AISM Association Internationale de Signalisation Maritime IALA International Association of Marine Aids to Navigation and Lighthouse Authorities

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on

Performance and Monitoring of DGNSS Services in the Frequency Band 283.5 – 325 kHz

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Document Revisions

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

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Performance and Monitoring of DGNSS Services in the Frequency Band 283.5 – 325 kHz

1 INTRODUCTION

This Guideline provides the design and implementation principles of IALA Recommendation R-121 on Performance and Monitoring of DGNSS Services in the frequency band 283.5 – 325 kHz.

1.1 Scope of document

A Global Navigation Satellite System (GNSS) is a space-based positioning, navigation and time distribution system designed for world-wide use. GPS and GLONASS are the first GNSS available. Future GNSS include modernised GPS and GLONASS along with new core constellations such as Galileo and BeiDou.

Differential GNSS (DGNSS) is a means of improving the accuracy of GNSS and providing integrity monitoring to the user. DGNSS involves having reference stations, at precisely known locations that provide real-time corrections and integrity information for GNSS signals.

This Guideline considers the generation and broadcast of code based corrections with a focus on the maritime domain. It describes the use of transmitters in the 285 – 325 kHz / 283.5 – 315 kHz LF/MF marine frequency band to provide DGNSS signals. It must be noted that at present DGNSS provides augmentation for GPS and GLONASS. Therefore DGNSS is not a stand-alone radio navigation system. DGNSS systems provide shore-to-ship services.

GNSS does not inherently provide integrity information and therefore the position may contain significant errors for extended periods of time, without notifying the user. Augmentation will provide the user with integrity information. A successful response on board the ship will depend on the navigator's correct perception of the meaning of the integrity information and that he takes the proper cause of action. Such information could indicate that the GNSS system is no longer reliable and the proper action should include a reversion to alternative navigation systems or to a reliance on visual and radar means of position fixing. The service provider may wish to emphasise this in its publications informing mariners about the DGNSS system.

The service provider should publish that they follow IMO and IALA Recommendations for the provision of DGNSS, giving emphasis to the provision of integrity information.

System performance is based on the assumptions that the system provider conforms to these Guidelines and that the user equipment meets the design and installation standards as specified in the beacon receiver standard[1], [1].

This document covers existing methods of providing marine beacon DGNSS. In addition to these Guideline the following recommendations from IALA should be taken into account:

- Future DGNSS options are captured in R-135 [2]
- Vulnerability of GNSS systems is discussed in R-129 [3]
- Recommendation to National Members to provide DGNSS is captured in R-115 [4]

[1] IEC 61108-4

1.2 Structure of document

Chapter 2 defines and details the overall performance parameters and requirements for the broadcast of the corrections. The performance parameters are absolute accuracy, integrity, continuity, availability and coverage. Each parameter has an associated requirement for ocean and harbour entrances, harbour approach and coastal waters.

Chapter 3 provides technical aspects for a service provider on how to develop, implement and maintain a DGNSS service. It gives guidance on which parts are needed to acquire, generate and broadcast the corrections and how to facilitate fulfilment of the requirements of the performance parameters: accuracy, integrity, continuity, availability and coverage.

This guideline gives details on two different types of implementation. One is the classical approach by generating the corrections and the integrity checks at the beacon site. The other is the Virtual Reference Station (VRS) approach which utilizes surrounding reference stations to calculate corrections for each beacon site.

Chapter 4 gives the service provider an understanding on how to operate and validate the DGNSS system during its lifetime with respect to the performance parameters. An overview is given to how a DGNSS system should contain different levels of self-monitoring, such as short-baseline monitors and far-field monitors. A DGNSS service provider should inform the user about the DGNSS system, and this chapter deals with which data to publicise.

Chapter 5 details the cross-references made in this document.

Annexes include examples on calculations, technical implementations and other relevant data. The following annexes are included:

- Annex A: Abbreviations
- Annex B: Example of DGNSS broadcast settings
- Annex C: Example of validation of availability and continuity in a DGNSS coverage area
- Annex D: Example for calculating DGNSS Signal Availability
- Annex E: MF Antenna Performance

2 PERFORMANCE REQUIREMENTS

2.1 Definitions

System performance is characterised by a number of different aspects, including Accuracy, Integrity, Continuity, Availability and Coverage[2], as:

Absolute accuracy (Geodetic or Geographic accuracy): The accuracy of a position estimate with respect to the geographic or geodetic co-ordinates of the Earth.

Integrity: The ability to provide users with warnings within a specified time when the system should not be used for navigation.

Continuity: The probability that, assuming a fault-free receiver, a user will be able to determine position with specified accuracy and is able to monitor the integrity of the determined position over the (short) time interval applicable for a particular operation within a limited part of the coverage area.

Availability: The percentage of time that an aid, or system of aids, is performing a required function under stated conditions (i.e. when it provides the required integrity for the given

[2] As defined in IMO 915 (22) & IMO 1046 (27)

accuracy level). Non-availability can be caused by scheduled and/or unscheduled interruptions.

Coverage: The coverage provided by a radionavigation system is that surface area or space volume in which the signals are adequate to permit the user to determine position to a specified level of performance.

2.2 Positioning Performance Requirements

IMO Resolution A.1046 (27) details the requirements on worldwide radio navigation systems considering vessels operating in ocean and harbour entrances, harbour approaches and coastal waters. The requirements are described by accuracy, integrity, availability, and continuity for positioning. Table 1 summarizes the requirements specified in A.1046 (27), augmented by those described for comparable performance levels in A.915(22).

Neither IMO Recommendation detail how these requirements should be met. GNSS alone can meet the requirements for ocean phase; however, augmentation services are needed to meet the accuracy, integrity and continuity requirements for harbour entrances, harbour approaches and coastal waters. It is assumed that the DGNSS service shall consist of areas of overlapping coverage, where each individual reference station availability is >99.5% and continuity is >99.95%. IMO Recommendation A.1046 (27) removed the duration over which availability should be calculated; however the 2 year duration has been retained in this Guideline in order to allow for comparison with previous performance statistics.

Table 1 Maritime requirements based on IMO Recommendations [IMO A.915(22) & A.1046 (27)]

	System Level				Service Level	
	Absolute Horizontal Accuracy (95%)	Integrity			Availability (2 years)	Continuity (over 15 minutes)
		Alarm Limit	Time to Alarm[1]	Integrity Risk		
Area	m	m	s	%	%	%
Ocean	≤ 100	N/A	N/A	N/A	≥ 99.8	N/A
Harbour entrances, harbour approaches and coastal waters	≤ 10	25	10	10^{-5}	≥ 99.8	99.97

[1] *Generation of integrity warnings in cases of system malfunctions, non-availability or discontinuities;*

Typically, DGNSS services achieve an accuracy in the order of <5m (95%). Should decimetre accuracy be required, alternative augmentation approaches such as Real Time Kinematic (RTK) or Precise Point Positioning (PPP) should be considered, but these are not considered in this guideline.

Service providers should consider the appropriate number, and location, of reference stations to achieve sufficient coverage to ensure these requirements are met.

3 SHORE SITE ARCHITECTURE

This chapter deals with the shore site architecture of a maritime DGNSS service in the frequency band 283.5 - 325 kHz, whose use enables the fulfilment of performance requirements given in Chapter 2. The purpose of a DGNSS service can be described by two general functionalities realised by two complementary services:

- The GNSS augmentation service is responsible for the generation of GNSS correction and integrity data. DGNSS messages are formed using the derived GNSS augmentation data;

- The MF transmission service generates and broadcasts MF signals in the radio beacon band, which are used as carrier of DGNSS messages. The opportunity to broadcast DGNSS messages on alternative transmissions is suggested by the dashed line.

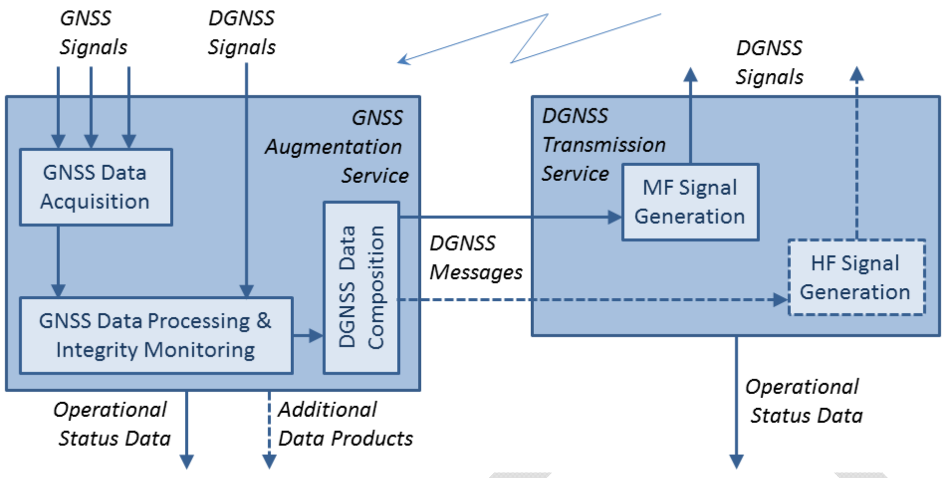

Figure 1 Generalised architecture of DGNSS Service

The generalised functional architecture of a system providing a DGNSS Service is shown in Figure 1 and reflects both the functionalities and assigned services. The functional separation of the DGNSS service is in compliance with the principles of a modular architecture design.

3.1 GNSS Augmentation Service

The primary aim of the GNSS Augmentation Service is the provision of DGNSS messages. For this purpose a suitable output data interface to the DGNSS Transmission Service is necessary. The generation of DGNSS messages requires the realisation of the following three tasks:

1. Task “GNSS Data Acquisition” to collect the required data for DGNSS service provision.
2. Task “GNSS Data Processing” to derive the GNSS augmentation data from available GNSS data.
3. Task “DGNSS Data Composition” to arrange the GNSS augmentation data in DGNSS messages.

Composed DGNSS messages are delivered to the DGNSS Transmission Service to enable the generation of DGNSS signals. At present DGNSS signals are mostly provided in the MF band, but a dashed line outlines the opportunity to broadcast alternative transmissions such as AIS, eLoran, mobile Internet (GSM), etc. The GNSS Augmentation Service should be equipped with an additional interface, which enables the monitoring of DGNSS service by the service provider based on provided status data. The opportunity to use DGNSS services as data sources for PNT relevant safety information is suggested by the second output data interface “Additional Data Products” of the GNSS Augmentation Service.

3.1.1 GNSS Data Acquisition

The task “GNSS Data Acquisition” deals with the provision of GNSS ranging and navigation data, which are commonly used for the determination of position, velocity, and time data (PVT). The GNSS Augmentation Service needs GNSS receivers to acquire the GNSS data from the GNSS signals. The type of GNSS receiver used determines which GNSS signals the service can generate DGNSS messages for.

Due to GNSS modernisation and the establishment of further satellite based navigation systems the number of GNSS signals with civil access will increase in the future. An improvement of GNSS based position, velocity and timing (PVT) determination can be expected if all available GNSS signals are used. Therefore service providers are encouraged to review IALA R-135, which considers the future use and role of DGNSS services. At present it is expected that the role of GNSS augmentation services focuses more and more on the improvement of integrity in the context of safety-critical GNSS applications. Consequently, service providers are also encouraged to extend the service provision on new GNSS signals.

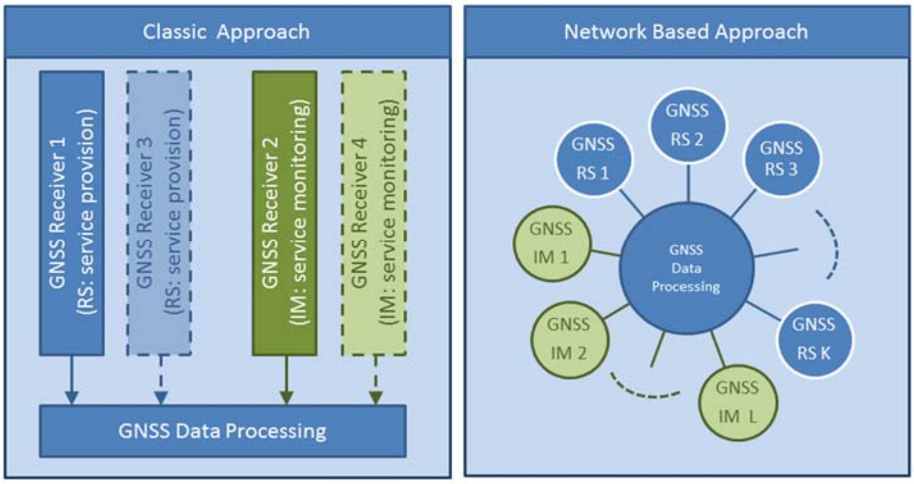

Figure 2 Opportunities of GNSS data acquisition for DGNSS service provision (RS: reference station, IM: integrity monitoring station)

GNSS data acquisition can be realised with a single GNSS receiver, a set of GNSS receivers or a network of receiver (Figure 2). The number of GNSS receivers used for data acquisition determines the achievable level of redundancy in the GNSS data basis. An increased level of redundancy in the GNSS data basis enables that the provision of DGNSS services and therefore the DGNSS based PVT determination can be improved.

<u>Classic Approach:</u>
In minimum a DGNSS service provision can be realised with GNSS data collected by a single GNSS receiver at the reference station (RS). Assuming, that integrity monitoring of DGNSS service provision is part of the classic approach, at least one other GNSS receiver is necessary. A fixed receiver operates as an integrity monitoring station (IM) and assesses the achievable PVT performance by applying GNSS augmentation data to its own GNSS measurements.

<u>Network based Approach:</u>
A network based approach can be established by using a suitable number of GNSS receivers distributed over the intended coverage area. Best results could be achieved when the service area is enclosed by the GNSS receiver network. The data of a single GNSS receiver within the network should be used either for service generation or for service monitoring to avoid correlation effects between service provision and monitoring.

The classic and the network based approaches to data acquisition are shown in Figure 2. As shown, the network based acquisition of GNSS data is realised with receivers at multiple reference stations (from 1 – K), whereby additional GNSS receivers are used for integrity evaluation at integrity monitoring stations (from 1-L).

3.1.2 GNSS Data Processing

The task “GNSS Data Processing” is responsible for the generation of DGNSS augmentation data. In this case correction data provided by the GNSS augmentation service covers pseudo range and range rate corrections for GNSS signals (currently only GPS and GLONASS) in the upper L-band as described in IMO Resolution MSC.114(73). Additionally, integrity data describes the operational status of GNSS augmentation service and characterises the usability of single GNSS signals as well as provided corrections.

Figure 3 shows a generic presentation of GNSS data processing, whereby the processing is divided into 4 stages, principally. The data basis for GNSS data processing covers GNSS range and phase measurements as well as navigation data provided by GNSS itself. The antenna position of GNSS receivers used in reference and integrity monitoring stations should be determined accurately in a common geographic reference system (see chapter 3.1.4 performance aspects).

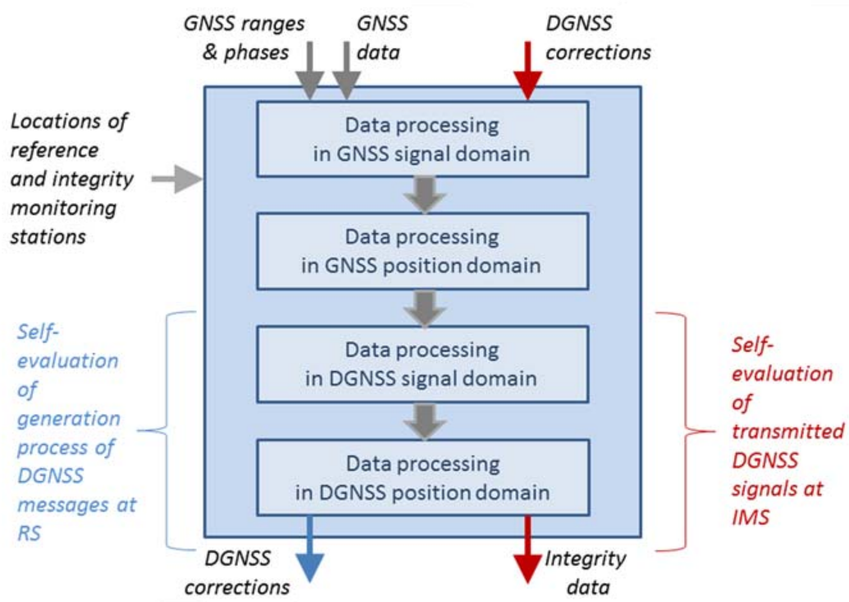

Figure 3 Stages of GNSS data processing during service provision

The first two processing stages deal with the assessment of GNSS as data base for DGNSS service provision and with the determination of the desired correction parameters:

- The usability of single GNSS signals for positioning as well as service provision stands in the focus of the first processing stage. For this purpose, range and range rate corrections to each satellite are determined using the known antenna position of the measuring point. These correction parameters can also be used as indicators to decide about the quality of single GNSS signals and assigned corrections. Both the number of GNSS satellites in view as well as the number of usable GNSS signals can be used to indicate if the data base is sufficient for GNSS position determination, as well as DGNSS service provision.
- The second processing stage accounts for the capability of GNSS taking into account the current usable GNSS signals and their spatial arrangement. In this context the

Dilution of Precision (DOP) is a suitable indicator to estimate the expected performance of GNSS-based positioning. Additionally, the achieved GNSS position accuracy, with or without application of receiver autonomous integrity monitoring techniques (RAIM), could improve the assessment of the GNSS database.

An intermediate result of the first 2 processing stages is the provision of GNSS correction data as well as integrity data characterising the usability of GNSS and its signals. The next processing stages deal with the self-assessment of the provided DGNSS services realised in DGNSS signal and position domain:

- In the DGNSS signal domain the independent acquired GNSS range measurements are corrected with the provided GNSS correction data. The residual error determined range and range rate at integrity monitoring site can be applied as indicator in the signal domain to assess the quality of provided corrections. It should be expected that the residuals of corrected range and range rates should be appreciable below the real error.
- In the DGNSS position domain the position is calculated using own but corrected GNSS measurements. The deviation between true and calculated position is a proper indicator to describe the achievable performance of DGNSS positioning at monitoring site.

Results of the GNSS data processing cover differential GNSS corrections as well as integrity data characterising the used GNSS, the operated DGNSS service, and the provided GNSS augmentation data.

3.1.3 DGNSS Data Composition

The data composition follows the rules given in ITU-R Recommendation M.823-3 [5]. The following message types should be used to provide augmentation data for GPS and GLONASS based on RTCM SC 104 V2.3:

- Type 1 (GPS Full Correction Set) or 31 (GLONASS Full Correction Set)
- Type 9 (GPS Partial Correction Set) or 34 (GLONASS Partial Correction Set)
- Type 3 (GPS Reference Station Parameters) or Type 32 (GLONASS Reference Station Parameters)
- Type 7 (DGPS Radiobeacon Almanac) or Type 35 (GLONASS Radiobeacon Almanac)
- Type 6 (Null frame, used as transmission fill).

Generic messages capable of conveying data for all GNSS are currently under development.

Further topics should be taken into account:

- Partial Correction Sets messages are preferred because of better performance in impulse noise conditions.
- Message Types 3/32, and 7/35 should be broadcast at the minimum time intervals specified in ITU-R Recommendation M.823.
- Message Type 5, which deals with GPS constellation health, is included in ITU-R Recommendation M.823, but is not normally used.
- Message Type 16/36 may be used to broadcast special messages in text form, but should not normally be used for integrity warnings, which are included in message headers.
- Type 16/36 messages may be used for status information, or for navigation related information such as hydrographic or meteorological data.
- Type 16/36 messages should never be broadcast consecutively as this will cause excessive receiver alarms, receiver memory overloads, and/or data link loading.

- Type 16 /36 messages should not be broadcast for a period of at least ninety seconds preceding or following a Type 3/32, 5, or 7/35 message and the interval between.
- Successive Type 16/36 messages should be no less than three minutes.
- Message Type 27 (DGPS extended radio beacon almanac) can be broadcast in conjunction with Message Type 7 to fulfil IMO [MSC 114 (73)] automatic radio beacon selection mode.

3.1.4 Performance Aspects

The aim of DGNSS augmentation services is the improvement of GNSS based position, velocity and time determination by provision of GNSS correction parameters and GNSS/DGNSS related integrity information. The performance of provided correction and integrity data depends on usable GNSS data bases and applied data processing techniques. Likewise the final settings of assessment and decision thresholds (ANNEX B) influence the achievable DGNSS service performance. Otherwise differences in the technical design and service realisation contribute to the achievable performance level of GNSS augmentation services. Therefore service providers are encouraged to inform users about their specific service implementation and to publish the achieved service performance.

3.1.4.1 Accuracy Aspects:

The accuracy of service provision depends on a number of factors. Invariant, installation specific factors result from architecture design, implemented functions and sensors of established GNSS augmentation service. Such factors cover for example:

- the quality of used GNSS sensors determining the accuracy and availability of range measurements and navigation data for service provision;
- the number of GNSS sensors used and their spatial arrangement (system architecture for GNSS data acquisition) determining the amount of data and included redundancy, which can be exploited for service provision and monitoring;
- the geographical latitude of measuring points determining number and geometry of GNSS satellites in view;
- the accuracy of antenna phase centres determined by initial measurement (e.g. 3D accuracy should be better than 5 centimetre);
- the chosen location of GNSS sensors (antennas) in relation to environmental conditions (shadowing, multipath) and occurrence of radio interferences; and
- the applied measures and methods to indicate and reduce propagation effects and system failures (e.g. carrier smoothing techniques, fault detection and exclusion techniques).

Variant factors come from the system in use taking into account the current occurrence of signal disturbances, increased latencies, malfunction or failures within GNSS and DGNSS components. A decreased number of measurements or a reduced quality of derived distances can result in temporary downgrading or loss of service provision. Increased latencies can result into the provision of GNSS corrections with higher age. Then temporal decorrelation results in an increase of residual errors in the corrected distance measurements.

A suitable accuracy indicator of DGNSS service usability is proven when, close to the reference station (e.g. within 50 m circumference), the horizontal position error is <0.5m (95%) measured over a period of 24 h, if DGNSS corrections are applied on independent GNSS measurements.

Service providers are requested to publish the level of accuracy. Furthermore service providers are encouraged to monitor the achieved accuracy in the service area by service monitors or routine service evaluation. Furthermore the service provider should ensure that service generation and provision is realised in a common reference datum. The user should be informed about the reference datum used, to allow them to transform the datum if necessary.

GNSS augmentation systems have the ability to estimate the current accuracy in the service area based on position accuracies determined at selected points (monitors). If the monitor is near the reference station, the estimated accuracy neglects the spatial decorrelation of several error sources and offers accuracies in the sub-meter level. Investigations [6] in Portugal have shown, that the DGPS position error coming from spatial error decorrelation could be modelled by

$$95\%\ \text{DGPS error [m]} = 0{,}41 + 0{,}0038 \cdot S\ \text{[NM]},$$

where S is the distance between reference station and user given in nautical miles. It should be noted that such estimations depend on the geographical region and the quality of the user's receiver. At present various opportunities exist, which could be used to reduce the influence of spatial error decorrelation. If several integrity monitors are located at service boundaries, the opportunity exists, to achieve a user-position related refinement of correction terms e.g. by interpolation. Alternatively, with a network of reference station the correction data can be determined for a virtual reference station, which will be placed in the vicinity of a single user.

3.1.4.2 Integrity Aspects:

Integrity monitoring within the GNSS Augmentation Service serves the quality control of used GNSS and provided DGNSS data. Tests performed in the GNSS signal domain and GNSS positions domain clarify the current usability of GNSS for PVT determination as well as DGNSS service provision. The results of assessment can induce alarms indicating single satellite signals as "do not use" or complete DGNSS stations as "unhealthy". In combination with integrity checks of the MF Transmission Service they evaluate the fulfilment of requirements on DGNSS service provision. In dependence on intra-system situations single GNSS/DGNSS signals or the complete service can be signed as "unusable" or "unmonitored".

- ***GNSS signal domain (GNSS SD)***

  Integrity monitoring in the GNSS signal domain checks the availability and quality of GNSS data regarding their usability for DGNSS service provision as well as monitoring. The usability of single GNSS satellites and its signals for service provision can be assessed for example based on:

  - completeness of GNSS range, phase, and navigation data per GNSS satellite in view;
  - integrity data or health status provided by GNSS itself;
  - validity of navigation data;
  - plausibility, consistency and accuracy of distance measurements.

  Incompleteness or insufficient quality of GNSS range and phase measurements as well as GNSS navigation data can result in the decision that specific GNSS satellite signals shall not be used for DGNSS service provision.

- ***GNSS position domain (GNSS PD)***

  Integrity monitoring in the GNSS position domain checks to see if the current availability of usable GNSS signals is sufficient for GNSS as well as DGNSS based positioning. In addition to RSIM standard the opportunity is seen to use the current achieved GNSS position accuracy as an additional quality indicator for DGNSS service provision. Integrity monitoring in the GNSS position domain shall be realised for each single station used for service provision and can cover for example:

- number of usable GNSS satellites for positioning;
- spatial arrangement of usable GNSS satellites given by Dilution of Precision (DOP);
- accuracy of GNSS positioning.

Therefore a poor data set or insufficient quality of GNSS data as well as worse GNSS position performance can result in the decision to exclude single stations from service provision. In extreme cases, where multiple satellites are affected, a DGNSS service provision can be impossible.

- ***DGNSS signal domain (DGNSS SD)***

Integrity monitoring in the DGNSS signal domain can be realised at the reference station and integrity monitoring sites, alternatively or complementary. Checks at reference sites can prove if the generation of GNSS correction data is successful or not. Only at integrity monitoring sites can the quality of provided GNSS corrections be assessed, considering residual errors by mixing own GNSS measurements with received correction terms.

- availability of generated correction terms at RS;
- plausibility of generated correction terms at RS;
- consistency of generated correction terms at RS;
- indicated validity and integrity of correction terms provided by RS;
- availability of correction terms at IM;
- latency and validity of available correction terms at IM;
- residual ranging error after application of RS corrections at IM.

Incomplete or insufficient quality of own GNSS measurements as well as received GNSS corrections can result in the decision at the IM that data assigned to specific GNSS satellite signals shall not be used for DGNSS based positioning.

- ***DGNSS position domain (DGNSS PD)***

Integrity monitoring in the DGNSS position domain checks to see if the current availability and quality of corrected GNSS signals is sufficient for DGNSS based positioning at integrity monitoring sites. In this case the IM is considered as an artificial user of the GNSS augmentation system. The evaluation can base for example on:

- number of GNSS satellites links, for which at IM own measurements and correction data are available – both classified as usable for positioning;
- spatial arrangement of usable GNSS satellites at IM given by DOP’s;
- accuracy of DGNSS positioning at IM.

Therefore a poor data set or an insufficient quality of corrected GNSS measurements at the IM as well as unacceptable positioning errors can result in the recommendation that the provided GNSS augmentation service should not be used for navigation purposes.

The service provider is encouraged to implement, as a minimum, the integrity monitoring functionalities described in RTCM 10401.2 (RSIM Standard). As outlined, the data bases usable for DGNSS service provision and monitoring differs depending on applied GNSS data acquisition (see Figure 2) and the placement of reference and integrity monitoring stations.

In the classic approach, the on-site integrity monitoring is performed by applying the Local Integrity Monitoring concept (LIM), the Far Field Integrity Monitoring concept (FFIM), or a combination both:

- A Local Integrity Monitoring concept (LIM) can be applied, if the integrity monitoring station is located in the vicinity of the reference station. In such cases it is impossible to estimate the influence of error decorrelation effects on achievable position performance at user site.
- The Far Field Integrity Monitoring concept (FFIM) can be applied, if one or more integrity monitoring stations operate at the boundary of the service area, where decorrelation error effects can be estimated. When the user operates in the vicinity of the integrity monitor, the monitored position error can be considered as representative of user's position error. Therefore, where possible, far field monitors should be located at the boundaries of the service area.

If a network based data acquisition is used, the opportunity exists to consider decorrelation error effects during generation and monitoring of GNSS corrections. Within a network based concept it should be clarified whether a single station operates as reference or monitoring station, to avoid as far as possible any correlation between service generation and monitoring processes. However, the integrity of a network based provision of GNSS augmentation data should consider the integrity of communication systems ensuring the data exchange between spatial distributed measuring and processing components.

The service provider is encouraged to make a suitable choice of integrity monitoring functionalities taking into account the available data basss and the desired level of integrity. Monitoring functionalities can be based for example on availability, plausibility, consistency, validity, latency, and accuracy tests. In principle, integrity statements are more meaningful, if they are derived from evaluated position accuracies in the service area. However, a comprehensive assessment of position accuracies in the service area increases the dependence of service integrity on communication integrity. Service providers are requested to publish the applied monitoring functionalities including decision rules for deciding about the usability of components and data. On the one hand this enables an improved understanding of usability information and allows on the other hand the exploitation of GNSS/DGNSS related integrity data within shipside alarm management.

3.1.4.3 Availability Aspects:

As defined in IMO A.915(22"Signal availability" is defined as the availability of a radio signal in a specified coverage area. "System availability" is defined as the availability of a system to a user, including signal availability and the performance of the user's receiver. Furthermore the availability of the used GNSS constellation is part of the overall system availability.

For the scope of this document the DGNSS service availability is based on the DGNSS signal availability due to the fact that the user's performance could not be measured.

In line with definitions in IMO A.915(22) DGNSS signal (or service) availability is given, if the radio reception of the DGNSS signal is ensured in the specified coverage area (see chapter 2) and if the DGNSS signal is provided according to its specification (see chapter 3.1.3 signal structure, data format and content). Due to its independence from GNSS availability the DGNSS signal availability $A_{Signal(DGNSS)}$ is suitable to measure the performance of provided DGNSS services.

A lost access on GNSS signals at service sites or a complete outage of GNSS implicates that the DGNSS service cannot provide GNSS correction data. The self-monitoring of the DGNSS service ensures the detection of GNSS data absence. In such cases it can be expected that the DGNSS signal provides integrity data informing about the absence of DGNSS correction data and the resulting impossibility of DGNSS based position determination. The DGNSS signal availability will be measured by the service provider at one or more monitoring sites. Due to spatial decorrelation effects the signal availability estimated by the provider at a single monitor site can be different to the signal availability observed at distant users. If two or more monitoring sites are used for service evaluation, the influence of decorrelation effects on the reliability of availability statements can be reduced.

An example how to calculate DGNSS service availability is given in ANNEX D

3.1.4.4 Continuity Aspects

Continuity in the coverage area can be measured (1) at broadcast site(s), (2) by the use of far-field monitor(s) or a combination of both. Chapter 4 will provide information how to measure and calculate continuity in this respect.

3.2 MF Transmission Service

As shown in figure 1 the main task of the MF transmission service is the provision of DGNSS messages by signals in the frequency band 283.5 to 325 kHz. For this purpose following three tasks are realised:

1. Task "Signal modulation" to modulate the MF carrier signal with the DGNSS messages composed by the GNSS augmentation service;
2. Task "Signal amplification" to amplify the signal on the specified signal power level to fulfil the range requirements;
3. Task "Signal tuning" and "Signal transmission" to emit the DGNSS signal with a suitable antenna system.

The MF transmission service should also provide status data describing the current progress of MF transmission service covering radio signal generation and distribution.

Figure **4** shows the different functional elements of the MF transmission service.

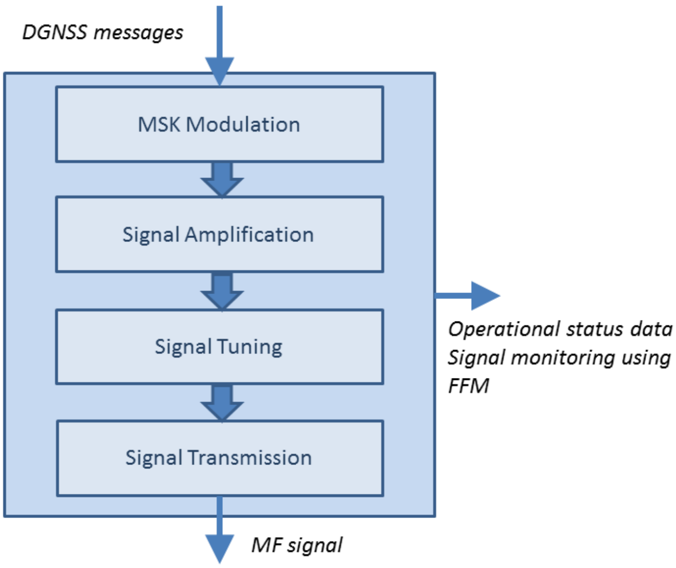

Figure 4: Main tasks of a MF transmission service

3.2.1 Signal Modulation (MSK Modulator)

The modulation technique applied for DGNSS signal generation is Minimum Shift Keying (MSK) (class of emission G1D) as defined in ITU-R Rec. M.823-3. The MSK modulated signals should have carrier frequencies in the MF beacon band between 283.5 to 325 kHz, which are separated by 500 Hz from each other. The DGNSS messages used as modulating signal shall be selectable to data rates of 25 (GLONASS only), 50, 100 or 200 bps. It should be noted that higher data rates enable a faster update and provision of DGNSS corrections but limit the coverage area of the DGNSS service due to lower signal to noise ratio.

3.2.2 Signal Amplification (MF Transmitter)

The MF Transmitter amplifies the modulated input signal on the required signal power level and provides the amplified DGNSS signal to the connected MF Antenna System.

3.2.3 Signal Tuning (Automatic Tuning Unit)

The ATU (Automatic Tuning Unit) matches the antenna system resistive component to the impedance of the feeder cable of the MF transmitter (typically 50 Ω). Furthermore, the ATU brings the MF antenna in resonance with the operational frequency of the DGNSS site. It is proposed that the ATU should provide a means to detect and correct any detuning of the antenna system, which can result from weather or seasonal conditions. The ATU should also provide measurements of antenna current to the MF-transmitter to enable meter readings from transmitter site or from connected remote control facilities. The use of an electronic impedance meter may be helpful to support the coarse and fine tuning of the MF antenna system used and to provide additional information regarding the quality of the tuning process. Readings of the proportion of transmitted and reflected power at the MF transmitter provide foreseen status data informing about the tuning and matching quality achieved.

3.2.4 Signal transmission (MF Antenna System)

The MF antenna system, consisting an MF antenna and grounding system, is a one of the most critical elements in the DGNSS service because the antenna can be affected by severe weather conditions and is typically not realised as a fully redundant antenna system. Therefore the requirements regarding reliable performance of the MF antenna as well as the ATU are very high. If no standby antenna is available at the DGNSS site, the required down time for regular and planned maintenance should be low. The required DGNSS coverage range is mainly dependent on the performance of the antenna system and the transmitted power. Annex E provides detailed information on how to calculate the performance of the MF antenna system.

3.2.5 Performance Aspects

3.2.5.1 Range/Coverage Aspects

Nominal ranges of stations over seawater paths should be published at stated field strengths (for example 50, 75 or 100 µV/m) [7]. Published coverage diagrams are normally based on software modelling predictions and should be verified by measurements. The modelling process can be quite complex and difficult, especially over mixed land/sea paths. Advice regarding modelling can be sought through IALA. In predicting coverage, each service provider should establish the required field strength considering following factors:

- Radiated power;
- Antenna system configuration, including horizontal and vertical polar diagrams;
- Antenna efficiency (η);

- Ground wave propagation curves for frequencies between 10kHz and 30MHz as applicable at 300 kHz as given in ITU-R P.368-7, [8];
- Ground conductivity along the propagation path as provided in ITU-R P.832-2 “World atlas of ground conductivities” [9];
- Fading due to skywave propagation of the station’s signal. At night the field strength at every point in the coverage should be not less than that specified at the nominal range for at least 95% of the time. Night-time field strengths may be calculated in accordance with references [10,11,12];
- Atmospheric noise. Assumed levels of atmospheric noise should be in accordance with current ITU-R data and practice applicable at 300 kHz. It is proposed that the noise level be that which is not exceeded more than 95% of the time on average throughout the year [13&14];
- Precipitation static. In those areas where precipitation static is known to be a significant problem, an appropriate factor should be added to the atmospheric noise [15];
- Man-made noise. In situations, such as harbours, where man-made noise is significant in comparison to natural noise sources, the local man-made noise level should be taken into account [16].

3.2.5.2 Signal Monitoring

Monitoring the Signal of the MF Transmission Service serves to prove that the functionalities of the transmission service have been fulfilled and is an essential requirement for a successful provision of DGNSS augmentation signals via MF radio. The signal monitoring of MF transmission service can be done considering the following performance parameters of received MF signals:

- signal strength (SS);
- signal to noise ratio (SNR);
- RTCM message throughput (WER);
- Temporal validity of message content.

The results of MF signal monitoring can provide alerts to service providers and may cause a switch to standby equipment of the MF Transmission Service.

3.2.5.3 Availability Aspects

The information given in chapter 3.1.4 for the DGNSS service availability also holds true for the MF transmission service. An example how to calculate DGNSS service availability is given in ANNEX D.

3.2.5.4 Continuity Aspects

Continuity in the coverage area can be measured (1) at broadcast site(s), (2) by the use of far-field monitor(s), or a combination of both. Similar to availability, the continuity of the MF transmission services contributes to the continuity of the DGNSS service which is based on the integrated use of GNSS augmentation service and MF transmission service.

3.3 Technical Implementation

This chapter provides guidelines how a radio beacon DGNSS site could be implemented based on the DGNSS augmentation and the MF transmission service. The implementation for the DGNSS augmentation service can be performed following the classical approach with local reference and monitoring receivers or the network approach based on virtual reference stations. The realisation of the MF transmission is following a straightforward design which is typically identical for both methods. Figure 5 illustrates the implementation concept for a DGNSS service in the radiobeacon band.

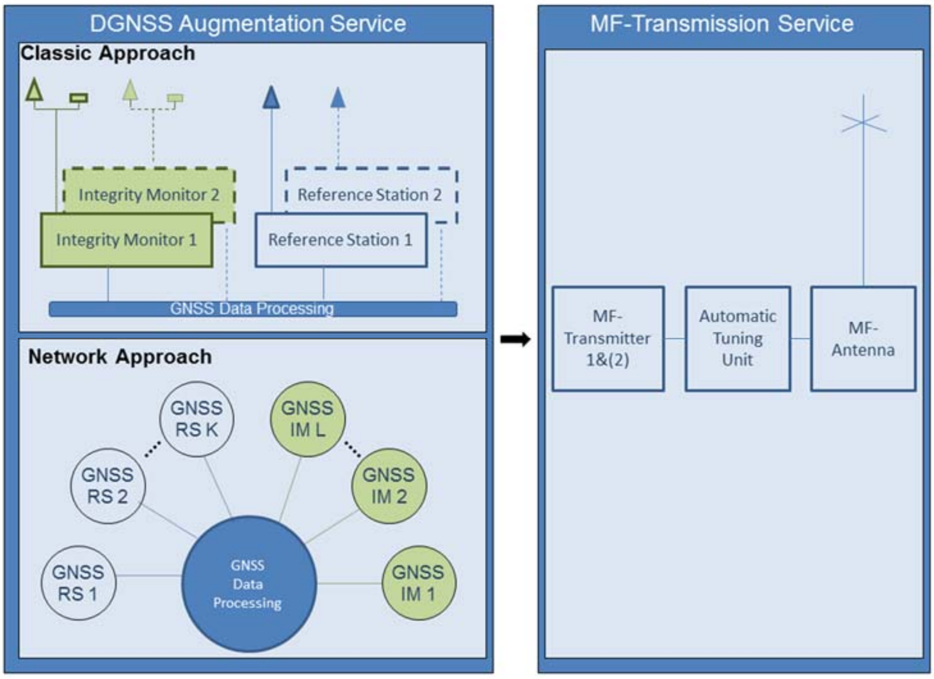

Figure 5: Implementation of a DGNSS service in the radiobeacon band

The functional details of the components of a DGNSS augmentation service are already described in chapter 3.1 and 3.2. The following sections are mainly focused on technical system components, which are required to establish a maritime DGNSS service in the MF radio beacon band.

3.3.1 Components of the classic approach

An implementation of the DGNSS augmentation service based on local reference and integrity receivers should provide at least the following system elements:

- **Reference Station:** Within the classic approach, the reference station consists of a minimum of a single GNSS reference receiver and an MSK modulator. Furthermore the GNSS data processing is usually part of the reference station. In Figure 5 the MSK modulator and GNSS data processing is considered as part of the reference station. To fulfil the availability requirements it is suggested to provide a backup reference station for redundancy.
- **Integrity Monitor:** The Integrity monitor uses a minimum of a single MF receiver/MSK demodulator and a single GNSS/DGNSS reference receiver to receive and assess the transmitted DGNSS corrections. In Figure 5 the MF receiver/MSK demodulator is considered as part of the integrity monitor. To fulfil the availability requirements it is suggested that a backup integrity monitor be provided for redundancy. Typically the integrity monitoring on the DGNSS position domain is performed as post-broadcast integrity, where transmitted GNSS corrections from a DGNSS site are received with a local integrity monitor (LIM), however some equipment providers also enable the use of pre-broadcast integrity monitoring where DGNSS data is checked before transmission.
- **Communication:** The reference and monitor receivers exchange information on the basis of the RTCM recommended standards for differential GPS reference stations and

integrity monitors [17]. It should be noted that the current RSIM messages (version 1.2) only support the GPS component in the context of DGNSS integrity monitoring. With the introduction of RSIM version 1.3 it can be expected that integrity monitoring for full DGNSS range will be possible. Typically a site PC is used for site control and data logging. External communication and remote control is typically performed using a TCP/IP router.

3.3.2 Components of the network approach

An implementation of the DGNSS augmentation service can be performed by a network approach, as shown in Figure 5. A network of GNSS sensor stations distributed within a defined area is used for GNSS data acquisition. The network approach should provide at least the following system elements:

- **Network of GNSS sensors:** A sufficient number of GNSS sensor sites are necessary to enable the provision of augmentation data (correction data and integrity information) in the desired service area. For example, in Germany it was demonstrated that 10 to 15 GNSS sensor sites are sufficient [18]. The sensor stations transmit their measured GNSS raw data to a central server for processing (GNSS data processing).

- **GNSS data processing at the VRS server:** DGNSS service providers may use alternative methods, based on a Virtual Reference Station concept, in order to generate DGNSS data stream for reference position(s) of interest. It is proposed that virtual reference stations should be located within the coverage range of the specific DGNSS site and in areas with highest demands concerning position accuracy and integrity. Another important task of GNSS data processing by VRS server is the implementation of the integrity monitoring functionality. For the network approach, the integrity monitoring is based on the Pre-Broadcast Monitoring (PBM) algorithm, which ensures that all relevant checks have been performed before DGNSS data are transmitted. For network-based integrity monitoring it is important that independent GNSS raw data streams are used for generation and monitoring of DGNSS augmentation data.

- **Communication:** There is a need for internal communication using the approach of the RSIM standard recommendations [17]. However the network approach results in high requirements concerning the availability and quality of the communication links to the connected MF transmission service at the remote DGNSS sites. Typically a software module installed on the VRS server is used for network control and data logging.

3.3.3 Components of the MF transmission service

The MF transmission service should provide at least the following system elements:

- **MSK modulator:** The MSK modulator modulates the generated RTCM messages on a signal carrier in the radio beacon band. The MSK modulator may be more or less regarded as the interface between the GNSS augmentation and the MF transmission service. In the classic approach the MSK modulator is typically an intrinsic part of a reference station and belongs to the DGNSS augmentation service. In the network approach the MSK modulator is usually a separate device and part of the MF transmission service. To achieve the required level of DGNSS signal availability the MSK modulator should consist of two identical but redundant modulator parts.
- **MF transmitter:** The MF transmitter amplifies the modulated input signal to the required signal power level. To achieve the required level of DGNSS signal availability the MF transmitter should consist of two identical but redundant transmitter parts.
- **Automatic Tuning Unit:** The Automatic Tuning Unit (ATU) matches the antenna system resistive component to the impedance of the feeder cable of the MF transmitter. A redundant ATU would only be necessary in the case of a redundant MF antenna system.
- **MF Antenna:** The MF antenna transmits the amplified DGNSS signal and provides the required coverage. It is up to the service provider if this is duplicated for redundancy, however if it is not, the requirements regarding the reliable performance of the single MF antenna and the ATU are very high.

3.3.4 Remote Control and Far Field Monitoring

The concept in Figure 5 does not show additional installations like control facilities or the difference between local and far field monitors. Independent to the applied service concept, DGNSS service provision is based on more or less spatial distributed components realising the functionalities of GNSS data acquisition and processing, as well as DGNSS service provision and assessment. Therefore the service providers may need one or more control stations depending on their network design.

As outlined in Figure 5, integrity monitors can be used to evaluate the GNSS augmentation service. Additionally, approaches are mentioned to monitor the MF transmission service. Integrity monitoring is usually based on local integrity monitors (LIM) as well as far field monitors (FFM), which provide signal monitoring in remote areas. An option is to use a far field monitor (FFM) to provide real integrity feedback to the reference site.

4 OPERATIONAL ASPECTS

The set of signals radiated from the DGNSS beacons operated by a DGNSS service provider is considered a DGNSS service. The operation of the service is considered as the set of tasks performed by the DGNSS service provider in the following domains:

- **Operation and Maintenance:** The DGNSS service provider should continuously monitor the DGNSS transmissions to detect service disruptions and anomalies.
- **Performance Verification:** The DGNSS service provider should verify that the service is performing according to specifications.
- **Publication of information:** The DGPS service provider should provide a description of the DGNSS service and provide up to date information of scheduled maintenance activities.

4.1 Operation and Maintenance

The DGNSS service provider is responsible for the operation and maintenance of the DGNSS service. To monitor the quality of the service the DGNSS service provider should provide means to:

- to monitor the service using local or remote integrity monitors (LIM, FFM) to detect service disruptions and anomalies;
- inform users using navigational warnings regarding service disruptions or scheduled interruptions;
- manage any service disruptions;
- manage maintenance work or changes to the service in such a way that service disruption is minimized and the users are provided with advance warning.

The service provider may wish to consider remote control options for all system components at their DGNSS sites as this will aid the swap of system components.

4.2 Performance verification

The DGNSS service provider should verify that accuracy and integrity requirements given in Table 1 are achieved. For this purpose it is necessary that GNSS availability is given and that these performance quantities are measured with appropriate monitoring facilities. The assessment of availability and continuity can be related either on fulfilment of accuracy and integrity requirements (DGNSS system availability and continuity) or the provision of DGNSS signals (DGNSS signal availability and continuity). This allows performance verification of DGNSS services to be performed taking into account whether GNSS availability is given or not. The service provider is advised to provide as a minimum the performance verifications given below.

4.2.1 DGNSS signal availability

The service provider should designate a geographical area where they operate their service within the required performance. The service area may be limited by beacon signal strength or may be a specific geographical area as designated by the operator. The service provider is advised to analyse service performance and include information about the extent of the service area in its publications.

In cases where coverage from DGNSS beacons belonging to separate service providers partially overlap, it is proposed to take this into account as these provide a contribution to performance in the overlapping area. In order to maximize the combined performance such service providers should:

- coordinate the scheduling of maintenance work that may affect the service performance in overlapping areas;
- exchange information about service disruptions affecting overlapping areas;
- exchange information about achieved performance for the beacons in the overlapping areas.

Availability requirements are stated in chapter 2.

The service provider should take the degree of coverage from multiple beacons into account when validating the service availability. Further the service provider should consider implementing signal far field monitors in order to monitor signal strength.

Availability of the signal from a single beacon can be written as:

$$\text{Availability } (A_1) = \text{UP TIME/TOTAL TIME}$$

Where:

UP TIME = the time that the beacon provides a signal with signal strength and SNR within stated limits and provides accuracy and integrity warnings within requirement;

TOTAL TIME should be an extended period of time up to 2 years.

In case of loss of signal from one DGNSS beacon, DGNSS receivers are capable of automatically re-acquiring signal from other beacons that normally provide sufficient signal strength at the user's location. In such areas of overlapping coverage service availability is defined as the probability that a signal from at least one beacon (which meets the accuracy and integrity requirements) is present.

Mathematically this can be written as:

$$A_{service} = 1 – (1 – A_1)^n$$

Where:

n = number of beacons that meet the performance requirements at the receiver location

A_1 = signal availability from a single beacon

The average availability over the service area as a whole may be estimated from the above and from the proportions of the service area covered from different numbers of beacons. See calculation example in ANNEX C.

4.2.2 DGNSS signal continuity

Continuity requirements are stated in chapter 2.

For a DGNSS beacon the continuity can be calculated as the probability that a signal failure incident will start during the Continuity Time Interval (CTI). Normally the CTI will be very small compared to the typical interval between failures (MTBF) and thus the continuity can be mathematically this written as:

$$\text{Continuity (C)} = 1\text{-CTI/MTBF}$$

Where:

CTI = Continuity Time Interval, 15 minutes as stated in A.1046(27)

MTBF = the Mean Time Between Failures, as measured by the service provider e.g. over 2 year period

There is no need to include the availability at the beginning of the time period of the operation because if there is no service, then the operation will not commence. If the beacon used during the CTI suffers a disruption there may, depending on the receiver design, be a delay of several minutes while the DGNSS receiver re-acquires signal from another beacon. This delay may be unacceptable for a particular operation and it is proposed that continuity should not take into account the presence of DGNSS signals from multiple beacons.

The average continuity for the service area as a whole may be estimated from the proportions of the service area covered from different beacons or, if beacons are experiencing similar MTBFs, as the average beacon continuity. See calculated example in ANNEX C.

4.2.3 Verification of integrity monitoring

Integrity requirements are stated in chapter 2.

It is proposed that, as a minimum, the service provider should monitor the transmission of integrity warnings from the beacons and identify instances where the time interval between the occurrence of a breach of integrity and the transmission of the integrity warning to the user does not meet the required Time to Alarm (TTA).

The proposed thresholds for detecting failures suggested appropriate action is provided in ANNEX B.

4.2.4 Verification of DGNSS Accuracy

Accuracy requirements are stated in chapter 3.

The service provider should measure the accuracy of the GNSS position as corrected by DGNSS inside the coverage area of each beacon. Such measurements can be done either by use of a far field monitor or by periodic measurement campaigns [19]. The formula (reference 3.1.4 performance aspects) may be utilised to estimate the accuracy at the edge of the beacon coverage area.

4.3 Publication of information

The DGNSS service provider should consider the DGNSS service to be a maritime aid to navigation and should accordingly publish sufficient information about the service to enable users to use the service safely at all times and to utilise it fully. It is proposed to employ information channels appropriate to the intended users and to the nature of the information. This includes Notices-to-Mariners, broadcasting of maritime safety information (MSI) in the GMDSS, radio beacon almanacs in DGNSS type 7, type 27 and type 35 messages (chapter 3.1.3) and the world-wide-web including the IALA Lists Of Radionavigation Services.

Relevant information should, as a minimum, include:

- description of the service [for example which GNSS is supported], and its intended purpose, identification of the service provider, identification of where information relating to the service can be found and references to the relevant standards and specifications the service comply to. Examples are given in references [20-24];
- advice for safe use of the service and cautionary notes taking into account user receiving equipment;
- technical parameters for each DGNSS beacon at the IALA Lists Of Radionavigation Services;
- achieved service performance for criteria explained in chapter 4.2;
- the geographical service area where the performance criteria apply;
- contact information for the service provider;
- navigational warnings regarding service disruptions or scheduled interruptions.

Individual Administrations are encouraged to publish service descriptions, including coverage predictions and system performance statistics. IALA maintains the master list of radio beacon DGNSS stations on the Internet (http://www.iala-aism.org). Administrations are responsible for updating their own sections of the IALA master list.

5 REFERENCES

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ANNEX A ABBREVIATIONS

DGNSS	-	Differential GNSS
DOP	-	Dilution of Precision
FFM	-	Far Field Monitor
GLONASS	-	Глобальная навигационная спутниковая система, Globalnaya Navigatsionnaya Sputnikovaya Sistema
GNSS	-	Global Navigation Satellite System
GPS	-	Global Positioning System
HF	-	High Frequency (3 – 30 MHz)
IALA	-	International Association of Marine Aids to Navigation and Lighthouse Authorities
IEC	-	International Electrical Commission
IMO	-	International Maritime Organisation
IM	-	Integrity Monitoring Station
ITU	-	International Telecommunication Union
MF	-	Medium Frequency (0.3 – 3 MHz)
MSC	-	Maritime Safety Committee (IMO)
MSI	-	Maritime Safety Information
PNT	-	Position, Navigation, and Timing
PVT	-	Position, Velocity and Timing
RAIM	-	Receiver Autonomous Integrity Monitoring
RS	-	Reference Station
RTCM	-	Radio Technical Commission for Maritime Services
VRS	-	Virtual Reference Station Technique

ANNEX B DGNSS BROADCAST SETTINGS

It is recognised that certain reference station and integrity monitor threshold settings are vital to the proper performance of DGNSS stations. This Appendix (Table 3) lists some parameters that affect the DGNSS service and/or the service provider with the suggested range of settings.

The parameters are related to the classic approach of DGNSS technical implementation (ref.3.3.1) and should be seen as an example and starting point when defining settings of an individual DGNSS Broadcast Site. In order to gain further insight into the functions of the reference station and integrity monitor, service providers should consult the RTCM 10401.2, "*Standard for Differential Navstar GPS Reference Stations and Integrity Monitors (RSIM)*".

Table 3 – DGNSS Broadcast Site Settings

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
REFERENCE STATION				
Minimum number of satellites Pseudorange corrections for three satellites are sufficient to generate a 2D horizontal position solution and correct the clock bias, assuming that the height is fixed and known. Generating the pseudorange corrections for four satellites will allow a user to also solve for the height and derive a 3D position. Since the user does not always know the correct input height, a 3D position solution using four satellites is preferred. Accordingly, the RS minimum satellite setting should be 4.	4 (FI: 4)	n/a	- Causes an alarm - Possibly automatic switch to standby equipment	- Degradation in position accuracy due to too few corrected SV (poor HDOP)

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
<u>Pseudorange Correction</u> Pseudorange corrections are generated by the RS to compensate for the delay that signals encounter as they pass through the ionosphere and troposphere, as well as clock and satellite ephemeris errors observed by the RS. The RS computes a pseudorange to the satellite and compares it with an absolute range based on its known surveyed antenna position. The RS measures the difference between the pseudorange and the absolute range and generates differential correction. Pseudorange corrections do not compensate for local errors in the user side like errors caused by multipath or receiver noise. According to the experience gathered from service providers this alarm threshold value should be set for 100-600m. If the pseudorange correction exceeds this value, it may indicate a satellite problem. Too small threshold value may cause the RS to halt corrections for a satellite unnecessarily. Larger threshold values may result in slightly greater system inaccuracies reaching the user.	100 – 600m (FI: 140-1000m)	n/a	- Causes an alarm - Will set PRC and RRC values for a specific SV to "do not use" as described within RTCM SC104	- Will drop "do not use" marked SV from position solution

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
<u>Range rate correction</u> Range rate is determined by measuring the Doppler shift of the satellite signal carrier. The Reference Station calculates the rate of change for the pseudorange of all the satellites it is tracking. Range Rate correction was earlier a very effective way of mitigating Selective Availability (SA) dither. This alarm threshold value is set for 0.5-10m/s. If the pseudorange correction exceeds this value, it may indicate that the satellite is actually moving erratically or has a clock problem. Smaller threshold values may result in the Reference Station halting satellite corrections unnecessarily. Larger threshold values may result in slightly greater system inaccuracies transmitted to the user. Now when the SA is no longer used range rate corrections may be set to zero to eliminate the effects of random noise error generation as long as DGPS corrections are broadcasted within 30 to 60 seconds.	0.5 – 10 m/s (FI: 4 m/s)	n/a	same as above	same as above

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
Integrity Monitor feedback IM feedback provides the RS with information on the accuracy of the DGPS broadcast. The threshold setting determines the maximum amount of time the RS will continue to transmit corrections after it received the last feedback from the IM. The feedback is done by sending a pre-set periodic "heartbeat" message (RSIM#20). The IM ensures the accuracy of the broadcast by determining its own position with its internal GPS receiver and monitoring the MSK broadcast from the DGPS transmitter. The IM applies corrections to the raw GPS data and determines the computed position of its receiving antenna. If the computed position drifts outside of an allowable window based on the surveyed antenna position, the IM informs RS (via the heartbeat message) about the situation and the RS will set the header of all RTCM messages to "not working". If the heartbeat message is not received within the Threshold Value, then the RS will set the header of all messages to "unmonitored." This alarm threshold value is set for 3s-12s. Smaller threshold values may result in excessive unavailability times at the site. Larger threshold values may result in unmonitored or poor quality corrections transmitted to the user.	3 – 12 s (FI: 12 s)	n/a	- Causes station health (header) to be set "unmonitored" - Possibly automatic switch to standby equipment	- Quality of corrections are unknown - Station should be used with caution and switch to another DGNSS site if available

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
Elevation angle (mask angle) The purpose of the mask angle is to screen all satellites below a predetermined angle above the horizon. The RS will not use satellites below this level in its position and/or clock solutions. Most RS do track satellites below the mask angle if an open channel is available and can pass observables via an open communication port. The mask angle is set at between 5 to 10 degrees. Operating at the lower end of the range will benefit the service provider as more useable satellites will improve availability, especially when some satellite(s) are unavailable. However, multipath, tropospheric and satellite observables errors tend to become more significant in degrading the user position solution as the mask angle is lowered (i.e. low elevation angle satellites are included in the solution).	5 – 10 degs. (FI: 7 deg)	n/a	- Improved availability at lower elevation angle setting	- Slight degradation of user position accuracy when operating at lower elevation angle setting
INTEGRITY MONITOR				

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
<u>RTCM correction age</u> RTCM correction age (measured in seconds) is the time difference between the time when a set of corrections is computed at the reference receiver and the time when the corrections are received within the IM's DGPS receiver. The correction age is directly related to the data rate used at the reference station. In normal operation the correction age is as follows: (using a set of 9 SV and Message type 9-3) - 50 Bit/s: this baud rate is not typically used - 100 Bit/s: 6-7 sec - 200 Bit/s: 3-4 sec. Since S/A was set to zero, the resulting position accuracy at a user GPS receiver is no longer affected by correction ages less than a few minutes. The remaining errors within the GPS signal like ionosphere and troposphere change slowly in time. Thus in an environment where S/A is set to zero, correction ages above the given threshold will primarily have an impact on the integrity functionality of a reference station. Taking into account the integrity requirement with a TTA of 10 seconds to inform the user, the correction age should not exceed this value significantly. Due to the method used to calculate the correction age, high settings (>10s) may need to be used in some applications to avoid frequent alarms. Correction age interval is a time period over which correction ages are observed and averaged. The IM is continuously monitoring the correction age interval so there should be little or no processing overhead change. If the value is out of tolerance an alarm is generated. This value is set at between 1–30 seconds. Longer intervals result in slower detection of excessive pseudorange correction age. Shorter intervals add processing overhead to the IM.	10 - 30 s (FI: 10-30 s)	1 – 30 s (FI: 60-100)	- Causes warning or alarm - Possibly automatic switch to standby equipment	- If correction age is higher than 10 sec it will affect TTA performance - Switch to another DGNSS site if available

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
<u>Message error ratio</u> During data link reception, message error ratio is calculated as the number of bad bits divided by the total number of bits. The value is set at 0.1. A higher ratio is an indication that there may be a problem with the data link. Lower threshold values hold the transmitter to a higher standard of modulation. When one of the 30-bit words in a message frame fails the parity test the bits for the entire message are considered bad. Message error ratio interval is a time period over which data is observed to use for calculating the message error ratio. There should be little or no extra processing overhead in the IM based on this interval because the MSK receiver is continuously monitoring the message error ratio. If the value is out of tolerance an alarm is generated. This value is set at between 10–60 seconds. Longer intervals result in slower detection of data link problems. Shorter intervals add processing overhead to the IM.*	0.1 (10%) (FI: 1-15)	10 - 60 s (FI: 60-100 s)	- Causes warning or alarm - Possibly automatic switch to standby equipment	- Switch to another DGNSS site if available
<u>Beacon SNR</u> The signal-to-noise ratio (SNR) is the minimum acceptable ratio of the amplitude of the data link signal to the amplitude of the ambient noise expressed in dB. This value is set at >7 dB. If the near-field SNR falls below this value, the data link signal may not be of sufficient quality that the user's receiver can properly decode the broadcast. Beacon SNR interval is a time period over which data is observed. The Integrity Monitor is continuously monitoring the SNR so there should be little or no processing overhead change. If the value is out of tolerance an alarm is generated. This value is set at between 10–30 seconds. Longer intervals result in slower detection of data link problems. Shorter intervals add processing overhead to the Integrity Monitor.*	> 7 dB (FI: 1-17 dB)	10-30 s (FI: 60-65 s)	- Causes warning or alarm - Possibly automatic switch to standby equipment	- Will reduce coverage area

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
Beacon signal strength The beacon signal strength is a measure of the near field signal strength expressed in dB (μV/m). This alarm threshold value is set 4dB-7dB bellow the n0minal value. If beacon signal strength falls below the threshold, the data link signal may not be at a level sufficient for the user's receiver to properly decode the broadcast. Threshold value is set by the service provider according to site specific measurements. Beacon signal strength interval is a time period over which data is observed. The Integrity Monitor is continuously monitoring the Beacon signal strength so there should be little or no processing overhead change. If the value is out of tolerance an alarm is generated. This value is set at between 10–60 seconds. Longer intervals result in slower detection of data link problems. Shorter intervals add processing overhead to the Integrity Monitor.*	4 to 7dB bellow nominal (FI: 1-100 dB)	10 – 60 s (FI: 60-65 s)	- Causes warning or alarm - Possibly automatic switch to standby equipment	- Will reduce coverage area
Minimum satellites This setting specifies the minimum number of satellites with accompanying pseudorange corrections required to generate a valid 3D differential position solution. The integrity monitor should be set to detect the PRCs of at least 4 satellites. When the visible satellite constellation goes below this threshold, an internal alarm may be sent to the service provider. This value is set to alarm when less than 4 satellites are visible.	4 (FI: 3-4)	(FI: 30-65)	- Causes an alarm - Causes station health (header) to be set "unmonitored" only if no position fix can be performed due to low number of SV	- Station should be used with caution and switch to another DGNSS site if available

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
SV Interval (Difference of used satellites) This parameter is not described in [25]. Some manufacturers, however, have implemented this setting. This interval is basically a time period over which data is observed, specifying the maximum time delta between correctors for use in a solution computation. The Integrity Monitor is continuously monitoring the SV interval so there should be little or no change in processing overhead. If the value is out of tolerance an alarm is generated. Service providers that employ this parameter typically set this value from 0-10s.		0 to 10 s	- Causes an alarm - Causes station health (header) to be set "unmonitored" - Possibly automatic switch to standby equipment - Possibly automatic switch to standby equipment	- Station should be used with caution and switch to another DGNSS site if available
<u>HDOP</u> The IM uses horizontal dilution of precision (HDOP) to measure the current quality of the constellation geometry as it relates to triangulation of the pseudoranges. This value is set at <7.5. Low HDOP numbers indicate good constellation geometry. High HDOP values indicate poor constellation geometry. If the HDOP is higher than the threshold, the validity of the corrections becomes uncertain and the site's pseudorange generation must be suspended. HDOP interval is a time period over which data is observed. The IM is continuously monitoring the HDOP so there should be little or no processing overhead change. If the value is out of tolerance an alarm is generated. This value is set at between 10–30 seconds. Longer intervals result in slower detection of HDOP data problems. Shorter intervals add processing overhead to the Integrity Monitor.	< 7.5 (FI: 4-6)	10 – 30 s (FI: 30-35 s)	- Causes an alarm - Causes station health (header) to be set "unmonitored" - Possibly automatic switch to standby equipment	- Station should be used with caution and switch to another DGNSS site if available

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
<u>Absolute Horizontal Position</u> Also referred to as Horizontal Position Error. The IM applies pseudorange corrections received over the data link to the pseudoranges generated by its internal GPS receiver. It uses these corrected pseudo ranges to generate a DGPS corrected position. The radial error in that position in relation to the surveyed position is the 2D position Error. This value is set at between 5-10 meters. Smaller threshold values may result in greater site unavailability time – more time out of tolerance. Larger threshold values may result in greater system inaccuracies transmitted to the user. 2D position interval is a time period over which data is observed. The IM is continuously monitoring the 2D position interval so there should be little or no processing overhead change. If the value is out of tolerance an alarm is generated. This value is set at between 10–30 seconds. Longer intervals result in slower detection of system position accuracy problems that may originate from a variety of sources. Shorter intervals add processing overhead to the IM.	5 – 10m (FI: 10 m)	10 – 30 s (FI: 20 s)	- Causes an alarm - Causes station health (header) to be set "unhealthy" - Possibly automatic switch to standby equipment	- Station should not be used - Switch to another DGNSS site if available

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
<u>Pseudorange residual (PRR)</u> The IM applies pseudorange corrections received over the data link to individual pseudoranges generated by its internal GPS receiver, and then compares them to the known surveyed position of its own antenna. The resulting value is the Pseudorange residual. This value is set at <12 meters. Smaller threshold values may result in the IM telling the RS to stop correcting satellites unnecessarily. Larger threshold values may result in greater system inaccuracies transmitted to the user. Pseudorange residual interval is a time period over which data is observed. The IM is continuously monitoring the Pseudorange residual interval so there should be little or no processing overhead change. If the value is out of tolerance an alarm is generated. This value is set at between 10–30 seconds. Longer intervals result in slower detection of pseudorange accuracy problems. Shorter intervals add processing overhead to the Integrity Monitor.	< 12m (FI: 100-150 m)	10 – 30 s (FI: 30-65 s)	- Causes an alarm - Will set PRC and RRC values for a specific SV to "do not use" as described	- Will drop "do not use" marked SV from position solution

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
<u>Range rate residual</u> The difference between the most recent range rate correction received and the current pseudorange rate measured at the IM. This value is set at <10m/s. Motion faster than the threshold value may indicate a problem with the satellite actually moving erratically or may indicate a satellite clock problem. Smaller threshold values may result in the IM telling the RS to stop correcting satellites unnecessarily. Larger threshold values may result in greater system inaccuracies transmitted to the user. Range rate residual interval is a time period over which data is observed. The IM is continuously monitoring the Range rate residual interval so there should be little or no processing overhead change. If the value is out of tolerance an alarm is generated. This value is set at between 10–60 seconds. Longer intervals result in slower detection of excessive Reference Station Range Rate correction values. Shorter intervals add processing overhead to the Integrity Monitor.	< 10 m/s (2-5 m/s)	10 – 60 s (FI: 30-65)	- Causes an alarm - Will set PRC and RRC values for a specific SV to "do not use" as described	- Will drop "do not use" marked SV from position solution

Parameter	Proposed setting/ threshold	Interval	System Impact	
			To system provider	To user
<u>Low UDRE</u> UDRE is a one-sigma estimate of the pseudorange correction error due to ambient noise and residual multipath. Basically, every PRC generated by the RS has a "reported" UDRE value in it and when the IM uses the PRC it tries to determine if the "reported" UDRE is correct. If the IM determines that the reported UDRE is set to a value "LOWER" than it should be, then we have a "Low UDRE" condition. This value is set at 1m-100m. Using higher UDRE threshold values may allow multipath and receiver noise errors to impact the user. Lower values may result in excessive site unavailable time. Low UDRE interval is a time period over which data is observed. The IM is continuously monitoring the UDRE so there should be little or no processing overhead change. If the value is out of tolerance an alarm is generated. This value is set at between 10–30 seconds. Longer intervals result in slower detection of problems. Shorter intervals add processing overhead to the Integrity Monitor.	1 – 100m (FI: 100-101m)	Please consult manufacturer for settings (FI: 100-600 s)	- Causes an alarm - Cause station health (header) to be set "unmonitored" - Possibly automatic switch to standby equipment	- Switch to another DGNSS site if available
<u>Elevation angle (Mask Angle)</u> The mask angle screens all satellites below a predetermined angle above the horizon. The IM will not use satellites below this level in its position and/or clock solutions. The mask angle is set at between 5 to 10 degrees. Operating at the lower end of the range will benefit the service provider as more useable satellites will improve availability, especially when some satellite(s) are unavailable. However, multipath, tropospheric and satellite observables errors tend to become more significant in degrading the user position solution as the mask angle is lowered (i.e. low elevation angle satellites are included in the solution).	0 – 10 deg. (FI: 7 deg.)	n/a	- Optimal monitoring of the broadcast when setting is identical to the RS's	- Optimal broadcast service

* Note: The Message Error Ratio, Beacon SNR and Signal Strength intervals are similar to moving window averages - calculations are being made every second no matter what the Interval is, but if during or for an entire Interval the value goes beyond the Threshold, an alarm is generated. Shorter Intervals show changes more quickly, and longer Intervals show changes more slowly (because it takes a greater number of changes to raise the "average").

ANNEX C EXAMPLE OF VALIDATION OF AVAILABILITY AND CONTINUITY

A DGNSS service provider designates its DGNSS service area as the area covered from at least one of the service provider's 12 DGNSS beacons. The coverage from each individual beacon is calculated. By using a geographical information analysis tool, the coverage areas for the individual beacons is found to combine in such a way that:

- 25% of the service area receive coverage from only one beacon
- 50% of the service area receive coverage from two beacons
- 25% of the service area receive coverage from three or more beacons

Signal outages on individual beacons are recorded over a period of time. The average MTBF for the 12 beacons was found to be 2 failures/year = 4380 hours. The average time to restore for the 12 beacons was 2 days = 48 hours.

From this the average signal availability for the signals from the 12 beacons is 1 - 2*48/4380 = 97,81% and the average service availability within the service area is 0,25*(1-(1-0,9781)) + 0,5*(1-(1-0, 9781)^2) + 0,25*(1-(1-0, 9781)^3) = 99,42%.

The average continuity is C = 1-CTI/MTBF =1-0,25/4380 = 99,994%.

ANNEX D EXAMPLE HOW TO CALCULATE DGNSS SERVICE AVAILABILITY

Mathematically the DGNSS service (signal) availability can be written as:

$$Availability_{DGNSS\ Service} = \frac{MTBO}{MTBO + MTSR} = \frac{UP\ TIME}{Total\ TIME}$$

Where:

MTBO = Mean time between outages; based on a 2 year averaged period (30 days ocean phase)

MTSR = Mean time to service restoration; based on a 2 year averaged period (30 days ocean phase)

This accounts for scheduled and unscheduled service interruptions, i.e. preventative and corrective maintenance.

<u>Example</u>

Assuming a scheduled maintenance cycle of 6 months, i.e. mean time between scheduled maintenance is 0.5 years – there will be 4 scheduled maintenance breaks in 2 years. Assuming a MTBF of 2 years, the average number of failures over 2 years is expected to be approximately 1.

Summing, there will be 5 outages over the two-year period. Therefore the mean time between outages is 2/5 years or approximately 3500 hours.

If the average out-of-service time for scheduled maintenance is 6 hours. The total out-of-service time for scheduled maintenance over the two-year period is 24 hours. Similarly, if the unscheduled maintenance period is 12 hours, the total time out of service over the two-year period is 36 hours. This covers 5 maintenance events and, therefore, the mean time to service restoration is 36/5 hours or approximately 7 hours.

The overall availability over the two year period is therefore (3500/(3500+7)) = 99.8%

ANNEX E MF ANTENNA PERFORMANCE

The overall performance of a transmitting antenna in the MF band is characterized by following technical items:

- effective antenna height and radiation resistance depending from antenna type and size (height, width, guy wires, if used, etc.);
- antenna efficiency, total antenna resistance and earth resistance;
- service range of the station as a function of transmitter output power;
- insulation resistance;
- influence of salt spray, dirt, ice and wind load .

To plan a DGNSS site with a planned range at a given field strength level (typically 50, 75 or 100 µV/m) it is essential to have a useful combination of transmitter output power and an MF antenna which ensures an adequate antenna efficiency. The antenna efficiency depends mainly on two factors:

- the radiation resistance which depends on the shape and height of the antenna (expressed by the efficient electrical height of an antenna (Heff);
- the total series resistance at the antenna input which is a sum of losses within the loading and tuning coil as well as the losses in the earth.

The following will provide short background information about the interrelation of the physical antenna height, effective antenna height, the radiation resistance (R_{rad}), and the antenna efficiency η. The antenna (or power) efficiency η is given by

$$\eta = \frac{P_{rad}}{P_{in}} = \frac{I_A^2 \cdot R_{rad}}{I_A^2 \cdot R_{tot}} = \frac{R_{rad}}{R_{rad}^* + R_L + R_E}, \quad with \quad R_{tot} = R_{rad} + R_L + R_E$$

and

P_{in}	-	input power
P_{rad}	-	radiated power
I_A	-	antenna current at antenna input
R_{tot}	-	total series resistance of the antenna resonant circuit
R_{rad}	-	radiation resistance
R_L	-	resistance of ATU and loading coil, (R_L typically between 2 and 7 Ω)
R_E	-	earth resistance (R_E typically between 3 and 9 Ω)

The table below presents the antenna efficiency for some typical values of the total resistance.

Antenna efficiency for some typical values of total resistance

R_E [Ω]	earth resistance and ground conductivity	η [%] for an antenna with a radiation resistance of 1 Ω and R_L=7 Ω
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

R_{rad} (H_{eff}) is an inherent property of the antenna, whereas η also depends on the earth mat and ground conductivity. An impedance meter allows to measure the total resistance R_{tot} and to determine the antenna efficiency η for a real installation.