IALA

IALA GUIDELINE

G1126
CALCULATION OF DGNSS ANTENNA EFFICIENCY

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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

This Guideline is intended to assist providers of DGNSS with establishing correct output signal levels from their LF/MF transmitter stations and measuring the antenna efficiency. The document is divided into the following sections:

1 Introduction

2 Regulatory and Technical background

3 Measurement of signal strength

4 Calculation of other system parameters

5 Worked example

6 Definitions

7 Abbreviation

8 References

2. REGULATORY AND TECHNICAL BACKGROUND

Having made the decision to establish a DGNSS station, the service provider will require to obtain a licence from their national radio regulatory authority. Within the licensing process, the service provider will need to identify:

1 The transmission frequency, which will be in the band 283.5-325 kHz. Ideally, a frequency should be selected that is not used by other services within the region of operation and is best chosen as part of a co-ordinated national or regional plan to minimize the possibility of interference (see IALA Guideline *G1119 Marine Beacon Coverage Prediction*) [1]. IALA can advise on choice of frequency.

2 The required effective radiated power (ERP) of the station, ERP is calculated from:

ERP = Transmitter output power x efficiency of MF antenna system

The required ERP is identified by the service provider by defining the service to be provided in terms of a required signal strength at a nominal range from the station. The required signal strength varies with the region and particularly the latitude of the station, but is defined by ITU-R as either 50, 75 or 100 microvolts/metre, as per the ITU-R *Radio Regulations Appendices* [2].

The nominal range of the station is selected by the service provider and is typically 100-300 NM (185-555 km). In practice the range of usable service is usually greater than the nominal range, as receivers are typically more sensitive than the ITU-R defined levels. IALA publishes details of all DGNSS stations on the IALA website.

2.1. SIGNAL PROPAGATION

Signal strength decreases as range from the transmitter station increases, at a rate dependent on the conductivity of the surface over which the signal propagates. The relationship between range and signal strength for a 1 kW ERP station over different ground conditions is modelled in the ITU-R Propagation curves (Ref 3), and the 300kHz curve (figure 1) is used as the basis for DGNSS calculations.

Seawater is a good conductor and propagates well, therefore DGNSS stations are ideally located in coastal locations with transmission paths entirely over seawater (use the curve for seawater of average salinity, i.e., $\varepsilon_r = 70$, $\sigma = 5$ S/m). This is not always possible, and some areas will have mixed propagation paths, resulting in lower signal strengths in these areas.

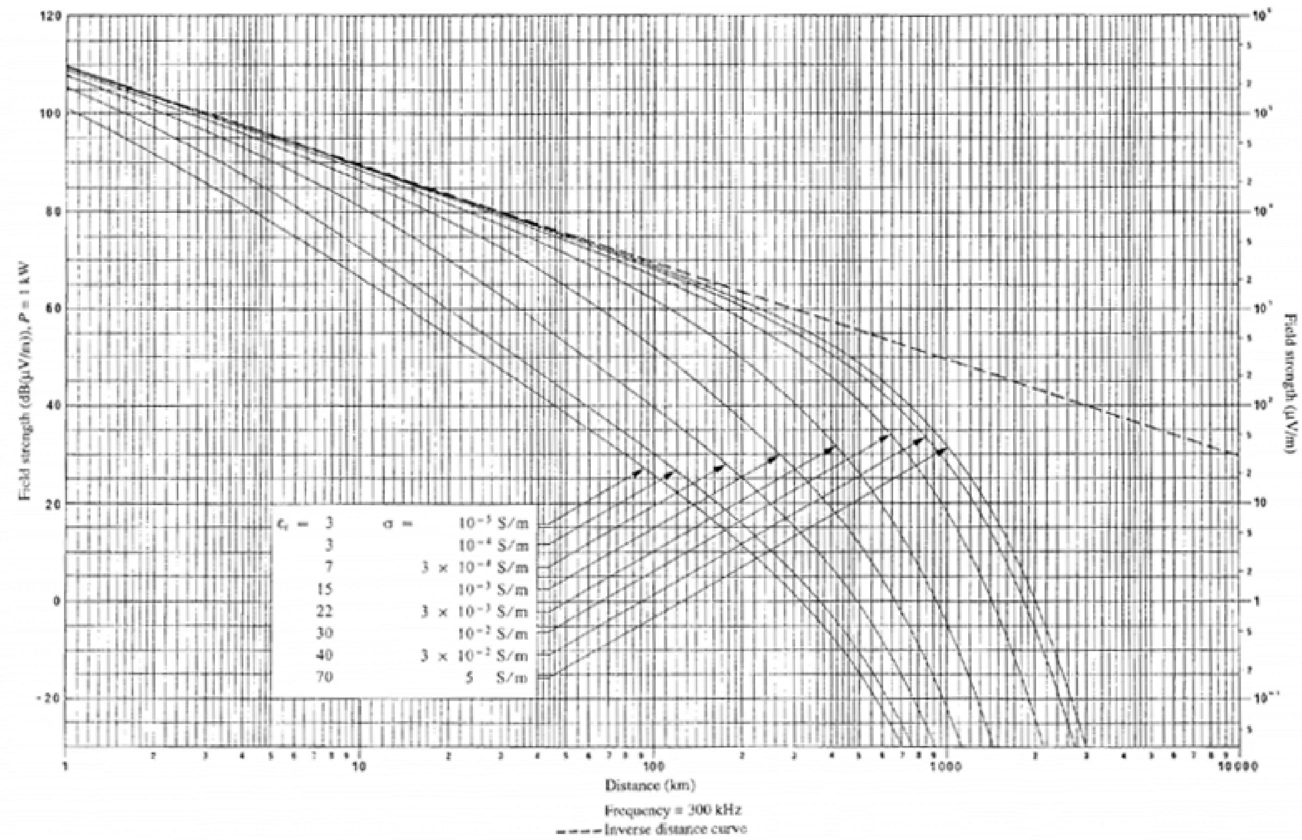

Figure 1 Ground-wave propagation for different ground conditions

Figure 1 is an extract from Rec. ITU-R *P.368-9*, where:

σ is the conductivity of the surface, measured in Siemens/metre (S/m), and

ε_r is the relative permittivity.

Note that the left axis is field (signal) strength expressed in dBmicrovolts/metre, where:

$$Signal\ strength\ (dB\mu V/m) = 20.\log_{10} Signal\ strength\ (\mu V/m)$$

To give two examples of use this curve, and demonstrate the significant difference between required power levels, we can look at two examples:

1 Transmitting a 100 NM (185 km) signal in a temperate area where the required nominal signal level is 50 microvolts/metre (34 dBμV/m).

2 Transmitting a 300 NM (555 km) signal in a tropical area where the required nominal signal level is 100 microvolts/metre (40 dBμV/m).

2.1.1. EXAMPLE 1

It can be seen that the nominal 1 kW ERP transmitter will produce a signal strength of approximately 62.5 dBμV/m at a range of 185 km. This gives a margin of 28.5 dB relative to the required signal strength of 34 dBμV/m). The ERP should therefore be 1 kW (30 dBW) less 28.5 dB i.e., 1.5 dBW or 1.4W.

2.1.2. EXAMPLE 2

It can be seen that the nominal 1 kW ERP transmitter will produce a signal strength of approximately 47 dBμV/m at a range of 555 km. This gives a margin of 7 dB relative to the required signal strength of 40 dBμV/m). The ERP should therefore be 1 kW (30 dBW) less 7 dB i.e., 23 dBW or 200W.

2.2. IMPACT ON EFFICIENCY AND ANTENNA DESIGN

Transmitting an ERP of 200W requires a much higher power transmitter and more effective antenna (e.g., 1kW transmitter and 20% efficient antenna) compared to transmitting an ERP of 1.4W (e.g., 100W transmitter and 1.4% efficient antenna). An antenna with an efficiency of 20% will require to be much larger than that required to achieve 1.4%.

A typical low efficiency antenna may be 10-15 metres in height, self-supporting (unstayed) and fitted with top loading coil and top capacitance. A higher efficiency antenna would usually be at least 25 metres high and typically either a “T” or inverted “V” design with top capacitance.

At low and medium frequencies, all antennae are inefficient. The performance of an antenna can be defined using several different terms, all of which are linked:

- Efficiency
- Effective height
- Radiation resistance

2.2.1. EFFICIENCY

Antenna efficiency is expressed as a percentage:

$$\eta = \frac{P_{rad}}{P_{in}}.100\ \%$$

Equation 1 Antenna efficiency

where:

η is the antenna efficiency (%)

P_{rad} is the Power radiated from antenna (W)

P_{in} is the Power input from transmitter (W). For a well-tuned antenna, this is effectively the Forward Power (P_{Fwd}) which can be measured.

2.2.2. EFFECTIVE HEIGHT

Effective height h_e is a property of the antenna design. It is not the same as the physical height of the antenna, but is usually a value:

$$\frac{h}{2} \leq h_e \leq h$$

Equation 2 Effective height

where:

h is the actual antenna height (m)

h_e is the effective antenna height (m)

It is desirable that h_e is as large as possible. This is why all LF/MF antenna use top loading capacitance, which has the effect of increasing h_e without increasing h.

2.2.3. RADIATION RESISTANCE

Radiation resistance is related to the antenna size and shape but is usually of the order of 1Ω. As noted in IALA Guideline G1112 [4], it is related to antenna efficiency:

$$\eta = \frac{R_{rad}}{R_{Total}}.100\ \%$$

Equation 3 Relationship of efficiency to radiation resistance

where:

R_{rad} is the Radiation resistance (Ω)

R_{Total} is the Total resistance of the antenna system (Ω)

In addition to the radiation resistance, the total resistance of the antenna system includes losses in the antenna tuning unit (ATU) tuning coil and any loading coil (R_L) and are typically of the order 2-7 Ω. They also include the ground losses / earth resistance R_E, which is a function of the ground conditions at the antenna location.

IALA Guideline *G-1112 Performance and Monitoring of DGNSS Services in the Frequency Band 283.5-325khz – 1112* gives the following typical values for the earth resistance R_E and its impact on antenna efficiency:

Table 1 Typical values for earth resistance and impact on antenna efficiency

R_E (Ω)	Earth resistance and ground conductivity	η (%) for an antenna with a radiation resistance of 1Ω and R_L = 7Ω
3	Good (low)	9.0
5	Good	7.7
7	Acceptable (medium)	6.6
9	Acceptable	5.8
11	Poor (high)	5.3
13	poor	4.7

It is therefore desirable to reduce R_E to as low a value as possible, which is achieved by increasing the length and number of the earth mat (also known as counterpoise or ground plane) in the ground below the antenna. DGNSS antennae typically have a symmetrical earth mat to ensure omnidirectional antenna performance.

Radiation resistance and antenna effective height are related:

$$R_{rad} = \frac{P_{rad}}{I^2} = 160.\pi^2 \left(\frac{h_e}{\lambda}\right)^2$$

Equation 4 Radiation Resistance

where:

P_{rad} is the radiated power (W)

λ is the wavelength in metres (= 3 x 10^8 / frequency)

I is the root-mean-square (rms) antenna current (Amps)

h_e is the effective antenna height (m)

3. MEASUREMENT OF SIGNAL STRENGTH

Signal strength should be measured at one or more test sites, at known ranges from the transmitter station. The signal strength should be measured either with a calibrated field strength meter, or with a DGNSS receiver which displays signal strength (and has been calibrated).

The use of a calibrated field strength meter (and a matched loop antenna oriented towards the transmitter site) is recommended. Measurements should be made at a distance between 10 km and 80 km from the transmitter station, however 20-30 km is recommended. An error will be introduced if the propagation path is not over seawater; this can be compensated by use of the appropriate curve of the ITU-R ground-wave propagation curves.

The output power of the transmitter should be adjusted to match the required signal strength against the relevant propagation curve. A 1dB increase in power transmitted results in a 1dB increase in signal strength. The revised signal strength should be recorded.

The output power from the transmitter should be recorded, preferably from a calibrated inline wattmeter, or from the transmitter own display.

The antenna current at the transmitter site should also be recorded, preferably using a calibrated inline thermocouple ammeter, or from the transmitter/ATU own display.

For a complete set of results, the inductance and resistance of the ATU and any loading coil should also be measured. To measure the ATU inductance the antenna should first be tuned for minimum reflective power. The transmitter is then isolated, and the antenna disconnected, before measuring with an inductance meter across the ATU coil output and ground connectors. Any additional loading coil inductance should also be measured and added to the ATU inductance.

Note: Care should be taken when working on 'live' transmitters as potentially lethal voltages may be present. Whenever possible, testing should be conducted in 'low power' mode.

ATU resistance may be provided from the manufacturers' data. Alternatively, it may be measured by disconnecting the antenna and connecting the ATU output and ground connectors to a dummy load consisting of a suitably rated capacitor and resistor in series. The ATU is tuned for this load and the Forward Power and Antenna current recorded. The ATU resistance can then be calculated:

$$R_L = \frac{P_{Fwd}}{I^2}$$

Equation 5 ATU resistance

where:

R_L is the ATU resistance (Ω)

P_{Fwd} is the forward power of the transmitter (W)

I is the is the root-mean-square (rms) antenna current (A)

In summary, at the conclusion of measurements, the following values have been recorded:

- Field strength E (µV/m) at range from r (metres) antenna;
- Transmitter Forward Power P_{Fwd} (W);
- Antenna Current I (A);
- Resistance R_L of ATU coil and any loading coil (Ω);
- Inductance L of ATU coil and any loading coil (H).

4. CALCULATION OF OTHER SYSTEM PARAMETERS

4.1. POWER RADIATED

$$P_{rad} = E_{rad}{}^2 . \frac{r^2}{180}$$

Equation 6 Radiated power

where:

P_{rad} is the radiated power (W)

E_{rad} is the peak electric field strength ($E_{rad} = \sqrt{2} . E$), where E is the field strength (µV/m)

r is the range from the antenna (m)

This equation represents the dashed line on the ITU-R propagation curves for transmission in free space. At distances greater than approximately 100 km this diverges from the field strength curves.

4.2. ANTENNA EFFECTIVE HEIGHT

$$h_e = \frac{E_{rad} . r}{I_o . f . \mu_o}$$

Equation 7 Effective antenna height

where:

h_e is the effective antenna height (m)

E_{rad} is the peak electric field strength (V/m)

r is the range from the antenna (m)

I_o is the peak antenna current in Amps ($I_o = \sqrt{2} . I$)

f is the carrier frequency (Hz)

μ_o is the permeability of free space ($4\pi \times 10^{-7}$H/m)

4.3. TOTAL RESISTANCE

$$R_{Total} = \frac{P_{Fwd}}{I^2}$$

Equation 8 Total resistance

where:

R_{Total} is the Total resistance of the antenna system (Ω)

P_{Fwd} is the Forward power of the transmitter (W)

I is the root-mean-square (rms) antenna current in Amps

Total resistance may also be measured directly using an impedance meter to perform impedance measurements for the entire antenna system. The total resistance could be measured at the resulting tuning point.

4.4. EARTH/GROUND RESISTANCE

$$R_E = R_{Total} - (R_{rad} + R_L)$$

Equation 9 Earth / Ground resistance

where:

R_E is the Earth / Ground resistance of the antenna system (Ω)

This is not easily measured and is therefore calculated from measurement of other Resistance values as above.

R_{Total} is the Total resistance of the antenna system (Ω)

R_{rad} is the Radiation resistance (Ω)

R_L is the loading coil(s) resistance (Ω)

4.5. ANTENNA CAPACITANCE

When the antenna is tuned the inductive reactance of the ATU and loading coils is equivalent to the capacitive reactance of the antenna:

$$C = \frac{1}{(2.\pi.f)^2 L}$$

Equation 10 Antenna capacitance

where:

C is the antenna capacitance (F)

f is the frequency (Hz)

L is the total coil inductance (H)

4.6. QUALITY FACTOR

The quality factor of the antenna, Q, is a measure of the tuning of the circuit; a high Q implies a finely tuned antenna, whereas a low Q implies a wider bandwidth (Hz), with less gain but more tolerance to antenna mismatch.

$$Q = \frac{1}{2.\pi.f.C.R_{Total}}$$

Equation 11 Quality factor

where:

Q is the quality factor

C is the antenna capacitance (F)

4.7. BANDWIDTH

$$BW = \frac{f}{Q}$$

Equation 12 Bandwidth

where:

BW is the bandwidth (Hz)

Q is the quality factor of the antenna

5. WORKED EXAMPLE

An organization requires to establish a DGNSS beacon transmitting a 300kHz signal and producing a nominal signal strength of 50µV/m (34 dBµV/m) at a range of 200 nautical miles (370 km).

To complete the radio licence application, it is necessary to identify the Effective Radiated Power to be transmitted.

From the ITU-R propagation curves we know that a 1kW ERP output would produce 53dBµV/m at 370 km range, so there is a margin of 19 dB, relative to this value.

$$Power\ (dBW) = 10\ log_{10} Power\ (W)$$

Therefore, an effective radiated power of 1000w (30dBW) less 19dB i.e., 11 dbW or **12.6W** is needed**.**

This forms the basis for the antenna design, which in this case results in the construction of wire 'T' antenna (for top loading capacitance) with a 200W transmitter.

At time of commissioning, the transmitter is set to output 160W. Measurement with a calibrated field strength metre at a range of 50km over a sea transmission path records a signal strength of 58dBµV/m.

From the ITU-R propagation curves we know that a 1kW ERP output would produce 75dBµV/m at this range. It is known that it is required to output 19dB below this level, i.e., 56dBµV/m. As a result, the transmitter output can be reduced by 2dB to 100W. On re-measuring it can be confirmed that a signal strength of 56dBµV/m (631µV/m) is being produced at 50km from the antenna.

At the transmitter site the following are also measured:

1 Antenna current 3.5 Amps.

2 ATU tuning coil inductance 280 µH.

The tuning coil resistance R_L is measured by disconnecting the antenna and inserting a dummy load of a 900pF 10kV capacitor in series with a non-inductive 10Ω 20W resistor across the ATU output and ground connectors. After tuning, a transmitter forward power of 97W and an antenna current of 2.6A are measured, which results in a calculated total resistance of 14.4Ω and therefore a loading coil resistance of 4.4Ω.

5.1. SYSTEM PARAMETERS

5.1.1. ANTENNA SYSTEM EFFICIENCY:

$$\eta = \frac{P_{rad}}{P_{in}}.100\ \%$$

$$\eta = \frac{12 \cdot 6}{100}.100\ \%$$

$$\eta = 12.6\ \%$$

5.1.2. ANTENNA EFFECTIVE HEIGHT

$$h_e = \frac{E_{rad}.r}{I_o.f.\mu_o}$$

$$h_e = \frac{\sqrt{2}.631.10^{-6}.50.10^3}{\sqrt{2}.3\cdot5\ .\ 300.10^3.4\pi.10^{-7}}$$

h_e = 23.9 metres

5.1.3. RADIATION RESISTANCE

$$R_{rad} = \frac{P_{rad}}{I^2} = 160.\pi^2.\left(\frac{h_e}{\lambda}\right)^2$$

$$R_{rad} = \frac{12\cdot6}{3\cdot5^2}$$

R_{rad} = 1.03 Ω

5.1.4. TOTAL RESISTANCE

$$R_{Total} = \frac{P_{Fwd}}{I^2}$$

$$R_{Total} = \frac{100}{3\cdot5^2}$$

R_{Total} = 8.16Ω

5.1.5. EARTH/GROUND RESISTANCE

$$R_E = R_{Total} - (R_{rad} + R_L)$$

$$R_E = 8\cdot16 - (1\cdot03 + 4\cdot4)$$

R_E = 2.7 Ω

5.1.6. ANTENNA CAPACITANCE

$$C = \frac{1}{(2.\pi.f)^2L}$$

$$C = \frac{1}{(2.\pi.300.10^3)^2\ .280.10^{-6}}$$

C = 1005pF

5.1.7. QUALITY FACTOR

$$Q = \frac{1}{2.\pi.f.C.R_{Total}}$$

$$Q = \frac{1}{2.\pi.300.10^3\ .1005.10^{-12}.8\cdot16}$$

Q = 65

5.1.8. BANDWIDTH

$$BW = \frac{f}{Q}$$

$$BW = \frac{300.10^3}{65}$$

BW = 4.6 kHz

6. DEFINITIONS

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.

7. ABBREVIATIONS

A	ampere
ATU	Antenna Tuning Unit
BW	bandwidth
dB	deciBel
DGNSS	Differential Global Navigation Satellite System
ERP	Effective Radiated Power
F	Farad
H	Henries
ITU-R	International Telecommunications Union – Radiocommunications Bureau
kHz	kilohertz
km	kilometre
kW	kilowatt
LF	Low Frequency (30 kHz–300 kHz)
m	metre
MF	Medium Frequency (300 kHz to 3 MHz)
NM	nautical miles
Q	Quality factor
rms	root mean square
μV	microvolt
V	Volt
W	Watt
Ω	Ohms

8. REFERENCES

[1] IALA. Guideline G1119 Marine Beacon Coverage Prediction.

[2] ITU. ITU-R Radio Regulations Appendices (Volume 2) 2012 Edition, Appendix 12 (page 257).

[3] ITU. Recommendation ITU-R P.368-9, 'Ground-wave propagation curves for frequencies between 10kHz and 30MHz', 2007. (0).

[4] IALA. Guideline G1112 Performance and Monitoring of DGNSS Services in the Frequency Band 283.5-325kHz, 2015 (Annex E)