IALA

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G1119
MARINE BEACON COVERAGE PREDICTION

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Revisions to this document are to be noted in the table prior to the issue of a revised document.

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1. INTRODUCTION

Many maritime administrations provide marine beacon differential GNSS correction services. IALA Guideline *G1112 Performance and monitoring of DGNSS services in the frequency band 283.5-325 kHz* [1] recommends that service providers advertise the coverage area of their systems.

2. SCOPE

Calculating the coverage area of a radiobeacon is a complex process taking into account the impact of signal attenuation, interference and receiver requirements. Purpose defined DGPS coverage prediction software is available. However, the aim of this Guideline is to provide guidance on calculating the expected signal strength of a single radiobeacon under different conditions. Repetition of the approach could then be used to give an indication of coverage regions. Given the complexities involved, readers are encouraged to review the references noted in section 10. Administrations seeking a software solution are invited to contact IALA ENAV Committee for further information.

3. BACKGROUND

A radiobeacon transmits omni-directionally. Its signal reaches the receiver via two main paths, groundwave and skywave. The groundwave-propagated component travels over the surface of the Earth. The skywave-propagated one is refracted by the ionosphere.

The coverage of an individual radiobeacon depends upon the effective radiated power of the radiobeacon, the attenuation of its groundwave and skywave signals as they propagate, interference from the accompanying time-dependent skywave component, atmospheric noise, and interference from other beacons on the same or adjacent frequencies.

The signal received by the groundwave path is generally used in the receiver due to the shorter distance. Data received via skywave could still be valid but is likely to be subject to greater spatial decorrelation error.

3.1. GROUNDWAVE PROPAGATION

Signals propagating over the ground is attenuated by different amounts, depending on the type of ground. Seawater has the lowest attenuation, while the signal is attenuated the greatest when crossing glacial. The International Telecommunications Union (ITU) provide significant guidance in this area through its world atlas of ground conductivities [2] and propagation curves [3]. In order to calculate the expected strength of the groundwave signal the location of the station is required, along with the different ground types that the signal will travel across before reaching the location of interest.

3.2. SKYWAVE PROPAGATION

At night, signal components propagating via skywave reach the receiver by refracting in ionospheric layers of the Earth’s atmosphere [4]. The Earth’s atmosphere is made up of several layers. The E-layer refracts the signal causing skywave propagation. Since, the height and degree of ionisation of the E-layer depend on solar activity, the strength and delay of the skywave signal changes with time of day and season of the year. By day, there is very little skywave propagation, principally because the lower D-layer absorbs the skywave component. After sunset, the D-layer gradually dissipates and the skywave signal appears.

Skywave signals are attenuated less than the groundwave component, resulting in signals propagating considerably further.

Calculating skywave signal strengths is more complex than calculating groundwave. Skywave calculations take into account the geomagnetic latitude of the mid-point of the propagation path, therefore the range and bearing of the path is required. In addition, if the receive antenna or broadcast antenna are within 5 km of the sea, there are additional gains which need to be considered. The ITU provide guidance on how to calculate skywave signal strengths in reference [4].

3.3. SELF-FADING

As a broadcast signal can reach the user via two propagation paths of different distances, there is a geographical region where the two signals will both be received and when they are out of phase with each other, and the signal cannot be tracked. The effect of skywave and groundwave interfering with each other's reception is known as 'self-fading'.

The amount of self-fading can be calculated through an approach outline by Poppe [5], who developed a model of the impact based on distance and a combination of the groundwave and skywave signal strengths. By calculating the skywave-to-groundwave ratio (SGR), Poppe predicted the level of fading using the following function:

$$Total_{dB} = \begin{cases} Gnd_{dB} & \text{SGR} < -30 \\ Gnd_{dB} + F_3(SGR) & -30 \leq SGR - 5 \\ Gnd_{dB} + F_4(SGR) & -5 \leq SGR < 15 \\ SGR + Gnd_{dB} - 8.45 & 15 \leq SGR \end{cases}$$

Equation 1 Self-fading levels as defined by Poppe [5]

where:

$$F_3 = -11.087 - (0.8536 \times SGR) - (0.0224 \times SGR^2) - (0.0002 \times SGR^3)$$

$$F_4 = -8.4614 + (0.2005 \times SGR) + (0.811 \times SGR^2) - (0.0014 \times SGR^3) - (3.5e^{-5} \times SGR^4)$$

3.4. ATMOSPHERIC NOISE

As with any radio system, background atmospheric noise can affect signal reception. The ITU has models of atmospheric noise for the world broken down to different season and periods of the day [6]. It also provides conversion factors to convert the noise levels to different frequencies and probability levels. At 300 kHz frequencies, atmospheric noise increases towards the equator and over winter months.

Rather than define coverage over different seasons it is recommended that the annual average atmospheric noise figure, not exceeded 95% of the time, is calculated. Table 1 shows the calculated noise level for the European Maritime Area (EMA) and surrounding regions [7]. Annual average noise figures not exceeded 95% of the time, for other areas can be calculated using guidance provided by references [6, 7].

Table 1 *Annual average noise values not exceeded 95% of the time, in dBµV/m [7].*

	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80
80	-3	-2	-4	-4	-4	-4	-3	-3	-2	-3	-3	-4	-6	-7
70	-2	-3	-4	-4	-3	-1	2	4	5	5	4	2	-1	-4
60	-1	-1	-1	1	3	5	9	11	11	10	8	7	2	-1
50	3	3	3	5	7	10	13	13	12	10	9	8	7	4
40	6	6	6	8	11	13	13	13	11	10	9	9	11	13
30	12	11	11	12	13	14	14	13	11	11	11	13	20	24
20	18	14	13	14	17	19	20	19	17	15	17	20	27	30

3.5. INTERFERENCE

Marine radiobeacons broadcast in frequency bands set by the ITU of 283.5-315 kHz in Region 1 and 285-325 kHz in Regions 2 and 3. These regions are defined in the World Radio Regulations [8]. Transmissions from aeronautical and direction finding beacons, in addition to other marine radiobeacons, are permitted within these bands and any signal, other than the wanted signal, can potentially cause interference.

The ITU provide interference protection levels for use in marine radiobeacon receivers [9], from which Table 2 is derived. The table considers the wanted signal strength in relation to the signal from the potential interference source, along with any frequency separation. From Table 2, it can be read that if the wanted signal was a differential beacon and the interference source was also a differential beacon and if they were both on the same channel, the wanted signal would need to be 15 dB greater than the interfering signal. If the stations were separated by 1 kHz, then the interference signal could be up to 22 dB stronger than the wanted signal without preventing reception of the wanted signal.

Table 2 *Protection radios as provided in ITU-R M.823 [9].*

Frequency separation between wanted and interfering signal (kHz)	**Protection ratio (dB)**			
Wanted	**Radio beacon(1) (A1A)**	**Differential (G1D)**	**Differential (G1D)**	**Radio beacon(1) (A1A)**
Interfering	**Differential (G1D)**	**Radio beacon (A1A)**	**Differential (G1D)**	**Radio beacon (A1A)**
0	15	15	15	15
0.5	−39	−25	−22	−39
1.0	−60	−45	−36	−60
1.5	−60	−50	−42	−60
2.0	–	−55	−47	–

(1) Applicable to radio beacons in the European maritime area under the 1985 Geneva Agreement.

While IALA maintains a list of all marine beacon transmissions, other sources may need to be considered (possibly from the local radio regulator) to get a full and up-to-date list of other transmissions in the band, in the area being considered. It should be noted that the strongest differential beacons can cause interference 4200 km away at night [7].

Interference by groundwave is present both during daytime and night time conditions, however skywave interference is only considered at night.

4. DEFINING THE COVERAGE AREA

The definition of a coverage area can have multiple parts. For example, it can be limited by signal characteristics and a required accuracy level. A transmission with a signal strength exceeding 10 µV/m (20dBµV/m) and a SNR exceeding 7 dB is required for a maritime receiver to maintain reception and operate effectively [9].

Service providers may also wish to limit the coverage area by accuracy, or a suitable distance within which they provide their service. Where accuracies are provided, the excepted accuracy can be calculated based on the known accuracy level at the reference station and then factoring in spatial decorrelation as described in IALA Guideline *G1112.*

The usable coverage area would then be the area where the signal and, if required, accuracy requirements were both met.

5. EXAMPLE CALCULATION

This section considers a worked example using the Flamborough Head DGPS station on the east coast of the UK as the wanted station and Blavandshuk DGPS station in Denmark as a potential source of groundwave interference and the Finish DGPS station of Kokkola as a potential source of skywave interference. Table 3 provides details of the station characteristics collated from the IALA list of radiobeacons.

Table 3 Details for the three stations used in the example, as taken from IALA list of radiobeacons [10]

Station name	Identification Numbers		Geographical Position Latitude Longitude (WGS84)	Nominal range		Station in operation	Integrity Monitoring	Transmitted message types	Freq. (kHz)	Bit Rate (bps)
	Reference Stations	Transmitting Station		km	at (µV/m)					
Flamborough	687	447	54° 07' N 000° 05' W	277	50	Yes	Yes	3 7 9 16 27	290.5	100
Blavandshuk	705 706	452	55° 33' N 008° 05' E	277	50	Yes	Yes	3 6 7 9 16	290	100
Kokkola	608	408	63° 52' N 023° 11' E	250	50	Yes	Yes	3 6 7 9 16	290.5	100

The worked example will consider the impact of the different signals at a location in the North Sea, to determine whether the signal from North Foreland is usable in this location. The test point is given as 51.5°N and 2°E.

5.1. GROUNDWAVE SIGNAL STRENGTH CALCULATION

To calculate the signal strength for a station for a given location the following information is needed:

- Distance between the transmitter and the test location
- Knowledge of the ground conductivity along the path
- Nominal range of the station

In this example, the test location is 45°N and 2°E. The distance can be calculated through a number of methods or measured from online tools such as Google Earth. In this example, the distance between the transmitting station and the test location is 137 km. It is also an all seawater propagation path.

Using the ITU propagation curves for 300 kHz the station field strength can be calculated (Figure 1). If the signal crossed land, then the type of land can be identified by reference to the ITU world atlas of ground conductivities [2] and different conductivity values can be averaged using Millington's method, as explained in the ITU document.

The 300 kHz curves relate to a 1 kW transmitter and each curve on the graph relates to the ground conductivity type and shows the attenuation over distance. The top curve relates to seawater and is the curve of interest at this point.

Table 4 Nominal range field strength reference levels for ITU Region 1 [8]

Latitude	Reference (µV/m)	Reference (dBµV/m)
North of 43°N	50	34
Between 43°N to 30°N	75	37.5

The nominal range is the distance at which the signal strength falls to a reference level, with different reference levels used depending on latitude of the transmission, as shown in Table 4.

In order to calculate the signal strength for Flamborough head DGPS station at the test location, the first step is to calculate the power of the station with respect to the 1 kW transmission used in the ITU curves. The nominal range of Flamborough Head is 277 km. The signal strength falls to 50 µV/m (34 dBµV/m) over an all seawater path this distance. This can be marked on the curve (shown by the orange line in Figure 1) and the difference between Flamborough Head DGPS signal strength and the 1 kW transmission at this distance can be calculated (1 kW signal strength shown in red in Figure 1). In this case, at 277 km, the 1 kW transmission would provide a signal strength of 57 dBµV/m over an all seawater path. The strength of Flamborough Head DGPS at this distance is its nominal range reference level of 34 dBµV/m therefore; Flamborough head is broadcasting 23 dB below that of the 1kW transmission (57 dB-34 dB).

At a distance of 137 km, the 1kW transmitter would have a signal strength of 66 dBµV/m. As Flamborough Head DGPS is operating 23 dB below this level, its signal strength should be 43 dBµV/m at this range, given an all seawater path. The tolerance in this approach is ±2 dB due to reading data off the graph.

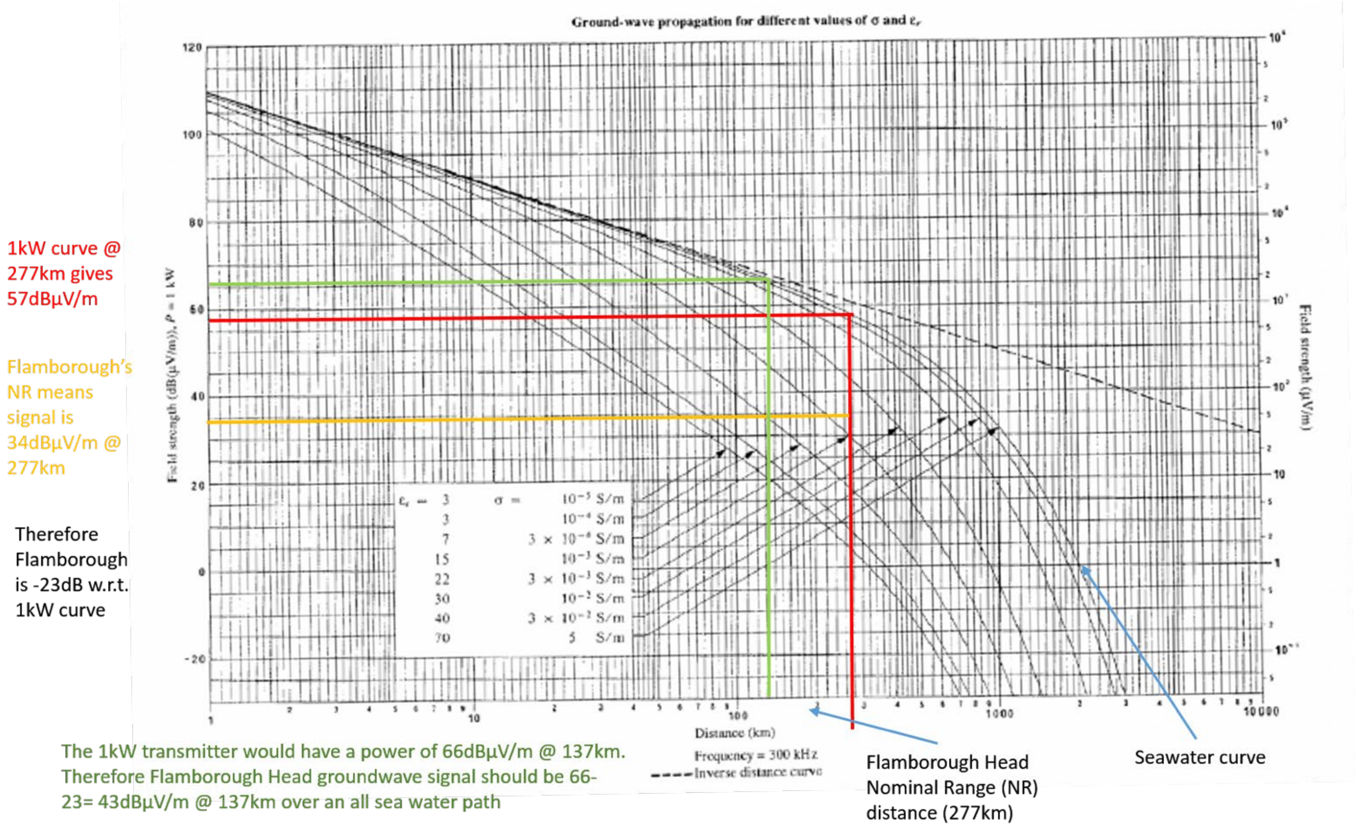

Figure 1 ITU-R ground-wave propagation curves at 300 kHz with results of calculating the groundwave signal strength shown (adapted from [3])

5.2. SKYWAVE SIGNAL STRENGTH CALCULATION

As outlined above, calculating skywave signals is considerable more difficult. From [4], supported by [5] and [7], the following expression is considered:

$$Sky_{dB} = A - 20log(p) - 10^{-3}kp + G_S + G_v + \Delta p$$

Equation 2 Skywave signal strength calculation [5]

where:

A is 106.6 – sin (Φ)

Φ is the geomagnetic latitude

k is the basic loss factor

p is the slant propagation distance in km

G_s is the sea gain

G_v is the antenna gain factor

Δp is the beacon's power with respect to 1kW

The geomagnetic latitude is the latitude with respect to the poles of Earth's magnetic field and the mid-point of the propagation path is used in this equation. The co-ordinates of the North Pole move, in this example 78.5°N, 69°W are used. Therefore, the geomagnetic latitude of a point at geographic latitude α and geographic longitude β is given by:

$$\Phi = arcsin\left(sin\alpha . sin(78.5°) + cos\alpha . cos(78.5°). cos(\beta - 69°)\right)$$

Equation 3 Geomagnetic latitude calculation

The slant propagation distance, p, is the total path length travelled by the skywave signal component. With a typical E-layer height of 100km this distance would be:

$$\mathrm{p} = \sqrt{\mathrm{d}^2 + 200^2}$$

Equation 4 Slant propagation distance calculation

where:

d is the Great Circle path distance, km

The basic loss factor attenuation due to the ionosphere, *k*, is calculated using:

$$k = 3.2 + 0.19 f_{kHz}^{0.4} tan^2(\Phi + 3)$$

Equation 5 Ionospheric loss calculation

where:

f_{kHz} is the frequency in kHz.

Sea gain, G_s, takes into account the small increase in skywave field strength experienced when either the transmitter or the receiver is located close to the sea. Poppe [5] shows that there is a sea gain of 1.5 dB over a 1000 km path, for each end of the propagation path when located near the sea. Sea gain falls with distance from the sea, becoming negligible by 5km (Figure 2 plots both).

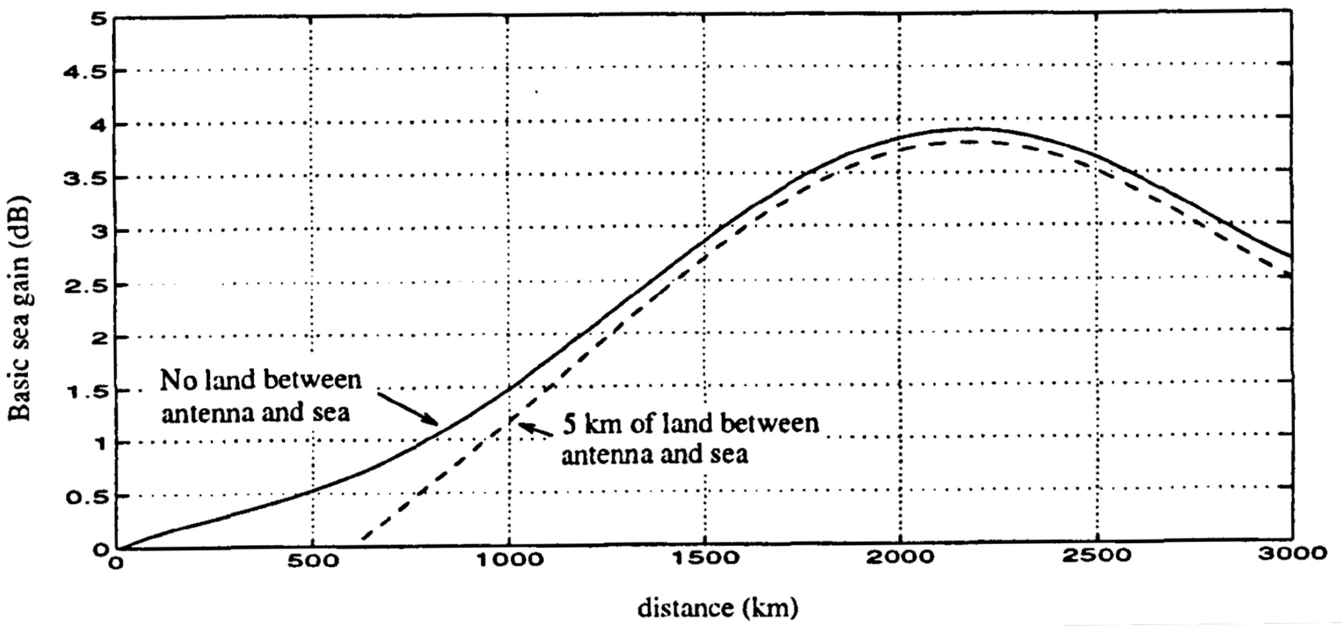

Figure 2 Sea gain occurs when either the transmitter or the receiver is located within 5km of the sea and is calculated for both ends of the transmission path [5].

G_v, the antenna gain factor, depends on the vertical polar diagram of the antenna. Almost all radiobeacon antennas are vertical monopoles, with or without capacity hats, and are short in terms of wavelength. As such, the antenna polar diagram has a maximum in the horizontal plane and a null vertically above. Poppe developed an approximation for this, from which the following polynomial can be used to calculate the amount of gain [5]:

$$G_v = -12.4530 + ld\big(91.2214 + ld(-26.8642 + 2.6164ld)\big)$$

Equation 6 Antenna gain polynomial

where:

ld is log10 (distance in km)

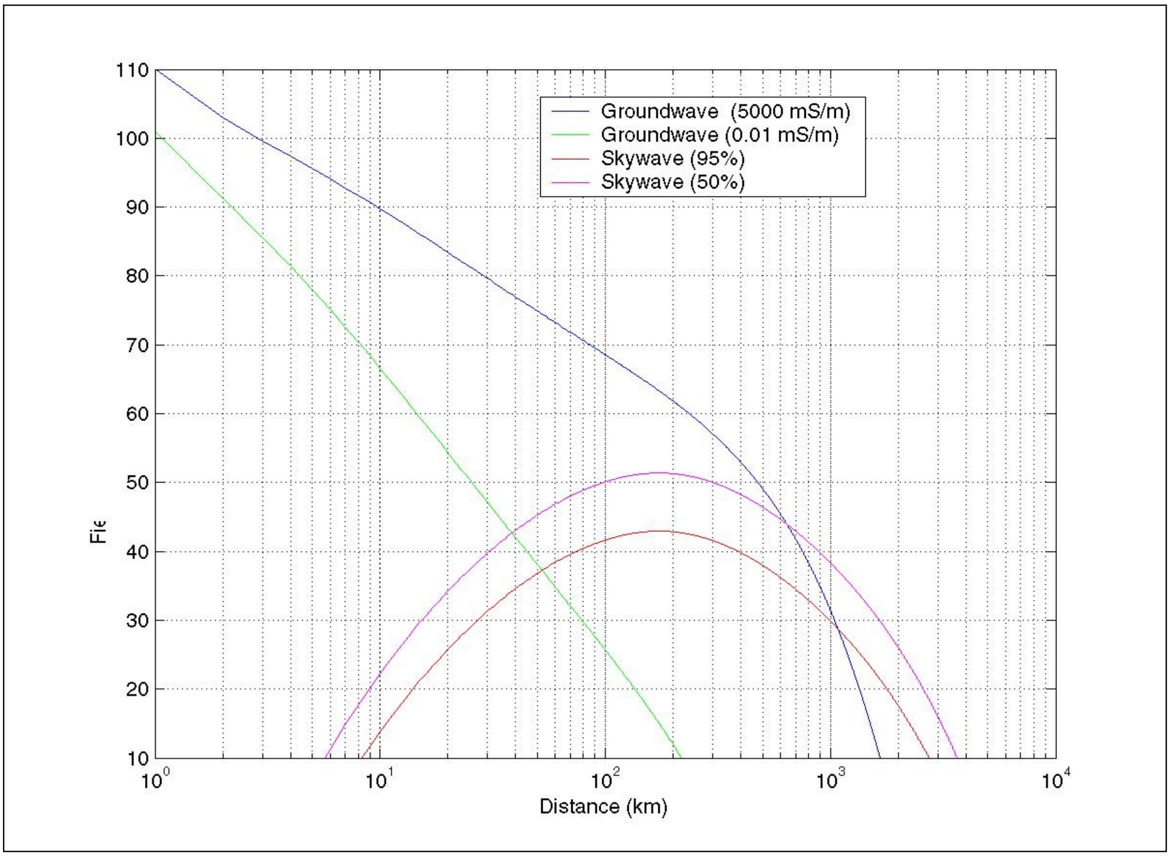

Figure 3 Groundwave and skywave curves for a 1kW transmitter (curves show extremes of propagation for groundwave and two different percentile signal strengths for skywave), [7]

An approximate skywave field strength can be calculated with the skywave propagation curves shown in Figure 3. The red and pink curves related to the 50%-tile and 95%-tile skywave signal strengths for a 1 kW transmission at mid-latitudes. By reference to the wanted station's power with respect to 1 kW (as outlined in the groundwave signal strength section), it is possible to approximate the expected skywave signal by adjusting the value from the curve.

From calculation, the skywave signal strength for Flamborough Head at the test location is 23 dBμV/m (95%). By recalling that Flamborough Head transmits -23 dB w.r.t. the 1 kW curve and reading from the graph (Figure 3) that at a range of 137 km, the 95% skywave plot indicates a signal strength of approximately 43dB, Flamborough DGPS skywave signal strength at the test location can be estimated as 20 dBμV/m.

It should be noted that the calculation should be used when calculating coverage; however, the curves provide a quick approximation.

5.3. SELF-FADING

Noting that the groundwave and skywave signal strengths calculated for Flamborough Head DGPS station are 43 dBμV/m and 23 dBμV/m respectively, a Sky-to-Groundwave ratio of -20 dB is calculated. Following the process outline in section 3.3, this means that the resulting signal strength is the groundwave signal strength added to the skywave fading term F_3, where F_3 is given by:

$$F_3 = -11.087 - (0.8536 \times SGR) - (0.0224 \times SGR^2) - (0.0002 \times SGR^3)$$

Equation 7 Skywave fading term F_3

Resulting in a fading term of -1.37.

Therefore, the resulting signal strength for Flamborough Head at the test location is 41.7 dBμV/m.

5.4. ATMOSPHERIC NOISE

By interpolating the figures given in Table 1 around the test location, an annual average atmospheric noise figure of 8.5 dB is calculated.

5.5. INTERFERENCE

As outlined in section 3.5, any other transmission in the band is considered a potential source of interference. In the worked example, Blavandshuk DGPS is considered as a potential groundwave interferer while Kokkola is considered as a potential skywave interference source.

Using the approaches outlined in sections 5.1 and 5.2, the signals strengths shown in Table 5 were calculated, noting that the groundwave signal from Blavandshuk is all seawater.

Table 5 Range and calculated signal strengths for the potential interference sources

Station	Approximate distance to test point (Km)	Groundwave (dBμV/m)	Skywave (dBμV/m)
Blavandshuk	430	4.7	N/A
Kokkola	1160	N/A	17.8

5.6. EVALUATION

To be deemed within the coverage area, all of the conditions needed to receive the signal need to be met. This means that signal must meet the minimum receiver requirements and exceed any interference protection ratios. If service providers include an accuracy limit, then this should be calculated in accordance with IALA Guideline *G1112.*

Therefore, at the test location, the following values are considered:

- wanted beacon (Flamborough Head) groundwave signal strength of 43 dBμV/m;
- wanted beacon (Flamborough Head) skywave signal strength of 23 dBμV/m;
- wanted beacon (Flamborough Head) signal strength at night, taking into account self-fading, of 41.7 dBμV/m;
- calculated atmospheric noise level of 8.5 dBμV/m;
- potential interference from Blavandshuk, with a groundwave signal strength of 4.7 dBμV/m; and
- potential interference from Kokkola, with a skywave signal strength of 17.8 dBμV/m.

Without considering interference, the signal from Flamborough head by day and night exceeds the receiver signal floor of 20 dBμV/m. The signal to (atmospheric) noise ratio is 34.5 dB – 33.2 dB depending on day and night conditions, both exceed the minimum SNR or 7 dB. This means that in the absence of any interference, a maritime receiver would be able to track the signal and decode the information from Flamborough head at this location by day and by night.

When calculating interference by day, only the effect of groundwave interference is considered. In this example, only one potential groundwave interference source was considered, this is a simplification, there are likely to be many. The number will be different depending on location and operating frequency and it should be noted that the band is shared by DGPS, marine and aeronautical beacons. When considering whether Blavandshuk causes interference, the protection ratios outlined in Table 2 need to be considered. 500 Hz separates the transmissions of Blavandshuk and Flamborough Head, meaning that the signal from Flamborough Head can be tracked even if it was 22 dB weaker than that of Blavandshuk. In this example, the signal from Flamborough Head is significantly stronger and as such is not affected by the signal from Blavandshuk.

When considering interference at night, self-fading and skywave interference need to be considered, in addition to groundwave interference. In general, the strongest component of any potential interference source is considered. The signal from Flamborough Head at the test location at night is 41.7 dBµV/m. The calculated signal strength for Kokkola is 17.8 dBµV/m. The protection ratios require the wanted signal to be at least 15 dB stronger than the interference source and in this case, that condition is met (41.7-17.8=23.9).

As such, the test location is within the usable coverage area of Flamborough Head DGPS station by day and by night.

6. NOMINAL RANGE

When undertaking maintenance on site, it is often necessary to confirm that a station is broadcasting at the appropriate signal strength, i.e., it conforms to the published nominal range.

Using the approach outlined in section 5.1, it is possible to calculate the expected signal strength for a given test location, recommended to be around 30-50 km from the station, along an all seawater path, if possible. At this test location, the expected signal strength can be calculated and compared to the received signal strength, as measured by calibrated field strength meter or spectrum analyser (see section 7).

The transmitter signal strength can be varied to ensure the signal received at the test location is correct to achieve the nominal range.

7. IN-FIELD MEASUREMENTS

7.1. EQUIPMENT

The following equipment will be needed to measure marine beacon field strengths:

- Field strength meter or spectrum analyser (calibrated)
- Appropriate loop antenna (calibrated, if required) and tripod
- Marine beacon receiver
- Compass
- A map with general location of transmitter and measurement location

7.2. MEASUREMENT PROCESS

At the selected measurement site, connect the field strength meter or spectrum analyser and configure to the correct frequency, bandwidth and attenuation, as required, to give a calibrated reading of the transmission of interest.

Then rotate the loop antenna so that the loop is aligned with the direction of the transmitter, using the compass (if required) to get the correct bearing. Check that when the loop antenna is then moved through 90 degrees the signal strength drops.

Find the point where the signal strength falls to the lowers point (null) and then turn the antenna back through 90 degrees. It should now be correctly aligned with the incoming signal and report the calibrated signal strength.

If data is to be recorded over a longer period, a marine beacon receiver can be configured to log the data via the NMEA $GPMSS string. The reported signal strength is not calibrated and therefore the calibrated equipment should be used to measure the field strength and a correction factor noted between the calibrated equipment and the figure reported by the receiver.

8. DEFINTIONS

The definitions of terms used in this Guideline can be found in the *International Dictionary of Marine Aids to Navigation* (IALA Dictionary) at http://www.iala-aism.org/wiki/dictionary and were checked as correct at the time of going to print. Where conflict arises, the IALA Dictionary should be considered as the authoritative source of definitions used in IALA documents.

9. ABBREVIATIONS

A1A	Keyed carrier modulation
Bps	Bits per second
dB	decibel
DGPS	Differential Global Positioning System
DGNSS	Differential Global Navigation Satellite System
EMA	European Maritime Area
ENAV	e-Navigation Committee (IALA)
G1D	phase modulation data transmission, without using a modulating subcarrier
GNSS	Global Navigation Satellite System
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union – Radiocommunications Bureau
kHz	kilohertz
km	kilometre
kW	kilowatt
m	metre
NMEA	National Marine Electronics Association
SGR	Skywave-to-Groundwave Ratio
SNR	Signal-to-Noise Ratio
µV	microvolt
WGS84	World Geodetic System 1984 (datum and spheroid)
w.r.t	with respect to

10. REFERENCES

[1] IALA Guideline No. G1112, 'Performance and monitoring of DGNSS services in the frequency band 283.5-325 kHz', May 2015.

[2] ITU Recommendation ITU-R P.832-4, 'World atlas of ground conductivities', 2015.

[3] ITU Recommendation ITU-R P.368-9, ‘Ground-wave propagation curves for frequencies between 10kHz and 30MMz’, 2007.

[4] ITU Recommendation ITU-R P.1147, ‘Prediction of Sky-Wave Field Strength at Frequencies between about 150 and 1700 kHz’, Recommendation ITU-R P.1147-4, 2007.

[5] Poppe, D., ‘Coverage and performance prediction of DGPS systems employing radiobeacon transmissions’, PhD Thesis, University of Wales, Bangor, 1995.

[6] ITU Recommendation ITU-R P.372-12, ‘Radio noise’, 2015.

[7] Grant, A., ‘Availability, continuity and beacon selection analysis and prediction for maritime radiobeacon DGNSS’, PhD Thesis, University of Wales, Bangor, 2002.

[8] ITU World radio regulations, 2012.

[9] ITU Recommendation ITU-R M823-3, ‘Technical characteristics of differential transmissions for global navigation satellite systems from maritime radio beacons in the frequency band 283.5-315 kHz in Region 1 and 285-325 kHz in Regions 2 and 3’, 2006.

[10] IALA List of radiobeacons (www.iala-aism.org).