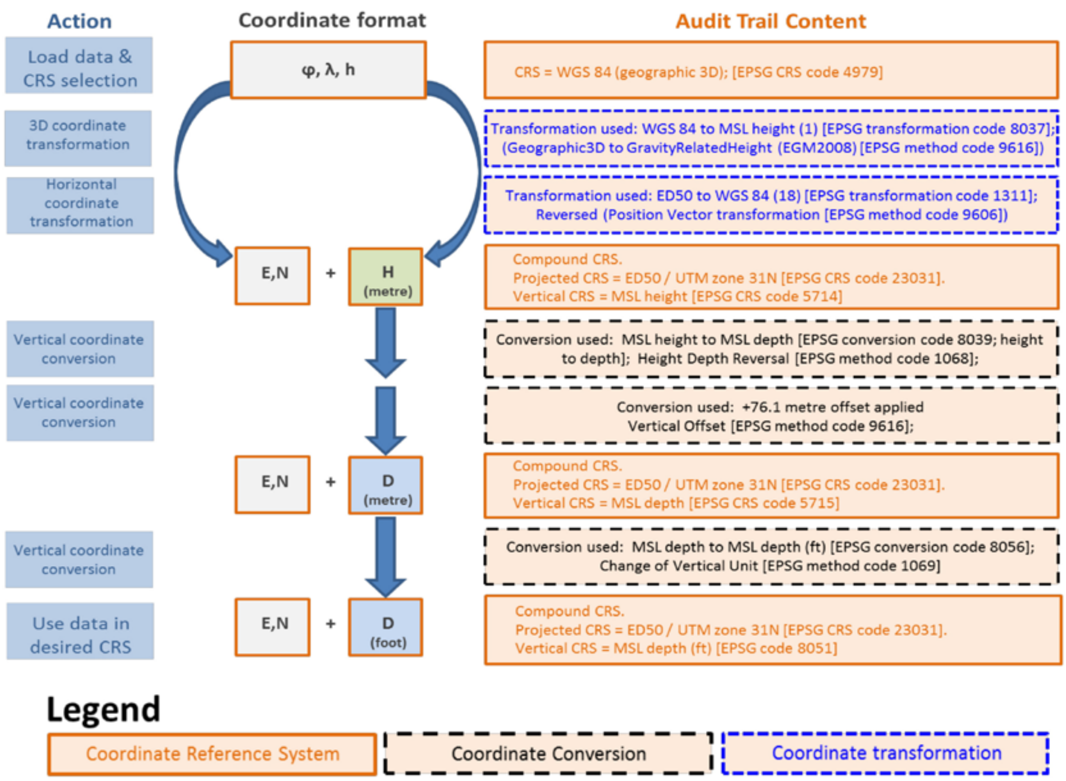


Figure 7: Example Audit Trail Schematic of the concatenated approach to transformation and conversion of vertical data

The specific coordinate operations used to move between the source CRS and the target CRS in the example illustrated in Figure 7 are the same as those that are used in the offshore well example in Appendix B. In Figure 7, the audit trail has been illustrated with explicit definitions of the coordinate operations as they are defined in the EPSG dataset. However, the same audit trail is also provided in Appendix B, Figure B.2, with definitions illustrated as though they are not populated in the ESPG dataset, therefore using the appropriate EPSG generic coordinate conversions instead.

A key recommendation of this guidance note is to ensure an audit trail is maintained to unambiguously record the changes made to the CRSs and associated data. If we take the example of the schematic of an audit trail in Figure 7 (and Figure B.2), the use of specific transformations and use of both explicit and generic coordinate conversions becomes clearer, with reference to the operation codes for each step.

For the coordinate operation methods 'Height Depth Reversal' (EPSG method code 1068) and 'Change of Vertical Unit' (EPSG method code 1069), the generic conversions 'Height <> Depth Conversion' (EPSG conversion code 7812) and 'Vertical Axis Unit Conversion' (EPSG conversion code 7813) have been populated in the EPSG dataset. Even though these generic conversions are present, they are not actually used between any specific vertical CRSs in the EPSG dataset. However, as examples, a small number of explicit conversions have been included. These explicit conversions also use the same underlying methods 1068 and 1069. However, it is IOGPs intention to populate further additional explicit conversions only where they are considered necessary. This is in order to prevent the creation of 'orphaned' vertical CRSs in the dataset (those which have no method of converting/transforming to any other vertical CRS). In most cases, the creation of specific conversions is left to the user community, because the use of these generic conversions is straightforward, and in practice many of the specific conversions required will not be suitable for publishing in the EPSG dataset. The availability of the generic coordinate conversions, allows the user to convert/transform between any source and target vertical CRSs that may be desired. This enables the user/system to appropriately document the processes applied to their coordinate data (referring to EPSG coordinate conversion codes), providing software developers with a consistent framework with which to create clear and unambiguous audit trails.

To facilitate vertical CRSs and anticipated improvements in vertical reference definitions in software, the approach to populating the EPSG dataset will follow existing precedent – to populate vertical CRSs by request. The specific population strategy for vertical CRSs is outlined in Ref. [4]. In summary, vertical CRSs relating to a geodetic datum will (by default) be added as vertical height CRS, and those relating to a hydrographic datum will (by default) be added as vertical depth CRS. Both variants may be included where a specific requirement justifies this, and where both are present, the explicit conversion between the two will also be added. Where a transformation between vertical CRSs is added to the dataset, it will only be between two CRSs which share the same unit of measure and axis direction. The coordinate conversions can then be used in a concatenated operation to get to any other variation of the CRS with different unit or axis direction.

Use of the EPSG dataset

The EPSG dataset contains coordinate operation methods that allow users to dynamically create vertical coordinate conversions (on-the-fly) to perform a height depth reversal or change the unit of measure while remaining referenced to the same vertical datum. These generic vertical CRS coordinate conversions can be concatenated with vertical datum transformations to perform the desired coordinate operation between any source and target vertical CRS.

For vertical CRS conversions (Height Depth Reversal or Change of Vertical Unit) present in the EPSG dataset, these are added as specific, explicit conversions, and will not use the generic conversions that have been created for users or software developers to use for their generic cases (EPSG conversion codes 7812 and 7813). The explicit definitions that are populated in the EPSG dataset use the same underlying methods (EPSG method codes 1068, and 1069) as the generic conversions.

The EPSG dataset is populated with one vertical CRS definition for each vertical datum (unless a valid request from a government entity is received to include additional vertical CRSs), with a terrestrial datum defined with height CRS and hydrographic datum defined with a depth CRS by default. Vertical CRS transformations are defined to that populated CRS. All other combinations including height/depth and unit of measure variants will not be added, unless used by a government entity or widely accepted practice in industry.

When additional CRSs corresponding to a vertical datum are included in the dataset, a transformation or conversion will also be included to ensure that these additional CRSs do not become orphaned systems (a CRS with no connection to any other entity in the dataset).

Conclusions and recommendations

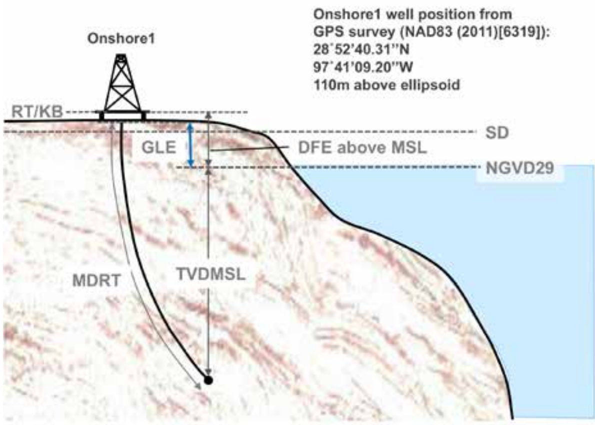
The following conclusions and recommendations are drawn from the preceding discussions:

- There is no standard unit of measure for vertical coordinate reference systems. Hence, the unit of measure of the vertical coordinate reference system should always be recorded explicitly.
- There is no standard convention in geoscience applications for the positive vertical axis direction. The positive vertical direction is typically defined by the context of the data, for example, depths are positive resulting in a downward positive convention. Both heights (up direction) and depths (down direction) can be considered positive at the same time in the same dataset.
- All differences in positive axis direction and unit of measure should be accounted for in an environment of integrated datasets, to maintain the 3D integrity of the data.
- Positive axis direction and unit of measure should be accounted for during data transfers (including import and export) to correctly apply height depth reversal and unit of measure conversions.
- Within any given integrated environment, all vertical data should be related to one consistent vertical reference surface, repeatable over time and fully documented.
- It is recommended to standardize on one vertical reference point for well data (RT, KB, etc.) within a company and/or application.
- Geoscience applications should follow industry standard terminology for all CRS definitions (including vertical CRSs), Ref. [1]
- All software should maintain and display the vertical CRS definition correctly for each data item and the working environment, including the clear annotation of the positive axis direction and unit of measure.
- File formats used for data exchange between applications should include sufficient metadata to completely define the vertical CRS (including positive axis direction and unit of measure) by:
    - Citing the EPSG code if present in the EPSG dataset (Ref. [1]). The positive axis direction and unit of measure must be consistent between the EPSG code and the data.
    - Including Well-Known Text (in compliance with ISO 19162, Ref. [7] and OGC standard 12-063r5, Ref. [8]) if the vertical CRS definition is not present in the EPSG dataset
- Software developers should include an audit trail to document all coordinate operations performed on data (transformations and conversions including Height Depth Reversal and Change of Vertical Unit). The audit trail should include EPSG names and codes (where available) plus sufficient metadata to unambiguously describe the coordinate operation.
- For further advice on vertical CRSs, coordinate transformations/conversions and associated metadata consult a Geomatics specialist.

Appendix A

Onshore well example

An example case is illustrated in Figure A.1, using a fictitious onshore well location with coordinate operations that are populated in the EPSG dataset to illustrate how the coordinate operation methods can be used.



Note: Values described in NGVD29 height (ftUS).

Acronym	Full Term	Value
KB	Kelly Bushing	16 ftUS
MDRT	Measured Depth Rotary Table	1850 ftUS
RT	Rotary Table	16 ftUS
SD	Seismic Datum	380.0 ftUS
TVD	True Vertical Depth	1836 ftUS
DFE	Drill Floor Elevation	449.09 ftUS*
GLE	Ground Level Elevation	433.09 ftUS*
TVDMSL	True Vertical Depth from MSL	1386.91 ftUS*

Note: Values marked * are calculated.

Figure A.1: Onshore1 well example

The Onshore1 well is drilled at the following location in Texas (location of the top hole at rotary table (RT)):

- Geographic 3D: NAD83(2011) [6319]
- 28°52'40.31"N
- 97°41'09.20"W
- Ellipsoidal height 110m.

The Onshore1 well has a MDRT of 1850 ftUS and a TVD of 1836 ftUS. The rotary table is measured as 16 ftUS above ground level.

Seismic data is already loaded in our subsurface application, with the project environment configured to use the positive up (height) convention and a seismic datum established at a height of 380 ftUS above NGVD29. The horizontal 2D CRS used for the project is NAD83(2011) / Texas South Central (ftUS) [EPSG CRS code 6588].

The Geographic 3D CRS is transformed into a 2D+1D compound system using the vertical transformation NAD83(2011) to NAVD88 height (1) (EPSG tfm code 6326) and coordinate conversion SPCS83 Texas South Central zone (US survey feet) (EPSG conversion code 15360). This is followed by a vertical transformation NGVD29 height to NAVD88 height (2) (EPSG tfm code 7970, reversed) to transform the data into the defined project vertical datum. Further conversions are described below to convert the vertical reference into the working project vertical CRS of NGVD29 height (ftUS).

The above position is transformed to the local working CRS:

- NAD83(2011) / Texas South Central (ftUS) [EPSG CRS code 6588]
- NGVD29 height (ftUS) [EPSG CRS code 5702].
- 888,880.50 ftUS E
- 10,808,612.74 ftUS N
- 449.09 ftUS.

The height of the rotary table is 16 ftUS above ground level at the well location and this is (449.09-16-380) ftUS = 53.09 ftUS above the seismic datum. In order to integrate these datasets the offsets need to be appropriately applied. In this case, the seismic data would be shifted to the well, which is currently referenced to the rotary table, and is moved to ground level. This is done by applying a vertical offset of -16 ftUS to the well data (the rotary table to ground level), and a +53.09 ftUS offset to the seismic data (to correctly position the seismic data relative to the well data at ground level). If other wells are integrated with the same seismic data at other locations (with different elevations) the seismic data would normally be warped to match the well data at these locations, if any discrepancy exists.

In summary, the coordinate operations applied to the well data in this example are detailed in Figure A.2:

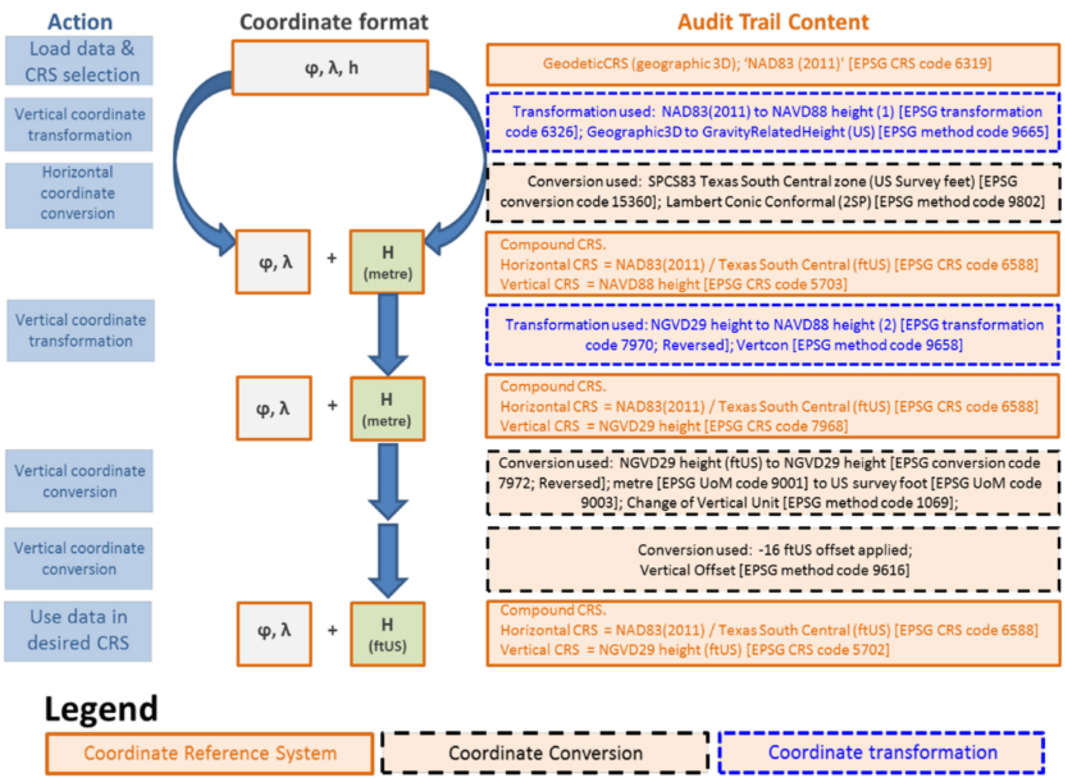


Figure A.2: Audit trail schematic for the onshore well example

The coordinate operations that need to be applied to the seismic data are:

- Vertical offset (+53.09 ftUS).

An audit trail example for the operations applied to the well data in the Onshore Well example is shown in Table A.1. The above schematic of the well data provides a visual description of the process and flow of data through the various coordinate operations to change the reference of the data to the working CRSs.

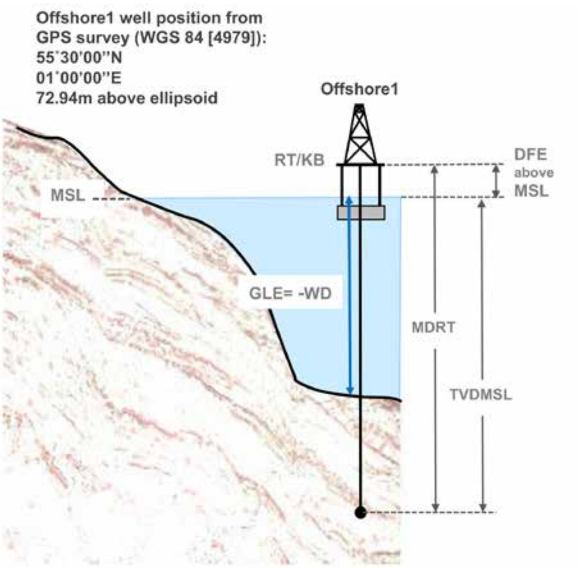
Table A.1: Example audit trail for the onshore well example

Entry	Date	User	Action	Description
1	Nov 14 2016 14:35:00	Anonymous	Load from	C:\USers\Anonymous\Documents\Data_examples\Onshore1_NAD83\
2	Nov 14 2016 14:35:25	Anonymous	CRS Selection	GeodeticCRS (geographic 3D); 'NAD83(2011)' [EPSG CRS code 6319]
3	Nov 14 2016 14:35:45	Anonymous	Set Name	Onshore1_NAD83_height
4	Nov 14 2016 14:37:00	Anonymous	Coordinate Transformation	NAD83(2011) to NAVD88 height (1) [EPSG tfm code 6326]; Geographic3D to GravityRelatedHeight (US) [EPSG method code 9665];
5	Nov 14 2016 14:37:15	Anonymous	Coordinate Conversion	ProjectedCRS 'NAD83(2011) / Texas South Central (ftUS)' [EPSG code 6588]; Coordinate conversion 'SPCS83 Texas South Central zone (US survey feet)' [EPSG conv code 15360]
6	Nov 14 2016 14:37:30	Anonymous	Coordinate Transformation	NGVD29 height to NAVD88 height (2) [EPSG tfm code 7970; reversed]; Vertcon [EPSG method code 9658]
7	Nov 14 2016 14:37:45	Anonymous	Coordinate Conversion	NGVD29 height (ftUS) to NGVD29 height [EPSG conv code 7972] Reversed; metre [EPSG UoM code 9001] to US survey foot [EPSG UoM code 9003]; Change of Vertical Unit [EPSG method code 1069]
8	Nov 14 2016 14:39:00	Anonymous	Change Name	Onshore1_NGVD29_Height_footUS_SeismicDatum

Appendix B

Offshore well example

An example case is illustrated in Figure B.1, using a fictitious offshore well location with coordinate operations that are populated in the EPSG dataset to illustrate how the coordinate operation methods can be used.



Acronym	Full Term	Value
DFE	Drill Floor Elevation	28.1 m
KB	Kelly Bushing	28.1 m
MDRT	Measured Depth Rotary Table	968 m
MSL	Mean Sea Level	0 m
RT	Rotary Table	28.1 m
TVD	True Vertical Depth	968 m
WD	Water Depth	52 m
GLE	Ground Level Elevation	-52 m*
TVDMSL	True Vertical Depth from MSL	939.9 m*

Note: Values marked * are calculated.

Figure B.1: Offshore1 well example

The Offshore1 well is drilled at the following location in the UKCS sector of the North Sea (location of the rotary table (RT) defined from GNSS observations on the drilling rig):

- Geographic 3D: WGS 84 [4979]
- 55°30'00"N
- 01°00'00"E
- 72.94 m above ellipsoid.

Water depth at the well location is 52 m relative to MSL.

The actual well head is measured 4m above seabed and therefore is calculated 48 m below MSL. The Rotary Table is calculated 28.1 m above MSL, using the EGM2008 geoid model (geoid ellipsoid separation of 44.84 m) to convert the rotary table WGS 84 ellipsoidal height to height above MSL at the site.

The Offshore1 well has a MDRT of 968 m, and this is a vertical well (TVD is the same).

The positive down (depth) convention is used in the working environment of the subsurface application to which Seismic data has been loaded, using MSL as the seismic datum. The horizontal 2D CRS used for the project is ED50 / UTM zone 31N [EPSG CRS code 23031], with the vertical CRS of the project defined as MSL depth (ft) (EPSG code 8051). Unit of measure of the vertical axis is the international foot [EPSG UoM code 9002].

The CRS is a compound 2D+1D system, so the 2D transformation ED50 to WGS 84 (18) (code 1311) can be used. A concatenated approach to the vertical CRS is required, to get from the initial WGS 84 ellipsoidal height, to the final working system MSL depth (ft). This is described in the summary below.

The above well head position is transformed to the local working CRS as follows:

- ED50 / UTM zone 31N [EPSG CRS code 23031]
- MSL Depth (ft) [EPSG CRS code 8051]
- 373,758.98m E
- 6,152,462.80m N
- 157.5 ft Depth MSL.

The information above tells us that the height of the rotary table is 28.1 m above MSL at the well location and water depth is 52 m relative to MSL, and the well head is 4m above seabed. The seismic datum is also MSL, which is the common vertical reference surface to integrate these datasets in the subsurface interpretation software. In this case, the well data needs to be transformed to change the sign of the data, as it is currently positive up convention (height) and will be interpreted by the software incorrectly. This is done by using coordinate operation method (EPSG method code 1069) and applying the explicit coordinate conversion for MSL height to MSL depth (EPSG conv code 8039, Figure 7). Another way to do this, and if conversion 8039 was not in the ESPG dataset, then the generic Height <> Depth Conversion (EPSG conv code 7812) would be used instead, as shown in Figure B.2. The final step is to convert to the correct vertical unit using Change of Vertical Unit EPSG method code 1069. This can be applied with an explicit conversion if it is available, in this case MSL depth to MSL depth (ft) is available as EPSG conv code 8056 (shown in Figure 7), but if this wasn't available then the generic conversion 'Vertical Axis Unit Conversion (EPSG conv code 7813) would be used instead (shown in Figure B.2). For entities that are not contained in the EPSG Dataset complete Well-Known Text (WKT) definitions should be included (examples shown in Figure B.3). If other wells are integrated with these seismic data then their position should also be calculated in the same horizontal CRS (EPSG CRS code 23031) and vertical CRS referenced to MSL depth (ft) (EPSG CRS code 8051).

In summary, the coordinate operations applied to the Offshore1 well data in this example are detailed in Figure B.2. This example is the same as that illustrated earlier in the document in figure 7, but this assumes that the conversions used to change the vertical axis direction and the unit of the vertical CRS are not included in the EPSG dataset as explicit definitions, therefore showing how the generic conversions can be used:

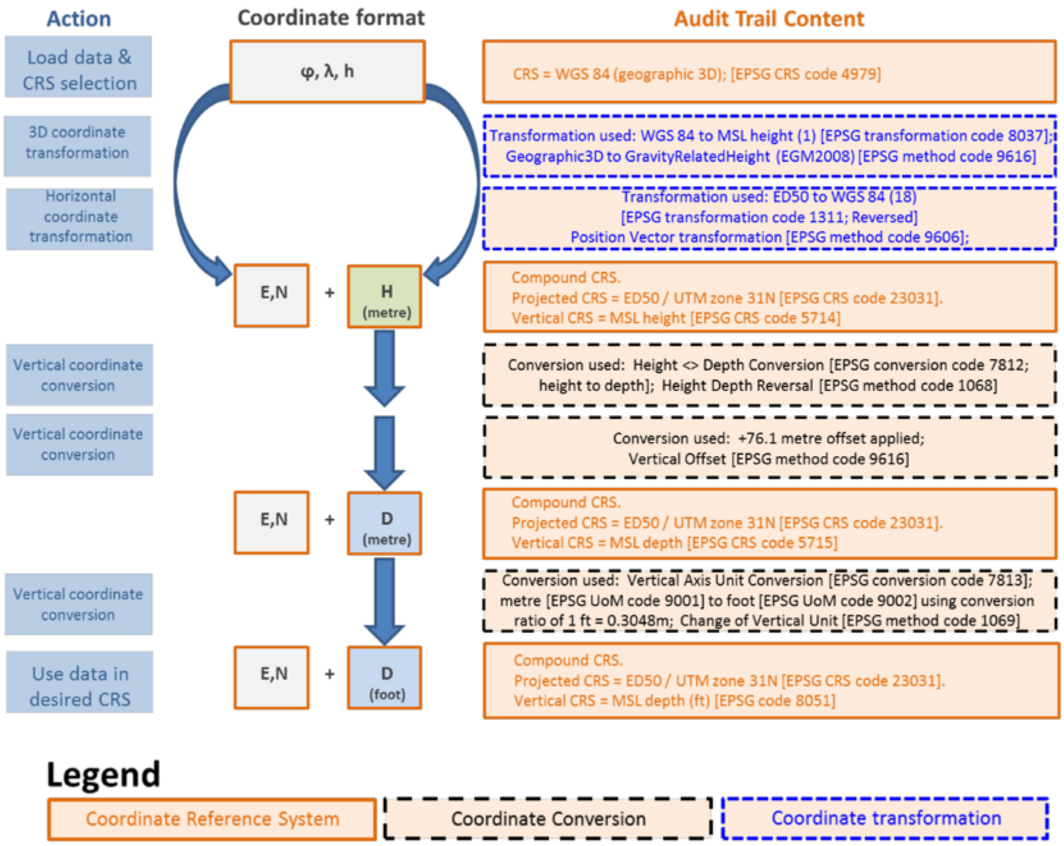


Figure B.2: Audit Trail Schematic for the offshore well example

No coordinate operations need to be applied to the seismic data.

An audit trail example for the operations applied to the well data in the Offshore Well example is shown in Table B.1, as it is loaded to the subsurface application and transformed to the project CRSs.

Table B.1: Example Audit Trail for the offshore well example

Entry	Date	User	Action	Description
1	Nov 14 2016 14:35:00	Anonymous	Load from	C:\USers\Anonymous\Documents\Data_examples\Offshore1_WGS 84\
2	Nov 14 2016 14:35:25	Anonymous	CRS Selection	GeodeticCRS (geographic 3D); 'WGS 84' [EPSG CRS code 4979]
3	Nov 14 2016 14:35:45	Anonymous	Set Name	Offshore1_WGS 84_height
4	Nov 14 2016 14:37:10	Anonymous	Coordinate Transformation	WGS 84 to MSL height (1) [EPSG tfm code 8037]; Geographic3D to GravityRelatedHeight (EGM2008) [EPSG method code 9616];
5	Nov 14 2016 14:37:10	Anonymous	Coordinate Transformation	ED50 to WGS 84 (18) [EPSG tfm code 1311, Reversed]; Position Vector transformation [EPSG method code 9606]
6	Nov 14 2016 14:37:30	Anonymous	Coordinate Conversion	MSL height to MSL depth [EPSG conv code 8039]; height to depth; Height Depth Reversal [EPSG method code 1068]
7	Nov 14 2016 14:37:40	Anonymous	Coordinate Conversion	Vertical offset [EPSG method code 9616] +76.1 metre offset applied.
8	Nov 14 2016 14:37:55	Anonymous	Coordinate Conversion	Vertical Axis Unit Conversion [EPSG conv code 7813]; metre [EPSG UoM code 9001] to foot [EPSG UoM code 9002] with conversion ratio 1ft = 0.3048m; Change of Vertical Unit [EPSG method code 1069]
9	Nov 14 2016 14:39:00	Anonymous	Change Name	Offshore1_ED50_MSL_Depth_foot_SeismicDatum

Figure B.3 shows the WKT for the local working CRS entities used in this example. These WKT strings were generated from the EPSG Dataset (via the online Registry). For entities that are not contained in the EPSG Dataset, similar WKT can be created but may not contain the Authority and ID (highlighted). To ensure the correct syntax, it is advisable to use the existing WKT of an entity with a similar definition generated from any 'reliable' source (one being the EPSG online Registry) which is then edited to suit user requirements.

Horizontal CRS WKT

```
PROJCRS["ED50 / UTM zone 31N",
  BASEGEODCRS["ED50",
    DATUM["European Datum 1950",
      ELLIPSOID["International 1924",6378388,297,LENGTHUNIT["metre",1.0]]]],
  CONVERSION["UTM zone 31N",
    METHOD["Transverse Mercator",ID["EPSG",9807]],
    PARAMETER["Latitude of natural origin",0,ANGLEUNIT["degree",0.01745329252]],
    PARAMETER["Longitude of natural origin",3,ANGLEUNIT["degree",0.01745329252]],
    PARAMETER["Scale factor at natural origin",0.9996,SCALEUNIT["unity",1.0]],
    PARAMETER["False easting",500000,LENGTHUNIT["metre",1.0]],
    PARAMETER["False northing",0,LENGTHUNIT["metre",1.0]]],
  CS[cartesian,2],
    AXIS["easting (E)",east,ORDER[1]],
    AXIS["northing (N)",north,ORDER[2]],
    LENGTHUNIT["metre",1.0],
  ID["EPSG",23031]]
```

Vertical CRS WKT

```
VERTCRS["MSL depth (ft)",
  VDATUM["Mean Sea Level"],
  CS[vertical,1],
    AXIS["depth (D)",down],
    LENGTHUNIT["metre",1.0],
  ID["EPSG",8051]]
```

Figure B.3: Example WELL-KNOWN TEXT (WKT)

Appendix C

Examples of coordinate operations required for data loading to an application environment

The coordinate operations that should be applied to a discrete dataset in order to correctly load the data to a specific application environment are described in Table C.1. While the table is written in the context of a data loading operation, it is equally applicable to reverse the operations for data export, if required (data export requirements may be different).

Table C.1: Coordinate operations for data loading

Application CRS convention	*Data CRS has height in m*	*Data CRS has depth in m*
Application uses positive up Application units same as data CRS	*No action required - use CRS*	1. Use CRS definition 2. Apply conversion code 7812
Application uses positive down Application units same as data CRS	1. Use CRS definition 2. Apply conversion code 7812	*No action required – use CRS*
Application uses positive up Application units different to data CRS (e.g. foot, US survey foot)	1. Use CRS definition 2. Apply conversion code 7813	1. Use CRS definition 2. Apply conversion code 7812 3. Apply conversion code 7813
Application uses positive down Application units different to data CRS (e.g. foot, US survey foot)	1. Use CRS definition 2. Apply conversion code 7812 3. Apply conversion code 7813	1. Use CRS definition 2. Apply conversion code 7813

References

[1] EPSG Geodetic Parameter Dataset.
See http://www.epsg.org and http://www.epsg-registry.org

[2] IOGP Report 373-01. Geomatics Guidance Note 1. *Geodetic awareness guidance note*. http://www.iogp.org/bookstore/product/geodetic-awareness-guidance-note-sp-01/

[3] IOGP Report 373-05. Geomatics Guidance Note 5. *Coordinate reference system definition — recommended practice.* http://www.iogp.org/bookstore/product/coordinate-reference-system-definition-recommended-practice-sp-05/

[4] IOGP Report 373-07-1. Geomatics Guidance Note Number 7 Part 1. *Using The EPSG Geodetic Parameter Dataset*. http://www.iogp.org/bookstore/product/using-the-epsg-geodetic-parameter-dataset-sp-07-1/

[5] IOGP Report 373-07-2. Geomatics Guidance Note Number 7 Part 2. *Coordinate Conversions and Transformations including Formulas*. This document is regularly revised. For the latest edition, see http://www.iogp.org/bookstore/product/coordinate-conversions-and-transformation-including-formulas-s-and-p-07-2/

[6] IOGP P7 Wellbore Survey Exchange Format (in preparation)

[7] International Organization for Standardization. ISO 19162:2015, *Geographic information – Well-known text representation of coordinate reference systems*.
Available at https://www.iso.org/standard/63094.html

[8] Open Geospatial Consortium document 12-063r5. *Geographic information – Well-known text representation of coordinate reference systems*.
Available at http://docs.opengeospatial.org/is/12-063r5/12-063r5.html

[9] International Organization for Standardization. ISO 19111:2007, *Geographic information – Spatial referencing by coordinates*. Available at https://www.iso.org/standard/41126.html

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This guidance note discusses issues associated with vertical Coordinate Reference Systems (CRSs), in particular those related to coordinate operations (coordinate conversions and coordinate transformations) and metadata. It is aimed at geoscientists, data managers and software developers.