



Morven Hawthorn Pit Grid Connection Project

Preliminary Environmental Information Report

Volume 2, Annex 8.3: Morven Compass Deviation
Assessment

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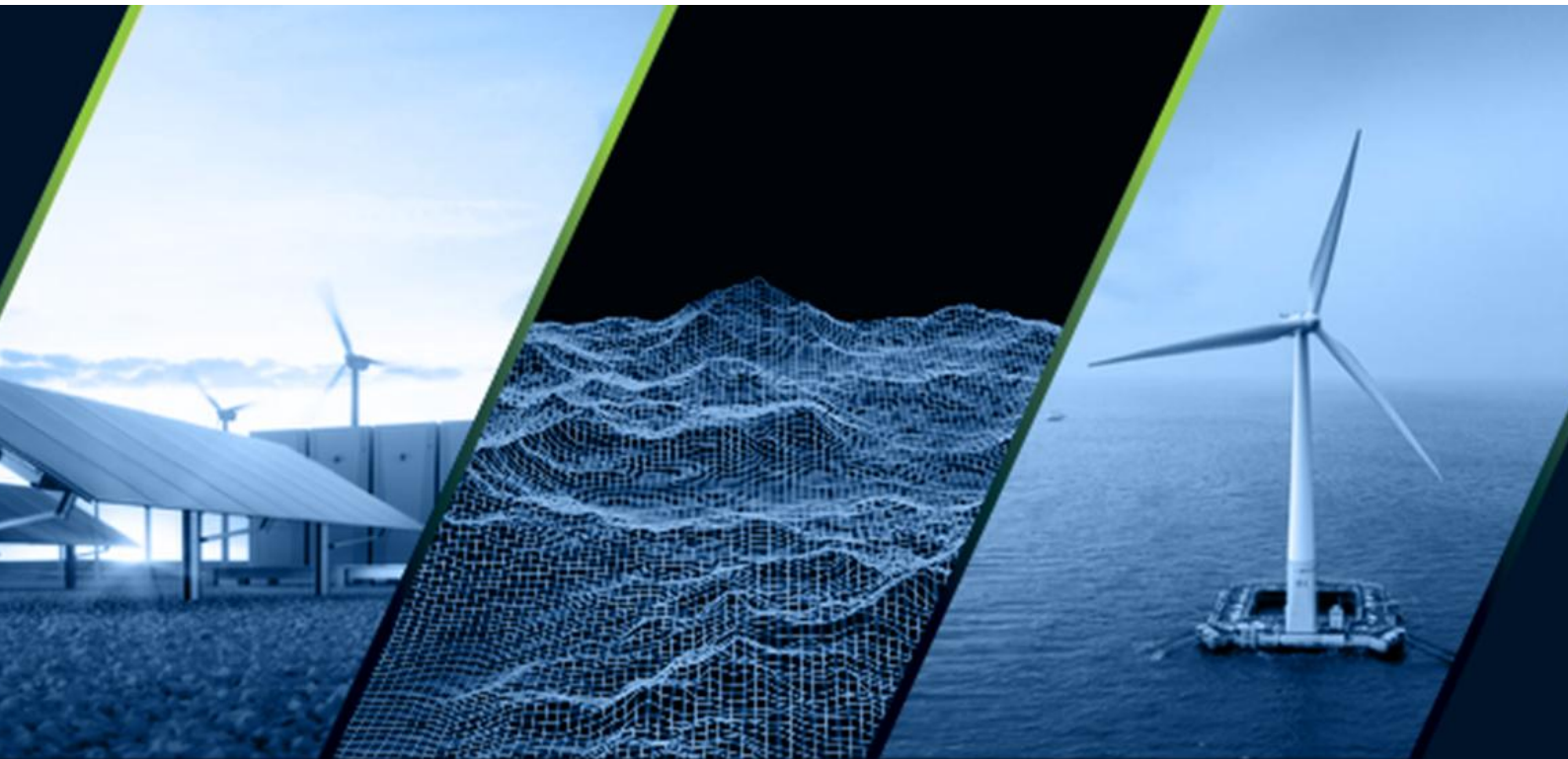
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The **Renewable Energy** Consultants.



Morven Offshore Windfarm Compass Deviation Assessment

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Acronyms

Acronym	Full Term
CIGRE	Conseil International des Grands Réseaux Electriques
ECC	Export Cable Corridor
EIA	Environmental Impact Assessment
EMF	Electromagnetic Field
EMODnet	European Marine Observation and Data Network
EnBW	Energie Baden-Württemberg AG
FO	Fibre Optic
GPS	Global Positioning System
GW	Gigawatt
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IAC	Inter Array Cables
JNBP	JERA Nex bp
KP	Kilometre Point
MMO	Marine Management Organisation
NOAA	National Oceanic and Atmospheric Administration
PDE	Project Design Envelope
SE	Southeast
TB	Technical Brochure
WMM	World Magnetic Model
WMMHR	World Magnetic Model High Resolution
WTG	Wind Turbine Generator(s)
XLPE	Cross-Linked Polyethylene

Executive Summary

OWC has undertaken a study to assess the compass deviation associated with the installation and operation of High Voltage Direct Current (HVDC) submarine cables for Morven offshore wind farm. The objective is to determine any deviations that occur along the offshore export route and that regulatory thresholds are adhered to, thereby supporting safe marine operations and informing post-installation survey requirements.

Compass deviation can be affected by magnetic fields outside the HVDC power cables. This has been assessed for depths ranging from 0.5 to 3 m and referenced at the water level, for a maximum cable current of 2,343.75 amps. The calculations cover two installation scenarios:

- Fully Bundled - This setup represents the most compact arrangement and presented the lowest external magnetic field due to mutual cancellation effects.
- Fully Separated - This scenario assumes the absence of any mitigating influence from a second cable and therefore provides the highest expected magnetic flux values.

All calculations were performed assuming maximum load and minimum phase separation giving a worst-case scenario. The magnetic fields produced by the bundled cables were highly localised, reducing rapidly from the source due to the two single cables significantly cancelling each other's EMF. The decrease in magnetic fields occurs both in the vertical water column and horizontally along the seabed. The magnetic fields reduced to as low as 0.01 μT for fully bundled cables, and 4.63 μT for fully separated cables due to the deep waters. For the shallow sections of the route, a maximum EMF of 0.37 μT and 32.40 μT was observed for the fully bundled and fully separated scenarios.

Results showcased in Section 3 indicate that when separated, the magnetic field reduces as cable size increases, but the inverse is true when the cables are bundled. This is because the two cables, when bundled, significantly cancel their magnetic fields, hence reducing the overall magnitude. As cable size is increased the separation between the two cores increase, slightly reducing the cancellation effects on one another. However, when the cables are separated and influence of the two cables upon one another is negligible, the increase in cable size slightly increased the depth to the centre of the core, which slightly reduces the observed magnetic field.

Results presented in Section 3.3 indicate that all scenarios modelled for fully bundled cables adhere to the MMO guidelines (a maximum compass deviation of 3° is permitted along 95% of the cable route and a maximum deviation of 5° is allowed for the remaining 5%). However, Table 3-5 and Table 3-6 indicate that with a 1 m burial depth, the maximum compass deviation along the route exceeds 5° for all cable sizes when the export route utilises Landfall 1 (northern route section). This occurs for 0.05% of the route for cable sizes of 2,000 mm² and 2,500 mm² and for 0.15% of the route for a cable size of 3,000 mm². If this must be avoided then use of Landfall 2, or increasing the burial depth, is shown to reduce the maximum compass deviation observed along the full route. Figure 3-2 indicates that the maximum compass deviation occurs at landfall where the water is most shallow.

Section 3.4 indicates that when a single cable is operational or when separation between the two cables is large enough so there is no mutual EMF cancellation, the magnetic flux density in combination with the earth's magnetic field causes the compass deviation to fall outside the MMO guidelines for all scenarios and conditions. Although these values present the worst-case operational/installation scenarios.

Even when reducing separation distance but ensuring EMF cancellation, as presented in Section 3.5, the compass deviation exceeded 5° at the landfall section of the route. To keep the maximum deviation below 5°, only a maximum separation of 1 m to 3 m at landfall can be allowed with either route option, for burial depths 0.5 m to 2 m. A maximum separation of 4 m is allowed only when the cable is buried 3 m deep. This is due to the shallow water depths associated with the route location. At deeper points further along the route (closer to the project area), the separation can be increased from 60 m to 128 m for a burial depth of 0.5 m (15 km to 107 km further along the route).

The use of the Southern Landfall location (Landfall 2) when cables are fully bundled presented a better case for consenting applications due to the low resultant deviation. If the Northern Landfall locations (Landfall 1) is to be used for the project, increasing the burial depth to greater than 1 m will decrease the risk of not meeting regulatory compliance.

1 Introduction

1.1 General

As part of the development efforts for Morven offshore wind farm, JERA Nex bp (JNBP) and Energie Baden-Württemberg AG (EnBW) (hereafter referred to as “the Client”) are working on the generation of the Environmental Impact Assessment (EIA) and Project Design Envelope (PDE). The Electromagnetic Field (EMF) emitted to the environment by the cables will feed into the PDE and be assessed as part of the EIA. The EMF levels emitted by the export cables may impact navigational equipment when combined with the earth’s magnetic field and hence an assessment outlining the effects has been undertaken.

The requested services involve a detailed assessment of compass deviation associated with the installation and operation of High Voltage Direct Current (HVDC) submarine cables. The objective is to determine any deviations that occur along the offshore export route and that regulatory thresholds are adhered to, thereby supporting safe marine operations and informing post-installation survey requirements.

Multiple scenarios are to be assessed to ensure any project design deviations that may arise further down the line are captured by this assessment. The varying parameters include burial depth to top of the cable and cable separation.

When assessing the HVDC transmission cables, results should showcase the deviations when a portion of the HVDC bundled cables are separated for a short portion of the route (for micro-routing purposes or in a repair scenario), as this represents a worse case compared to the scenario of the cable pair bundled together.

This report will focus on the influence to compass deviations due to the EMF generated by cables in combination with the earth’s natural magnetic field.

1.2 Scope of Work

OWC has undertaken a comprehensive compass deviation assessment for subsea HVDC export cable systems. The study involved modelling the difference in bearing between the cable’s orientation and the earth’s magnetic pole and calculating the combination of earth’s magnetic field with the EMF produced by the cables for the range of water depths along the route. This was studied under a variety of operational and installation scenarios, including varying burial depths (1–3 m) and circuit configurations (unbundled for micro-routing).

With reference to Morven offshore windfarm, the Marine Management Organisation (MMO) has issued the additional following guidance regarding electromagnetic interference from the cables and their permissible impact on compass deviation study:

- A maximum compass deviation of 3° is permitted along 95% of the cable route.
- A maximum deviation of 5° is allowed for the remaining 5%.
- A post-lay deviation survey must be conducted to verify compliance.
- Survey results must be submitted to the UK Hydrographic Office (UKHO) via a Hydrographic Note (H102).
- The UKHO may apply a precautionary notation on relevant Admiralty Charts based on the findings

Magnetic fields have been calculated using established electromagnetic theory, applying Maxwell’s equations and Ampère’s circuital law. The modelling has been performed using validated internal tools benchmarked against industry standards such as CIGRE TB 104.

To ensure conservative outputs, the assessment excluded shielding effects from cable armour and induced sheath/screen circulating currents. Electric fields (E-Field) were not modelled explicitly as they are expected to be contained by the metallic sheaths which are earthed at both ends.

The results quantify the magnetic field at the water level and the resulting compass deviation, supporting environmental assessments and informing mitigation strategies such as cable spacing and burial depth. The methods were applied to the HVDC transmission cables.

The HVDC transmission characteristics have been assessed for 0.5, 1, 2, and 3 m burial depths and bundled and unbundled cables (significant separation of between them).

1.3 Project Background

The Morven Project is a proposed fixed-bottom offshore wind farm located approximately 60 km southeast off the coast of Aberdeen in the North Sea. It is being developed by Morven Offshore Wind Limited, a joint venture between JNBP and EnBW, as part of the ScotWind leasing round. The project is expected to generate 2.9 GW of electricity from turbines installed in water depths of 65–75 metres and has a proposed commercial operation date of 2029.



Figure 1-1: Morven Windfarm Overview [1]

The project will utilise HVDC subsea cables to realise the transfer of power from the wind farm to the onshore grid connection. The Inter Array Cables (IAC) use High Voltage Alternating Current (HVAC) to connect the Wind Turbine Generators (WTG) to the offshore substation and then the offshore converter station. The IAC may be rated at 132 kV or 66 kV and the symmetric-monopole HVDC cables will be rated for ± 320 kV transmission. There will be two fully bundled HVDC cables rated for 1.5 GW of power transfer. The transmission cable landfall options are in the vicinity of Seaham where the power is then transmitted to the onshore converter substation, and final grid connection at Hawthorn Pit substation.

2 Method

2.1 General

Electricity has two principal components: an electrical component and a magnetic component. Electric fields are determined by voltage, and the electric field around a transmission line will be essentially constant at any given location. Magnetic fields are determined by current and will change in strength over time in line with the magnitude of the current.

2.2 Magnetic fields

Magnetic fields are one part of electromagnetism. The magnetic field is a time-varying field that occurs in the presence of an electric field. The magnetic field presents a force that results from a moving charge. Electrical current in a cable is a flow of moving charges and thus generates magnetic fields. The magnetic field is proportional to the current; the higher the current, the higher the magnetic field.

The magnetic flux density is a vector field and thus consists of an amplitude component and direction component. The vector field is represented by $\vec{B}$ and is expressed in terms of Teslas (T) or micro-Teslas (μT , 10^{-6} Teslas). OWC has estimated and discussed the magnetic flux density in terms of its amplitude, B . Its relation to the vector field is:

$$B = |\vec{B}|.$$

The magnetic field intensity, $\vec{H}$, is also used to describe magnetic fields. The magnetic field intensity is a vector field that describes the magnetizing force (strength of the magnetic field). It is measured in A/m. The magnetic field intensity is considered a derived quantity of $\vec{B}$ and does not add extra value to this study. For most materials it can be simplified to the following equation (μ is the permeability of the material).

$$\vec{H} = \frac{\vec{B}}{\mu}$$

In this report, the term "magnetic field" is used as the convention for magnetic flux density, the B-field. While technically distinct in electromagnetic theory, in engineering practice, particularly in cable design and short-circuit analysis, the term "magnetic field" is commonly used to refer to the B-field, the vector quantity that represents the density and direction of magnetic flux.

It is important to note that magnetic field strength, denoted as the H-field, is a separate quantity related to the B-field through the material's permeability (i.e., $B = \mu H$). However, unless specifically stated, references to the "magnetic field" in this document pertain to the B-field.

The magnetic field can be determined using Maxwell's equations, Ampère's circuital law (which relates the magnetic field to the electric current passing through a loop), and the superposition principle. OWC has used this principle to calculate the magnetic field the DC system would produce without a conductive or ferromagnetic shield. Magnetic fields cannot easily be shielded, and pass-through non-magnetic materials.

Estimated magnetic fields were calculated for the cables. Magnetic fields above the buried cables were calculated as the value of the field along a transect perpendicular to the centreline of the cables at the representative target burial depths.

Sheath induced currents are not included as these are not applicable to HVDC cables. The modelling was only conducted with respect to the main conductors. The magnetic fields calculated in this analysis represent the worst case, given that several cable design features that reduce magnetic field levels outside the cables were not included.

However, this analysis assumes no magnetic armour, which reflects the situation of a break in the armour or use of nonmagnetic armour. This is considered a worst-case scenario as the magnetic permeability of cable armouring can attenuate the magnetic field outside of the cables.

The main variable related to magnetic fields is relative permeability (μ_r), a dimensionless gauge of the ability of a material to support a magnetic field compared to the ability of free space. Materials with a high permeability value will act to support a magnetic field. The relative permeability values used for this study are summarised in Table 2-1.

Table 2-1: Magnetic properties of the cable materials and the surrounding medium

Item	Relative Permeability μ_r
Conductor (Copper)	1.0
Conductor (Aluminium)	1.0
Insulator (XLPE)	1.0
Sheath (Lead)	1.0
Armour (Steel Wire) – subsea cable only	100.0 – Excluded, Not Applied
Seawater	1.0
Seabed	1.0
Soil	1.0
Air	1.0

It is important to consider that any magnetic fields generated by the cables will be superimposed on the earth's magnetic field and any other existing magnetic fields. The earth's magnetic field has a flux of about 60 μT at the poles where the field is vertical and 30 μT at the equator where it is horizontal. A fixed magnitude of 50 μT was used for this study.

Magnetic fields have been calculated using OWC's internal tools. These tools have been validated against test cases presented in Conseil International des Grands Réseaux Electriques (CIGRE) 104 [2].

2.3 Compass Deviation

The Earth's geomagnetic field is a static magnetic field with no associated frequency. Similarly, the EMF produced by a HVDC cable is also static with the associated vector in a constant direction, varying in magnitude in line with the cable current. Interactions between EMF components occur only when they share the same frequency; therefore, the static field generated by a HVDC cable can interact with the Earth's geomagnetic field.

A compass needle aligns with magnetic north due to the influence of the Earth's geomagnetic field. It's important to note that magnetic north differs from geographic (or true) north, and the angular difference between them is known as magnetic declination (D), which varies by location and can be either positive (east) or negative (west).

The static EMF from a subsea HVDC cable alters both the direction and intensity of the horizontal magnetic field components in its vicinity. For compass deviation assessments, only the horizontal components, those in the X and Y axes (north-south and east-west), are relevant. The vertical component (Z-axis) does not affect compass readings, as illustrated in Figure 2-1.

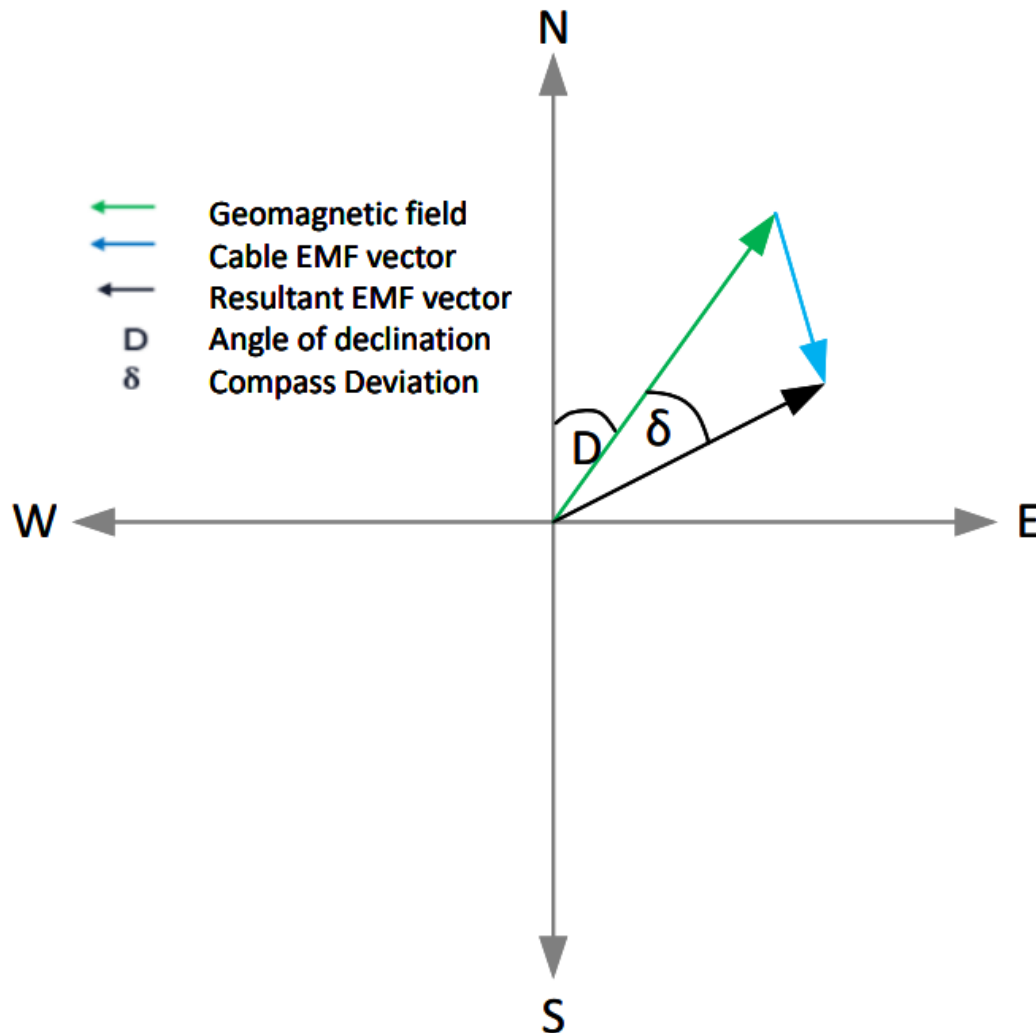


Figure 2-1: Compass Deviation due to Interaction with HVDC EMF

Compass deviation calculations have been carried out for the sea surface level at each KP location. The EMF component perpendicular to the cable, in the Z-axis direction (towards the seabed surface) is not considered, as it will not affect compass orientation. At each KP location the mean seawater depth was estimated with coordinate data and use of the online tool (EMODnet). The geomagnetic field component directions were calculated with the NOAA online tool.

For HVDC systems, the static magnetic field is directly superimposed on the geomagnetic field. Using vector field superposition, the resultant magnetic field was calculated and used to determine the angular deviation from magnetic north at various distances above the seabed by mapping the burial depth along the entire route (using the EMODnet high resolution bathymetry dataset [3]) to capture the magnetic flux density at the sea level, where the navigational equipment will exist.

To assess compass deviation along the entire subsea cable route, the transmission corridor is discretised into regular intervals of 100 m. The assessment has been benchmarked against regulatory thresholds (e.g. MMO guidance of $\leq 3^\circ$ deviation across 95% of the route), and will inform mitigation strategies such as cable spacing, burial depth, and route alignment.

Two calculation methods were performed, the first is the compass deviation when the cable is bundled which likely reflects the situation associated with the limit of $\leq 3^\circ$ limit for 95% of the route. The second is a worst-case scenario (unbundled cables), a situation associated with the limit of $\leq 5^\circ$ for 5% of the route. Results are presented as deviation profiles along the cable corridor, supporting safe offshore navigation and compliance with marine consent conditions.

The earth's magnetic field was assumed to be uniform along the route, with a magnitude of 50 μT and was directionally aligned with magnetic north. Two models exist to represent the earth's natural magnetic field, the World Magnetic Model (WMM) [4] and the World Magnetic Model High Resolution (WMMHR) [5].

The WMMHR provides a more accurate and detailed depiction of the Earth's magnetic field than the standard WMM. While both models describe the main magnetic field generated within the Earth's core, WMMHR includes additional data on the magnetic fields from the Earth's crust, leading to greater precision.

Table 2-2: Comparison of Earth's Magnetic Field Models [6]

Feature	WMM	WMMHR
Resolution	Standard, with a spatial resolution of approximately 3,300 km at the equator.	High, with a spatial resolution of approximately 300 km at the equator.
Data Included	Covers only the Earth's main magnetic field and its slow temporal changes.	Includes the main magnetic field and a more comprehensive model of the Earth's crustal magnetic field.
Accuracy	Sufficient for most standard navigation applications.	Provides greater directional accuracy, especially at higher latitudes and near tectonic features.
Complexity	Uses fewer coefficients for its calculations.	Requires significantly more coefficients (18,210 vs. 336 for WMM2025) and more precise data, resulting in a larger file size.
Application	Standard for general navigation, such as in GPS-enabled devices, civilian aircraft, and ships.	Recommended for advanced, high-precision applications by military and defence systems.

OWC has conducted this assessment by utilising the WMM. The degree of accuracy offered in the WMMHR requires a level of precision not yet available to the project and requires significantly higher computational efforts. Furthermore, the WMM offers a sufficient level of accuracy required for navigational equipment, which is the focus of this assessment.

Figure 2-2 below shows the WMM declination projected onto a portion of the export route (near landfall, Export Cable Corridor (ECC) 1 and ECC 2). The declination is represented by the green lines and is used to determine the magnetic north bearing.

Please note that the WMM declination values shown in the figure and used in the analysis in this report are specific to a date (01 September 2025), location and have a typical $\pm$ accuracy of 0.4 degrees. This reflects the capabilities of current models which are available to assess the changing locational properties of the earth's magnetic fields. Further information on this subject can be obtained at the geomagnetism pages of the NOAA website [7] [8].

The KP locations and the bearings of the initial cable sections can also be observed; this was repeated for the entire route length; the cable location was assumed to coincide with the centre line of the provided export cable corridor.

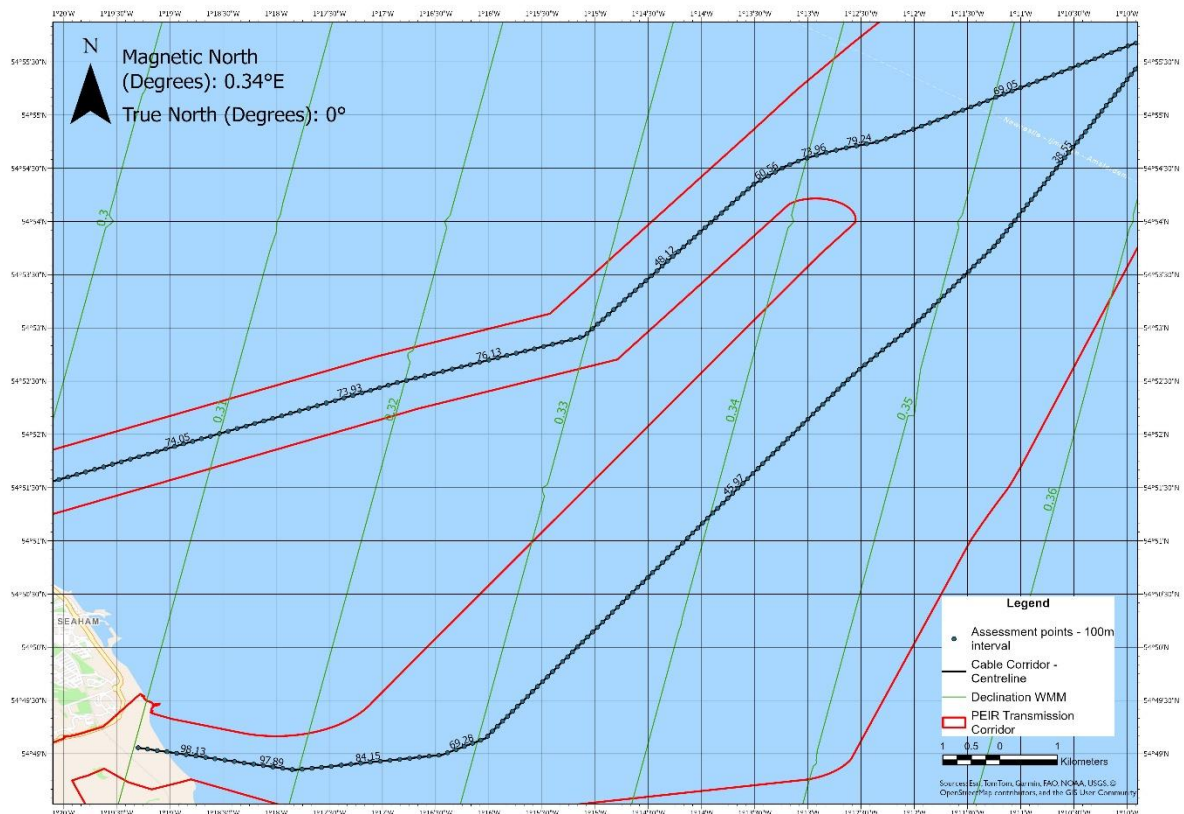
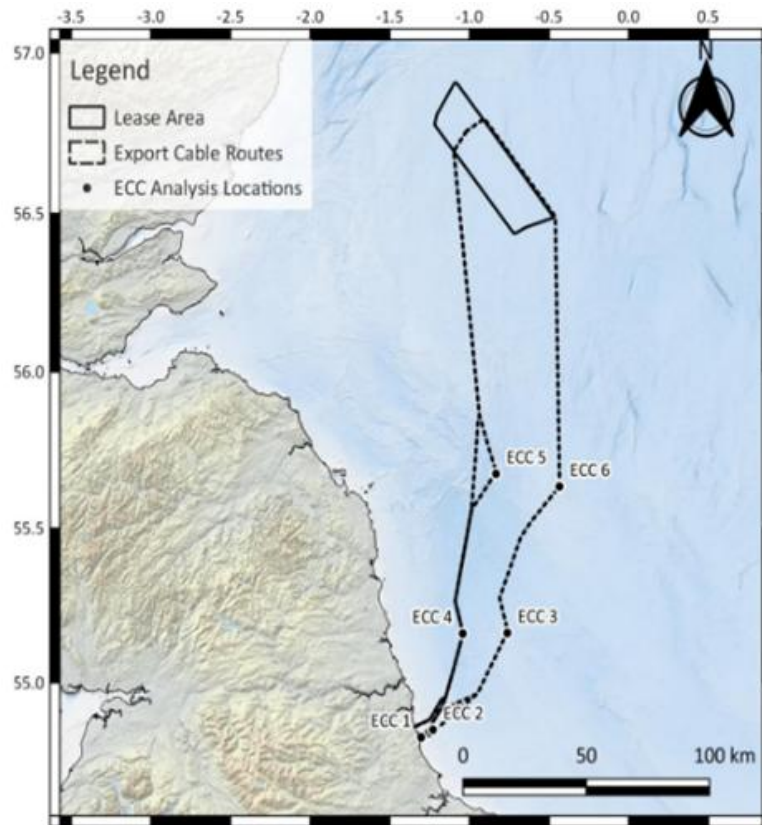


Figure 2-2: WMM magnetic declination projected onto a section of the transmission corridor

The northern route of cable section shown in Figure 2-2 has been denoted as Landfall 1 and the southern section as Landfall 2 for the purpose of this study. The results will also include the rest of the cable route that connects to Morven Offshore Windfarm.

2.4 Project Data and Input Assumptions

The cable route is broken down into distinct Export Cable Corridors (ECC) numbered ECC 1 to ECC 6. A diagram illustrating the export cable corridors is shown in Figure 2-3.



Location ID	Position WGS84	Position ED50 UTM30N	MSL Depth [m]
ECC_1	54.8219° N, 1.3040° W	609067.1, 6076511.2	13.4
ECC_2	54.8466° N, 1.2300° W	613751.6, 6079376.8	34.2
ECC_3	55.1620° N, 0.7630° W	642609.9, 6115322.9	69.4
ECC_4	55.1600° N, 1.0430° W	624781.2, 6114564.4	100.2
ECC_5	55.6752° N, 0.8340° W	636309.5, 6172278.4	86.0
ECC_6	55.6342° N, 0.4360° W	661500.7, 6168570.6	65.7

Figure 2-3: Export Cable Route Sections [9] [10] [11]

The current magnitude for the project cables was supplied to OWC by the Client, since only one value was provided, OWC assumed that the magnitude is the same for each cable since this value is based on a 1.5 GW capacity with a ± 320 kV operational voltage. The table below gives the necessary physical dimensions of the cables. With this OWC can calculate the spacing between cables when bundled together and the depth to the centre of the cables from the seabed.

Table 2-3: Project HVDC Cable Data

Cable Size	2,000 mm ²	2,500 mm ²	3,000 mm ²
Outer Diameter of Cable (mm)	135	150	165
Bundle Diameter (2 cables) (mm)	270	300	330
Current Magnitude (A)	2,343.75	2,343.75	2,343.75

As seen in Figure 2-4 below the vertical diameter of the bundle is slightly larger than the outer diameter of a single cable. No information is available on the dimensions of the fibre optic (FO) cable hence for modelling purposes it was disregarded which presents a worst case, and the outer diameter of a single cable was used as the vertical diameter of the bundle.

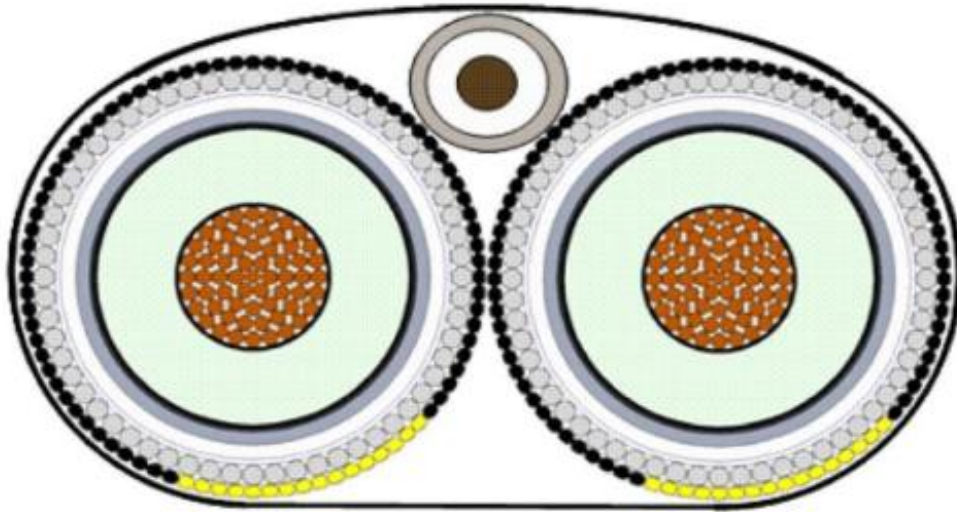


Figure 2-4: Depiction of a Symmetrical Monopole, Bundled Configuration with FO Cable

The impact to the magnetic and electric fields when increasing burial depths from 1 to 3 m has been assessed during this study, this refers to the depth of cover to the top of cable. The dimensions of the cables and bundles will then be used to understand the depth to the centre of the cables. On top of varying burial depths and cable sizes (and thus installation dimensions), two distinct scenarios have been assessed. These are listed below in Table 2-4.

Table 2-4: Definition of Scenarios Assessed

Scenarios	Description
Scenario 1 Fully Bundled	Two cables bundled together with no spacing as depicted in Figure 2-4.
Scenario 2 Fully Separated	The cables are laterally separated enough that the influence of the second cable can be neglected, and hence the results showcase the values associated for a single operational cable.

3 Results

3.1 General

Presented below are the outcomes of the compass deviation assessment conducted for HVDC submarine cables under varying burial depths and cable configurations. The study evaluated magnetic fields and compass deviation at burial depths ranging from 1 to 3 metres, across two distinct cable lay scenarios designed to reflect realistic and conservative installation conditions:

- Scenario 1 considered a fully bundled configuration, where two HVDC cables are placed adjacently within the same trench.
- Scenario 2 represented a worst-case condition, where only a single HVDC cable was considered. This scenario assumes the absence of any mitigating influence from a second cable and therefore provides the highest expected magnetic flux values.

The results presented herein quantify the compass deviation and at varying depths of cover and for various water depths observed along the route, offering insight into the influence of burial depth and cable configuration on EMF exposure levels at the surface water level and the resultant compass deviation.

3.2 Maximum EMF at Water Level

The water depth along the route length changes due to the complex bathymetry, to give an understanding of the observed EMF levels at the water level, the following magnitudes have been calculated for the provided water depths at key sections of the export route for both fully bundled cables and fully separated cables (single cable influence) and provided in Table 3-1 for burial depths of 1 m for each cable size. The corresponding route locations are shown in Figure 2-3.

Table 3-1: Maximum EMF Observed at Water Level for 1 m Burial Depth

Route Characteristics		Bundled Cables (μT)			Fully Separated Cables (μT)		
Location	Water Depth (m)	2000 mm ²	2500 mm ²	3000 mm ²	2000 mm ²	2500 mm ²	3000 mm ²
ECC_1	13.4	0.30	0.34	0.37	32.40	32.38	32.37
ECC_2	34.2	0.05	0.06	0.06	13.29	13.29	13.29
ECC_3	69.4	0.01	0.01	0.02	6.65	6.65	6.65
ECC_4	100.2	0.01	0.01	0.01	4.63	4.63	4.63
ECC_5	86	0.01	0.01	0.01	5.38	5.38	5.38
ECC_6	65.7	0.01	0.02	0.02	7.02	7.02	7.02

3.3 Compass Deviation for Fully Bundled

3.3.1 Cable Burial Depth of 0.5 m

The data presented summarises the compass deviation effects for fully bundled HVDC cables buried at a depth of 1 metre, considering different cable cross-sectional areas and two possible landfall locations.

Table 3-2 shows the maximum compass deviation observed for each scenario. Table 3-3 and Table 3-4 compare the percentage of the cable route where the compass deviation falls within or exceeds specific MMO bounds. Figure 3-1 depicts the deviation across the entire route length.

Table 3-2: Maximum Compass Deviation Observed for 0.5 m Burial Depth

Route	2,000 mm ² (Degrees)	2,500 mm ² (Degrees)	3,000 mm ² (Degrees)
Landfall 1 Route	8.08	8.88	9.66
Landfall 2 Route	2.90	3.22	3.53

Table 3-3: Compass Deviation compared with MMO Bounds for Route with Landfall 1

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	0.15%	0.15%	0.15%
≤ 5 Degrees	99.85%	99.85%	99.85%
>3 Degrees	0.20%	0.26%	0.26%
≤ 3 Degrees	99.80%	99.74%	99.74%

The deviation greater than 5 degrees occurs from 0 m to 300 m from the shore. The MMO guidance does not give an indication as to the starting distance from shore where the boundary guidelines should come in. The larger deviation is due to the shallow water depths in this region.

Table 3-4: Compass Deviation compared with MMO Bounds for Route with Landfall 2

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	0.00%	0.00%	0.00%
≤ 5 Degrees	100.00%	100.00%	100.00%
>3 Degrees	0.00%	0.00%	0.00%
≤ 3 Degrees	100.00%	100.00%	100.00%

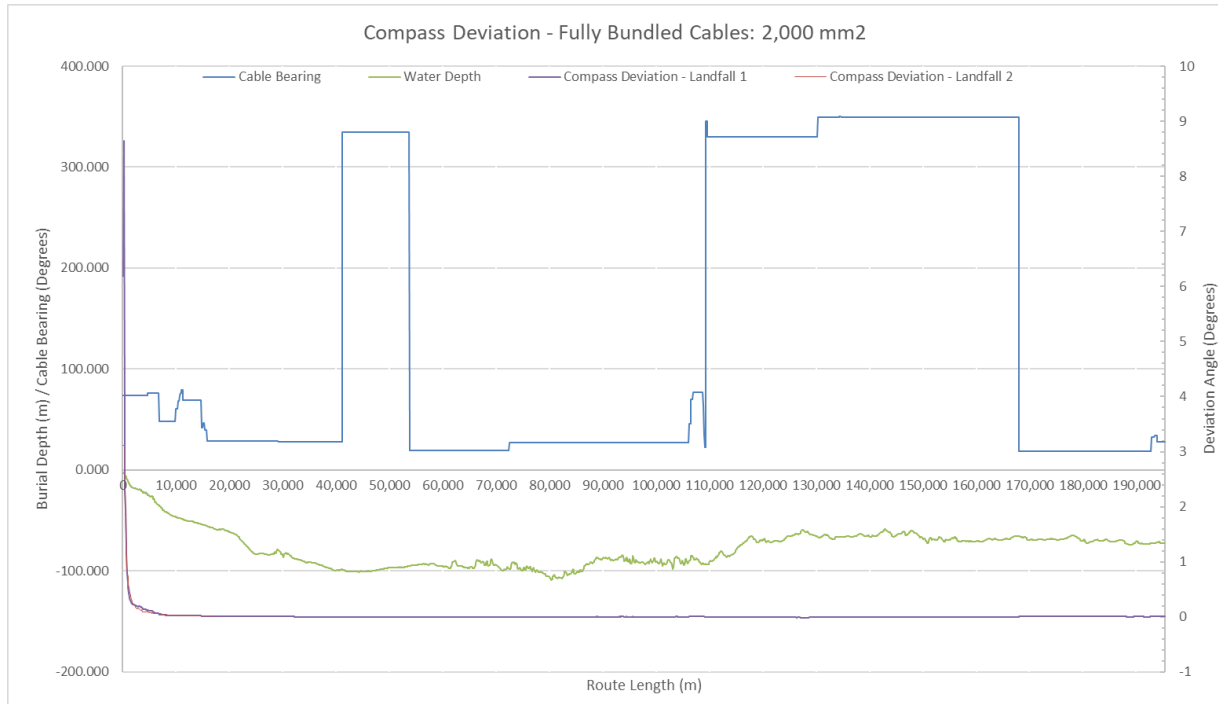


Figure 3-1: Compass Deviation along Route for 0.5 m Burial Depth - 2,000 mm² Cable

3.3.2 Cable Burial Depth of 1 m

The data presented summarises the compass deviation effects for fully bundled HVDC cables buried at a depth of 1 metre, considering different cable cross-sectional areas and two possible landfall locations.

Table 3-5 shows the maximum compass deviation observed for each scenario. Table 3-6 and Table 3-7 compare the percentage of the cable route where the compass deviation falls within or exceeds specific MMO bounds. Figure 3-2 depicts the deviation across the entire route length.

Table 3-5: Maximum Compass Deviation Observed for 1 m Burial Depth

Route	2,000 mm ² (Degrees)	2,500 mm ² (Degrees)	3,000 mm ² (Degrees)
Landfall 1 Route	5.94	6.54	7.13
Landfall 2 Route	2.40	2.66	2.92

Table 3-6: Compass Deviation compared with MMO Bounds for Route with Landfall 1

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	0.05%	0.05%	0.15%
≤ 5 Degrees	99.95%	99.95%	99.85%
>3 Degrees	0.15%	0.15%	0.20%
≤ 3 Degrees	99.85%	99.85%	99.80%

The deviation greater than 5 degrees occurs from 0 m to 300 m from the shore. The MMO guidance does not give an indication as to the starting distance from shore where the boundary guidelines should come in. The larger deviation is due to the shallow water depths in this region.

Table 3-7: Compass Deviation compared with MMO Bounds for Route with Landfall 2

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	0.00%	0.00%	0.00%
≤ 5 Degrees	100.00%	100.00%	100.00%
>3 Degrees	0.00%	0.00%	0.00%
≤ 3 Degrees	100.00%	100.00%	100.00%

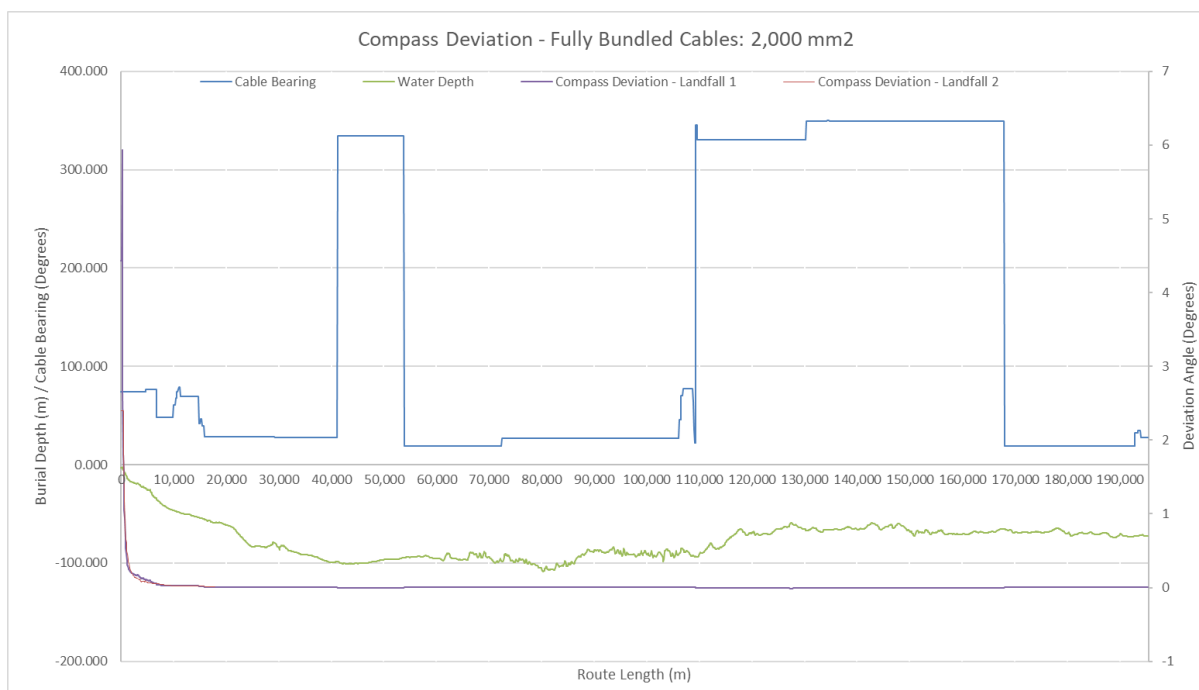


Figure 3-2: Compass Deviation along Route for 1 m Burial Depth - 2,000 mm² Cable

3.3.3 Cable Burial Depth of 2 m

The data presented summarises the compass deviation effects for fully bundled HVDC cables buried at a depth of 2 meters, considering different cable cross-sectional areas and two possible landfall locations.

Table 3-8 shows the maximum compass deviation observed for each scenario. Table 3-9 and Table 3-10 compare the percentage of the cable route where the compass deviation falls within or exceeds specific MMO bounds. Figure 3-3 depicts the deviation across the entire route length.

Table 3-8: Maximum Compass Deviation Observed for 2 m Burial Depth

Route	2,000 mm ² (Degrees)	2,500 mm ² (Degrees)	3,000 mm ² (Degrees)
Landfall 1 Route	3.58	3.95	4.32
Landfall 2 Route	1.71	1.90	2.08

Table 3-9: Compass Deviation compared with MMO Bounds for Route with Landfall 1

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	0.00%	0.00%	0.00%
≤ 5 Degrees	100.00%	100.00%	100.00%
>3 Degrees	0.05%	0.15%	0.15%
≤ 3 Degrees	99.95%	99.85%	99.85%

Table 3-10: Compass Deviation compared with MMO Bounds for Route with Landfall 2

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	0.00%	0.00%	0.00%
≤ 5 Degrees	100.00%	100.00%	100.00%
>3 Degrees	0.00%	0.00%	0.00%
≤ 3 Degrees	100.00%	100.00%	100.00%

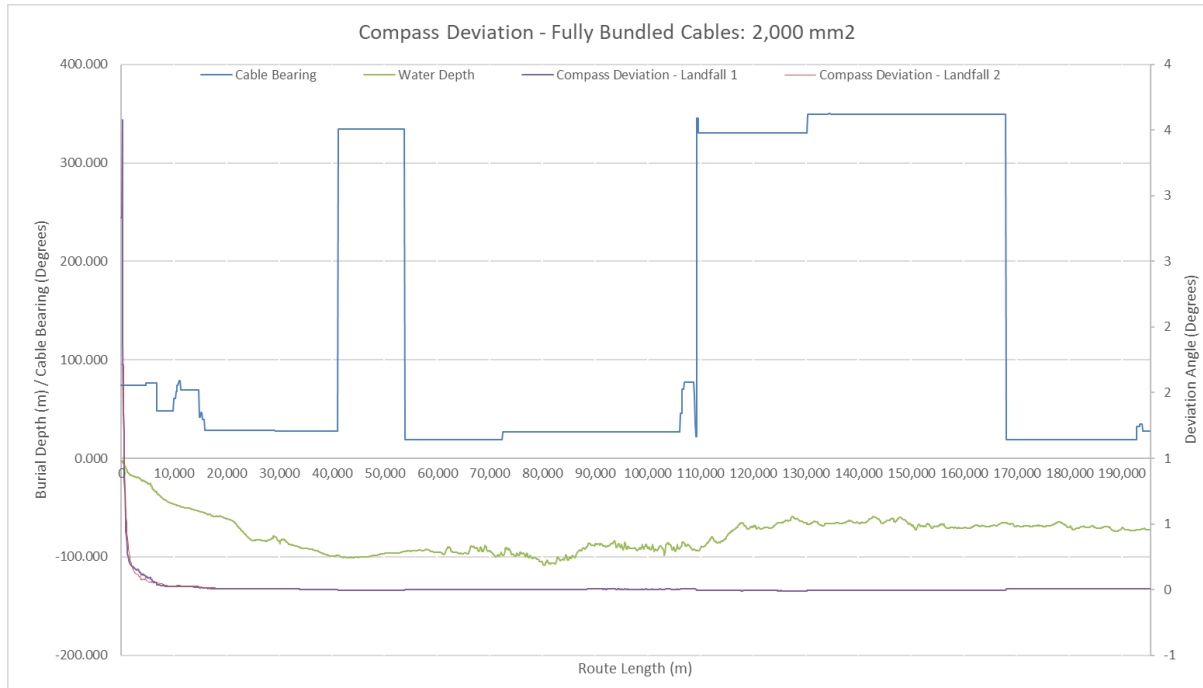


Figure 3-3: Compass Deviation along Route for 2 m Burial Depth - 2,000 mm² Cable

3.3.4 Cable Burial Depth of 3 m

The data presented summarises the compass deviation effects for fully bundled HVDC cables buried at a depth of 3 meters, considering different cable cross-sectional areas and two possible landfall locations.

Table 3-11 shows the maximum compass deviation observed for each scenario. Table 3-12 and Table 3-13 compare the percentage of the cable route where the compass deviation falls within or exceeds specific MMO bounds. Figure 3-4 depicts the deviation across the entire route length.

Table 3-11: Maximum Compass Deviation Observed for 3 m Burial Depth

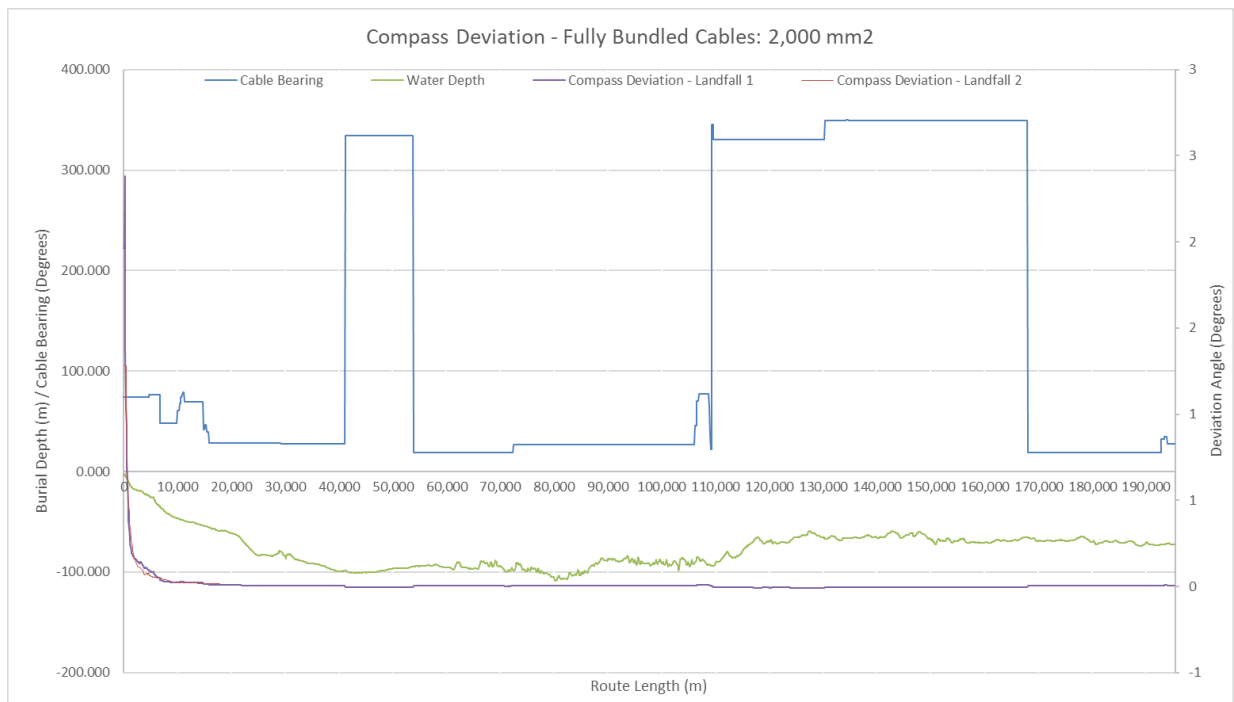
Route	2,000 mm ² (Degrees)	2,500 mm ² (Degrees)	3,000 mm ² (Degrees)
Landfall 1	2.38	2.64	2.89
Landfall 2	1.28	1.42	1.56

Table 3-12: Compass Deviation compared with MMO Bounds for Route with Landfall 1

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	0.00%	0.00%	0.00%
≤ 5 Degrees	100.00%	100.00%	100.00%
>3 Degrees	0.00%	0.00%	0.00%
≤ 3 Degrees	100.00%	100.00%	100.00%

Table 3-13: Compass Deviation compared with MMO Bounds for Route with Landfall 2

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	0.00%	0.00%	0.00%
≤ 5 Degrees	100.00%	100.00%	100.00%
>3 Degrees	0.00%	0.00%	0.00%
≤ 3 Degrees	100.00%	100.00%	100.00%

**Figure 3-4: Compass Deviation along Route for 3 m Burial Depth - 2,000 mm² Cable**

3.4 Compass Deviation for Fully Separated

3.4.1 Cable Burial Depth of 1 m

The data presented summarises the compass deviation effects for fully separated HVDC cables buried at a depth of 1 metre, considering different cable cross-sectional areas and two possible landfall locations.

Table 3-14 shows the maximum compass deviation observed for each scenario. Table 3-15 and Table 3-16 compare the percentage of the cable route where the compass deviation falls within or exceeds specific MMO bounds. Figure 3-5 depicts the deviation across the entire route length.

Table 3-14: Maximum Compass Deviation Observed for 1 m Burial Depth

Route	2,000 mm ² (Degrees)	2,500 mm ² (Degrees)	3,000 mm ² (Degrees)
Landfall 1	56.33	56.30	56.26
Landfall 2	65.54	65.50	65.46

Table 3-15: Compass Deviation compared with MMO Bounds for Route with Landfall 1

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	9.31%	9.31%	9.31%
≤ 5 Degrees	90.69%	90.69%	90.69%
>3 Degrees	22.71%	22.71%	22.71%
≤ 3 Degrees	77.29%	77.29%	77.29%

Table 3-16: Compass Deviation compared with MMO Bounds for Route with Landfall 2

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	10.73%	10.73%	10.73%
≤ 5 Degrees	89.27%	89.27%	89.27%
>3 Degrees	23.92%	23.92%	23.92%
≤ 3 Degrees	76.08%	76.08%	76.08%

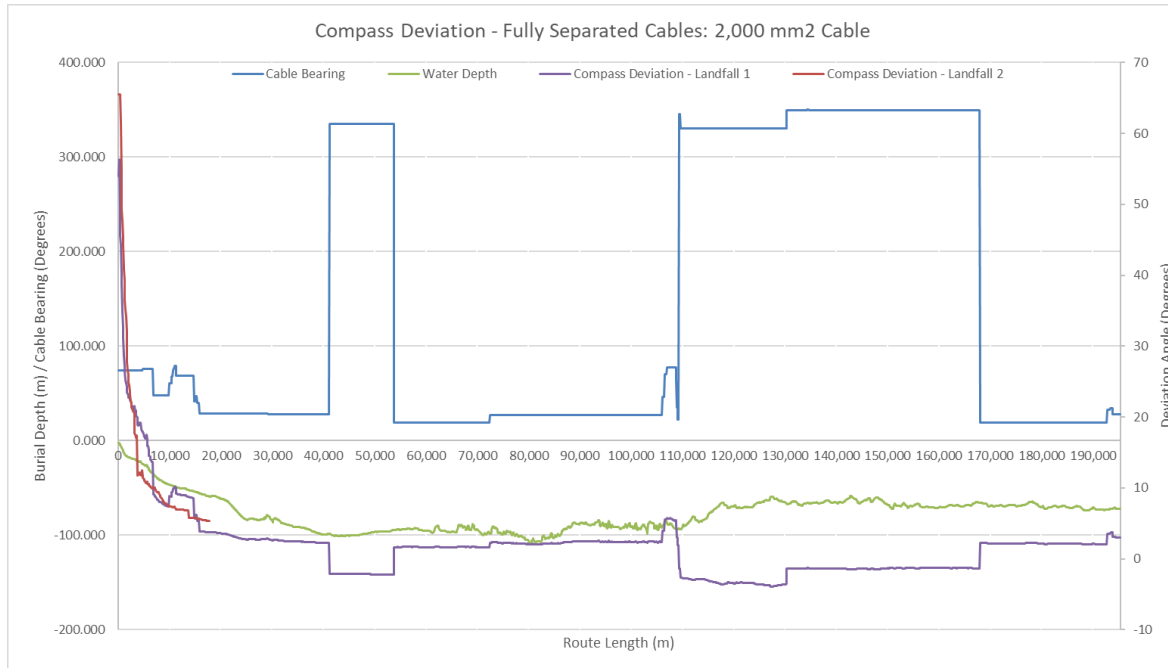


Figure 3-5: Compass Deviation along Route for 1 m Burial Depth - 2,000 mm² Cable

3.4.2 Cable Burial Depth of 2 m

The data presented summarises the compass deviation effects for fully separated HVDC cables buried at a depth of 2 metres, considering different cable cross-sectional areas and two possible landfall locations.

Table 3-17 shows the maximum compass deviation observed for each scenario. Table 3-18 and Table 3-19 compare the percentage of the cable route where the compass deviation falls within or exceeds specific MMO bounds. Figure 3-6 depicts the deviation across the entire route length.

Table 3-17: Maximum Compass Deviation Observed for 2 m Burial Depth

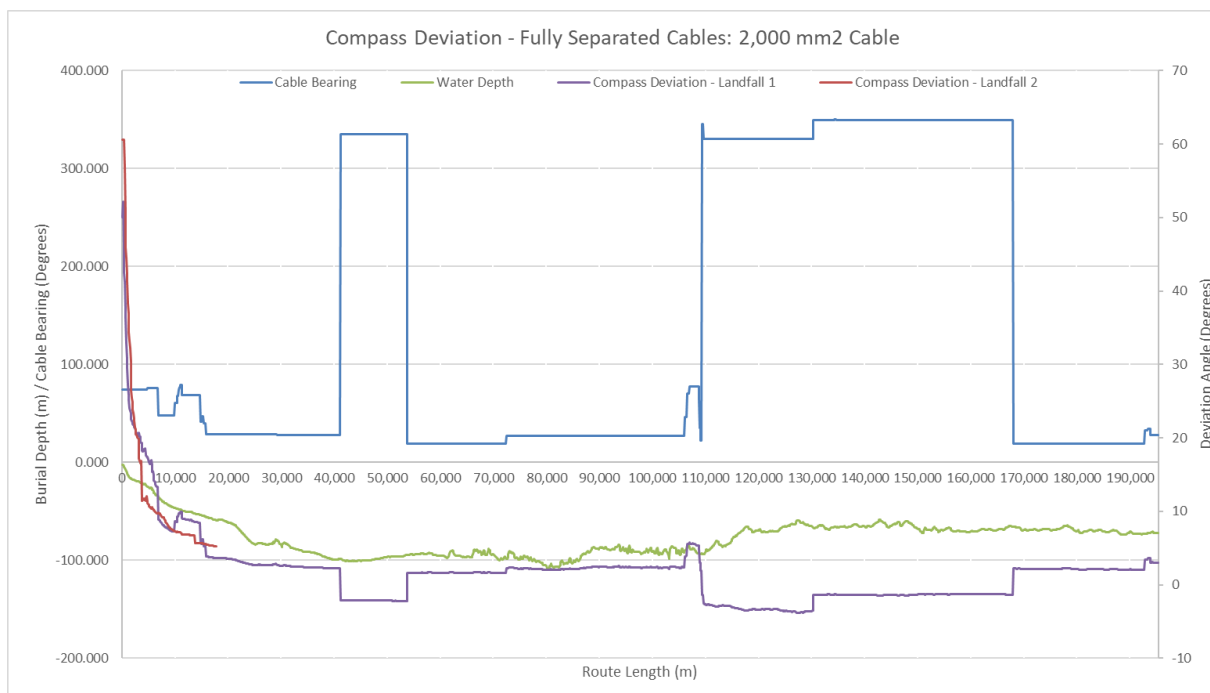
Route	2,000 mm ² (Degrees)	2,500 mm ² (Degrees)	3,000 mm ² (Degrees)
Landfall 1	52.13	52.10	52.07
Landfall 2	60.62	60.58	60.55

Table 3-18: Compass Deviation compared with MMO Bounds for Route with Landfall 1

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	9.31%	9.31%	9.31%
≤ 5 Degrees	90.69%	90.69%	90.69%
>3 Degrees	22.46%	22.46%	22.46%
≤ 3 Degrees	77.54%	77.54%	77.54%

Table 3-19: Compass Deviation compared with MMO Bounds for Route with Landfall 2

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	10.73%	10.73%	10.73%
≤ 5 Degrees	89.27%	89.27%	89.27%
>3 Degrees	23.67%	23.67%	23.67%
≤ 3 Degrees	76.33%	76.33%	76.33%

**Figure 3-6: Compass Deviation along Route for 2 m Burial Depth - 2,000 mm² Cable**

3.4.3 Cable Burial Depth of 3 m

The data presented summarises the compass deviation effects for fully separated HVDC cables buried at a depth of 3 metres, considering different cable cross-sectional areas and two possible landfall locations.

Table 3-20 shows the maximum compass deviation observed for each scenario. Table 3-21 and Table 3-22 compare the percentage of the cable route where the compass deviation falls within or exceeds specific MMO bounds. Figure 3-7 depicts the deviation across the entire route length.

Table 3-20: Maximum Compass Deviation Observed for 3 m Burial Depth

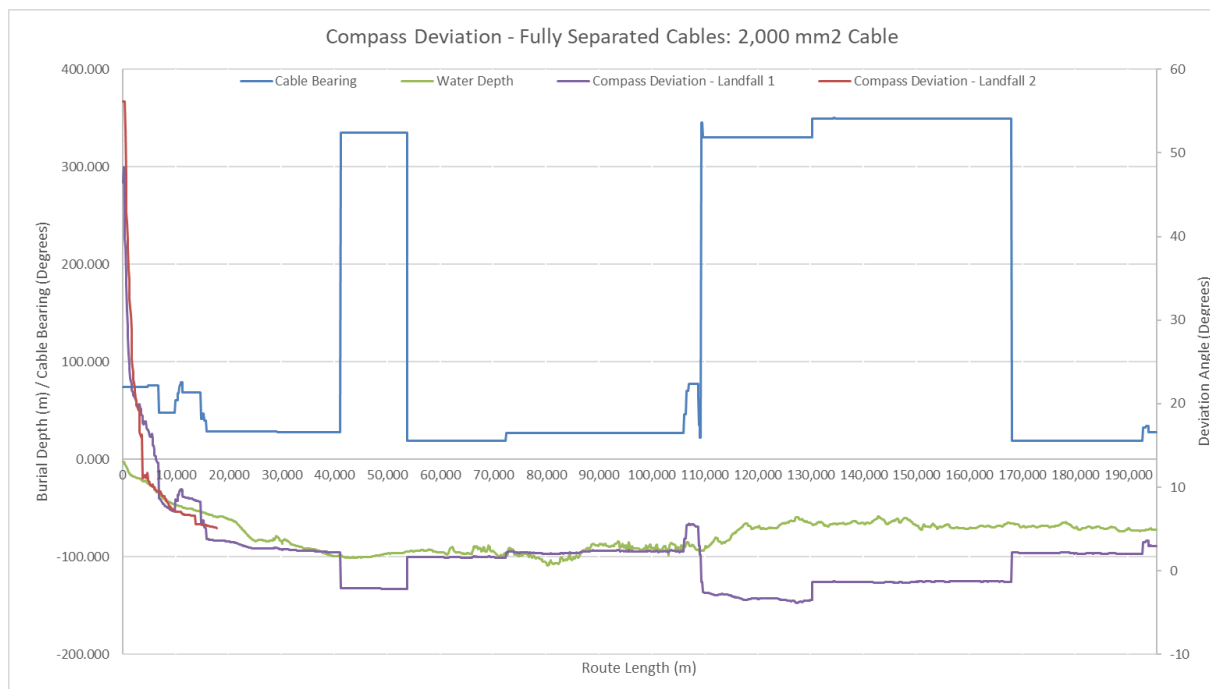
Route	2,000 mm ² (Degrees)	2,500 mm ² (Degrees)	3,000 mm ² (Degrees)
Landfall 1	48.36	48.33	48.30
Landfall 2	56.13	56.10	56.07

Table 3-21: Compass Deviation compared with MMO Bounds for Route with Landfall 1

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	9.31%	9.31%	9.31%
≤ 5 Degrees	90.69%	90.69%	90.69%
>3 Degrees	21.64%	21.64%	21.64%
≤ 3 Degrees	78.36%	78.36%	78.36%

Table 3-22: Compass Deviation compared with MMO Bounds for Route with Landfall 2

MMO Bounds	2,000 mm ²	2,500 mm ²	3,000 mm ²
> 5 Degrees	10.73%	10.73%	10.73%
≤ 5 Degrees	89.27%	89.27%	89.27%
>3 Degrees	22.86%	22.86%	22.86%
≤ 3 Degrees	77.14%	77.14%	77.14%

**Figure 3-7: Compass Deviation along Route for 3 m Burial Depth - 2,000 mm² Cable**

3.5 Maximum Allowable Cable Separation

This section presents the results of a compass deviation analysis conducted to determine the maximum allowable cable separation distance while remaining compliant with MMO guidelines. The allowable separation is presented for various 1 km long sections along the route. The sections been selected based on the cable bearing and water depth. Sections where the compass deviation for fully separated cabled is less than the MMO thresholds have not been studied. By comparing the observed deviations against MMO thresholds of 3° and 5°, the analysis identifies configurations that minimise navigational impact.

It was assumed for the purpose of this study that the separated cables share the same bearing as when bundled. The values presented below allow the route to maintain a compass deviation of $\leq 3^\circ$ for 95% and $\leq 5^\circ$ for the rest of the route. The measurements start from 300 m from the shore as the compass deviation before this point is greater than the 5° bound even when the cables are bundled. The cables have been modelled to be separated from the measurement point to a point 1 km towards the OSS from this point, with the remaining cable length modelled as bundled.

It should be noted that each cable size shows the same allowable separation due to the separation distance being significantly larger than the cable diameter.

3.5.1 Cable Burial Depth of 0.5 m

The results presented in Table 3-23 and Table 3- show the maximum permissible separation for a 1 km selection at different measurement points along the route. The remaining route section is modelled as bundled. For the measurement point at 0.5 km it should be noted that a 1 m separation results in ~0.3% of the route causing a deviation greater than 5° due to the shallow burial depth close to shore.

Table 3-23: Landfall 1 Maximum Permissible Separation at 0.5 m Burial Depth

Measurement Point (km)	Maximum Allowable Separation (m)
0.5	1
2	3
5	6
7	20
10	25
15	60
107	128

Table 3-24: Landfall 2 Maximum Permissible Separation at 0.5 m Burial Depth

Measurement Point (km)	Maximum Allowable Separation (m)
0.5	1
2	3
5	8
7	14
10	34
15	60
107	128

3.5.2 Cable Burial Depth of 1 m

The results presented in Table 3- and Table 3-26 show the maximum permissible separation for a 1 km selection at different measurement points along the route. For the measurement point at 0.5 km it should be noted that a 1 m separation results in ~0.3% of the route causing a deviation greater than 5° due to the shallow burial depth close to shore.

Table 3-25: Landfall 1 Maximum Permissible Separation at 1 m Burial Depth

Measurement Point (km)	Maximum Allowable Separation (m)
0.5	1
2	3
5	6
7	21
10	26
15	62
107	131

Table 3-26: Landfall 2 Maximum Permissible Separation at 1 m Burial Depth

Measurement Point (km)	Maximum Allowable Separation (m)
0.5	1
2	3
5	10
7	15
10	35
15	62
107	131

3.5.3 Cable Burial Depth of 2 m

The results presented in Table 3-27 and Table 3-28 show the maximum permissible separation for a 1 km selection at different measurement points along the route. For the measurement point at 0.5 km it should be noted that a 1 m separation results in ~0.3% of the route causing a deviation greater than 5° due to the shallow burial depth close to shore.

Table 3-27: Landfall 1 Maximum Permissible Separation at 2 m Burial Depth

Measurement Point (km)	Maximum Allowable Separation (m)
0.5	1
2	3
5	7
7	22
10	27
15	65
107	138

Table 3-28: Landfall 2 Maximum Permissible Separation at 2 m Burial Depth

Measurement Point (km)	Maximum Allowable Separation (m)
0.5	1
2	3
5	11
7	16
10	37
15	65
107	138

3.5.4 Cable Burial Depth of 3 m

The results presented in Table 3-29 and Table 3-30 show the maximum permissible separation for a 1 km selection at different measurement points along the route. For the measurement point at 0.5 km it should be noted that a 1 m separation results in ~0.3% of the route causing a deviation greater than 5° due to the shallow burial depth close to shore.

Table 3-29: Landfall 1 Maximum Permissible Separation at 3 m Burial Depth

Measurement Point (km)	Maximum Allowable Separation (m)
0.5	1
2	4
5	8
7	23
10	28
15	70
107	145

Table 3-30: Landfall 2 Maximum Permissible Separation at 3 m Burial Depth

Measurement Point (km)	Maximum Allowable Separation (m)
0.5	1
2	4
5	12
7	17
10	39
15	70
107	145

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