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Radiocommunication Sector of ITU

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(11/2018)

Technical studies on the satellite component of the VHF data exchange system

M Series

Mobile, radiodetermination, amateur and related satellite services

International Telecommunication Union

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***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R M.2435-0

Technical studies on the satellite component of the VHF data exchange system[1]

(2018)

Scope

At the WRC-15, Resolution **360 (Rev.WRC-15)** was revised and updated to invite the WRC-19 to consider modifications of the Radio Regulations (RR) in order to introduce the VHF data exchange system (VDES) satellite component (VDE-SAT) in support of the digitization of maritime communications. In preparation for WRC-19, ITU-R was invited to conduct sharing and compatibility studies between VDE-SAT and incumbent services in the same and adjacent frequency. This Report is the response from ITU-R to that invitation. This report provides a summary of why a VDES satellite component is required, identifies the spectrum requirements and provides a technical description of the satellite component of VDES and the results of the appropriate sharing and compatibility studies.

Keywords

VDES, VDE-SAT, maritime

Glossary / abbreviations

ACM	Adaptive coding and modulation
AIS	Automatic identification system
ARQ	Automatic repeat request
ASC	announcement signalling channel
ASM	Application specific message
AWGN	Additive white gaussian noise
BCH	Bose-Chaudhuri-Hocquenghem coding
dBd	Antenna gain (dB) relative to a dipole
DVB-S	Digital Video Broadcasting – Satellite
e.i.r.p.	Equivalent isotropic radiated power
e.r.p.	Equivalent radiated power
EOC	Emergency operations centre
E_s/N_0	Symbol energy to noise density ratio
FEC	Forward error correction
FFM	Fixed-Frequency Mode
FPGA	Field programmable gate array
GMDSS	Global Maritime Distress and Safety System
LDPC	Low density parity-check coding
LEO	Low earth orbit
LNA	Low noise amplifier

[1] The Russian Federation notes that pfd mask taken from the Recommendation ITU-R M.2092 and used in this ITU-R Report in §§ 6.1.1 and 6.1.2 to justify the View 1 is relaxed of 12 dB compared to the pfd mask which shall guarantee protection of land mobile and fixed service systems. The Russian Federation is of the view that this pfd mask was developed with arithmetical mistake occurred when $I/N = -6$ dB protection criteria was taken into account.

MMSS	Maritime mobile-satellite service
MSI	Maritime safety information
PA	Power amplifier
PDF	Probability density function
PER	Packet error rate
pfd	Power flux-density
PG	Processing gain
QPSK	Quadrature phase shift keying
RHCP	Right hand circular polarization
RR	Radio regulations
Rx	Receive
SAR	Search and rescue
SAT-AIS	Satellite – automatic identification system
SDR	Software defined radio
SER	Symbol error rate
SBB	Satellite bulletin board
TBB	Terrestrial bulletin board
Tx	Transmit
VDES	VHF data exchange system
VDE-SAT	VHF data exchange – satellite
VDE-TER	VHF data exchange – terrestrial
VDL	VHF datalink
VTS	Vessel traffic service
UTC	Universal time coordinated

Related ITU-R Recommendations and Reports

Recommendation ITU-R SM.329 – Unwanted emissions in the spurious domain

Recommendation ITU-R P.372 – Radio noise

Recommendation ITU-R F.699 – Reference radiation patterns for fixed wireless system antennas for use in coordination studies and interference assessment in the frequency range from 100 MHz to 86 GHz

Recommendation ITU-R F.758 – System parameters and considerations in the development of criteria for sharing or compatibility between digital fixed wireless systems in the fixed service and systems in other services and other sources of interference

Recommendation ITU-R RA.769 – Protection criteria used for radio astronomical measurements

Recommendation ITU-R SM.1055 – The use of spread spectrum techniques

Recommendation ITU-R M.1184 – Technical characteristics of mobile satellite systems in the frequency bands below 3 GHz for use in developing criteria for sharing between the mobile-satellite service and other services

Recommendation ITU-R F.1336 – Reference radiation patterns of omnidirectional, sectoral and other antennas for the fixed and mobile service for use in sharing studies in the frequency range from 400 MHz to about 70 GHz

Recommendation ITU-R P.1546 – Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3 000 MHz

Recommendation ITU-R M.1802 – Characteristics and protection criteria for radars operating in the radiolocation service in the frequency band 30-300 MHz

Recommendation ITU-R M.1808 – Technical and operational characteristics of conventional and trunked land mobile systems operating in the mobile service allocations below 869 MHz to be used in sharing studies

Recommendation ITU-R M.2092 – Technical characteristics for a VHF data exchange system in the VHF maritime mobile band

Report ITU-R M.1021 – Equipment characteristics for digital transmission in the land mobile services

Report ITU-R M.2172 – Radiolocation service sharing feasibility in the frequency band 154-156 MHz

Report ITU-R S.2173 – Multi-carrier based transmission techniques for satellite systems

Report ITU-R M.2317 – VHF data exchange system channel sounding campaign

1 Introduction

At the WRC-15, Resolution **360 (Rev.WRC-15)** was revised and updated to invite the WRC-19 to consider, based on the results of ITU-R studies, modifications of the Radio Regulations (RR), including new spectrum allocations to the maritime mobile-satellite service (MMSS) (Earth-to-space and space-to-Earth), preferably within the frequency bands 156.0125-157.4375 MHz and 160.6125-162.0375 MHz of RR Appendix **18**, to enable a new VHF data exchange satellite component (call VDE-SAT), while ensuring that this component will not degrade the current VHF data exchange terrestrial component (call VDE-TER), application specific message (ASM) and automatic identification system (AIS) operations and not impose any additional constraints on existing services in these and adjacent frequency bands as stated in *recognizing d)* and *e)* of Resolution **360 (Rev.WRC-15)**.

Furthermore, in preparation for WRC-19, ITU-R was invited to conduct, as a matter of urgency, and in time for WRC-19, sharing and compatibility studies between VDE-SAT component and incumbent services in the same and adjacent frequency bands specified in *recognizing d)* and *e)* of Resolution **360 (Rev.WRC-15)** to determine potential regulatory actions, including spectrum allocations to the MMSS (Earth-to-space and space-to-Earth) for VDES applications.

This Report is the response from ITU-R to that invitation. This Report provides a summary of why a VDE-SAT component is required, identifies the spectrum requirements, and gives a technical description of the VDE-SAT and the results of the appropriate sharing and compatibility studies.

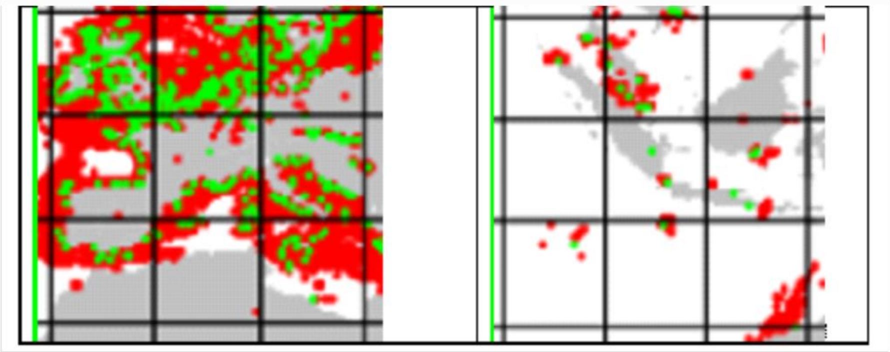
2 VHF data exchange-satellite, the essential supplement to terrestrial VHF data exchange system

2.1 Practical aspects of deploying coastal coverage

Analysis of ship density on a global scale shows that coastal areas play a key role in ship traffic and safety management and the VDE-TER will be a vital component upon successful implementation of VDES for a competent authority. However, the current state of terrestrial AIS deployment shows that, while some areas like Europe, the US and Japan are largely covered, others like the West of Africa or the South West of Asia have much sparser coverage. This is illustrated in Fig. 1.

FIGURE 1

Automatic identification system costal station locations (green points) and automatic identification system data (red points)



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Many countries with long coastlines are currently not able to provide terrestrial infrastructure to cover their coastlines. There are numerous challenges, including finding appropriate hosting sites with access to a reliable power supply. Figure 2 represents a 10-minute distribution of terrestrial AIS data over three consecutive days in the Gulf of Guinea illustrating critical gaps in routine operations.

FIGURE 2

Representation of the 10 minute distribution of terrestrial automatic identification system data over three consecutive days in the Gulf of Guinea

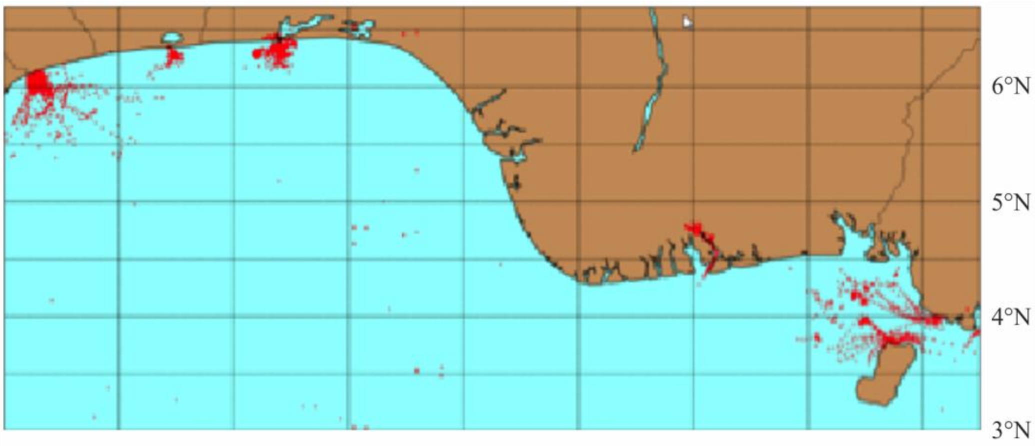

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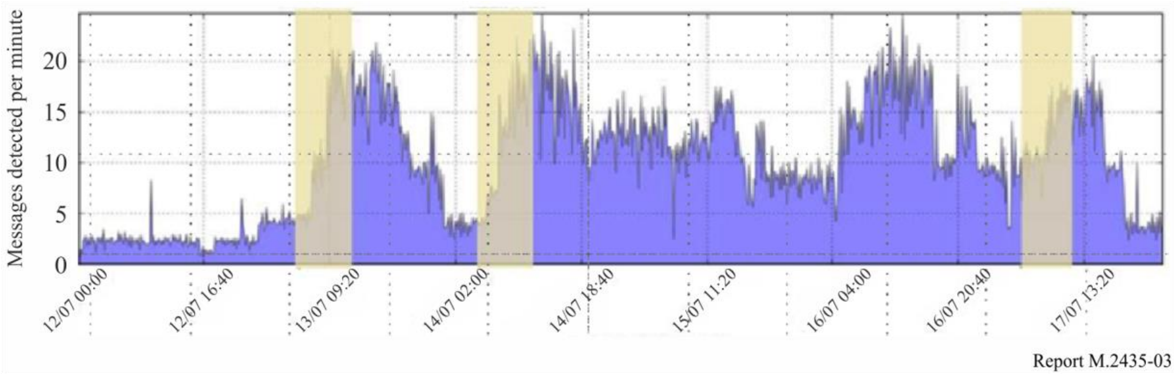
Figure 3 exemplifies the high variability observed on the temporal distribution of AIS messages collected from coastal stations. Such high variability indicates severe disruption to ship tracking. Since AIS is a component of VDES, it can be assumed these same sites are likely to be used for VDES, thus VDES will suffer from similar issues of infrastructure distribution, reliability and maintenance in remote and difficult to access areas, and the requirement for sufficient budget for technical support.

Because many administrations already have a good foundation of AIS sites throughout their coverage area, implementing VDES on existing sites will greatly enhance e-navigation within the VHF band. However, some administrations are concerned about how VDE-TER will co-locate with AIS1, AIS2, ASM1 and ASM2. These administrations believe there is a significant challenge to implement the existing VDE-TER channel plan without causing interference to AIS1, AIS2, ASM1 and ASM2. Either a sufficient frequency separation or a physical geographical separation may be required between VDE-TER and AIS operations. Physical geographical separation implies building additional sites which, in some countries, would be difficult especially in remote areas with limited infrastructure.

Some Administrations have remotely operated AIS sites. In order to implement VDES for coverage that is similar to AIS, it is expected that similar additional sites would be required to operate VDES. Alternatively, a frequency separation could solve anticipated interference to AIS. One option would be to allow the operation of VDE-TER in simplex mode on channels 1024, 1084, 1025 and 1085. This would eliminate desensitization to AIS from VDE-TER and enable co-location of AIS and VDES. Furthermore, operating the VDE-TER in simplex mode on the lower legs would greatly reduce the sharing of resources between VDE-TER and VDE-SAT, which would in turn provide better performance of the VDE-SAT.

FIGURE 3

High variability observed on the distribution of automatic identification system messages collected from coastal stations in the Gulf of Guinea



Note: The grey line corresponds to sunrise when power generators possibly are activated on some sites

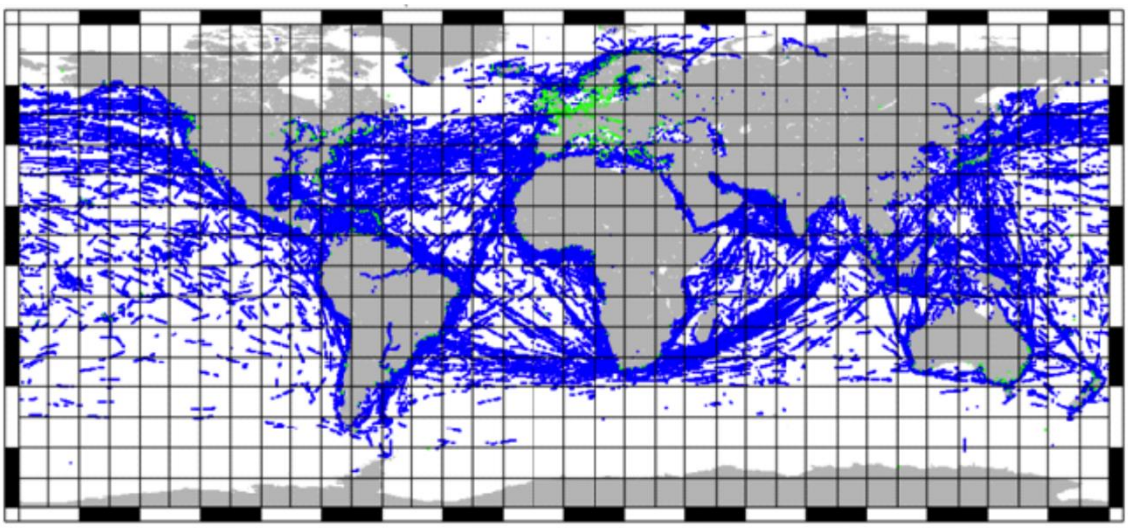
VDE-SAT will provide an opportunity to fill the gaps in the coverage of coastal areas. VDE-SAT can also provide redundancy in operations in a situation where parts of the terrestrial infrastructure experience outages. VDE-SAT technical characteristics provide a flexible mode of operation, allowing VDE-SAT communications to dynamically adapt to changes in the terrestrial VDE coverage.

2.2 Expanding VHF data exchange system from the coastal area to global coverage

The implementation of the satellite – automatic identification system (SAT-AIS) has already demonstrated how the capabilities of the terrestrial AIS can be extended to global coverage; this is illustrated in Fig. 4. Like SAT-AIS, VDE-SAT will enable the extension of terrestrial VDE capabilities to long-range communications on a global scale. With polar orbiting satellites, the Arctic and Antarctic will also be covered. VDE-SAT is designed specifically for satellite services and thus it is not subject to some of the limitations experienced with SAT-AIS.

FIGURE 4

Comparison of one day of terrestrial automatic identification system data (green dots) to one day of satellite automatic identification system data (blue dots) – April 2015 [Source CLS]



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2.3 Use case descriptions

VDES has been developed to address the indications of overload of the AIS VHF datalink (VDL) and also enable a wider, seamless, data exchange capability to support e-Navigation. VDES supports the increasing communications requirements identified through the development of e-Navigation and could potentially support the modernization of the global maritime distress and safety system (GMDSS).

A number of use-cases for VDES have been developed, based on the work carried out on user need analysis for e-Navigation. Seven high level use-cases have been identified for VDES[2]:

– Supporting communications during search and rescue (SAR) operations
– Distributing maritime safety information (MSI)
– Facilitating ship reporting
– Supporting vessel traffic services
– Providing updates for charts and publications
– Supporting exchange of ship route information (route exchange)
– Supporting additional communications requirements such as information to tugs (logistics).

The following sections provide further information on some of these use-cases.

2.3.1 Distributing MSI

Maritime Safety Information consists of navigational and meteorological warnings, meteorological forecasts, and other urgent safety-related messages broadcasted to ships. VDE-SAT, as the only standard (non-proprietary) global communications link for the maritime community would provide for the global distribution of MSI extending existing terrestrial coverage and providing coverage where a terrestrial infrastructure isnot practical such as the Arctic Sea. MSI may include the following information:

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[2] Refer to International Association of Marine Aids to Navigation and Lighthouse Authorities Guideline 1117 for further information on VDES use-cases.

– warnings of severe live or forecasted weather conditions to make the trip as safe and comfortable (passengers' trip) as possible;

– warnings of navigation hazards like dangers at sea (floating objects like containers, offshore structures, drifting buoys or ships);

– route information, protected marine environment areas, restricted navigation zones, under keel clearance;

– piracy or armed robbery at sea information including scene identification, warnings, and procedures.

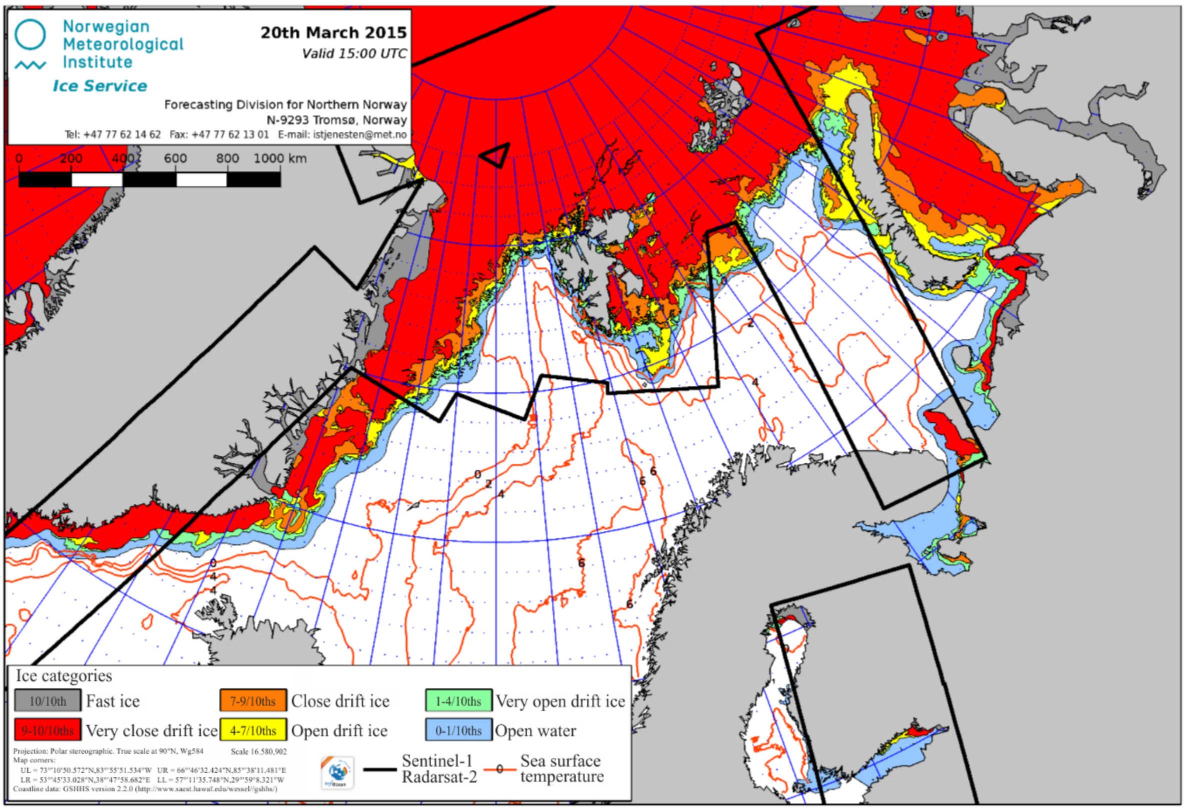
2.3.1.1 Ice chart distribution

Information on sea ice conditions is important to help ensure safe passage. Knowledge of areas with sea ice along a ship's planned route allows the ship to find the most efficient route. Together with prognoses for expected ice movements, ice charts allow mariners to plan ahead and significantly reduce the risk of vessels becoming ice locked.

The Norwegian Meteorological Institute produces ice charts for the European part of the Arctic. Currently ice charts and prognoses for the next 24 hours are generated on a daily basis. The ice charts are available as graphic files from the website of the Norwegian Meteorological Institute for free. An example ice chart showing the European part of the Arctic is provided in Fig. 5.

FIGURE 5

Example ice chart graphics showing the European part of the arctic, available online from the Norwegian Meteorological Institute



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The ice information should also become available as a grid of geographical positions, with both the current ice situation and prognoses. It could then be formatted in a way suitable for distribution to electronic chart plotters. The amount of data to transfer depends on the size of the area and the geographical resolution of the ice information.

The distribution systems currently in use require manual downloads. With VDE-SAT the distribution systems could become automated and more user friendly. Ships should have access to the updated ice charts and prognoses as soon as possible, as well as upon request when needed by the navigator on-board.

2.3.2 Facilitating ship reporting

Ship reporting may be related to a mandatory requirement, a collaborative approach to collect and share information or of specific interest. VDE-SAT will facilitate ship reporting.

IMO has published guidelines on implementing a “maritime single window” system in maritime transport with the aim to reduce administrative burden and facilitate coordination between stakeholders. The guidelines include reporting requirements for ships visiting foreign ports, known as a notice of arrival. This 96 hour pre-entry report, and other reports identified within the guidelines, use pre-determined templated forms (IMO Fal forms). While static information may be provided from a ship’s agent (shore/shore communications) more dynamic data, and updates on information previously provided, can be sent from the ship via the VDE-SAT to the relevant authority. Similar procedures can also be used for mandatory reporting of specific items, for example, catch amounts for fishing vessels.

Another ship reporting case relevant for VDE-SAT is the voluntary observing ship program in which ships regularly report weather. Using VDE-SAT the recording and data transmission could be automated, providing data from ship sensors in a machine to machine format, without the requirement for manual reporting. This data is critical for accurate weather forecasting and modelling.

2.3.3 Small vessel fleets or developing areas

The VDE-SAT is designed for satellite communications and will support a simplified low cost transceiver. This low cost, highly robust option will provide significant value for a large number of fishermen in developing areas. VDE-SAT could be used to provide weather warnings and alerts to small vessels, allowing them to seek a safe harbour.

The VDE-SAT may also provide a solution for developing countries to manage the coverage areas of their areas of maritime responsibility where a terrestrial infrastructure is cost prohibitive or where the necessary power infrastructure does not exist.

3 Identification of spectrum requirements and rationale for the use of the frequency bands of RR Appendix 18

3.1 Spectrum requirement for the VHF data exchange-satellite

The VDE-SAT communications functions (ship-to-satellite and satellite-to-ship) are intended to be fully integrated with the VDE-TER communications functions (AIS, ASM, ship-to-ship, ship-to-shore and shore-to-ship) in the shipborne VDES equipment. The shipborne VDES equipment will preferably utilize one combined transmitting/receiving VDES antenna system. For this reason, it is desirable to utilize frequencies that are within the range of RR Appendix **18** (156.025 MHz to 162.025 MHz), as shown in Fig. 6. The bandwidth allocated to each function should be as wide as possible, considering the large number of ships globally that carry AIS and may decide to upgrade to VDES.

The spectrum requirements and the use of the frequencies specified in Recommendation ITU-R M.2092-0 were determined based on:

– Assessment of the maritime electromagnetic environment in ports, waterways and open sea, plus the shipborne electromagnetic operating environment as documented in Report ITU-R M.2317-0 – VHF data exchange system channel sounding campaign, and

– Assessment of the data requirements to support the use cases as documented in Report ITU-R M.2371-0 – Selection of the channel plan for a VHF data exchange system.

For terrestrial operations ship-to-ship, ship-to-shore and shore-to-ship, the channel plan designated in Recommendation ITU-R M.2092-0 was developed prior to WRC-15. However, further studies were prescribed under Resolution **360 (Rev.WRC-15)** for the VDE-SAT component which is the foundation for WRC-19 agenda item 1.9.2 and the subject of this Report.

For the satellite uplink, potential vulnerability of the satellite receiving station from other terrestrial services has been noted, and techniques to mitigate this interference are proposed in this Report, including frequency diversity by the addition of a second 50 kHz uplink at 4.6 MHz frequency separation, as proposed in frequency plan alternative 2.

For the satellite downlink, the pfd mask specified in Recommendation ITU-R M.2092-0 that was agreed by the effected ITU-R Working Parties, is set to a very low level to avoid interference with terrestrial services, and this poses a potential vulnerability to adverse conditions due to a low link margin satellite-to-ship. To mitigate this potential vulnerability, application of spread spectrum techniques, which requires a wider bandwidth, is proposed in frequency plan alternative 2.

3.2 Potential use of the frequency band 160.975-161.475 MHz versus channels 2024/2084/2025/2085/2026/2086 for the satellite downlink

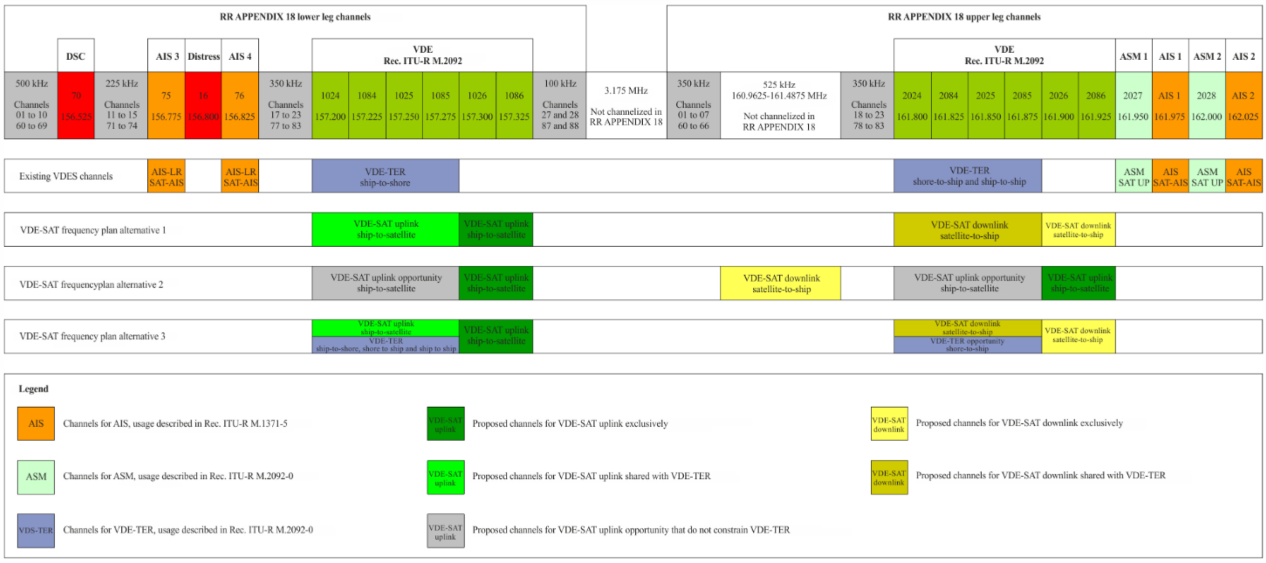
Noting the organization and frequency use of RR Appendix **18**, which is channelized in two sections of 25 kHz channels, the lower section has center frequencies of 156.025 MHz to 157.425 MHz and the upper section has center frequencies of 160.625 MHz to 162.025 MHz, spaced 4.6 MHz apart. The channels are numbered in two groups, 60 numbers apart, 01 to 28 and 60 to 88. Some of the channels are duplex channels with paired frequencies that are 4.6 MHz apart, for example, channel 60 (156.025 MHz and 160.625 MHz) is followed by channel 01 (156.050 MHz and 160.650 MHz), then by channel 61 (156.075 MHz and 160.675 MHz), then by channel 02 (156.100 MHz and 160.700 MHz), etc., and this sequence continues to channel 07 (156.350 MHz and 160.950 MHz). But then the channels 67 to 77 are implemented as simplex channels, where only the lower side (156.375 MHz to 156.875 MHz) is used. The unused upper side of these 25 kHz channels with center frequencies of 160.975 MHz to 161.475 MHz comprises a 525 kHz bandwidth that may be considered as an alternative for the VDE-SAT downlink, since it poses no conflict to incumbent maritime services and could be constrained with an appropriate pfd mask to protect incumbent terrestrial services. Utilization of this band could provide very robust satellite-to-ship communications.

3.3 Frequency plan alternatives

The channels 24, 84, 25, 85, 26 and 86 are allocated for VDE-TER after WRC-15, with the lower leg frequencies used for ship-to-shore and the upper leg frequencies used for shore-to-ship and ship-to-ship. The channels 2027 (ASM 1) and 2028 (ASM 2) are allocated for ASM. This Report considers three alternative frequency utilization plans for VDE-SAT. They describe how resources are allocated and shared between VDE-TER and VDE-SAT. These three alternative frequency utilization plans are illustrated in Fig. 6 in two different manners, and described further below.

FIGURE 6

RR Appendix 18 and VHF data exchange system frequency utilization plans



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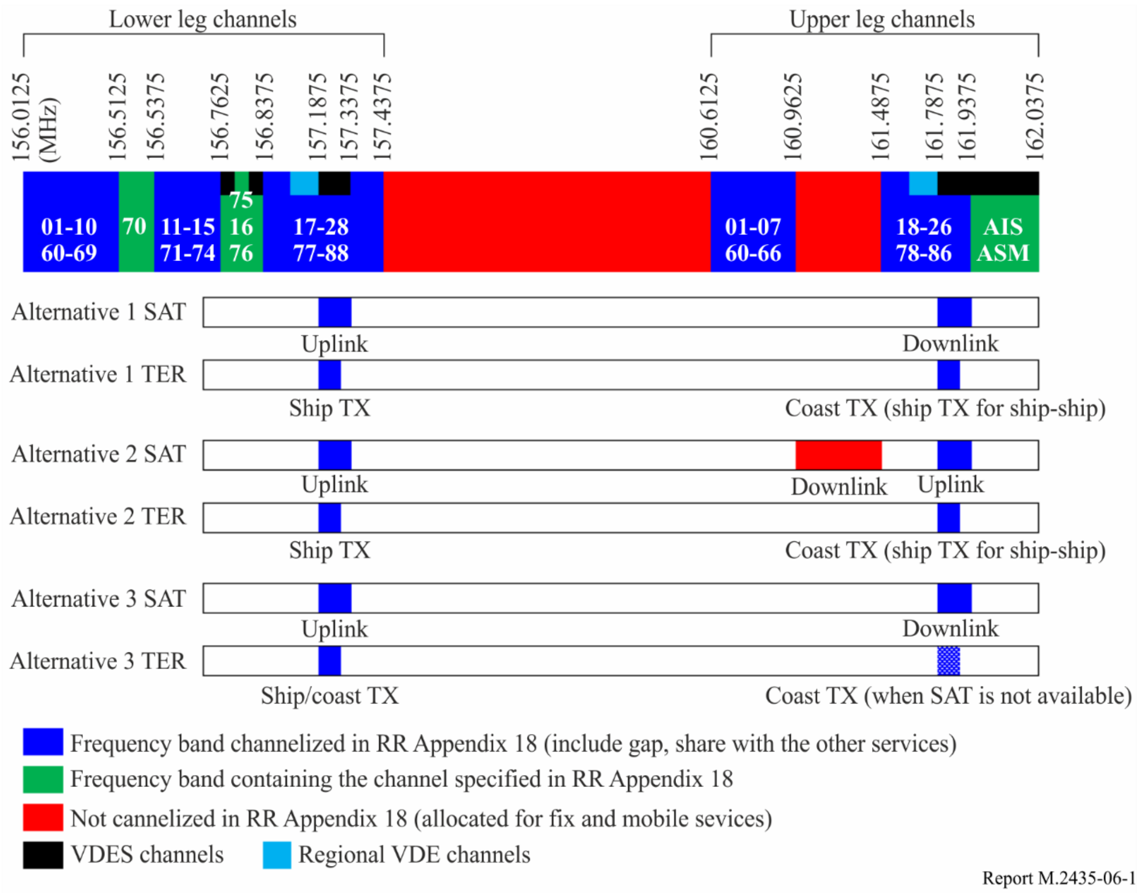

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3.3.1 Frequency plan alternative 1

Alternative 1 has been evaluated according to the criteria defined within the Report ITU-R M.2371-0.

Frequency plan alternative 1 allows for utilization of the channels 24, 84, 25, 85, 26 and 86 in a shared manner between VDE-TER and VDE-SAT.

– The four channels 1024, 1084, 1025 and 1085 are shared between ship-to-shore and ship-to-satellite (VDE-SAT uplink) communications
– The two channels 1026 and 1086 are identified for ship-to-satellite (VDE-SAT uplink) communications, and are not used for VDE-TER communications
– The four channels 2024, 2084, 2025 and 2085 are shared among shore-to-ship, ship-to-ship and satellite-to-ship (VDE-SAT downlink) communications
– The two channels 2026 and 2086 are identified for satellite-to-ship (VDE-SAT downlink) communications, and are not used for VDE-TER communications

3.3.2 Frequency plan alternative 2

This alternative plan 2 is similar to alternative 1 except for the satellite downlink which has been relocated. In addition, parts of this alternative have not been evaluated according to the criteria defined within the Report ITU-R M.2371-0.

Frequency plan alternative 2 allows for utilization of channels 24, 84, 25 and 85 primarily for VDE-TER, while channels 26 and 86 are identified for VDE-SAT uplink communications, and are not used for VDE-TER communications. VDE-SAT uplink is also possible in channels 24, 84, 25 and 85, but the VDE-SAT uplink on these channels should not impose constraints on VDE-TER. Frequencies are identified for VDE-SAT downlink within the frequency range 160.9625 MHz to 161.4875 MHz, which is not channelized in RR Appendix **18**.

– The four channels 1024, 1084, 1025 and 1085 are identified for ship-to-shore communications, but ship-to-satellite (VDE-SAT uplink) communications are possible without imposing constraints on ship-to-shore communications
– The four channels 2024, 2084, 2025 and 2085 are identified for shore-to-ship and ship-to-ship communications, but ship-to-satellite (VDE-SAT uplink) communications are possible without imposing constraints on shore-to-ship and ship-to-ship communications
– The four channels 1026, 1086, 2026 and 2086 are identified for ship-to-satellite (VDE-SAT uplink) communications, and are not used for VDE-TER communications
– Frequencies are identified for satellite-to-ship (VDE-SAT downlink) communications within the frequency range 160.9625 MHz to 161.4875 MHz, which is not channelized in RR Appendix **18**.

3.3.3 Frequency plan alternative 3

This alternative plan 3 is similar to alternative 1 except the VDE-TER plan has been slightly modified to permit the option of operating in simplex mode on the lower legs. In addition, parts of this alternative have not been evaluated according to the criteria defined within the Report ITU-R M.2371-0.

Frequency plan alternative 3 allows for the utilization of the channels 24, 84, 25 and 85 in a shared manner between VDE-TER and VDE-SAT, while channels 26 and 86 are identified for VDE-SAT communications and are not used for VDE-TER communications.

– The four channels 1024, 1084, 1025 and 1085 are shared between ship-to-shore, ship-to-ship, shore-to-ship and ship-to-satellite (VDE-SAT uplink) communications.
– The two channels 1026 and 1086 are identified for ship-to-satellite (VDE-SAT uplink) communications, and are not used for VDE-TER.
– The four channels 2024, 2084, 2025 and 2085 are primarily for satellite-to-ship (VDE-SAT downlink) communications, while shore-to-ship communications may be possible without imposing constraints on ship-to-satellite communications.

– The two channels 2026 and 2086 are identified for satellite-to-ship (VDE-SAT downlink) communications, and are not used for VDE-TER communications.

3.4 Evaluation of the three frequency plan alternatives

A comparison of the relative merits of the three frequency plan alternatives is shown in Table 1.

TABLE 1

Comparison of frequency plan alternatives 1, 2 and 3

	Frequency plan alternative 1	**Frequency plan alternative 2**	**Frequency plan alternative 3**
Resource Sharing	Bulletin board based. Time-sharing Band-sharing For the upper 150 kHz band	No resource sharing required between VDES services Dedicated separate frequency bands with satellite downlink outside Appendix **18**	No resource sharing required between VDES services Dedicated separate bands
Available bandwidth	Both in upper and lower leg: 50 kHz for VDE-TER 50 kHz for VDE-SAT 50 kHz is time shared based on bulletin board	In upper leg: 100 kHz for VDE-TER 575 kHz for VDE-SAT In lower leg: 100 kHz for VDE-TER 50 kHz for VDE-SAT	In upper leg: 150 kHz for VDE-SAT In lower leg: 100 kHz for VDE-TER 150 kHz for VDE-SAT
Service interdependency	High for both services Coordination of resource usage between VDES services required for efficient spectrum utilization	Low for both service VDES services operate independently	Low for both service VDES services operate without interdependency
Service capacity and link robustness	Moderate for VDE-TER Limited for VDE-SAT	High for both services	Limited for both services
Interference from land stations	Limited interference from land stations in coastal and no interference in high-sea areas	Interference from land stations possible in coastal areas, none in high-sea areas	Limited interference from land stations in coastal and no interference in high-sea areas
Test status	VDE-SAT uplink and downlink tested	VDE-SAT uplink tested	VDE-SAT uplink and downlink tested

3.4.1 Conclusions for the selection of a frequency plan alternative

Based on the discussion in § 3.1 and the comparison of the three alternatives in Table 1, it can be concluded that frequency plan alternatives 2 and 3 are preferable to frequency plan alternative 1 when evaluating for VDE-SAT independent from VDE-TER. In coastal areas, frequency plan alternative 3 may be preferable for VDE-SAT due to less interference from the land mobile service. Furthermore, frequency plan alternative 3 will eliminate the operational interdependency between VDE-TER and AIS/ASM at coastal stations. On the other hand, frequency plan alternative 2 offers significant advantages in terms of higher available bandwidth, improved system capacity and link robustness for both the terrestrial and the satellite components of the VDES.

4 Technical description of the VHF data exchange-satellite

4.1 VHF data exchange – satellite key parameters

This section outlines key parameters regarding the VDE-SAT system that are used in the various studies throughout this report and are common for uplink and downlink.

4.1.1 Satellite to surface distance range

The orbit height determines the satellite range variations. For example, for a 600 km, low earth orbit (LEO) satellite the maximum range is 2 830 km. For timing purposes, a maximum range of 3 000 km will be used.

The minimum range is equal to the orbit height. For a LEO satellite at 600 km altitude the minimum range will be 600 km. This value is used to determine the minimum propagation delay time. Considering these exemplary values for the minimum and maximum ranges, the path delay will vary from 2 ms to 10 ms, a variation of 8 ms as shown in Figs 7 and 8.

For the VDE-SAT downlink, in addition to the relative propagation delays between signal receptions at a vessel from different satellites, there could be delays due to other factors such as signal processing delay. The satellite service provider should pre-compensate for the minimum propagation delay.

FIGURE 7

VHF data exchange-satellite downlink timing

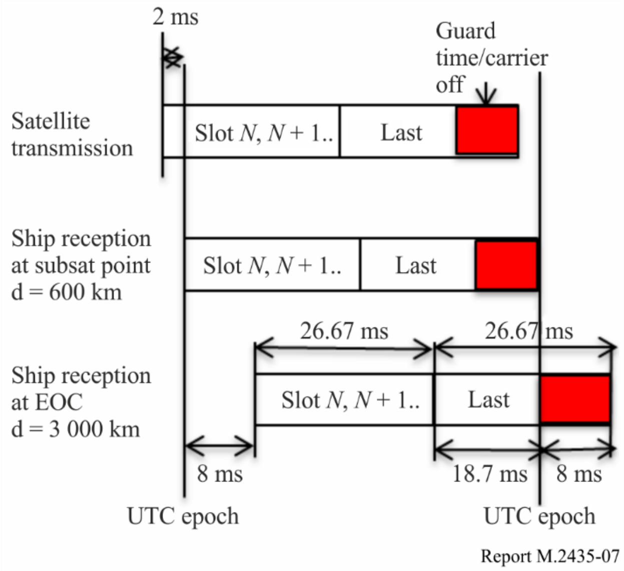
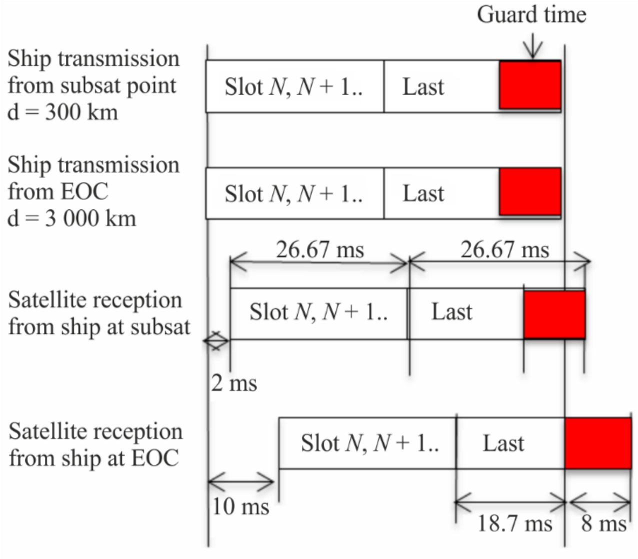


FIGURE 8

VHF data exchange uplink timing



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4.1.2 Satellite transmission carrier frequency error

The transmit frequency tolerance at the satellite shall be less than 1 ppm, i.e. ±160 Hz.

A LEO satellite will move at a speed of about 8 km/s and this will cause a maximum Doppler shift of ±4 kHz at VHF.

4.1.3 Ship station antenna gain and transmitter requirements

Ship station antenna gain and transmitter requirements are defined in Annex 1 of Recommendation ITU-R M.2092. From that definition it is expected that a ship transmitter will have linear output power of at least 6 W.

The assumed ship antenna gain and minimum ship equivalent isotropic radiated power (e.i.r.p.) versus elevation angle is shown in Table 2. There are no minimum e.i.r.p. requirements above 80 degrees elevation. Table 2 is based on a linear transmitter that meets the maximum Adjacent Channel Interference levels defined in Annex 1 of Recommendation ITU-R M.2092, which is expected to provide an output power of at least 6 W. For saturated operation the e.i.r.p. shall be 3 dB higher.

TABLE 2

Ship antenna gain and minimum ship equivalent isotropic radiated power versus elevation angle

Ship elevation angle	Ship antenna gain	Minimum ship e.i.r.p. with 6 W transmitter
degrees	dBi	dBW
0	3	10.8
10	3	10.8
20	2.5	10.3
30	1	8.8
40	0	7.8
50	−1.5	6.3
60	−3	4.8

TABLE 2 (*end*)

Ship elevation angle	Ship antenna gain	Minimum ship e.i.r.p. with 6 W transmitter
70	−4	3.8
80	−10	−2.2
90	−20	−12.2

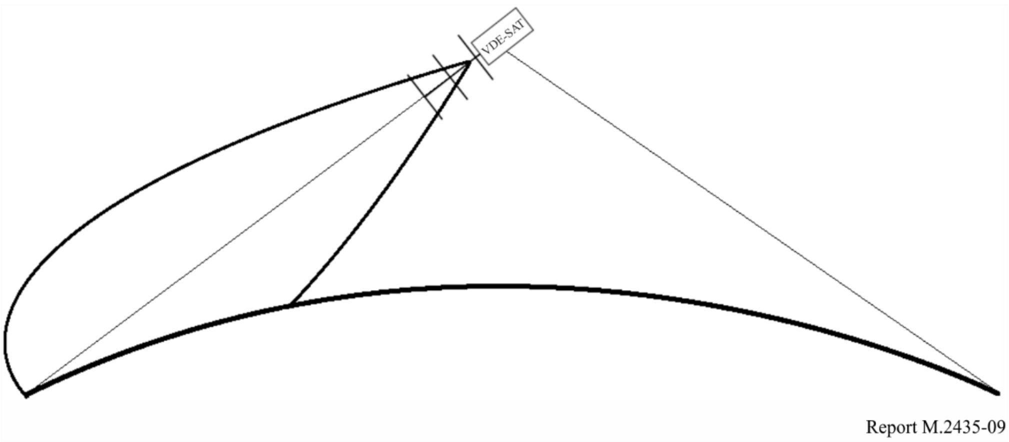
4.1.4 Satellite antenna gain

The following two satellite antennas have been analysed and provide acceptable performance for VDE-SAT:

1) Yagi Antenna: This antenna uses a three crossed two element circularly polarized Yagi antennas with the antenna boresight pointed at the horizon. This is illustrated in Fig. 9, showing how the Yagi antenna and its main lobe is pointed towards the horizon of the earth. The thin solid line indicates the field of view from the satellite, but the communications coverage area will be limited to the area within the main lobe of the Yagi antenna. Assuming a peak antenna gain of 8 dBi, satellite antenna gain versus ship elevation angle and nadir offset angle are shown in Table 3. It is the responsibility of the VDE-SAT service provider to ensure that the pointing of the antenna and the e.i.r.p. are set in a manner which keeps the VDE-SAT downlink emissions within the pfd-mask limit specified in Table 5.

FIGURE 9

Illustration showing how the Yagi antenna and its main lobe is pointed towards the horizon of the earth



Note: The thin solid line indicates the field of view from the satellite, but the communications coverage area will be limited to the area within the main lobe of the Yagi antenna.

2) Isoflux antenna: This antenna is designed to point at the nadir direction providing a symmetric radiation pattern around the pointing direction. This is illustrated in Fig. 10, showing how the whole field of view, indicated by the thin solid line, is within the communications coverage of the Isoflux antenna. Assuming a peak antenna gain of 2 dBi, satellite antenna gain versus ship elevation and nadir offset angle are shown in Table 4.

FIGURE 10

Illustration showing how the whole field of view, indicated by the thin solid line, is within the communications coverage of the Isoflux antenna

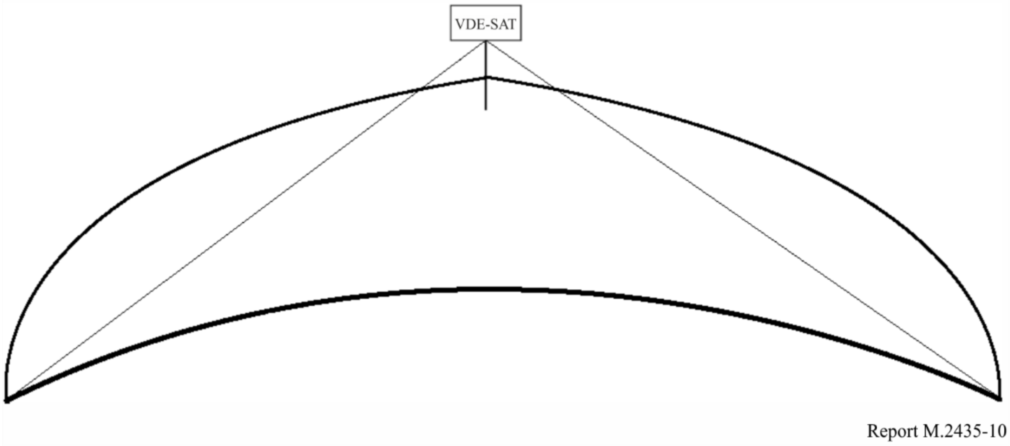


TABLE 3

Satellite Yagi-antenna gain versus nadir offset angle

Ship elevation angle (degrees)	**Nadir offset angle** (degrees)	**Satellite antenna gain** (dBi)
0	66.1	8
10	64.2	8
20	59.2	8
30	52.3	7.8
40	44.4	6.9
50	36	5.5
60	27.2	3.6
70	18.2	0.7
80	9.1	–2.2
90	0	–5.5

TABLE 4

Satellite Isoflux-antenna gain versus nadir offset angle

Ship elevation angle (degrees)	**Nadir offset angle** (degrees)	**Satellite antenna gain** (dBi)
0	66.1	2
10	64.2	1.5
20	59.2	1
30	52.3	–0.5
40	44.4	–2
50	36	–4
60	27.2	–5
70	18.2	–7

TABLE 4 (*end*)

Ship elevation angle (degrees)	**Nadir offset angle** (degrees)	**Satellite antenna gain** (dBi)
80	9.1	–8
90	0	–8.5

4.2 Technical characteristics of the VHF data exchange -satellite downlink in the VHF maritime mobile frequency band

This section outlines key parameters and link budgets for the VDE-SAT system that are used in the various studies of the downlink throughout this Report.

4.2.1 Satellite downlink equivalent isotropic radiated power

It is assumed that the VDE-SAT downlink is in compliance with the pfd mask specified in Recommendation ITU-R M.2092-0. The pfd mask is presented in Table 5. There are different views on the appropriateness of this mask, and these views are deliberated on and addressed in § 6 of this Report.

Table 5

Proposed power spectral and pfd mask

$$\boldsymbol{\theta^\circ = earth - satellite\ elevation\ angle}$$

$$PFD(\theta^\circ)_{\,(\mathrm{dBW/(m^2{*}4\ kHz)})} = \begin{cases} -149 + 0.16 * \theta^\circ & 0^\circ \leq \theta < 45^\circ; \\ -142 + 0.53 * (\theta^\circ - 45^\circ) & 45^\circ \leq \theta < 60^\circ; \\ -134 + 0.1 * (\theta^\circ - 60^\circ) & 60^\circ \leq \theta \leq 90^\circ. \end{cases}$$

From the mask given in Table 5 a theoretical maximum satellite e.i.r.p. can be calculated as a function of ship elevation angle. The result is provided in Table 6.

TABLE 6

Satellite maximum equivalent isotropic radiated power versus elevation angle

Ship elevation angle θ **(**degrees**)**	**pfd on ground** **(**dBW/m^2*4 kHz**)**	**Satellite range** (km)	**Maximum downlink satellite e.i.r.p.** **(**dBW in 25 kHz**)**
0	−149.0	2 831	−1.0
10	−147.4	1 932	−2.7
20	−145.8	1 392	−4.0
30	−144.2	1 075	−4.6
40	−142.6	882	−4.7
45	−142.0	815	−4.8
50	−139.4	761	−2.8
60	−134.0	683	1.6
70	−133.0	635	2.0
80	−132.0	608	2.6
90	−131.0	600	3.5

The maximum achievable satellite e.i.r.p. depends on the antenna on-board the satellite, and how well the antenna pattern can be made to fit the theoretical maximum satellite e.i.r.p. mask. Most of the satellite coverage area and visibility time will be at low elevation angles, and high elevation angle coverage may be sacrificed without significant system capacity loss.

The two satellite antenna types given in § 4.1.4 have been analysed to calculate the maximum possible satellite e.i.r.p. that meets the pfd mask:

1) Yagi Antenna: For this antenna the link budget is optimised for 0 degrees ship elevation angle using a three element circularly polarized crossed two Yagi antennas with the satellite pointed at the horizon. Assuming a peak antenna gain of 8 dBi, a transmit RF power of −12.4 dBW in 25 kHz will ensure compliance with the pfd mask. Satellite e.i.r.p. versus ship elevation angle and resulting margin to the pfd mask are shown in Table 7.

TABLE 7

Satellite equivalent isotropic radiated power vs. elevation using a Yagi antenna

Ship elevation angle (degrees)	**Nadir offset angle** (degrees)	**Boresight offset** (degrees)	**Satellite antenna gain** (dBi)	**Satellite e.i.r.p. in circular polarization** (dBW)	**Satellite range** (km)	**pfd** (dBW/m^2 *4 kHz)	**Table 6 pfd limit** (dBW/m^2* 4 kHz)	**pfd margin** (dB)
0	66.1	0	8	−4.4	2 830	−152.4	−149.0	3.4
10	64.2	1.9	8	−4.4	1 932	−149.1	−147.4	1.7
20	59.2	6.9	8	−4.4	1 392	−146.2	−145.8	0.4
30	52.3	13.8	7.8	−4.6	1 075	−144.2	−144.2	0.0
40	44.4	21.7	6.9	−5.5	882	−143.4	−142.6	0.8
50	36	30.1	5.5	−6.9	761	−143.5	−139.4	4.1
60	27.2	38.9	3.6	−8.8	683	−144.5	−134.0	10.5
70	18.2	47.9	0.7	−11.7	635	−146.7	−133.0	13.7
80	9.1	57	−2.2	−14.6	608	−149.2	−132.0	17.2
90	0	66.1	−5.5	−17.9	600	−152.4	−131.0	21.4

2) Isoflux antenna: This antenna is designed to point at the nadir direction providing a symmetric radiation pattern around the pointing direction. Assuming a peak antenna gain of 2 dBi, a transmit RF power of −5 dBW in 25 kHz will ensure compliance with the pfd mask. Satellite e.i.r.p. versus ship elevation and resulting margin to the pfd mask are shown in Table 8.

TABLE 8

Satellite equivalent isotropic radiated power versus elevation using an isoflux antenna

Ship elevation angle (degrees)	**Nadir offset angle** (degrees)	**Boresight offset** (degrees)	**Satellite antenna gain** (dBi)	**Satellite e.i.r.p. in circular polarization** (dBW)	**Satellite range** (km)	**pfd** (dBW/m2*4 kHz)	**Table 6 pfd limit** (dBW/m2* 4 kHz)	**pfd margin** (dB)
0	66.1	0	2	−3.0	2 830	−151.0	−149.0	2.0
10	64.2	1.9	1.5	−3.5	1 932	−148.2	−147.4	0.8
20	59.2	6.9	1	−4.0	1 392	−145.8	−145.8	0.0
30	52.3	13.8	−0.5	−5.5	1 075	−145.1	−144.2	0.9
40	44.4	21.7	−2	−7.0	882	−144.9	−142.6	2.3
50	36	30.1	−4	−9.0	761	−145.6	−139.4	6.2
60	27.2	38.9	−5	−10.0	683	−145.7	−134.0	11.7
70	18.2	47.9	−7	−12.0	635	−147.0	−133.0	14.0
80	9.1	57	−8	−13.0	608	−147.6	−132.0	15.6
90	0	66.1	−8.5	−13.5	600	−148.0	−131.0	17.0

4.2.2 Ship station noise and interference level

The noise floor for a ship receiver is a function of many sources such as vessel electronics, other radio equipment, power supplies, etc. Sensitivity is also reduced by RF cabling losses and the low noise amplifier (LNA) noise figure. Table 9 presents representative values for the receiver noise figure.

TABLE 9

Ship receiver noise figure calculations

Parameter	**Value**
Antenna noise temperature (K)*	245.0
LNA noise figure (dB)	6.0
LNA noise temperature (K)	813.8
Feed loss noise temp at LNA (K)	0.0
Antenna noise temp at LNA (K)	245.0
System noise temp at LNA (K)	1058.8
System noise temp at LNA (dBK)	30.2

* The galactic background antenna noise temperature is 245 K at 160 MHz according to Recommendation ITU-R P.372.

A typical ship station receiver is expected to observe an interference level of –116 dBm per 25 kHz at the antenna input.

4.2.3 VHF data exchange- satellite downlink receiver thresholds

The VDES maximizes frequency efficiency by using adaptive coding and modulation based on the actual link quality. Initial system access is done using a combination of spread spectrum, low bitrate and powerful forward error correction (FEC). The VDE-SAT uses the waveforms defined in Table 10 for downlink. The thresholds C/N_0 and $C/(N+I)$ on a Gaussian channel have been estimated.

TABLE 10

Estimated thresholds for the VHF data exchange-satellite downlink waveforms

Physical layer frame format #	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Channel bandwidth (kHz)	50	50	50	100	150	300	500
Occupied bandwidth (kHz)	42	42	42	90	141	291	492
CDMA chip rate (kcps)	33.6	NA	NA	72.0	112.8	232.8	393.6
Symbol rate (ksps)	4.2	33.6	33.6	18.0	28.2	58.2	98.4
Burst length (slots)	90	90	90	90	90	90	90
Modulation	BPSK/CDMA	π/4 QPSK	8PSK	BPSK/CDMA			
FEC rate	½	¼	½	½	½	½	½
Information rate (kbit/s)	2.1	16.8	50.4	9.0	14.1	29.1	49.2
Estimated threshold E_s/N_0 for a Gaussian channel (PER=10^{-2}) (dB)	−2.0	−2.4	5.0	−2.0	−2.0	−2.0	−2.0
Estimated required C/N_0 (dBHz)	34.2	42.9	50.3	40.6	42.5	45.6	47.9
Estimated required $C/(N+I)$ (dB)	−11.0	−2.4	5.0	−8.0	−8.0	−8.0	−8.0

4.2.4 VHF data exchange-satellite downlink link budget

The nominal signal level, $C/(N_0+I_0)$ and the link budget versus elevation for a 25 kHz channel are provided in Table 11 for a Yagi antenna and Table 12 for an Isoflux antenna. The assumed maximum ship antenna gain is 3 dBi and the system noise temperature is 30.2 dBK as shown in Table 3.

Because the downlink is pfd limited, increasing the channel bandwidth to 50 kHz or 100 kHz will increase the signal level and $C/(N_0+I_0)$ by 3 dB and 6 dB respectively. Limiting the service area to ship elevation angles between 10 and 55 degrees also improves the link margin by 3 dB.

The Isoflux antenna improves the link budget at low elevation angles and provides a wider symmetrical coverage area, but requires five times larger transmit power on the satellite.

TABLE 11

Link budget with satellite Yagi antenna (transmit RF power = −12.4 dBW/25 kHz)

Ship elevation angle (degrees)	**Satellite e.i.r.p. in circular polarization** (dBW)	**Satellite range** (km)	**Path loss** (dB)	**Polarization loss** (dB)	**Ship antenna gain** (dBi)	**Antenna signal level** (dBm)	***C/N*₀** (dBHz)	**Ship on-board interference level in 25 kHz** (dBm)	**$C/(N_0+I_0)$** (dBHz)
0	−4.4	2 830	145.6	3	3	−120.0	48.4	−116	40.0
10	−4.4	1 932	142.2	3	3	−116.7	51.7	−116	43.3
20	−4.4	1 392	139.4	3	2.5	−114.3	54.1	−116	45.7
30	−4.6	1 075	137.2	3	1	−113.8	54.6	−116	46.2
40	−5.5	882	135.4	3	0	−114.0	54.4	−116	46.0
50	−6.9	761	134.2	3	−1.5	−115.6	52.8	−116	44.4
60	−8.8	683	133.2	3	−3	−118.0	50.4	−116	41.9
70	−11.7	635	132.6	3	−4	−121.3	47.1	−116	38.7
80	−14.6	608	132.2	3	−10	−129.8	38.6	−116	30.2
90	−17.9	600	132.1	3	−20	−143.0	25.4	−116	17.0

TABLE 12

Link budget using Isoflux antenna (transmit RF power = −5.0 dBW/25 kHz)

Ship elevation angle (degrees)	**Satellite e.i.r.p. in circular polarization** (dBW)	**Satellite range** (km)	**Path loss** (dB)	**Polarization loss** (dB)	**Ship antenna gain** (dBi)	**Antenna signal level** (dBm)	***C/N*$_0$** (dBHz)	**Ship on-board interference level in 25 kHz** (dBm)	***C/(N$_0$+I$_0$)*** (dBHz)
0	−3.0	2 830	145.6	3	3	−118.6	49.8	−116	41.4
10	−3.5	1 932	142.2	3	3	−115.7	52.7	−116	44.2
20	−4.0	1 392	139.4	3	2.5	−113.9	54.5	−116	46.1
30	−5.5	1 075	137.2	3	1	−114.7	53.7	−116	45.3
40	−7.0	882	135.4	3	0	−115.4	53.0	−116	44.5
50	−9.0	761	134.2	3	−1.5	−117.7	50.7	−116	42.3
60	−10.0	683	133.2	3	−3	−119.2	49.2	−116	40.8
70	−12.0	635	132.6	3	−4	−121.6	46.8	−116	38.4
80	−13.0	608	132.2	3	−10	−128.2	40.2	−116	31.8
90	−13.5	600	132.1	3	−20	−138.6	29.8	−116	21.4

4.3 Technical characteristics of the VHF data exchange-satellite uplink in the VHF maritime mobile frequency band

This section outlines key parameters and link budgets for the VDE-SAT system that are used in the various studies of the uplink throughout this report.

4.3.1 VHF data exchange-satellite uplink receiver thresholds

The VDES maximizes frequency efficiency by using adaptive coding and modulation based on the actual link quality. Initial system access is done using a combination of spread spectrum, low bitrate and powerful FEC. The VDE-SAT uses the waveforms defined in Table 13 for uplink. The thresholds C/N_0 and $C/(N+I)$ on a Gaussian channel have been estimated.

TABLE 13

Estimated thresholds for the VHF data exchange-satellite uplink waveforms

Physical layer frame format #	**1**	**2**	**3**	**4**	**5**
Channel bandwidth (kHz)	50	50	50	50	50
Occupied bandwidth (kHz)	42	42	42	42	42
CDMA chip rate (kcps)	33.6	NA	NA	NA	NA
Symbol rate (ksps)	2.1	33.6	33.6	33.6	33.6
Burst length (slots)	5	1	3	3	3
Modulation	QPSK/CDMA	π/4 QPSK	π/4 QPSK	8PSK	16QAM
FEC rate	1/4	2/3	2/3	2/3	5/6
Information rate (kbit/s)	1.1	44.8	44.8	67.2	112.0
Threshold E_s/N_0 for a Gaussian channel (PER=10^{-2}) (dB)	−1.5	3.9	3.9	8.0	12.2
Required C/N_0 (dBHz)	31.7	49.2	49.2	53.3	57.5
Required $C/(N+I)$ (dB)	−13.5	2.9	2.9	7.0	11.2

Recommendation ITU-R M.1184 provides information on non-GSO systems operating below 1 GHz, including associated required *C/(N+I)* thresholds. However, the systems described in Recommendation ITU-R M.1184 do not implement the advanced coding, forward error correcting and spread spectrum techniques utilized by the VDES.

There are two views on the material in this section. One view state that the $C/(N+I)$ performance thresholds provided in this section is correct and appropriate to use. Another view states that the $C/(N+I)$ values provided in Annex 2 of Recommendation ITU-R M.1184-3 should be used as protection criteria. The following discussion describes the advantages of the advanced modulation and coding techniques proposed for VDE-SAT, that are not implemented by the systems described in Recommendation ITU-R M.1184.

Waveform *1* uses a combination of spread spectrum, low bitrate and powerful FEC to create a waveform with high robustness against interference. VDES, as defined in Recommendation ITU-R M.2092-0, implements FEC as specified by ETSI EN 302 583 (V1.2.1) – Digital Video Broadcasting (DVB); Framing Structure, channel coding and modulation for Satellite Services to Handheld devices (SH) below 3 GHz, and used in the DVB-SH standard, as well as adaptive coding and modulation (ACM) and automatic repeat request (ARQ).The use of spread spectrum techniques is considered in Recommendation ITU-R SM.1055. Specifically, it defines the processing gain (PG) as the ratio between the output wanted signal-to-interference ratio and the input wanted signal-to-interference ratio. For a direct sequence (DS) spread spectrum signal, as used in waveform *1*, this corresponds to the ratio between the spread spectrum chip rate and the symbol rate. Recommendation ITU-R SM.1055 also clearly states that from the point of the output power ratios, a DS spread spectrum signal overcomes interference to the same degree that it overcomes noise.

Report ITU-R S.2173 provides an overview of channel coding techniques, link rate adaption methods, such as ARQ and ACM, and review standards and transmission methods for satellite communications, including DVB-SH, and associated performance parameters.

A QPSK modulated carrier with Turbo FEC code rate of ¼ has a symbol energy to noise density ratio (E_s/N_0) threshold of –1.5 dB for a packet error ratio (PER) of 10^{-2}. The threshold can be extracted from Figure 11, and is based on simulations performed according to an additive white Gaussian Channel model for a packet containing 88 information bits encoded at a coding rate ¼. This result is supported and cross-checked against Report ITU-R S.2173, which provides the performance of QPSK with FEC code rate ¼ for DVB-S2 as –2.35 dB at a PER of 10^{-7}. This is further supported by *Informational Report CCSDS 130.1-G-2: TM Synchronization and channel coding – Summary of concept and rationale*, see Figure 7-6 of that Report. The same level of performance cannot be expected from the FEC implementation in VDE-SAT due to significantly shorter information block length and smaller packets. Thus, the simulation results showing an E_s/N_0 threshold of -1.5 dB for a PER of 10^{-2} should be viewed as a conservative design point. As VDES will implement both FEC and ARQ in a hybrid manner, see Report ITU-R S.2173, a target PER of 10^{-2} is considered a conservative design point to maintain the target quality of service in VDES.

Recommendation ITU-R SM.1055 defines the processing gain, PG, as

$$PG = 2B_{S_{in}}T_S$$

where $2B_{S_{in}}$ is the bandwidth of the RF input signal power density spectrum at first nulls and T_S is the time duration of the input signal information. For a root raised cosine filtered direct sequence spread spectrum signal, $2B_{S_{in}}$ corresponds to the chip rate, which for waveform 1 in Table 13 is 33.6 kHz. For any digital signal, T_S corresponds to the inverse of the information symbol rate, R_S, which for waveform 1 in Table 13 is 2.1 ksps. Thus, the processing gain, PG, for waveform 1 in Table 13 is:

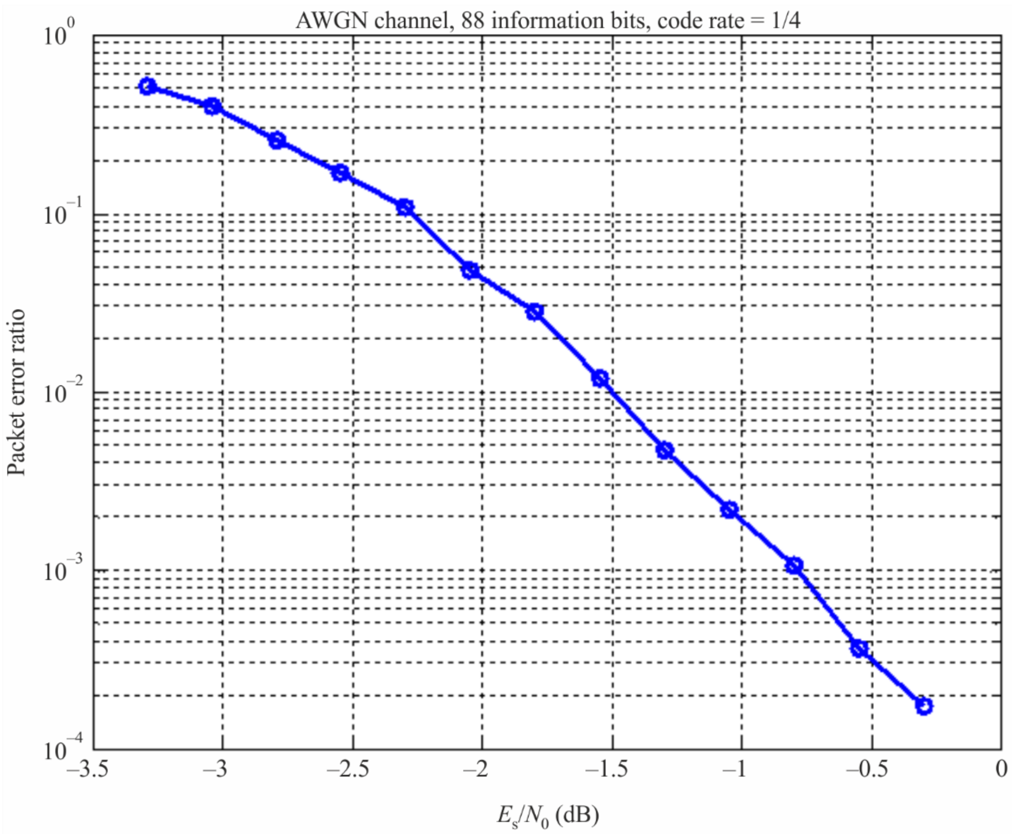
$$PG = 2B_{S_{in}}T_S = \frac{2B_{S_{in}}}{R_S} = \frac{33.6}{2.1} = 16$$

A PG of 16 corresponds to 12.0 dB. When the PG of 12.0 dB is combined with the E_s/N_0 threshold of –1.5 dB for waveform *1* the result is a required $C/(N+I)$ threshold of –13.5 dB:

$$\frac{C}{N+I} = \frac{E_S}{N_0} - PG = -1.5\text{ dB} - 12.0\text{ dB} = -13.5\text{ dB}$$

FIGURE 11

Estimated symbol energy to noise density ratio threshold after de-spreading versus packet error ratio for a quadrature phase shift keying modulated carrier using turbo forward error correction coding according to ETSI EN 302 583 (V1.2.1)



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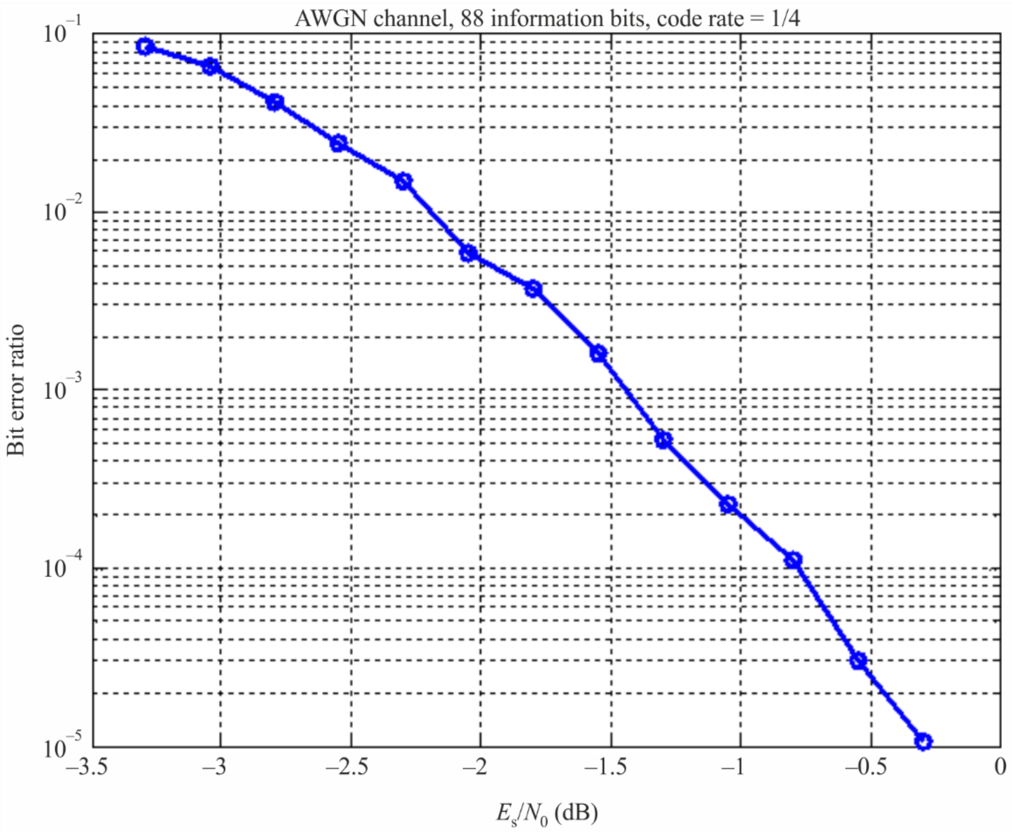
Furthermore, according to Fig. 12, a QPSK modulated carrier with FEC code rate of ¼ has an estimated E_s/N_0 threshold of −0.3 dB for a bit error ratio (BER) of 10^{-5}. This estimated threshold is based on simulations carried out based on an Additive White Gaussian Channel model. In addition, this result has been performed using packets of 88 information bits.

FIGURE 12

Estimated symbol energy to noise density ratio threshold after de-spreading versus bit error rate for a quadrature phase shift keying modulated carrier using turbo forward error correction coding according to ETSI EN 302 583 (V1.2.1)



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The report "TM synchronization and channel coding summary of concept and rationale" [1] shows performance results for the same family of turbo codes and the same FEC rate, but with different information block size of 1 784 bits. Figure 7.6 of the report presents an E_b/N_0 value of 0.55 dB for a bit error ratio (BER) of 10^{-5}. Using the following formula:

$$E_s/N_0 \text{ (dB)} = E_b/N_0 \text{ (dB)} + 10^* \log 10\ (k/N * m)$$

with k/N = code rate, m = number of bits per symbol. In this case, k/N = ¼ and m = 2 (for a quadrature phase shift keying (QPSK) modulation, M =2, m = 4).

Therefore, the following is obtained:

$$E_s/N_0 = 0.55+10^*\log 10\ (1/4^*2) = 0.55 - 3 = -2.45 \text{ dB.}$$

This result was derived from simulations using a larger number of bits per code block (blocks of 1 784 bits).

In Fig. 12 (VDES simulation), the comparative E_s/N_0 requires −0.3 dB in order to achieve a BER of 10^{-5}. The 2.15 dB difference can be explained as below.

It is known that shortening the information block length would increase the required decoder E_b/N_o threshold, as a penalty in the code performance. This penalty can be analytically computed (for example see Fig. 2 in the report "Code Performance as a Function of Block Size" [2]). For code rate 1/4, reducing the block length from 1 784 bits to 88 bits would increase the required E_b/N_o threshold by around 1.9 dB as per Fig. 2 of [2]. This theoretical analysis confirms the simulation results reported in this report versus results reported in [1].

Therefore, the results as presented in Fig. 12 and in Table 13 for the physical layer frame format #1, have been verified and cross checked through existing technical literature (see [1] and [2]).

4.3.2 VHF data exchange-satellite uplink receiver characteristics

Satellite noise levels at the receiver front end are presented in Table 14. The system noise temperature is taken to be 25.7 dBK assuming no external interference. The required $C/(N+I)$ listed in Table 14 is for the most robust waveform, as given in Table 13. Adaptive coding and modulation allow the usage waveforms with higher throughput when the necessary link quality is available.

TABLE 14

Characteristics of the VHF data exchange-satellite receiver

Parameter	Value
Antenna noise temperature (K)	200.0
Feed losses (dB)	1.0
LNA noise figure (dB)	2.0
LNA noise temperature (K)	159.7
Feed loss noise temperature at LNA (K)	56.1
Antenna noise temperature at LNA (K)	158.9
System noise temperature at LNA (K)	374.7
System noise temperature at LNA (dBK)	25.7
Intrinsic noise power density (dBW/Hz)	−202.9
Intrinsic noise power in 42 kHz bandwidth (dBW)	−156.6
Required carrier-to-noise-plus-interference ratio ($C/(N+I)$) (dB)	−13.5

4.3.3 VHF data exchange-satellite uplink link budget

Tables 15 and 16 present link budgets for VDE-SAT uplink with a satellite receiver in a 600 km altitude orbit using Isoflux and Yagi antennas. A 6 W ship station transmitter is assumed. For the most robust waveform, the link margin is high for all elevation angles and both satellite antenna types. Furthermore, in an interference free environment, all five waveforms given in Table 13 will be usable up to 70 degrees elevation angle for the Isoflux antenna and up to 80 degrees elevation angle for the Yagi-antenna.

TABLE 15

Worst-case link budget for the VHF data exchange-satellite uplink with 6 W ship transmitter, Isoflux satellite receiving antenna without interference

Ship elevation angle (degree)	**Ship antenna gain** (dBi)	**Ship e.i.r.p.** (dBW)	**Polarization loss** (dB)	**Path length** (km)	**Path loss** (dB)	**Satellite antenna gain** (dBi)	**Carrier level at LNA, including feed loss** (dBW)	C/N_0 (dBHz)	C/N (dB)	**Link margin for waveform 1** (dB)
0.0	3.0	10.8	3.0	2 830	145.4	2.0	–136.6	66.2	20.0	33.5
10.0	3.0	10.8	3.0	1 932	142.1	1.5	–133.8	69.0	22.8	36.3
20.0	2.5	10.3	3.0	1 392	139.3	1.0	–132.0	70.9	24.7	38.2
30.0	1.0	8.8	3.0	1 075	137.0	–0.5	–132.7	70.1	23.9	37.4
40.0	0.0	7.8	3.0	882	135.3	–2.0	–133.5	69.4	23.1	36.6
50.0	–1.5	6.3	3.0	761	134.0	–4.0	–135.7	67.1	20.9	34.4
60.0	–3.0	4.8	3.0	683	133.1	–5.0	–137.3	65.6	19.3	32.8
70.0	–4.0	3.8	3.0	635	132.4	–7.0	–139.7	63.2	17.0	30.5
80.0	–10.0	–2.2	3.0	608	132.1	–8.0	–146.3	56.6	10.4	23.9
90.0	–20.0	–12.2	3.0	600	131.9	–8.5	–156.7	46.2	0.0	13.5

TABLE 16

Worst-case link budget for the VHF data exchange-satellite uplink with 6 W ship transmitter, Yagi satellite receiving antenna without interference

Ship elevation angle (degree)	**Ship antenna gain** (dBi)	**Ship e.i.r.p.** (dBW)	**Polarization loss** (dB)	**Path length** (km)	**Path loss** (dB)	**Satellite antenna gain** (dBi)	**Carrier level at LNA, including feed loss** (dBW)	***C*/*N*$_0$** (dBHz)	***C*/*N*** (dB)	**Link margin for waveform 2** (dB)
deg	dBi	dBW	dB	km	dB	dBi	dBW	dBHz	dB	dB
0.0	3.0	10.8	3.0	2 830	145.4	8.0	–130.6	72.2	26.0	39.5
10.0	3.0	10.8	3.0	1 932	142.1	8.0	–127.3	75.5	29.3	42.8
20.0	2.5	10.3	3.0	1 392	139.3	8.0	–125.0	77.7	31.7	45.2
30.0	1.0	8.8	3.0	1 075	137.0	7.8	–124.4	78.4	32.2	45.7
40.0	0.0	7.8	3.0	882	135.3	6.9	–124.6	78.3	31.2	45.5
50.0	–1.5	6.3	3.0	761	134.0	5.5	–126.2	76.6	30.4	43.9
60.0	–3.0	4.8	3.0	683	133.1	3.6	–128.7	74.2	27.9	41.4
70.0	–4.0	3.8	3.0	635	132.4	0.7	–132.0	70.9	24.7	38.2
80.0	–10.0	–2.2	3.0	608	132.1	–2.2	–140.5	62.4	16.2	29.7
90.0	–20.0	–12.2	3.0	600	131.9	–5.5	–153.7	49.2	3.0	16.5

5 Interoperability and resource sharing with VHF data exchange-terrestrial and between VHF data exchange-satellite

5.1 Resource sharing method for VHF data exchange-terrestrial and VHF data exchange-satellite

The VDES resource assignment between the VDE-TER and the VDE-SAT services is outlined in the following sections. In particular the signaling and control mechanisms envisaged to coordinate the use of each time slot either for terrestrial or satellite communication.

Shore stations utilize the terrestrial bulletin board (TBB) and the announcement signaling channels (ASC) to coordinate the resource assignment within the control area. Shore stations may provide information regarding VDE-SAT communications and availability as part of their information service. VDE-SAT information may be acquired by shore stations, either directly from the satellite bulletin board (SBB) and the ASC or through coordination with the satellite service providers.

There are dedicated time slots and frequency bands for TBB and ASC that are reserved to communicate the required information to each vessel in the control area of a shore station.

Each satellite system will use SBB and ASC, as described in Recommendation ITU-R M.2092-0, to communicate the VDE-SAT resource assignments, for both downlink and uplink, to vessels in the coverage area. There are dedicated time slots and frequency bands for the SBB and ASC to communicate the required information to each vessel in the field of view of a satellite.

Since the satellite coverage may include several shore station control areas, the VDE-SAT resource assignment should respect all requirements of shore control areas that are within the field of view at any given time. Within each satellite orbit the information regarding the resource assignment should be updated according to the shore station control areas in the satellite field of view.

How, and to what extent, resources are shared between VDE-TER and VDE-SAT are closely linked to the frequency utilization plan selected for VDES. Section 3 discusses three alternative frequency plans and their implications on resource sharing between VDE-TER and VDE-SAT. Methods for resource sharing are discussed in the following sections.

5.2 VHF data exchange-terrestrial and VHF data exchange-satellite downlink resource sharing

5.2.1 Resource sharing with frequency plan alternative 1

With frequency plan alternative 1, the channels 2026 and 2086 are identified for VDE-SAT downlink communications, and not used for VDE-TER communications. Within these VDE-SAT channels, there are dedicated time slots that are assigned to the satellite bulletin board and announcement signaling channels as described in Recommendation ITU-R M.2092-0. Other slot assignments in the VDE-SAT frequency bands are managed based on the content of the bulletin board and announcement signaling channels. The assignment may change dynamically (according to the satellite coverage or temporal demands).

Channels 2024, 2084, 2025 and 2085 are shared between VDE-SAT downlink and VDE-TER. Depending on the satellite coverage area and the shore control areas, the resource assignment may vary.

There are dedicated time slots in channel 2024 and 2084 that are assigned to the terrestrial signaling channel and terrestrial bulletin board, as described in Recommendation ITU-R M.2092-0. These slots should not be used for VDE-SAT downlink communications when a VDE shore station is within the satellite coverage area.

A shore station may assign the full resources of channels 2024, 2084, 2025 and 2085 for VDE-TER communications when there is no transmitting VDE-SAT satellite in the field of view.

When a transmitting VDE-SAT satellite is in the field of view the resource sharing between VDE-SAT downlink and VDE shore-to-ship and ship-to-ship must be coordinated between the shore operator and the satellite operator. This coordination can be done either directly between the operators or rely on the bulletin board and announcement channels of the satellite and shore stations. As an initial configuration for resource sharing, a static assignment in time and frequency should be adopted by the terrestrial and satellite entities.

– Channels 2024 and 2084 are identified for VDE-TER communications and are not used for VDE-SAT communications, maintaining the original signaling assignment that was described above
– Channels 2026 and 2086 are identified for VDE-SAT downlink communications and are not used for VDE-TER communications, maintaining the original signaling assignment that was described above
– Channels 2025 and 2085 are time-shared between VDE-SAT downlink and VDE-TER communications. The time sharing is based on time intervals of 2.4 s (90 slots) that are assigned periodically to VDE-SAT and VDE-TER communications

This resource sharing method should be used as a starting point for resource sharing between VDE-TER and VDE-SAT, or in the absence of coordination between the shore and satellite operation.

Coordination of resource sharing between VDE-TER ship-to-ship and VDE-SAT downlink communications for areas not controlled by a VDE-TER shore station is managed by the VDE-SAT bulletin board, as described in Recommendation ITU-R M.2092-0. As a starting point for this resource sharing or in the absence of any VDE-SAT bulletin board, the resource sharing method described above should be used.

5.2.2 Resource sharing with frequency plan alternative 2

With frequency plan alternative 2, the frequency band from 160.9625 MHz to 161.4875 MHz is identified for VDE-SAT downlink communications. The frequencies in this band are not channelized in RR Appendix **18**. Within this VDE-SAT band, there are dedicated channels and time slots that are assigned to the satellite bulletin board and announcement signaling channels as described in Recommendation ITU-R M.2092-0. Other slot assignments in this VDE-SAT frequency band are managed based on the content of the bulletin board and announcement signaling channels. The assignment may change dynamically according to the satellite coverage or temporal demands.

5.2.3 Resource sharing with frequency plan alternative 3

With frequency plan alternative 3, the channels 2026 and 2086 are identified for VDE-SAT downlink communications, and not used for VDE-TER communications. Within these VDE-SAT channels, there are dedicated time slots that are assigned to the satellite bulletin board and announcement signaling channels as described in Recommendation ITU-R M.2092-0. Other slot assignments in the VDE-SAT frequency bands are managed based on the content of the bulletin board and announcement signaling channels. The assignment may change dynamically according to the satellite coverage or temporal demands.

The channels 2024, 2084, 2025 and 2085 are identified for VDE-SAT downlink communications. VDE-TER shore-to-ship communications are also possible in channels 2024, 2084, 2025 and 2085, but the VDE-TER shore-to-ship communications in these channels may not impose constraints on VDE-SAT downlink communications.

A shore station may assign the full resources of channels 2024, 2084, 2025 and 2085 for VDE-TER communications when there is no transmitting VDE-SAT satellite in the field of view.

When a transmitting VDE-SAT satellite is in the field of view, the resource sharing between VDE-SAT downlink and VDE-TER shore-to-ship communications must be coordinated between the shore operator and the satellite operator. This coordination can be done either directly between the operators or rely on the bulletin board and announcement channels of the satellite and shore stations. As an initial configuration for resource sharing, a static assignment in time and frequency should be adopted by the terrestrial and satellite entities.

– Channels 2026 and 2086 are identified for VDE-SAT downlink communications and are not used for VDE-TER communications, maintaining the original signaling assignment that was described above
– Channels 2024, 2084, 2025 and 2085 are identified for VDE-SAT downlink communications, but VDE-TER shore-to-ship communications may be possible when there is no transmitting VDE-SAT satellite in view.

This resource sharing method should be used as a starting point for resource sharing between VDE-TER and VDE-SAT, or in the absence of coordination between the shore and satellite operation.

5.3 VHF data exchange-terrestrial and VHF data exchange-satellite uplink resource sharing

5.3.1 Resource sharing with frequency plan alternative 1

With frequency plan alternative 1, the lower frequency bands, channel 1026 and 1086 are identified for VDE-SAT uplink communications, while channels 1024, 1084, 1025 and 1085 are shared between VDE-TER and VDE-SAT.

The VDE-SAT uplink channels may be used for dedicated (demand assigned) or random access to satellite. Since there is no interference from VDE-TER on these two channels, these channels should be used for higher priority message (safety, distress, acknowledgement, etc.).

Through the bulletin board, a shore station may assign the full resources of channels 1024, 1084, 1025 and 1085 for VDE-TER communications when there is no receiving VDE-SAT satellite in the field of view.

When a receiving VDE-SAT satellite is in the field of view the resource sharing between VDE-SAT uplink and VDE-TER ship-to-shore communications must be coordinated between the shore operator and the satellite operator. This coordination can be done either directly between the operators or rely on the bulletin board and announcement channels of the satellite and shore stations. As an initial configuration for resource sharing, a static assignment in time and frequency should be adopted by the terrestrial and satellite entities.

– Channels 1024 and 1084 are identified for VDE-TER ship-to-shore communications, and are not used for VDE-SAT communications
– Channels 1026 and 1086 are identified for VDE-SAT uplink (ship-to-satellite) communications, and are not used for VDE-TER communications
– Channels 1025 and 1085 are time-shared between VDE-SAT uplink and VDE-TER communications. The time-sharing is based on time intervals of 1 hexslot (6 slots) that are assigned alternately to VDE-SAT and VDE-TER communications.

As the starting point for resource sharing between VDE-TER and VDE-SAT or in the absence of coordination between the shore and satellite operation, this resource sharing method should be used.

5.3.2 Resource sharing with frequency plan alternative 2

With frequency plan alternative 2, the channels 24, 84, 25 and 85 are identified for VDE-TER communications. VDE-SAT uplink communications is also possible in channels 24, 84, 25 and 85, but VDE-SAT uplink communications in these channels may not impose constraints on VDE-TER communications and should only use resources not reserved for VDE-TER communications.

Channels 26 and 86 are identified for VDE-SAT uplink communications, and are not used for VDE-TER communications. Therefore, on these channels no resources are shared and therefore no sharing scheme is required.

5.3.3 Resource sharing with frequency plan alternative 3

With frequency plan alternative 3, the lower frequency bands, channel 1026 and 1086 are identified for VDE-SAT uplink communications and not used for VDE-TER communications, while channels 1024, 1084, 1025 and 1085 are shared between VDE-TER and VDE-SAT.

The VDE-SAT uplink channels may be used for dedicated (demand assigned) or random access to satellite. Since there is no interference from VDE-TER on these two channels, these channels should be used for higher priority message (safety, distress, acknowledgement, etc.).

There are dedicated time slots in channels 1024 and 1084 that are assigned to the terrestrial signaling channel and terrestrial bulletin board. These slots should not be used by the VDE-SAT uplink communications when a VDE-TER shore station is within the satellite coverage area.

Through the bulletin board, a shore station may assign the full resources of channels 1024, 1084, 1025 and 1085 for VDE-TER communications when there is no receiving VDE-SAT satellite in the field of view.

When a receiving VDE-SAT satellite is in the field of view the resource sharing between VDE-SAT uplink and VDE-TER communications must be coordinated between the shore operator and the satellite operator. This coordination can be done either directly between the operators or rely on the bulletin board and announcement channels of the satellite and shore stations. As an initial configuration for resource sharing, a static assignment in time and frequency should be adopted by the terrestrial and satellite entities.

– Channels 1024 and 1084 are identified for VDE-TER communications, and are not used for VDE-SAT communications
– Channels 1026 and 1086 are identified for VDE-SAT uplink (ship-to-satellite) communications, and are not used for VDE-TER communications
– Channels 1025 and 1085 are time-shared between VDE-SAT uplink and VDE-TER communications. The time-sharing is based on time intervals of 1 hexslot (6 slots) that are assigned alternately to VDE-SAT and VDE-TER communications.

As the starting point for resource sharing between VDE-TER and VDE-SAT or in the absence of coordination between the shore and satellite operation, this resource sharing method should be used.

Coordination of resource sharing between VDE-TER ship-to-ship and VDE-SAT uplink communications for areas not controlled by a VDE-TER shore station is managed by the VDE-SAT bulletin board, as described in Recommendation ITU-R M.2092-0. As a starting point for this resource sharing or in the absence of any VDE-SAT bulletin board, the resource sharing method described above should be used.

5.4 Resource sharing between multiple satellite VHF data exchange systems

The sharing between two or more satellite systems is coordinated between the satellite operators and organized through the bulletin board, delivered by satellites in the VDE-SAT downlink band, as described in Recommendation ITU-R M.2092-0. Ships use the satellite bulletin boards for channel and resource configuration.

The waveform used for the bulletin board should allow for detection of overlapping signals received from multiple satellites. The use of direct sequence spreading as defined in Recommendation ITU-R M.2092-0 allows for detection of up to eight overlapping satellite signals.

6 Interference to incumbent services and those in adjacent frequency bands

6.1 In-band interference

6.1.1 Fixed services in-band

6.1.1.1 Analysis of the interference effect of the VHF data exchange-satellite uplink

The VDE-SAT uplink has common characteristics with VDE terrestrial ship-to-shore. Therefore, it will not create any additional interference to land and aeronautical mobile services.

6.1.1.2 Analysis of the interference effect of the VHF data exchange-satellite downlink

There are two views on the interference effect of the VDE-SAT downlink into the fixed service. The pfd mask contained in view 1 is specified in Recommendation ITU-R M.2092. The pfd mask contained in view 2 is based on protection criteria defined in Recommendation ITU-R F.758-6.

6.1.1.2.1 View 1 on the pfd mask

The VDE-SAT downlink is in compliance with the pfd mask specified in Recommendation ITU-R M.2092-0 and provided in § 4.2.1. The pfd mask is presented in Table 5.

Given this mask, a study on the compatibility between the VDE-SAT downlink and the fixed service has been performed. The study evaluates the effect of the interference from the VDE-SAT downlink received by a fixed service station on the transmission from another fixed service station. The basis for the study is technical characteristics of fixed service stations as provided in Recommendation ITU-R F.758 and methods for point-to-area predictions for terrestrial services as provided in Recommendation ITU-R P.1546.

The methodology used to evaluate the compatibility between the VDE-SAT downlink and the fixed service is based on carrier-to-interference (*C*/*I*) considerations and performance degradation of the bit error ratios specified in Recommendation ITU-R F.758 and bit error ratio performance provided in Recommendation ITU-R F.1101.

6.1.1.2.1.1 Characteristics of fixed service systems operating in the frequency band 156-162 MHz band

Representative technical and operational characteristics of fixed service systems operating in the fixed service in the frequency band 156-162 MHz are not available in the current set of ITU-R Recommendations and Reports. However, Recommendation ITU-R F.758 provide technical characteristics of fixed service systems in the frequency band 406.1 MHz-450 MHz. As these technical characteristics are those available which are closest in frequency, they have been used as reference for a fixed service system in this study. Table 17 provide the technical characteristics of fixed service systems in the frequency band 406.1 MHz-450 MHz from Recommendation ITU-R F.758, Annex 3.

TABLE 17

Technical characteristics of fixed service systems in the frequency band 406.1 MHz to 450 MHz from Recommendation ITU-R F.758, Annex 3

Frequency band (MHz)	**406.1–450**
Modulation type	QPSK
Channel bandwidth (kHz)	50/100/150/200/**250**/300/500/600/750/ 1000/1750/**3500**
Maximum Tx output power range (dBW)	7
Maximum Tx output power density range (dBW/MHz) (1)	1.6 … 13
Minimum feeder/multiplexer loss range (dB)	2
Maximum antenna gain range (dBi)	25
Maximum e.i.r.p. range (dBW)	30
Maximum e.i.r.p. density range (dBW/MHz)	25 … 36
Receiver noise figure (dB)	5
Receiver noise power density typical (=N_{RX}) (dBW/MHz)	−139
Normalized Rx input level for 10^{-6} BER (dBW/MHz)	−125.5
Nominal long-term interference power density (dBW/MHz) (2)	−139 + *I*/*N*

(1) To calculate the values for the Tx/e.i.r.p. densities, channel spacing/bandwidth needs to be identified. In these tables, the channel spacing indicated in bold letter is used.

(2) ominal long-term interference power density is defined by “Receiver noise power density +(required *I*/*N*)” as described in § 4.13 in Annex 2 (see also § 4.1 in Annex 1).

For the studies of the compatibility of the VDE-SAT downlink with the fixed service the relevant values from Table 17 have been used. These technical characteristics and values are summarized in Table 18. Recommendation ITU-R F.758 does not provide antenna height values typical for FS systems. An antenna height of 75 metres is assumed to be a nominal value, and has been used in this study.

TABLE 18

Typical values for technical characteristics of fixed service stations used in compatibility study

Modulation type	**QPSK**
Channel bandwidth (kHz)	250
Output power (dBW)	7
Feed loss (dB)	2
Maximum antenna gain (dBi)	25
Maximum e.i.r.p. (dBW)	30
Antenna height (m)	75
Distance to horizon from station (km)	30.9

Figure 13 shows an antenna pattern for a typical 25 dBi antenna used in the fixed service as described in Recommendation ITU-R F.699-4. The antenna gain versus elevation angle can be tabulated as in Table 19. Table 19 also present the resulting e.i.r.p. versus elevation angle.

FIGURE 13

Antenna pattern the for typical antenna used in the fixed service as described in Recommendation ITU-R F.699-4

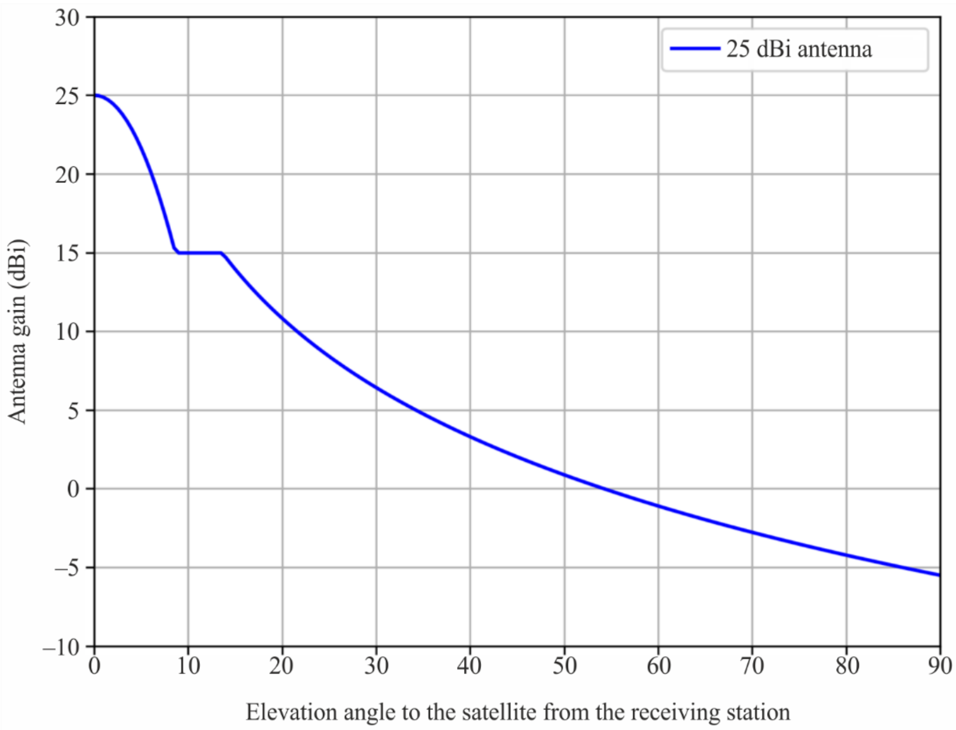

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TABLE 19

Fixed service station antenna gain and e.i.r.p. versus elevation angle

Elevation angle (degrees)	**Antenna gain** (dBi)	**e.i.r.p.** (dBW)
0	25.0	30.0
10	15.0	20.0
20	10.8	15.8
30	6.4	11.4
40	3.3	8.3
50	0.9	5.9
60	−1.1	3.9
70	−2.8	2.2
80	−4.2	0.7
90	−5.5	−0.5

6.1.1.2.1.2 Link budget calculations for transmission between two fixed service stations

Given the typical antenna height for fixed service stations listed in Table 17, the distance to the horizon from a fixed service station can be calculated. Then the fixed service station to station range can be found to be 61.8 km. Based on the fixed service station to station range the transmission free space loss can be calculated to 112.4 dB.

In addition to the free space loss, a land mobile transmission channel will experience additional path loss. Recommendation ITU-R P.1546 provides methods for point-to-area predictions for terrestrial services for the relevant frequency band. Based on tabulated field strengths available from the Radiocommunication Bureau, as discussed in Annex 1 of that Recommendation, combined with formulas for interpolation of field strength as function of antenna height, distance and frequency as provided in Annex 5 of that Recommendation, the additional path loss can be estimated. The tabulated field strengths exceeded 50% of the time from Recommendation ITU-R P.1546 assumes a transmit e.r.p. of 1 kW, and the values needed to perform the interpolation to the frequency of 162 MHz and the antenna height and fixed service station to station range given in Table 17, are provided in Table 20.

TABLE 20

Tabulated field strength values exceeded 50% of the time from Rec. ITU-R P.1546 needed to perform the interpolation to the frequency of 162 MHz and the antenna height and mobile station to base station range

Frequency (MHz)	**Antenna height** (m)	**Distance** (km)	**Field strength value** (dB(uV/m))
100	75	60	31.9
		65	30.0
600	75	60	26.6
		65	24.5

Through the use of the interpolation formulas provided in Annex 5 of Recommendation ITU-R P.1546 the estimated field strength can be calculated for the frequency of 160 MHz, antenna height of 75 metres and a distance of 61.8 km. The result is an estimated field strength of 29.8 dB(uV/m). The corresponding field strength if only free space loss is considered will be 67.0 dB(uV/m). The additional path loss experienced on a fixed service transmission channel is equal to this difference, which is 37.1 dB. The calculation steps are provided in Table 21 for transparency.

TABLE 21

Calculation steps for interpolation of field strength values exceeded 50% of the time from Rec. ITU-R P.1546 to the frequency of 162 MHz and the antenna height and fixed service station to station range

	Frequency (MHz)	**Antenna height** (m)	**Distance** (km)	**Field strength value** (dB(uV/m))
Free space loss and additional path loss	162	75	60	30.5
			65	28.5
	162	75	61.8	29.8
Free space loss only	100		60	71.3
	162		61.8	66.9
Additional path loss only (dB)	162	75	61.8	37.1

The additional terrestrial path loss of 37.1 dB must be taken into consideration in the link budget. Taking into account the fixed station EIRP at 0-degree elevation and the fixed station antenna gain at 0 degree elevation this leads to the received carrier power of −96.5 dBW for a fixed station to station transmission link. The results are provided in Table 22.

TABLE 22

Link budget calculations for transmissions between fixed service stations

Parameter	**Value**
Modulation type	QPSK
Output power (dBW)	7.0
Feed loss (dB)	2.0
Maximum antenna gain (dBi)	25.0
Maximum e.i.r.p. (dBW)	30.0
Antenna height (m)	75
Distance to horizon from station (km)	30.9
Fixed service station to station range (km)	61.8
Free space loss (dB)	112.4
Additional terrestrial path loss (dB)	37.1
Received carrier power C (dBW)	−96.5

6.1.1.2.1.3 *C*/*I* analysis for the interference level from the VDE-SAT downlink into a fixed service station

Recommendation ITU-R M.2092-0 and § 4.2.1 provides the pfd mask for the VDE-SAT downlink. Based on the pfd-mask, and the fixed service station characteristics given in Table 17, a link budget for the interference level from the VDE-SAT downlink into a fixed service station can be calculated. Combining the interference level with the received carrier power for the fixed service station to station link from Table 22, the carrier to interference ratio (*C*/*I*) can be found. The outcome is presented in Table 23.

It should be noted that a practical realization of the VDE-SAT downlink with the Yagi antenna concept as described in § 4.1.4 will not match the pfd mask perfectly. As shown in Table 7 of that document, there will be margin to the pfd mask at all elevation angles, except at 30 degrees. When this additional margin is accounted for the *C*/*I* will improve further, as shown in Table 23.

TABLE 23

***C*/*I* considerations for transmissions between fixed stations with received carrier power, C, of −96.5 dBW and interference from the VDE-SAT downlink according to the pfd mask specified in Rec. ITU-R M.2092-0**

Fixed station elevation angle (degrees)	**pfd mask specified in Rec. ITU-R M.2092-0** (dBW/(m^2 * 4 kHz))	**pfd per 42 kHz** (dBW/(m^2 * 42 kHz))	**Fixed station antenna gain including feed loss** (dBi)	**Effective area of fixed station antenna** (dB(m^2))	***I* per 42 kHz** (dBW)	***C*/*I*** (dB)	***C*/*I* with realizable pfd** (dB)
0	−149.0	−138.8	23.0	17.4	−121.4	24.9	28.3
10	−147.4	−137.2	13.8	7.4	−129.8	33.3	35.0
20	−145.8	−135.6	8.8	3.2	−132.8	35.9	36.3
30	−144.2	−134.0	4.4	−.44	−135.2	38.7	38.7
40	−142.6	−132.4	1.3	−.32	−136.7	40.2	41.0
50	−139.4	−129.2	−129	−129	−135.9	39.4	43.5
60	−134.0	−123.8	−123	−123	−132.5	36.0	46.5
70	−133.0	−122.8	−122	−122.	−133.5	36.7	50.4
80	−132.0	−121.8	−121	−121.	−133.6	37.1	54.2
90	−131.0	−120.8	−120	−120.	−133.9	37.4	58.8

The *C*/*I* considerations presented in Table 23 is correct for the VDE-SAT downlink waveforms with an occupied bandwidth of 42 kHz. In Table 10 four additional waveforms are proposed for the VDE-SAT downlink having wider occupied bandwidth; 90 kHz, 141 kHz, 291 kHz and 492 kHz. Assuming these additional waveforms are transmitted with the same spectral density, the total interference level from the VDE-SAT downlink into a FS station receiver will be higher, reducing the fixed service station receiver *C*/*I* level correspondingly. The waveform with an occupied bandwidth of 90 kHz will reduce the fixed service station receiver *C*/*I* by 3.3 dB, while the waveform with an occupied bandwidth of 141 kHz will reduce the fixed service station receiver *C*/*I* by 5.3 dB.

Considering the typical technical characteristic for transmissions between fixed service stations as summarized in Table 17, the bandwidth of 250 kHz constrains the interference impact from the last two additional waveforms, which have larger occupied bandwidths. Thus, both these waveforms will reduce the fixed service station receiver *C*/*I* by 7.7 dB.

6.1.1.2.1.4 Conclusions

As shown in Table 23, the carrier to interference ratio (*C*/*I*) for the fixed service station to station link with interference from the VDE-SAT downlink waveform with an occupied bandwidth of 42 kHz will be between 24.9 dB and 40.2 dB. The wider bandwidth waveforms proposed for the VDE-SAT downlink may reduce this *C*/*I* level by 7.7 dB down to 17.2 dB.

Recommendation ITU-R M.1101, Annex 1, provides *C*/(*N*+*I*) threshold values for 10^{-6} BER for digital fixed wireless systems. For QPSK the *C*/(*N*+*I*) threshold is 13.5 dB. A *C*/*I* level of more than 24.9 dB for the fixed service station to station link with interference from the VDE-SAT downlink is then negligible for the fixed service. The wider bandwidth waveforms may reduce the *C*/*I* down to

17.2 dB, but there will still be a substantial margin compared to the 13.5 dB $C/(N+I)$ threshold. Furthermore, when considering the actual realizable pfd level, the situation will improve even further.

Therefore, it can be concluded that the fixed service will not experience harmful interference from the VDE-SAT downlink with the pfd mask specified in Recommendation ITU-R M.2092-0.

6.1.1.2.2 View 2 on the pfd mask

6.1.1.2.2.1 Typical characteristics of fixed systems in the frequency band 150-167 MHz

TABLE 24

Characteristics of fixed service station receivers used for compatibility studies in the frequency band 150.5-166.7 MHz

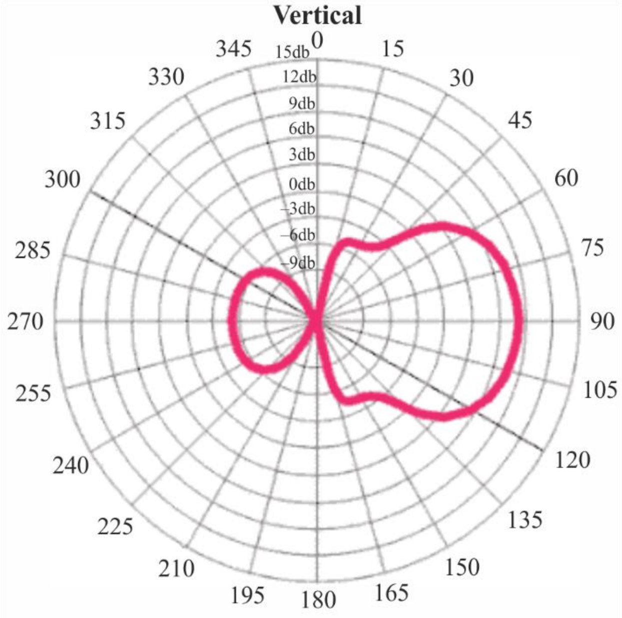
Parameter	Value
Frequency band (MHz)	150.5 ... 166.7
Modulation	QPSK
Channel spacing and receiver noise bandwidth (kHz)	100 … 200
Antenna gains (dBi)	9 ... 12
Antenna type	Directional (Yagi-Uda)
Feeder/multiplexer losses (dB)	0 … 4
Typical noise figure of a receiver (dB)	7
Permissible interference to thermal noise ratio of a receiver, I/N (dB) [(1)]	−6

[(1)] Recommendation ITU-R F.758-6.

In order to take into account selectivity of digital radio relay station antennas, the Yagi-Uda antenna radiation pattern in a vertical plane with a maximum antenna gain of 9 dBi is used, see Fig. 14.

FIGURE 14

Typical VHF antenna pattern in vertical plane (G_{max} = 9 dBi)



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I/N = −6 dB was used as the protection criterion according to Recommendation ITU-R F.758-6.

6.1.1.2.2.2 Estimation of the pfd mask required to protect fixed service systems

Power flux-density of permissible interference to FS receiver in $\Delta F = 4$ kHz bandwidth could be calculated using the following equation:

$$pfd(\theta°)_{(\text{dBW/m}^2 * 4\text{ kHz})} = 10 * \log(kT\Delta F) + NF + {}^{I}/_{N} - G(\theta°) + 20 * \log(f) + aRx + apol - 38.55$$

where:

NF	noise factor, dB
$k = 1.37 \times 10^{-23}$	Boltzmann constant, J/K
$T =$	288 K
$\Delta F =$	4 kHz
${}^{I}/_{N} = -6$ dB	
$apol$	polarization mismatch loss, dB
aRx	total loss between antenna and receiver, dB
$G(\theta)$	isotropic antenna gain, dBi
f=	160 MHz.

$$pfd(\theta°)max_{(\text{dBW/m}^2 * 4\text{ kHz})} = pfd(\theta° = 0)_{(\text{dBW/m}^2 * 4\text{ kHz})} = -168 + 7 - 6 - 9 + 44.08 + 2 + 3 - 38.55 = -165.5$$

Table 25 shows estimated pfd limits required to protect fixed service stations from harmful interference caused by the satellite downlink of a new VDES satellite component.

TABLE 25

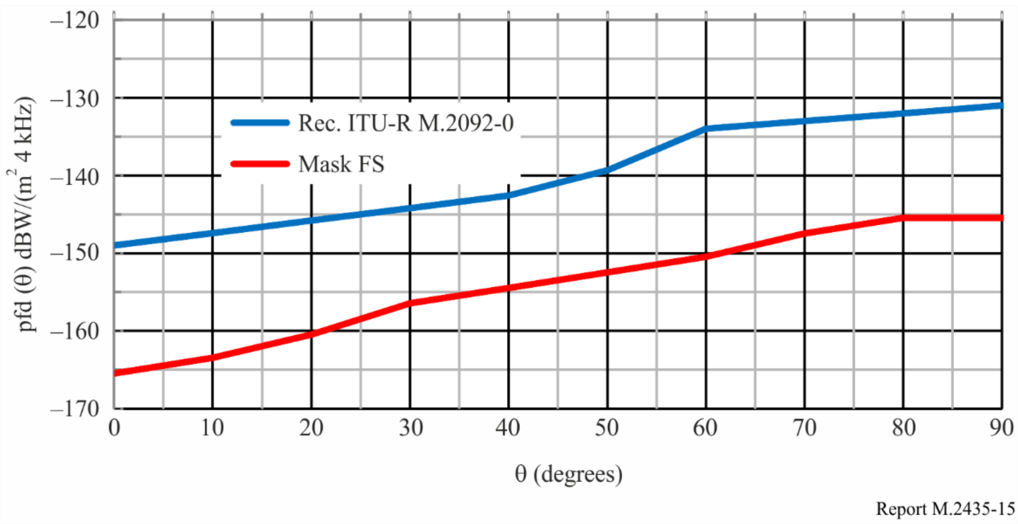
Estimated power flux-density limits required to protect fixed service stations

Elevation angle (degree)	**NF** (dB)	N_0=10*log($kT\Delta F$)+NF (dBW(4 kHz))	I=N_0+(I/N) (dBW (4 kHz))	**Antenna gain with feeder loss** (dB)	**Polarization loss** (dB)	**Required pfd** (dBW/ (m^2 4 kHz))
0	7	−161.0	−167.0	7	3	−165.5
10	7	−161.0	−167.0	5	3	−163.5
20	7	−161.0	−167.0	2	3	−160.0
30	7	−161.0	−167.0	−2	3	−156.5
40	7	−161.0	−167.0	−4	3	−154.3
50	7	−161.0	−167.0	−6	3	−152.1
60	7	−161.0	−167.0	−8	3	−149.9
70	7	−161.0	−167.0	−11	3	−147.7
80	7	−161.0	−167.0	−13	3	−145.4
90	7	−161.0	−167.0	−13	3	−145.4

Figure 15 below compares the pfd mask from Recommendation ITU-R M.2092-0, which shall ensure no harmful interference is caused by the satellite downlink to fixed service stations, and pfd limits required to protect receivers of fixed service stations.

FIGURE 15

Comparison of pfd masks



6.1.1.2.2.3 Estimation of VHF data exchange system satellite component downlink impact to systems of the fixed service

Table 26 below compares pfd levels caused by VDE-SAT[3] downlink emissions, and pfd limits required to protect receivers of fixed service stations.

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3 pfd levels are taken from Table A4-1 of Recommendation ITU-R M.2092-0.

Table 26

Estimated excess of pfd levels created by VDE-SAT over the pfd levels required to protect stations in the fixed service with the maximum antenna gain of 9 dBi

Elevation angle (degree)	**VDE-SAT pfd** (dBW/(m^2 *4 kHz))	**Required pfd** (dBW/(m^2 *4 kHz))	**Excess** (dB)
0	−149.0	−165.5	16.5
10	−147.4	−163.5	16.1
20	−145.8	−160.0	14.2
30	−144.2	−156.5	12.3
40	−142.6	−154.3	11.7
50	−139.4	−152.1	12.8
60	−134.0	−149.9	15.9
70	−133.0	−147.7	14.7
80	−132.0	−145.4	13.4
90	−131.0	−145.4	14.4

6.1.1.2.2.4 Proposed pfd mask for VHF data exchange system satellite downlink

Table 27 shows the proposed pfd mask required to protect receivers of FS systems operating in the frequency bands being considered for the VDE-SAT downlink.

TABLE 27

Proposed pfd mask

θ° is "Earth-satellite" elevation angle

$$pfd(\theta°)_{(\mathrm{dBW/m^2{*}4\ kHz})} = \begin{cases} -165.5 + 0.2 * \theta°, & 0° \leq \theta° < 10° \\ -163.5 + 0.35 * (\theta° - 10) & 10° \leq \theta° < 30° \\ -156.5 + 0.22 * (\theta° - 30) & 30° \leq \theta° < 80° \\ -145.4 & 80° \leq \theta° \end{cases}$$

6.1.1.2.2.5 Conclusions

Estimations in Table 25 show that emissions of VDE-SAT downlink, while meeting the required pfd mask limits from Recommendation ITU-R M.2092-0 (Table A4-1), would cause unacceptable interference to receivers of FS systems. Thus, for those conditions, the coexistence between VDE-SAT downlink and FS stations is not possible in the considered frequency bands. In order to protect FS station receivers from unacceptable interference of VDE-SAT downlink in the considered frequency bands, the required pfd mask limits from Table 27 shall be met.

6.1.2 Land and aeronautical mobile services in-band

6.1.2.1 Analysis of the interference effect of the VHF data exchange-satellite uplink

The VDE-SAT uplink has common characteristics with VDE terrestrial ship-to-shore. Therefore, it will not create any additional interference to land and aeronautical mobile services.

6.1.2.2 Analysis of the interference effect of the VHF data exchange-satellite downlink

There are three views on the interference effect of the VDE-SAT downlink into the land mobile service. The pfd mask contained in view 1 is specified in Recommendation ITU-R M.2092. The pfd masks contained in views 2 and 3 are based on protection criteria defined in Recommendation ITU-R M.1808-0.

6.1.2.2.1 View 1 on the pfd mask

It is assumed that the VDE-SAT downlink is compliant with the pfd mask specified in Recommendation ITU-R M.2092-0 and provided in Table 5 of § 4.2.1.

Given this mask, a study on the compatibility between the VDE-SAT downlink and the land mobile service has been performed. The study evaluates the effect of the interference from the VDE-SAT downlink received by a land mobile base station on the transmission between a mobile station and a base station. The basis for the study is the technical characteristics of land mobile systems as provided in Recommendation ITU-R M.1808, including interference criteria based on performance degradation, and methods for point-to-area predictions for terrestrial services as provided in Recommendation ITU-R P.1546.

The methodology used to evaluate the compatibility between the VDE-SAT downlink and the land mobile service is based on carrier-to-interference (C/I) considerations and performance degradation, as proposed in Recommendation ITU-R M.1808, Annex 1, § 2.1.

6.1.2.2.1.1 Characteristics of land mobile systems operating in the frequency band 156-162 MHz

Representative technical and operational characteristics of conventional and trunked land mobile systems operating in the mobile service in the frequency band 156-162 MHz are given in Recommendation ITU-R M.1808. Table 28 provides the technical characteristics of base stations and Table 29 provides technical characteristics of mobile stations as they are given in that Recommendation. Recommendation ITU-R P.372 provides additional relevant information regarding interference.

TABLE 28

Technical characteristics for base stations operating in the mobile service in the frequency band 138-174 MHz

Frequency band (MHz)	**138–174**	
Type of emission	**Analogue**	**Digital**
System-wide		
Channel bandwidth (kHz)	12.5/15/25/30	6.25/7.5/12.5/15
Modulation type	FM	C4FM
Type of operation	Simplex/duplex	Duplex
Typical SINAD or BER (dB or %)	12 dB	5%
Transmitter		
Output power (W)	5–125 (30) (100)	20–125 (60) (100)

TABLE 28 (*end*)

Frequency band (MHz)	**138–174**	
Type of emission	**Analogue**	**Digital**
e.r.p. (dBW)	7–26 (19) (24)	13–26 (18) (24)
Necessary bandwidth (kHz)	11/11/16/16	5.5/5.5/8.1/8.1
Coverage radius (km)	1–75 (50)	1–75 (50)
Antenna gain (dBd)	0–9 (6)	0–9 (6)
Antenna height (relative to ground level) (m)	10–150 (60)	10–150 (65)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–7 (2)	3–9 (6) (2)
Receiver		
Noise figure (dB)	6–12 (7)	6–12 (7)
IF filter bandwidth (kHz)	8/11/12.5/16	5.5/5.5/5.5/5.5
Sensitivity (dBm)	−116 to −121 (−119)	−116 to −121 (−119)
Antenna gain (dBd)	0–9 (6)	0–9 (8)
Antenna height (relative to ground level) (m)	10–150 (60)	10–150 (65)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–6 (3)	0–6 (3)

NOTE 1 – Simplex systems use the same frequency for both the base station and mobile station to transmit.

NOTE 2 – Frequency division duplex systems have different frequencies for the base station and mobile station which allows simultaneous communications.

NOTE 3 – Typical values are shown in parenthesis. In some instances, more than one typical value is provided.

NOTE 4 – e.r.p. is equal to the output power (dBW) plus antenna gain (dBd) minus total losses (dB).

TABLE 29

Technical characteristics for mobile stations operating in the mobile service in the frequency band 138-174 MHz

Frequency band (MHz)	**138–174**	
Type of emission	**Analogue**	**Digital**
System-wide		
Channel bandwidth (kHz)	12.5/15/25/30	6.25/7.5/12.5/15
Modulation type	FM	C4FM
Type of operation	Simplex/duplex	Duplex
Typical SINAD or BER (dB or %)	12 dB	5%
Transmitter		
Output power (W)	1–100 (H: 5 V: 30, 50)	1–100 (H: 5 V: 30, 50)
e.r.p. (dBW)	−3 to –18 (H: −3 V: 14, 16)	−3 to –18 (H: −3 V: 14, 16)
Necessary bandwidth (kHz)	11/11/16/16	5.5/5.5/8.1/8.1
Antenna gain (dBd)	−10 to–4 (H: −10, V: 0)	−10 to 4 (H: −10, V: 0)
Antenna height (relative to ground level) (m)	(2)	(2)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–1 (H: 0, V: 1)	0–1 (H: 0, V: 1)
Receiver		
Noise figure (dB)	6–12 (7)	6–12 (7)
IF filter bandwidth (kHz)	8/11/12.5/16	5.5/5.5/5.5/5.5
Sensitivity (dBm)	−116 to −121 (−119)	−116 to −121 (−119)
Antenna gain (dBd)	−10 to 4 (H: −10, V: 0)	−10 to 4 (H: −10, V: 0)
Antenna height (relative to ground level) (m)	(2)	(2)
Radiation pattern	Omnidirectional	Omnidirectional

TABLE 29 (*end*)

Frequency band (MHz)	**138–174**	
Type of emission	**Analogue**	**Digital**
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–1 (H: 0, V: 1)	0–1 (H: 0, V: 1)

NOTE 1 – Simplex systems use the same frequency for both the base station and mobile station to transmit.

NOTE 2 – Frequency division duplex (FDD) systems have different frequencies for the base station and mobile station which allows simultaneous communications.

NOTE 3 – Typical values are shown in parenthesis, “H:” represents the value for handheld mobile stations and “V:” represents the value for vehicular mobile stations. In some instances, more than one typical value is provided.

NOTE 4 – e.r.p. is equal to the output power (dBW) plus antenna gain (dBd) minus total losses (dB).

For the studies of the compatibility of the VDE-SAT downlink with the land mobile service the typical values from Table 28 and Table 29 have been used. These technical characteristics and values are summarized in Table 30.

TABLE 30

Typical values for technical characteristics of land mobile service stations used in compatibility study

Station type	**Base station**	**Mobile station**
Necessary bandwidth (kHz)	16	16
Output power (W)	100	50
Output power (dBW)	20	17
Feed loss (dB)	2.0	1.0
Maximum antenna gain (dBd)	6.0	0.0
Maximum antenna gain (dBi)	8.2	2.2
Maximum e.r.p. (dBW)	24.0	16.0
Maximum e.i.r.p. (dBW)	26.2	18.2
Antenna height (m)	60	2
Distance to horizon from station (km)	27.7	5.1

Figure 16 shows antenna patterns for typical antennas used in the land mobile service as described in Recommendation ITU-R F.1336-4. Assuming a 6 dBd antenna is used at the base station and a 0 dBd antenna is used at the mobile station, the antenna gain versus elevation angle can be tabulated as in Table 31 and Table 32 for the base station and mobile station respectively. Table 31 and Table 32 also present the resulting e.i.r.p. versus elevation angle for the two station types.

FIGURE 16

Antenna patterns for typical antennas used in the land mobile service as described in Rec. ITU-R F.1336-4

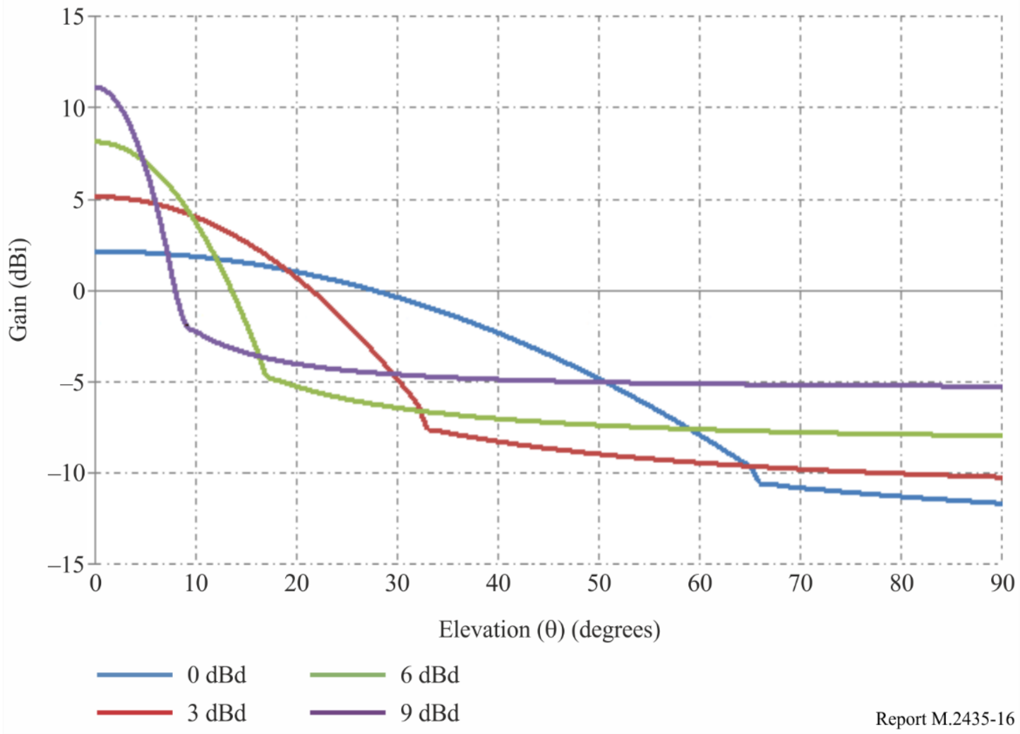


TABLE 31

Base station antenna gain and e.i.r.p. versus elevation angle

Elevation angle (degrees)	**Antenna gain** (dBi)	**e.i.r.p.** (dBW)
0	8.2	26.2
10	3.7	21.7
20	−5.2	12.8
30	−6.4	11.6
40	−7.0	11.0
50	−7.4	10.6
60	−7.6	10.4
70	−7.7	10.3
80	−7.9	10.1
90	−7.9	10.1

TABLE 32

Mobile station antenna gain and e.i.r.p. versus elevation angle

Elevation angle (degrees)	**Antenna gain** (dBi)	**e.i.r.p.** (dBW)
0	2.2	18.2
10	1.9	17.9
20	1.0	17.0
30	−0.4	15.6
40	−2.3	13.7
50	−4.8	11.2
60	−7.9	8.1
70	−10.8	5.2
80	−11.3	4.7
90	−11.6	4.4

6.1.2.2.1.2 Link budget calculations for transmission from base station to mobile station

Given the typical antenna heights for the land mobile base station and mobile station summarized in Table 30, the distance to the horizon from the base or mobile station can be calculated. Then the mobile station to base station range can be found to be 32.7 km. Based on the mobile station to base station range the transmission free space loss can be calculated to 106.9 dB.

In addition to the free space loss, a land mobile transmission channel will experience additional path loss. Recommendation ITU-R P.1546 provide methods for point-to-area predictions for terrestrial services for the relevant frequency band. Based on tabulated field strengths available from the Radiocommunication Bureau, as discussed in Annex 1 of that Recommendation, combined with formulas for interpolation of field strength as function of antenna height, distance and frequency as provided in Annex 5 of that Recommendation, the additional path loss can be estimated. The tabulated field strengths exceeded 50% of the time from Recommendation ITU-R P.1546 assumes a transmit e.r.p. of 1 kW, and the values needed to perform the interpolation to the frequency of 162 MHz and the antenna height and mobile station to base station range given in Table 30, are provided in Table 33.

TABLE 33

Tabulated field strength values exceeded 50% of the time from Rec. ITU-R P.1546 needed to perform the interpolation to the frequency of 162 MHz and the antenna height and mobile station to base station range

Frequency (MHz)	**Antenna height** (m)	**Distance** (km)	**Field strength value** (dB(uV/m))
100	37.5	30	41.3
		35	38.1
	75	30	47.5
		35	44.2
600	37.5	30	37.5
		35	34.2
	75	30	44.2
		35	40.5

Through the use of the interpolation formulas provided in Annex 5 of Recommendation ITU-R P.1546 the estimated field strength can be calculated for the frequency of 162 MHz, antenna height of 60 meters and a distance of 32.7 km. The result is an estimated field strength of 42.7 dB(uV/m). The corresponding field strength if only free space loss is considered will be 72.5 dB(uV/m). The additional path loss experienced on a land mobile transmission channel is equal to this difference, which is 29.8 dB. The calculation steps are provided in Table 34 for transparency.

TABLE 34

Calculation steps for interpolation of field strength values exceeded 50% of the time from Rec. ITU-R P.1546 to the frequency of 162 MHz and the antenna height and mobile station to base station range

	Frequency (MHz)	**Antenna height** (m)	**Distance** (km)	**Field strength value** (dB(uV/m))
Free space loss and additional path loss	162	37.5	30	40.3
			35	37.0
		75	30	46.6
			35	43.2
	162	60	30	44.5
			35	41.2
	162	60	32.7	42.7
Free space loss only	100		30	77.4
	162		32.7	72.5
Additional path loss only (dB)	*162*	*60*	*32.7*	*29.8*

The additional terrestrial path loss of 29.8 dB must be taken into considered in the link budget. Taking into account the mobile station EIRP at 0-degree elevation and the base station antenna gain at

0-degree elevation this leads to the received carrier power of −112.4 dBW for the mobile station to base station link and −109.4 dBW for the base station to mobile station link. The results are provided in Table 35.

TABLE 35

Link budget calculations for transmissions between mobile stations and base stations

Station type	Units	Base station	Mobile station
Output power	(W)	100	50
Output power	(dBW)	20.0	17.0
Feed loss	(dB)	2.0	1.0
Maximum antenna gain	(dBd)	6.0	0.0
Maximum antenna gain	(dBi)	8.2	2.2
Maximum e.r.p.	dBW	24.0	16.0
Maximum e.i.r.p.	dBW	26.2	18.1
Antenna height	m	60	2.0
Distance to horizon from station	km	27.7	5.0
Mobile station to base station range	km	32.7	
Free space loss	dB	106.9	
Additional terrestrial path loss	dB	29.8	
Received carrier power C	dBW	−112.4	−109.4

6.1.2.2.1.3 C/I analysis for the interference level from the VDE-SAT downlink into a base station and a mobile station

Recommendation ITU-R M.2092-0 and § 4.2.1 of this Report provide the pfd mask for the VDE-SAT downlink. Based on the pfd mask, and the base and mobile station characteristics given in Table 30, a link budget for the interference level from the VDE-SAT downlink into a base station and a mobile station can be calculated. Combining the interference level with the received carrier power for transmissions between mobile stations and base stations from Table 35, the carrier to interference ratio (*C*/*I*) can be found. The outcome is presented in Tables 36 for a base station and 37 for a mobile station.

It should be noted that a practical realization of the VDE-SAT downlink with the Yagi antenna concept as described in § 4.1.4 will not match the pfd mask perfectly. As shown in Table 7, there will be margin to the pfd mask at all elevation angles, except at 30 degrees. When this additional margin is accounted for the *C*/*I* will improve further, also shown in Tables 36 and 37.

TABLE 36

C/I considerations for transmissions from mobile station to base station with received carrier power, C, of −112.4 dBW and interference from the VDE-SAT downlink according to the pfd mask specified in Rec. ITU-R M.2092-0

Elevation angle (degrees)	**pfd mask specified in Rec. ITU-R M.2092-0** (dBW/(m^2 * 4 kHz))	**pfd per 16 kHz** (dBW/(m^2 * 16 kHz))	**Base station antenna gain including feed loss** (dBi)	**Effective area of base station antenna** (dB(m^2))	***I* per 16 kHz** (dBW)	***C/I*** (dB)	***C/I* with realizable pfd** (dB)
0	–149.0	–143.0	6.2	0.6	–142.4	30.0	33.4
10	–147.4	–141.4	1.7	−3.9	–145.3	32.9	34.6
20	–145.8	–139.8	−7.2	−12.8	–152.6	40.2	40.6
30	–144.2	–138.2	−8.4	−14.0	–152.2	39.8	39.8
40	–142.6	–136.6	−9.0	−14.6	–151.2	38.8	39.6
50	–139.4	–133.4	−9.4	−15.0	–148.4	36.0	40.1
60	–134.0	–128.0	−9.6	−15.2	–143.2	30.8	41.3
70	–133.0	–127.0	−9.7	−15.3	–142.3	29.9	43.6
80	–132.0	–126.0	−9.9	−15.5	–141.5	29.1	46.3
90	–131.0	–125.0	−9.9	−15.5	–140.5	28.1	49.5

TABLE 37

C/I considerations for transmissions from base station to mobile station with received carrier power, C, of −109.4 dBW and interference from the VDE-SAT downlink according to the pfd mask specified in Rec. ITU-R M.2092-0

Elevation angle (degrees)	**pfd mask specified in Rec. ITU-R M.2092-0** (dBW/(m^2 * 4 kHz))	**pfd per 16 kHz** (dBW/(m^2 * 16 kHz))	**Base station antenna gain including feed loss** (dBi)	**Effective area of base station antenna** (dB(m^2))	***I* per 16 kHz** (dBW)	***C/I*** (dB)	***C/I* with realizable pfd** (dB)
0	–149.0	–143.0	1.2	−4.4	–147.4	38.0	41.4
10	–147.4	–141.4	0.9	−4.7	–146.1	36.7	38.4
20	–145.8	–139.8	0.0	−5.6	–145.4	36.0	36.4
30	–144.2	–138.2	−1.4	−7.0	–145.2	35.8	35.8
40	–142.6	–136.6	−3.3	−8.9	–145.5	36.1	36.9
50	–139.4	–133.4	−5.8	−11.4	–144.8	35.4	39.5
60	–134.0	–128.0	−8.9	−14.5	–142.5	33.1	43.6
70	–133.0	–127.0	−11.8	−17.4	–144.4	35.0	48.7
80	–132.0	–126.0	−12.3	−17.9	–143.9	34.5	51.7
90	–131.0	–125.0	−12.6	−18.2	–143.2	33.8	55.2

6.1.2.2.1.4 Conclusions

As shown in Table 36, the carrier to interference ratio (C/I) for the mobile station to base station link with interference from the VDE-SAT downlink will be between 28.1 dB and 40.2 dB. For the base station to mobile station link the C/I with interference from the VDE-SAT downlink will be between 33.1 and 38.0 dB, as shown in Table 37.

Recommendation ITU-R M.1808, § 2.2 of Annex 1, provides SINAD ratio values of 12 dB to 20 dB for establishing degradation protection for land mobile systems. The C/N required to achieve these SINAD ratio values can be derived from the FM improvement formulae, which calculates the audio S/N as a function of C/N in FM systems operating above the detection threshold. The detection threshold can also be referred to as the minimum discernible signal level. The FM improvement formulae is as follows:

$$\left(\frac{S}{N}\right)_{FM} = \left(\frac{C}{N}\right) \cdot \frac{3}{2} \cdot \frac{BW_{FM}}{B_m} \cdot \left(\frac{\Delta f}{B_m}\right)^2$$

where BW_{FM} is the bandwidth of the FM signal obtained using Carson's rule, Δf is the peak frequency deviation and B_m is the bandwidth of the information signal.

The FM improvement formulae can be expressed in dB form as follows:

$$\left(\frac{S}{N}\right)_{FM} = \left(\frac{C}{N}\right) + 1.8 + 10log_{10}\left(\frac{BW_{FM}}{B_m}\right) + 20log_{10}\left(\frac{\Delta f}{B_m}\right)$$

Table 38 shows the C/N values required to achieve SINAD ratio values of 12 dB and 20 dB, respectively for FM system with 12.5 kHz and 25 kHz channel spacing.

TABLE 38

C/N required for audio SINADs of 12 dB and 20 dB in FM systems with 12.5 and 25 kHz channel spacing

Channel spacing	**12.5**	**25**	**kHz**
SINAD	12	20	dB
S/N_{FM}	11.7	20	dB
B_m	3	3	kHz
Δf	2.5	5	kHz
BW_{FM}	11	16	kHz
C/N	7.8	6.4	dB

A *C*/*I* level of more than 28.1 dB for the mobile station to base station link with interference from the VDE-SAT downlink is negligible relative to the *C*/*N* values of 7.8 dB and 6.4 dB required to meet the SINAD degradation protection values for land mobile systems provided in Recommendation ITU-R M.1808, Annex 1. When considering the actual realizable pfd level, the situation will improve even further.

Furthermore, Report ITU-R M.1021 provides equipment characteristics for digital transmission in the land mobile service, including a bit energy to noise density ratio (E_b/N_0) reference sensitivity of 12 dB corresponding to a bit error ratio (BER) of 1%. According to Recommendation ITU-R M.1808, digital land mobile systems use C4FM modulation and a BER threshold of 5%. C4FM modulation has two bits per symbol. Given that C/I corresponds to symbol energy to noise density ratio (E_s/N_0), digital land mobile systems have a typical *C*/(*N*+*I*) threshold of 15 dB. A *C*/*I* level of more than 28.1 dB for the mobile station to base station link with interference from the VDE-SAT downlink is negligible relative to the reference sensitivity provided in Report ITU-R M.1021. When, considering the actual realizable pfd level, the situation will improve even further.

Therefore, it can be concluded that the land mobile service will not experience harmful interference from the VDE-SAT downlink with the pfd mask specified in Recommendation ITU-R M.2092-0.

6.1.2.2.2 View 2 about the pfd mask

Three methods were considered in this section to evaluate the pfd mask of the VDE-SAT downlink, aiming to provide protection to the land mobile service in the same frequency band. One method is based on *I*/*N* defined in Recommendation ITU-R M.1808-0, Annex 1, § 2.1, and the second method is similar to method 1 except that the noise floor was calculated considering the environment noise floor. The third method is to calculate the *C*/(*I*+*N*).

6.1.2.2.2.1 Pfd mask with the method I/N

Recommendation ITU-R M.1808-0, Annex 1, § 2.1, presents the protection criteria of *I*/*N* of −6 dB for the land mobile service. The typical characteristics of mobile systems in the frequency band 138-174 MHz extracted from Table 1 of Appendix 1 to Annex 1 in Recommendation ITU-R M.1808-0 are shown in Table 39.

TABLE 39

Base station and mobile station characteristics for frequency sharing in the frequency band 138-174 MHz

	Base station		**Mobile station**	
Type of emission	Analogue	Digital	Analogue	Digital
Receiver				
Noise figure (dB)	6 to 12 (7)	6 to 12 (7)	6 to 12 (7)	6 to 12 (7)
IF filter bandwidth (kHz)	8/11/12.5/16	5.5/5.5/5.5/5.5	8/11/12.5/16	5.5/5.5/5.5/5.5
Antenna gain (dBd)	0 to 9 (6)	0 to 9 (8)	−10 to 4 (H: −10, V: 0)	−10 to 4 (H: −10, V: 0)
Radiation pattern	Omnidirectional	Omnidirectional	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical	Vertical	Vertical
Total loss (dB)	0 to 6 (3)	0 to 6 (3)	0 to 1 (H: 0, V: 1)	0 to 1 (H: 0, V: 1)

If I/N = –6 dB, the permitted received interference power in the port of receiver is P(dBm/4 kHz) = $N_0 + NF + I/N$ = –174 + 7 – 6 + 10*log (4000) = –136.98 dBm/4 kHz.

With P being the received interference power (W), pfd being the pfd (W/(m^2 * 4 kHz)), G_0 being the isotropic antenna gain (dBi, in dBd + 2.15), a_c being total loss between antenna and receiver (dB), L_p being polarization mismatch loss (3 dB) and f being 160 MHz, pfd could be calculated with equation (1):

$$\text{pfd}(\text{dBm}/(\text{m}^2{*}4\text{kHz})) = P(\text{dBm}/4\text{kHz}) - (38.55 + G_0 - 20{*}\log(f/\text{MHz})) - 30\text{ dB} + a_c(\text{dB}) + L_p(\text{dB}) \quad (1)$$

The maximum permitted pfd to surface of antenna of land mobile base station will be pfd = −163.6 dBm/(m^2*4kHz).

For the base stations the average side-lobe patterns (in vertical) are considered in sharing study according to Recommendation ITU-R F.1336 for omnidirectional radiation patterns (in azimuth) as presented in equation (2) below.

$$G(\theta) = \begin{cases} G_0 - 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ G_0 - 15 + 10\log_{10}(k+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ G_0 - 15 + 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + k\right) & \text{for } \theta_5 < |\theta| < 90^{\circ} \end{cases} \quad (2)$$

with:

$$\theta_5 = \theta_3\sqrt{1.25 - \frac{1}{1.2}\log_{10}(k+1)}$$

where:

$G(\theta)$: gain relative to an isotropic antenna (dBi)

G_0: the maximum gain in the azimuth plane (dBi) knowing that G_0 in dBi equals G_0 in dBd + 2.15

θ: elevation angle relative to the angle of the maximum gain (degrees) $(-90^{\circ} \leq \theta \leq 90^{\circ})$

θ_3: the 3 dB beamwidth in the elevation plane (degrees) $\theta_3 = 107.6 \times 10^{-0.1\,G_0}$

k: parameter which accounts for increased side-lobe levels above what would be expected for an antenna with improved side-lobe performance (for antennas operating in the 400 MHz to 3 GHz range, the parameter k should be 0.7).

Given that pfd is calculated with equation (1) and that $G(\theta)$ as defined in equation (2) is a function of the elevation angle θ, then the VDE-SAT downlink pfd is also a function of the elevation angle:

$$PFD_{MAX,BS}^{I/N}(\theta) = \begin{cases} -163.6 + 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ -148.6 - 10\log_{10}(\mathrm{k}+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ -148.6 - 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + \mathrm{k}\right) & \text{for } \theta_5 < |\theta| < 90^{\circ} \end{cases} \quad (4)$$

with θ the elevation angle, $\theta_3 = 16.47°$, $\theta_5 = 16.95°$ and $\mathrm{k} = 0.7$.

$$PFD_{MAX,MS}^{I/N}(\theta) = \begin{cases} -159.5 + 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ -144.5 - 10\log_{10}(k+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ -144.5 - 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + k\right) & \text{for } \theta_5 < |\theta| < 90^{\circ} \end{cases} \quad (5)$$

with θ the elevation angle, $\theta_3 = 65.59°$, $\theta_5 = 67.46°$ and $\mathrm{k} = 0.7$.

6.1.2.2.2.2 pfd mask with the method I/N where N includes environment noise

The Recommendation ITU-R P.372-13 "Radio Noise" provides methods on calculation of the man-made noise level depending on the environment and galactic noise for different bands. For the VHF maritime mobile band, galactic noise with temperature of T_g = 24 dBK and man-made noise with temperature in the range from T_m = 31 to 38 dBK are the main sources of external noise. The overall equivalent temperature is $T \approx 34$dBK while a rural scenario is considered.

Therefore, the noise floor equals -153 dBW/16 kHz, considering the environment noise. For *I/N* = –6 dB, the permitted received interference power in the port of receiver is –162 dBW per 4 kHz. Then the maximum permitted pfd to the antenna surface of a base station will be pfd =

−158.5 dBW/(m^2*4kHz) and the maximum permitted pfd to surface of antenna of mobile station will be pfd = –154.5 dBW/(m^2*4kHz) with equation (1). With elevation angle θ, the PFD is:

$$PFD^{I/N_1}_{MAX,BS}(\theta) = \begin{cases} -158.5 + 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ -143.5 - 10\log_{10}(k+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ -143.5 - 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + k\right) & \text{for } \theta_5 < |\theta| < 90^\circ \end{cases} \quad (6)$$

with θ the elevation angle, $\theta_3 = 16.47°$, $\theta_5 = 16.95°$ and $k = 0.7$.

$$PFD^{I/N_1}_{MAX,MS}(\theta) = \begin{cases} -154.5 + 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ -141.5 - 10\log_{10}(k+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ -141.5 - 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + k\right) & \text{for } \theta_5 < |\theta| < 90^\circ \end{cases} \quad (7)$$

with θ the elevation angle, $\theta_3 = 65.59°$, $\theta_5 = 67.46°$ and $k = 0.7$.

6.1.2.2.2.3 The pfd masks based on *C*/(*I*+*N*)

6.1.2.2.2.3.1 Link calculations for transmissions between mobile stations and base stations

The link between the base station and the vehicle mobile station has been evaluated in § 6.1.2.2.1.2, therefore, in this section, only the link between the handheld mobile station and the base station was calculated.

TABLE 40

Technical characteristics of land mobile service stations used in link budget study

Station type	Base station		Mobile station(H)	
	Digital	**Analogue**	**Digital**	**Analogue**
Modulation type	**C4F4**	**FM**	**C4F4**	**FM**
Output power (typical/min) (W)	60/30	30/5	30/5	30/5
Total loss (dB)	2		0	
Maximum antenna gain (dBd)	6.0		−10	
Maximum antenna gain (dBi)	8.15		−7.85	
Antenna height (m)	60		2	
Distance to horizon from station (km)	27.7		5	

NOTE 1 – Simplex systems use the same frequency for both the base station and mobile station to transmit.

NOTE 2 – Frequency division duplex systems have different frequencies for the base station and mobile station which allows simultaneous communications.

NOTE 3 – Typical values are shown in parenthesis. In some instances, more than one typical value is provided.

NOTE 4 – e.r.p. is equal to the output power (dBW) plus antenna gain (dBd) minus total losses (dB).

Given the typical antenna heights for the land mobile base station and the mobile station, and the distance to the horizon from the base or mobile station shown in Table 40, the mobile station to base station range can be found to be the sum of the two distances, which is 32.8 km. Other typical characteristics of mobile systems are according to Recommendation ITU-R M.1808-0.

For the frequency of 162 MHz, based on Recommendation ITU-R P.1546-5, the field strengths exceeded 50% of the time and 90% of the locations assuming a transmission e.i.r.p. of 1 kW can be calculated as 37.7 dB(μV/m). Then the path loss experienced on a land mobile transmission channel is equal to 145.8 dB.

For the analogue land mobile systems, the expected received signal level in mobile station and base station are $C^{A}_{BS\to MS} = -132.73$ dBW and $C^{A}_{MS\to BS} = -140.5$ dBWwith 16 kHz necessary bandwidth.

For the digital land mobile systems, the expected received signal level in mobile station and base station are $C^{D}_{BS\to MS} = -129.8$ dBWand $C^{D}_{MS\to BS} = -140.5$ dBW with 8 kHz necessary bandwidth.

6.1.2.2.2.3.2 The requirement to protect the land mobile service

For the analogue land mobile systems, in § 2.2 of Annex 1 of Recommendation ITU-R M.1808, SINAD ratio values of 12 dB to 20 dB was proposed for establishing degradation protection, which corresponds to $C/(N+I)$ levels of 6.4 dB to 7.8 dB (see § 6.1.2.2.1.4). In this section, $C/(N+I) = 6$ dB providing a SINAD ratio value of 12 dB, is considered to provide protection to the land mobile service from VDE-SAT downlink signals.

For digital land mobile systems in the frequency band between 138 and 174 MHz, a bit error rate of 2-5% with C4FM modulation is targeted. Given that C/I corresponds to symbol energy to noise density ratio (E_b/N_0), $C/(N+I) = 13$dB was considered, which could be referred to the Report ITU-R M.1021-0.

6.1.2.2.2.3.3 Calculation of the pfd mask

For analogue land mobile system, the system noise level is N= −153dBW (see § 6.1.2.2.2.2). Then the maximum interference for the base station is $I^{MAX}_{BS-A} = -147.6$dBW (per 16 kHz) and $I^{MAX}_{MS-A} = -139$ dBW (per 16 kHz) for the mobile station.

For digital land mobile system, the maximum interference is $I^{MAX}_{BS-D} = -154$ dBW (per 16 kHz) for the base station and $I^{MAX}_{MS-D} = -140$ dBW (per 16 kHz) for the mobile station.

Considering the digital land mobile system is vulnerable to interference, the required pfd was calculated with the permitted interference to a digital system.

The permitted received interference power in the port of base station is -160 dBW (per 4 kHz) and -146 dBW (per 4 kHz) for a mobile station. The permitted pfd could be calculated with equation (8):

$$PFD = P(\text{dBw/4kHz}) - (38.55 + G_0 - 20 * log(f/\text{MHz})) + a_c(\text{dB}) + L_p(\text{dB}) \tag{8}$$

The maximum permitted pfd to the antenna surface of a base station will be $\text{PFD}_{MAX,BS} = -157.5\text{dBW}/(m^2 * 4\text{kHz})$ and $\text{PFD}_{MAX,MS} = -139.5\text{dBW}/(m^2 * 4\text{kHz})$. Given that PSFD is calculated with equations (4) and (5), and that $\text{G}(\theta)$ as defined in (2) is a function of the elevation angle θ, then the VDES downlink pfd is also a function of the elevation angle:

$$\text{PFD}_{\text{MAX,BS}}(\theta) = \begin{cases} -157.5 + 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ -142.5 - 10\log_{10}(\text{k}+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ -142.5 - 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + \text{k}\right) & \text{for } \theta_5 < |\theta| < 90^\circ \end{cases} \tag{9}$$

with θ the elevation angle, $\theta_3 = 16.47°$, $\theta_5 = 16.95°$ and $\text{k} = 0.7$.

$$PFD_{MAX,MS}(\theta) = \begin{cases} -139.5 + 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ -124.5 - 10\log_{10}(k+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ -124.5 - 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + k\right) & \text{for } \theta_5 < |\theta| < 90^\circ \end{cases} \quad (10)$$

with θ the elevation angle, $\theta_3 = 65.59°$, $\theta_5 = 67.46°$ and k = 0.7.

6.1.2.2.2.4 Conclusions

The comparison of different pfd masks is illustrated in Fig. 17. The pfd masks of *I*/*N* are derived from calculations only considering receiver noise floor. The pfd masks of I/N_1 are the result of evaluation, in which the noise floor composed of receiver noise and radio noise. The pfd masks of *C*/(*I*+*N*) are based on the analysis considering the link between the base station and the handheld mobile station in the land mobile service.

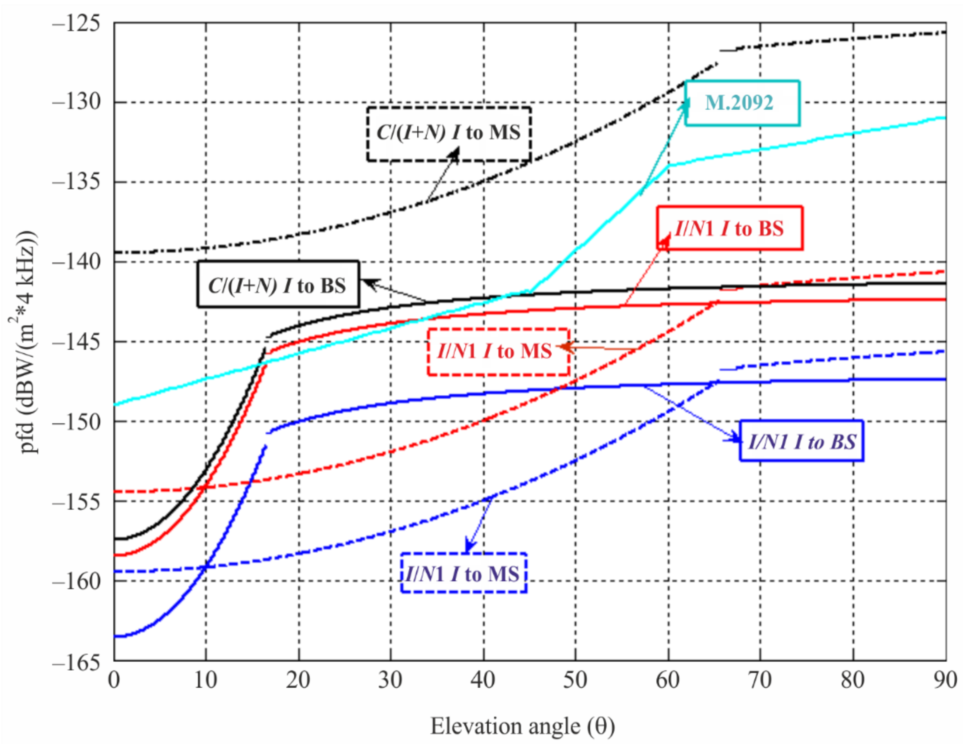
In Fig. 17, the pfd mask of I/N_1 and pfd mask of *C*/(*I*+*N*) for the base station are close to each other (only 1 dB in difference), which means the method I/N_1 and method *C*/(*I*+*N*) could produce similar results. Therefore, the pfd mask for the VDE-SAT downlink is suggested as below, which is in compliance with the protection criteria to the land mobile service in § 2.1 of Annex 1 of Recommendation ITU-R M.1808-0.

$$\mathrm{PFD}(\theta) = \begin{cases} -158.5 + 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ -143.5 - 10\log_{10}(\mathrm{k}+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ -143.5 - 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + \mathrm{k}\right) & \text{for } \theta_5 < |\theta| < 90^\circ \end{cases}$$

with θ the elevation angle, $\theta_3 = 16.47°$, $\theta_5 = 16.95°$ and k = 0.7.

FIGURE 17

Comparison of pfd masks derived from methods in § 6.1.2.2.2 and in Recommendation ITU-R M.2092-0



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6.1.2.2.3 View 3 about pdf mask

6.1.2.2.3.1 Characteristics of the systems operating in the 156-162 MHz in the mobile service

The characteristics of systems in the mobile service operating in the frequency band 156-162 MHz are given in Recommendation ITU-R M.1808. Table 41 presents the characteristics of base stations and Table 42 contains characteristics of mobile stations taken from the mentioned Recommendation.

TABLE 41

Base station receiver characteristics in the frequency band 138-174 MHz

Frequency band (MHz)	**138–174**	
Type of emission	**Analogue**	**Digital**
Noise figure (dB)	6–12 (7)	6–12 (7)
IF filter bandwidth (kHz)	8/11/12,5/16	5,5/5,5/5,5/5,5
Sensitivity (dBm)	−116 – −121 (−119)	−116 – −121 (−119)
Antenna gain (dBi = dBd + 2.15) (dBd)	0–9 (6)	0–9 (8)
Antenna height (relative to ground level) (m)	10–150 (60)	10–150 (65)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–6 (3)	0–6 (3)

NOTE 1 – Simplex systems use the same frequency for both the base station and mobile station to transmit.

NOTE 2 – Frequency division duplex systems have different frequencies for the base station and mobile station which allows simultaneous communications.

NOTE 3 – Typical values are shown in parenthesis. In some instances, more than one typical value is provided.

TABLE 42

Mobile station receiver characteristics in the frequency band 138-174 MHz

Frequency band (MHz)	**138–174**	
Type of emission	**Analogue**	**Digital**
Noise figure (dB)	6–12 (7)	6–12 (7)
IF filter bandwidth (kHz)	8/11/12,5/16	5,5/5,5/5,5/5,5
Sensitivity (dBm)	−116 – −121 (−119)	−116 – −121 (−119)
Antenna gain (dBi = dBd + 2.15) (dBd)	−10–4 (H: −10, V: 0)	−10–4 (H: −10, V: 0)
Antenna height (relative to ground level) (m)	(2)	(2)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–1 (H: 0, V: 1)	0–1 (H: 0, V: 1)

NOTE 1 – Simplex systems use the same frequency for both the base station and mobile station to transmit.

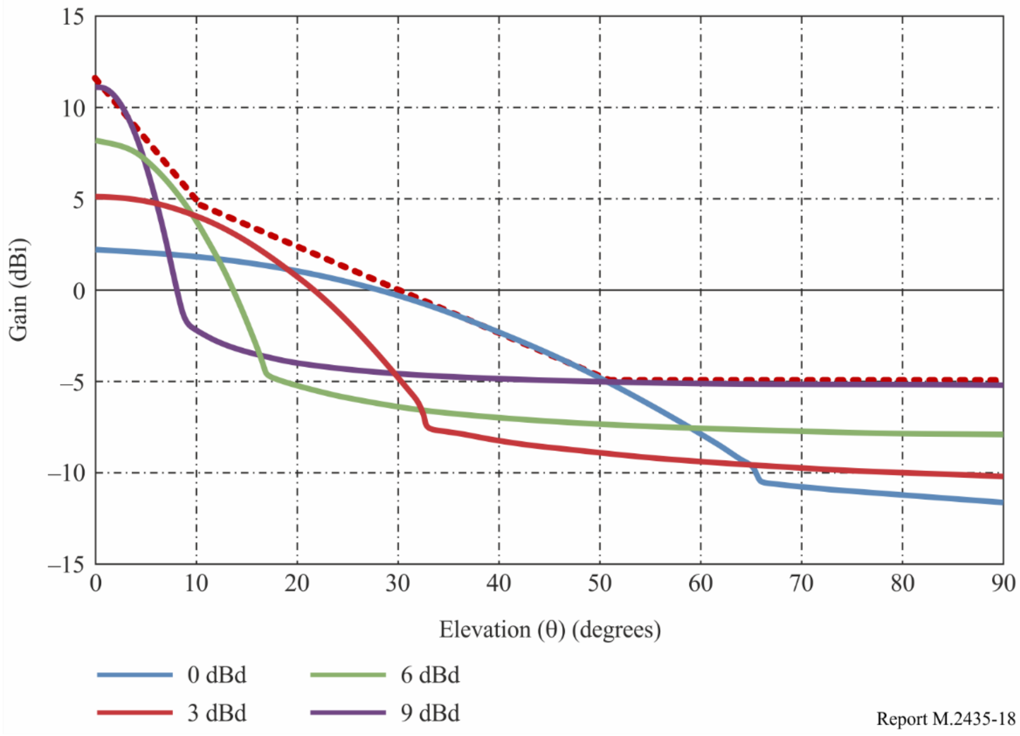
NOTE 2 – Frequency division duplex (FDD) systems have different frequencies for the base station and mobile station which allows simultaneous communications.

NOTE 3 – Typical values are shown in parenthesis, “H:” represents the value for handheld mobile stations and “V”: represents the value for vehicular mobile stations. In some instances, more than one typical value is provided.

Figure 18 shows antenna patterns for typical antennas used in the land mobile service as described in Recommendation ITU-R F.1336-4. The red dotted line shows the approximation that was used to determine the pfd mask.

FIGURE 18

VHF typical antenna pattern in vertical plane



In accordance with Recommendation ITU-R M.1808 the protection ratio *I*/*N* of –6 dB was used as the protection criteria.

6.1.2.2.3.2 Estimation of the pfd mask to ensure protection for the systems in the mobile service

Tables 43 and 44 contain the estimation of the required pfd limits for protection of base and mobile stations.

TABLE 43

Estimation of the required pfd limits for protection of base stations

Elevation angle (degree)	***N*** (dB)	T_{noise} (K)	N_0 (dBW(4 kHz))	I_{add} (dBW (4 kHz))	**Antenna gain with feeder loss** (dB)	**Required pfd** (dBW/(m^2 *4 kHz))
0	7	1175	–161.9	–167.9	10	–172.3
10	7	1175	–161.9	–167.9	4	–168.3
20	7	1175	–161.9	–167.9	1.5	–163.8
30	7	1175	–161.9	–167.9	–1	–161.3
40	7	1175	–161.9	–167.9	–3.5	–158.8
50	7	1175	–161.9	–167.9	–6	–156.3
60	7	1175	–161.9	–167.9	–6	–156.3

TABLE 43 (*end*)

Elevation angle (degree)	***N*** (dB)	***T_{noise}*** (K)	***N_0*** (dBW(4 kHz))	***I_{add}*** (dBW (4 kHz))	**Antenna gain with feeder loss** (dB)	**Required pfd** (dBW/(m^2 *4 kHz))
70	7	1175	–161.9	–167.9	–6	–156.3
80	7	1175	–161.9	–167.9	–6	–156.3
90	7	1175	–161.9	–167.9	–6	–156.3

TABLE 44

Estimation of the required pfd limits for protection of mobile stations

Elevation angle (degree)	***N*** (dB)	***T_{noise}*** (K)	***N_0*** (dBW (4 kHz))	***I_{add}*** (dBW (4 kHz))	**Antenna gain with feeder loss** (dB)	**Required pfd** (dBW/(m^2 *4 kHz))
0	7	1175	–161.9	–167.9	1	–163.3
10	7	1175	–161.9	–167.9	1	–163.3
20	7	1175	–161.9	–167.9	1	–163.3
30	7	1175	–161.9	–167.9	1	–163.3
40	7	1175	–161.9	–167.9	1	–163.3
50	7	1175	–161.9	–167.9	1	–163.3
60	7	1175	–161.9	–167.9	1	–163.3
70	7	1175	–161.9	–167.9	1	–163.3
80	7	1175	–161.9	–167.9	1	–163.3
90	7	1175	–161.9	–167.9	1	–163.3

6.1.2.2.3.3 Estimation of VHF data exchange system satellite component downlink impact to the systems of the mobile service

The comparison of the pfd levels created by VDE-SAT[4] downlink with the pfd levels required for protection of the systems in the mobile service obtained in Tables 24 and 25 are shown in Tables 45 to 48.

[4] The pfd levels are taken from Table A4-3 Recommendation ITU-R M.2092-0.

TABLE 45

Estimation of pfd level excess created by VHF data exchange system satellite with Yagi antenna against the required pfd level for protection of base station with the maximum antenna gain of 9 dBi

Elevation angle (degree)	**VDE-SAT pfd** (dBW/(m^2 *4 kHz))	**Required pfd** (dBW/(m^2 *4 kHz))	**Excess** (dB)
0	–152.4	–172.3	19.9
10	–149.1	–168.3	19.2
20	–146.2	–163.8	17.6
30	–144.2	–161.3	17.1
40	–143.4	–158.8	15.4
50	–143.5	–156.3	12.8
60	–144.5	–156.3	11.8
70	–146.7	–156.3	9.6
80	–149.2	–156.3	7.1
90	–152.4	–156.3	3.9

TABLE 46

Estimation of pfd level excess created by VHF data exchange system satellite with Yagi antenna against the required pfd level for protection of mobile station

Elevation angle (degree)	**VDE-SAT pfd** (dBW/(m^2 *4 kHz))	**Required pfd** (dBW/(m^2 *4 kHz))	**Excess** (dB)
0	−152.4	−163.3	10.9
10	−149.1	−163.3	14.2
20	−146.2	−163.3	17.1
30	−144.2	−163.3	19.1
40	−143.4	−163.3	19.9
50	−143.5	−163.3	19.8
60	−144.5	−163.3	18.8
70	−146.7	−163.3	16.6
80	−149.2	−163.3	14.1
90	−152.4	−163.3	10.9

TABLE 47

Estimation of pfd level excess created by VHF data exchange system satellite with Isoflux antenna against the required pfd level for protection of base station

Elevation angle (degree)	**VDE-SAT pfd** (dBW/(m^2 *4 kHz))	**Required pfd** (dBW/(m^2 *4 kHz))	**Excess** (dB)
0	−151	−172.3	21.3
10	−148.2	−166.3	18.1
20	−145.8	−163.8	18.0
30	−145.1	−161.3	16.2
40	−144.9	−158.8	13.9
50	−145.6	−156.3	10.7
60	−145.7	−156.3	10.6
70	−147	−156.3	9.3
80	−147.6	−156.3	8.7
90	−148	−156.3	8.3

TABLE 48

Estimation of pfd level excess created by VHF data exchange system satellite with Isoflux antenna against the required pfd level for protection of mobile station

Elevation angle (degree)	**VDE-SAT pfd** (dBW/(m^2 *4 kHz))	**Required pfd** (dBW/(m^2 *4 kHz))	**Excess** (dB)
0	−151	−163.3	12.3
10	−148.2	−163.3	15.1
20	−145.8	−163.3	17.5
30	−145.1	−163.3	18.2
40	−144.9	−163.3	18.4
50	−145.6	−163.3	17.7
60	−145.7	−163.3	17.6
70	−147	−163.3	16.3
80	−147.6	−163.3	15.7
90	−148	−163.3	15.3

6.1.2.2.3.4 Conclusions

The estimation results given in Tables 45 to 48 show that the VDE-SAT downlink emissions can cause unacceptable interference to the systems in the mobile service. Therefore, sharing of VDE-SAT downlink with the stations of the mobile service is unfeasible in the considered frequency bands.

6.2 Out-of-band interference

6.2.1 Maritime distress and voice services

The impact of introducing VDE-SAT downlink into channels 24, 84, 25, 85, 26 and 86 of RR Appendix **18** was addressed in Report ITU-R M.2371, along with introduction of VDE-TER in channel 24, 84, 25 and 85 of RR Appendix **18**.

The VDE-SAT uplink has common characteristics with VDE-TER ship-to-shore. Therefore, VDE-SAT uplink will not create any additional interference to maritime distress and voice services.

The VDE-SAT downlink is located in the upper leg channels of RR Appendix **18**, while maritime distress services and ship-to-ship and ship-to-shore voice is located in the lower leg channels. The 4.6 MHz frequency separation between VDE-SAT downlink and these services ensure that they can be protected from harmful interference.

6.2.2 Satellite automatic identification system

The impact of introducing VDE-SAT downlink into channels 24, 84, 25, 85, 26 and 86 of RR Appendix **18** was addressed in Report ITU-R M.2371, along with introduction of VDE-TER in channel 24, 84, 25 and 85 of RR Appendix **18**.

The VDE-SAT uplink has common characteristics with VDE-TER ship-to-shore. Therefore, VDE-SAT uplink will not create any additional interference to satellite AIS.

The impact of the VDE-SAT transmission on the AIS1, AIS2, ASM1, ASM2 and LR-AIS reception by satellite has been highlighted in Report ITU-R M.2371. Due to a large frequency separation between VDE-SAT transmission frequencies and LR-AIS frequencies, no impact on the satellite detection of LR-AIS is expected. The impact of VDE-SAT transmission on the reception of AIS1, AIS2 and ASM1 and ASM2 depends on the system scenarios.

In a system scenario where the VDE-SAT transmission and SAT-AIS reception are hosted on different satellites the impact will be reduced by the separation between the satellite orbits and their coverage. In this case, when the two satellites are close together, the use of bulletin boards and the announcement channels as specified in Recommendation ITU-R M.2092-0, provides a practical solution to coordinate and control the duty cycle of the VDE-SAT transmission. Using this mechanism, system operators can schedule the VDE-SAT transmission in a dynamic manner (with a repetitive control as frequent as every minute) to avoid the interference of the VDE-SAT on the detection of SAT-AIS. The high repetition rate for AIS transmissions from ships also increases the detection of ships by SAT-AIS, even if some AIS messages are lost to interference from VDE-SAT transmissions. The time that a VDE-SAT satellite is within interference range of a SAT-AIS satellite will not be continuous, and in most circumstances, will be limited to only a few minutes.

The co-location of a SAT-AIS receiver and a VDE-SAT transmission may require a more sophisticated solution on board of the satellite. One such solution can be a full-duplex radio design that would allow for the cancellation of interference caused by the transmitted signal. This may have an effect on the complexity of the on-board transceivers. However, the high repetition rate for AIS transmissions from ships also increases the detection of ships by SAT-AIS even if some AIS messages are lost due to interference from VDE-SAT transmissions.

6.2.2.1 Satellite – automatic identification system receiver blocking analysis

Reception of a strong signal on a nearby channel will result in compression in the SAT-AIS receiver, which can result in blocking of the SAT-AIS receiver. The blocking performance of a radio receiver is typically described as the input level of the unwanted signal where it will generate a 1 dB compression of the wanted signal. A 1 dB compression level result in an insignificant impact on the receiver performance.

SAT-AIS receivers, commercially available, typically have a 1 dB compression level of -48 dBm, for the most sensitive receiver setting. To ensure that the VDE-SAT downlink is operating within the mask defined in Recommendation ITU-R M.2092-0 and provided in § 4.2.1, the maximum output power of a VDE-SAT transceiver is 22.0 dBm in a 50 kHz channel. This also assumes Yagi antenna case. With frequency plan alternative 1 and 3, up to 150 kHz will be available for the VDE-SAT downlink, while with frequency plan alternative 2 up to 525 kHz will be available for the VDE-SAT downlink. If the full VDE-SAT downlink band is used by a satellite, either as single or multi-carrier, the total output power of the VDE-SAT transceiver will then be either 26.8 dBm or 32.2 dBm. These two output power levels are the basis for the analysis of required separation distance presented in Table 49.

TABLE 49

Satellite – automatic identification system receiver blocking analysis

	Frequency plan alternative 1	**Frequency plan alternative 2**
VDE-SAT tx output power (dBm)	26.8	32.2
Feed loss (dB)	1.1	1.1
Max VDE-SAT tx antenna gain (RHCP) (dBi)	8.0	8.0
SAT-AIS rx antenna gain (LP) (dBi)	0.0	0.0
Polarization loss (dB)	3.0	3.0
Max acceptable SAT-AIS rx input level (dBm)	−48	−48
Required free space loss (dB)	78.7	84.1
Required separation distance (km)	1.3	2.4

From Table 49 it can be observed that even in a worst-case scenario, with full output power from the VDE-SAT transceiver using frequency plan alternative 2, the required separation distance to avoid blocking of a SAT-AIS receiver on another satellite is only 2.4 km. Such proximity between two satellites occurs very rarely. Furthermore, given that satellites travel at a speed of about 7.5 km/s, if such proximity between two satellites occurs it will only last for a fraction of a second. Thus, it can be concluded that AIS receiver blocking on other satellites by a VDE-SAT transceiver is not a problem, and no mitigation measures are needed.

6.2.2.2 Satellite – automatic identification system receiver front end burnout analysis

Reception of a very strong signal within the operating frequency range of a SAT-AIS receiver may cause receiver front end burnout. A burn out protection level typically defines the receiver front end input level that can be sustained over a longer period of time without damaging the receiver front end. SAT-AIS receivers, commercially available, typically have front end burnout protection level of 8 dBm. This value is used in the nominal case analysis of required separation distance for avoiding SAT-AIS receiver front end burnout. Assuming there are SAT-AIS receivers on the commercial market of lower quality, a worst-case analysis using a front-end burnout protection level of 0 dBm has also been performed. The two analysis cases also assume the same two VDE-SAT transceiver output power levels as those used in the AIS receiver blocking analysis discussed in § 6.2.2.1. Table 50 presents the analysis of the separation distance required for avoiding SAT-AIS receiver front end burnout.

TABLE 50

Satellite – automatic identification system receiver front end burnout analysis

	Worst case	Nominal case
VDE-SAT tx output power (dBm)	32.2	26.8
Feed loss (dB)	1.1	1.1
Max VDE-SAT tx antenna gain (RHCP) (dBi)	8.0	8.0
SAT-AIS rx antenna gain (LP) (dBi)	0.0	0.0
Polarization loss (dB)	3.0	3.0
Max acceptable SAT-AIS rx input level (dBm)	0.0	8.0
Required free space loss (dB)	36.1	22.7
Required separation distance (km)	0.009	0.002

From Table 50 it can be observed that even in a worst-case scenario, with full output power from the VDE-SAT transceiver using frequency plan alternative 2 and a very sensitive AIS receiver, the required separation distance to avoid AIS receiver front end burnout on another satellite is only 0.009 km. Such proximity between two satellites occurs extremely rarely. Furthermore, given that satellites travel at a speed of about 7.5 km/s, if such proximity between two satellites occurs it will only last for a fraction of a second. Also, such proximity events do not happen without ample warning, allowing a planned shutdown of the VDE-SAT transceiver if so deemed necessary. Thus, it can be concluded that SAT-AIS receiver front end burnout on other satellites by a VDE-SAT transceiver is not a problem, and no mitigation measures are needed.

6.2.3 Radiolocation service in the frequency band 154-156 MHz

6.2.3.1 Introduction

Radio regulations (RR) No. **5.225A** specifies that in certain countries of Region 1 the frequency band 154-156 MHz is allocated to the radiolocation service on the primary basis. Application of the radiolocation service in those frequency bands is limited to the space surveillance radars. Study results reflected in Report ITU-R M.2172-1 show that the mentioned radars could operate in a shared manner with the maritime mobile service (MMS) ground systems operating in the adjacent frequency band 156-174 MHz.

A sharing study has been performed to ascertain if the potential VDE-SAT downlink service will generate harmful interference into the radiolocation service.

6.2.3.2 Transmitter and receiver characteristics of the radiolocation service used for the sharing study

Table 51 presents characteristics of the space surveillance radars operating in the frequency band 154-156 MHz. The characteristics were taken from Report ITU-R M.2172-1 and were used in the compatibility studies.

TABLE 51

Radiolocation service systems characteristics

	Radar A (narrow-band radar)	Radar B (wideband radar)
Frequency band (MHz)	154-156	
Output pulse power (min/max) (dBW)	27/46	40/46
Mean output power (min/max) (dBW)	22/41	35/41
Polarization	Linear	
Pulse duration (μs)	13 000	3 200
Duty cycle	0.322	
Modulation type	Pulse	
Altitude above the ground level (m)	19	
Antenna type	Phased array	
Maximum antenna gain (dB) – transmitter – receiver	 25 30	
Maximum antenna gain on the horizon (dB)	9	
Antenna pattern	See § 1.1 in Appendix 1 of Report ITU-R M.2172-1	
Main beam pattern (degrees) – horizontal plane (Rx/Tx) – vertical plane (Rx/Tx)	 2.6/5.2 2.6/2.6	
Receiver noise temperature (K)	800	
Operational receiver passband (−3 dB level) (kHz)	0.132	625
Receiver thermal noise (dBW)	−178.4	−141.6

In Recommendation ITU-R M.1802-1 the protection criteria for the radiolocation service is given as I/N = –6 for both radar types. When converting the receiver thermal noise level stated for Radar A and Radar B in Table 51 to receiver thermal noise density, they both end up with a receiver thermal noise density level of –199.6 dBW/Hz. To ensure the protection of the radiolocation service, any interference must be at least 6 dB below that noise level. That corresponds to an I_0 of –205.6 dBW/Hz.

According to the technical characteristics of the radiolocation service as presented in Table 51, the maximum receiver gain is 30 dB. It is assumed this is the gain at 156 MHz. The effective aperture area of the receiver antenna is then $A_{eff} = (G{*}c^2)/(f^2{*}4\boldsymbol{\pi})$ = 24.7 dBm^2. Thus, to ensure protection of the radiolocation service, the interference pfd in the 154-156 MHz band must be less than −230.3 dBW/(m^2 *Hz).

6.2.3.3 VHF data exchange-satellite downlink proposed power spectral and pfd mask

The VDE-SAT downlink has an imposed pfd mask, as specified in Recommendation ITU-R M.2092-0 and provided in § 4.2.1 for the in-band signal. This mask is presented in Table 5 and again here in Table 52.

TABLE 52

Proposed power spectral and pfd mask

$$\boldsymbol{\theta}° = \boldsymbol{earth - satellite\ elevation\ angle}$$

$$PFD(\theta°)_{\ (\mathrm{dBW/(m^2*4\ kHz)})} = \begin{cases} -149 + 0.16 * \theta° & 0° \le \theta < 45°; \\ -142 + 0.53 * (\theta° - 45°) & 45° \le \theta < 60°; \\ -134 + 0.1 * (\theta° - 60°) & 60° \le \theta \le 90°. \end{cases}$$

$$PFD(\theta°)_{\ (\mathrm{dBW/(m^2*Hz)})} = \begin{cases} -185 + 0.16 * \theta° & 0° \le \theta < 45°; \\ -178 + 0.53 * (\theta° - 45°) & 45° \le \theta < 60°; \\ -170 + 0.1 * (\theta° - 60°) & 60° \le \theta \le 90°. \end{cases}$$

6.2.3.4 VHF data exchange – satellite downlink out of band noise

Without additional filtering of the spectral side lobes, the noise generated by a VDE-SAT transmitter in the frequency band 154-156 MHz be will more than 50 dB below that of the in-band signal. Appropriate filtering can ensure an additional 15 dB of reduction of the out of band noise. Table 53 presents the resulting interference pfd mask for the 154-156 MHz frequency band.

TABLE 53

Proposed interference pfd mask for the frequency band 154-156 MHz

$$\boldsymbol{\theta}° = \boldsymbol{earth - satellite\ elevation\ angle}$$

$$PFD(\theta°)_{\ (\mathrm{dBW/(m^2*Hz)})} = \begin{cases} -250 + 0.16 * \theta° & 0° \le \theta < 45°; \\ -243 + 0.53 * (\theta° - 45°) & 45° \le \theta < 60°; \\ -235 + 0.1 * (\theta° - 60°) & 60° \le \theta \le 90°. \end{cases}$$

The significant frequency separation between the radiolocation service in the frequency band 154-156 MHz and the upper leg of the RR Appendix **18** frequencies starting at 160.625 MHz ensures that this interference pfd mask will be the worst-case interference level in the frequency band 154-156 MHz.

6.2.3.5 Conclusions

According to § 7.2.5, the radiolocation service in the frequency band 154-156 MHz operates in an elevation span from 2-70 degrees. The proposed interference pfd mask presented in Table 53 provides a maximum interference pfd at 70 degrees of –239.0 dBW/(m^2* Hz). This is 3.7 dB below the protection criteria level calculated in § 6.2.3.2.

The VDE-SAT downlink uses circular polarisation, while the radiolocation service uses linear polarisation. This results in a 3 dB reduction in interference from the VDE-SAT downlink to the radiolocation service due to polarisation loss. The additional 3 dB of margin ensure an *I*/*N* of less than −12.7 dB.

Based on these calculations it is concluded that the VDE-SAT downlink, in compliance with the proposed interference mask, will not cause harmful interference to stations operating in the radiolocation service in the 154-156 MHz frequency band according to Report ITU-R M.2172-1 and Recommendation ITU-R M.1802-1.

6.2.4 Broadcasting service in the frequency band 162-164 MHz

Radio Regulations No. **5.229** stipulates an alternative allocation in Morocco in the frequency band 162-174 MHz to the broadcasting service on a primary basis. The use of this band for this allocation shall be subject to agreement with administrations having services, operating or planned, in accordance with the Table of Frequency Allocations in RR Article **5** which are likely to be affected.

Thus, outside of Morocco, any changes to the VDE-SAT downlink to avoid interference to the broadcasting service in this band requires agreement between relevant administrations.

6.2.5 Space operation service (space-to-Earth) in the frequency band 162-164 MHz

Radio Regulations No. **5.230**, stipulates an alternative allocation in China in the band 163-167 MHz to the space operation service (space-to-Earth) on a primary basis, subject to agreement obtained under RR No. **9.21**. RR No. **9.21** stipulates the requirement to seek agreement of other administrations to use this service. Thus, outside of China, any changes to the VDE-SAT downlink to avoid interference to the space operations service (space-to-Earth) in this band requires agreement between relevant administrations.

6.2.6 Land and aeronautical mobile services in adjacent frequency bands

The VDE-SAT uplink has common characteristics with VDE-TER ship-to-shore. Therefore, it will not create any additional interference to land and aeronautical mobile services.

The VDE-SAT downlink is in compliance with the pfd mask specified Recommendation ITU-R M.2092-0 and provided in § 4.2.1. The pfd mask is presented in Table 5. In addition, as discussed in § 6.2.3.4, the out of band emissions from the VDE-SAT downlink will be at least 65 dB below the in-band emissions when more than 500 kHz away from the VDE-SAT downlink. Thus, land mobile stations in adjacent frequency bands will not experience harmful interference from the VDE-SAT downlink.

6.2.7 Radio astronomy out of band pfd mask

Before WRC-15, studies were performed and a pfd mask was defined for the VDE-SAT downlink emissions and for the protection of the RAS operating in the nearby band 150.05-153.00 MHz. This mask is included and described in Recommendation ITU-R M.2092-0, and it specifies that the VDE-SAT downlink emissions not exceed –238 dBW/m^2 in a 2.95 MHz bandwidth centred around 152 MHz. Application of this pfd mask will ensure the protection of the RAS band 150.05-153.00 MHz.

A technical analysis provided at CPM15 (CPM15-2/106) shows that the implementation of a filter on board the VDE-SAT provides an attenuation of 90 dB in the nearby (radio astronomy) band (150.05-153 MHz) and it was demonstrated that compatibility between MMSS in the band 161.7875-161.9375 MHz and the RAS in the band 150.05-153 MHz is feasible. An attenuation of 90 dB ensures the protection of the radio astronomy station, regardless of total measurement duration (even in the worst case considering measurements by the radio astronomy station 100% of the time) and minimum elevation angle.

The 150.05-153 MHz band is commonly used in all ITU-R Regions by large radio telescopes (often an array of antennas). This band is frequently used for pulsar detection, and only for broadband continuum observations (never for narrow-band spectral line observations). In addition to these observations, it is also necessary to protect the Radioastronomy band centred at f_c = 325.3 MHz, frequency width = 6.6 MHz, from harmonics in the spurious domain.

According to Recommendation ITU-R SM.329-12, the following can be found:

> Unwanted emissions in the spurious domain
>
> Attenuation (dB) below the power (W) supplied to the antenna transmission line for space services should be 43 + 10 log *P*, or 60 dBc, whichever is less stringent.
>
> (Under reference bandwidth of 4 kHz)

Spurious emission under the existing recommendation shown above is compared with threshold levels of interference detrimental to radio astronomy observations (Recommendation ITU-R RA.769-2).

Using a total mean radiated power of 50 W by the VDE-SAT component, the corresponding attenuation relative to total mean power equals 43 + 10 log 50 = 60 dB. So, the maximum power emitted from the satellite in the spurious domain is 50(W) / $10^{60/10}$ = 50(μW)

The pfd of radio emission from a source (satellite) received at a receiver on the ground, *S_pS*, is expressed as:

$$S\_pS = P/(4\pi r^2) = E^2/120\,\pi$$

where P(W) is radiation power from the source, r(m) distance from the source to the receiver, E(V/m) electric field strength at the receiver. Isotropic radiation and radiation efficient of unity are assumed.

In a case of P = 50 μW (df = 4 kHz) and distance between the satellite and the RAS station = 1 000 km,

$SpS = 50\times10^{-6}/(4\pi\times(10^6)^2) = 4.0\times10^{-18}$ W/ m^2

$= -174$ dB(W/m^2)

$SpS/df = 1.0\times10^{-21}$ W/ m^2*Hz

$= -210$ dB(W/m^2*Hz)

The threshold levels of interference detrimental to radio astronomy observations (Recommendation ITU-R RA.769-2) are for continuum observations (fc=325.3 MHz, df=6.6 MHz)

pfd: –189 dB(W/m^2)

Spectral pfd: –258 dB(W/m^2*Hz),

and for spectral line observations (fc=327 MHz, df=10 kHz)

pfd: –204 dB(W/m^2)

Spectral pfd: –244 dB(W/m^2*Hz)

Comparison of the received pfd of –174 dB(W/m^2) with these threshold values lead to excesses of emission of respectively of 15 dB and 30 dB for continuum and spectral line observations.

Spurious emission of the candidate frequency bands, typically by harmonics, may impact RAS bands such as 322-328.6 MHz. For protecting the RAS frequency bands, all downlink emissions of the satellite in the spurious domain including harmonics need to meet the interference threshold defined in Recommendation ITU-R RA.769.

The excesses of spurious emissions may be compensated by the implementation if on-board filtering is implemented on the VDE-SAT downlink, as mentioned above.

7 Satellite receiver resilience to harmful interference from incumbent services in the same and adjacent frequency band

7.1 Compatibility of VHF data exchange – satellite with the mobile service operating in the frequency band 156-162 MHz

7.1.1 Introduction

The three frequency plan alternatives currently under consideration, as discussed in § 3, propose to use frequencies for the VDE-SAT uplink that are allocated to the mobile service (except aeronautical mobile in Region 1) subject to the Radio Regulations. It is therefore necessary to study the potential impact of the mobile service into the VDE-SAT uplink.

This section presents results of studies of the compatibility of the VDE-SAT uplink in the frequency bands 157.1875 to 157.2275 MHz and 161.7875 to 161.9375 MHz with the land mobile service operating in the 156 to 162 MHz band.

7.1.2 Characteristics of land mobile systems operating in the 156 to 162 MHz band

Representative technical and operational characteristics of conventional and trunked land mobile systems operating in the mobile service in the frequency band 156-162 MHz are given in Recommendation ITU-R M.1808. Table 54 provides the technical characteristics of base stations and Table 55 provides technical characteristics of mobile stations as they are given in that Recommendation.

TABLE 54

Technical characteristics for base stations operating in the mobile service in the frequency band 138-174 MHz

Type of emission	**Analogue**	**Digital**
System-wide		
Channel bandwidth (kHz)	12.5/15/25/30	6.25/7.5/12.5/15
Modulation type	FM	C4FM
Type of operation	Simplex/duplex	Duplex
Typical SINAD or BER (dB/%)	12 dB	5%
Transmitter		
Output power (W)	5–125 (30) (100)	20–125 (60) (100)
e.r.p. (dBW)	7–26 (19) (24)	13–26 (18) (24)
Necessary bandwidth (kHz)	11/11/16/16	5.5/5.5/8.1/8.1
Coverage radius (km)	1–75 (50)	1–75 (50)
Antenna gain (dBd)	0–9 (6)	0–9 (6)
Antenna height (m) (relative to ground level)	10–150 (60)	10–150 (65)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–7 (2)	3–9 (6) (2)
Receiver		
Noise figure (dB)	6–12 (7)	6–12 (7)
IF filter bandwidth (kHz)	8/11/12.5/16	5.5/5.5/5.5/5.5

TABLE 54 (*end*)

Type of emission	Analogue	Digital
Sensitivity (dBm)	−116 – −121 (−119)	−116 – −121 (−119)
Antenna gain (dBd)	0–9 (6)	0–9 (8)
Antenna height (m) (relative to ground level)	10–150 (60)	10–150 (65)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–6 (3)	0–6 (3)

NOTE 1 – Simplex systems use the same frequency for both the base station and mobile station to transmit.

NOTE 2 – Frequency division duplex systems have different frequencies for the base station and mobile station which allows simultaneous communications.

NOTE 3 – Typical values are shown in parenthesis. In some instances, more than one typical value is provided.

NOTE 4 – e.r.p. is equal to the output power (dBW) plus antenna gain (dBd) minus total losses (dB).

TABLE 55

Technical characteristics for mobile stations operating in the mobile service in the frequency band 138-174 MHz

Type of emission	Analogue	Digital
System-wide		
Channel bandwidth (kHz)	12.5/15/25/30	6.25/7.5/12.5/15
Modulation type	FM	C4FM
Type of operation	Simplex/duplex	Duplex
Typical SINAD or BER (dB/%)	12 dB	5%
Transmitter		
Output power (W)	1–100 (H: 5 V: 30, 50)	1–100 (H: 5 V: 30, 50)
e.r.p. (dBW)	−3–18 (H: −3 V: 14, 16)	−3–18 (H: −3 V: 14, 16)
Necessary bandwidth (kHz)	11/11/16/16	5.5/5.5/8.1/8.1
Antenna gain (dBd)	−10–4 (H: −10, V: 0)	−10–4 (H: −10, V: 0)
Antenna height (relative to ground level) (m)	(2)	(2)

TABLE 55 (*end*)

Type of emission	Analogue	Digital
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–1 (H: 0, V: 1)	0–1 (H: 0, V: 1)
Receiver		
Noise figure (dB)	6–12 (7)	6–12 (7)
IF filter bandwidth (kHz)	8/11/12.5/16	5.5/5.5/5.5/5.5
Sensitivity (dBm)	−116 – −121 (−119)	−116 – −121 (−119)
Antenna gain (dBd)	−10–4 (H: −10, V: 0)	−10–4 (H: −10, V: 0)
Antenna height (relative to ground level) (m)	(2)	(2)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–1 (H: 0, V: 1)	0–1 (H: 0, V: 1)

NOTE 1 – Simplex systems use the same frequency for both the base station and mobile station to transmit.

NOTE 2 – Frequency division duplex (FDD) systems have different frequencies for the base station and mobile station which allows simultaneous communications.

NOTE 3 – Typical values are shown in parenthesis, “H:” represents the value for handheld mobile stations and “V:” represents the value for vehicular mobile stations. In some instances, more than one typical value is provided.

NOTE 4 – e.r.p. is equal to the output power (dBW) plus antenna gain (dBd) minus total losses (dB).

For the studies of the compatibility of the VDE-SAT uplink with the land mobile service the typical values from Table 54 and Table 55 have been used. These technical characteristics and values are summarized in Table 56.

TABLE 56

Typical values for technical characteristics of land mobile service stations used in compatibility study

Station type	Base station	Mobile station
Necessary bandwidth (kHz)	16	16
Output power (W)	100	50
Output power (dBW)	20	17
Feed loss (dB)	2	1
Maximum antenna gain (dBd)	6	0
Maximum antenna gain (dBi)	8	2
Maximum e.r.p. (dBW)	24	16
Maximum e.i.r.p. (dBW)	26	18

Figure 19 shows antenna patterns for typical antennas used in the land mobile service as described in Recommendation ITU-R F.1336-4. Assuming a 6 dB antenna is used at the base station and a 0 dBd antenna is used at the mobile station, the antenna gain versus elevation angle can be tabulated as in Table 57 and Table 58 for the base station and mobile station respectively. Table 57 and Table 58 also present the resulting e.i.r.p. versus elevation angle for the two station types.

FIGURE 19

Antenna patterns for typical antennas used in the land mobile service as described in Recommendation ITU-R F.1336-4

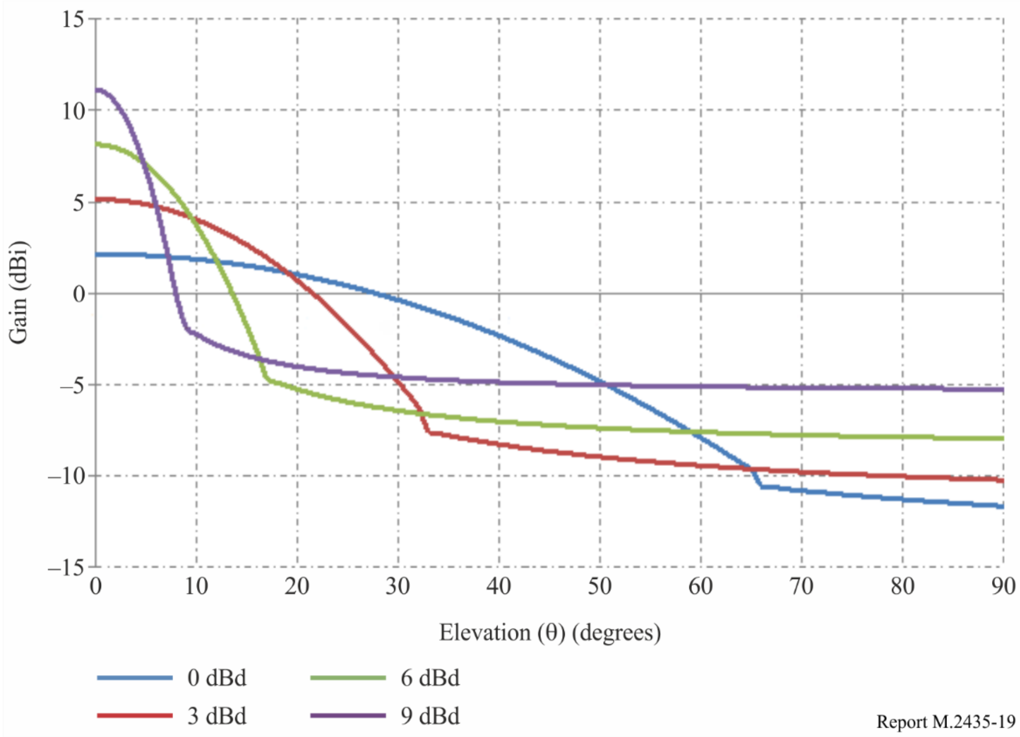


TABLE 57

Base station antenna gain and e.i.r.p. versus elevation angle

Elevation angle (degrees)	**Antenna gain** (dBi)	**e.i.r.p.** (dBW)
0	8.0	26.0
10	3.5	21.5
20	−5.5	12.5
30	−6.5	11.5
40	−7.0	11.0
50	−7.5	10.5
60	−8.0	10.0
70	−8.0	10.0
80	−8.0	10.0
90	−8.0	10.0

TABLE 58

Mobile station antenna gain and e.i.r.p. versus elevation angle

Elevation angle (degrees)	**Antenna gain** (dBi)	**e.i.r.p.** (dBW)
0	2.0	18.0
10	2.0	18.0
20	1.0	17.0
30	−0.5	15.5
40	−2.5	13.5
50	−5.0	11.0
60	−8.0	8.0
70	−11.0	5.0
80	−11.5	4.5
90	−12.0	4.0

7.1.3 Characteristics of the VHF data exchange – satellite uplink

The technical characteristics of the VDE-SAT uplink are described in §§ 4.1 and 4.3 and summarized in Table 59.

TABLE 59

Characteristics of VHF data exchange system satellite receiver

Parameter	**Value**
Antenna noise temperature (K)	200.0
Feed losses (dB)	1.0
LNA noise figure (dB)	2.0
LNA noise temperature (K)	159.7
Feed loss noise temperature at LNA (K)	56.1
Antenna noise temperature at LNA (K)	158.9
System noise temperature at LNA (K)	374.7
System noise temperature at LNA (dBK)	25.7
Intrinsic noise power density (dBW/Hz)	−202.9
Intrinsic noise power in 42 kHz bandwidth (dBW)	−156.6
Required carrier-to-noise-plus-interference ratio ($C/(N+I)$) (dB)	−13.5

7.1.4 Estimation of interference level from base and mobile stations operating in the land mobile service in the 156 to 162 MHz band

Based on the technical characteristics for base stations and mobile stations in the land mobile service and the VDE-SAT uplink receiver characteristics, the level of interference to the VDE-SAT uplink can be estimated. Tables 60 to 63 provides estimate of the interference level from base and mobile station at the satellite receiver input for both Isoflux and Yagi antenna. The analysis shows that the maximum interference level at elevation angles of more than 10 degrees will be equal to:

– Interference from base station:
 −123.1 dBW to satellite receiver with Isoflux antenna
 −116.6 dBW to satellite receiver with Yagi antenna
– Interference from mobile station:
 −125.3 dBW to satellite receiver with Isoflux antenna
 −117.7 dBW to satellite receiver with Yagi antenna

TABLE 60

Estimate of interference from base station to VHF data exchange – satellite uplink receiver with Isoflux antenna

Radar elevation angle (degrees)	**Base station e.i.r.p.** (dBW)	**Polarization loss** (dB)	**Path length** (km)	**Path loss** (dB)	**Satellite antenna gain** (dBi)	**Interference level at LNA, including feed loss** (dBW)
0.0	26.0	3.0	2 830	145.4	2.0	−121.4
10.0	21.5	3.0	1 932	142.1	1.5	−123.1
20.0	12.5	3.0	1 392	139.3	1.0	−129.8
30.0	11.5	3.0	1 075	137.0	−0.5	−130.0
40.0	11.0	3.0	882	135.3	−2.0	−130.3
50.0	10.5	3.0	761	134.0	−4.0	−131.5
60.0	10.0	3.0	683	133.1	−5.0	−132.1
70.0	10.0	3.0	635	132.4	−7.0	−133.4
80.0	10.0	3.0	608	132.1	−8.0	−134.1
90.0	10.0	3.0	600	131.9	−8.5	−134.4

TABLE 61

Estimate of interference from base station to VHF data exchange – satellite uplink receiver with Yagi antenna

Radar elevation angle (degrees)	**Base station e.i.r.p.** (dBW)	**Polarization loss** (dB)	**Path length** (km)	**Path loss** (dB)	**Satellite antenna gain** (dBi)	**Interference level at LNA, including feed loss** (dBW)
0.0	26.0	3.0	2 830	145.4	8.0	−115.4
10.0	21.5	3.0	1 932	142.1	8.0	−116.6
20.0	12.5	3.0	1 392	139.3	8.0	−122.8
30.0	11.5	3.0	1 075	137.0	7.8	−121.7
40.0	11.0	3.0	882	135.3	6.9	−121.4
50.0	10.5	3.0	761	134.0	5.5	−122.0
60.0	10.0	3.0	683	133.1	3.6	−123.5
70.0	10.0	3.0	635	132.4	0.7	−125.7
80.0	10.0	3.0	608	132.1	−2.2	−128.3
90.0	10.0	3.0	600	131.9	−5.5	−131.4

TABLE 62

Estimate of interference from mobile station to VHF data exchange – satellite uplink receiver with Isoflux antenna

Radar elevation angle (degrees)	**Mobile station e.i.r.p.** (dBW)	**Polarization loss** (dB)	**Path length** (km)	**Path loss** (dB)	**Satellite antenna gain** (dBi)	**Interference level at LNA, including feed loss** (dBW)
0.0	18.0	3.0	2 830	145.4	2.0	−129.4
10.0	18.0	3.0	1 932	142.1	1.5	−126.6
20.0	17.0	3.0	1 392	139.3	1.0	−125.3
30.0	15.5	3.0	1 075	137.0	−0.5	−126.0
40.0	13.5	3.0	882	135.3	−2.0	−127.8
50.0	11.0	3.0	761	134.0	−4.0	−131.0
60.0	8.0	3.0	683	133.1	−5.0	−134.1
70.0	5.0	3.0	635	132.4	−7.0	−138.4
80.0	4.5	3.0	608	132.1	−8.0	−139.6
90.0	4.0	3.0	600	131.9	−8.5	−140.5

TABLE 63

Estimate of interference from mobile station to VHF data exchange – satellite uplink receiver with Yagi antenna

Radar elevation angle (degrees)	**Mobile station e.i.r.p.** (dBW)	**Polarization loss** (dB)	**Path length** (km)	**Path loss** (dB)	**Satellite antenna gain** (dBi)	**Interference level at LNA, including feed loss** (dBW)
0.0	18.0	3.0	2 830	145.4	8.0	−123.4
10.0	18.0	3.0	1 932	142.1	8.0	−120.1
20.0	17.0	3.0	1 392	139.3	8.0	−118.3
30.0	15.5	3.0	1 075	137.0	7.8	−117.7
40.0	13.5	3.0	882	135.3	6.9	−118.9
50.0	11.0	3.0	761	134.0	5.5	−121.5
60.0	8.0	3.0	683	133.1	3.6	−125.5
70.0	5.0	3.0	635	132.4	0.7	−130.7
80.0	4.5	3.0	608	132.1	−2.2	−133.8
90.0	4.0	3.0	600	131.9	−5.5	−137.5

7.1.5 Effect on VHF data exchange – satellite uplink link budget from interference from base and mobile stations operating in the land mobile service in the 156-162 MHz band

The most robust waveform format defined for the VDE-SAT uplink is waveform 1, as provided in § 4.3 and Table 13. This waveform is used in the analysis of the effect on VDE-SAT uplink link budget from interference from a single base or mobile station operating in the land mobile service in the 156 to 162 MHz band. An additional interfering land mobile base station 10 degree away from worst case position will increase the $I+N$ level by approximately 0.9 dB. The analysis is based on the interference free link budgets provided in § 4.3. Tables 64 to 67 present link budgets for VDE-SAT up-link when interference from a base station or mobile station in the land mobile service is present. The tables show that the VDE-SAT uplink waveform format 1 will ensure link availability with margins with interference from base station and mobile station for the most relevant ship elevation angles. The VDE-SAT uplink will be available for ship elevation angles between 10 and 60 degrees with Yagi antenna on the satellite and between 10 and 50 degrees with Isoflux antenna on the satellite. Furthermore, Table 68 summaries some potential discrimination factors and mitigation techniques.

TABLE 64

Link budget for VHF data exchange – satellite uplink with Isoflux antenna and interference from base station

Ship elevation angle (degrees)	Carrier level at LNA, including feed loss (dBW)	C/N_0 (dBHz)	C/N (dB)	Interference level at LNA, including feed loss (dBW)	$C/(N+I)$ (dB)	Link margin for waveform 1 (dB)	Link margin for waveform 2, 3 (dB)	Link margin for waveform 4 (dB)	Link margin for waveform 5 (dB)
0.0	–136.6	66.2	20.0	−123.1	−13.5	0.0	−16.4	−20.5	−24.7
10.0	–133.8	69.0	22.8	−123.1	−10.7	2.8	−13.6	−17.7	−21.9
20.0	–132.0	70.9	24.7	−123.1	−8.9	4.6	−11.8	−15.9	−20.1
30.0	–132.7	70.1	23.9	−123.1	−9.6	3.9	−12.5	−16.6	−20.8
40.0	–133.5	69.4	23.1	−123.1	−10.4	3.1	−13.3	−17.4	−21.6
50.0	–135.7	67.1	20.9	−123.1	−12.6	0.9	−15.5	−19.6	−23.8
60.0	–137.3	65.6	19.3	−123.1	−14.2	−0.7	−17.1	−21.2	−25.4
70.0	–139.7	63.2	17.0	−123.1	−16.6	−3.1	−19.5	−23.6	−27.8
80.0	–146.3	56.6	10.4	−123.1	−23.2	−9.7	−26.1	−30.2	−34.4
90.0	–156.7	46.2	0.0	−123.1	−33.6	−20.1	−36.5	−40.6	−44.8

TABLE 65

Link budget for VHF data exchange – satellite uplink with Yagi antenna and interference from base station

Ship elevation angle (degrees)	Carrier level at LNA, including feed loss (dBW)	C/N_0 (dBHz)	C/N (dB)	Interference level at LNA, including feed loss (dBW)	$C/(N+I)$ (dB)	Link margin for waveform 1 (dB)	Link margin for waveform 2, 3 (dB)	Link margin for waveform 4 (dB)	Link margin for waveform 5 (dB)
0.0	–130.6	72.2	26.0	−116.6	−14.0	−0.5	−16.9	−21	−25.2
10.0	–127.3	75.5	29.3	−116.6	−10.7	2.8	−13.6	−17.7	−21.9
20.0	–125.0	77.9	31.7	−116.6	−8.4	5.1	−11.3	−15.4	−19.6
30.0	–124.4	78.4	32.2	−116.6	−7.8	5.7	−10.7	−14.8	−19
40.0	–124.6	78.3	32.0	−116.6	−8.0	5.5	−10.9	−15	−19.2
50.0	–126.2	76.6	30.4	−116.6	−9.6	3.9	−12.5	−16.6	−20.8
60.0	–128.7	74.2	27.9	−116.6	−12.1	1.4	−15	−19.1	−23.3
70.0	–132.0	70.9	24.7	−116.6	−15.4	−1.9	−18.3	−22.4	−26.6
80.0	–140.5	62.4	16.2	−116.6	−23.9	−10.4	−26.8	−30.9	−35.1
90.0	–153.7	49.2	3.0	−116.6	−37.1	−23.6	−40	−44.1	−48.3

TABLE 66

Link budget for VHF data exchange – satellite uplink with Isoflux antenna and interference from mobile station

Ship elevation angle (degree)	Carrier level at LNA, including feed loss (dBW)	C/N_0 (dBHz)	C/N (dB)	Interference level at LNA, including feed loss (dBW)	$C/(N+I)$ (dB)	Link margin for waveform 1 (dB)	Link margin for waveform 2, 3 (dB)	Link margin for waveform 4 (dB)	Link margin for waveform 5 (dB)
0.0	–136.6	66.2	20.0	−125.3	−11.4	2.1	−14.3	−18.4	−22.6
10.0	–133.8	69.0	22.8	−125.3	−8.6	4.9	−11.5	−15.6	−19.8
20.0	–132.0	70.9	24.7	−125.3	−6.7	6.8	−9.6	−13.7	−17.9
30.0	–132.7	70.1	23.9	−125.3	−7.5	6.0	−10.4	−14.5	−18.7
40.0	–133.5	69.4	23.1	−125.3	−8.2	5.3	−11.1	−15.2	−19.4
50.0	–135.7	67.1	20.9	−125.3	−10.5	3.0	−13.4	−17.5	−21.7
60.0	–137.3	65.6	19.3	−125.3	−12.0	1.5	−14.9	−19	−23.2
70.0	–139.7	63.2	17.0	−125.3	−14.4	−0.9	−17.3	−21.4	−25.6
80.0	–146.3	56.6	10.4	−125.3	−21.0	−7.5	−23.9	−28	−32.2
90.0	–156.7	46.2	0.0	−125.3	−31.4	−17.9	−34.3	−38.4	−42.6

TABLE 67

Link budget for VHF data exchange – satellite uplink with Yagi antenna and interference from mobile station

Ship elevation angle (degree)	Carrier level at LNA, including feed loss (dBW)	C/N_0 (dBHz)	C/N (dB)	Interference level at LNA, including feed loss (dBW)	$C/(N+I)$ (dB)	Link margin for waveform 1 (dB)	Link margin for waveform 2, 3 (dB)	Link margin for waveform 4 (dB)	Link margin for waveform 5 (dB)
deg	dBW	dBHz	dB	dBW	dB	dB	dB	dB	dB
0.0	–130.6	72.2	26.0	−117.7	−12.9	0.6	−15.8	−19.9	−24.1
10.0	–127.3	75.5	29.3	−117.7	−9.6	3.9	−12.5	−16.6	−20.8
20.0	–125.0	77.9	31.7	−117.7	−7.3	6.2	−10.2	−14.3	−18.5
30.0	–124.4	78.4	32.2	−117.7	−6.7	6.8	−9.6	−13.7	−17.9
40.0	–124.6	78.3	32.0	−117.7	−6.9	6.6	−9.8	−13.9	−18.1
50.0	–126.2	76.6	30.4	−117.7	−8.5	5.0	−11.4	−15.5	−19.7
60.0	–128.7	74.2	27.9	−117.7	−11.0	2.5	−13.9	−18	−22.2
70.0	–132.0	70.9	24.7	−117.7	−14.2	−0.7	−17.1	−21.2	−25.4
80.0	–140.5	62.4	16.2	−117.7	−22.8	−9.3	−25.7	−29.8	−34
90.0	–153.7	49.2	3.0	−117.7	−35.9	−22.4	−38.8	−42.9	−47.1

TABLE 68

Summary of a few potential discrimination factors and mitigation techniques for VHF data exchange – satellite uplink against interference from base and mobile stations in the land mobile service

Factor	Description	Effect
Range	Base and mobile stations are below horizon	No interference
Land mobile station operating mode	Land mobile systems typically operate in simplex mode without continuous transmission	In the gaps between transmissions from a land mobile station VDE-SAT uplink transmissions can be received, and intermittent interference blocking can be handled by FEC and/or ARQ
Frequency diversity	Both frequency plan alternative 1 and 2 provide multiple VDE-SAT uplink channels	In case of interference from a land mobile station on one VDE-SAT uplink channel, the satellite can move traffic to a different VDE-SAT uplink channel without interference from base or mobile station
Yagi antenna isolation	The Yagi antenna provides better spatial selectivity than the Isoflux antenna when pointed away from areas with land mobile stations	The Yagi antenna provides discrimination when pointed away from areas with land mobile stations. Table 3 shows typical Yagi isolation of 10 dB, 60 degrees off boresight and 20 dB 75 degrees off boresight.

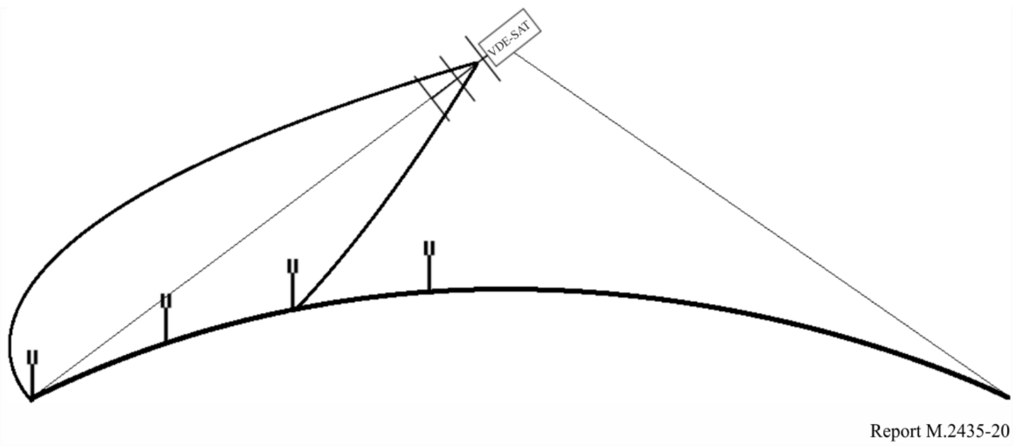
7.1.6 Effect of interference from multiple land mobile stations

7.1.6.1 Study 1

As a satellite at all times will cover a large area, there is a chance that the VDE-SAT receiver on-board a satellite will experience simultaneous interference from multiple land mobile stations. To evaluate the effect of simultaneous interference from multiple land mobile stations an interference scenario as illustrated in Fig. 20 has been defined.

FIGURE 20

Illustration of interference scenario to evaluate the effect of simultaneous interference from multiple land mobile stations



The land mobile stations are illustrated by the antennas, and are placed along the boresight axis of the Yagi antenna. The number of interfering land mobile stations are given by the separation distance between the stations. Given the coverage radius for land mobile base station provided Table 54 of typically 50 km. To limit interference between land mobile systems, the separation distance will normally be larger than 250 km.

Figures 21 to 23 presents estimated link margin for a range of land mobile base station separation distances. The results are based on interference power calculations performed using the same approach as that used in Tables 60 and 63, and summarizing multiple interference sources. For interference from land mobile base stations with a separation distance of 250 km the link margin is positive for a large range of ship elevation angles between about 20 and 44 degrees. The range of elevation angles with positive link margin grows to between 17 and 50 degrees with a land mobile base station separation distance of 300 km and to between about 10 and 57 with a land mobile base station separation distance of 500 km.

FIGURE 21

Estimated link margin for the VHF data exchange – satellite uplink waveform 1 with eight interfering land mobile stations separated by 250 km

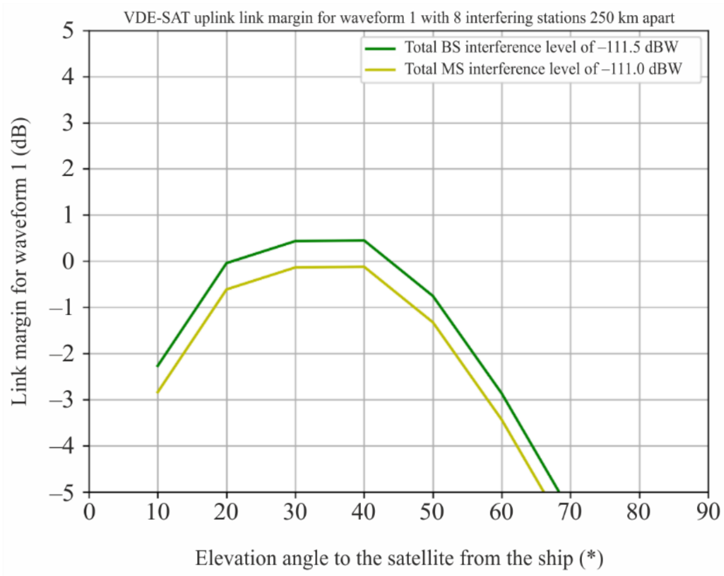


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FIGURE 22

Estimated link margin for the VHF data exchange – satellite uplink waveform 1 with six interfering land mobile stations separated by 300 km

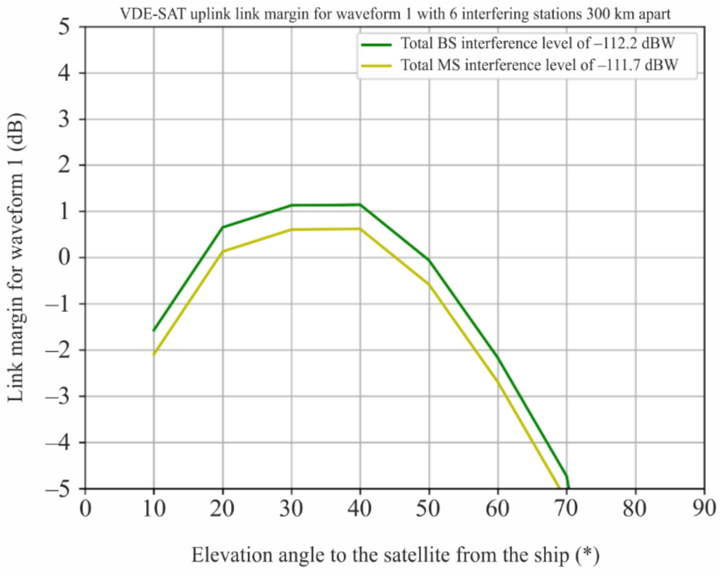

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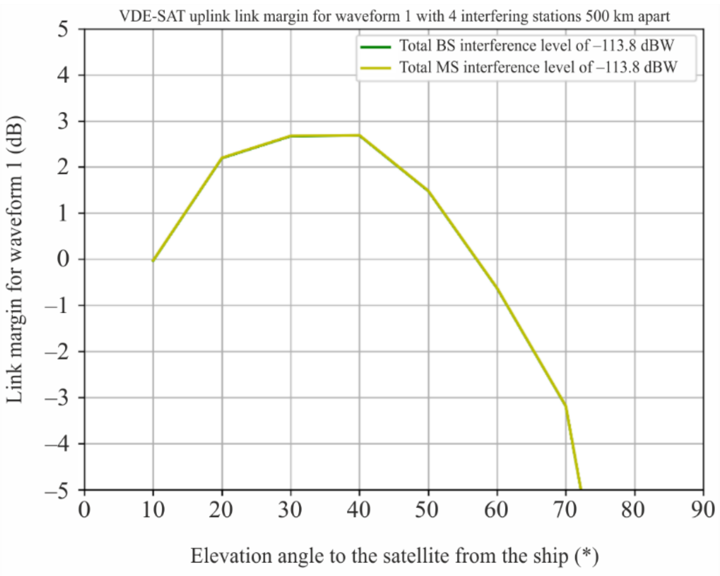
FIGURE 23

Estimated link margin for the VHF data exchange – satellite uplink waveform 1 with four interfering land mobile stations separated by 500 km



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A separation distance of 250 km can be assumed to represent a worst case scenario, since the VDE-SAT system is designed for maritime usage and the antenna therefore will be pointed towards sea and ocean areas where there are no land mobile stations. In addition, the discrimination factors and mitigation techniques summarized in Table 68 can be applied.

7.1.6.2 Study 2

7.1.6.2.1 Initial data

This study takes into account the fact that the stations in the land mobile service can be located not only at the VDE-SAT antenna axis. A three element Yagi antenna is used as the VDE-SAT antenna in the study. The maximum antenna gain (antenna pattern main beam axis) is pointed to the horizon in accordance with Fig. 9 and Table 3.

Currently there is no common view with respect to the protection criteria for VDE-SAT receiver. Several Administrations consider that signal/(interference + noise) ratio equal to minus 13.5 dB can be used as the protection criteria for the VDE-SAT receiver. Other Administrations consider that signal/(interference + noise) ratio, given in Annex 2 to Recommendation ITU-R M.1184 should be used as the protection criteria. In accordance with this Recommendation the signal/(interference + noise) ratio shall be from 5.5 dB to 10.3 dB for MSS satellite receivers.

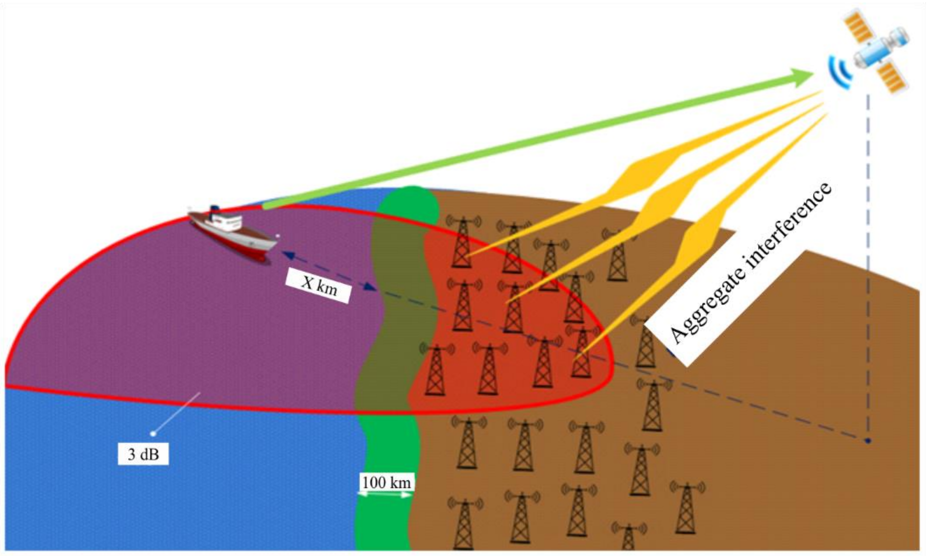
The characteristics of the stations in the land mobile service notified in Master International Frequency Register (MIFR) in the territory of the Russian Federation were used for estimation of interference from the stations in the land mobile service. The analysis of the MIFR showed that the typical base stations in the land mobile service (FB type) with e.i.r.p. of 17 dBW are notified in the frequency bands corresponding to channels 24, 84, 25, 85, 26 and 86 of RR Appendix **18**. The stations with such characteristics are used for estimation of interference to VDE-SAT receiver. With this it was assumed that these stations use near-omnidirectional antennas. The estimation of potential interference was carried out for distances of 100 km and 250 km between stations.

7.1.6.2.2 Interference estimation methodology

The scenario presented in Fig. 24 was used for estimation of interference impact. It was assumed that VDE-SAT receiver is onboard of the satellite located at the altitude of 600 km from the Earth surface. The maximum satellite receiver antenna pattern is pointed towards the horizon. However, it is assumed that this scenario represents a worst case situation.

FIGURE 24

Scenario of interference impact to VDE-SAT satellite receiver



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In the calculations it was assumed that the VDE-SAT earth station is onboard the ship, located at the point of the axis projection of the satellite receiver antenna pattern to the Earth surface at the distance of X km from the coast (see Fig. 24) which can vary from 50 km to 500 km. The calculations are carried out for two elevation angles of VDE-SAT satellite receiver:

– 0 degree when the ship emitting the wanted signal is at the horizon point where the maximum of satellite receiver antenna pattern is pointed;

– 5 degrees when the ship emitting the wanted signal is at the point of the axis projection of the satellite receiver antenna pattern main beam between the horizon and the Earth surface

The wanted signal C is defined by the VDE-SAT earth station transmitter power, its antenna gain in the direction of satellite, the distance from the VDE-SAT earth station to satellite receiver and the satellite antenna gain in the direction of the ship. The propagation model in free space given in Recommendation ITU-R P.525-3, is used for estimation of the wanted signal.

It was assumed in the estimations that stations in the land mobile service are not deployed in the area of 100 km located along the coast (highlighted in green in Fig. 24). In some CEPT countries including the Russian Federation such measures are taken in order to provide compatibility of the stations in the land mobile service with the stations of the maritime mobile service including VDE-TER. Therefore, the area highlighted in green in Fig. 24 will not cause interference to operation of the VDE-SAT satellite receiver.

In the estimation of the aggregate interference impact, the transmitting stations in the land mobile service falling into the main beam footprint of the antenna pattern with the border of –3 dB level and out of the area with the width of 100 km mentioned above are taken into account. This area is highlighted in red in Fig. 24. The number of stations in the land mobile service falling into this area is defined by the main beam width of the VDE-SAT receiver antenna pattern and by the distance between the stations in the mobile service.

In estimation of interference power I experienced by the VDE-SAT receiver, the interference power value caused by each contributing station of the land mobile service I_k, is determined using the following equation:

$$I_k \text{ [dBW]} = EIRP_{MSk} - L_k + G_{SATk}$$

where:

$EIRP_{MSk}$ – e.i.r.p. of MS station with index k in direction of VDE-SAT, dBW

L_k – free space loss on the path between MS station with index k and VDES satellite (propagation model given in Recommendation ITU-R P.525-3 is used), dB

G_{SATk} – VDE-SAT antenna gain in direction of MS station with index k, dBi.

Then the aggregate interference power value I at the satellite receiver front end is determined by summing up:

$$I \text{ [dBW]} = 10lg \sum_{k=1}^{N} 10^{Ik/10}$$

where:

N – number of stations in the land mobile service falling into the main lobe of the satellite antenna pattern.

The obtained values of the wanted signal C and interference I were used for estimation of signal/(interference + noise) ratio.

7.1.6.2.3 Compatibility assessment results

The interference estimation methodology mentioned above is used for interference assessment for the case when the distance from the ship to the coast is varied from 50 km to 500 km and the distances between the stations in the land mobile service of 100 km and 250 km. The estimation results of signal/(interference + noise) ratio for VDE-SAT satellite elevation angle of 0 degree are given in Table 69. The estimation results of signal/(interference + noise) ratio for elevation angle of 5 degrees are given in Table 70.

TABLE 69

Estimation of aggregate interference from the stations in the land mobile service for elevation angle of 0 degree

Distance from the ship to coast (km)	**Number of MS stations in satellite antenna beam area**	**Wanted signal level** (dBW)	**Interference level I** (dBW)	***C/N+I*** (dB)
Distance between MS stations 100 km				
500	321	−130.6	−88.33	−42.27
300	410	−130.6	−88.02	−42.58
150	482	−130.6	−87.75	−42.85
50	534	−130.6	−87.63	−42.97
Distance between MS stations 250 km				
500	51	−130.6	−96.31	−34.29
300	65	−130.6	−95.92	−34.68
150	77	−130.6	−95.59	−35.01
50	85	−130.6	−95.59	−35.01

TABLE 70

Estimation of aggregate interference from the stations in the land mobile service for elevation angle of 5 degrees

Distance from the ship to coast (km)	**Number of MS stations in satellite antenna beam area**	**Wanted signal level** (dBW)	**Interference level I** (dBW)	***C/N+I*** (dB)
Distance between MS stations 100 km				
500	14	−129.1	−94.37	−34.73
300	37	−129.1	−92.62	−36.48
150	60	−129.1	−92.05	−37.05
50	79	−129.1	−91.54	−37.56
Distance between MS stations 250 km				
500	2	−129.1	−102.27	−26.83
300	5	−129.1	−99.84	−29.26
150	9	−129.1	−99.84	−29.26
50	12	−129.1	−98.76	−30.34

The analysis of the estimation results given in Tables 69 and 70 shows that in the considered case the signal/(interference + noise) ratio is significantly less than the minus 13.5 dB value proposed by some Administrations as the protection criterion. It means that even in the most stable operation mode with the minimal data rate (Waveform 1) the VDE-SATe receiver will suffer unacceptable interference from the terrestrial stations in the land mobile service.

It should be noted that the results presented above were obtained for the stations in the land mobile service with e.i.r.p. of 17 dBW. Recommendation ITU-R M.1808 notes that the typical value of e.i.r.p. of base stations in the mobile service operating in the considered frequency range is 26 dBW which is 9 dB more than is the value used in the studies. It leads to a conclusion that taking into account the stations in the land mobile service described in Recommendation ITU-R M.1808 as interference sources, the interference caused to VDE-SAT receiver will be higher even at a large distance between the stations in the land mobile service.

The results mentioned above are obtained for the case when a Yagi antenna is used as a receiving and transmitting antenna. When an Isoflux antenna is used as the VDE-SAT component antenna the study results will be significantly worse since it receives more interference during a longer period of time.

7.1.7 Conclusions

7.1.7.1 Study 1

The calculations and estimations presented show that the most robust waveform, which provides low data rate operation, is resilient to harmful interference from base and mobile stations operating in the land mobile service in the band 156-162 MHz for all elevation angles between 0 and 60 degrees. The more efficient waveforms, which provide higher data rates, will not be available in presence of harmful interference from base and mobile stations operating in the land mobile service. Together with the interference mitigation techniques listed in Table 68, the adaptive coding and modulation scheme defined for VDE-SAT will ensure the use of the most efficient waveform with a positive link margin.

7.1.7.2 Study 2

The analysis of another study results showed that the proposed VDE-SAT receiver will suffer unacceptable interference from the stations in the land mobile service operating in the frequency band 156-162 MHz in a wide sector of elevation angles even in an operation mode with low data rate (1.1 Kbit/s with waveform 1, the most resistant to interference). Therefore, operation of VDE-SAT component in any available mode of data transmission with interference caused by the base and mobile stations in the land mobile service will be unfeasible.

7.2 Compatibility of VHF data exchange – satellite with the radiolocation service operating in the frequency band 154-156 MHz

7.2.1 Introduction

Radio Regulations (RR) No. **5.225A** specifies that in certain countries of Region 1 the frequency band 154-156 MHz is allocated to the radiolocation service on a primary basis. Applications of the radiolocation service in those frequency bands is limited to the space surveillance radars. Study results reflected in Report ITU-R M.2172-1 show that the mentioned radars could operate in a shared manner with the maritime mobile service (MMS) ground systems operating in the adjacent frequency band 156-174 MHz. At the same time to provide protection for the MMS stations in the frequency bands 156.5125-156.5375 MHz, 156.7625-156.8375 MHz, 161.9625-161.9875 MHz and 162.0125-162.0375 MHz additional constrains specifying that e.i.r.p. of out-of-band emissions produced by the space surveillance radars should not exceed the level of –16 dBW was imposed by RR No. **5.225A**. The requirement is met by integrating additional notch filters into radar transmitting circuits for the mentioned frequency bands. The rest of the frequency bands related to provisions of RR Appendix **18** contain no constraints on the operation of the space surveillance systems, and no specific measures are applied to reduce out-of-band emissions.

Recommendation ITU-R M.2092-0 specifies that the VDE-SAT up-link may be established in the frequency band 157.1875-157.3375 MHz by combining channels 1024, 1084, 1025, 1085, 1026, 1086 of RR Appendix **18** into a single channel of 150 kHz.

This section presents results of studies on compatibility of a new VDE-SAT component up-link in the frequency band 156.0125-157.4375 MHz with space surveillance radars operating in the frequency band 154-156 MHz.

7.2.2 Characteristics of space surveillance radars operating in the frequency band 154-156 MHz

Table 71 presents characteristics of the space surveillance radars operating in the frequency band 154-156 MHz. The characteristics were taken from Recommendation ITU-R M.1802-1 and were used in the compatibility studies.

TABLE 71

Characteristics of radars operating in the frequency band 154-156 MHz

Parameter	**Value**	
	Radar A	**Radar B**
Radar type	Primary ranging radar	
Radar function	Space objects recognition and tracking	
Frequency band (MHz)	154–156	
Relative frequency instability	10^{-11}	
Output pulse power (min/max) (dBW)	27/46	40/46
Mean output power (min/max) (dBW)	22/41	35/41
Polarization	Linear	
Pulse length (μs)	13 000	3 200
Duty cycle	0.322	
Modulation type	Pulse	
Altitude above the ground level (m)	19	
Antenna type	Phased array	
Maximum antenna gain: (dB) – transmitter – receiver	 25 30	
Max antenna gain into horizon (dB)	9	12
Main beam pattern (degrees) – horizontal plane (Rx/Tx) – vertical plane (Rx/Tx)	 2.6/5.2 2.6/2.6	
Scan angle ranges: (degrees) – horizontal plane – vertical plane	 0–360 2–70	
Receiver noise temperature (K)	800	
Operation receiver passband (kHz)	0.132	625
Required frequency band (kHz)	0.132	625
Emission class	P0N	MXN
I/*N* protection ratio (dB)	−6	
Level of unwanted emissions	Complies with provisions of RR Appendix **3**[5]	

5 Values of unwanted emissions in the VDES receiver frequency band are described in § 6.

7.2.3 Characteristics of VHF data exchange – satellite uplink (ship-to-satellite)

The technical characteristics of the VDE-SAT uplink are described in §§ 4.1 and 4.3 and summarized in Table 72. The required $C/(N+I)$ listed in Table 72 is for the most robust waveform. Adaptive coding and modulation allow the usage of waveforms with higher throughput when the necessary link quality is available.

TABLE 72

Characteristics of VHF data exchange system satellite receiver

Parameter	**Value**
Antenna noise temperature (K)	200.0
Feed losses (dB)	1.0
LNA noise figure (dB)	2.0
LNA noise temperature (K)	159.7
Feed loss noise temperature at LNA (K)	56.1
Antenna noise temperature at LNA (K)	158.9
System noise temperature at LNA (K)	374.7
System noise temperature at LNA (dBK)	25.7
Intrinsic noise power density (dBW/Hz)	−202.9
Intrinsic noise power in 42 kHz bandwidth (dBW)	−156.6
Required carrier-to-noise-plus-interference ratio ($C/(N+I)$) (dB)	−13.5

7.2.4 Scenario of interference from unwanted emissions by radars operating in the frequency band 154-156 MHz on VHF data exchange system satellite receiver

Subject to Recommendation ITU-R M.2092-0, the VDE-SAT up-link may be established in the frequency band 157.1875–157.3375 MHz by combining channels 1024, 1084, 1025, 1085, 1026, 1086 of RR Appendix **18** into a single channel of 150 kHz.

FIGURE 25

Scenario of radar unwanted emission interference effect on VHF data exchange system satellite receiver

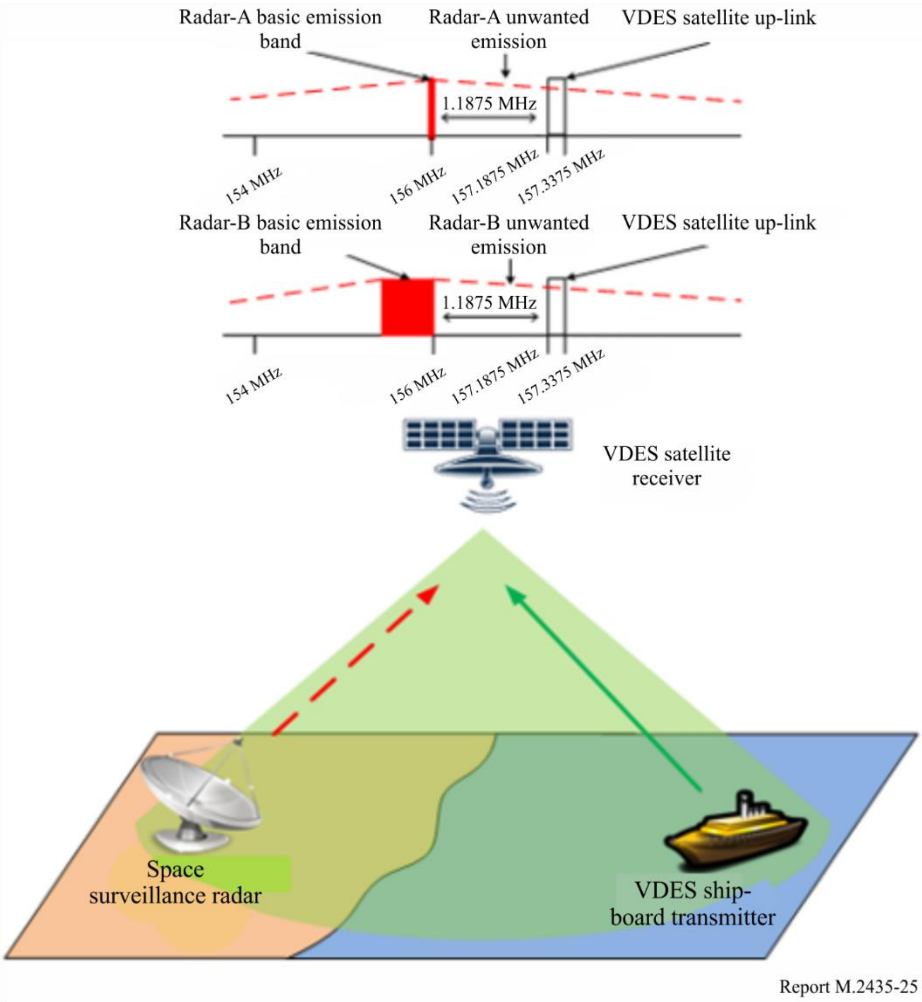


Figure 25 depicts a scenario of the interference from space surveillance radar emissions on the VDE-SAT receivers. A wanted signal from the ship transmitter is shown as a solid green arrow whereas interference from the space surveillance radar is reflected as a dashed red arrow.

7.2.5 Estimation of interference level from unwanted emissions by radars operating in the frequency band 154-156 MHz on VHF data exchange system satellite receiver

The methodology described in Report ITU-R M.2172-1 was used for estimating the levels of unwanted emissions from Radar A in the band of the VDE-SAT receiver. Assuming a frequency separation of 1.2 MHz it was found that the unwanted emission power at the radar antenna front end in a 25 kHz bandwidth would be minus 30.7 dBW and that in a 150 kHz bandwidth would be −22.9 dBW. Given the 25 dB transmit gain of the radar, this is equal to a peak e.i.r.p. in 42 kHz of −3.4 dBW.

The result meets the RR Appendix **3** provisions for spurious emissions specifying that, for radars of the given type, the level power delivered to the antenna feed shall not exceed –21.3 dBW in a 77 Hz reference band.

For Radar B, the unwanted emissions level is a function of modulation parameters. Therefore, for Radar B, in accordance with requirements of RR Appendix **3**, the value of its unwanted emissions at the radar antenna front end would be –33 dBW in a bandwidth of 25 kHz and minus 25.2 dBW in a bandwidth of 150 kHz. This radar contributes less interference than Radar A, so the worst-case scenario of Radar A is used to assess feasibility in this Report.

A satellite with a VDE-SAT on-board receiver is in a circular orbit of 600 km in altitude. Carrier-to-interference (*C*/*I*) ratios are estimated using satellite elevation angle steps of 10 degrees for the angles of satellite visibility by the ship station from 0 to 90 degrees corresponding to appropriate angles of satellite visible by the radar. Since space surveillance radar scans in a vertical plane within an angle sector of 2 to 70 degrees, the estimation assumes that a receiving antenna onboard a satellite will be aligned with the space surveillance radar main lobe. Table 73 and Table 74 show the resulting received interference power using the satellite Isoflux antenna and the 8 dBi Yagi antenna as defined in Recommendation ITU –R M.2092-0. These calculations present the worst-case in that they assume that the radar and satellite antenna boresights are aligned, which is a rare occurrence. It can be seen that the worst-case interference level is −144.7 dBW for the Isoflux antenna. The worst-case interference level for the Yagi antenna is −135.8 dBW for a radar elevation angle to the satellite of 40 degrees.

TABLE 73

Radar emissions into a 600 km low earth orbit satellite using Isoflux antenna

Radar elevation angle (degrees)	Radar peak e.i.r.p. in 42 kHz at 157 MHz (dBW)	Polarization loss (dB)	Path length (km)	Path loss (dB)	Satellite antenna gain (dBi)	Interference level at LNA, including feed loss (dBW)
0.0	−3.4	3.0	2 830	145.4	2.0	−150.9
10.0	−3.4	3.0	1 932	142.1	1.5	−148.0
20.0	−3.4	3.0	1 392	139.3	1.0	−145.7
30.0	−3.4	3.0	1 075	137.0	−0.5	−145.0
40.0	−3.4	3.0	882	135.3	−2.0	−144.7
50.0	−3.4	3.0	761	134.0	−4.0	−145.5
60.0	−3.4	3.0	683	133.1	−5.0	−145.5
70.0	−3.4	3.0	635	132.4	−7.0	−146.9
80.0	−3.4	3.0	608	132.1	−8.0	−147.5
90.0	−3.4	3.0	600	131.9	−8.5	−147.9

TABLE 74

Radar emissions into a 600 km low earth orbit satellite using 8 dBi Yagi antenna

Radar elevation angle (degrees)	Radar peak e.i.r.p. in 42 kHz at 157 MHz (dBW)	Polarization loss (dB)	Path length (km)	Path loss (dB)	Satellite antenna gain (dBi)	Interference level at LNA, including feed loss (dBW)
0.0	−3.4	3.0	2 830.0	145.4	8.0	−144.9
10.0	−3.4	3.0	1 932.0	142.1	8.0	−141.5
20.0	−3.4	3.0	1 392.0	139.3	8.0	−138.7
30.0	−3.4	3.0	1 075.0	137.0	7.8	−136.7
40.0	−3.4	3.0	882.0	135.3	6.9	−135.8
50.0	−3.4	3.0	761.0	134.0	5.5	−136.0
60.0	−3.4	3.0	683.0	133.1	3.6	−136.9
70.0	−3.4	3.0	635.0	132.4	0.7	−139.2
80.0	−3.4	3.0	608.0	132.1	−2.2	−141.7
90.0	−3.4	3.0	600.0	131.9	−5.5	−144.9

7.2.6 Estimation of link budget for VHF data exchange system up-link with a satellite receiver in a 600 km altitude orbit

The most robust waveform format defined for the VDE-SAT uplink is waveform 1, as provided in § 4.3 and Table 13. This waveform is used in the analysis of the effect on VDE-SAT uplink link budget from interference from radars operating in the 154-162 MHz band. The analysis is based on the interference free link budgets provided in § 4.3. Tables 75 and 76 present the resulting worst-case C/N and $C/(N+I)$, when the interference level from unwanted emissions by radars operating in the frequency band 154-156 MHz as calculated in Table 54 and Table 55 is included. Table 75 and Table 76 show that waveform1 will ensure link availability with substantial margins under the worst-case radar interference condition for all ship elevation angles. Waveforms 2 and 3 will be available for ship elevation angles up to 70 degrees. Waveform 4 will be available for ship elevation angles up to 60 degrees, but waveform 5 will require additional discrimination or mitigation techniques. Table 77 summarizes some potential discrimination factors and mitigation techniques.

TABLE 75

Worst-case link budget for VHF data exchange-satellite uplink with 6 W ship transmitter, Isoflux satellite receiving antenna with interference radar type A

Ship elevation angle (degrees)	Carrier level at LNA, including feed loss (dBW)	C/N_0 (dBHz)	C/N (dB)	Interference level at LNA, including feed loss	C/I (dB)	$C/(N+I)$ (dB)	Link margin for waveform 1 (dB)	Link margin for waveform 2, 3 (dB)	Link margin for waveform 4 (dB)	Link margin for waveform 5 (dB)
0.0	–136.6	66.2	20.0	−144.7	8.1	7.8	21.3	4.9	0.8	−3.4
10.0	–133.8	69.0	22.8	−144.7	10.9	10.6	24.1	7.7	3.6	−0.6
20.0	–132.0	70.9	24.7	−144.7	12.7	12.5	26.0	9.6	5.5	1.3
30.0	–132.7	70.1	23.9	−144.7	12.0	11.7	25.2	8.8	4.7	0.5
40.0	–133.5	69.4	23.1	−144.7	11.2	11.0	24.5	8.1	4	−0.2
50.0	–135.7	67.1	20.9	−144.7	9.0	8.7	22.2	5.8	1.7	−2.5
60.0	–137.3	65.6	19.3	−144.7	7.4	7.2	20.7	4.3	0.2	−4
70.0	–139.7	63.2	17.0	−144.7	5.0	4.8	18.3	1.9	−2.2	−6.4
80.0	–146.3	56.6	10.4	−144.7	−1.6	−1.8	11.7	−4.7	−8.8	−13
90.0	–156.7	46.2	0.0	−144.7	−12.0	−12.2	1.3	−15.1	−19.2	−23.4

TABLE 76

Worst-case link budget for VHF data exchange-satellite uplink with 6 w ship transmitter, Yagi satellite receiving antenna with interference radar type A

Ship elevation angle (degrees)	Carrier level at LNA, including feed loss (dBW)	C/N_0 (dBHz)	C/N (dB)	Interference level at LNA, including feed loss	C/I (dB)	$C/(N+I)$ (dB)	Link margin for waveform 1 (dB)	Link margin for waveform 2, 3 (dB)	Link margin for waveform 4 (dB)	Link margin for waveform 5 (dB)
0.0	–130.6	72.2	26.0	−135.8	5.2	5.2	18.7	2.3	−1.8	−6
10.0	–127.3	75.5	29.3	−135.8	8.5	8.5	22.0	5.6	1.5	−2.7
20.0	–125.0	77.7	31.7	−135.8	10.8	10.8	24.3	7.9	3.8	−0.4
30.0	–124.4	78.4	32.2	−135.8	11.4	11.4	24.9	8.5	4.4	0.2
40.0	–124.6	78.3	31.2	−135.8	11.2	11.2	24.7	8.3	4.2	0
50.0	–126.2	76.6	30.4	−135.8	9.6	9.6	23.1	6.7	2.6	−1.6
60.0	–128.7	74.2	27.9	−135.8	7.1	7.1	20.6	4.2	0.1	−4.1
70.0	–132.0	70.9	24.7	−135.8	3.8	3.8	17.3	0.9	−3.2	−7.4
80.0	–140.5	62.4	16.2	−135.8	−4.7	−4.7	8.8	−7.6	−11.7	−15.9
90.0	–153.7	49.2	3.0	−135.8	−17.9	−17.9	−4.4	−20.8	−24.9	−29.1

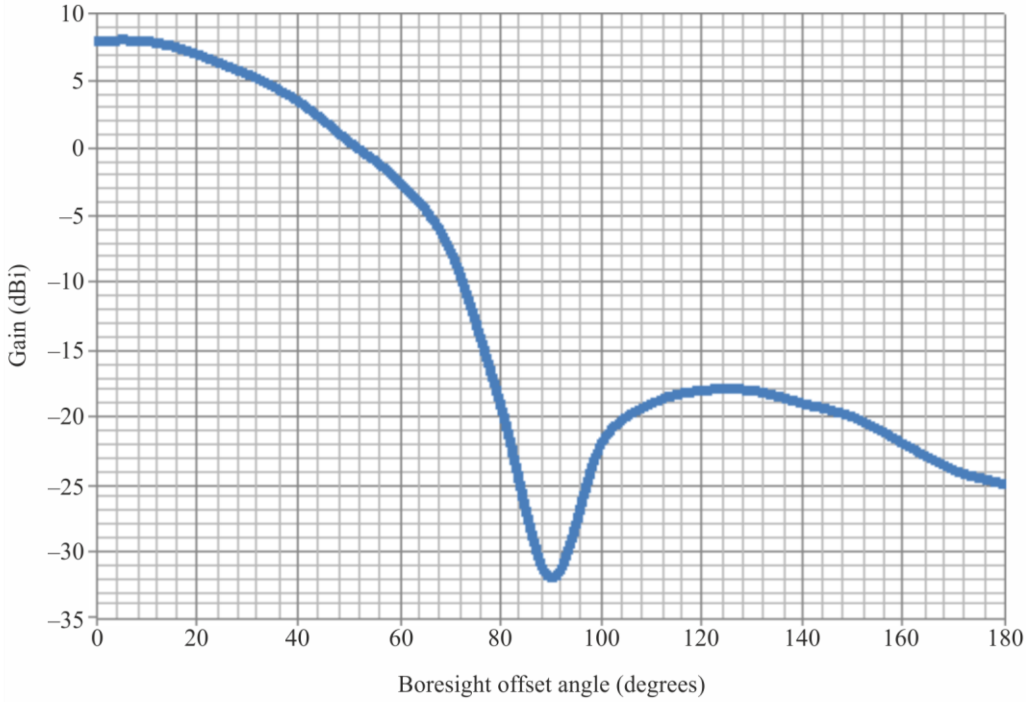
TABLE 77

Summary of a few potential discrimination factors and mitigation techniques for VHF data exchange-satellite uplink against interference from unwanted emissions by radars

Factor	Description	Effect
Range	Radars that are below horizon	No interference
Radar operating mode	When the radar is operating in a scan mode, it will only affect the satellite for the short time it points directly at it.	There are approximately 69 horizontal beam positions and 27 vertical beam positions, or a total of 1 863 beam positions. Assuming a beam offset of 2 beamwidths provides sufficient discrimination, the probability that transmission in one of the seven possible beams is 0.4 %. This level of interference blocking can be handled by FEC and/or ARQ
Radar scan loss	Planar phased array radars have a scan loss when not pointing orthogonal to the flat surface.	The scan loss depends on the number of planar arrays used. A horizontal scan of 60 degrees will cause a 3 dB loss, a vertical scan of 35 degrees will cause a scan loss of 0.9 dB. The worst-case condition when the main beam is orthogonal to the array is considered.
Yagi antenna isolation	The Yagi antenna provides better spatial selectivity than the Isoflux antenna when pointed away from the radar	The Yagi antenna provides discrimination when pointed away from the radar. Figure 26 and Table 3 shows typical Yagi isolation of 10 dB, 60 degrees off boresight and 20 dB 75 degrees off boresight.

FIGURE 26

Typical Yagi gain pattern as a function of boresight offset angle



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7.2.7 Potential for burnout and blocking of the VHF data exchange-satellite receiver caused by unwanted emissions from the radar

Table 78 and Table 79 show the radar levels at the antenna for both the Isoflux and Yagi antennas, with peak output e.i.r.p. from the radar of 71 dBW at 156 MHz. It can be seen that the maximum level is less than −61 dBW. This is more than 30 dB below expected burnout levels. Thus, the VDE-SAT receiver will not be exposed to an interference level from the radar that potentially can be capable of destroying the satellite receiver.

The presence of a radar signal between 154 and 156 MHz will add a blocking performance requirement for the VDE-SAT receiver. This requirement is not expected to be a concern.

TABLE 78

Maximum signal level of unwanted emissions from radar with Isoflux antenna onboard the satellite

Elevation angle (degrees)	Radar e.i.r.p. (dBW)	Polarization loss (dB)	Range (km)	Pathloss (dB)	Satellite antenna gain (dBi)	Received signal level (dBW)
0	71.0	3.0	2 830.0	–145.3	2.0	–76.3
10	71.0	3.0	1 932.0	–142.0	1.5	–73.5
20	71.0	3.0	1 392.0	–139.2	1.0	–71.2
30	71.0	3.0	1 075.0	–136.9	–0.5	–70.4
40	71.0	3.0	882.0	–135.2	–2.0	–70.2
50	71.0	3.0	761.0	–133.9	–4.0	–70.9
60	71.0	3.0	683.0	–133.0	–5.0	–71.0

TABLE 78 (*end*)

Elevation angle (degrees)	Radar e.i.r.p. (dBW)	Polarization loss (dB)	Range (km)	Pathloss (dB)	Satellite antenna gain (dBi)	Received signal level (dBW)
70	71.0	3.0	635.0	–132.4	–7.0	–72.4
80	71.0	3.0	608.0	–132.0	–8.0	–73.0
90	71.0	3.0	600.0	–131.9	–8.5	–73.4

TABLE 79[6]

Maximum signal level of unwanted emissions from radar with Yagi antenna onboard the satellite

Elevation angle (degrees)	Radar e.i.r.p. (dBW)	Polarization loss (dB)	Range (km)	Pathloss (dB)	Satellite antenna gain (dBi)	Received signal level (dBW)
deg	dBW	dB	km	dB	dBi	dBW
0.0	71.0	3.0	2 830.0	–145.3	8.0	–70.3
10.0	71.0	3.0	1 932.0	–142.0	8.0	–67.0
20.0	71.0	3.0	1 392.0	–139.2	8.0	–64.2
30.0	71.0	3.0	1 075.0	–136.9	7.8	–62.1
40.0	71.0	3.0	882.0	–135.2	6.9	–61.3
50.0	71.0	3.0	761.0	–133.9	5.5	–61.4
60.0	71.0	3.0	683.0	–133.0	3.6	–62.4
70.0	71.0	3.0	635.0	–132.4	0.7	–64.7
80.0	71.0	3.0	608.0	–132.0	–2.2	–67.2
90.0	71.0	3.0	600.0	–131.9	–5.5	–70.4

7.2.8 Conclusions

Based on the calculations and estimations presented above, waveforms 1 to 4 defined for the VDE-SAT uplink (see Table 13) are resilient to harmful interference from radars operating in the frequency band 154-156 MHz for all elevation angles up to 60 degrees. Allowing for potential discrimination factors and mitigation techniques discussed in Table 77, waveform 5 is also expected to perform. Together with the interference mitigation techniques listed in Table 77, the adaptive modulation and coding scheme defined for VDE-SAT will ensure use of the most efficient waveform with a positive link margin.

Furthermore, the calculations and estimations show that the interference level from the radar will not harm the onboard satellite VDE-SAT receiver.

8 Testing, demonstrations and measurements

This section is intended to provide results from actual demonstration and measurement projects involving VDE-SAT.

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[6] Antenna pointing is described in § 4.1.4.

8.1 Measurement results of VHF data exchange – satellite downlink using NorSat-2

The Norwegian NorSat-2 LEO satellite with a VDE-SAT test-payload was launched 14 July 2017. The satellite is in a 600 km polar orbit and uses a Yagi antenna with performance as described in Recommendation ITU-R M.2092-0, Table A4-3.

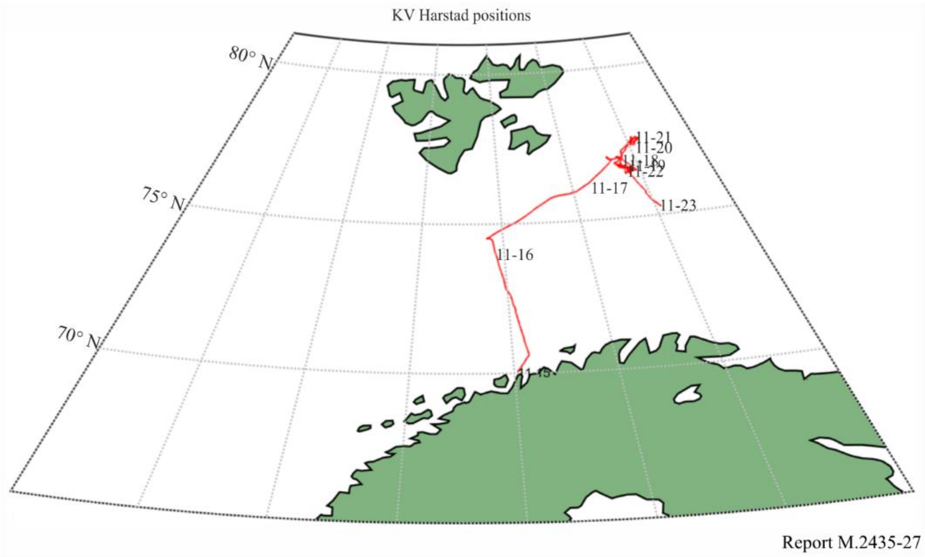
Initial VDE-SAT downlink signal level measurement from a single satellite placed the median signal level at the antenna port of the ship terminal at −15.9 dBm.

Signal level measurements from 103 satellite downlink passes on Norwegian Coastguard vessel operating in the Arctic (Fig. 27) have now been analyzed. The median received signal level was measured to be −117.1 dBm, confirming the initial downlink signal level measurement.

As expected, the signals suffered specular multipath fading, with a lognormal distribution and a standard deviation of 4.2 dB.

FIGURE 27

VDES downlink test area



Using modern modulation and FEC, the measurements show that VDE-SAT can be used to provide a range of digital downlink e-Navigation services to areas with limited communications today.

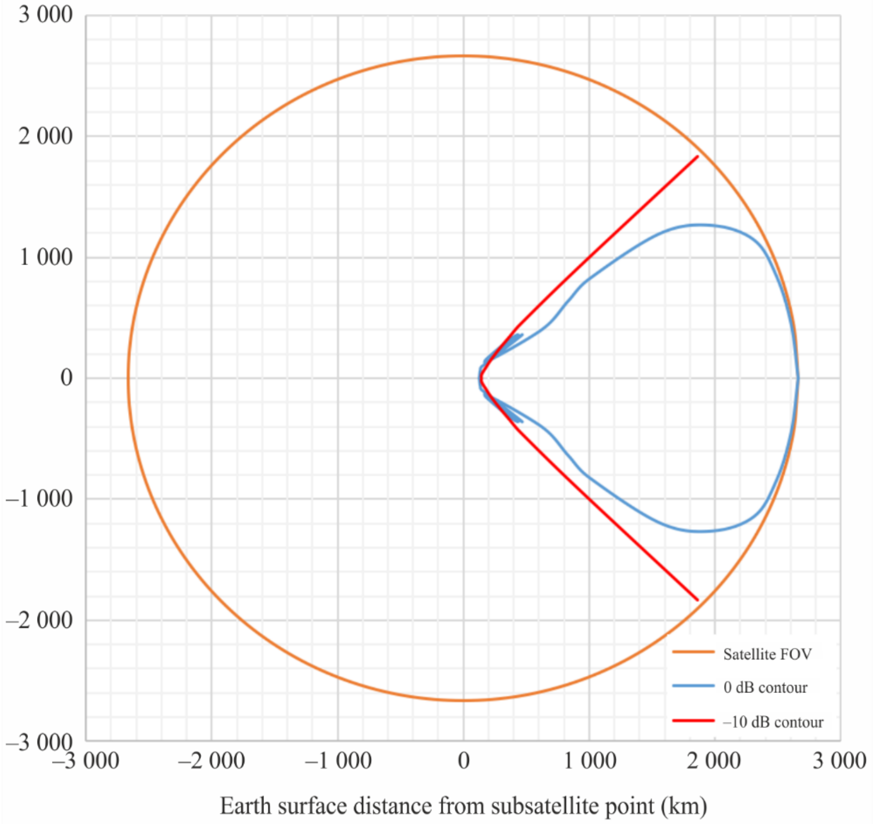
8.1.1 NorSat-2 VHF data exchange – satellite

The satellite has a mass of 15.7 kg and an orbit period of 97 minutes. The satellite can typically be used for communications 12 times per day and for an average period of 10 minutes at 80 degrees north. VDE-SAT is a store and forward system, and 2-3 satellites can deliver two-way messaging with a latency of less than one hour using a shared earth station at Svalbard. The low infrastructure cost makes such a solution financially viable, even with the limited number of vessels in the Arctic.

The satellite is three-axis stabilized and rotates its body around the nadir axis to point an 8 dBi Yagi antenna towards the service area. Figure 28 shows the ground area coverage taking into account the satellite antenna gain in blue, the free space path loss and the ship antenna gain. The 0 dB contour is referenced to a ship located at the satellite antenna boresight seeing the satellite with an elevation of 0 degrees. The coverage fits well with NAVAREA XIX which is 1400 km at its widest.

FIGURE 28

Coverage area



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8.1.2 Background, explanation

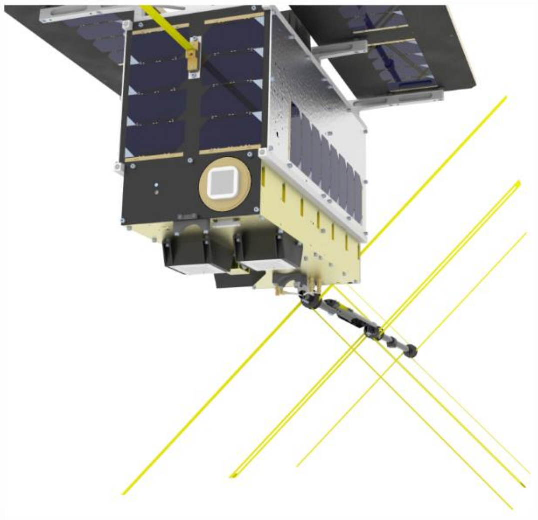
The three-axis stabilized satellite rotates the body to point the antenna boresight to the earth limb (67 degrees nadir angle). It is programmed to support two active attitude modes, along track or through a variable height point above a defined service area centre.

For the test campaign, the 8 dBi Yagi antenna transmitted with a peak e.i.r.p. of -1.4 dBW in RHCP, in compliance with the pfd mask for a 50 kHz channel given in § 4.2.1, Table 5.

The satellite with the antenna deployed is shown in Fig. 29.

FIGURE 29

Norsat-2 with 8 dBi circular polarized Yagi antenna



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The Norwegian Coastguard vessel KV Harstad had VDE-SAT test equipment installed that measured received signal levels from Norsat-2. A 1.25 m commercial ship antenna was used. The ship antenna gain vs the ship-to-satellite elevation angle is given in Table 80. It should be noted that this antenna has approximately 2 dB lower gain between 0 and 30 degrees compared to the antenna used in Recommendation ITU-R M.2092-0.

TABLE 80

Ship antenna gain vs elevation angle

Ship elevation angle (degrees)	Ship antenna gain, Table 2 (dBi)	Test antenna (dBi)	Difference (dB)
0	3	1	−2
10	3	1.5	−1.5
20	2.5	0.5	−2
30	1	−2.8	−3.8
40	0	−4.4	−4.4
50	−1.5	−2.3	−0.8
60	−3	−1.4	−1.6
70	−4	−2.2	−1.8
80	−10	−4.8	5.2
90	−20	−9.4	10.6

The ship antenna position on the vessel is shown in Fig. 30 (red dot). It was not optimum in terms of azimuth coverage which limited the pass time, but was selected for practical reasons. Normally the combined VDES/AIS antenna would be installed on the upper platform. The feed losses were estimated to be 0.5 dB. The transmitted satellite signal contained five 2.4 s VDES frames (12 s) followed by 12 s pauses repeated up to five times, starting at every UTC minute epoch. Not all 12 s periods were used for transmissions.

FIGURE 30

Antenna installation on Norwegian CG Harstad vessel

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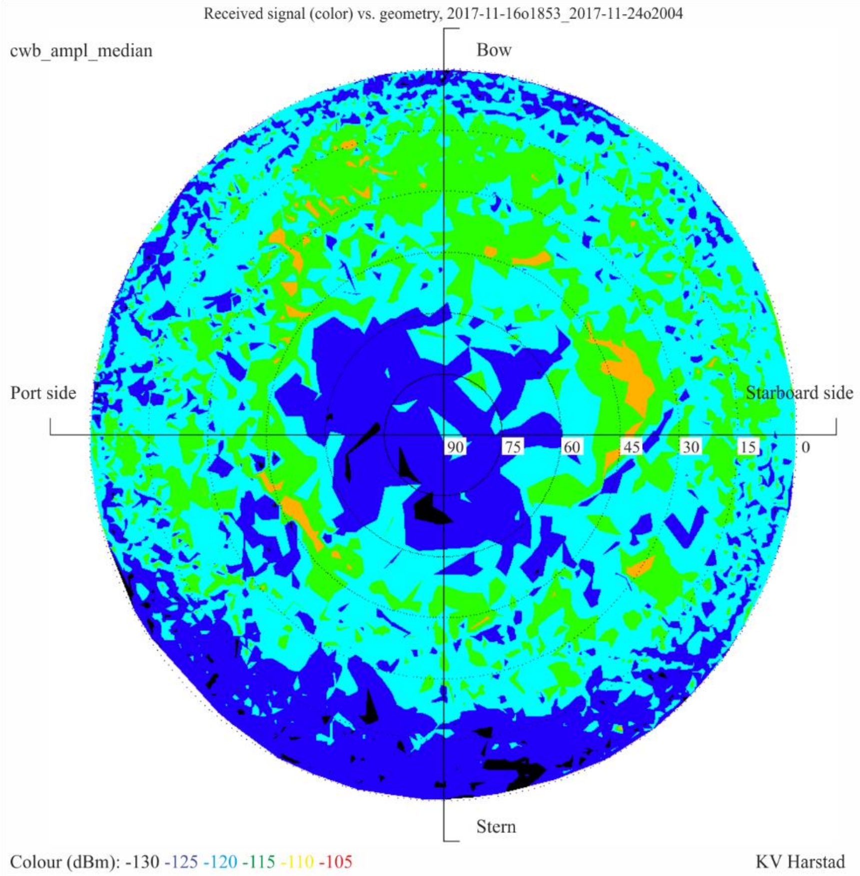
8.1.3 VHF data exchange – satellite downlink test results

8.1.3.1 Signal level vs azimuth and elevation

The Norwegian Coastguard vessel KV Harstad´s antenna installation was not optimum in terms antenna location at a railing on a lower deck, with partial azimuth blockage by the chimney aft and on the port side. Figure 31 shows the received signal level contours vs. elevation and azimuth (relative to ship bow). The blockage effects were much less than anticipated, showing that the VHF signals do not require line of sight for communications.

FIGURE 31

Received signal levels vs. azimuth and elevation



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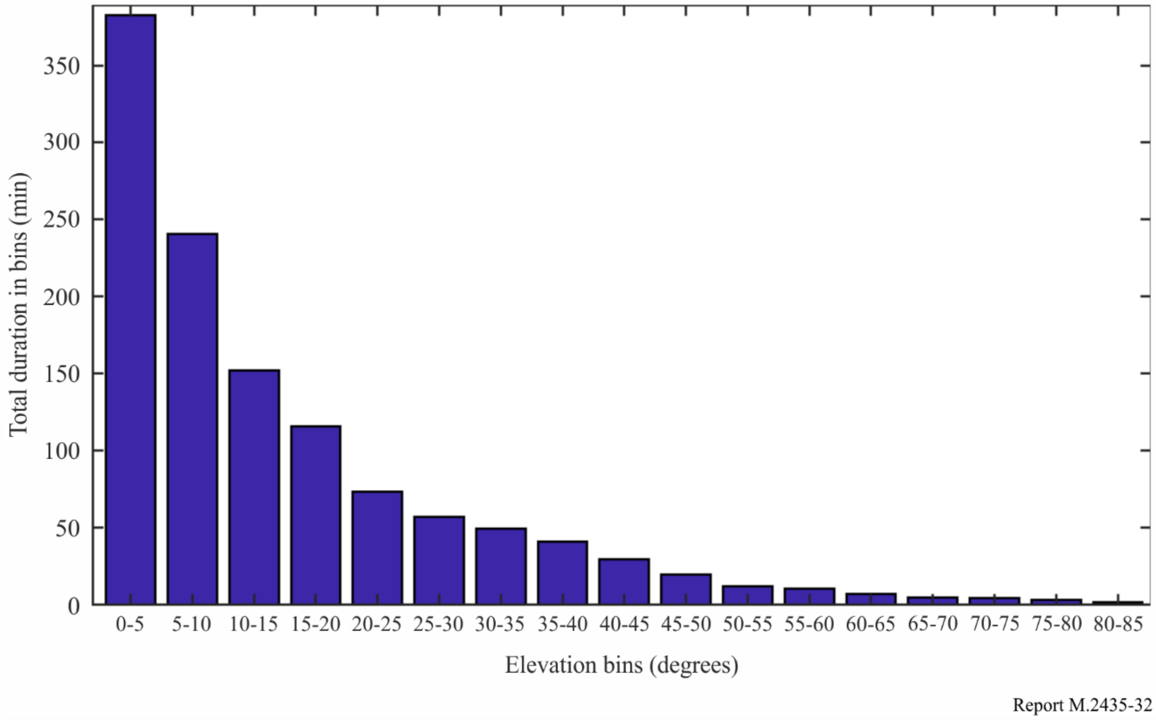
8.1.3.2 Elevation statistics

Most of the time the satellite is visible at low elevation angles. Figure 32 shows the observation time vs elevation for the measurements for the 103 passes.

FIGURE 32

Satellite visibility time vs elevation angle



8.1.3.3 Signal level measurements

Figure 33 shows the mean signal level and standard deviation vs ship elevation angle. Figure 34 shows the probability density function for the signal level at the receiver input (0.5 dB losses). Figure 35 shows the cumulative signal level probability.

FIGURE 33

Mean signal level and standard deviation vs elevation angle

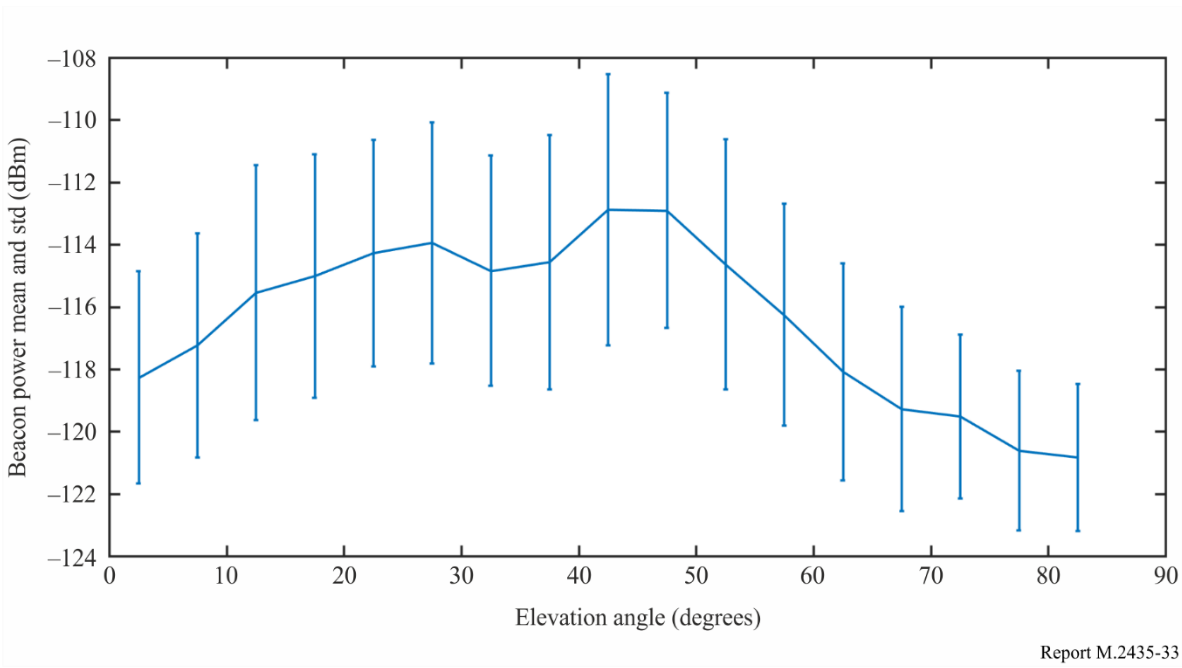


FIGURE 34

Received signal level probability density function

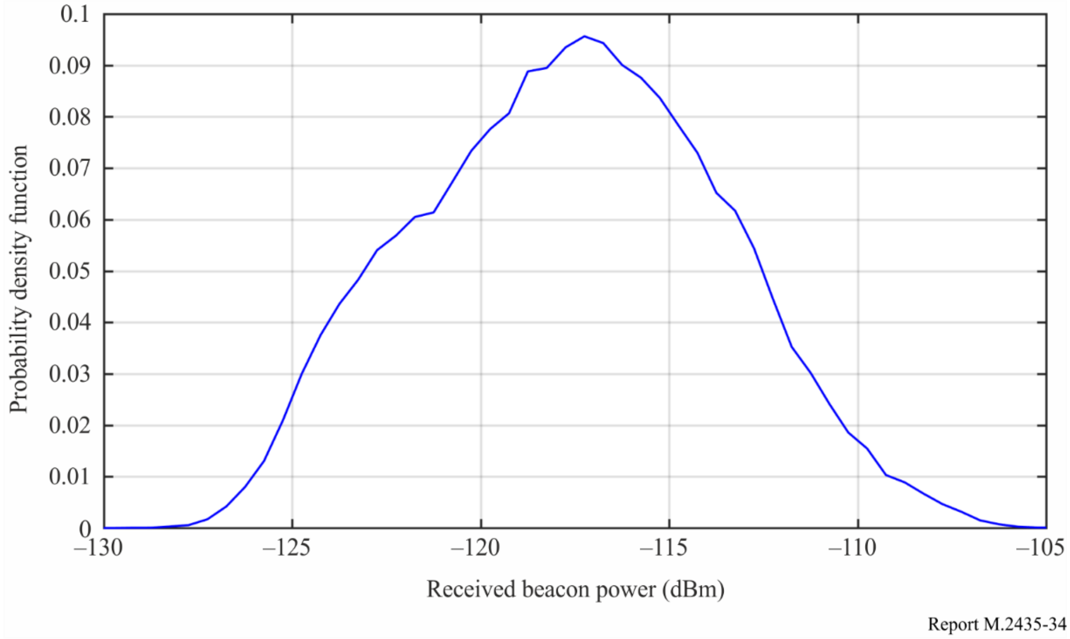


FIGURE 35

Cumulative signal level probability (dBm at antenna)

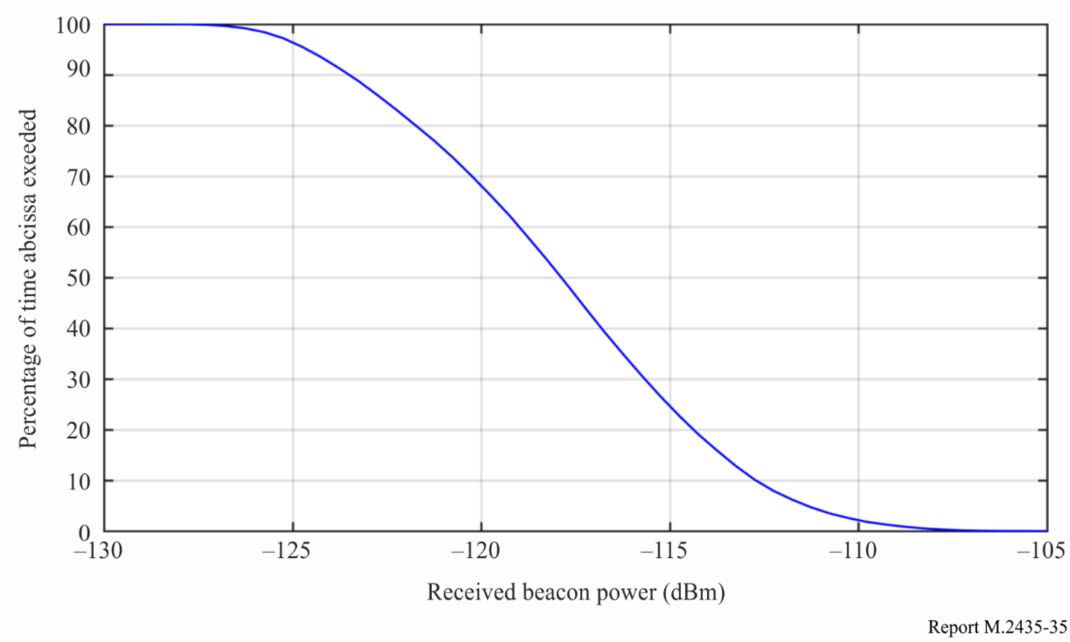


Table 81 shows the median measured signal levels at the receiver input and the theoretical values from link budget calculations. Most of the time (at low ship elevation angles) the level is within 1.5 dB of theoretical calculations. It can also be seen that the rx input level is higher than −118.3 dBm for elevation angles between 2.5 and 62.5 degrees.

TABLE 81

The median measured signal levels at the receiver input and the theoretical values from link budget calculations

Ship elevation bin (degrees)	Satellite e.i.r.p. (dBW/50 kHz)	Ship antenna gain (dBi)	Measured rx input level (dBm)	Theoretical link budget rx level (dBm)	Difference (dB)
0-5	−1.1	1.0	−118.3	−117.6	−0.7
5-10	−1.1	1.3	−117.2	−115.7	−1.5
10-15	−1.1	1.4	−115.5	−114.3	−1.2
15-20	−1.2	0.9	−115.0	−113.5	−1.5
20-25	−1.4	−0.3	−114.3	−113.5	−0.8
25-30	−1.5	−1.9	−113.9	−114.2	0.3
30-35	−1.8	−3.5	−114.8	−115.1	0.3
35-40	−2.2	−4.3	−114.6	−115.4	0.8
40-45	−2.6	−3.9	−112.9	−114.7	1.8
45-50	−3.1	−2.8	−112.9	−113.5	0.6
50-55	−3.8	−2.0	−114.6	−112.7	−1.9
55-60	−4.6	−1.5	−116.3	−112.6	−3.7
60-65	−5.5	−1.5	−118.1	−113.1	−5.0
65-70	−6.5	−1.9	−119.3	−114.2	−5.1
70-75	−7.7	−2.7	−119.5	−115.9	−3.6
75-80	−8.9	−4.0	−120.6	−118.2	−2.4
80-85	−10.3	−5.9	−120.8	−121.4	0.6

8.1.4 Major findings from the measurement results

This section summarises the major findings relevant for future work on the VDES standard and in the preparations for WRC-19 agenda item 1.9.2.

8.1.4.1 Channel fading

The cumulative distribution of signal amplitude fits a log-normal model with 4.2 dB standard deviation well. The time series of the received signal variations matches a specular multipath model. The dominating mechanism seems to be a strong coherent specular sea reflection received by the vertically polarized ship antenna. The fading period is in the order of 60 s, the fade duration depends on the fade margin, but typically exceeds 10 s.

With an antenna height of 15 m the difference in distance between the direct and coherently sea reflected ray is less than 30 m, corresponding to 100 ns or less. The chiprate is 33.6 kchip/s; the chip duration 30 µs. Hence, the signal and multipath cannot be separated in time by correlators (RAKE receiver). Time diversity was also investigated; repeating transmission with approximately 30 s interval and selecting the strongest burst increase the link margin 6 dB for 99% of the time, but halves the capacity.

Ship antenna diversity was not tested nor analysed, but vertical antenna separation is a well-known method and intelligent combining should provide even better link margin improvements than simple repetitions without the capacity reduction. The downside is a more complex ship antenna and a two-channel ship receiver.

The use of link layer coding for multicasting (without ARQ) was successfully demonstrated with 20% overhead.

8.1.4.2 Interference and noise

As part of the receiver installation, measurements were made while the various communications and radar systems on-board KV Harstad were operated in a controlled time sequence. The analysis of the received VDE-SAT signal showed noise/interference from the vessel's own AIS and one of several VHF communications systems.

During the campaign, the man-made noise levels found could typically be characterized as residential or city in Recommendation ITU-R P.372. As experienced during installation, significant interference relative to the thermal noise floor occurred on-board KV Harstad. Narrowband interference occurred regularly; if such interference is representative for vessels in general, waveforms utilising spreading are considered beneficial. Wideband interference occurred with durations exceeding the pass time, sometimes initiated with a strong narrowband pulse. The equipment causing this interference has not been identified, and such interference is expected to vary both with time and vessel equipment. To summarise, the noise plus interference level measured did not represent white Gaussian noise, and it is beneficial if the waveform(s) is robust with respect to both narrowband and wideband noise.

The amount of noise to take into consideration also depends on the required link availability, commonly assumed equal to or larger than 95% of the time. An LNA with noise figure of 9 dB has a system noise temperature of 2014 K, and the external interference and man-made noise will dominate most of the time.

8.1.4.3 Measured performance of VHF data exchange – satellite downlink waveforms

The downlink validation experiment has shown that the combination of received signal, noise and interference power, given the implemented system, is good enough to operate a downlink communications system towards a Coast Guard vessel and presumably also other common classes of vessels. The quality of the received signal is sufficiently good to expect that the spread BPSK-CDMA carrier should function satisfactory in 96 per cent of the time given a required SER of 0.12.

Recommendation ITU-R M.2092 assumes a medium rate Rician fading channel, our measurements showed a specular slowly fading log-normal channel and significant local interference. Good demodulator algorithms are important to achieve acceptable performance.

8.1.4.4 Predicted performance of current waveforms

In this section it is assumed that the measured carrier level, C, at KV Harstad is a representative case. Furthermore, it is assumed that it is possible to obtain demodulator performance close to the theoretical BER/SER performance expected for the uncoded version.

It has been assumed in Recommendation ITU-R M.2092 that the existing ship antenna shall be re-used, and this would exclude two antennas that could otherwise provide diversity improvements. The use of a RHCP antenna would be bulkier than the current whip antenna, but could reduce multipath degradation as the reflected signals will have the opposite polarization and would be supressed.

8.1.5 Ice chart distribution demonstration

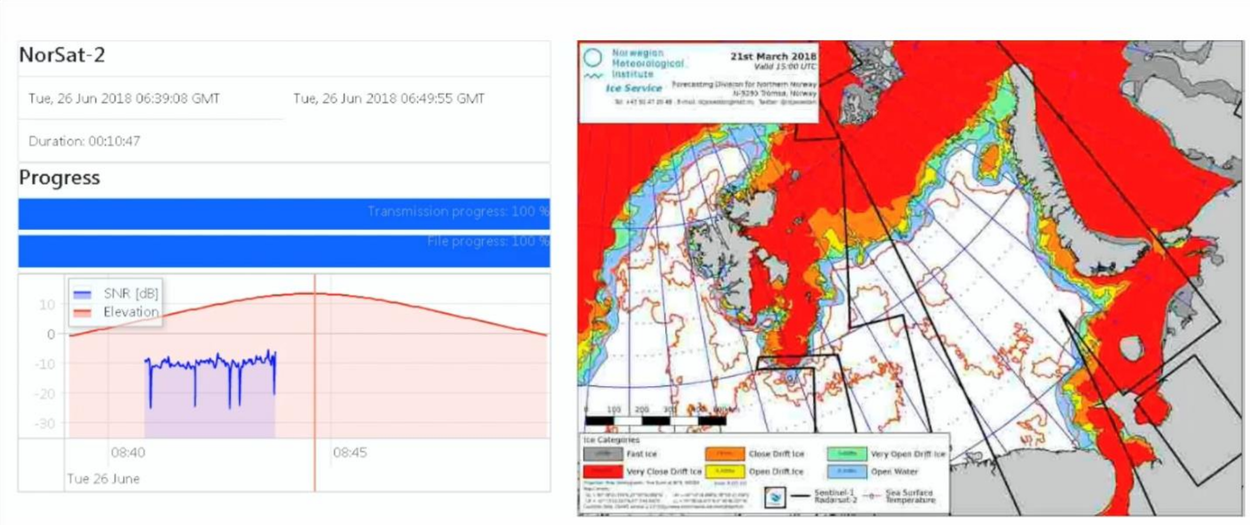
The activity called for a demonstration of ice-chart broadcasting. The Norwegian Meteorological Institute provide daily updates on their website, and the 21 March 2018 version was selected. The image was compressed using progressive JPG until the image quality was considered good enough. This reduced the image size to 29 kB.

It was decided to test out the CDMA-16 waveform defined for VDE-SAT uplink, as hardware and software for this waveform was available and had been fully optimized for low C/N_0 AWGN channel (−1.5 dB E_s/N_0 threshold).

The first broadcast of an Arctic ice-chart (Fig. 36) via VDES to a receiver located in Trondheim harbour (Seatex facilities) was demonstrated on June 26th 2018. Three 50 kHz VDES channels transmitted the chart in 200 s. A two-dimensional Reed-Solomon link layer block code was used, it reduced the PER from a typical 7% to 0%. Simulations showed that this FEC could correct PER of up to 21%.

FIGURE 36

First ice-chart transmitted via NorSat-2 VDE-SAT 26 June 2017



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8.1.6 Conclusions

The purpose of the reported work was to verify the assumed performance of three downlink waveforms as well as studying channel degradations. The measurements and tests have shown that the VDE-SAT downlink can provide useful services in a real maritime environment.

The Norwegian satellite NorSat-2, launched in July 2017 into a sun synchronous polar orbit, transmitted a VHF signal for validation of the downlink (satellite-to-ship) waveform performance.

The world's first ice-chart broadcast via VDE-SAT was demonstrated on June 26th 2018.

Received carrier power, noise environment including interference and performance of three modulated waveforms were analysed and compared with theory and simulations. The median received power levels were close to theoretical link budgets, however the signal levels were subject to slow fading (interval 60 s) and a variation with 4.2 dB standard deviation. No major degradation was identified due to ionospheric amplitude scintillation.

Measured noise and interference levels revealed significant man-made time varying interference. Both wideband and narrowband interference were observed. Although time periods with significant interference were observed, most of the time the noise floor can be classified as residential or city according to Recommendation ITU-R P.372. It is recommended to use a receive filter able to reduce out of band interference, and to implement robust waveforms able to handle both wideband and narrowband interference.

Satellite downlink signal levels have been measured during 103 passes in the Arctic and are close to theoretical values. The VDE-SAT downlink formats in Table 10 provides physical layer details and

Table 82 summarizes the margins for the two noise and interference environments defined in Recommendation ITU-R M.2092-0 for VDES.

TABLE 82

Norsat-2 VHF data exchange system downlink margins measured with a 2 dBi ship antenna

Measured antenna level 50% of time (dBm)	−117.1		
Thermal noise density (N_0) Rec. ITU-R M.2092-0 (dBm/Hz)	−168.4		
Noise and interference density (N_0+I_0) Rec. ITU-R M.2092-0 (dBm/Hz)	−160.0		
Measured/calculated C/N_0 (dBHz)	51.2		
Measured/calculated $C/(N_0+I_0)$ (dBHz)	44.1		
Physical layer waveform (from Table 10)	1	2	3
Unfaded C/N_0 thresholds (from Table 10) (dBHz)	34.2	42.9	50.3
Margin in thermal noise/interference limited environments (dB)	17/9.9	8.3/1.2	0.9/-6.2

The most robust VDE-SAT downlink waveform (waveform 1) in Table 10 would work very well under the noise and interference conditions defined in Recommendation ITU-R M.2092-0. Waveform 2 would work with a good margin in a thermal noise limited environment and acceptable margin for the defined interference environment. Waveform 3 would only work in a thermal noise limited environment.

VDE-SAT use both ACM and ARQ, and the results from 103 passes show that all waveforms would close the link budget under thermal noise conditions.

8.2 Measurement results for the VHF data exchange-satellite uplink

8.2.1 Background and explanations

Recommendation ITU-R M.2092-0 describes the new VHF Data Exchange System technical characteristics. VDES is designed to support ship-to-ship, ship-to-shore and ship-to-satellite digital data communications using simple low-cost equipment. Frequencies to the terrestrial part were allocated at WRC-15 and administrations were invited to undertake satellite testing prior to WRC-19 which will address satellite allocations.

The Norwegian NorSat-2 AIS/VDES test-satellite was launched in July 2017 and has been used for initial uplink tests under real conditions. VDE-SAT test equipment has been mounted on a Norwegian Coastal Administration tow vessel operating on the Arctic coast at 71N, 31E and at a fixed reference site.

The VDE-SAT test equipment transmits position reports using waveform 1 as defined Table 13. During a 150 second observation time of a single pass, 17 position reports were received by the satellite. Hence, confirming that the VDE-SAT uplink works under real conditions, even before optimization, and in areas where significant interference from other services is expected. During the short test the satellite was located North of Svalbard pointing in the direction of Vardø.

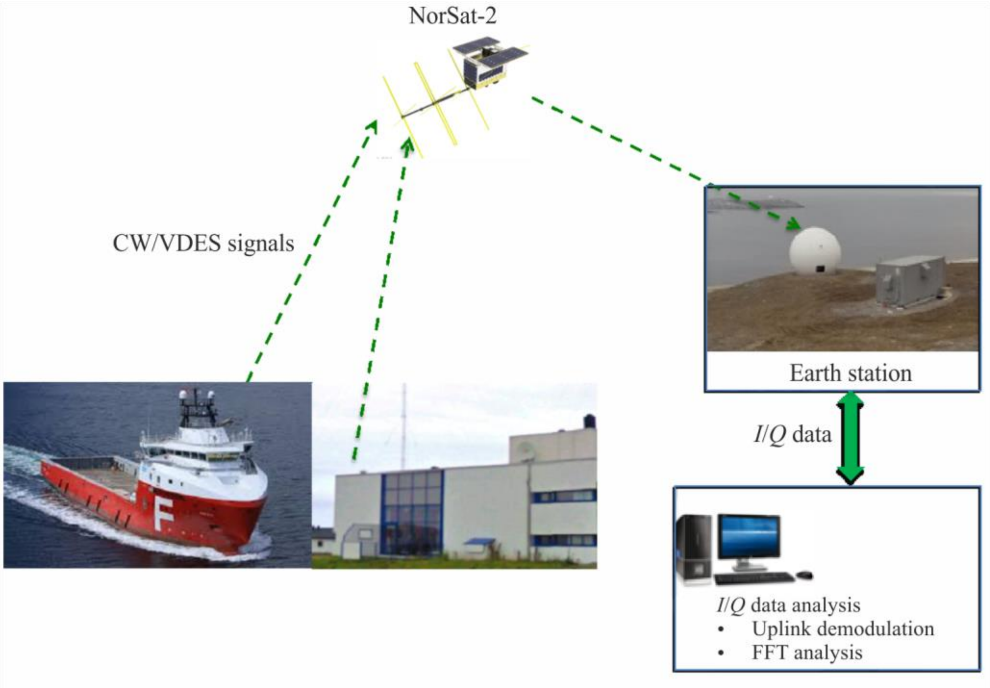
The demodulator including FEC has measured to be within 0.6 dB of theory and simulations as described in § 4.3.1.

8.2.2 Test setup

The test setup is shown in Fig. 37. The test configurations consist of the following elements described below:

– VDES ship terminal with transmitter, antenna and GNSS receiver;
– Software defined VDE-SAT payload onboard NorSat-2 capturing uplink signals in a file;
– A S-band ground station receiving the sampled file;
– A software-based modem demodulating the file;
– Analysis software on a PC (demodulator).

FIGURE 37
VHF data exchange-satellite uplink test configuration



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8.2.2.1 Coverage and link budgets

Unlike current AIS satellite, the VDE-SAT payload onboard NorSat-2 uses a directional antenna with the capability of pointing mainly towards the Arctic oceans, thereby minimizing any terrestrial uplink interference.

The satellite coverage pattern is shown in Fig. 38. The limb pointing satellite is rotated around the nadir axis to provide maximum gain over the service area. It should be noted that the interference is suppressed by 10 dB for more than 75% of the satellite field of view. Figure 38 shows the coverage area for the period analyzed when the satellite coverage area is Barents Sea, Scandinavia and North Western parts of Russia.

The Norsat-2 receiver noise temperature is shown in Table 83. The link budget is shown in Table 84.

FIGURE 38

Satellite ground footprint

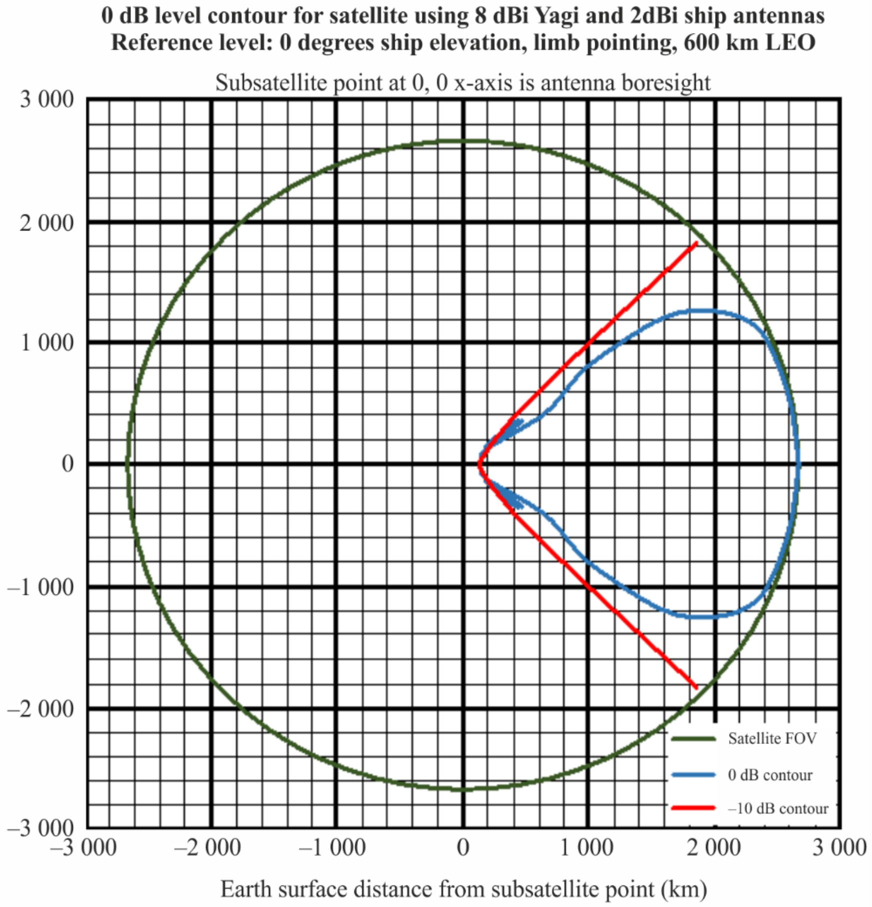

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FIGURE 39

Uplink coverage area during measurement period

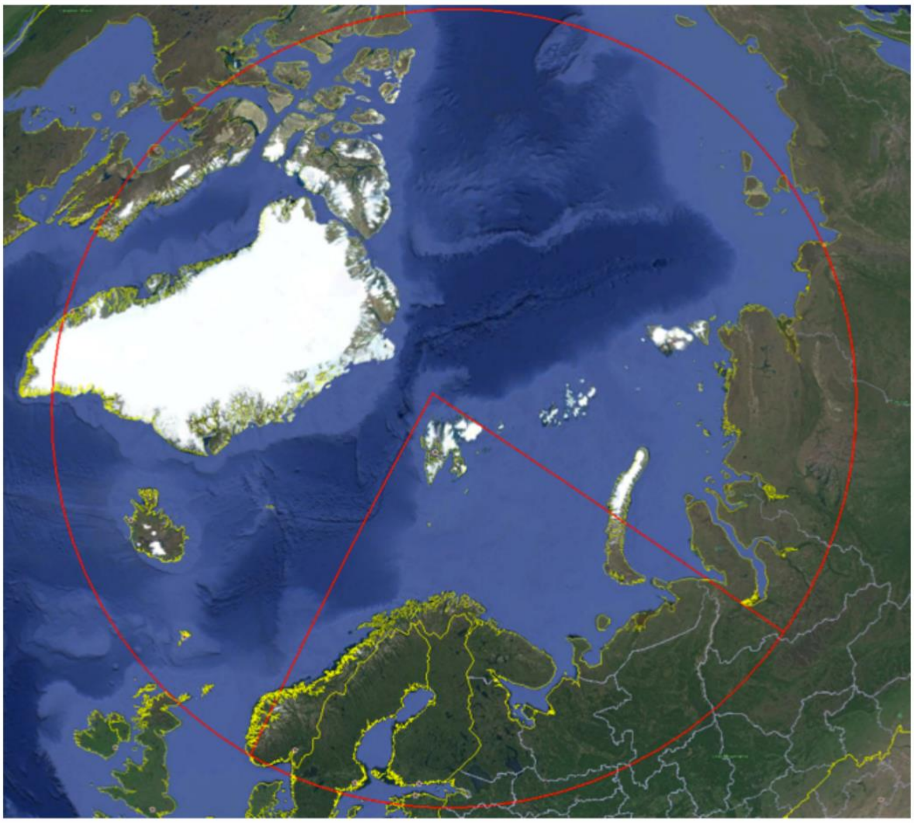

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TABLE 83

Satellite receiver noise temperature

Antenna noise temp (K)	250.0
Cable and mismatch losses (dB)	0.5
LNA noise figure (dB)	2.0
System noise temperature at LNA input (dBK)	26.2

TABLE 84

VHF data exchange system uplink link budget

Ship elevation (degrees)	Range (km)	Ship antenna gain (dBi)	e.i.r.p. (dBW)	Pathloss (dB)	Polarization loss (dB)	Satellite antenna gain (dBi)	G/T (dB/K)	C/N_0 (dBHz)
0	2830	2.0	8.6	145.4	3	8.0	−18.7	70.2
5	2162	1.7	8.3	143.1	3	7.7	−19.0	71.9
10	1932	0.7	7.3	142.1	3	7.7	−19.0	71.9
15	1626	−1.0	5.6	140.6	3	7.7	−19.0	71.7
20	1392	−3.0	3.6	139.2	3	7.6	−19.1	70.9
25	1213	−4.8	1.8	138.0	3	7.5	−19.2	70.2
30	1075	−5.1	1.5	137.0	3	7.3	−19.4	70.8
40	882	−2.6	4.0	135.3	3	6.8	−19.9	74.5
50	761	−1.5	5.1	134.0	3	5.9	−20.8	76.0
60	683	−2.2	4.4	133.1	3	4.7	−22.0	75.0
70	635	−4.7	1.9	132.4	3	3.0	−23.7	71.5
80	608	−10.1	−3.5	132.0	3	0.7	−26.0	64.1
90	600	−26.6	−20.0	131.9	3	−2.1	−28.8	45.0

From Table 84 it can be seen that in the absence of interference, the C/N_0 exceeds 70 dBHz for all elevation angles below 70 degrees. For waveform 1, with a chip rate of 33.6 kcps, the corresponding E_c/N_0 is 35 dB.

8.2.2.2 VHF data exchange system ship terminal with transmitter

The key technical characteristics of the VDES ship terminal transmitter and the waveform used for the VDE-SAT uplink tests are given in Table 85. The equipment was installed on the Norwegian Coastal Administration vessel Far Sabre located operating on the northern coast of Norway, around 71N. A standard commercial 2 dBi ship antenna was used. The antenna was mounted on the railing at the upper deck for practical reasons. In addition, a fixed transmitter was installed at the Norwegian Costal Administration VTS center in Vardø (71N, 31E). The terminals were set to report position and auxiliary data every 12 s. The burst duration was 125 ms.

TABLE 85

Transmitter characteristics

Parameter		Value
Waveform No.		1
Frequency	MHz	157.3125
Chip rate	kcps	33.6
Bandwidth	kHz	42
Modulation		QPSK/spread spectrum
Direct sequence codelength	chips	16
FEC rate		¼
FEC type		Turbo
Transmit power	W	6.5
Antenna cable loss	dB	0.9
Antenna gain	dBi	2
e.i.r.p.	dBW	9.1
Burst duration	ms	128

Further waveform details are given Table 13.

The VDES antenna was mounted approximately 6 m from the vessels AIS antenna, and no adverse effects were noted on the ships ECDIS system.

8.2.2.3 Norsat-2 satellite

The satellite has a VDE-SAT payload with a software defined transceiver that supports store and forward operation. The onboard FPGA processor has more than sufficient processing power to demodulate the signals defined for VDE-SAT, but for these tests demodulation on ground could be implemented earlier, which was necessary to be able to report to the May 2018 meeting of ITU-R Working Party 5B.

A novel deployable 3 element crossed Yagi antenna provides 8 dBi gain in RHCP. This antenna has a beamwidth of 69 degrees and points at the earth limb. To maximize coverage time, the reaction wheels in the satellite are preprogrammed to rotate the satellite body and point the antenna towards the service area. The pointing error has been measured to be less than 1 degree.

For these VDE-SAT uplink tests, the receiver software sampled the VDE-SAT uplink I/Q signals and stored them to memory during each pass.

Norsat-2 has a size of 200x300x400 mm and a weight of 15 kg. A few such satellites are well suited to provide cost effective eNavigation services in regions with limited communications infrastructures.

8.2.2.4 Ground segment

The raw I/Q samples are downlinked via a high bitrate downlink to an S-band earth station and demodulated on ground using digital signal processing. The demodulation software decodes all samples and generates the source data in a csv file. Auxiliary parameters relating to signal quality and demodulator parameters are also available.

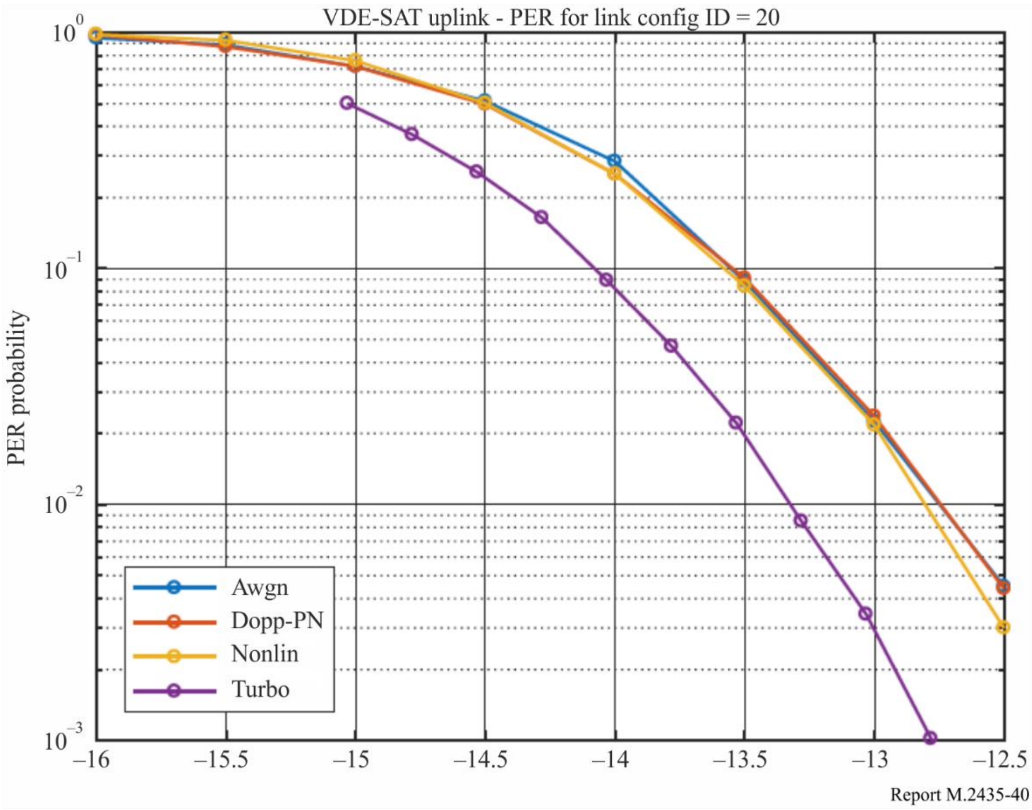
The demodulator performance was tested and found to be within 0.6 dB of theory and simulations as described in § 4.3.1.

The measured PER curves vs E_c/N_0 for the demodulator is shown in Fig. 40. There is insignificant degradation caused by Doppler or PA non-linearities. It can be seen that the demodulator threshold corresponds to an E_c/N_0 of −13.5 dB. Thus, giving a 48.5 dB theoretical fade and interference margin.

The E_s/N_0 threshold is −1.5 dB after dispreading with a spreading factor of 16. The spreading factor of 16 provides a processing gain of 12 dB as defined in Recommendation ITU-R SM.1055.

FIGURE 40

Measured demodulator performance (E_c/N_0) in dB waveform 1



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8.2.3 VHF data exchange-satellite uplink test results

A partial initial pass from the vessel has been analyzed. The satellite service area pointing was towards Vardø, Norway, located at 71N inside NAVAREA XIX. The vessels position reports are shown in Fig. 41. During a 150 second observation time of a single pass, 17 position reports were received by the satellite. Hence, confirming that the VDE-SAT uplink works under real conditions, even before optimization, and in areas where significant interference from other services is expected.

The results from the VDE-SAT uplink tests are summarized in Table 86. It is evident that the VDE-SAT uplink performs well in this region.

FIGURE 41

Ship transmitter location

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TABLE 86

Initial uplink test results

Parameter	Value	Comment
Date	3 May 2018, 6:13 UTC	
Subsatellite location	81.6 N, 8.6E	North of Svalbard
Satellite antenna pointing	71N, 31E	Vardø
Analysis time	150 s	
Coverage area	Barents sea Scandinavia, and North West parts of Russia	
Number of packets received correctly	17	

8.2.4 Conclusions

Measurements of an implemented demodulator using FEC rate ¼ Turbo code as defined in § 4.3.1 shows that the thresholds defined there are reasonable and achievable. 10% PER rate is achieved for an E_s/N_0 of −1.5 dB. When the processing gain of 12 dB for that waveform is considered this corresponds to a $C/(N+I)$ threshold of −13.5 dB.

In initial field measurements of the VDE-SAT uplink, position reports using waveform 1 as defined in Table 13 were detected. The uplink tests were performed using a ship on the northern coast of Norway at about 71N. Hence, confirming that the VDE-SAT uplink works under real conditions, even before optimization, and in areas where significant interference from other services is expected.

Considering the limited availability of low-cost communications solutions in some NAVAREAs, VDE-SAT could be an import contributor to IMOs eNavigation strategy and the digitalization of the maritime industry. A frequency allocation to VDE-SAT would therefore be an important contribution to improve maritime safety and efficiency.

8.3 VHF data exchange-satellite downlink test campaign in the Netherlands

From 12 to 16 of January 2018, the European Space Agency together with their industry partners Lacuna Space in the Netherlands carried out a test campaign measuring a VHF transmission from NorSat2 Satellite centered around 161.8625 MHz spanning 125 kHz of bandwidth.

A special waveform was generated and uploaded to NorSat-2 in coordination with ESA Norwegian industry partner, Space Norway for the test purposes. The software defined capability of the NORSAT-2 was used to accommodate the waveform that contained a number of short messages. The signal to noise (and interference) quality was estimated at the receiver and used to evaluate the link quality, as reported in the Annex 1.

For the purpose of this test, typical ship-borne RF equipment for VHF terrestrial maritime communications was deployed. For the signal detection, existing receivers capable of detecting and decoding the transmit waveform were used.

During the test period from the 12 to 16 of January 2018, passes of NorSat-2 were successfully detected at the test location. The test signal consisting of several short messages were repeatedly transmitted during each pass. The message lengths varied from 0.60 seconds to 1.64 seconds. During the test campaign, around 6000 messages were detected and successfully decoded. A signal quality (signal to noise and interference) estimator provided an indicative measure of each captured signal. As shown in § 8.3.1, the signal quality measure can vary up to 25 dB. However, the signal quality variation is significantly reduced if only detectable messages above 10 degrees of elevation angles are considered. This can provide a guideline in designing the waveform for the VDE-SAT downlink based on the e.i.r.p. constraints.

The National Measurement Network Telecom (LMT) in the Netherlands monitored the signal on 15 and 16 January while VDES broadcasting were made by NorSat-2 while above the Netherlands. Their results are presented in § 8.3.2.

8.3.1 VHF data exchange-satellite downlink signal measurement

During the test campaign over the Netherlands, a special waveform was designed and uploaded on NorSat-2 that allowed for a signal detection and measurement over a wide range of link conditions. Over the entire test campaign (28 passes of NorSat-2) around 5956 messages were detected. A distribution of the satellite elevation angle at the time of signal reception is shown in Fig. 42.

FIGURE 42

Distribution of 5956 detected messages vs. elevation angle

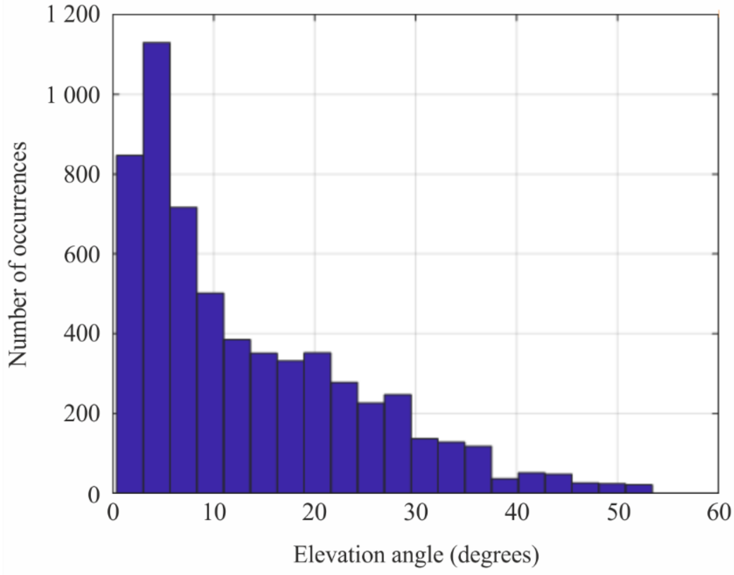

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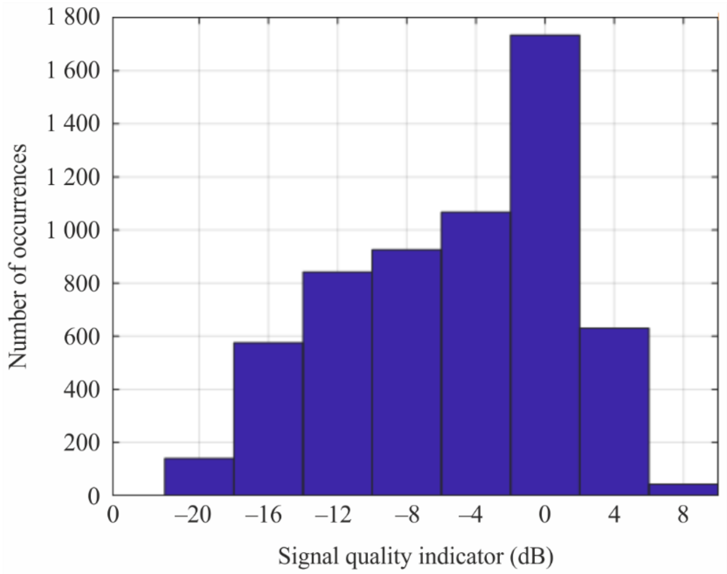
FIGURE 43

Distribution of signal quality of 5 956 detected messages (measured in dB)



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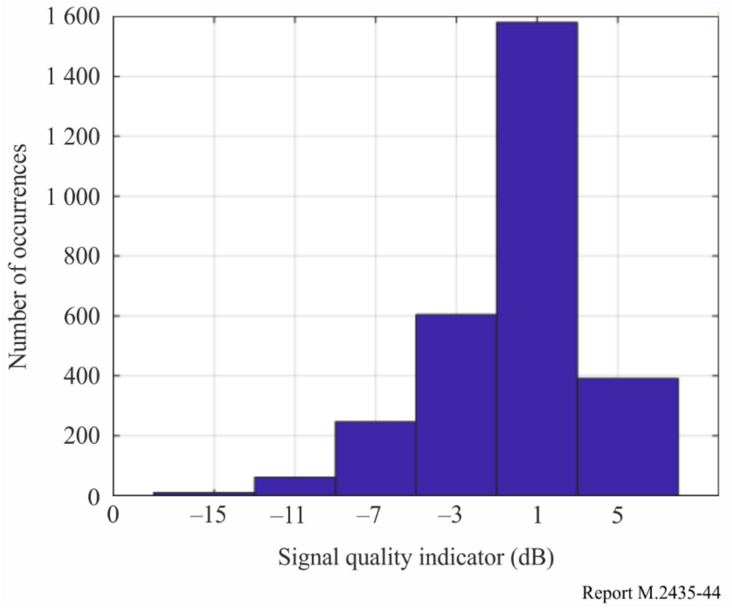
As indicated in Fig. 43, the quality of detected messages varies considerably. The variation is partly due to the change of geometry (mostly elevation angle and partly due to the azimuth).

It has been noted that for signal detection at elevation angles above 10 degrees the signal quality variation is significantly reduced, as shown in Fig. 44. The signal can be designed to operate at a higher detection threshold, hence improving the spectral efficiency and transmission throughput.

FIGURE 44

Distribution of signal quality of 2 895 detected messages (measured in dB) at elevation angles larger than 10 degrees



8.3.2 VHF downlink monitoring by Dutch National Monitoring Network

The National Measurement Network Telecom (LMT) in the Netherlands continuously monitors the radio frequency spectrum covering 20 MHz to 3 GHz.

LMT monitored the signal on 15 and 16 January while VDES broadcasts were made by NorSat-2 while above the Netherlands. The expected signal is a digital modulated signal following an active period of 12 seconds followed by 12 seconds of silence at 161.8625 MHz with a 125 kHz bandwidth. The transmission pattern repeated every 60 seconds.

Two different methods were used to detect the transmitted signal from NorSat-2. The first method was based on conventional monitoring network deployed by LMT. Subsequently, a special measurement method with higher sensitivity was used to detect the signal.

Each of the 15 LMT measurement locations are unique, with different antenna height, cable length and different environment interference level. The lowest noise (and interference) floor at 161 MHz, at about −17 dBuV/m was identified at one of the monitoring locations. This gives the most sensitivity and the best chance to detect the signals. The normal measurement tasks use a broad bandwidth, which reduces the sensitivity. Subsequently the second measurement method concentrated on a narrow bandwidth for maximum sensitivity.

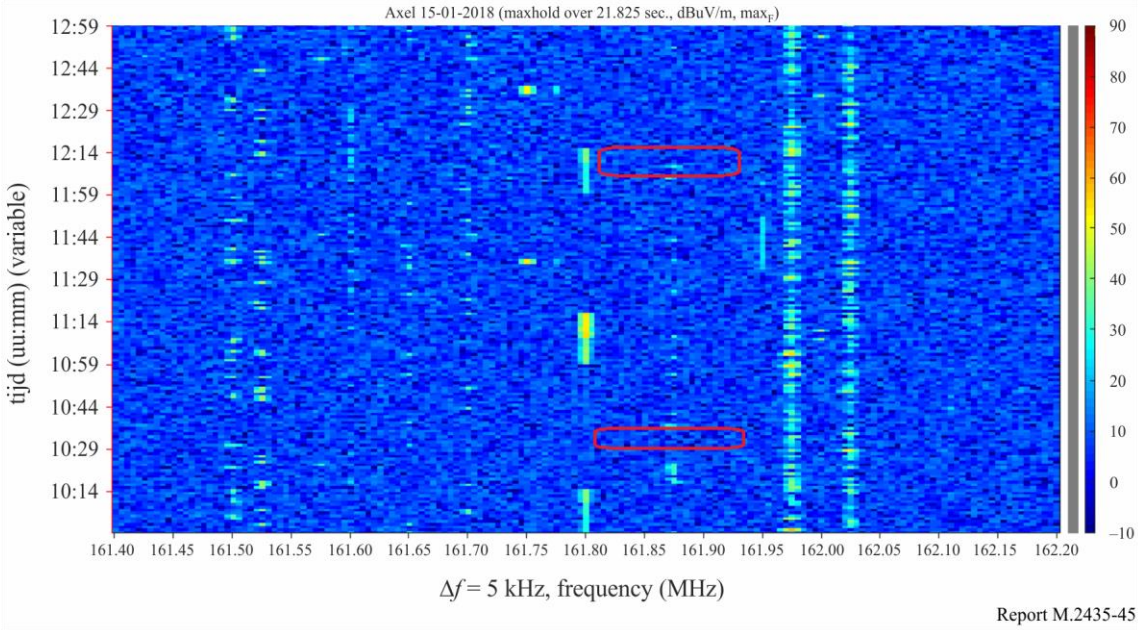
The signal from NorSat-2 was detected using these approaches, however, the detection was rather irregular and not available on all daily measurements (taking into account the limited coverage over the Netherlands). The LMT did not intend to demodulate digital signals. It should also be noted that signal level readings may not be fully calibrated.

Method 1: Conventional measurement

The data from the normal measurement tasks of the LMT was used to plot data as a spectrogram that displays a range of frequencies over time, or as a chart with a single frequency in time. The stored data that was captured during the test period did not show any sign of the NORSAT-2 signals due to the lower sensitivity. An example is shown in Fig. 45.

FIGURE 45

Red rectangles indicate where signals were expected



Report M.2435-45

Method 2: Narrow bandwidth special measurement

The radio equipment of the LMT was manually controlled and tuned to a narrower range of frequencies. For this test a Fixed-Frequency-Mode (FFM) is used at 161.8625 MHz with a bandwidth of 200 kHz. With these parameters the produced measurements had a much lower noise floor than the normal measurement tasks.

On January 16, one of the monitoring stations of LMT was used to observe two passes of the NorSat-2 satellite. Coinciding with the expected passing time, the transmitted signal around 161.8625 MHz was detected. The signal covered a width of 125 kHz and lasted for about 10 seconds and then faded. After a silence of 12 seconds it would start again.

Figures 46 and 47 below show a series of broad signals (lasting 10 seconds) with a 12 second pause between them. These are the parallel yellow lines. It also shows the Doppler shift of the signal (about 10 kHz).

Terrestrial signals are also recorded in both plots. Signals at 161.8750 MHz are much narrower and stronger.

FIGURE 46

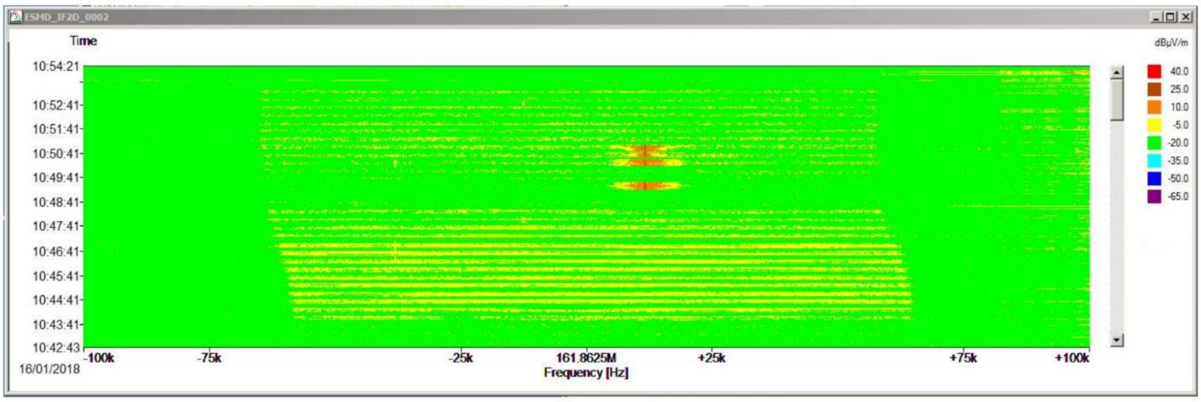


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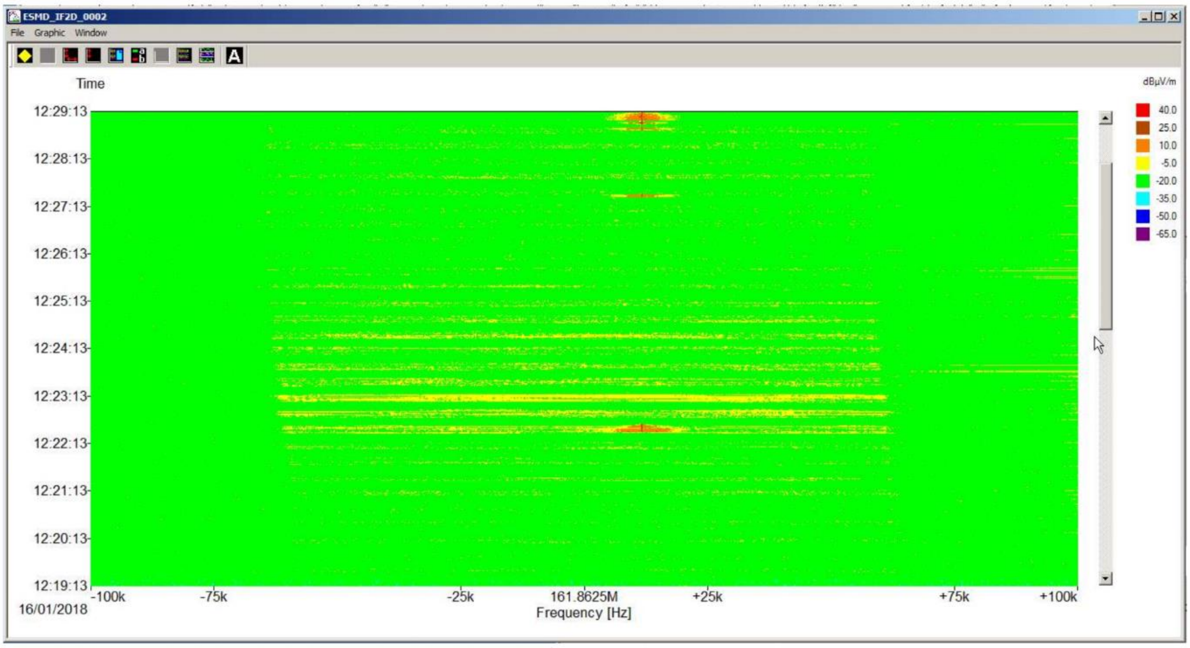
FIGURE 47



Report M.2435-47

8.3.3 Conclusions

The results of VHF data downlink from NorSat-2, as detected in the Netherlands, indicate the feasibility of reliable data downlink transmission given that the waveforms with proper detection thresholds are deployed.

The VHF transmission by NorSat-2 at nominal level, as observed during the test campaign are observable by terrestrial monitoring equipment but unlikely to interfere with terrestrial systems due to the low signal power.

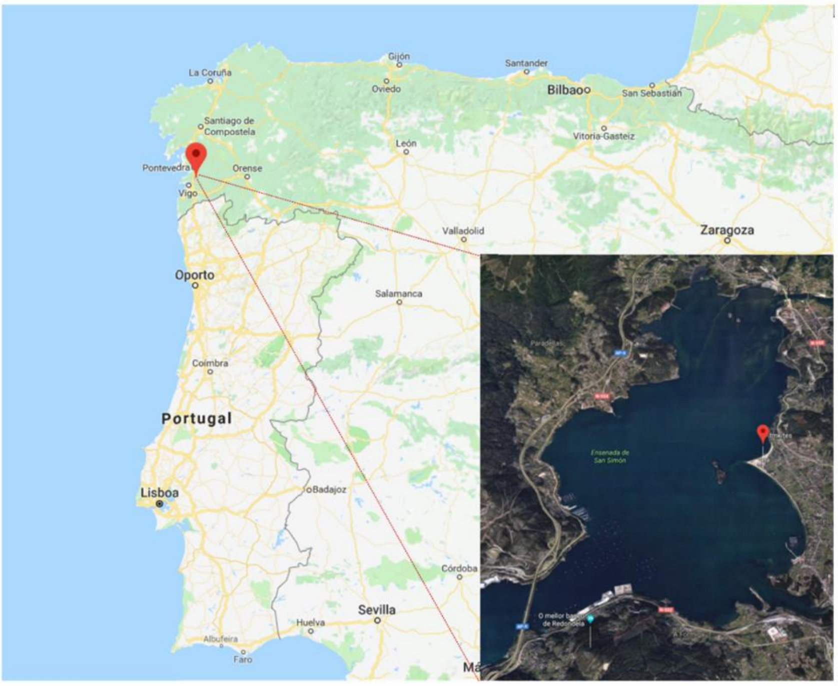
8.4 VHF data exchange-satellite downlink signal measurement in Vigo, Spain

8.4.1 Measurement Campaign

The measurement campaign was carried out in Cesantes, a coastal village near Vigo (Pontevedra), in Spain. The location of the receiver is shown in Figs 48 and 49 (42.2461272N, 8.6361776W). The measurement campaign was carried out starting on March 22 until April 13 of 2018 using the VHF transmission from NorSat-2 satellite. From all the satellite passes with visibility over the region, only the ones that had the maximum elevations above 5 degrees were considered for post-analysis.

FIGURE 48

Location of the receiver (Cesantes, Spain)



Report M.2435-48

The Ministry of Energy, Tourism and the Digital Agenda (Spain) granted Egatel the right to a temporary use of radioelectric public domain for maritime mobile-satellite services. This license covers the use of the following VHF channels:

Link	Frequency [MHz]	Designation
Downlink VHF	161.81250	42K0G1X
Downlink VHF	161.83750	8K00N1X
Downlink VHF	161.86250	42K0G1X
Downlink VHF	161.91250	42K0G1X

This license had a validity period of three months, starting on the 22nd of January until the 22nd of April, in 2018.

FIGURE 49

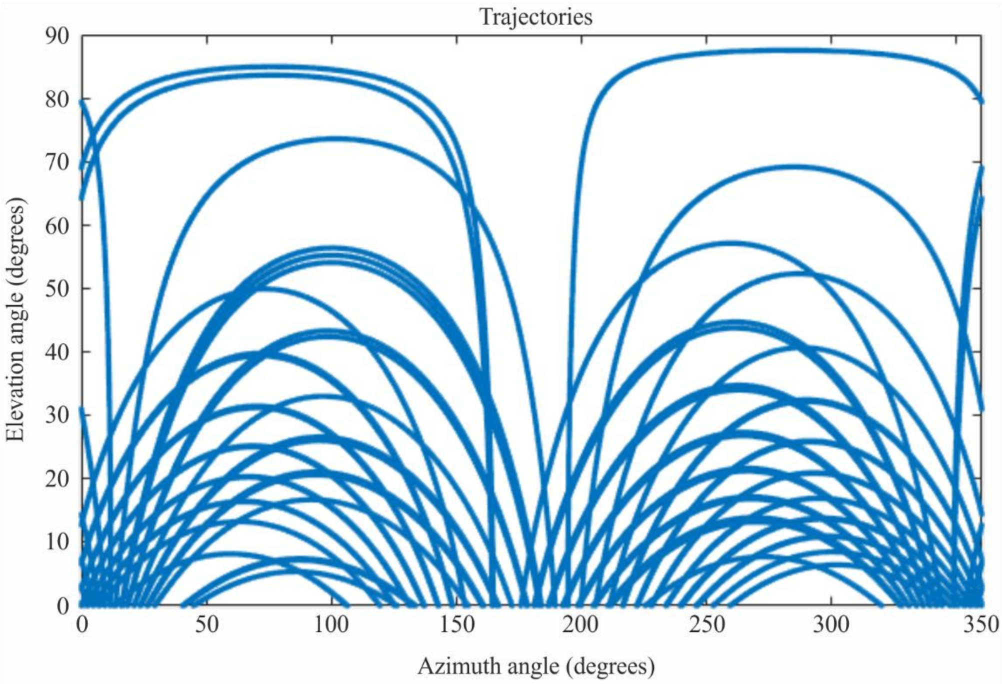
Views from the receiver location (highlighted in red)

Report M.2435-49

During the measurement campaign the continuous wave (CW) was detected in 64 satellite passes, excluding satellite passes with very low peak elevation angles (below 5 degrees). All the trajectories followed by the satellite over these passes were aggregated to obtain Fig. 50, where elevation versus azimuth is represented.

FIGURE 50

Aggregation of all satellite passes trajectories

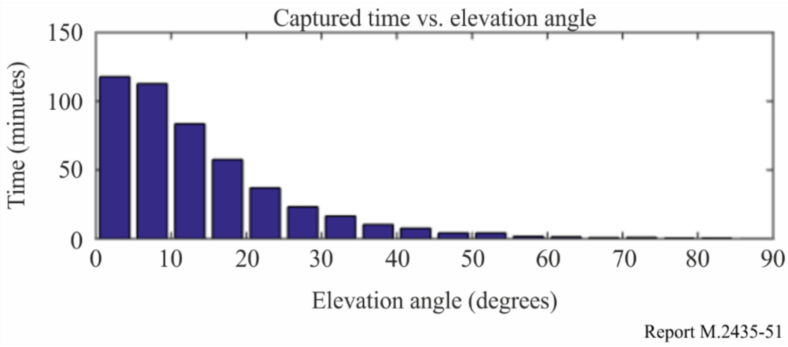


Report M.2435-50

From the trajectories it is expected to have more satellite visibility at lower elevations than at higher elevations. Figure 51 shows the visibility time distributions (in minutes) per every 5-degree elevation angle interval.

FIGURE 51

Captured time per elevation angle



It should be noted that most of the samples recorded from the satellite have an elevation lower than 30 degrees. For elevation angles between 60 and 90 degrees there are barely a few samples, contributed by the only five passes within these elevations.

FIGURE 52

Comrod AV7[7] whip antenna

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7 http://www.comrod.com/getfile.php/13179/Datasheets/T%20Antennas%20-%20Marine/AV7M.pdf.

8.4.2 Receiving Antenna

The antenna used in the measurement campaign is the Comrod AV7 whip, a commercial antenna for maritime communications (see Fig. 52). It is important to note that a representative antenna has been chosen for a real scenario, i.e. not only for the reception of the satellite component of VDES but also for terrestrial communications (including VDE, AIS and ASM). A couple of points should be remarked about the radiation pattern (see Figure) since it will have important impact on the results:

– The antenna gain for high elevation angles is very low.

– The antenna gain for negative elevation angles (from 180º to 360º) is not negligible, which means that antenna does not protect the receiver from multipath due to water reflections.

Some of its technical characteristics are:

– Frequency range: 156 to 162 MHz

– Gain: 2 dBi

– Radiation pattern

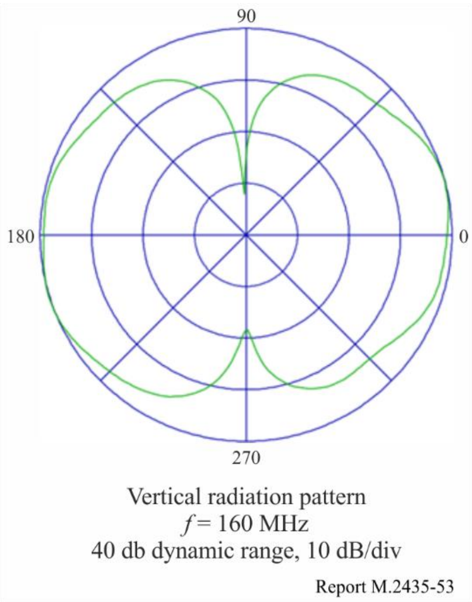
  • Horizontal plane: omnidirectional

  • Vertical plane: see Fig. 53

– Height: 1.25 metres

FIGURE 53

Comrod AV7 whip radiation pattern

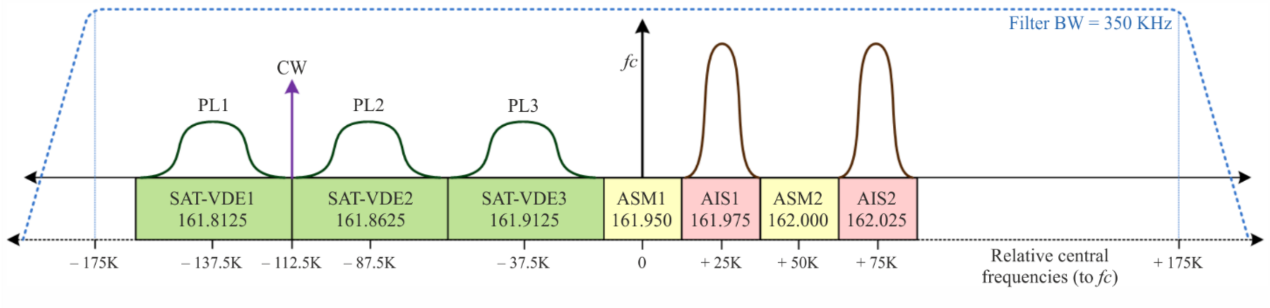


8.4.3 Radio configuration

A software defined radio (SDR) platform is used to configure the radio parameters so that the resulting baseband signal according to the frequency range illustrated in Fig. 54.

FIGURE 54

Baseband signal captured by the SDR platform



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The configuration of the main radio parameters is the following:

– **Centre frequency: 161.95 MHz**

The platform is configured to use direct RF conversion. In this mode it is unavoidable to have DC suppression and local oscillator effects at the centre frequency (in the baseband signal this would mean at 0 Hz). This is the reason why the center frequency was configured to be at the center of ASM1 channel, since there is no interest in analyzing this channel and thus preventing these effects from altering the VDE band.

– **Analogue filter bandwidth: 350 kHz**

Value large enough to keep VDE channels in-band.

– **Sampling frequency: 500 ksamples/s**

Value large enough to allow for an adequate signal post-processing, also meeting Nyquist criterion.

8.4.4 Signal Analyses

The captured signals were processed as explained below:

– **Time synchronization**: it involves detecting ON and OFF periods and to match them to the ON-OFF expected pattern.

– Doppler compensation:
  - Correcting Doppler shift by using expected satellite Doppler.
  - Apply a low pass filter and averaging.
  - Estimate and correct residual Doppler.

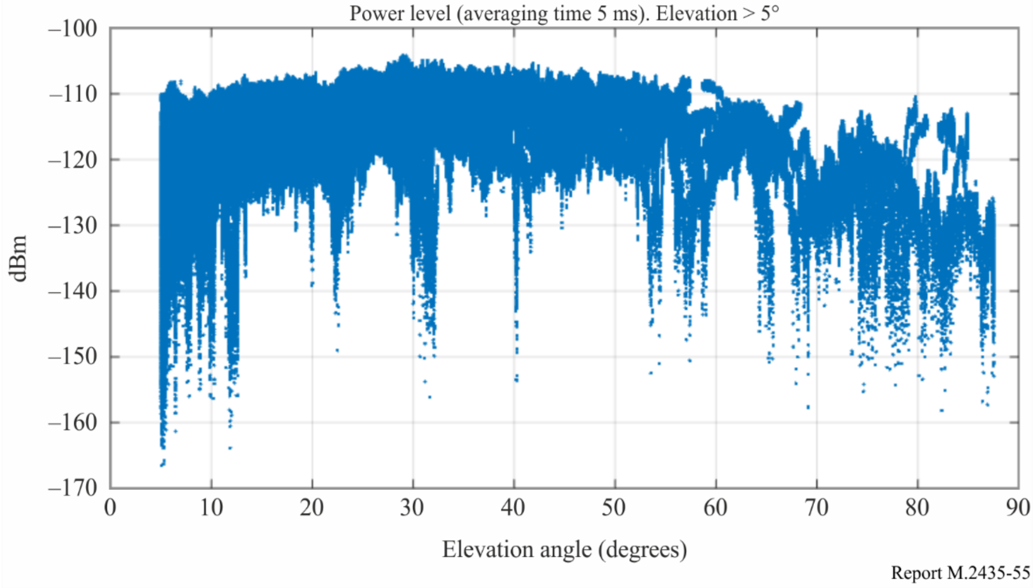
– The power of the resulting signal is estimated as follows:
  - Select an average time.
  - Compute power of each sample.
  - Split samples in non-overlapping blocks
    – Samples during transitions between ON and OFF periods are not considered in order to not distort the results.
  - Compute the arithmetic mean of each block in natural units.

8.4.5 Signal power measurement (Continuous Wave)

Figure 55 presents the power level of all captured signals versus elevation angle. Only ON periods are considered in this case. Every dot represents the power average of a 5 milliseconds block.

FIGURE 55

Power level per elevation angle (all captures)



Report M.2435-55

Some observations can be made from Fig. 55:

– Power for elevations below 15 degrees shows a lot of variance/fading. The explanation for this could be that satellite signal is being blocked by the surrounding topography for some azimuth values, as there are several mountains presenting non-negligible height near the receiver location and specular multipath fading. In any case it can be noticed that, considering the power level for other elevations, some signals show high power levels (up to −110 dBm) for these elevations.

– Power for elevations above 60 degrees presents a lot of variance/fading as well, and the power start to decrease quickly. This makes sense as these elevations corresponds to the passes where the satellite is higher, i.e. closer to the vertical from the point of view of the antenna, where it has its null. It is also important to recall there are only five captures that reach elevation angles higher than 60 degrees, so the sample size for this interval is scarce.

– Elevations between 30 and 60 degrees show more consistent power levels, ranging from −125 dBm to −105 dBm. However, it can be seen there is a fading effect for these elevations at least in a few captures.

The same power level values represented in Fig. 55 are used now to obtain the Probability Density Function (PDF) for different elevation angle intervals. Figure 56 shows the amplitude and elevation PDFs for the following elevation angle intervals:

– From 5º to 15º: left column, blue line;

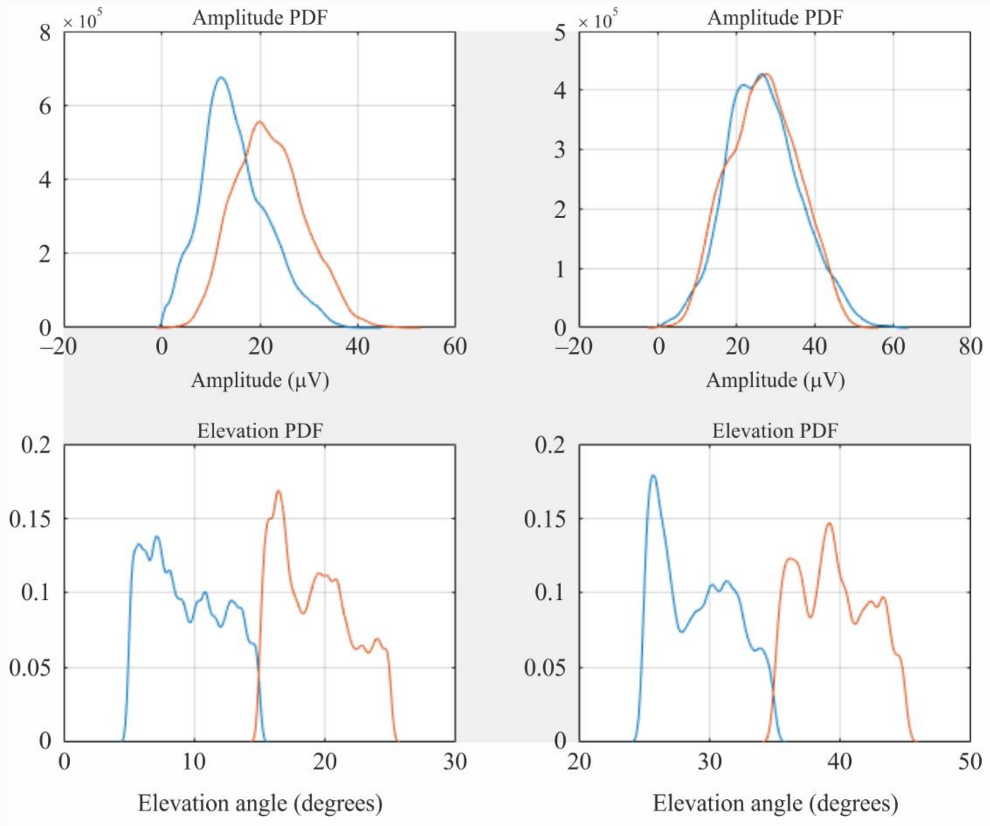
– From 15º to 25º: left column, orange line;

– From 25º to 35º: right column, blue line;

– From 35º to 45º: right column, orange line.

FIGURE 56

Amplitude and elevation distributions



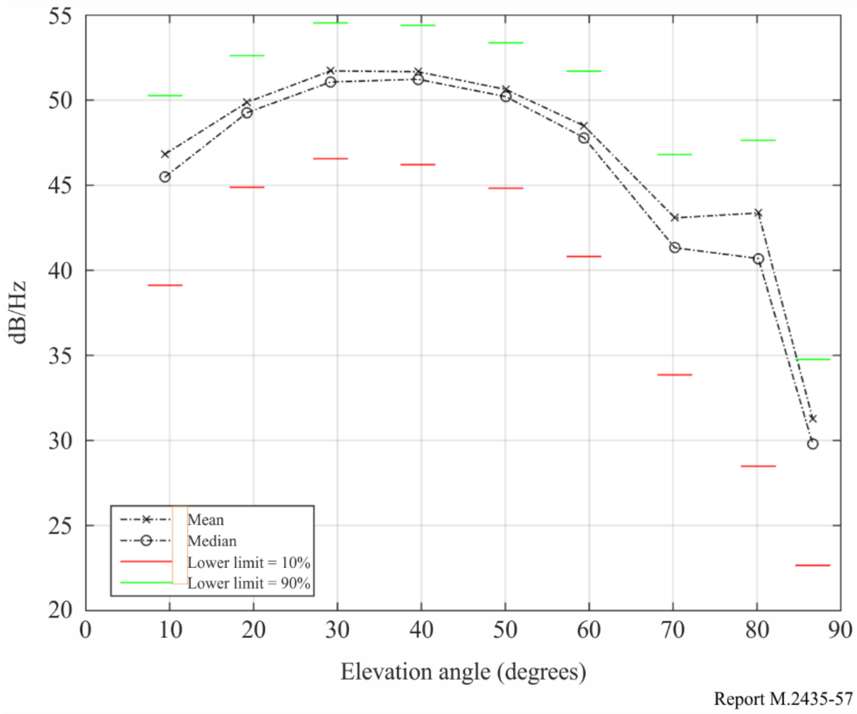
Report M.2435-56

8.4.6 Expected $C/(N_0+I_0)$

The power level values obtained from the signal power computation were used to represent an estimation of the expected carrier to noise plus interference density ratio $C/(N_0+I_0)$ for CW, as shown in Fig. 57. Every point in the X axis in the figure was calculated considering all the values within 10-degree elevation intervals, exactly as it was done for pdf calculation of the signal power. Apart from the mean and the median values, also the 10% and 90% percentiles are represented (red and green lines respectively).

FIGURE 57

$C/(N_0+I_0)$ per elevation angle (all captures)



It can be seen that for elevations lower than 60º there are just three points where the mean barely rises above 50 dB/Hz (30º, 40º and 50º). Meanwhile for elevations higher than 60º the values of $C/(N_0+I_0)$ should be taken with care as they were estimated from a small batch of data points.

8.4.7 Concluding remarks

VHF signal measurements were carried out based on 64 passes of NorSat-2 satellite. The measurement of signal and noise and interference during the test campaign indicates promising results in detecting the proposed waveform in Recommendation ITU-R M.2092-0 since for the majority of test results, the signal quality is above the detection threshold of the most robust waveform (that is 34.2 dBHz for waveform 1) for VDE-SAT downlink in Recommendation ITU-R M.2092-0.

The VHF downlink signal measurement from NorSat-2 in Vigo, Spain confirms the signal strength that allows for a reliable detection of VDE-SAT downlink by selecting proper waveforms from Recommendation ITU-R M.2092-0. The actual detectability of the signal depends on the level of environment noise and interference. The measurement results in Vigo provides a set of measurements for the signal strength as well as the noise plus interference at the test location.

References

[1] TM synchronization and channel coding summary of concept and rationale, Informational Report CCSDS 130.1-G-2 Green Book, November 2012, https://public.ccsds.org/Pubs/130x1g2.pdf.

[2] S. Dolinar, D. Divsalar, and E Pollara. "Code Performance as a Function of Block Size". JPL TDA Progress Report 42-133. 15 May 1998, https://ipnpr.jpl.nasa.gov/progress_report/42-133/133K.pdf.

Annex 1

Considerations for the pfd mask for the VHF data exchange – satellite downlink (Recommendation ITU-R M.2092-0, Annex 4)

A1.1 Introduction and purpose

The purpose of WRC-19 Agenda 1.9.2 is to investigate the compatibility of the satellite component of the VDES, as described in Recommendation ITU-R M.2092-0, with incumbent systems operating in the same and adjacent frequency bands. In this context, the pfd mask for the VDE-SAT downlink has recently been brought under review by WP5A and WP5B. This Annex provides a technical analysis of some possible approaches for pfd masks that may provide improved protection for incumbent systems.

A1.2 VHF data exchange system – satellite

VDE-SAT is envisioned to operate in the frequency bands 156.0125-157.4375 MHz and 160.6125-162.0375 MHz. The technical characteristics, based on previous ITU-R studies, effecting the satellite e.i.r.p. and the pfd coordination mask are further described below.

A1.3 Assumptions for operation of VHF data exchange system

The frequency plan for the entire VDES, both the terrestrial and the satellite components, is in the bands 156.0125-157.4375 MHz and 160.6125-162.0375 MHz stated in § A1.2 above. This facilitates a realistic implementation of the proposed system in co-existence with, and complementing, the current AIS. The following points regarding the frequency plan are highlighted:

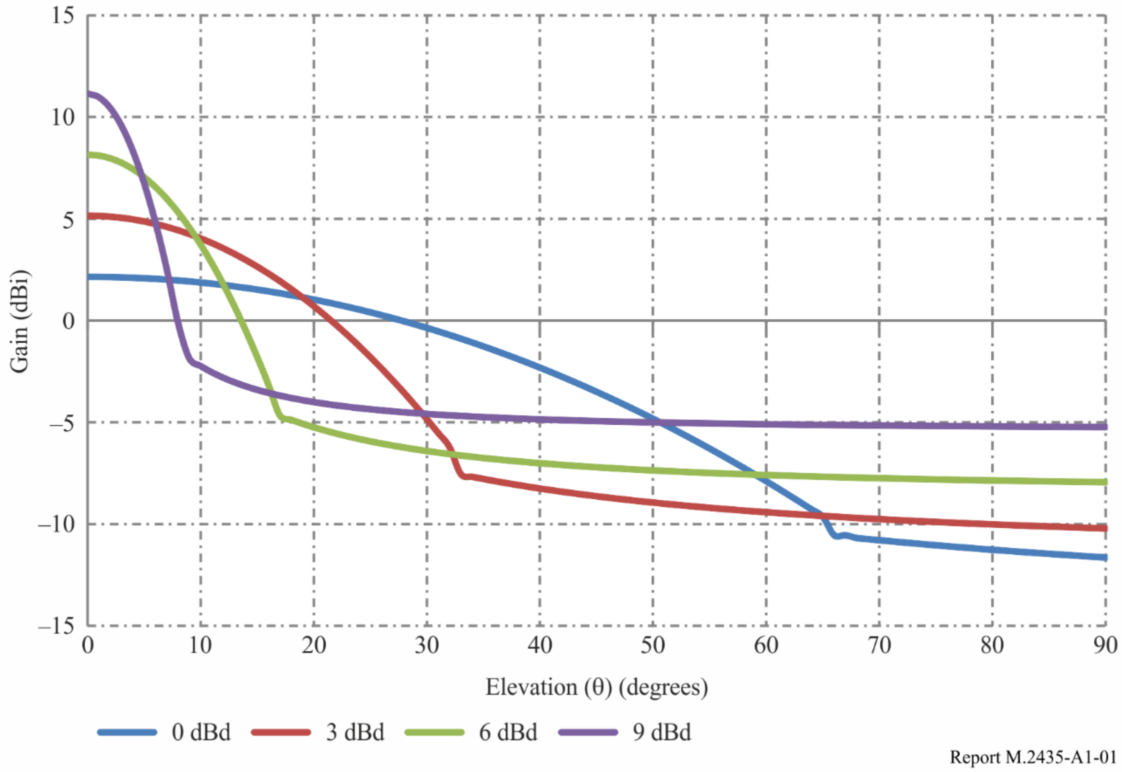
- The requirements for VDES concentrate the reception frequencies on board of the ship that is limited to the upper maritime VHF band (160.6125-162.0375 MHz). This provides an efficient implementation of VDES on-board receivers by narrowing the input filter bandwidth, reducing potential impairments due to other activities within the maritime VHF band;
- The VDE-SAT downlink shares the same frequency band (160.6125-162.0375 MHz) as the terrestrial VDE and AIS. This allows sharing the same antenna as well as the receiver front-end design;
- Satellite and shore reception frequencies of shipborne VDE signals occupy the lower band (156.0125-157.4375 MHz). This allows for a complementary service close to the shore and at the high sea while sharing the same spectrum. The frequency separation between the upper and lower spectra (with 4.6 MHz separation) provides an acceptable level of isolation between VDES receiving chain and the VDE ship-borne transmitters;
- The frequency separation between the uplink and downlink allows hosting VDE-SAT transmitter and receiver on the same satellite which allows for a more cost-effective satellite mission concepts (i.e. reduce number of satellites, improved efficiency and possible interactivity).

A1.4 Antenna options for VHF terrestrial stations

Commercially available antenna options for the terrestrial stations are characterized in Fig. A1-1 below. The mobile station antennas typically use the 0 dBd (2.15 dBi) option, and the base station antennas typically use the 6 dBd (8.15 dBi) option.

FIGURE A1-1

Antenna options for VHF terrestrial stations8



A1.5 Example VHF data exchange system satellite implementation

The following example VDE-SAT implementation fits the pfd angular mask and comports with the technical characteristics found in Recommendation ITU-R M.2092-0.

A1.5.1 Determine the VHF data exchange system satellite orbital characteristics

The following VDE-SAT implementation is considered. The satellite orbital characteristics that are needed to support this application are determined as follows.

A1.5.1.1 Determine the satellite's orbit

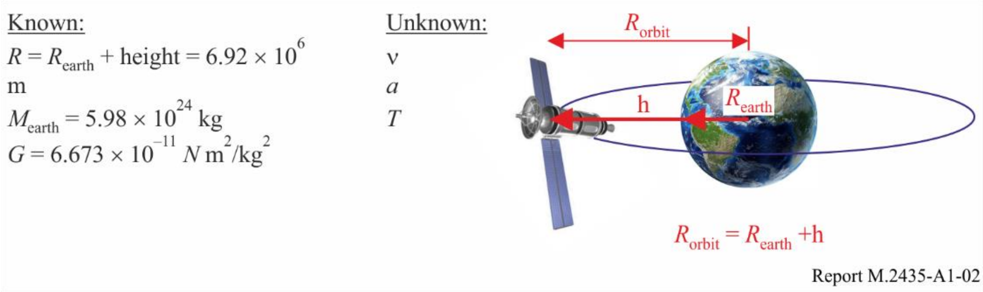
The example VDE-SAT employs a polar orbit at a height of 550 km above the surface of the Earth. The velocity, acceleration and orbital period of the satellite are determined, given: $M_{earth} = 5.98 \times 10^{24}$ kg, $R_{earth} = 6.37 \times 10^{6}$ m.

The satellite's orbit and the known and unknown parameters are shown in Fig. A1-2 below.

[8] Antenna patterns are derived from the mathematical formulas in Recommendation ITU-R F.1336.

FIGURE A1-2

Satellite orbital characteristics



The radius of a satellite's orbit can be determined from the Earth's radius and the height of the satellite above the Earth. As shown in Fig. A1-2, the radius of orbit for a satellite is equal to the sum of the Earth's radius and the height above the Earth. These two quantities are added to yield the orbital radius. The 550 km altitude is first converted to 0.550×10^6 m and then added to the radius of the Earth.

Determine the velocity of the satellite,

$$v = \text{SQRT}\ ((G \times M_{\text{central}}) / R)$$

$$v = \text{SQRT}\ ((6.673 \times 10^{-11}\ N\ \text{m}^2/\text{kg}^2) \times (5.98 \times 10^{24}\ \text{kg}) / (6.92 \times 10^6\ \text{m}))$$

$$v = 7.594 \times 10^3\ \text{m/s}.$$

Determine the acceleration of the satellite,

$$a = (G \times M_{\text{central}})/R^2$$

$$a = (6.673 \times 10^{-11}\ N\ \text{m}^2/\text{kg}^2) \times (5.98 \times 10^{24}\ \text{kg}) / (6.92 \times 10^6\ \text{m})^2$$

$$a = 8.333\ \text{m/s}^2.$$

Determine the orbital period of the satellite,

$$T = \text{SQRT}\ ((4 \times \pi^2 \times R^3) / (G \times M_{\text{central}}))$$

$$T = \text{SQRT}\ ((4 \times (3.1415)^2 \times (6.92 \times 10^6\ \text{m})^3) / (6.673 \times 10^{-11}\ N\ \text{m}^2/\text{kg}^2) \times (5.98 \times 10^{24}\ \text{kg}))$$

$$T = 5725.7\ \text{s} = 1.59\ \text{h}.$$

A1.5.1.2 Determine the Earth's rotation at the equator between each satellite orbit

The period of the Earth $\boldsymbol{T_e}$ is approximately 24 hours (86.4×10^3 s), the radius of the Earth $\boldsymbol{R_e}$ is 6.37×10^6 m and the circumference of the Earth (distance around the equator) is $C_{\text{earth}} = 2 \times (3.1415) \times (6.37 \times 10^6\ \text{m}) = 40.0239 \times 10^6$ m. Therefore, in each pass of the satellite, the Earth will have rotated at the equator by $ROT_{\text{equator}} = C_{\text{earth}} \times T / T_e = 40.0239 \times 10^6\ \text{m} \times 5725.7\ \text{s} / 86.4 \times 10^3\ \text{s} = 2.6524 \times 10^6$ m = 2652.4 km.

A1.5.1.3 Determine the slant distance to the Earth's horizon

The slant distance $\boldsymbol{D_s}$ from the satellite to the Earth's horizon is $\boldsymbol{D_s}$ = SQRT $(\boldsymbol{R^2} - \boldsymbol{R_e^2})$ = SQRT $((6.92 \times 10^6\ \text{m})^2 - (6.37 \times 10^6\ \text{m})^2) = 2.7036 \times 10^6$ m = 2 703.6 km.

A1.5.1.4 Determine the slant downward tilt angle to the Earth's horizon

The satellite's downward tilt angle to the Earth's horizon is:

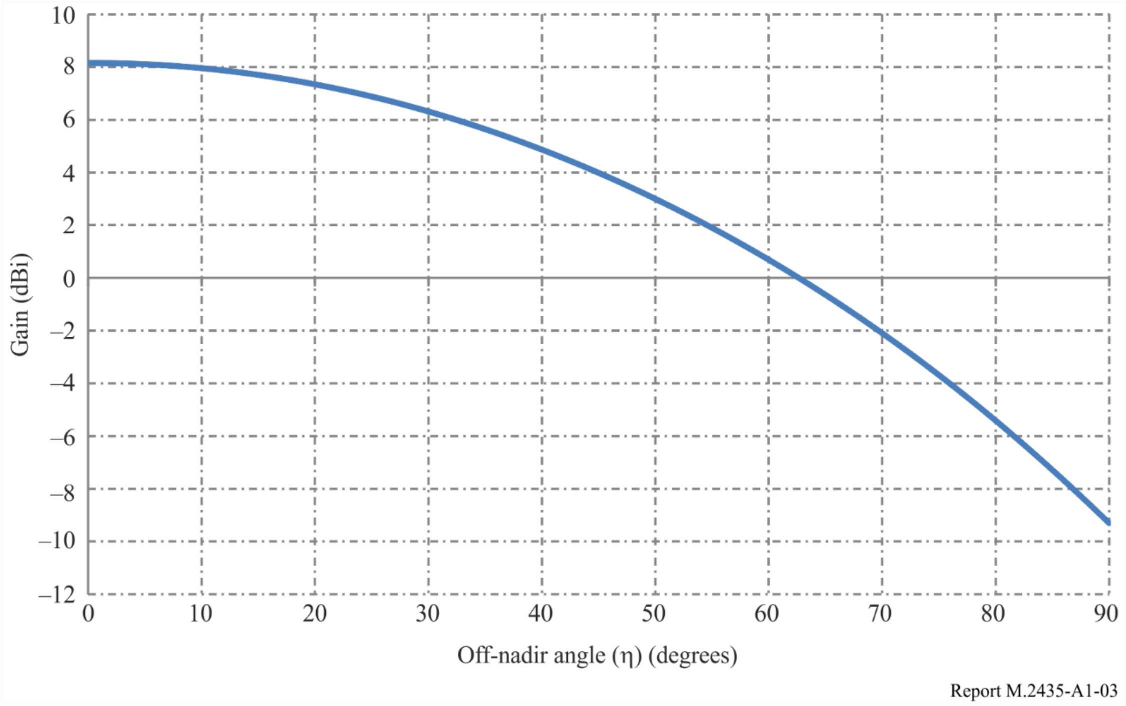
$\theta_d = 90° - \sin^{-1} (R_e / R) = 90° - \sin^{-1}(6.37 \times 10^6\ \text{m} / 6.92 \times 10^6\ \text{m}) = 90° - 67° = 23$ degrees.

A1.5.2 VHF data exchange – satellite antenna characteristics

A directional circularly polarized Yagi-Uda antenna with 8.15 dBi gain is used for communicating with ships' vertical antennas. The antenna characteristics are shown in Fig. A1-3.

FIGURE A1-3

Example VHF data exchange system satellite antenna characteristics



A1.5.3 Determine the width of the antenna coverage path

The example VDE-SAT antenna pattern was shown in Fig. A1-3. The beam width (±3 dB) of the antenna is 80 degrees. The width of the satellite antenna's coverage path is:

$$W_c = 2\,(D_s \cos(90° - \theta_a/2))$$

$$W_c = 2 \times 2.7036 \times 10^6 \text{ m} \times \cos(90° - 80° / 2) = 3.4757 \times 10^6 \text{ m} = 3\,475.6 \text{ km.}$$

Note: From § A1.5.1.2 that since ROT_{equator} = 2 652.4 km, this antenna beamwidth (θ_a = 80°) is sufficiently wide for contiguous earth coverage by one satellite every 24 hours. This circularly-polarized Yagi-Uda antenna is pointed in the forward direction with an optimized downward tilt angle to provide the vertical component of radiation for reception by ships' vertical dipole antennas.

A1.5.4 Determine the maximum Doppler frequency shift between the satellite and ships in the satellite's antenna coverage area

The maximum Doppler frequency shift (f_d) between the satellite and a ship will occur when the relative velocity between them is a maximum, i.e. when the ship is situated on the satellite's earth horizon. Note that the coverage for this satellite is only in the forward direction and that the satellite's antenna pattern will cover ships in the range of 23 degrees (earth's horizon) downward from the satellite's velocity vector. Therefore, the maximum Doppler shift is f_d (max) = f_{VDES} $(v/c) \times \cos\theta_d$ = $162 \times 10^6\,(7.594 \times 10^3)/(3 \times 10^8) \times \cos 23°$ = 3 775 Hz. The satellite transmitter frequency should be reduced by half of f_d (max) to provide a range of ±1 887.5 Hz in the coverage area.

A1.5.5 Determine the optimum downward tilt angle for the satellite VHF data exchange system antenna for coverage of ships in the forward direction

From the VDE-SAT satellite antenna characteristics in Fig. A1-3 above, note that the gain is flat to approximately 12°. This supports an additional downward tilt of 12 degrees below the horizon of 23 degrees for an optimized total downward tilt angle of 35 degrees below the line that is tangent to the satellite's orbital path. This provides a sufficient vertical radiation component for ships and extends the downward coverage area. It can be determined by analysis that the additional downtilt of the satellite antenna to 12 degrees below the horizon, whilst conforming to the required pfd mask, and without loss of performance at the 0-degree elevation angle, strengthens the actual pfd (Table A1-2) and the resulting *C/N* (Table A1-4) by 5.9 dB at the 60-degree elevation angle, compared to pointing the antenna directly at the horizon.

A1.5.6 Consideration of the pfd mask for VHF data exchange – satellite transmission

The signal level generated by the satellite should be kept below the pfd mask limit (referred to the Earth's surface) specified in Table 63 (Note that this was previously studied at the ITU-R and that the pfd level refers to the vertical component of radiation normal to the Earth's surface).

The pfd angular mask (the maximum allowable pfd in dB(W/(m^2 × 4 kHz)) as a function of the elevation angle from the Earth), is shown in Table 1. Note that the pfd mask at 0 degree (horizon) is −149 dB(W/(m^2 × 4 kHz)), at 45-degree elevation is −142 dB(W/(m^2 × 4 kHz)), at 60-degree elevation is −134 dB(W/(m^2 × 4 kHz)) and at 90 degrees (overhead) is −131 dB(W/(m^2 × 4 kHz)).

Note also that since the pfd mask level refers to the vertical component of radiation normal to the Earth's surface, the polarization loss (≈ 3 dB @ 45° elevation angle) based on the angular relationship between the vertical axis of the satellite antenna and the Earth's surface should be considered in the determination of the VDE-SAT satellite transmitter power.

TABLE A1-1

Pfd mask

$$\boldsymbol{\theta^\circ = earth - satellite\ elevation\ angle}$$

$$pfd(\Theta^\circ)_{\ (\mathrm{dB(W/m^2*4\ kHz)})} = \begin{cases} -149 + 0.16 * \Theta^\circ & 0^\circ \le \Theta < 45^\circ; \\ -142 + 0.53 * (\Theta^\circ - 45^\circ) & 45^\circ \le \Theta < 60^\circ; \\ -134 + 0.1 * (\Theta^\circ - 60^\circ) & 60^\circ \le \Theta \le 90^\circ. \end{cases}$$

This pfd mask is to ensure that there is no harmful interference caused by the satellite downlink on non-maritime terrestrial services sharing the same frequency (ensuring in-band carrier-to-interference requirements of terrestrial service receivers).

A1.5.6.1 Determine the pfd levels at elevations of 0°, 10°, 30°, 60° and 90° when the pfd level at 45° elevation is set to −142 dB(W/(m^2 × 4 kHz))

This section confirms that the elevation angle of 45 degrees is the closest point of approach between the pfd mask and the actual radiated VDE-SAT space-earth downlink signal.

Calculations of the slant ranges and elevation angles note from the previous calculations that the slant range from the satellite earth horizon is 2 703.6 km. The results of these calculations are shown in Table A1-2 below. Note that the "orbital angle" (the angle of rotation of the satellite's orbit above the Earth) is used as a reference for geometric calculations (angles and distances) and for time-keeping (elapsed time from the horizon to the point of rotation).

The slant ranges from the satellite to an earth station are determined from the law of cosines (c = SQRT ($a^2 + b^2 + c^2 - 2ab$ cos (C)), where c = slant range, $a = R_e + h$, $b = R_e$ and C = the satellite orbital angle. The calculations start with $C = 23°$ (the angle to the horizon) and proceed to $C = 0°$ (the directly above/below position), shown in Table A1-2 below.

To find the elevation angles, reference angles are determined from the inverse law of cosines ($C = \cos^{1}((a^2 + b^2 + c^2)/(2ab))$ where C = the reference angle between the slant range (line of observation) and the Earth radius (line from the Earth station to the centre of the Earth), a = slant range, b = earth radius and $c = R_e + h$. The elevation angles for the Earth stations are determined by subtracting 90° from the reference angles, also shown in Table A1-2 below.

A1.5.6.2 Determine reference levels based on the 45-degree elevation angle

From Table A1-2, the slant range to the satellite at 45-degree elevation is 748.3 km and the pfd at 45-degree elevation is set to the mask limit of −142 dB(W/(m^2 × 4 kHz)). Since the relative angle of the satellite antenna (down-tilted by 35°) in that direction is approximately (45° − 35°) = 10°, the gain of the satellite antenna in that direction, from Fig. A1-3, is 8 dB. These values were used as the set point values (the 0 dB reference levels) to calculate the pfd levels for the other elevation angles.

A1.5.6.3 Determine the pfd level for the elevation angle of 0 degrees

The slant range at 0 degrees (horizon) is 2 703.6 km, the satellite relative angle to the horizon is −23°, the satellite antenna relative angle with a 35° down-tilt is (35° − 23°) = 12° and the gain, from Fig. A1-3, is 8 dB. Since the relative range loss is (20 log (748.3/2 703.6)) = −11.2 dB, the pfd at 0° is 11.2 dB below the 45° level (−142 − 11.2) = **−153.2 dB(W/(m^2 × 4 kHz))** which is (−149 − (−153.2)) = 4.2 dB below the 0° mask limit.

A1.5.6.4 Determine the pfd level for the elevation angle of 10 degrees

The slant range at 10-degree elevation is 1 818.4 km, the satellite relative angle to the horizon is −23°, the satellite antenna relative angle with a 35° down-tilt is (35° − 23°− 10°) = 2° the gain, from Fig. A1-3, is 8 dB (the same as the reference), the relative range loss is 20 log (748.3/1 818.4) = −7.7 dB and thus the pfd at 10° is (−142 − 7.7) = **−149.7 dB(W/(m^2 × 4 kHz))** which is 2.3 dB below the 10° mask limit of −147.4 dB(W/(m^2 × 4 kHz)).

A1.5.6.5 Determine the pfd level for the elevation angle of 30 degrees

The slant range at 30-degree elevation is 993.5 km, the satellite relative angle to the horizon is −23°, the satellite antenna relative angle with a 35° down-tilt is (35° − 30°) = 5° the gain, from Fig. A1-3, is 8 dB (the same as the reference), the relative range loss is 20 log (748.3/993.5) = −2.5 dB and thus the pfd at 30° is (−142 – 2.5) = **−144.5 dB(W/(m^2 × 4 kHz))** which is 0.3 dB below the 30° mask limit of −144.2 dB(W/(m^2 × 4 kHz)).

A1.5.6.6 Determine the pfd level for the elevation angle of 60 degrees

The slant range at 60-degree elevation is 632.7 km, the satellite relative angle to the horizon is −23°, the satellite antenna relative angle with a 35° down-tilt is (35° − 60°) = −18° the gain, from Fig. A1-3, is 7.5 dB (0.5 dB below the reference), the relative range is 20 log (748.3/632.7) = +1.5 dB (1.5 dB above the reference) and thus the pfd at 60° is (−142 − 0.5 + 1.5) = **−141.0 dB(W/(m^2 × 4 kHz))** which is 7.0 dB below the 60° mask limit of −134.0 dB(W/(m^2 × 4 kHz)).

A1.5.6.7 Determine the pfd level for the elevation angle of 90 degrees

The slant range at 90 degrees (overhead) is the satellite altitude of 550 km, the gain of the satellite antenna in that direction, from Fig. A1-3, with a down-tilt of 35 degrees is the gain at (35° − 90°) = −55 degrees is 2 dB (6 dB below the reference), the relative range factor is 20 log (748.3/550) = +2.7 dB (2.7 dB above the reference) and thus the pfd at 90 degrees is (−142 − 6 + 2.7) =

−145.3 dB(W/(m^2 × 4 kHz)) which is 14.3 dB below the 90-degree mask limit of −131 dB(W/(m^2 × 4 Hz)).

The pfd values for elevation angles from 0° to 90° are shown in Table A1-2 below.

TABLE A1-2

pfd for various elevation angles

Orbital angle (degrees)	**Elapsed time from horizon** (seconds)	**Slant range** (km)	**Reference angle** (degrees)	**Elevation angle** (degrees)	**pfd actual/mask/margin** (dB(W/(m^2 × 4 kHz)))
23	0	2 703.6	90	0	−153.2/−149/4.2
22	15.9	2 592.7	90.5	0.5	−152.8/−148.9/3.9
21	31.8	2 481.6	91.0	1.0	−152.4/−148.8/3.6
20	47.7	2 370.5	93.2	3.2	−152/−148.5/3.5
19	63.6	2 259.6	94.4	4.4	−151.6/−148.3/3.3
18	79.5	2 148.8	95.6	5.6	−151.2/−148.1/3.1
17	95.4	2 038.3	97.0	7.0	−150.7/−147.9/2.8
16	111.3	1 928.1	98.4	8.4	−150.2/−147.7/2.5
15	127.2	1 818.4	100.0	10.0	−149.7/−147.4/2.3
14	143.1	1 709.2	101.6	11.6	−149.2/−147.1/2.1
13	159.0	1 600.6	103.5	13.5	−148.6/−146.8/1.8
12	175.0	1 493.0	105.5	15.5	−148/−146.5/1.5
11	190.9	1 386.5	107.8	17.8	−147.4/−146.1/1.3
10	206.8	1 281.4	110.3	20.3	−146.7/−145.8/0.9
9	222.7	1 178.1	113.2	23.2	−145.9/−145.3/0.6
8	238.6	1 077.3	116.6	26.6	−145.2/−144.7/0.5
7.145	252.2	993.5	120.0	30.0	−144.5/−144.2/0.3
7	254.5	979.6	120.6	30.6	−144.3/−144.1/0.2
6	270.4	886.3	125.3	35.3	−143.5/143.35/0.15
5	286.3	798.7	131.0	41.0	−142.5/−142.4/0.1
4.38	296.1	748.3	135.0	45.0	−142/−142/0 *(ref : pfd mask limit)*
4	302.2	719.2	137.8	47.8	−141.7/−140.5/1.2
3	318.1	650.6	146.2	56.2	−141.5/−136.1/5.4
2.7	322.9	632.7	150.0	60.0	−141/−134/7
2	334.0	596.8	156.1	66.1	−141.8/−133.4/8.4
1	349.9	562.1	167.6	77.6	−143.1/−132.2/10.9
0	365.8	550.0	180	90	−145.3/−131/14.3

Notes to Table A1-2:

1. When the pfd level is set to the mask limit of −142 dB (W/(m^2 × 4 kHz)) at 45° elevation angle, the PFD levels at all other elevation angles are below the mask.
2. The maximum pfd level is −141 dB (W/(m^2 × 4 kHz)) at 60° elevation angle, which is 7 dB below the mask limit level of −134 dB(W/(m^2 × 4 kHz)).

A1.5.6.8 Consider the shipborne VHF data exchange system antenna and receiver characteristics

The shipborne antenna and receiver characteristics are considered, along with the satellite radiated pfd levels, to determine the performance of the example VDE-SAT downlink.

A1.5.6.8.1 Consider the shipborne VHF data exchange system antenna characteristics

The available shipborne antenna options are comprised of stacked vertical dipole elements of various lengths and gain values, were previously shown in Fig. A1-1. This analysis considers the 0 dBd antenna because it has the best performance for the elevation angles required for satellite detection. Note that this antenna has the same characteristics as the terrestrial antenna noted in § A1-6.

A1.5.6.8.2 Consider the shipborne VHF data exchange system receiver characteristics

The shipborne VDES receiver characteristics and the coordination levels for the terrestrial service are considered, and the set of metrics in Table A1-3 below are used to determine a reference value of *C*/*N* (carrier-to-noise ratio) for the example shipborne VDES receiver.

TABLE A1-3

Metrics for considering coordination levels and calculating *C*/*N* in a shipborne VHF data exchange system receiver

Power received (referred to the Rx antenna) by a shipborne VDES receiver (reference 25 kHz channel):
P_r (Watts) = Power received (linear formula): $P_r = GE^2c^2/480\pi^2f^2$, where
G = gain of a half-wavelength (λ/2) dipole antenna = 1.64
E = field strength = 4×10^{-6} V/m (4μV/m = +12 dBμV) = coordination threshold for land mobile service
c = speed of light in free space = 3×10^8 m/s
f = VDES downlink frequency = 161.9×10^6 (161.9 MHz)
λ = 1.852 m (at 161.9 MHz)
P_r = 19.02×10^{-15} W = −137.2 dBW = −107.2 dBm (−137.2 dBW)
pfd[9] = dB(E) −153.72 = 12−153.72 = −141.72 dB(W/(m^2 *4 kHz)) from a vertically-polarized source
A_e = effective area for a dipole antenna (0 dBd = 2 dBi) = $0.13\lambda^2$ = 0.446 m^2
P_r (25 kHz channel) = pfd + 10 log A_e + 10 log (25/4) = −141.7 − 3.5 +8 = −137.2 dBW = −107.2 dBm
Power received by a shipborne VDES receiver (reference 50 kHz bandwidth):
Noise floor in a 50 kHz bandwidth: kTB = 10 log ((1.38×10^{-23}) (290) (50×10^3))= −157 dBW
Rx carrier power (reference) in a 50 kHz bandwidth: C = 10 log ((19.02×10^{-15}) (50/25))= −134.2 dBW
Applying adjustments for cable loss (2 dB) and Rx noise figure (4 dB), the *C*/*N* calculation follows:
C/*N* (50 kHz bandwidth): C/N_{ref} = (−134.2 − 2) − (−157 + 4) = 16.8 dB (Rx 0 dBd (2.1 dBi) antenna, 0° elevation)

[9] The conversion from dB (μV/m) (25 kHz reference bandwidth) to dB(W/(m^2 × 4 kHz)) can be computed with the following formula:

$$dB(W/(m^2 \cdot 4kHz)) = dB\left(\frac{\mu V}{m}\right) - 10 \cdot \log_{10}(120 \cdot \pi \cdot 10^{12}) - 10 \cdot \log_{10}(25kHz/4kHz) = dB\left(\frac{\mu V}{m}\right) - 153.72$$

A1.5.6.8.3 Determine the values of carrier to noise vs. elevation angle for the shipborne VHF data exchange system receiver

Based on the C/N reference level (C/N_{ref}) from Table A1-3, determine the C/N for the pfd values and elevation angles in Table A1-2, taking into account the shipborne antenna angular gain values for the 0 dBd antenna in Fig. A1-1. For this antenna, G_a = 2.1 dBi at 0° elevation angle.

$C/N = C/N_{ref} - (-142 - \text{pfd} - (G_a - 2.1))$, where G_a = shipborne antenna gain at the elevation angle.

– At 0° elevation, $C/N = 16.8 - (-142 - (-153.2) - (2.1 - 2.1)) = 5.6$ dB
– At 10° elevation, $C/N = 16.8 - (-142 - (-149.7) - (1.9 - 2.1)) = 8.9$ dB
– At 30° elevation, $C/N = 16.8 - (-142 - (-144.5) - (-0.3 - 2.1)) = 11.9$ dB
– At 45° elevation, $C/N = 16.8 - (-142 - (-142) - (-3.5 - 2.1)) = 11.2$ dB
– At 60° elevation, $C/N = 16.8 - (-142 - (-141) - (-7.6 - 2.1)) = 8.1$ dB
– At 90° elevation, $C/N = 16.8 - (-142 - (-145.3) - (-11.6 - 2.1)) = -0.2$ dB

The C/N values for elevation angles from 0° to 90° are shown in Table A1-4 below.

TABLE A1-4

Carrier to noise and pfd for various elevation angles

Orbital angle (degrees)	**Elapsed time from horizon** (seconds)	**Slant range** (km)	**Elevation angle** (degrees=	**Pfd actual/mask/margin** (dB(W/(m^2 × 4 kHz)))	***C/N* ship receiver** (dB)
23	0	2 703.6	0	−153.2/−149/4.2	5.6
22	15.9	2 592.7	0.5	−152.8/−148.9/3.9	6
21	31.8	2 481.6	1.0	−152.4/−148.8/3.6	6.4
20	47.7	2 370.5	3.2	−152/−148.5/3.5	6.8
19	63.6	2 259.6	4.4	−151.6/−148.3/3.3	7.2
18	79.5	2 148.8	5.6	−151.2/−148.1/3.1	7.6
17	95.4	2 038.3	7.0	−150.7/−147.9/2.8	8
16	111.3	1 928.1	8.4	−150.2/−147.7/2.5	8.5
15	127.2	1 818.4	10.0	−149.7/−147.4/2.3	8.9
14	143.1	1 709.2	11.6	−149.2/−147.1/2.1	9.4
13	159.0	1 600.6	13.5	−148.6/−146.8/1.8	9.7
12	175.0	1 493.0	15.5	−148/−146.5/1.5	10.2
11	190.9	1 386.5	17.8	−147.4/−146.1/1.3	10.8
10	206.8	1 281.4	20.3	−146.7/−145.8/0.9	10.9
9	222.7	1 178.1	23.2	−145.9/−145.3/0.6	11.5
8	238.6	1 077.3	26.6	−145.2/−144.7/0.5	11.8
7.145	252.2	993.5	30.0	−144.5/−144.2/0.3	11.9
7	254.5	979.6	30.6	−144.3/−144.1/0.2	11.9
6	270.4	886.3	35.3	−143.5/143.35/0.15	11.9

TABLE A1-4 (*end*)

Orbital angle (degrees)	**Elapsed time from horizon** (seconds)	**Slant range** (km)	**Elevation angle** (degrees=	**Pfd actual/mask/margin** (dB(W/(m^2 × 4 kHz)))	***C/N* ship receiver** (dB)
5	286.3	798.7	41.0	−142.5/−142.4/0.1	11.7
4.38	296.1	748.3	45.0	−142/−142/0 *(ref : pfd mask limit)*	11.2
4	302.2	719.2	47.8	−141.7/−140.5/1.2	11.0
3	318.1	650.6	56.2	−141.5/−136.1/5.4	8.6
2.7	322.9	632.7	60.0	−141/−134/7	8.1
2	334.0	596.8	66.1	−141.8/−133.4/8.4	4.4
1	349.9	562.1	77.6	−143.1/−132.2/10.9	2.4
0	365.8	550.0	90	−145.3/−131/14.3	−0.2

A1.5.6.8.4 Determine the data rate for elevation angles 0 degrees to 60 degrees using the digital video broadcast by satellite standards

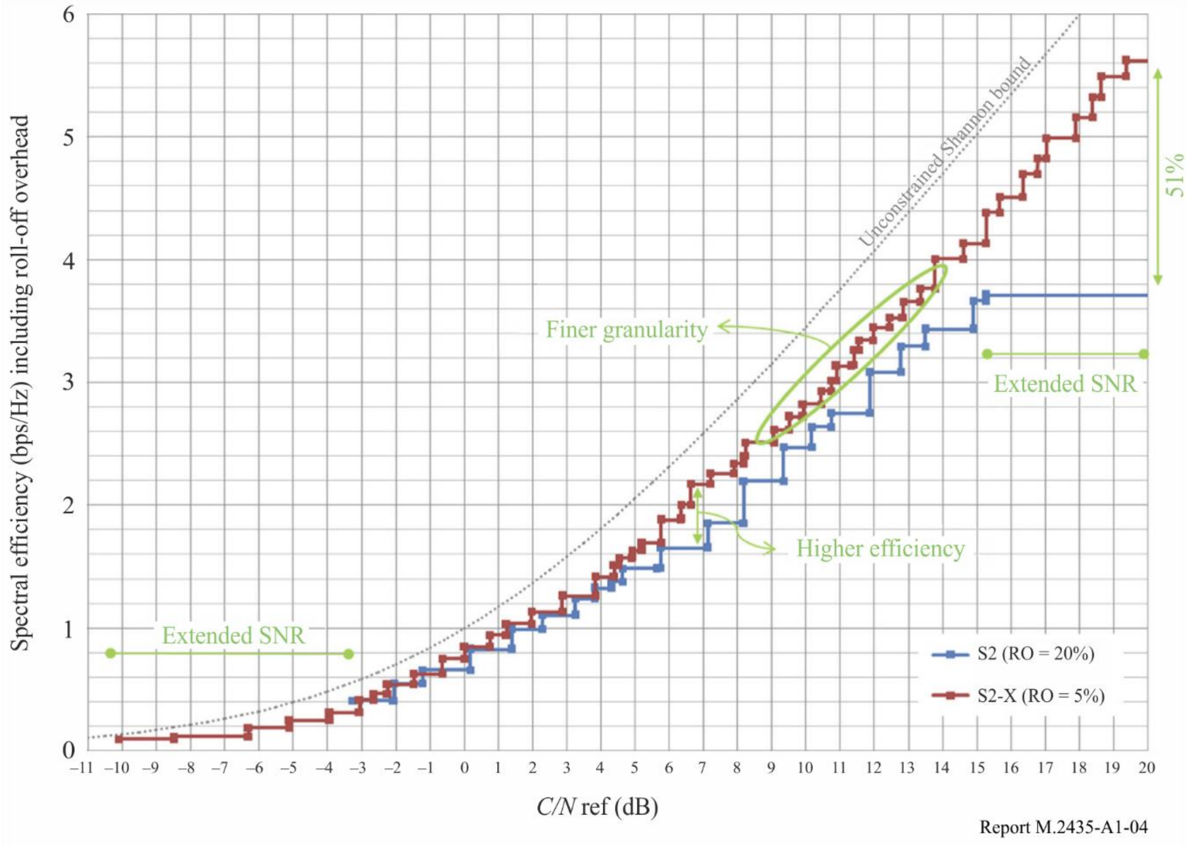
The digital video broadcast standards, by satellite (DVB-S), are designed to provide the maximum utilization of the available bandwidth in a low-to-moderate *C*/*N* ratio. The spectral efficiencies for DVB-S2X and DVB-S2 are shown in Fig. A1-4 below.

DVB-S2X is based on the well-established DVB-S2 specification. It uses the proven and powerful LDPC FEC scheme in combination with BCH FEC as outer code and introduces the following additional elements:

– Smaller roll-off options of 5% and 10% (plus 20%, 25% and 35% in DVB-S2);
– A finer gradation and extension of number of modulation and coding modes;
– New constellation options for linear and non-linear channels;
– Additional scrambling options for critical co-channel interference situations;
– Channel bonding of up to three channels;
– Very Low SNR operation support down to −10 dB SNR; and
– Super-frame option.

FIGURE A1-4

Performance of DVB-S2X and DVB-S2



A1.5.6.8.5 VHF data exchange – satellite downlink performance Results

From Fig. A1-4 above, it is concluded that the DVB-S2X standard transmission applied to the VDE-SAT downlink provides spectral efficiency of 1.6 bps/Hz for $C/N \geq 5$ dB, which, from Table A1-4, includes elevation angles from 0° to 60°.

A1.6 Consideration of a pfd mask based on available land mobile service characteristics

Recommendation ITU-R M.1808 provides the characteristics of mobile systems and the useful information is reproduced in Tables A1-5 and A1-6.

TABLE A1-5

Base station characteristics for frequency sharing below 869 MHz

Frequency band (MHz)	**138 to 174**	
Type of emission	Analogue	Digital
Receiver		
Noise figure (dB)	6 to 12 (7)	6 to 12 (7)
IF filter bandwidth (kHz)	8/11/12.5/16	5.5/5.5/5.5/5.5
Antenna gain (dBd)	0 to 9 (6)	0 to 9 (8)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0 to 6 (3)	0 to 6 (3)

TABLE A1-6

Mobile station characteristics for frequency sharing below 869 MHz

Frequency band (MHz)	**138 to 174**	
Type of emission	Analogue	Digital
Receiver		
Noise figure (dB)	6 to 12 (7)	6 to 12 (7)
IF filter bandwidth (kHz)	8/11/12.5/16	5.5/5.5/5.5/5.5
Antenna gain (dBd)	−10 to 4 (H: −10, V: 0)	−10 to 4 (H: −10, V: 0)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0 to 1 (H: 0, V: 1)	0 to 1 (H: 0, V: 1)

For the mobile and base stations an average side-lobe pattern is considered in our study according to the Recommendation ITU-R F.1336 for omnidirectional radiation patterns as presented in equation (A1-1) below.

$$G(\theta) = \begin{cases} G_0 - 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ G_0 - 15 + 10\log_{10}(k+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ G_0 - 15 + 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + k\right) & \text{for } \theta_5 < |\theta| < 90^\circ \end{cases} \tag{A1-1}$$

with:

$$\theta_5 = \theta_3\sqrt{1.25 - \frac{1}{1.2}\log_{10}(k+1)} \tag{A1-2}$$

where:

$G(\theta)$: gain relative to an isotropic antenna (dBi)

G_0: the maximum gain in the azimuth plane (dBi) knowing that G_0 in dBi equals G_0 in dBd + 2.15

θ: elevation angle relative to the angle of the maximum gain (degrees) $(-90^{\circ} \leq \theta \leq 90^{\circ})$

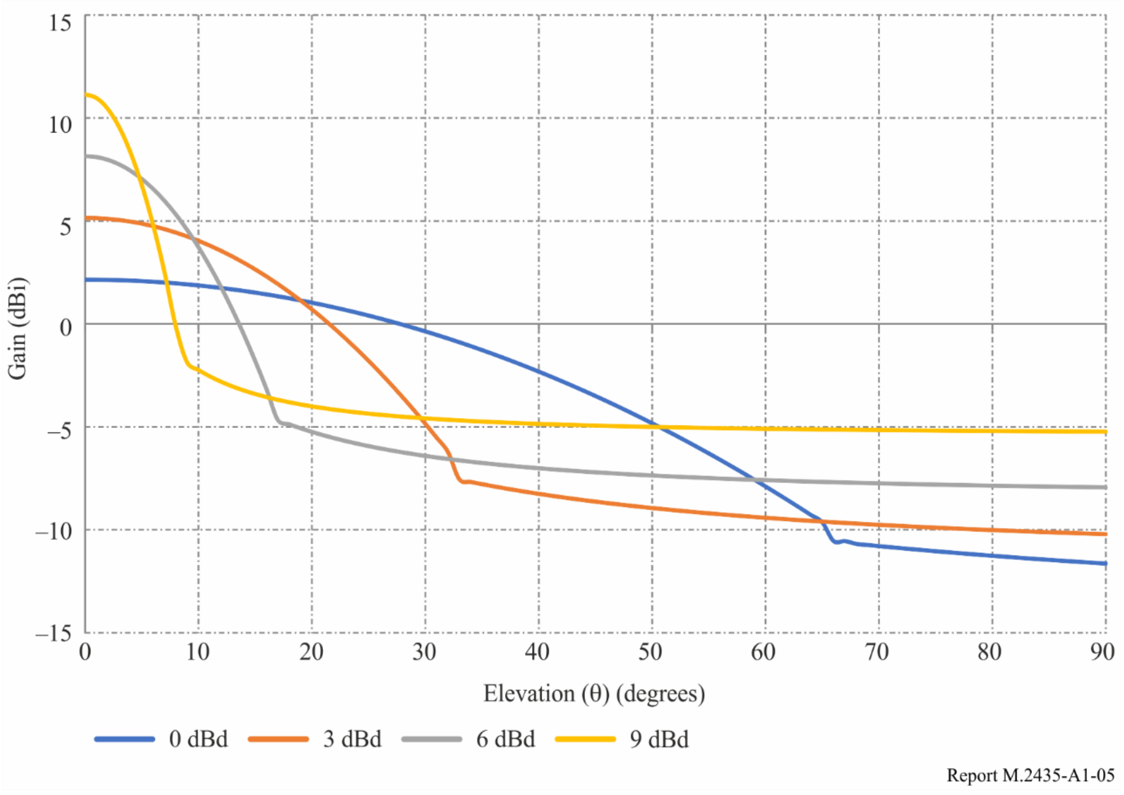
θ_3: the 3 dB beamwidth in the elevation plane (degrees) $\theta_3 = 107.6 \times 10^{-0.1\,G_0}$

k: parameter which accounts for increased side-lobe levels above what would be expected for an antenna with improved side-lobe performance (for antennas operating in the 1-3 GHz range, the parameter k should be 0.7).

Figure A1-5 represents the resulting mobile/base station antenna patterns with antenna gain from 0 dBd to 9 dBd.

FIGURE A1-5

Mobile/base station antenna patterns



The indicative coordination thresholds for narrowband (up to 25 kHz) applications (co-channel, 50% locations, 10% time, 10 m receiving antenna height, at the border-line) are:

0 dB(μV/m) for frequencies between 29.7 and 47 MHz;

6 dB(μV/m) for frequencies between 47 and 108 MHz;

12 dB(μV/m) for frequencies between 108 and 380 MHz;

18 dB(μV/m) for frequencies between 380 and 400 MHz;

20 dB(μV/m) for frequencies between 400 and 606 MHz;

26 dB(μV/m) for frequencies between 606 and 921 MHz.

Thus, the appropriate coordination threshold would be 12 dB(μV/m). The maximum power spectral density PSD_{Rx_MAX} at the antenna output that would be produced by a vertically polarized signal with a power spectral and flux-density of 12 dBμV/m in 25 kHz, corresponds to -141.72 dB(W/(m2 * 4 kHz))[10]. Such maximum value will occur for signals coming at 0 degrees of elevation ($\theta = 0$) as this is the point where the mobile station has maximum gain (G_0).

Using the Friis formula in its simplest form:

$$PSD_{Rx} = PSD_{Tx} G_{Tx} \left(\frac{\lambda}{4\pi d}\right)^2 G_{Rx} \tag{A1-3}$$

where PSD_{Rx} is the received power spectral density (PSD), PSD_{Tx} is the transmitted power spectral density, G_{Tx} is the gain of the transmitting antenna in the direction of the receiver, λ is the wavelength, d is the distance between transmitter and receiver and G_{Rx} is the gain of the receiving antenna in the direction of the transmitter.

The power spectral and flux-density is given by:

$$PSFD = \frac{PSD_{Tx} G_{Tx}}{4\pi d^2} \tag{A1-4}$$

therefore (A1-3) can be rewritten accordingly:

$$PSD_{Rx} = PSFD \frac{\lambda^2}{4\pi} G_{Rx} \tag{A1-5}$$

The maximum power spectral and flux-density that would produce the maximum allowed power spectral density PSD_{Rx_MAX} is then:

$$PSD_{Rx\_MAX} = PSFD_{Ref} \frac{\lambda^2}{4\pi} G_0 \tag{A1-6}$$

where $PSFD_{Ref}$ is -141.72 dB(W/(m2 * 4 kHz)).

From (A1-5) it is possible to express the power spectral and flux-density as a function of the received power spectral density:

$$PSFD = PSD_{Rx} \frac{4\pi}{\lambda^2} \frac{1}{G_{Rx}} \tag{A1-7}$$

Given that PSD_{Rx_MAX} is constant and that $G_{Rx} = G(\theta)$ as defined in (A1-1) is a function of the elevation angle θ, then by substituting (A1-6) in (A1-7) the maximum power spectral and flux-density is also a function of the elevation angle:

$$PSFD_{MAX}(\theta) = \frac{PSFD_{Ref}}{G'(\theta)} \tag{A1-8}$$

where:

$$G'(\theta) = \frac{G(\theta)}{G_0} \tag{A1-9}$$

It should be noted that with this approach, the electric field strength thresholds are achieved for 100% of the time and 100% locations, which is a conservative interpretation of the threshold values depicted in the equations above.

[10] The conversion from dB (μV/m) (25 kHz reference bandwidth) to dB(W/(m2 * 4 kHz)) can be computed with the following formula:

$$dB(W/(m^2 \cdot 4kHz)) = dB\left(\frac{\mu V}{m}\right) - 10 \cdot \log_{10}(120 \cdot \pi \cdot 10^{12}) - 10 \cdot \log_{10}(25kHz/4kHz) = dB\left(\frac{\mu V}{m}\right) - 153.72$$

When applying equation (A1-1) to the $PSFD_{MAX}$, the result is elevation dependent. Assuming the typical antenna gain given in Table A1-5 for the base station of 6 dBd (8.15 dBi) the $PSFD_{MAX,BS}$ in $(\mathrm{dBW}/(\mathrm{m}^2 * 4\ \mathrm{kHz}))$ will be:

$$PSFD_{MAX,BS}(\theta) = \begin{cases} -142.72 - 8.15 + 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ -142.72 + 6.85 - 10\log_{10}(k+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ -142.72 + 6.85 - 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + k\right) & \text{for } \theta_5 < |\theta| < 90^{\circ} \end{cases} \quad \text{(A1-10)}$$

with θ the elevation angle, $\theta_3 = 16.47°$, $\theta_5 = 16.95°$ and $k = 0.7$.

Assuming the typical antenna gain given in Table A1-2 for the mobile station of 0 dBd (2.15 dBi) the $PSFD_{MAX,MS}$ in $(\mathrm{dBW}/(\mathrm{m}^2 * 4\ \mathrm{kHz}))$ will be:

$$PSFD_{MAX,MS}(\theta) = \begin{cases} -142.72 - 2.15 + 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ -142.72 + 12.85 - 10\log_{10}(k+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ -142.72 + 12.85 - 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + k\right) & \text{for } \theta_5 < |\theta| < 90^{\circ} \end{cases} \quad \text{(A1-11)}$$

with θ the elevation angle, $\theta_3 = 65.59°$, $\theta_5 = 67.46°$ and $k = 0.7$.

Table A1-7 presents the $PSFD_{MAX,BS}$ and $PSFD_{MAX,MS}$ for elevation angles from 0° to 90° in 10° increments, together with the pfd mask specified in Recommendation ITU-R M.2092-0.

TABLE A1-7

$PSFD_{MAX,BS}$ and $PSFD_{MAX,MS}$ for elevation angles from 0° to 90° in 10° increments, together with the pfd mask specified in Rec. ITU-R M.2092-0

Receiver station elevation angle θ (degrees)	**$PSFD_{MAX,BS}$** (dBW/m²*4 kHz)	**$PSFD_{MAX,MS}$** (dBW/m²*4 kHz)	**pfd mask specified by Rec. ITU-R M.2092-0** (dBW/m²*4 kHz)	**Margin between pfd mask and $PSFD_{MAX,BS}$** (dB)	**Margin between pfd mask and $PSFD_{MAX,MS}$** (dB)
0	−150.9	–144.9	–149.0	−1.9	4.1
10	−146.4	–144.6	–147.4	1.0	2.8
20	−137.5	–143.8	–145.8	8.3	2.0
30	−136.3	–142.4	–144.2	7.9	1.8
40	−135.7	–140.4	–142.6	6.9	2.2
50	−135.4	–137.9	–139.4	4.0	1.5
60	−135.1	–134.8	–134.0	−1.1	–0.8
70	−135.0	–131.9	–133.0	−2.0	1.1
80	−134.9	–131.5	–132.0	−2.9	0.5
90	−134.8	–131.1	–131.0	−3.8	–0.1

The information provided in Table A1-7 shows that the margin between the pfd mask specified in Recommendation ITU-R M.2092-0 with respect to $PSFD_{MAX,BS}$ and $PSFD_{MAX,MS}$ is negative for some of the receiver station elevation angles. Thus, the pfd mask specified in Recommendation ITU-R M.2092-0 exceeds the coordination threshold of 12 dB (μV/m) at very low elevation angles and very high elevation angles. Minor changes to the pfd mask specified in Recommendation ITU-R M.2092-0 are appropriate to ensure the protection of the land mobile service. An updated mask that would provide protection of the land mobile service is presented in Table A1-8.

TABLE A1-8

Power spectral and pfd mask to ensure protection of the land mobile service

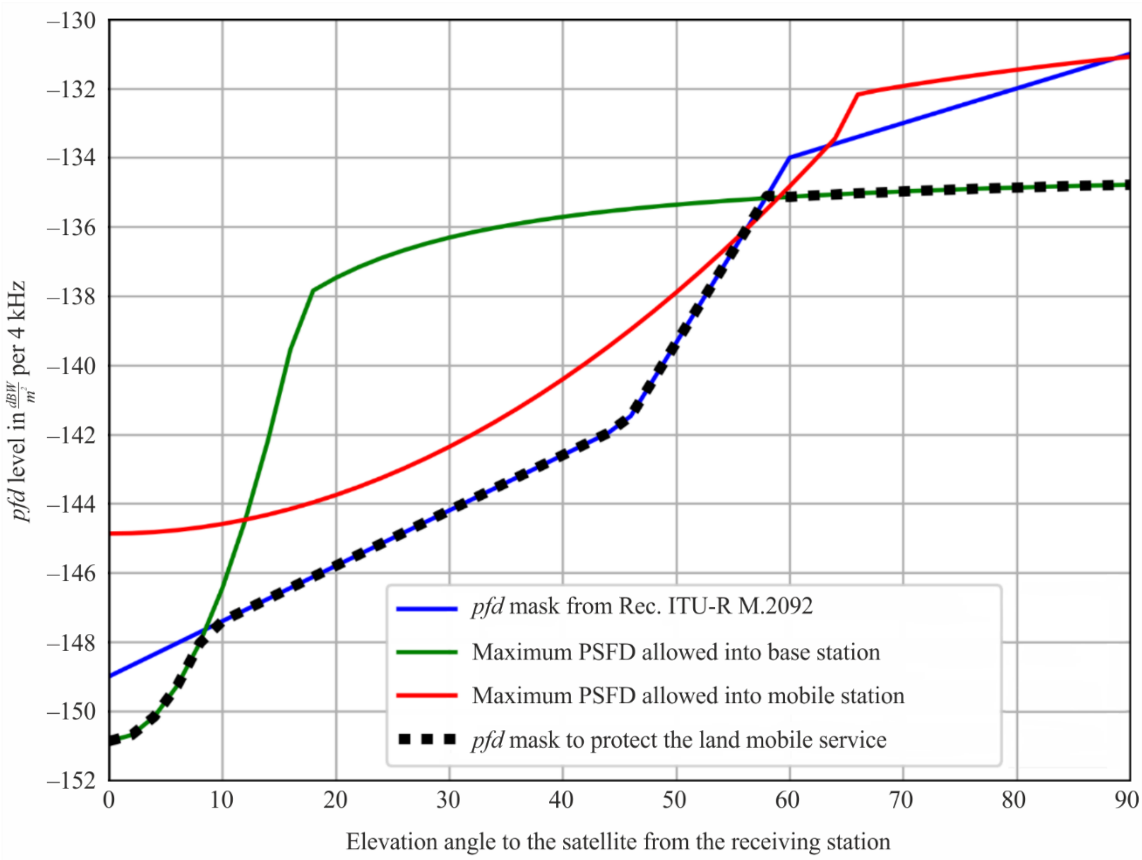
$$\boldsymbol{\theta° = earth - satellite\ elevation\ angle}$$

$$pfd(\Theta°)_{\,(\mathrm{dB(W/m^2*4\ kHz)})} = \begin{cases} -142.72 - 8.15 + 12\left(\frac{\Theta}{16.47}\right)^2 & 0° \le \Theta < 8.5° \\ -149 + 0.16 * \Theta° & 8.5° \le \Theta < 45° \\ -142 + 0.53 * (\Theta° - 45°) & 45° \le \Theta < 58.5° \\ -142.72 + 6.85 - 10\,\mathrm{LOG}_{10}\left(\left(\frac{\Theta}{16.47}\right)^{-1.5} + k\right) & 58.5° \le \Theta \le 90° \end{cases}$$

Figure A1-6 shows the $PSFD_{MAX,BS}$ and $PSFD_{MAX,MS}$ for elevation angles from 0° to 90°, together with the pfd mask specified in Recommendation ITU-R M.2092-0. Also shown in Fig. A1-6 is the updated pfd mask from Table A1-8 that ensures protection of the land mobile service.

FIGURE A1-6

***$PSFD_{MAX,BS}$* and *$PSFD_{MAX,MS}$* as a function of receiver station elevation angles, together with the specified in Rec. ITU-R M.2092-0 and the updated pfd mask ensuring protection of the land mobile service**



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A1.6.1 VHF data exchange system satellite downlink performance assessment of the proposed alternative compromise pfd mask based on coordination thresholds

VDE-SAT downlink performance assessment of the current pfd mask and the alternative compromise pfd mask in Fig. A1-6 is shown in Table A1-9 below. Note that the current mask would be lowered by a worst-case amount of 3.8 dB at 90^0 elevation angle, but there would be no actual change in the actual pfd based on Table A1-2, and the resulting actual *C/N* would be unchanged from Table A1-4 which is 5.6 dB and 11.9 dB from elevation angles 0^0 to 60^0 as shown in Table A1-5 below.

TABLE A1-9

Performance assessment of the compromise pfd mask based on coordination thresholds

Elevation angle (degrees)	**Antenna gain** (dBi)	**Current pfd mask Rec. ITU-R M.2092** (dBW/m²*4 kHz)	**Compromise pfd mask Rec. T/R 25-08 (Fig. A1-6)** (dBW/m²*4 kHz)	**Margin to current pfd mask** (dB)	**Margin to actual pfd mask (Table A1-2)** (dB)	**Resulting actual *C/N* (Table A1-4)** (dB)
0	8.2	−149.0	−150.9	−1.9	2.3	5.6
10	3.7	−147.4	−147.4	0.0	2.3	8.9
20	−5.3	−145.8	−145.8	0.0	0.9	10.9
30	−6.3	−144.2	−144.2	0.0	0.3	11.9
40	−6.8	−142.6	−142.6	0.0	0.1	11.7
50	−7.3	−139.4	−139.4	0.0	1.2	10.0
60	−7.8	−134.0	−135.1	−1.1	5.9	8.1
70	−7.8	−133.0	−135.0	−2.0	7.5	3.6
80	−7.8	−132.0	−134.9	−2.9	9.1	2.0
90	−7.8	−131.0	−134.8	−3.8	10.5	−0.2

A1.7 Assessment of protection for land mobile services

Portions of the frequency band 156.0125-157.4375 MHz and 160.6125-162.0375 MHz are currently allocated worldwide to the mobile services on a primary basis. The Recommendation ITU-R M.1808-0 provides technical and operational characteristics of conventional and trunked land mobile systems.

In § A1-2.1 it is stated that “there are many methodologies used to ensure coexistence between conventional and trunked land mobile systems (e.g. field-strength contours, carrier-to-interference). For simplicity, an *I/N* of −6 dB could be used to determine the impact of interference. For applications with greater protection requirements, such as public protection and disaster relief (PPDR), an *I/N* of −10 dB may be used to determine the impact of interference”. The characteristics of base station and mobile station for frequency sharing below 869 MHz were also listed in Table 1 and Table 2 of Appendix 1 to Annex 1 of Recommendation ITU-R M.1808-0.

A1.7.1 Protection calculations

When the protection criteria are given in the term of the *I/N*, the interference threshold level, I_I (dBm) can be calculated by equation (A1-12):

$$I_I = I/N_{required} + N \qquad \text{(A1-12)}$$

where:

$I/N_{required}$: required *I/N* at the detector input (IF output) necessary to maintain acceptable performance criteria (dB)

N: receiver inherent noise level (dBm)

$$(N = -174 \text{ dBm} + 10 \log B_{IF} + NF)$$

where:

B_{IF}: receiver IF bandwidth (Hz)

NF: receiver noise figure (dB)

Interference threshold level I_I (dBm) could be converted to field strength E_I (dBμV/m) with equation (A1-13):

$$E_I = I_I - (G_R - L_{loss}) + 20 \log(f) + 77.2 \quad \text{(A1-13)}$$

where:

f: frequency (MHz)

L_{loss}: Total loss of feeder link (dB)

G_R: receiver antenna gain (dBi).

Calculation results of interference threshold level in term of field strength for base stations and mobile stations in the frequency 160 MHz are listed in Table A1-10.

Sample calculation (Table A1-10, Field strength for I/N = -6 dB, land mobile base station, analogue):

$$B_{IF} = 16 \text{ kHz}; NF = 7 \text{ dB}; G_R = 6 \text{ dB}; L_{loss} = 3 \text{ dB}; f = 160 \text{ MHz}; I/N_{required} = -6 \text{ dB}$$

$$I_I = I/N_{required} + N = -6 \text{ dB} + -174 \text{ dBm} + 42 \text{ dB} + 7 \text{ dB} = -131 \text{ dBm}$$

$$E_I = I_I - (G_R - L_{loss}) + 20 \log(f) + 77.2 = -131 \text{ dBm} - (6 \text{ dB} - 3 \text{ dB}) + 44.1 \text{ dB} + 77.2 = -12.7$$

$$\text{pfd} = -12.7 - 10 \log (120*\pi*10^{12}) - 10 \log (16/4) = -12.7 - 151.78 = -164.5 \text{ dB(W/m}^2\text{*4 kHz)}$$

Note: The values of E_I and pfd are referred to the antenna gain at 0-degree elevation angle.

TABLE A1-10

Typical values of land mobile service systems (based on Rec. ITU-R M.1808-0)

Characteristics	Land mobile systems (Base station)		Land mobile systems (Mobile station)	
Type of emission	Analogue	Digital	Analogue	Digital
B_{IF} (kHz)	8/11/12.5/16[11]	5.5	8/11/12.5/16	5.5
Antenna	Omnidirectional / Vertical		Omnidirectional / Vertical	
G_R–typical value (dB)	6	8	0	0
L_{loss} –typical value (dB)	3	3	1	1
N_F –typical value (dB)	7	7	7	7
Interference to noise ratio	Field strength: E_I at 0^0 elevation angle			
$I/N = -6$ dB (dB(μV/m))	−12.7/16 kHz	−19.3/5.5 kHz	−8.7/16 kHz	−13.3/5.5 kHz
$I/N = -10$ dB (dB(μV/m))	−16.7/16 kHz	−23.3/5.5 kHz	−12.7/16 kHz	−17.3/5.5 kHz
Interference to noise ratio	Power flux-density: *pfd* at 0^0 elevation angle			
$I/N = -6$ dB (dB(W/m^2*4 kHz))	−164.5	−166.5	−160.5	−165.1
$I/N = -10$ dB (dB(W/m^2*4 kHz))	−168.5	−170.5	−164.5	−169.1

A1.7.2 Consideration of noise background from man-made noise per Recommendation ITU-R P.372-13

Recommendation ITU-R P.372-13 provides recommendations on calculations of the man-made noise level depending on the environment, from rural to city environment. Recommendation ITU-R M.1808-0 provides the transmission line loss and receiver noise figure for typical land mobile base stations (the worst-case condition)[12]:

$$F_{am,city} = 15.7 \text{ dB}$$

$$F_{am,rural} = 6.1 \text{ dB}$$

$$L_t = 3.0 \text{ dB}$$

$$F_r = 7.0 \text{ dB}$$

then the system noise factor for city environment, f_{city}, is:

$$f_{city} = f_{am} + l_t f_r = 10^{\frac{F_{am}}{10}} + 10^{\frac{L_t}{10}} * 10^{\frac{F_r}{10}} = 47.2$$

$$F_{city} = 16.7 \text{ dB}$$

then the system noise factor for rural environment, f_{rural}, is:

$$f_{rural} = f_{am} + l_t f_r = 10^{\frac{F_{am}}{10}} + 10^{\frac{L_t}{10}} * 10^{\frac{F_r}{10}} = 14.1$$

$$F_{rural} = 11.5 \text{ dB}$$

The equivalent system noise temperature, T_S, can be calculated from the system noise factor:

---

[11] In the calculations on analogue land mobile systems, 16 kHz receiver IF bandwidth was used.

[12] The protection level in Table 6 for base stations is lower by 4 dB than for mobile stations.

$$T_S = T_0 f$$

then:

$$T_{S,city} = 13\,688 \text{ K}$$

$$T_{S,rural} = 4\,081 \text{ K}$$

The receiver noise power *N* is then:

$$N = kT_s B$$

where *k* is Boltzmann's constant and *B* is the bandwidth. With a reference bandwidth of 4 kHz, *N* then is:

$$N_{city} = kT_{s,city}B = -151.2 \text{ dBW per 4 kHz}$$

$$N_{rural} = kT_{s,rural}B = -156.5 \text{ dBW per 4 kHz}$$

A1.7.2.1 pfd mask assessment

The pfd masks (Tables A1-7 and A1-8) for meeting the *I*/*N* of −6 dB requirement should ensure that $I_{s,max}$ is not higher than, but the transmission line loss, L_t, of 3 dB must also be accounted for:

$$I_{S,max,city} = N_{city} - 6 \text{ dB} + 3\text{dB} = -154.2 \text{ dBW per 4 kHz}$$

$$I_{S,max,rural} = N_{rural} - 6 \text{ dB} + 3\text{dB} = -159.5 \text{ dBW per 4 kHz}$$

when converting to pfd limit expressed as dBW/(m² * 4 kHz):

$$pfd_{\ city} = I_{S,\ max,\ city} - 10 * \log((c/f)^2/4\pi) = -148.6 \text{ dBW/(m}^2 * 4 \text{ kHz)}$$

$$pfd_{\ rural} = I_{S,\ max,\ rural} - 10 * \log((c/f)^2/4\pi) = -153.9 \text{ dBW/(m}^2 * 4 \text{ kHz)}$$

TABLE A1-11

pfd mask for land mobile base stations in urban environment

Elevation angle (degrees)	**Antenna gain (dBi)**	**pfd mask (pfd limit – antenna gain) (dBW/(m² * 4 kHz))**
0	8.2	−156.8
10	3.7	−152.3
20	−5.3	−143.3
30	−6.3	−142.3
40	−6.8	−141.8
50	−7.3	−141.3
60	−7.8	−140.8
70	−7.8	−140.8
80	−7.8	−140.8
90	−7.8	−140.8

TABLE A1-12

pfd mask for land mobile base stations in suburban environment

Elevation angle (degrees)	Antenna gain (dBi)	pfd mask (pfd limit – antenna gain) (dBW/(m^2 * 4 kHz))
0	8.2	−162.1
10	3.7	−157.6
20	−5.3	−148.6
30	−6.3	−147.6
40	−6.8	−147.1
50	−7.3	−146.6
60	−7.8	−146.1
70	−7.8	−146.1
80	−7.8	−146.1
90	−7.8	−146.1

A1.7.3 Alternative pfd mask based on protection criteria

If an alternative pfd mask based on protection criteria is needed, then allowing for man-made noise per Recommendation ITU-R P.372-13 provides a reasonable basis for this compromise. Assessment of the current pfd mask and the compromise pfd mask is shown in Table A1-9 below. Note that the current mask would be lowered by 7.8 dB, but the reduction in pfd would be only 3.6 dB, and the resulting actual *C*/*N* is between 2.0 dB and 4.5 dB from elevation angles 0^0 to 60^0.

TABLE A1-13

Assessment of the alternative pfd mask based on protection criteria

Elevation angle (degrees)	Antenna gain (dBi)	Current pfd mask Rec. ITU-R M.2092 (dBW/(m^2 * 4 kHz))	Alternative pfd mask[13] Rec. ITU-R M.1808 + P.372 (dBW/(m^2 * 4 kHz))	Margin to current pfd mask (dB)	Margin to actual pfd mask (Table A1-2) (dB)	Resulting actual *C*/*N* (Table A1-4) (dB)
0	8.2	−149.0	−156.8	−7.8	−3.6	2.0
10	3.7	−147.4	−152.3	−4.9	−2.6	5.3
20	−5.3	−145.8	−143.3	2.5	−3.4	7.3
30	−6.3	−144.2	−142.3	1.9	2.2	8.3
40	−6.8	−142.6	−141.8	0.8	0.7	8.2
50	−7.3	−139.4	−141.3	−1.9	0.3	7.3
60	−7.8	−134.0	−140.8	−6.8	0.2	4.5
70	−7.8	−135.0	−140.8	−5.8	1.2	0.0
80	−7.8	−132.0	−140.8	−8.8	2.7	−1.6
90	−7.8	−131.0	−140.8	−9.8	4.5	−3.8

[13] For base stations, an urban environment is assumed and therefore Table 7 is used.

A1.8 Results of assessment of pfd masks

Two pfd masks are assessed in Table A1-5 and Table A1-9. By comparison of the two, the mask described in Table A1-5 and illustrated in Figure A1-6 results in a stronger downlink because the resulting *C/N* is higher by 3.6 dB. Since the *C/N* values for both pfd masks are very low, direct sequence spread spectrum techniques, depending on the spreading bandwidths for each mask, could provide significant improvement in robustness to the downlink.

Annex 2

Carrier to interference analysis of pfd masks for the VDE-SAT downlink

A2.1 VHF data exchange satellite downlink

VHF data exchange by satellite (VDE-SAT) is proposed to use frequencies in the bands 156.0125-157.4375 MHz and 160.6125-162.0375 MHz. Technical characteristics effecting the satellite e.i.r.p. and the pfd coordination mask are further described below.

A2.2 Consideration of an alternative pfd mask based on available land mobile service characteristics in Recommendation ITU-R M.1808-0

Recommendation ITU-R M.1808 provides the characteristics of mobile systems and the useful information is reproduced in Tables A2-1 and A2-2.

TABLE A2-1

Base station characteristics for frequency sharing below 869 MHz

Frequency band (MHz)	138 to 174	
Type of emission	Analogue	Digital
Receiver		
Noise figure (dB)	6 to 12 (7)	6 to 12 (7)
IF filter bandwidth (kHz)	8/11/12.5/16	5.5/5.5/5.5/5.5
Antenna gain (dBd)	0 to 9 (6)	0 to 9 (8)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0 to 6 (3)	0 to 6 (3)

TABLE A2-2

Mobile station characteristics for frequency sharing below 869 MHz

Frequency band (MHz)	138 to 174	
Type of emission	Analogue	Digital
Receiver		
Noise figure (dB)	6 to 12 (7)	6 to 12 (7)
IF filter bandwidth (kHz)	8/11/12.5/16	5.5/5.5/5.5/5.5
Antenna gain (dBd)	−10 to 4 (H: −10, V: 0)	−10 to 4 (H: −10, V: 0)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0 to 1 (H: 0, V: 1)	0 to 1 (H: 0, V: 1)

NOTE 1 – Simplex systems use the same frequency for both the base station and mobile station to transmit.

NOTE 2 – Frequency division duplex systems have different frequencies for the base station and mobile station which allows simultaneous communications.

NOTE 3 – Typical values are shown in parenthesis. In some instances, more than one typical value is provided.

NOTE 4 – e.r.p. is equal to the output power (dBW) plus antenna gain (dBd) minus total losses (dB).

For the mobile and base stations an average side-lobe pattern is considered in our study according to the Recommendation ITU-R F.1336 for omnidirectional radiation patterns as presented in equation (A2-1) below.

$$G(\theta) = \begin{cases} G_0 - 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ G_0 - 15 + 10\log_{10}(k+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ G_0 - 15 + 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + k\right) & \text{for } \theta_5 < |\theta| < 90^\circ \end{cases} \tag{A2-1}$$

with:

$$\theta_5 = \theta_3\sqrt{1.25 - \frac{1}{1.2}\log_{10}(k+1)} \tag{A2-2}$$

where:

$G(\theta)$: gain relative to an isotropic antenna (dBi)

G_0: the maximum gain in the azimuth plane (dBi) knowing that G_0 in dBi equals G_0 in dBd + 2.15

θ: elevation angle relative to the angle of the maximum gain (degrees) $(-90^\circ \leq \theta \leq 90^\circ)$

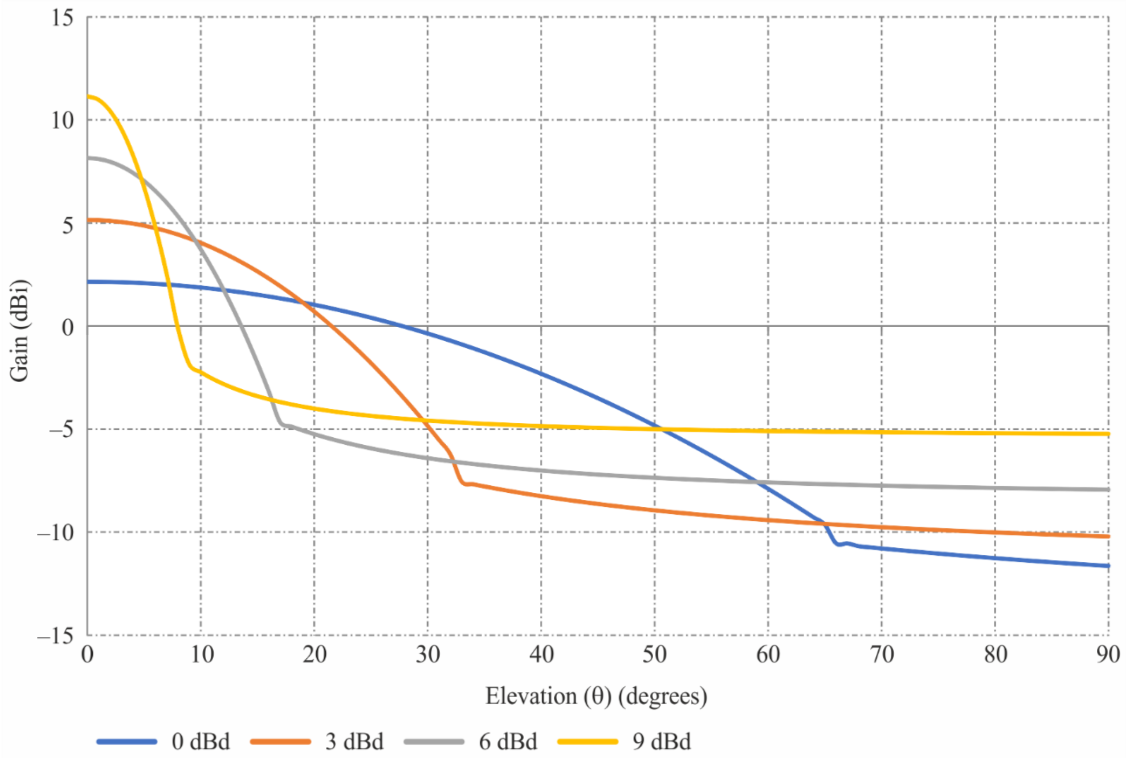
θ_3: the 3 dB beamwidth in the elevation plane (degrees) $\theta_3 = 107.6 \times 10^{-0.1\,G_0}$

k: parameter which accounts for increased side-lobe levels above what would be expected for an antenna with improved side-lobe performance (for antennas operating in the 1-3 GHz range, the parameter k should be 0.7).

Figure A2-1 represents the resulting mobile/base station antenna radiation patterns (in dBi) with antennas (typically specified in dBd) from 0 dBd to 9 dBd.

FIGURE A2-1

Mobile/base station antenna patterns for typical antennas used in the land mobile service as described in Rec. ITU-R F.1336-4



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The coordination thresholds, derived from ECC Recommendation T/R 25-08, used by the land mobile services for narrowband (up to 25 kHz) applications (co-channel, 50% locations, 10% of the time, 10 m receiving antenna height, at the border-line) is:

12 dB (μV/m) for frequencies between 108 and 380 MHz;

Thus, the coordination threshold for the VDE-SAT frequency range would be 12 dB(μV/m). The maximum power spectral density PSD_{Rx_MAX} at the antenna output that would be produced by a vertically polarized signal with a power spectral and flux-density of 12 dBμV/m in 25 kHz, corresponds to -141.72 dB(W/(m^2 * 4 kHz))[14]. Such maximum value will occur for signals coming at 0 degrees of elevation ($\theta = 0$) as this is the point where the mobile station has maximum gain (G_0).

Using the Friis formula in its simplest form:

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[14] The conversion from dB (μV/m) (25 kHz reference bandwidth) to dB(W/(m2 * 4 kHz)) can be computed with the following formula:

$$dB(W/(m^2 \cdot 4kHz)) = dB\left(\frac{\mu V}{m}\right) - 10 \cdot \log_{10}(120 \cdot \pi \cdot 10^{12}) - 10 \cdot \log_{10}(25kHz/4kHz) = dB\left(\frac{\mu V}{m}\right) - 153.72$$

$$PSD_{Rx} = PSD_{Tx} G_{Tx} \left(\frac{\lambda}{4\pi d}\right)^2 G_{Rx} \quad \text{(A2-3)}$$

where PSD_{Rx} is the received power spectral density (PSD), PSD_{Tx} is the transmitted power spectral density, G_{Tx} is the gain of the transmitting antenna in the direction of the receiver, λ is the wavelength, d is the distance between transmitter and receiver and G_{Rx} is the gain of the receiving antenna in the direction of the transmitter.

The power spectral and flux-density is given by:

$$PSFD = \frac{PSD_{Tx} G_{Tx}}{4\pi d^2} \quad \text{(A2-4)}$$

therefore equation (A2-3) can be rewritten accordingly:

$$PSD_{Rx} = PSFD \frac{\lambda^2}{4\pi} G_{Rx} \quad \text{(A2-5)}$$

The maximum power spectral and flux-density that would produce the maximum allowed power spectral density PSD_{Rx_MAX} is then:

$$PSD_{Rx\_MAX} = PSFD_{Ref} \frac{\lambda^2}{4\pi} G_0 \quad \text{(A2-6)}$$

where $PSFD_{Ref}$ is -141.72 dB(W/(m2 * 4 kHz)).

From equation (A2-5) it is possible to express the power spectral and flux-density as a function of the received power spectral density:

$$PSFD = PSD_{Rx} \frac{4\pi}{\lambda^2} \frac{1}{G_{Rx}} \quad \text{(A2-7)}$$

Given that PSD_{Rx_MAX} is constant and that $G_{Rx} = G(\theta)$ as defined in equation (A2-1) is a function of the elevation angle θ, then by substituting equation (A2-6) in equation (A2-7) the maximum power spectral and flux-density is also a function of the elevation angle:

$$PSFD_{MAX}(\theta) = \frac{PSFD_{Ref}}{G\prime(\theta)} \quad \text{(A2-8)}$$

where:

$$G'(\theta) = \frac{G(\theta)}{G_0} \quad \text{(A2-9)}$$

It should be noted that with this approach, the electric field strength thresholds are achieved for 100% of the time and 100% locations, that is a conservative interpretation of the threshold values depicted in the equations above.

When applying equation (1) to the $PSFD_{MAX}$, the result is elevation dependent. Assuming the typical antenna gain given in Table A2-1 for the base station of 6 dBd (8.15 dBi) the $PSFD_{MAX,BS}$ in $(\text{dBW}/(\text{m}^2 * 4\ \text{kHz}))$ will be:

$$PSFD_{MAX,BS}(\theta) = \begin{cases} -141.72 - 8.15 + 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ -141.72 + 6.85 - 10\log_{10}(k+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ -141.72 + 6.85 - 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + k\right) & \text{for } \theta_5 < |\theta| < 90^{\circ} \end{cases} \quad \text{(A2-10)}$$

with θ the elevation angle, $\theta_3 = 16.47°$, $\theta_5 = 16.95°$ and $k = 0.7$.

Assuming the typical antenna gain given in Table A2-2 for the mobile station of 0 dBd (2.15 dBi) the $PSFD_{MAX,MS}$ in $(\text{dBW}/(\text{m}^2 * 4\ \text{kHz}))$ will be:

$$PSFD_{MAX,MS}(\theta) = \begin{cases} -141.72 - 2.15 + 12\left(\frac{\theta}{\theta_3}\right)^2 & \text{for } 0 < |\theta| < \theta_3 \\ -141.72 + 12.85 - 10\log_{10}(k+1) & \text{for } \theta_3 < |\theta| < \theta_5 \\ -141.72 + 12.85 - 10\log_{10}\left(\left(\frac{|\theta|}{\theta_3}\right)^{-1.5} + k\right) & \text{for } \theta_5 < |\theta| < 90^\circ \end{cases} \quad \text{(A2-11)}$$

with θ the elevation angle, $\theta_3 = 65.59°$, $\theta_5 = 67.46°$ and $k = 0.7$.

Table A2-3 presents the $PSFD_{MAX,BS}$ and $PSFD_{MAX,MS}$ for elevation angles from 0° to 90° in 10° increments, together with the pfd mask specified in Recommendation ITU-R M.2092-0.

TABLE A2-3

$PSFD_{MAX,BS}$ and $PSFD_{MAX,MS}$ for elevation angles from 0° to 90° in 10° increments, together with the pfd mask specified in Rec. ITU-R M.2092-0

Receiver station elevation angle θ (degrees)	***$PSFD_{MAX,BS}$*** (dBW/m²*4 kHz)	***$PSFD_{MAX,MS}$*** (dBW/m²*4 kHz)	**pfd mask specified by Rec. ITU-R M.2092-0** (dBW/m²*4 kHz)	**Margin between pfd mask and *$PSFD_{MAX,BS}$*** (dB)	**Margin between pfd mask and *$PSFD_{MAX,MS}$*** (dB)
0	−150.9	−144.9	−149.0	−1.9	4.1
10	−146.4	−144.6	−147.4	1.0	2.8
20	−137.5	−143.8	−145.8	8.3	2.0
30	−136.3	−142.4	−144.2	7.9	1.8
40	−135.7	−140.4	−142.6	6.9	2.2
50	−135.4	−137.9	−139.4	4.0	1.5
60	−135.1	−134.8	−134.0	−1.1	−0.8
70	−135.0	−131.9	−133.0	−2.0	1.1
80	−134.9	−131.5	−132.0	−2.9	0.5
90	−134.8	−131.1	−131.0	−3.8	−0.1

The information provided in Table A2-3 shows that the margin between the pfd mask specified in Recommendation ITU-R M.2092-0 with respect to $PSFD_{MAX,BS}$ and $PSFD_{MAX,MS}$ is negative for some of the receiver station elevation angles. Thus, the pfd mask specified in Recommendation ITU-R M.2092-0 exceeds the coordination threshold of 12 dB (μV/m) at very low elevation angles and very high elevation angles. Minor changes to the pfd mask specified in Recommendation ITU-R M.2092-0 are appropriate to ensure the protection of the land mobile service. An updated mask that would provide protection of the land mobile service is presented in Table A2-4.

TABLE A2-4

Power spectral and pfd mask to ensure protection of the land mobile service

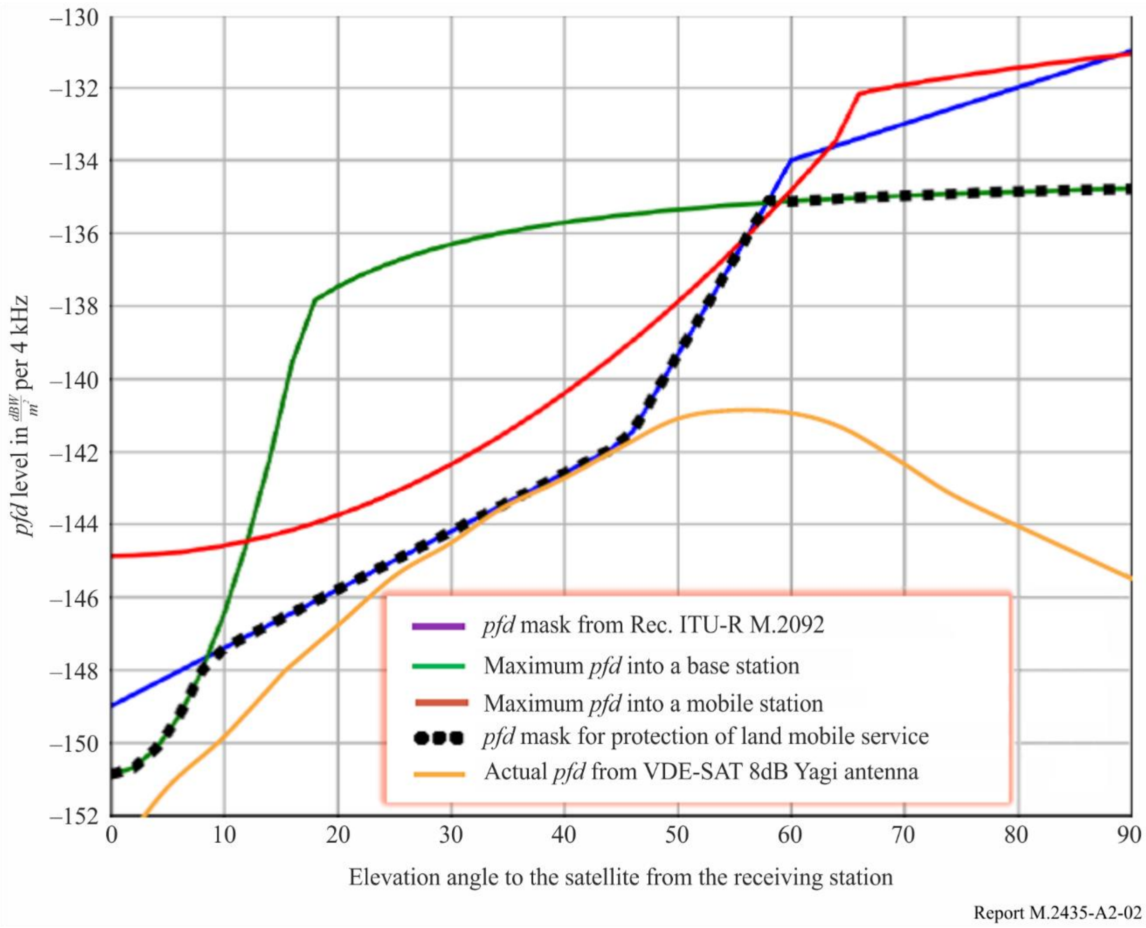
$$\boldsymbol{\theta^\circ = earth - satellite\ elevation\ angle}$$

$$pfd(\theta^\circ)_{\ (\mathrm{dBW/(m^2{*}4\ kHz)})} = \begin{cases} -141.72 - 8.15 + 12\left(\dfrac{\theta}{16.47}\right)^2 & 0^\circ \le \theta < 8.5^\circ \\ -149 + 0.16 * \theta^\circ & 8.5^\circ \le \theta < 45^\circ \\ -142 + 0.53 * (\theta^\circ - 45^\circ) & 45^\circ \le \theta < 58.5^\circ \\ -141.72 + 6.85 - 10\log_{10}\left(\left(\dfrac{\theta}{16.47}\right)^{-1.5} + k\right) & 58.5^\circ \le \theta \le 90^\circ \end{cases}$$

Figure A2-2 shows the $PSFD_{MAX,BS}$ and $PSFD_{MAX,MS}$ for elevation angles from 0° to 90°, together with the pfd mask specified in Recommendation ITU-R M.2092-0, together with the updated pfd mask from Table A2-4 (above) that ensures protection of the land mobile service. Also shown is the actual pfd from the VDE-SAT reference design with the 8 dB Yagi antenna. Note that the actual pfd from the 8 dB Yagi antenna complies with both the current pfd mask and the updated pfd mask to protect the land mobile services.

FIGURE A2-2

***PSFD**$_{MAX,BS}$* **and** ***PSFD**$_{MAX,MS}$* **as a function of receiver station elevation angles, together with the specified in Rec. ITU-R M.2092-0 and the updated pfd mask ensuring protection of the land mobile service. Also shown is the actual pfd from the VDE-SAT reference design with the 8dB Yagi antenna**



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A2.2.1 VHF data exchange system satellite downlink *C/N* performance assessment of the proposed alternative pfd mask to ensure the protection of the land mobile service

VDE-SAT downlink performance assessment of the current pfd mask and the alternative pfd mask in Fig. A2-2 is shown in Table A2-5 below. Note that the current mask would be lowered by 3.8 dB at the 90-degree elevation angle, but there would be no change in the actual pfd from the 8dB Yagi antenna reference design, and the resulting actual *C/N* would remain between 5.6 dB and 11.9 dB from elevation angles 0 degrees to 60 degrees as shown in Table A2-5 below.

TABLE A2-5

***C/N* performance assessment of the pfd mask to ensure the protection of the land mobile service**

Elevation angle (degrees)	Antenna gain (8dB Yagi) (dBi)	Current pfd mask Rec. ITU-R M.2092 (Fig. A2-2) (dBW/m²*4 kHz)	Alternative pfd mask (Table A2-4 and Fig. A2-2) (dBW/m²*4 kHz)	Margin to current pfd mask (dB)	Margin to actual pfd (8dB Yagi) (dB)	Resulting actual *C/N* (8dB Yagi) (dB)
0	8.2	−149.0	−150.9	−1.9	2.3	5.6
10	3.7	−147.4	−147.4	0.0	2.3	8.9
20	−5.3	−145.8	−145.8	0.0	0.9	10.9
30	−6.3	−144.2	−144.2	0.0	0.3	11.9
40	−6.8	−142.6	−142.6	0.0	0.1	11.7
50	−7.3	−139.4	−139.4	0.0	1.2	10.0
60	−7.8	−134.0	−135.1	−1.1	5.9	8.1
70	−7.8	−133.0	−135.0	−2.0	7.5	3.6
80	−7.8	−132.0	−134.9	−2.9	9.1	2.0
90	−7.8	−131.0	−134.8	−3.8	10.5	−0.2

A2.2.2 Carrier to interference (*C/I*) performance comparison of the current pfd mask and the alternative pfd mask to ensure the protection of the land mobile service

Given this mask, a study on the compatibility between the VDE-SAT downlink and the land mobile service has been performed. The study evaluates the effect of the interference from the VDE-SAT downlink received by a land mobile base station on the transmission from a mobile station to a base station. Basis for the study is technical characteristics of land mobile systems as provided in Recommendation ITU-R M.1808, including interference criteria and performance criteria, and methods for point-to-area predictions for terrestrial services as provided in Recommendation ITU-R P.1546.

The methodology used to evaluate the compatibility between the VDE-SAT downlink and the land mobile service is based on *C/I* considerations and degradation protection, as proposed in Recommendation ITU-R M.1808, Annex 1, § 2.1.

A2.2.2.1 Characteristics of land mobile systems operating in the 156 to 162 MHz band

Representative technical and operational characteristics of conventional and trunked land mobile systems operating in the mobile service in the frequency band 156-162 MHz are given in Recommendation ITU-R M.1808. Table A2-6 provides the technical characteristics of base stations and Table A2-7 provides technical characteristics of mobile stations as they are given in that

Recommendation. Recommendation ITU-R P.372 provides additional relevant information regarding interference.

TABLE A2-6

Technical characteristics for base stations operating in the mobile service in the frequency band 138-174 MHz

Frequency band (MHz)	**138–174**	
Type of emission	**Analogue**	**Digital**
System-wide		
Channel bandwidth (kHz)	12.5/15/25/30	6.25/7.5/12.5/15
Modulation type	FM	C4FM
Type of operation	Simplex/duplex	Duplex
Typical SINAD or BER (dB or %)	12 dB	5%
Transmitter		
Output power (W)	5–125 (30) (100)	20–125 (60) (100)
e.r.p. (dBW)	7–26 (19) (24)	13–26 (18) (24)
Necessary bandwidth (kHz)	11/11/16/16	5.5/5.5/8.1/8.1
Coverage radius (km)	1–75 (50)	1–75 (50)
Antenna gain (dBd)	0–9 (6)	0–9 (6)
Antenna height (m) (relative to ground level)	10–150 (60)	10–150 (65)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–7 (2)	3–9 (6) (2)
Receiver		
Noise figure (dB)	6–12 (7)	6–12 (7)
IF filter bandwidth (kHz)	8/11/12.5/16	5.5/5.5/5.5/5.5
Sensitivity (dBm)	−116 – −121 (−119)	−116 – −121 (−119)
Antenna gain (dBd)	0–9 (6)	0–9 (8)
Antenna height (m) (relative to ground level)	10–150 (60)	10–150 (65)

TABLE A2-6 (*end*)

Frequency band (MHz)	**138–174**	
Type of emission	**Analogue**	**Digital**
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–6 (3)	0–6 (3)

Notes to Table A2-6:

Note 1 – Simplex systems use the same frequency for both the base station and mobile station to transmit.

Note 2 – Frequency division duplex systems have different frequencies for the base station and mobile station which allows simultaneous communications.

Note 3 – Typical values are shown in parenthesis. In some instances, more than one typical value is provided.

Note 4 – e.r.p. is equal to the output power (dBW) plus antenna gain (dBd) minus total losses (dB).

TABLE A2-7

Technical characteristics for mobile stations operating in the mobile service in the frequency band 138-174 MHz

Frequency band (MHz)	**138–174**	
Type of emission	**Analogue**	**Digital**
System-wide		
Channel bandwidth (kHz)	12.5/15/25/30	6.25/7.5/12.5/15
Modulation type	FM	C4FM
Type of operation	Simplex/duplex	Duplex
Typical SINAD or BER (dB or %)	12 dB	5%
Transmitter		
Output power (W)	1–100 (H: 5 V: 30, 50)	1–100 (H: 5 V: 30, 50)
e.r.p. (dBW)	−3–18 (H: −3 V: 14, 16)	−3–18 (H: −3 V: 14, 16)
Necessary bandwidth (kHz)	11/11/16/16	5.5/5.5/8.1/8.1
Antenna gain (dBd)	−10–4 (H: −10, V: 0)	−10–4 (H: −10, V: 0)
Antenna height (m) (relative to ground level)	(2)	(2)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–1 (H: 0, V: 1)	0–1 (H: 0, V: 1)
Receiver		
Noise figure (dB)	6–12 (7)	6–12 (7)
IF filter bandwidth (kHz)	8/11/12.5/16	5.5/5.5/5.5/5.5
Sensitivity (dBm)	−116 – −121 (−119)	−116 – −121 (−119)
Antenna gain (dBd)	−10–4 (H: −10, V: 0)	−10–4 (H: −10, V: 0)

TABLE A2-7 (*end*)

Frequency band (MHz)	**138–174**	
Type of emission	**Analogue**	**Digital**
Antenna height (m) (relative to ground level)	(2)	(2)
Radiation pattern	Omnidirectional	Omnidirectional
Antenna polarization	Vertical	Vertical
Total loss (dB)	0–1 (H: 0, V: 1)	0–1 (H: 0, V: 1)

Notes to Table A2-7:

Note 1 – Simplex systems use the same frequency for both the base station and mobile station to transmit.

Note 2 – Frequency division duplex systems have different frequencies for the base station and mobile station which allows simultaneous communications.

Note 3 – Typical values are shown in parenthesis. In some instances, more than one typical value is provided.

Note 4 – e.r.p. is equal to the output power (dBW) plus antenna gain (dBd) minus total losses (dB).

For the studies of the compatibility of the VDE-SAT downlink with the land mobile service the typical values from Table A2-6 and Table A2-7 have been used. These technical characteristics and values are summarized in Table A2-8.

TABLE A2-8

Typical values for technical characteristics of land mobile service stations used in compatibility study

Station type	**Units**	**Base station**	**Mobile station**
Necessary bandwidth (kHz)		16	16
Output power	W	100	50
Output power	dBW	20	17
Feed loss	dB	2.0	1.0
Maximum antenna gain	dBd	6.0	0.0
Maximum antenna gain	dBi	8.2	2.2
Maximum e.r.p.	dB	24.0	16.0
Maximum e.i.r.p.	dB	26.2	18.2
Antenna height	m	60	2
Distance to horizon from station	km	27.7	5.1

Regarding the mobile station, this analysis only takes into account the vehicular mobile stations, which is considered as the worst-case scenario compared to handheld mobile stations.

Note from the previous reference, Fig. A2-1, the antenna patterns for typical antennas used in the land mobile service as described in Recommendation ITU-R F.1336-4 are shown graphically. Assuming a 6 dBd antenna is used at the base station and a 0 dBd antenna is used at the mobile station, the antenna gain versus elevation angle can be tabulated as in Tables A2-9 and A2-10 for the base station and mobile station respectively. Tables A2-9 and A2-10 also present the resulting e.i.r.p. versus elevation angle for the two station types.

TABLE A2-9

Base station antenna gain and e.i.r.p. versus elevation angle

Elevation angle (degrees)	Antenna gain (dBi)	e.i.r.p. (dBW)
0	8.2	26.2
10	3.7	21.7
20	−5.2	12.8
30	−6.4	11.6
40	−7.0	11.0
50	−7.4	10.6
60	−7.6	10.4
70	−7.7	10.3
80	−7.9	10.1
90	−7.9	10.1

TABLE A2-10

Mobile station antenna gain and e.i.r.p. versus elevation angle

Elevation angle (degrees)	Antenna gain (dBi)	e.i.r.p. (dBW)
0	2.2	18.2
10	1.9	17.9
20	1.0	17.0
30	−0.4	15.6
40	−2.3	13.7
50	−4.8	11.2
60	−7.9	8.1
70	−10.8	5.2
80	−11.3	4.7
90	−11.6	4.4

A2.2.2.2 Link budget calculations for transmissions between base stations and mobile stations

Given the typical antenna heights for the land mobile base station and mobile station summarized in Table A2-7, the distance to the horizon from the base or mobile station was calculated, as previously shown in Table A2-8. Then the mobile station to base station range can be found to be the sum of the two distances, which is 32.8 km. Based on the mobile station to base station range the transmission free space loss can be calculated to 106.9 dB.

In addition to the free space loss, a land mobile transmission channel will experience additional path loss. Recommendation ITU-R P.1546 provides methods for point-to-area predictions for terrestrial services for the relevant frequency band. Based on tabulated field strengths available from the Radiocommunication Bureau, as discussed in Annex 1 of that Recommendation, combined with formulas for interpolation of field strength as function of antenna height, distance and frequency as provided in Annex 5 of that recommendation, the additional path loss can be estimated. The tabulated field strengths exceeded 50 % of the time from Recommendation ITU-R P.1546 assumes a transmit e.i.r.p. of 1 kW, and the values needed to perform the interpolation to the frequency of 162 MHz and the antenna height and mobile station to base station range given in Table A2-8, are provided in Table A2-11.

TABLE A2-11

Tabulated field strength values exceeded 50% of the time from Rec. ITU-R P.1546 needed to perform the interpolation to the frequency of 162 MHz and the antenna height and mobile station to base station range

Frequency (MHz)	**Antenna height** (m)	**Distance** (km)	**Field strength value** (dB μV/m)
100	37.5	30	41.3
		35	38.1
	75	30	47.5
		35	44.2
600	37.5	30	37.5
		35	34.2
	75	30	44.2
		35	40.5

Through the use of the interpolation formulas provided in Annex 5 of Recommendation ITU-R P.1546 the estimated field strength can be calculated for the frequency of 162 MHz, antenna height of 60 m and a distance of 32.8 km. The result is an estimated field strength of 42.7 dB(uV/m). The corresponding field strength if only free space loss is considered will be 72.5 dB(uV/m). The additional path loss experienced on a land mobile transmission channel is equal to this difference, which is 29.8 dB. The calculation steps are provided in Table A2-12 for transparency.

TABLE A2-12

Calculation steps for interpolation of field strength values exceeded 50% of the time from Rec. ITU-R P.1546 to the frequency of 162 MHz and the antenna height and mobile station to base station range

	Frequency (MHz)	**Antenna height** (m)	**Distance** (km)	**Field strength value** (dB µV/m)
Free space loss and additional path loss	162	37.5	30	40.3
			35	37.0
		75	30	46.6
			35	43.2
	162	60	30	44.5
			35	41.2
	162	60	32.7	42.7
Free space loss only	100		30	77.4
	162		32.7	72.5
Additional path loss only (dB)	162	60	32.7	29.8

The additional terrestrial path loss of 29.8 dB must be taken into considered in the link budget. Taking into account the mobile station e.i.r.p. at 0-degree elevation and the base station antenna gain at 0-degree elevation this leads to the received carrier power of -112.4 dBW for the mobile station to base station link and -109.4 dBW for the base station to mobile station link. The results are provided in Table A2-13.

TABLE A2-13

Link budget calculations for transmissions between mobile stations and base stations

Station type	**Units**	**Base station**	**Mobile station**
Output power	W	100	50
Output power	dBW	20.0	17.0
Feed loss	dB	2.0	1.0
Maximum antenna gain	dBd	6.0	0.0
Maximum antenna gain	dBi	8.2	2.2
Maximum e.r.p.	dBW	24.0	16.0
Maximum e.i.r.p.	dBW	26.2	18.1
Antenna height	m	60	2.0
Distance to horizon from station	km	27.7	5.0
Mobile station to base station range	km	32.8	
Free space loss	dB	106.9	
Additional terrestrial path loss	dB	29.8	
Received carrier power C	dBW	−112.4	−109.4

A2.2.2.3 *C*/*I* analysis for the interference levels from the VHF data exchange system – satellite downlink into communications links between base stations and mobile stations

As previously discussed in § A2.2.1, Table A2-5 shows the pfd values for the VDE-SAT downlink based on the pfd mask in Recommendation ITU-R M.2092-0 and the alternative pfd mask ensuring protection of the land mobile services. Based on these two pfd masks, and the base station characteristics given in Table A2-6, a link budget for the interference level from the VDE-SAT downlink into a base station can be calculated. Combining the interference levels with the received carrier power for transmissions between mobile stations and base stations from Table A2-13, the carrier to interference ratio (*C*/*I*) can be found. The outcome is presented in Tables A2-14, A2-15, A2-16 and A2-17.

TABLE A2-14

***C*/*I* analysis for transmissions from mobile station to base station with received carrier power, *C*, of -112.4 dBW and interference, *I*, resulting from the pfd-mask specified in Rec. ITU-R M.2092-0**

Elevation angle (degrees)	**pfd-mask specified in Rec. ITU-R M.2092-0** (dBW/(m^2 * 4 kHz))	**pfd per 16 kHz** (dBW/(m^2 * 16 kHz))	**Base station antenna gain including feed loss** (dBi)	**Effective area of base station antenna** (dB(m^2))	***I* per 16 kHz** (dBW)	***C*/*I*** (dB)
0	–149.0	–143.0	6.2	0.6	–142.4	30.0
10	–147.4	–141.4	1.7	−3.9	–145.3	32.9
20	–145.8	–139.8	−7.2	−12.8	–152.6	40.2
30	–144.2	–138.2	−8.4	−14.0	–152.2	39.8
40	–142.6	–136.6	−9.0	−14.6	–151.2	38.8
50	–139.4	–133.4	−9.4	−15.0	–148.4	36.0
60	–134.0	–128.0	−9.6	−15.2	–143.2	30.8
70	–133.0	–127.0	−9.7	−15.3	–142.3	29.9
80	–132.0	–126.0	−9.9	−15.4	–141.4	29.0
90	–131.0	–125.0	−9.9	−15.5	–140.5	28.1

TABLE A2-15[15]

***C/I* analysis for transmissions from mobile station to base station with received carrier power, *C*, of -112.4 dBW and interference, *I*, resulting from the alternative pfd-mask ensuring protection of the land mobile services**

Elevation angle (degrees)	**Alternative pfd mask ensuring protection of the land mobile services** (dBW/(m² * 4 kHz))	**pfd per 16 kHz** (dBW/(m² * 16 kHz))	**Base station antenna gain including feed loss** (dBi)	**Effective area of base station antenna** (dB(m²))	***I* per 16 kHz** (dBW)	***C/I*** (dB)
0	–150.9	–144.9	6.2	0.6	–144.3	31.9
10	–147.4	–141.4	1.7	−3.9	–145.3	32.9
20	–145.8	–139.8	−7.2	−12.8	–152.6	40.2
30	–144.2	–138.2	−8.4	−14.0	–152.2	39.8
40	–142.6	–136.6	−9.0	−14.6	–151.2	38.8
50	–139.4	–133.4	−9.4	−15.0	–148.4	36.0
60	–135.1	–129.1	−9.6	−15.2	–144.3	31.9
70	–135.0	–129.0	−9.7	−15.3	–144.3	31.9
80	–134.9	–128.9	−9.9	−15.4	–144.4	31.9
90	–134.8	–128.8	−9.9	−15.5	–144.3	31.9

TABLE A2-16

***C/I* analysis for transmissions from base station to mobile station with received carrier power, *C*, of -109.4 dBW and interference, *I*, resulting from the pfd-mask specified in Rec. ITU-R M.2092-0**

Elevation angle (degrees)	**pfd-mask specified in Rec. ITU-R M.2092-0** (dBW/(m² * 4 kHz))	**pfd per 16 kHz** (dBW/(m² * 16 kHz))	**Mobile station antenna gain including feed loss** (dBi)	**Effective area of mobile station antenna** (dB(m²))	***I* per 16 kHz** (dBW)	***C/I*** (dB)
0	–149.0	–143.0	1.2	−4.4	–147.4	38.0
10	–147.4	–141.4	0.9	−4.7	–146.1	36.7
20	–145.8	–139.8	0.0	−5.6	–145.4	36.0
30	–144.2	–138.2	−1.4	−7.0	–145.2	35.8
40	–142.6	–136.6	−3.3	−8.9	–145.5	36.1
50	–139.4	–133.4	−5.8	−11.4	–144.8	35.4
60	–134.0	–128.0	−8.9	−14.5	–142.5	33.1
70	–133.0	–127.0	−11.8	−17.4	–144.4	35.0
80	–132.0	–126.0	−12.3	−17.9	–143.9	34.5
90	–131.0	–125.0	−12.6	−18.2	–143.2	33.8

[15] Note that the worst-case *C/I* performance shown in Table A2-15 is 31.9 dB, which provides a 3.8 dB advantage to the *C/I* performance shown in Table A2-14.

TABLE A2-17[16]

C/I analysis for transmissions from base station to mobile station with received carrier power, C, of -109.4 dBW and interference, I, resulting from the alternative pfd-mask ensuring protection of the land mobile services

Elevation angle (degrees)	**Alternative pfd mask ensuring protection of the land mobile services** (dBW/(m^2 * 4 kHz))	**pfd per 16 kHz** (dBW/(m^2 * 16 kHz))	**Mobile station antenna gain including feed loss** (dBi)	**Effective area of mobile station antenna** (dB(m^2))	***I* per 16 kHz** (dBW)	***C/I*** (dB)
0	–150.9	–144.9	1.2	−4.4	–149.3	39.9
10	–147.4	–141.4	0.9	−4.7	–146.1	36.7
20	–145.8	–139.8	0.0	−5.6	–145.4	36.0
30	–144.2	–138.2	−1.4	−7.0	–145.2	35.8
40	–142.6	–136.6	−3.3	−8.9	–145.5	36.1
50	–139.4	–133.4	−5.8	−11.4	–144.8	35.4
60	–135.1	–129.1	−8.9	−14.5	–143.6	34.2
70	–135.0	–129.0	−11.8	−17.4	–146.4	37.0
80	–134.9	–128.9	−12.3	−17.9	–146.8	37.4
90	–134.8	–128.8	−12.6	−18.2	–147.0	37.6

A2.2.2.4 Conclusions

As shown in Tables A2-14 and A2-15, the carrier to interference ratios (C/I) for the mobile station to base station links with interference from the VDE-SAT downlinks will be significantly better, by at least 3.8 dB, when the alternative pfd mask for ensuring the protection of the land mobile service is used. For the base station to mobile station links, Tables A2-16 and A2-17 show that the C/I with interference from the VDE-SAT downlink is also significantly better when this alternative pfd mask is used.

Annex 1 of Recommendation ITU-R M.1808 provides SINAD ratio values of 12 dB to 20 dB for establishing degradation protection for land mobile systems. The C/N required to achieve these SINAD ratio values can be derived from the FM improvement formula[17], which calculates the audio S/N as a function of C/N in FM systems operating above the detection threshold. The detection threshold can also be referred to as the minimum discernible signal level. The FM improvement formula is as follows:

$$\left(\frac{S}{N}\right)_{FM} = \left(\frac{C}{N}\right) \cdot \frac{3}{2} \cdot \frac{BW_{FM}}{B_m} \cdot \left(\frac{\Delta f}{B_m}\right)^2$$

Or in dB form as:

$$\left(\frac{S}{N}\right)_{FM} = \left(\frac{C}{N}\right) + 1.8 + 10\log_{10}\left(\frac{BW_{FM}}{B_m}\right) + 20\log_{10}\left(\frac{\Delta f}{B_m}\right)$$

where BW_{FM} : bandwidth of the FM signal obtained using Carson's rule

Δf : peak frequency deviation which is equal to $\Delta f = k_f \cdot m_p$

[16] Note that the C/I performance in Table A2-17 is significantly better than Table A2-16.

[17] "Reference Data for Radio Engineers," Fifth Edition, March, 1970, Section 21-11 to 21-12.

B_m : bandwidth of the information signal.

Table A2-18 shows the *C*/*N* values required to achieve SINAD ratio values of 12 dB and 20 dB, respectively for FM system with 12.5 kHz and 25 kHz channel spacing.

TABLE A2-18

C/N required for audio SINADs of 12 dB and 20 dB in FM systems with 12.5 and 25 kHz channel spacings

Channel spacing	12.5	25	kHz
SINAD	12	20	dB
S/N_{FM}	11.7	20	dB
B_m	3	3	kHz
Δf	2.5	5	kHz
BWFM	11	16	kHz
C/N	7.8	6.4	dB

Therefore, a worst-case *C*/*I* level of more than 31.9 dB (Table A2-15) for the mobile station to base station link with interference from the VDE-SAT downlink provides considerable margin to the *C*/*N* values of 7.8 dB and 6.4 dB required to meet the SINAD degradation protection values for land mobile systems provided in Annex 1 of Recommendation ITU-R M.1808.

Also according to Annex 1 of Recommendation ITU-R M.1808, digital land mobile systems use C4FM modulation and a BER threshold of 5%. C4FM modulation has two bits per symbol. Given that *C*/*I* corresponds to symbol energy to noise density ratio (E_s/N_0), digital land mobile systems have a typical *C*/*(N+I)* threshold of 15 dB. A *C*/*I* level of more than 31.9 dB (Table A2-15) for the mobile station to base station link with interference from the VDE-SAT downlink provides considerable margin for BER.

Therefore, based on the results of this *C*/*I* analysis, it can be concluded:

1 That a *C*/*I* level of better than 31.9 dB can be achieved and an improvement of 3.8 dB or better can be realized if the alternative pfd mask is used, and

2 That this *C*/*I* level provides considerable margin for land mobile systems to satisfy the performance criteria specified in Annex 1 of Recommendation ITU-R M.1808.