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Radiolocation service sharing feasibility in the 154-156 MHz bands

M Series

Mobile, radiodetermination, amateur and related satellite services

International Telecommunication Union

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REPORT ITU-R M.2172

Radiolocation service sharing feasibility in the 154-156 MHz bands

(2009)

Executive summary

The report summarizes the sharing studies conducted in accordance with Resolution 611 (WRC-07) on WRC-12 Agenda item 1.14 which is to consider a primary allocation to the radiolocation service in the portion of the band 30-300 MHz for the implementation of new applications in the radiolocation service. The sharing studies presented in this Report were conducted in frequency band 154-156 MHz in order to assess sharing feasibility with fixed and mobile services. The results of sharing studies are summarized in the conclusion section of the Report.

1 Introduction

Studies on protection criteria and technical characteristics of the radiolocation systems operating in VHF frequency range resulted in preparation of Recommendation ITU-R M.1802 Characteristics and protection criteria for radars operating in the radiolocation service in the frequency band 30-300 MHz. This Recommendation contains the typical characteristics of radars operating in the VHF band.

Development of new applications in the radiolocation service closely related to significant growth of the number of space objects including artificial debris. These applications are planned for used of aerospace surveillance and tracking the launch and manoeuvring of spacecrafts. They are based on design of effective and economical radars that can be implemented in the VHF range.

WRC-12 Agenda item 1.14 was adopted at WRC-07 in order to address existing lack of spectrum available for radiolocation service in VHF band required for large-scale air and space surveillance operations.

VHF radio waves propagate well through the ionosphere, thus enabling various space object detection applications including remote space sensing and asteroid detection, as well as for defining the position of natural and artificial earth satellites, from terrestrial-based radiolocation systems.

ITU-R studies based on the current requirements were limited to radiolocation systems for space-object detection from terrestrial locations in a portion of the band 30-300 MHz up to 2 MHz bandwidth systems, however allocation with a wider frequency range may provide flexibility and facilitate sharing with existing services.

This report presents sharing studies between the radiolocation services systems and systems from other services in the band 154-156 MHz.

2 Current use of the band 154-156 MHz and interference susceptibility of systems operating in the considered band

The band 154-156 MHz is currently allocated worldwide to the fixed and mobile services on a primary basis.

2.1 Fixed, mobile, maritime mobile and aeronautical mobile services susceptibility used in the study

Recommendation ITU-R M.1808 provides technical and operational characteristics of conventional and trunked land mobile systems.

Section 2.1 of Annex 1 of Recommendation ITU-R M.1808 states 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”.

Reference[1] shows that in the 108-389 MHz frequency band, a permitted interference field strength is 12 dB(μV/m) in 25 kHz for co-channel operation for 10% of time and 50% of locations. This value is commonly used in many Region 1 countries in bilateral and multilateral coordination in the land mobile service. Exceeding the above interference field strength reflects the need for coordination and for detailed studies on interference effect. Since it is applied at the border of potentially affected administrations and specifies the limitation for interference field strength it is not dependant on different mobile service receiver characteristics.

3 Characteristics of radiolocation service (RLS) used for the sharing studies

3.1 Spectrum requirement

The spectrum requirement in the 30-300 MHz frequency range is currently up to 2 MHz for radiolocation systems. The band 154-156 MHz was proposed in order to address this requirement.

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[1] Recommendation CEPT T/R 25-08 [Rev.2008] – Planning criteria and coordination of frequencies in the land mobile service in the frequency range 29.7-921 MHz.

3.2 Transmitter and receiver characteristics used for the sharing study

TABLE 1

Radiolocation service (RLS) 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	
Main beam pattern, degree – horizontal plane (Rx/Tx) – vertical plane (Rx/Tx)	 2.6/5.2 2.6/2.6	
Receiver noise temperature (K)	800	
Operational receiver passband (kHz) (−3 dB level)	0.132	625
Receiver thermal noise (dBW)	−178.4	−141.6

Characteristics of unwanted emission of radiolocation systems are given in § 3 of Appendix 3.

4 Sharing studies methodology

4.1 Impact from RLS into fixed, mobile and maritime mobile services systems

For terrestrial (fixed, mobile and maritime mobile) radiocommunication stations, Recommendation ITU-R P.1546-4 methodology is used for calculation of propagation losses , and it is possible to determine limiting distances where this allowable field strength will be implemented. This distance will obviously be determined by propagation environment and transmitter e.i.r.p.

Space navigation and tracking of the natural and man-made space objects does not require a large number of space surveillance radars. It seems sufficient for any major space-exploring agency to operate 1-2 such radars, taking into account the opportunity to establish data exchange networks between such stations to update the orbital parameters of natural and man-made space assets.

Thus it is expected that MS/FS stations may be susceptible to interference produced by no more than one space surveillance radar. Therefore, in sharing studies single radar is considered.

5 Results

5.1 Impact from RLS into fixed, mobile, maritime mobile and aeronautical (OR) mobile services systems

5.1.1 Results of sharing studies in the frequency band 154-156 MHz

The sharing studies between space surveillance radars and fixed/mobile stations in the 154-156 MHz frequency band were conducted using two approaches.

The first approach to studies is based on protection criteria and technical characteristics of mobile stations as specified in Recommendation ITU-R M.1808 and indicated in § 2.1.

Those studies have defined separation distances to enable acceptable interference levels to the mobile stations. The estimation results for narrow-band radars are shown in Table 2 and those for wideband radars are presented in Table 3. The estimation of interference caused by a wideband signal assumed that only a portion of the electromagnetic energy emitted from the radar transmitter fell into the receiver passband.

TABLE 2

Protection distances for the narrow-band signal

***I/N* (dB)**	**E_{add} dB(µV/m)**	**Protection distance (km)**	
		Land path	**Sea path**
Without polarization decoupling			
−6	−11.9	650	710
−10	−15.9	695	760
With polarization decoupling (polarization discrimination is assumed to be 16 dB)			
−6	−11.9	470	520
−10	−15.9	520	570

TABLE 3

Protection distances for the wideband signal

***I/N* (dB)**	**E_{add} dB(µV/m)**	**Protection distance (km)**	
		Land path	**Sea path**
Without polarization decoupling			
−6	−11.9	490	540
−10	−15.9	540	590
With polarization decoupling (polarization discrimination is assumed to be 16 dB)			
−6	−11.9	320	360
−10	−15.9	365	400

The correction factor is defined as a ratio between the radar signal bandwidth and mobile service channel bandwidth. Technical characteristics from Table 1 and the channel bandwidth[2] of 25 kHz results in the correction factor of 14 dB to be equivalent to reducing the e.i.r.p. towards the horizon down to 41 dBW.

The discussed estimations show that the protection distances for the wideband signal do not exceed 590 km assuming no polarization decoupling and 400 km assuming polarization decoupling. Narrow-band operation features significant increase in the protection distances, which could be up to 760 km assuming no polarization decoupling and up to 570 km assuming polarization decoupling. These results are based on assumed base station antenna heights of 60 m for fixed/ mobile systems; higher base station antenna heights would lead to greater separation distances.

The obtained levels of protection distances would not signify infeasibility of sharing between the space surveillance radars and the mobile stations. They only imply that the narrow-band operating radar would cause interference to mobile stations only in a co-channel scenario, and that the problem of their shared operation could be possibly addressed using interference mitigation techniques and frequency-distance separation.

The additional study provided in Appendix 2. This study is based on propagation model in Recommendation ITU-R P.1546 with 1% of time propagation mode.

The study show that the required protection distances are as follows:

– for the narrow-band radar signal:
  – $I/N = -6$ (dB): 892 km for analogue to 929 km for digital;
  – $I/N = -10$ (dB): 939 km for analogue to 979 km for digital;
– for the wideband radar signal:
  – $I/N = -6$ (dB): 706 km for digital to 721 km for analogue;
  – $I/N = -10$ (dB): 748 km for digital to 763 km for analogue.

The difference between protection distances obtained in this study with respect to the results in other studies is because of the 1% of time propagation curves which were used in calculations. However, it should be noted that the application of 1% of time propagation curves was not agreed in ITU-R studies under WRC-12 Agenda item 1.14 and its application subject to agreement between administrations concerned. It also worth mentioning that the application, for example, of 50% of time propagation curves will result in much lower distances (around 300 km lower) required for protection of mobile services. In this study the scenario was considered when surrounding clutter is not obstructed and antenna height much higher than the height of surrounding clutter.

The results mentioned in above studies correspond to worst case scenario and do not take into account statistical nature of interferences at FS/MS receiver front end. The mathematical model of antenna which characteristics are presented in Table 1 was developed in order to estimate impact of statistical nature of interferences. In interference impact simulation it was taken into account that radar antenna scans in the vertical plane at angle from 2 to 70° and in the horizontal plane at angle from 0 to 360°. The simulation results are presented in Table 4.

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[2] Assumption on channel bandwidth of 25 kHz for mobile service. The results may differ if the MS is operating with narrower bandwidth.

TABLE 4

The simulation results of statistical interference impact

<table>
<tr><th colspan="3">Antenna height of MS/FS systems is 15 m</th></tr>
<tr><td>I/N
(dB)</td><td colspan="2">Narrow-band signal</td></tr>
<tr><td rowspan="7">−6</td><td>Without cross-polarization</td><td>With cross-polarization</td></tr>
<tr><td>Separation distance (km)</td><td>Separation distance (km)</td></tr>
<tr><td>460</td><td>290</td></tr>
<tr><td colspan="2">Wideband signal</td></tr>
<tr><td>Without cross-polarization</td><td>With cross-polarization</td></tr>
<tr><td>Separation distance (km)</td><td>Separation distance (km)</td></tr>
<tr><td>310</td><td>170</td></tr>
</table>

The analysis of the results shows that for the selected separation distances $I/N = -6$ dB is exceeded at not more than 20% of time.

The increase of MS/FS station antenna height up to 65 m leads to increase of distances where $I/N = -6$ dB will be exceeded at not more than 20% of time. The simulation results of interference impact for FS/MS station antenna height of 65 m are presented in Table 5.

TABLE 5

The simulation results of statistical interference impact

<table>
<tr><th colspan="3">MS/FS system antenna height of 65 m</th></tr>
<tr><td>I/N
(dB)</td><td colspan="2">Narrow-band signal</td></tr>
<tr><td rowspan="7">−6</td><td>Without cross-polarization</td><td>With cross-polarization</td></tr>
<tr><td>Separation distance (km)</td><td>Separation distance (km)</td></tr>
<tr><td>510</td><td>330</td></tr>
<tr><td colspan="2">Wideband signal</td></tr>
<tr><td>Without cross-polarization</td><td>With cross-polarization</td></tr>
<tr><td>Separation distance (km)</td><td>Separation distance (km)</td></tr>
<tr><td>350</td><td>205</td></tr>
</table>

The analysis of the obtained results shows that the separation distance, which provides protection criteria excess at the indicated percent of time with increase of receiving antenna height up to 65 m, increases not more than by 50 km.

Analysis of Recommendation ITU-R F.758-4 shows that long-term protection criteria is used to provide protection of fixed service. The $I/N = –6$ dB which can be exceeded at not more than 20% of time is used as such criteria.

Analysis of Recommendation ITU-R F.755-2 shows that the frequency band 150 MHz is used in the fixed service for systems which provide operation of point-to-multipoint communications.

Analysis of Recommendation ITU-R. M.1808 shows that this frequency band is used for similar systems in the mobile service. The analysis of the technical characteristics of FS and MS systems in this frequency band leads to conclusion that the considered systems have similar technical characteristics. Therefore it can be concluded that the protection distances for FS and MS systems in this frequency band will be similar i.e. the protection distances for MS systems will be not worse than indicated in Table 5.

The second approach protection criterion for fixed/mobile stations used an permitted interference field-strength level of 12 dB(µV/m) in 25 kHz as indicated in § 2.1.

The conducted studies based on a maximum interference field strength of 12 dB(µV/m) resulted in the following conclusions:

– Protection distances for MS stations depend significantly on height of MS base station antenna.
– Propagation conditions affect the protection distance values significantly. Location of mobile base stations in urban conditions would result in the protection distances 100 km less than those obtained for rural conditions.
– Taking into account the above conclusions it is valid to assume that the usage of screening facilities can significantly reduce the interference caused by space surveillance radar in the direction of MS base stations.

The required protection distance for MS based stations (using antenna height of base stations 30 m):

– for the radar wideband signal (Radar B) km would exceed 152 km for no more than 0.1% of time;
– for the radar narrow-band signal (Radar A) km would not exceed 314 km for more than 0.1% of time.

The required protection distance for MS user terminals:

– for the radar wideband signal (Radar B) for 0.01% of time −70 km;
– for the radar narrow-band signal (Radar A) for no more than 0.1% of time − 155 km.

Thus the necessary protection distance for MS based stations would not exceed 315 km for more than 0.1% of time, depending on the class of the signal and for user terminals it should not exceed 155 km at more than 0.1%.

The necessary protection distance for FS stations would not exceed 315 km for more than 0.00028% of time depending on the class of the signal.

The obtained protection distance values are required for MS and FS protection for no more than 0.1% of time. For 99.9% of time the protection distances for MS and FS should be significantly shorter than those obtained in this study.

The details of sharing studies are provided in Appendix 1.

5.1.2 Possible mitigation technique to protect mobile service stations

The issue for sharing between the space surveillance radars and mobile stations admits the other solution, featuring a selection of appropriate radar operating frequencies.

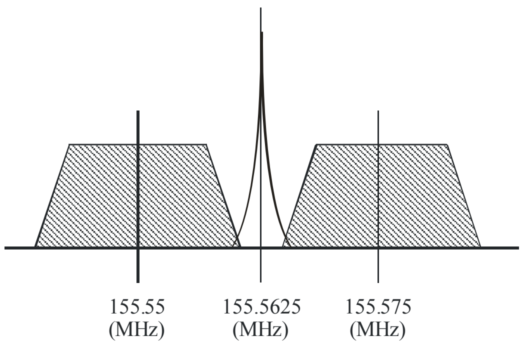
Regarding the channel arrangement for mobile stations in the frequency range, the narrow-band operation modes for space surveillance radars could be used when arranging the carriers between the channels of the mobile service. Since the mobile service channels are usually arranged with a regular frequency spacing (a step of 25 kHz) with a sufficient guard-band then the existing mobile stations would not be affected by interference, even if narrow-band space surveillance radars operated between the mobile service channels.

The example of a possible mitigation technique based on 25 kHz channelization plan is provided below.

For example, if two mobile stations operate at frequencies of 155.550 MHz and 155.575 MHz, then it is probable that a space surveillance radar (narrow-band Radar A) operating at 155.5625 MHz would not cause interference to those mobile stations. This example is illustrated in Fig. 1.

FIGURE 1

Identification of operating frequency for a space surveillance radar (narrow-band Radar A)



The above-mentioned example of mitigation technique of interference impact is not the only one. Another example of mitigation technique that can be considered is an increase of elevation angle of the radar antenna main lobe while scanning the selected azimuths. Thus increase of the elevation angle from 2º to 4º provides reduction of e.i.r.p. by 9 dB towards the horizon and increase of the minimum elevation angle to 5º provides reduction of e.i.r.p. by 12 dB towards the horizon. In accordance with the results obtained in Annex 1 the required protection distance can be reduced by 80 km for the elevation angle of 4º and by 100 km for the elevation angle of 5º. Additional reduction of protection distance under increase of radar antenna elevation angle can be achieved by changing of current distribution at radar antenna aperture.

5.1.3 Results of adjacent band compatibility between space surveillance radars operating in the 154-156 MHz and MMS stations operating in the band above 156 MHz

These studies (see Appendix 3) refer to estimating the out-of-band emissions of the radiolocation service operating in the 154-156 MHz frequency band to assess feasibility of sharing with maritime mobile service above 156 MHz. In spite of the fact that studies were not requested to be conducted in the adjacent frequency bands, it is obvious that estimation of out-of-band compatibility for radiolocation service and determination of appropriate conditions for sharing would facilitate the sharing for a new potential allocation.

The conducted studies show that out-of-band emissions from space surveillance radars operating in the 154-156 MHz frequency band would cause no unacceptable interference to MMS receivers operating in the 156-174 MHz frequency band. Imbedding the band-pass filters in the transmitters providing for additional attenuation by 30 dB outside the operation frequency band together with polarization discrimination would ensure feasible operation of radiolocation radars and MMS stations even in the same geographical areas. However it is to mention that given operation scenario would not be practically implemented.

5.2 Impact of FS, MS into space surveillance radars receivers

5.2.1 Impact of mobile service stations into space surveillance radars receivers

The protection distances were calculated for different radar operation modes in order to estimate the impact of interferences caused by the MS stations into space surveillance radars. It was taken into account that antenna pattern of the space surveillance radar is narrow in the horizontal plane and the average radius of the MS station coverage area is 50 km (see Recommendation ITU-R M.1808). Taking account of these factors, it can be concluded that if several MS stations operating in the same frequency with radars fall into the main lobe of the radar antenna pattern, then the main interferences will be caused by the nearest MS station. Therefore only interference caused by one MS station is taken into account in the estimation of the required protection distances.

The maximum permissible interference level at the radar receiver input is defined for calculation of the protection distances. The radar receiver thermal noise values of −178.4 dBW in the narrow-band mode and −141.6 dBW in the wideband mode are given in Table 1. The $I/N = -6$ dB is used as the protection criterion for the space surveillance radars as specified in Recommendation ITU-R M.1802.

The use of this protection criteria shows that the maximum interference power at the radar receiver input is:

– –184.6 dBW in the narrow-band mode;

– –147.6 dBW in the wideband mode.

The obtained maximum interference power values at the receiver input correspond to the following maximum permissible field strength at the point of the radar antenna location:

– –39.4 dB(μV/m) for the narrow-band mode;

– –2.6 dB (μV/m) for the wideband mode.

The protection distances for different operation modes of the space surveillance radar were defined for the following typical characteristics of the MS base stations and user terminals:

– the MS base station e.r.p. is 19 dBW;

– the MS base station antenna height is 60 m;

– the MS user terminal e.r.p. changes from –3 dBW up to 18 dBW depending on the used antenna type;

– the MS user terminal antenna height is 2 m;

– the MS bandwidth is 25 kHz.

The calculation of the protection distance for narrow-band operation mode assumes that only a portion of interference power emitted by the MS station will fall into the radar receiver input. The calculations of the protection distances are given for 10% of time and 50% of locations in accordance with methodology specified in Recommendation ITU-R P.1546-4.

The performed studies show that for the above-mentioned characteristics of the MS base stations the protection distance value required for interference-free operation of the space surveillance radar is:

– without polarization discrimination:
  – from 340 km to 380 km for the narrow-band operation mode;
  – from 215 km to 250 km for the wideband operation mode;

– taking into account polarization discrimination (16 dB polarization discrimination):
  – from 200 km to 230 km for the narrow-band operation mode;
  – from 100 km to 130 km for the wideband operation mode.

For the above-mentioned characteristics of the MS user terminals, the protection distance value required for interference-free operation of the space surveillance radar is:

– without polarization discrimination:
  – from 120 km to 340 km for the narrow-band operation mode;
  – from 30 km to 210 km for the wideband operation mode;
– taking into account polarization discrimination (16 dB polarization discrimination):
  – from 30 km to 190 km for the narrow-band operation mode;
  – from 10 km to 60 km for the wideband operation mode.

The analysis of the obtained results shows that for the interferences caused by the MS base stations the protection distances required for interference-free operation of the space surveillance radar taking into account possible polarization discrimination are less than the protection distances required for free-interference operation of the MS stations. The protection distance for the user terminals depends significantly on the terminal e.r.p. value and antenna type. The protection distances for the radars from the user terminals with omnidirectional antennas are significantly less than the distances required for protection of the user terminals from the space surveillance radar emissions.

5.2.2 Impact of fixed service stations into space surveillance radar receivers

In Recommendation ITU-R F.755-2 it is mentioned that the range 150 MHz is used for systems which provide operation of point-to-multipoint communications. Thus MS and FS systems are used for the similar purpose in the frequency band 154-156 MHz. Therefore it can be assumed that MS and FS systems have the similar technical characteristics in this frequency band. It leads to the conclusion that the protection distances obtained in § 5.2.1 will be applicable for protection of space surveillance radars from FS systems emission, operating in the frequency band 154-156 MHz.

6 Conclusions

The conducted studies based on maximum *I*/*N* levels of −6 and −10 dB resulted in the following conclusions (see § 2.1):

The discussed estimations show that the protection distances for the wideband signal with the *I*/*N* equal to −10 dB do not exceed 590 km assuming no polarization decoupling and 400 km assuming polarization decoupling. Narrow-band operation using an *I*/*N* of −10 dB results in a significant increase in the protection distances which could be up to 760 km assuming no polarization decoupling and up to 570 km assuming polarization decoupling. These results are based on assumed base station antenna heights of 60 m for fixed/mobile systems; higher base station antenna heights would lead to greater separation distances.

If the propagation curves of 1% of time in Recommendation ITU-R P.1546-4 are considered then the protection distances would be higher than the above-mentioned.

The conducted studies based on a maximum interference field strength of 12 dB(μV/m) resulted in the following conclusions:

– Protection distances for MS stations depend significantly on height of MS base station antenna.

– Propagation conditions affect the protection distance values significantly. Location of mobile base stations in urban conditions would result in the protection distances 100 km less than those obtained for rural conditions.

– Taking into account the above conclusions it is valid to assume that the usage of screening facilities can significantly reduce the interference caused by space surveillance radar in the direction of MS base stations.

The required protection distance for MS based stations (this study assumed a height of base stations 30 m; typical base stations antenna heights will vary and are often greater; therefore, affecting the protection distance results):

– for the radar wideband signal (Radar B) km would exceed 152 km for no more than 0.1% of time;

– for the radar narrow-band signal (Radar A) km would not exceed 314 km for more than 0.1% of time.

The required protection distance for MS user terminals:

– for the radar wideband signal (Radar B) for 0.01% of time −70 km;

– for the radar narrow-band signal (Radar A) for no more than 0.1% of time − 155 km.

Thus the necessary protection distance for MS based stations would not exceed 315 km for more than 0.1% of time, depending on the class of the signal and for user terminals it should not exceed 155 km at more than 0.1%.

The necessary protection distance for FS stations would not exceed 315 km for more than 0.00028% of time depending on the class of the signal.

The obtained protection distance values are required for MS and FS protection for no more than 0.1% of time. For 99.9% of time the protection distances for MS and FS should be significantly shorter than those obtained in this study.

Taking into account the long-term protection criteria the protection distances for MS/FS will not exceed 510 km.

The conducted studies in the 154-156 MHz band show that sharing between the space surveillance radars and fixed and land mobile stations would be feasible when using adequate protection distances and appropriate mitigation techniques.

Appendix 1

Estimation of interference caused by space surveillance radar radiation to MS/FS stations

This appendix presents updated characteristics related to space surveillance radars operating in the 154-156 MHz frequency band. It also discusses scenarios related to the impact of interference caused by space surveillance radars to mobile/fixed (MS/FS) service stations. Also it contains the simulation results of the space surveillance radar interference to MS/FS stations. The results were obtained using Monte-Carlo simulation software program (SEAMCAT[3]).

The study presented in this appendix is using protection criterion for fixed/mobile stations based on permissible interference field-strength level of 12 dB(µV/m) as indicated in § 2.1 of the report.

1 Refinement of radiolocation stations characteristics and scenarios of interference caused by space surveillance radars to MS/FS stations

1.1 Refinement of technical characteristics for space surveillance radars

Recommendation ITU-R M.1802 provides characteristics of the space surveillance radars on the basis of the worst case of their interference effect on MS/FS stations. In that case maximum e.i.r.p. in the horizon direction is 81 dBW. Since the main lobe of the radar antenna pattern is slightly raised above the horizon its antenna gain in the horizon direction reduces significantly compared with that in the direction of the pattern maximum. Therefore practical e.i.r.p. of the space surveillance radars in the horizon direction is 55 dBW (for Radar A and B), 59 dBW (for Radar C) and those radars operate at both vertical and horizontal polarizations. It is obvious that reduction in radar e.i.r.p. in the horizon direction would result in reduction of protection distance for MS/FS stations thus facilitating their compatibility with radiolocation stations. Additional reduction of the protection distance could be gained using polarization decoupling.

As specified in Recommendation ITU-R P.1406-1, propagation of radio waves over the Earth's surface could feature scattering a portion or all of the transmitted energy due to different polarization from emission polarization related to diffraction and reflection of the radio waves. Therefore it is appropriate to take this effect into consideration using the cross-polarization discrimination (XPD) factor defined in Recommendation ITU-R P.310-9.

The XPD factor level is a function of emitted radio-wave frequency. For example, the averaged level of the XPD factor for a frequency of 900 MHz varies from 5 dB to 8 dB for urban and rural areas, and exceeds 10 dB in regular terrain. Reducing the frequencies results in an increasing XPD factor, which becomes equal to 18 dB at 35 MHz.

However, Recommendation ITU-R BT.419-3 specifies that cross-polarization discrimination is 16 dB in the 174-230 MHz and 470-862 MHz frequency bands. The cross-polarization discrimination levels from that Recommendation may be used for approximating the level of cross-polarization product in the 154-156 MHz band. The approximating plot in the 35-900 MHz band is shown in Fig. 2.

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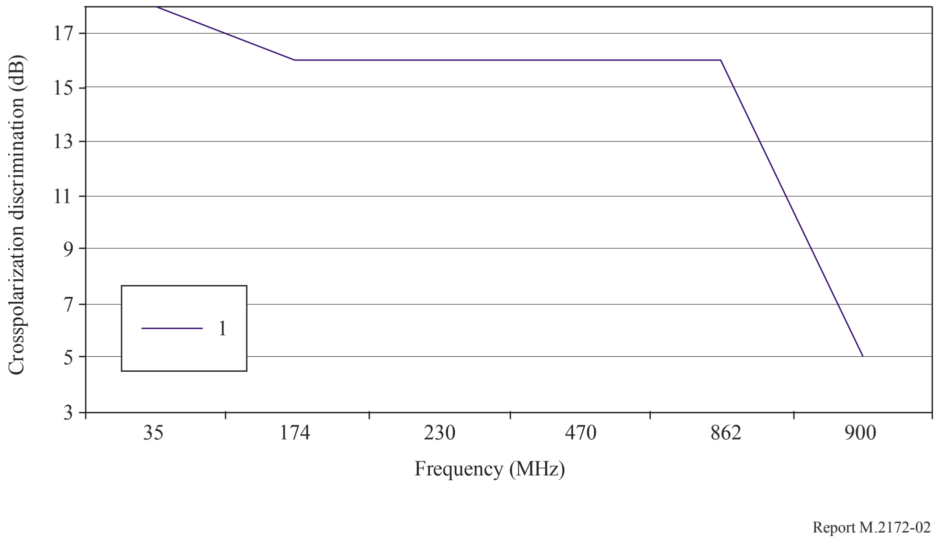
3 http://www.ero.dk/seamcat.

FIGURE 2

Frequency relation for XPD factor



Analysis of the obtained relation shows that additional interference attenuation level due to polarization decoupling in the 154-156 MHz frequency band could be specified to be 16.2 dB for any propagation conditions. For the cases when polarization of interfering signal cannot be fixed (e.g. mobile user terminals) this value may be significantly lower.

Recommendation ITU-R M.1802 specifies that the space surveillance radars use phased array antennas. The phased antenna consists of a set of similar radiating elements and each of them is used for shaping a total antenna pattern. Phased antenna pattern depends on a quantity of array elements, a distance between them, a rule of their spatial arrangement and on a rule of distributing the driving current amplitudes in the array elements.

Flat equidistant antenna arrays with their elements arranged in a single plane are widely used in radiolocation. The pattern of a specific rectangular flat array (see Fig. 3) is described with the following equation:

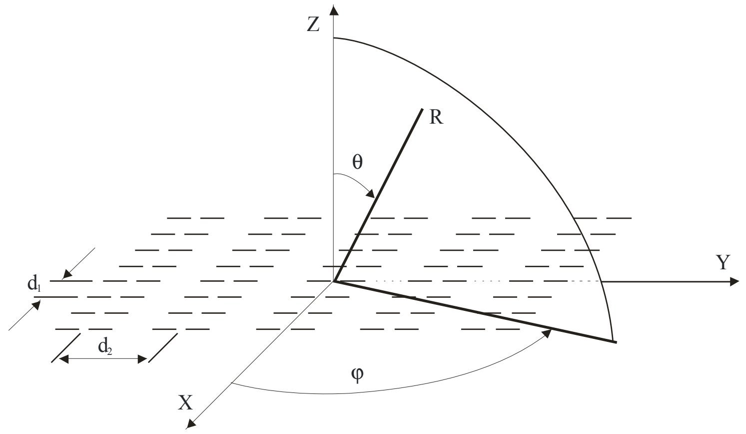
$$F(\theta,\varphi)=f_1(\theta,\varphi)\frac{\sin\left[\frac{N}{2}(\beta d_1\sin\theta\cos\varphi-\xi_1)\right]}{\sin\left[\frac{1}{2}(\beta d_1\sin\theta\cos\varphi-\xi_1)\right]}\frac{\sin\left[\frac{M}{2}(\beta d_2\sin\theta\sin\varphi-\xi_2)\right]}{\sin\left[\frac{1}{2}(\beta d_2\sin\theta\sin\varphi-\xi_2)\right]}$$

where:

$f_1(\theta,\varphi)$:	pattern of a single element in the array
d_1 :	distance between the array elements in the X-axis
d_2 :	distance between the array elements in the Y-axis
$\beta = 2\pi/\lambda$, λ :	operation wavelength
N :	number of array elements in the X-axis
M :	number of array elements in the Y-axis
ξ_1 :	drive currents phase displacement between adjacent elements in the X-axis
ξ_2 :	drive currents phase displacement between adjacent elements in the Y-axis
θ,φ :	spherical coordinates for the array pattern reference point.

FIGURE 3

Example flat rectangular antenna array



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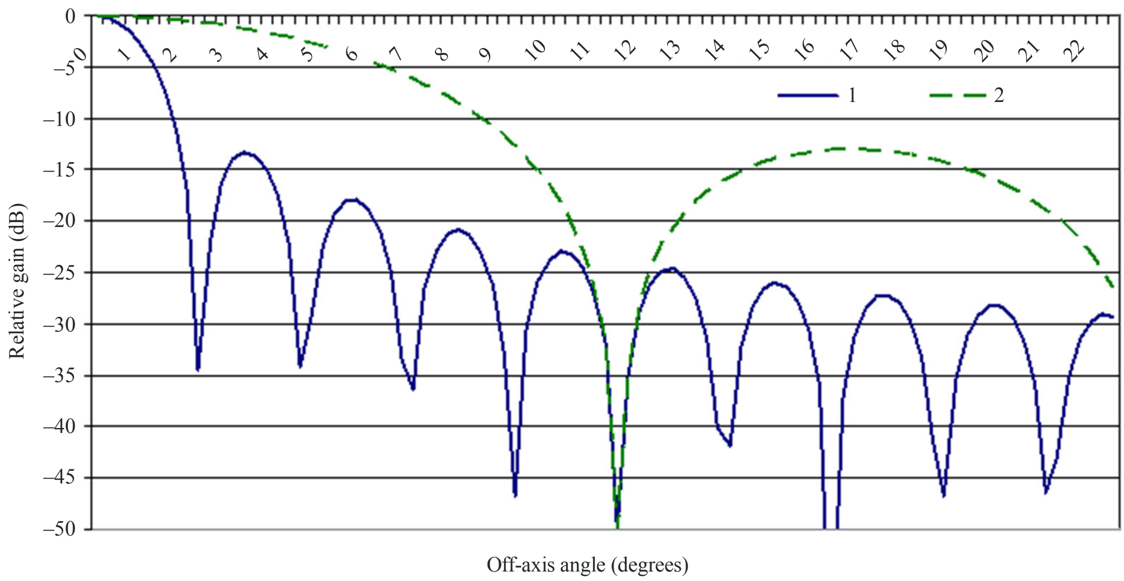
It is worth mentioning that the width of the array main lobe in the both primary planes is defined by dimensions and shape of array aperture, by rule of power distribution between array elements and by pattern of a single element. For example, Fig. 4 shows patterns for rectangular arrays of 5λ × 5λ (curve 2) and 25λ × 25λ (curve 1) for equi-amplitudinal drive and for array elements as isotropic emitters. Analysis of Fig. 4 data shows that relative side lobe level in the primary planes is of −13 dB, irrespective of the array size.

FIGURE 4

Antenna array pattern



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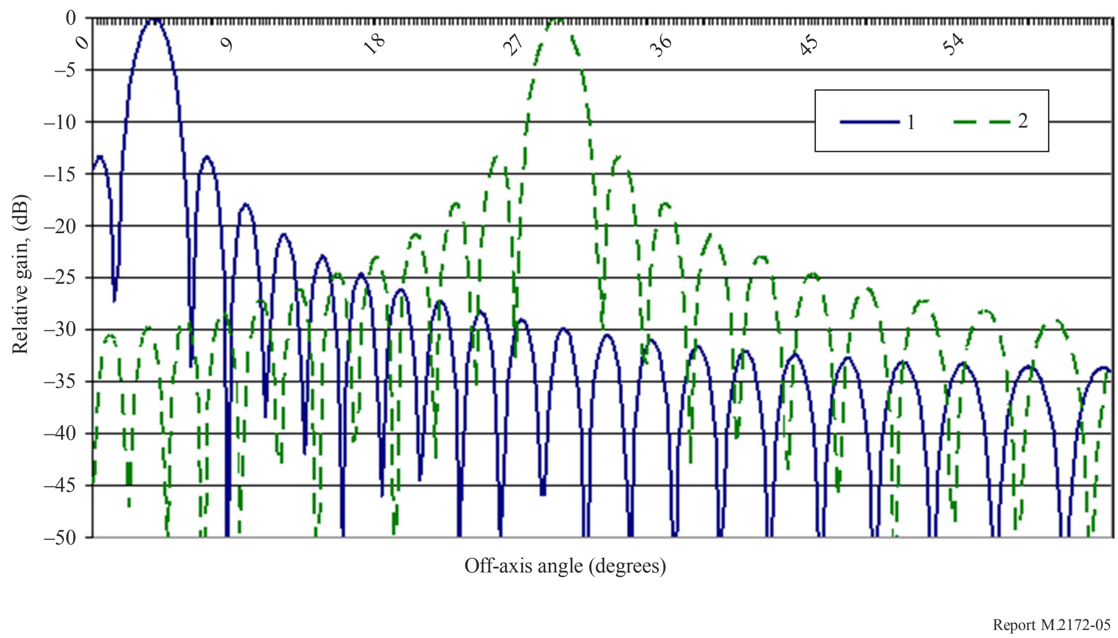
Varying the rule of drive amplitude distribution by array modules provides for controlling the side-lobe level. In particular, this explains the transmitting antenna side-lobe level of −16 dB in the vertical plane, as implied in Recommendation ITU-R M.1802. Additional opportunity for controlling the side-lobe level is provided by selecting the shape of antenna aperture.

Thus, transition from a rectangular aperture array to one with a circular aperture would result in obtaining a side-lobe level of −17 dB.

The advantage of phased array consists in the feasibility of independent electronic control for current phase and amplitude in each array element usually using the computer. Varying the phase incursion between array elements (ξ_1, ξ_2) provides for scanning the beam electronically. For example, Fig. 5 shows the pattern of antenna having a rectangular aperture of $25\lambda \times 25\lambda$ with phase shift of 0.2 rad (curve 1) and 1.5 rad (curve 2) between the array elements. Analysis of the obtained results shows that increase in phase displacement between the array elements is accompanied with an increasing shift of the main lobe from normal to its aperture with the constant level of side lobes.

FIGURE 5

Scanning the array pattern



The principle of controlling the main lobe scanning electronically may be applied for arrays operating in both transmitting and receiving modes. That approach to controlling the spatial aiming of the main lobe provides for a higher scanning rate, as required for tracking the moving assets.

1.2 Refinement of scenario for interference effect from space surveillance radars to MS stations

Definition of interference effect on MS stations should consider the following features of their operation:

– An MS base station is a stationary one and it serves user terminals in its service area.

– Distance between the base station and the space surveillance radar is constant and interference power is a function of base station antenna gain, radar antenna gain and its pattern shape as well as beam scan rate.

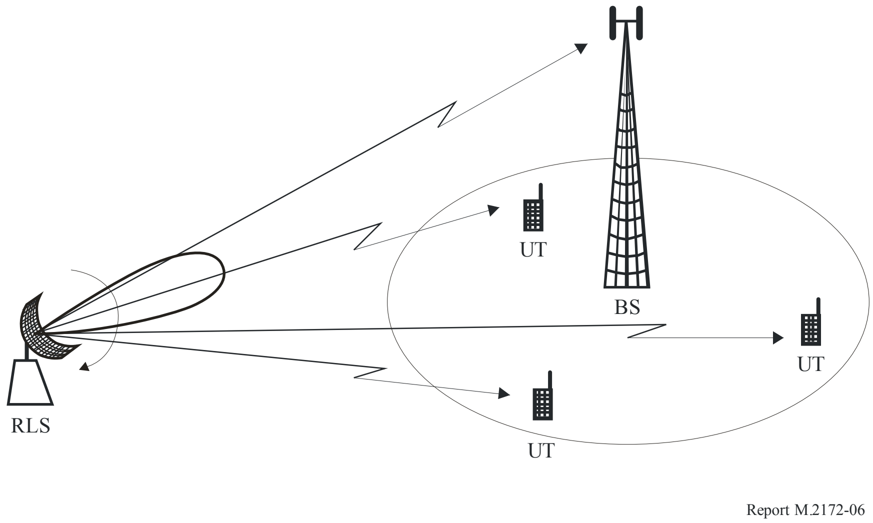
– User terminals move randomly within the service area. Thus distance between the user terminals and the radar antenna varies in a random way from minimum to maximum values.

– The user terminals and the base stations are equipped with horizontally omnidirectional antennas.

Figure 6 shows a summarized scenario of interference caused by space surveillance radars to mobile communication links.

FIGURE 6

Summarized scenario of interference caused by space surveillance radars to MS stations



To simplify the summarized scenario may be divided into two scenarios. They are:

– a space surveillance radar causes interference to a MS base station receiver having antenna at a fixed height over the Earth's surface. In that case distance between the space surveillance radar antenna and MS base station receiving antenna would remain constant and a level of interference caused to the MS base station is a function of the radar antenna pattern width and its antenna scan rate (Scenario 1);

– a space surveillance radar causes interference to a MS user terminal receiver which antenna height could evenly vary from 1 m to 2.5 m. In that case, the user terminal could move within the service area thus varying the distance from the radar antenna to that of the user terminal. Variation of interference level affecting the user terminal is a function of its location variation and radar antenna directivity parameters (Scenario 2).

The following factors which could define interference caused by space surveillance radars to MS base stations and user terminals should be taken into consideration. They are:

– heights of MS receiving antennas and that of radar transmitting antenna;

– polarization decoupling;

– terrain irregularities for "radar-MS station receiver" route.

Interference level could be estimated using Recommendation ITU-R P.1546-4 adapted in the SEAMCAT software which could be amended to account for additional attenuation due to urban wave propagation conditions if required.

1.3 Refinement of scenario for interference effect from space surveillance radars to FS stations

Development of scenario for interference caused to FS stations should consider certain factors. They are:

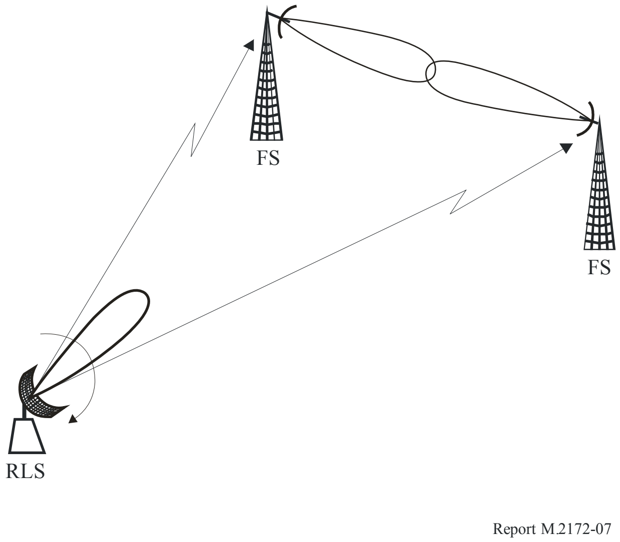
– location of FS stations remains constant in relation to each other and to a space surveillance radar antenna;

– FS stations feature directional antennas with their pattern main lobes oriented along the line connecting those stations. The factor would facilitate mitigation in interference effect due to interfering signal reception via FS antenna side lobes.

A summarized scenario of interference effect on FS stations is shown in Fig. 7.

FIGURE 7

Summarized scenario of interference effect on FS stations



Analysis of the scenario shows that level of interference caused to FS stations is a function of space surveillance radar antenna pattern and gain, effective radar e.i.r.p. and distance between the radar and the FS stations. Similar to the MS scenario the level of interference would also depends on polarization decoupling and on terrain features between locations of the radar and FS receivers.

Interference could be estimated using Recommendation ITU-R P.1546-4 as adapted in the SEAMCAT software program.

2 Space surveillance radar and MS stations characteristics used for interference estimation

Estimation of interference caused by space surveillance radars in the direction to MS/FS stations used the radar parameters shown in Table 6.

TABLE 6

Space surveillance radar characteristics used for interference estimation

Parameter	Narrow-band mode	Wideband mode
e.i.r.p. towards horizon (dBW)	55	55
Antenna gain towards horizon (dB)	9	9
−3 dB required frequency band (kHz)	1.5	625
Operating frequency (MHz)	154.33	154.33
Antenna height (m)	19	19
−3 dB pattern width (degrees)	5.2	5.2
Relative side-lobe level (dB)	−13	−13
Frequency band (MHz)	154-156	154-156

Table 7 contains MS user terminal and base station parameters used for the estimation.

TABLE 7

Characteristics of MS user terminals and base stations

Parameter	User terminal	Base station
Operation frequency (MHz)	154.33	154.33
Frequency band (kHz)	16	16
Antenna gain (dB)	3	9
Antenna height (m)	1-2	10, 15, 25, 30
Service area radius (km)	15	
Protected field strength (dB(µV/m))	12	
Polarization	Vertical	

3 Estimation of interference caused by space surveillance radar radiation to MS stations

Interference caused by space surveillance radar radiation was estimated for the above-mentioned scenarios. The results presented below were obtained using the SEAMCAT software program for both rural and urban wave propagation conditions. The SEAMCAT program is designed for statistical simulation of different interference effect scenarios. The interference simulation uses the Monte-Carlo method. The Recommendation ITU-R P.1546-4 model was used as a propagation model.

The results shown below were obtained using a protection criteria associated with maximum permitted interference field strength of 12 dB(µV/m) for 10% of time and 50% of locations.

Scenario 1: Interference caused to MS base stations was estimated by calculating the maximum field strength for interference caused by radar operation at the location of the victim MS base station receiving antenna with calculating the probability of such event. In Scenario 1 the SEAMCAT program was used for accounting possible variations in signal propagation within a selected propagation model.

It is worth noting that Recommendation ITU-R M.1802 analyses a case with the radar transmitting antenna height of 19 m and the receiving antenna height of 10 m. Table 8 shows the results of calculations for the radar transmitting antenna height of 19 m and for four receiver antenna height values of 10 m, 15 m, 25 m and 30 m.

The following designations are used in Table 8 and the successive tables:

– $h_{radar\ ant}$ – radar antenna height;
– R – distance between radar antenna and that of MS base station;
– $h_{RX\ ant}$ – MS receiver antenna height;
– E_{urban} – interference field strength for urban wave propagation;
– E_{rural} – interference field strength for rural wave propagation;
– $R_{protect\ urban}$ – protection distance for urban wave propagation;
– $R_{protect\ rural}$ – protection distance for rural wave propagation.

TABLE 8

The calculation results for radar narrow-band signal

R (km)	200	300	400	500	600
$h_{RX\ ant}$ (m)	10				
E_{urban} (dB(μV/m))	21.7	10.2	0.4	−8.6	−17.4
E_{rural} (dB(μV/m))	34.4	22.8	13	4	−4.7
$h_{RX\ ant}$ (m)	15				
E_{urban} (dB(μV/m))	26.7	15.2	5.2	−3.7	−12.5
E_{rural} (dB(μV/m))	37.4	25.8	15.9	7	−1.8
$h_{RX\ ant}$ (m)	25				
E_{urban} (dB(μV/m))	36	24.5	14.6	5.7	−3.1
E_{rural} (dB(μV/m))	41.2	29.5	19.6	10.7	1.9
$h_{RX\ ant}$ (m)	30				
E_{urban} (dB(μV/m))	37.3	25.8	16	7	−1.8
E_{rural} (dB(μV/m))	42.3	31	21	12.1	3.3

The results shown in Table 3 were used for calculating the protection distances as a function of the MS base station receiving antenna height. The calculation results are shown in Table 9.

TABLE 9

The protection distance dependence on MS base station antenna height for radar narrow-band signal

$h_{RX\ ant}$ (m)	10	15	25	30
$R_{protect\ urban}$ (km)	285	332	430	445
$R_{protect\ rural}$ (km)	412	444	485	502

Analysis of the results in Table 9 shows that protection distance depends significantly on propagation conditions and on receiving antenna height. It is clear that for the receiving antenna height of 10 m the difference in protection distance values is 127 km between rural and urban calculations but for the receiving antenna height of 30 m the difference in protection distance values is 57 km.

The calculation results for wideband signal are shown in Table 10. In the calculations the frequency band of the MS receiver is 16 kHz, so that only some radar power gets into it. This factor allows to reduce the radar e.i.r.p. by 16 dB.

TABLE 10

The calculation results for radar wideband signal

R (km)	150	200	250	300	350
$h_{RX\,ant}$ (m)	10				
E_{urban} (dB(μV/m))	12.3	6	0	−5.6	−10.7
E_{rural} (dB(μV/m))	25	18.7	13	7.2	1.9
$h_{RX\,ant}$ (m)	15				
E_{urban} (dB(μV/m))	17.6	11	5.0	−0.7	−5.8
E_{rural} (dB(μV/m))	28	21.7	15.6	10.0	4.8
$h_{RX\,ant}$ (m)	25				
E_{urban} (dB(μV/m))	26.5	20.3	14.3	8.7	3.5
E_{rural} (dB(μV/m))	31.5	25.4	19.4	13.7	8.6
$h_{RX\,ant}$ (m)	30				
E_{urban} (dB(μV/m))	28	21.7	15.7	10	4.9
E_{rural} (dB(μV/m))	33	26.8	20.8	15.1	9.9

The results shown in Table 10 were used for calculating the protection distance dependence on MS base station antenna height. The calculation results are presented in Table 11.

TABLE 11

The protection distance dependence on MS base station receiving antenna height for radar wideband signal

$h_{RX\,ant}$ (m)	10	15	25	30
$R_{protect\ urban}$ (km)	153	192	271	282
$R_{protect\ rural}$ (km)	259	282	317	330

Analysis of the results depicted in Tables 10 and 11 shows that use of a wideband signal results in a significant decrease of the required protection distance. Thus for the radar antenna height of 10 m and 15 m the protection distance decreased by 130 km for urban propagation conditions and for higher antennas the protection distance decreased by 160 km. For rural propagation, change of the protection distance does not depend on changing antenna height. The protection distance is decreased by 160 km.

The effect of e.i.r.p. on the protection distance value for both signals was also analysed. The estimations assumed the MS base station antenna height of 15 m for two radio-wave propagation conditions. The estimates are shown in Table 12.

TABLE 12

The effect of radar e.i.r.p. on the protection distance value

$h_{RX\ ant}$ (m)			**15**				
	Narrow-band signal						
e.i.r.p. (dBW)	55	50	45	40	35	30	25
$R_{protect\ urban}$ (km)	332	286	241	200	160	120	83
$R_{protect\ rural}$ (km)	444	390	340	291	247	205	166
	Wideband signal						
e.i.r.p. (dBW)	55	50	45	40	35	30	25
$R_{protect\ urban}$ (km)	192	154	112	73	49	36	26
$R_{protect\ rural}$ (km)	282	239	197	156	116	81	52

Analysis of the results presented in Table 12 shows that a 5 dBW reduction of the space surveillance radar e.i.r.p. results in diminishing the required protective distance by about 40 km for both signals.

Moreover the effect of polarization decoupling on the MS protection distance value was also examined. The wave propagation conditions analysis in this frequency range shows that the polarization decoupling is 16.2 dB. This corresponds to a decrease of the required protective distance minimum by 130 km. The protection distance values, obtained with account taken of polarization decoupling for both signals are presented in Table 13.

TABLE 13

The effect of polarization decoupling on the MS protection distance with account to polarization decoupling

$h_{RX\ ant}$ (m)			**15**				
	Narrow-band signal						
e.i.r.p. (dBW)	55	50	45	40	35	30	25
$R_{protect\ urban}$ (km)	202	156	111	70	30	–	–
$R_{protect\ rural}$ (km)	314	260	210	161	117	75	36
	Wideband signal						
e.i.r.p. (dBW)	55	50	45	40	35	30	25
$R_{protect\ urban}$ (km)	62	24	–	–	–	–	–
$R_{protect\ rural}$ (km)	152	109	67	26	–	–	–

The probability of causing interference to a MS base station receiver from space surveillance radar antenna main lobe depends on the radar antenna pattern width and on scan angle sector. The probability for a constant scanning angular rate is described by the following expression:

$$P\% = \frac{2\theta_{0.5}^{H}}{\Psi^{H}} \frac{2\theta_{0.5}^{V}}{\Psi^{V}} \times 100\%$$

NOTE 1 − Monte-Carlo simulation can be considered for this analysis.

where:

$2\theta_{0.5}^{V}$, $2\theta_{0.5}^{H}$: radar antenna pattern width in the vertical and horizontal planes;

Ψ^{V}, Ψ^{H} : scan angle sector in the vertical and horizontal planes.

The probability of causing maximum interference is equal to 0.1% for the radar pattern width shown in Table 7 and for scan angle sector in the horizontal plane of 360º and for scan angle sector in the vertical plane of 70º. Thus, the conclusion could be drawn that the protection distances, mentioned in Tables 12 and 13 are required only for MS protection at 0.1% operation time. At 99.9% operation time of MS the protection distances should be significantly shorter. These protection distances can be estimated on the basis of radar antenna pattern characteristics.

The time of usage of protection distances mentioned in Tables 12 and 13 can be significantly reduced if the main beamwidth is decreased in the both planes.

Scenario 2: The scenario deals with interference caused by radar to MS user terminals moving around an MS base station service area. Estimation of interference effect on the user terminals included calculating the field strength for interference caused by space surveillance radar radiation as a function of distance between the radar antenna and that of the MS base station. The calculations accounted for the radar antenna pattern rotation and assumed the space surveillance radar antenna height of 19 m and that of user terminal antennas uniformly distributed from 1 m to 2 m. The space surveillance radar e.i.r.p. was assumed to be 55 dBW. It was taken into account the space surveillance radar antenna scan in the angle sector in the vertical plane from 2º to 70º in the process of stimulation.

Figure 8 presents the results of estimating a cumulative distribution function related to interference field strength for MS user terminals under urban (the red curve) and rural (the dotted green curve) radio-wave propagation conditions for a distance of 200 km between the radar and the MS base station.

FIGURE 8

Interference field strength cumulative distribution function for a distance of 200 km between the radar and the MS base station

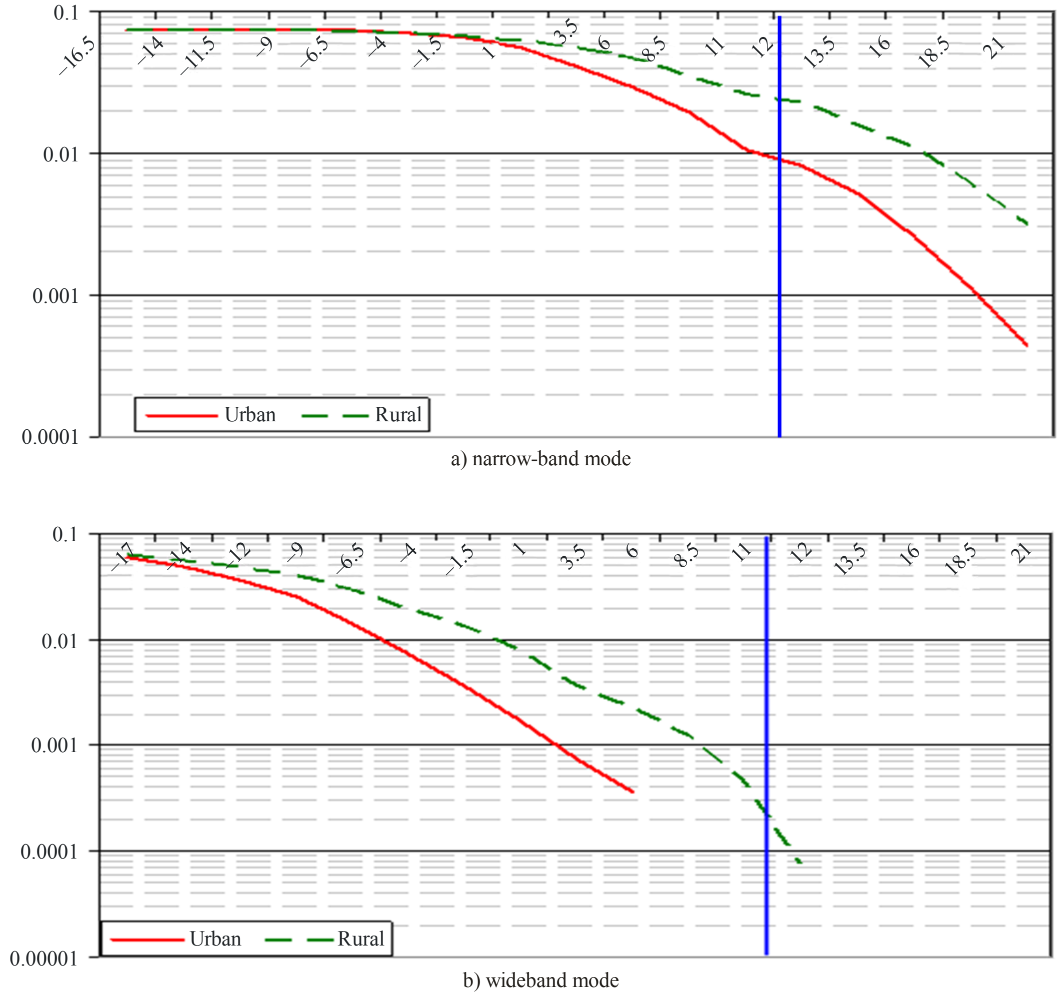


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Figure 8a depicts interference estimation results for interference field strength for a narrow-band signal with Fig. 8b depicting the results for a wideband signal The blue line in those figures shows threshold field strength of 12 dB(μV/m).

Analysis of the obtained data for a distance of 200 km between the radar and the MS base station shows that probability of exceeding the threshold field strength of 12 dB(μV/m) would be as follows:

– for narrow-band signal:
  – for urban conditions – 0.8%;
  – for rural conditions – 2.2%;
– for wideband signal:
  – for urban conditions – less than 10^{-7}%;
  – for rural conditions – less than 10^{-4}%.

A further increase of the distance between the radar and MS base station to 285 km would result in the probability of exceeding the threshold field strength for the narrow-band signal of less than 0.1% for any propagation conditions.

It should be noted that the obtained probabilities of exceeding the threshold value can be further decreased if the polarization discrimination between space surveillance radar and MS is taken into account. In accordance with Table 12, the required protection distance will be reduced by more than 130 km. Thus, the protection distance between space surveillance radar and MS base station for providing protection to user terminals will be reduced to 155 km for 0.1% time in the case of narrow-band signals, and in case of wideband signals the protection distance will be reduced to 70 km for 0.01% time.

4 Estimation of interference caused by space surveillance radar to FS stations

The analysis of interference caused by space surveillance radar to FS was carried out for the worst case. It was assumed that the maximum FS stations antenna is directed to the space surveillance radar. Similar to Scenario 1 discussed above distance between space surveillance radar antenna and those of FS station antennas remain constant during operation. The value of maximum interference field strength could be estimated using the method applied for estimating the interference in Scenario 1. Therefore data presented in Tables 8, 10, 12 and 13 coincide with the obtained calculation results.

Moreover it should be noted that the possibility of causing unaccepted interference to FS stations is less than in the case of interference to MS stations. It can be estimated based on FS stations antenna beamwidth. Assuming an FS typical antenna beamwidth of 10º in the horizontal plane, the probability that FS station will be pointed towards the radar station does not exceed 10/360 * 100% = 2.8%. The probability of causing interference to FS stations will be less than (0.001 * 0.0028 * 100% = 0.00028%) taking into account the radar main beam pointing.

5 Conclusions

The conducted studies resulted in the following conclusions:

– Protection distances for MS stations depend significantly on the height of the MS base station antenna.

– Propagation conditions affect the protection distance values significantly. Location of mobile base stations in urban conditions would result in the protection distances 100 km less than those obtained for rural conditions.

– Taking into account the above conclusions it is valid to assume that the usage of screening facilities deployed in the line between location points for radars and mobiles antennas outside of the mobile stations operating areas can significantly reduce the interference caused by space surveillance radar in the direction of MS base stations.

The required protection distance for MS based stations (using antenna height of 30 m):

– for the radar wideband signal would not exceed 152 km for more than 0.1% of time;

– for the radar narrow-band signal would not exceed 314 km for more than 0.1% of time.

The required protection distance for MS user terminals:

– for the radar wideband signal for 0.01% of time would not exceed 70 km;

– for the radar narrow-band signal for no more than 0.1% of time would not exceed 155 km.

Thus the necessary protection distance for MS based stations would not exceed 314 km for more than 0.1% of time depending on the class of the signal and for user terminals it should not exceed 155 km at no more than 0.1%.

The necessary protection distance for FS stations would not exceed 314 km for more than 0.00028% of time depending on the class of the signal.

The obtained protection distance values are required for MS and FS protection for no more than 0.1% of time. For 99.9% of time the protection distances for MS and FS should be significantly shorter than those obtained in this study.

Appendix 2

Sharing study between radiolocation system and mobile system in the 154-156 MHz frequency band

This appendix contains a study on separation distances for land mobile station from the space surveillance radar operating in 154-156 MHz frequency band using methodology given in Recommendation ITU-R M.1461-1. Recommendation ITU-R P.1546-4 model is used for calculation of propagation losses and time rate of 1% is applied. Calculation results presented in this report are using protection criteria based on $I/N = -6$ dB for land mobile stations and $I/N = -10$ dB for applications with greater protection requirements, such as public PPDR.

1 Systems characteristics

The following sections contain the technical characteristics for radiolocation system and land mobile system operating in 154-156 MHz frequency bands that will be used in the sharing analysis.

1.1 Radiolocation system

Recommendation ITU-R M.1802 contains technical characteristics and protection criteria for radiolocation radars in the 154-156 MHz frequency band. The system characteristics for radar A and radar B operating in 154-156 MHz band are shown in Table 14.

TABLE 14

Radiolocation systems characteristics

Characteristics	Radiolocation Systems	
Function	**Radar A**	**Radar B**
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	
Altitude above the ground level (m)	19	
Maximum antenna gain (dB) – transmitter – receiver	 25 30	
Maximum antenna gain on the horizon (dB)	9	
Operational receiver passband (kHz)	0.132	625
3 dB bandwidth (kHz)	0.132	625
I/*N* protection ratio (dB)	−6	

1.2 Land mobile systems

Characteristics and the protection criteria to be used in sharing studies involving land mobile systems in the VHF band shall be taken from table the 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.

Table 15 lists the technical characteristics of base station and mobile station of the land mobile service operating the VHF band.

TABLE 15

Land mobile systems characteristics

Characteristics	**Land mobile systems**			
Station type	**Base station**		**Mobile Station**	
Type of emission	**Analogue**	**Digital**	**Analogue**	**Digital**
Frequency band (MHz)	138-174		138-174	
Channel bandwidth (kHz)	12.5/15/25/30	6.25/7.5/12.5/15	12.5/15/25/30	6.25/7.5/12.5/15
Modulation type	FM	C4FM	FM	C4FM
Type of operation	Simplex/duplex	Duplex	Simplex/duple x	Duplex
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 (dBi)	0 to 9 (6)	0 to 9 (8)	−10 to 4 (H: −10, V: 0)	−10 to 4 (H: −10, V: 0)
Antenna height (m) (relative to ground level)	10 to 150 (60)	10 to 150 (65)	(2)	(2)
Radiation pattern	Omni	Omni	Omni	Omni
Antenna polarization	Vertical	Vertical	Vertical	Vertical

2 Protection criteria

When the protection criteria are given in the term of the I/N, the interference threshold level, I_T (dBm) can be calculated by equation (1):

$$I_T = I/N_{required} + N \tag{1}$$

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)

($N = -144$ dBm + 10 log $B_{IF} + NF$ or = −168.6 dBm + 10 log B_{IF} + 10 log T)

where:

B_{IF}: receiver IF bandwidth (kHz)

NF: receiver noise figure (dB)

T: system noise temperature (K).

Interference threshold level I_T (dBm) can be converted to electric field strength E_T (dBμV/m) using equation (2):

$$E_T = I_T - G_R + 20 \log f + 77.2 \qquad (2)$$

where:

f: frequency (MHz)

G_R: receiver antenna gain (dBi).

Calculation results of interference threshold level in term of electric field strength for base station and mobile station in the 154-156 MHz band are listed in Table 16 and Table 17.

TABLE 16

Protection criteria for base station of land mobile systems

Characteristics	**Land mobile systems**				
Type of emission	**Analogue**	**Analogue**	**Analogue**	**Analogue**	**Digital**
f (MHz)	155	155	155	155	155
B_{IF} (kHz)	8	11	12.5	16	5.5
G_R (dBi)	4.0	4.0	4.0	4.0	4.0
NF (dB)	10.0	10.0	10.0	10.0	12.0
Protection criteria	**Converted interference threshold levels**				
Interference to noise ratio (dB)	**Electric field strength: E_T (dB(μV/m))**				
$I/N = -6$ (dB): General Case	−11.0	−9.6	−9.0	−8.0	−10.6
$I/N = -10$ (dB): Special Case	−15.0	−13.6	−13.0	−12.0	−14.6
Electric field strength	**Interference to noise ratio: I/N (dB)**				
12 dB(μV/m)	20.0	18.6	18.0	17.0	19.6

TABLE 17

Protection criteria for mobile station of land mobile systems

Characteristics	**Land mobile systems**				
Type of emission	**Analogue**	**Analogue**	**Analogue**	**Analogue**	**Digital**
f (MHz)	155	155	155	155	155
B_{IF} (kHz)	8	11	12.5	16	5.5
G_R (dBi)	0.0	0.0	0.0	0.0	0.0
NF (dB)	10.0	10.0	10.0	10.0	12.0
Protection criteria	**Converted interference threshold levels**				
Interference to noise ratio (dB)	**Electric field strength: E_T (dB(μV/m))**				
$I/N = -6$ (dB): General Case	−7.0	−5.6	−5.0	−4.0	−6.6
$I/N = -10$ (dB): Special Case	−11.0	−9.6	−9.0	−8.0	−10.6
Electric field strength	**Interference to noise ratio: I/N (dB)**				
12 dB(μV/m)	16.0	14.6	14.0	13.0	15.6

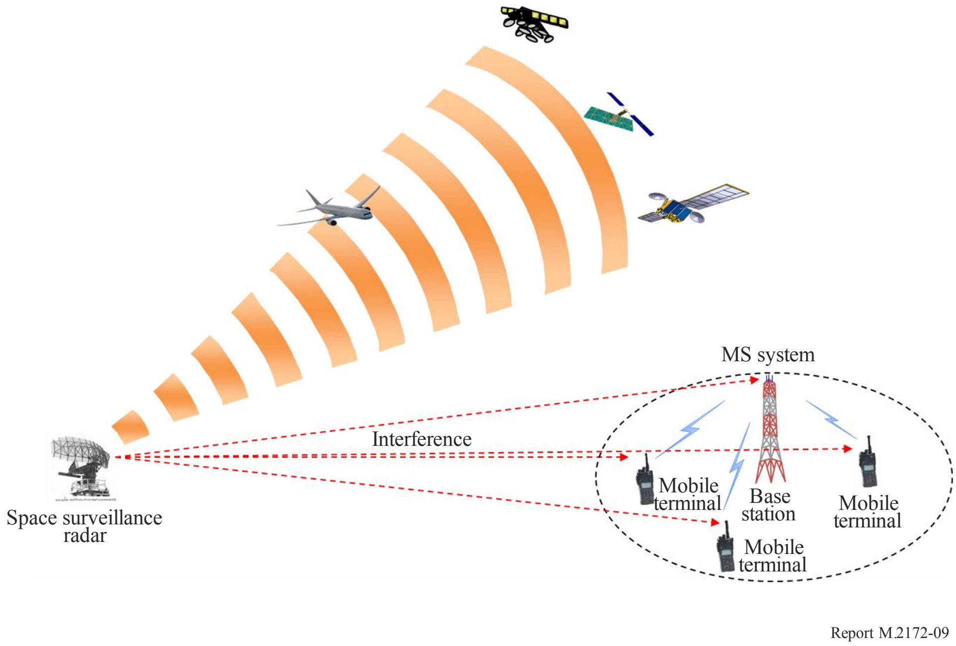
3 Sharing analysis/methodology

3.1 Sharing analysis scenario and assumptions

Sharing analysis scenario is shown in Fig. 9:

FIGURE 9

Sharing analysis scenario



The analysis assumptions are:

1 A radiolocation system causes interference to a base station and a mobile station receiver of land mobile service.

2 Antenna coupling: side lobe of radiolocation radar and main lobe of receiver for land mobile system (maximum antenna gain on the horizon (dB) of radar is adapted).

3 Frequency

− 155 MHz for 154-156 MHz band.

4 Antenna height of the radiolocation system (Recommendation ITU-R M.1802):

− 19 m for 154-156 MHz band.

5 Antenna height of the victim receiver (Recommendation ITU-R M.1808):

− 60 m for analogue system and 65 m for digital system of base station

− 2 m for analogue and digital system of mobile station.

6 Transmission loss: calculated using Recommendation ITU-R P.1546-4:

− Propagation path: land path, suburban area

− Percentage of time is 1%.

3.2 Sharing analysis

Recommendation ITU-R M.1461-1 is used as a methodology of the procedure for determining the potential for interference between radars operating in the radiodetermination service and systems in other services.

Procedure of determining whether radar transmitter emission interference is likely when radars operate within particular distances of other stations and are separated in frequency by certain amounts, is provided in the § 2.2 of Annex 1 of Recommendation ITU-R M.1461-1. Received peak power of the radar pulses at the victim receiver input can be calculated as follow:

$$I = P_T + G_T + G_R - L_T - L_R - L_P - FDR_{IF} \tag{3}$$

where:

I : peak power of the radar pulses at the victim receiver (dBm)

P_T : peak power of the radar transmitter under analysis (dBm)

G_T : main beam antenna gain of the radar under analysis (dBi)

L_T : insertion loss in the radar station transmitter (dB)

L_R : insertion loss in the victim receiver (dB)

L_P : propagation path loss between transmitting and receiving antennas (dB)

FDR_{IF} : frequency-dependent rejection produced by the receiver IF selectivity curve on an unwanted transmitter emission spectra (dB).

Propagation curves in Recommendation ITU-R P.1546-4, which is used as a propagation loss model in this calculation, represent received electric field-strength values (dB(μV/m)) for 1 kW effective radiated power (e.r.p.). 1 kW e.r.p. is equal to 62.1 dBm equivalently isotropic rated power (e.i.r.p.). Therefore, propagation path loss L_P (dB) can be calculated using equation (4):

$$L_P = 139.3 - E_{P.1546} + 20 \log f \tag{4}$$

where:

$E_{P.1546}$: field strength (dB(μV/m)= for 1 kW e.r.p. in Recommendation ITU-R P.1546.

Using equations (2), (3) and (4), electric field strength E (dB(μV/m)) can be calculated from $E_{P.1546}$ equation (5). Here, L_T and L_R are assumed to be zero.

$$E = E_{P.1546} + P_T + G_T - 62.1 - FDR_{IF} \tag{5}$$

The FDR value to be used in the equation (3) and (5) can be determined as follow from Recommendation ITU-R SM.337-6. The FDR can be divided into two terms, the on-tune rejection (OTR) and the off-frequency rejection (OFR), the additional rejection which results from off-tuning the radar and the receiver.

$$FDR_{IF}(\Delta f) = OTR + OFR(\Delta f) \tag{6}$$

For CW and phase-coded pulsed signals, the OTR factor is given by:

$$OTR = 0 \qquad \text{for } B_R \geq B_T \tag{7}$$

$$OTR = 20 \log (B_R/B_T) \qquad \text{for } B_R < B_T \tag{8}$$

where:

B_R : receiver 3 dB bandwidth (Hz)

B_T : transmitter 3 dB bandwidth (Hz).

As the Δf, frequency difference between transmitting frequency and receiving frequency is zero, *OFR*(Δf) value is assumed to be zero. Calculation results of frequency dependent rejection are Table 18.

TABLE 18

Frequency-dependent rejection

Characteristics		**Land mobile service(base/mobile station)**				
Type of emission		**Analogue**	**Analogue**	**Analogue**	**Analogue**	**Digital**
Radar A	B_T (kHz)	0.132				
	B_R (kHz)	8.0	11.0	12.5	16.0	5.5
	FDR (dB)	0.0	0.0	0.0	0.0	0.0
Radar B	B_T (kHz)	625.0				
	B_R (kHz)	8.0	11.0	12.5	16.0	5.5
	FDR (dB)	18.9	17.5	17.0	15.9	20.6

Electric field strengths at the input of land mobile receiver from radiolocation transmitter are calculated for the distances between 1 km and 1 000 km using equation (5).

Electric field strengths are calculated for several cases. These are:

1 Narrow bandwidth radar system (Radar A) and wide bandwidth radar system (Radar B).

2 Base station and mobile station of land mobile service.

3 Analogue(16 kHz IF bandwidth) and digital system (5.5 kHz IF bandwidth) of land mobile service.

4 Protection criteria of $I/N = -6$ (dB) for general land mobile system and $I/N = -10$ (dB) for special land mobile system(such as PPDR).

Plots of the electric field-strength curves in the 154-156 MHz band for base station of land mobile service are shown in Fig. 10 to Fig. 13 and curves for mobile station of land mobile service are shown in Fig. 14 to Fig. 17. Separation distances of land mobile system from radiolocation system for each case are figured out through comparing the electric field strength and the required protection criteria for land mobile service (Tables 16 and 17).

FIGURE 10

Received field strength of analogue base station for Radar A

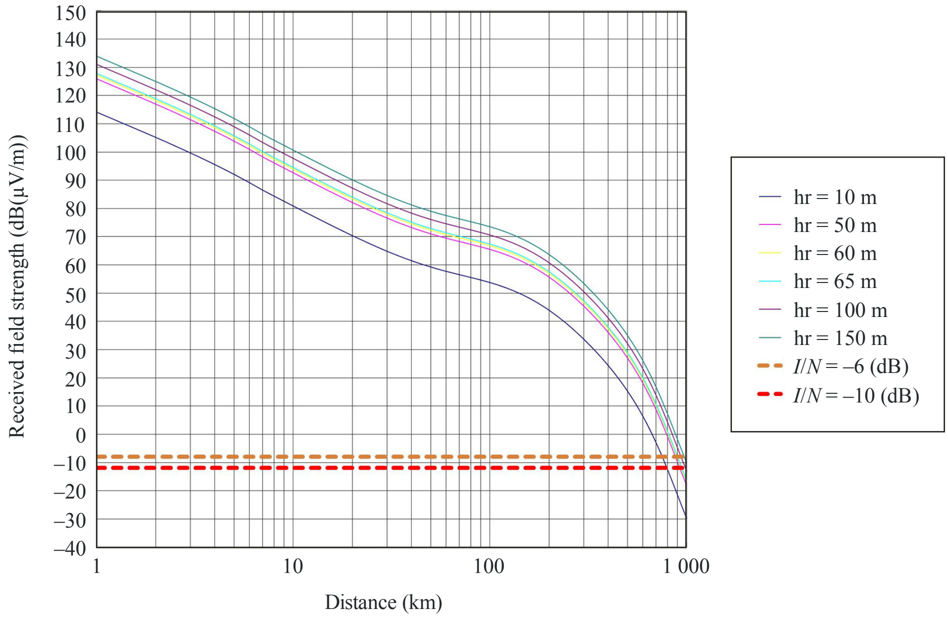


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FIGURE 11

Received field strength of digital base station for Radar A

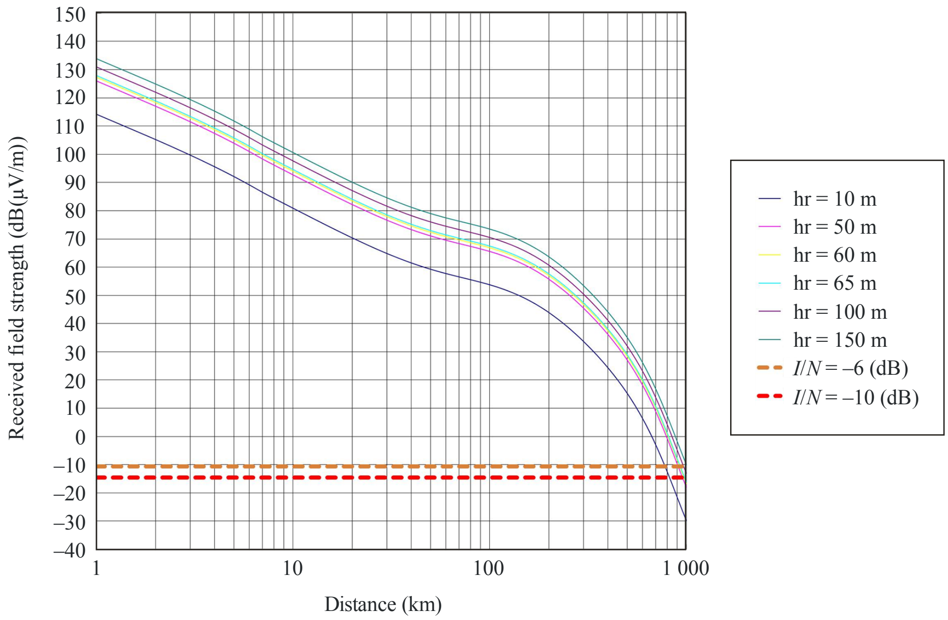

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FIGURE 12

Received field strength of analogue base station for Radar B

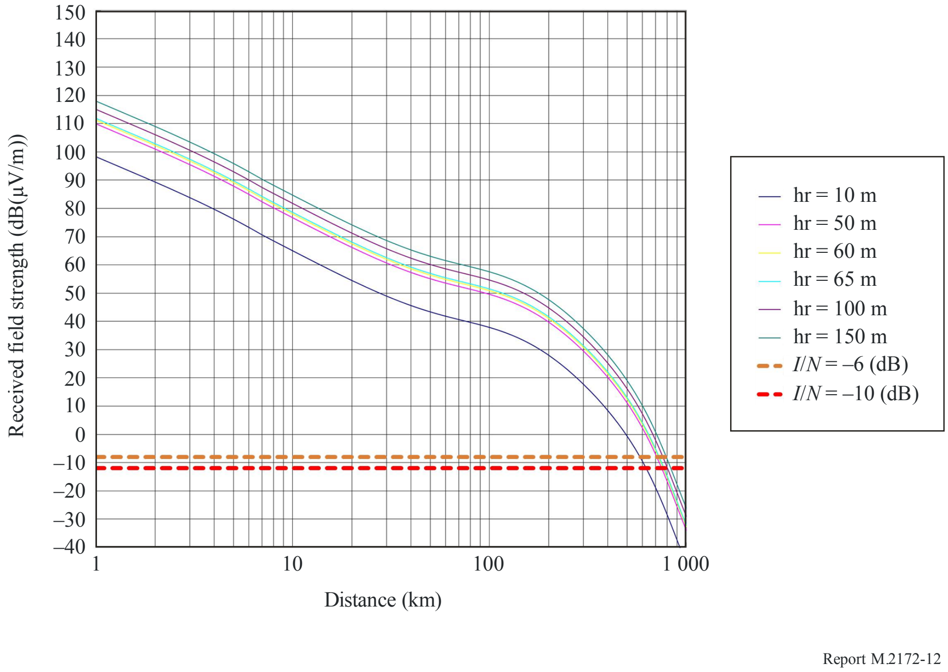

FIGURE 13

Received field strength of digital base station for Radar B

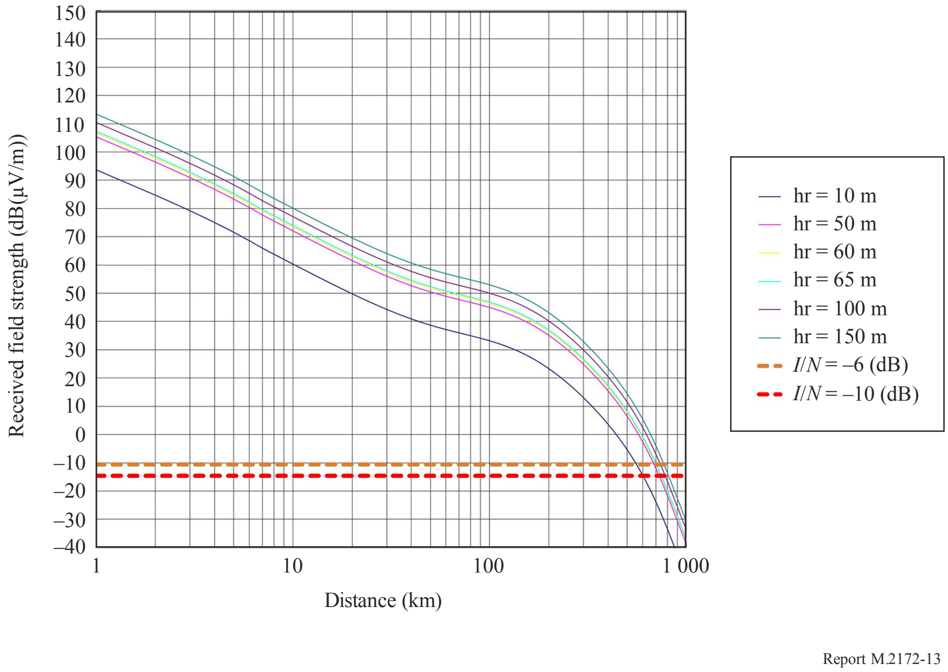

FIGURE 14

Received field strength of analogue mobile station for Radar A

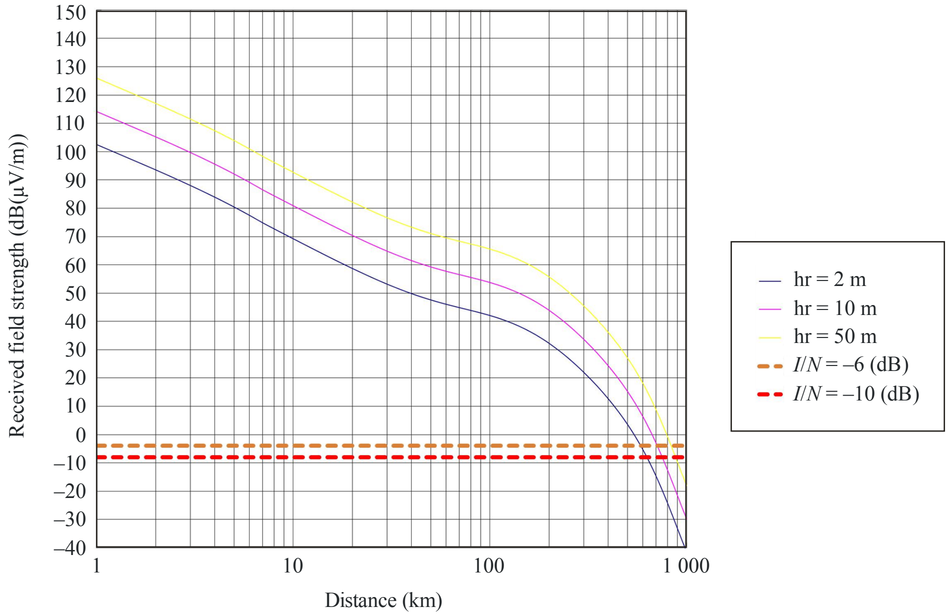

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FIGURE 15

Received field strength of digital mobile station for Radar A

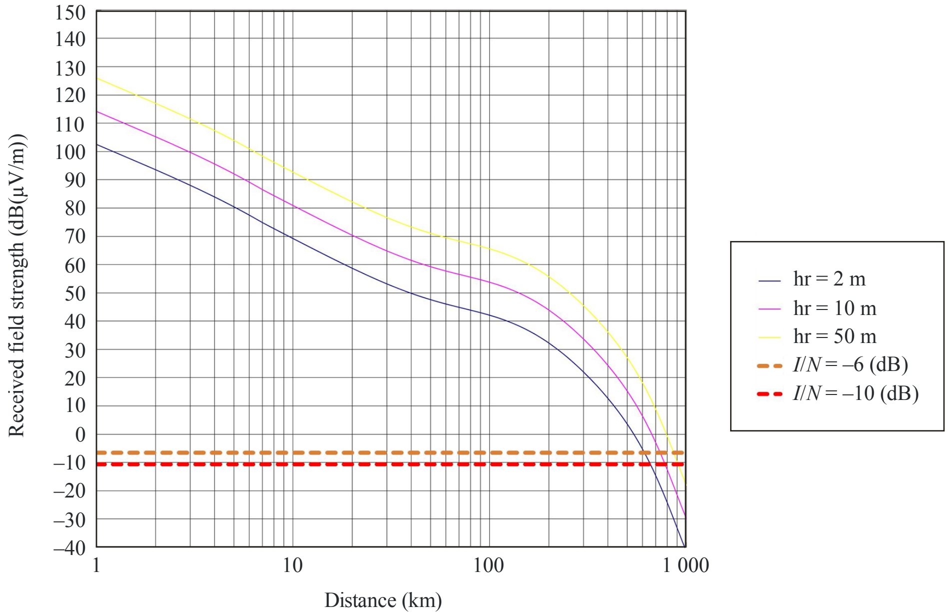

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FIGURE 16

Received field strength of analogue mobile station for Radar B

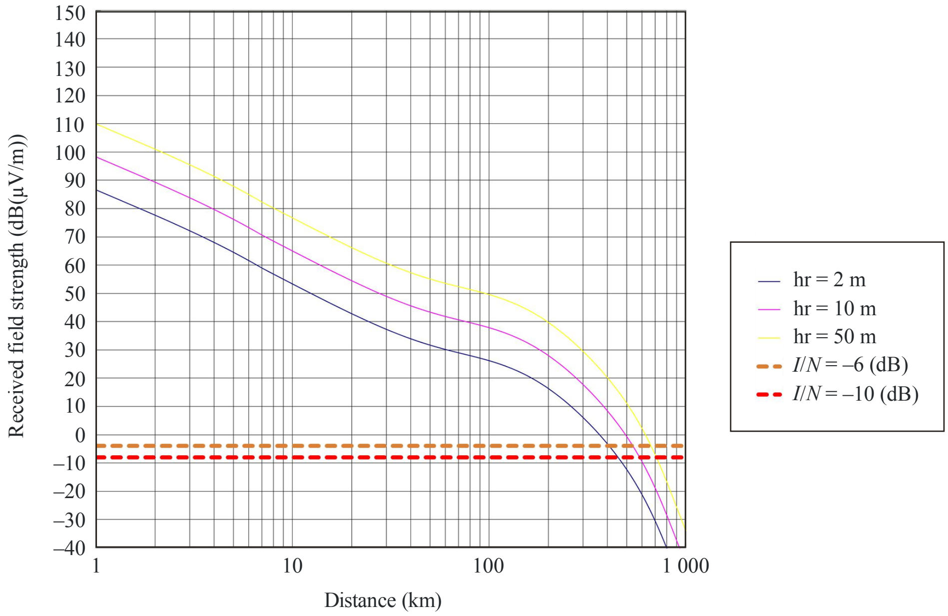

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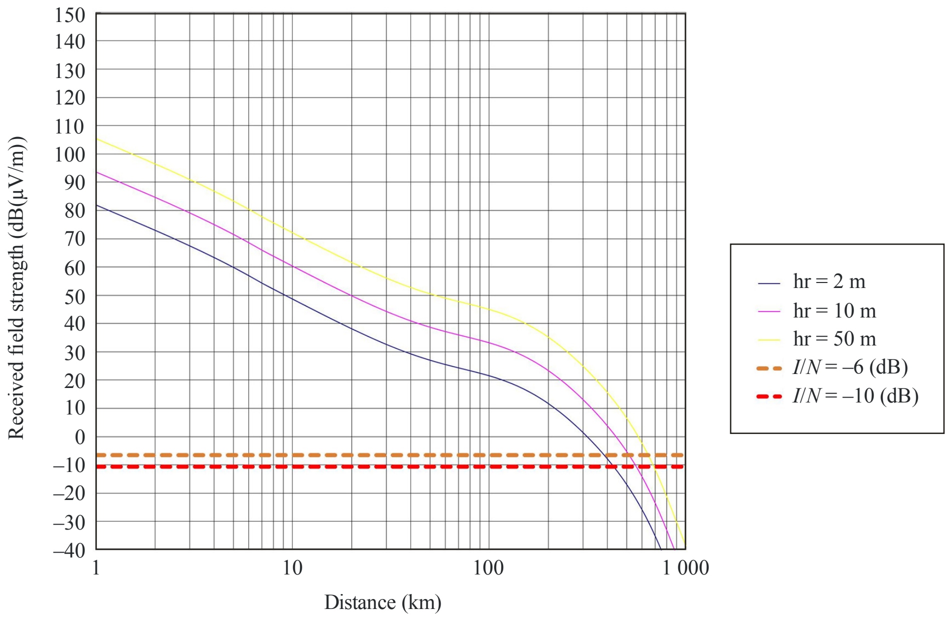
FIGURE 17

Received field strength of digital mobile station for Radar B



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3.3 Assessment of analysis results

Required separation distances of land mobile system are summarized in Tables 19 and 20 for arrow-band and wideband radar in the 154-156 MHz band. The assessment can be made regarding the separation distances that are required to ensure sharing between the radiolocation system and the land mobile system.

TABLE 19

Separation distance of land mobile system from Radar A in the 154-156 MHz

Station	Emission type	h_r (m)	Separation distance (km)	
			$I/N = -6$ (dB)	$I/N = -10$ (dB)
Base	Analogue	60	892	939
	Digital	65	929	979
Mobile	Analogue	2	583	627
	Digital	2	612	655

TABLE 20

Separation distance of land mobile system from Radar B in the 154-156 MHz

Station	Emission type	h_r (m)	Separation distance (km)	
			$I/N = -6$ (dB)	$I/N = -10$ (dB)
Base	Analogue	60	721	763
	Digital	65	706	748
Mobile	Analogue	2	406	451
	Digital	2	384	429

4 Conclusions

This study between radiolocation service and land mobile service is conducted based on the methodology introduced in Recommendation ITU-R M.1461-1. System characteristics of radiolocation radar and land mobile system are referenced from Recommendation ITU-R M.1802 and Recommendation ITU-R M.1808, respectively. Recommendation ITU-R P.1546 propagation model is applied for the calculation of path losses and propagation path of land and time rate of 1% are assumed. Summary of the sharing studies are as follows.

The required protection distance for base stations of mobile service (using antenna height of 60 m for analogue system, 65 m for digital system) are:

– for the narrow-band radar signal in the frequency 154-156 MHz band:
  – $I/N = -6$ (dB): 892 km for analogue to 929 km for digital;
  – $I/N = -10$ (dB): 939 km for analogue to 979 km for digital;

– for the wideband radar signal in the frequency 154-156 MHz band:
  – $I/N = -6$ (dB): 706 km for digital to 721 km for analogue;
  – $I/N = -10$ (dB): 748 km for digital to 763 km for analogue.

The required protection distance for mobile stations (using antenna height of 2 m) are:

– for the narrow-band radar signal in the frequency 154-156 MHz band:
  – $I/N = -6$ (dB): 583 km for analogue to 612 km for digital;
  – $I/N = -10$ (dB): 627 km for analogue to 655 km for digital.
– for the wideband radar signal in the frequency 154-156 MHz band:
  – $I/N = -6$ (dB): 384 km for digital to 406 km for analogue;
  – $I/N = -10$ (dB): 429 km for digital to 451 km for analogue.

Study results for mobile station indicates shorter separation distances than those for base station, because the height of the mobile station is lower than that of base station. If the cross polarization effect is considered as the interference mitigation techniques, the required separation distance would be reduced. However, it would be difficult to achieve the cross polarization effects for mobile stations. Moreover if the propagation path of sea is considered, separation distance would be increased due to propagation characteristics.

Appendix 3

Studies on radar out-of-band emissions impact on MMS stations operation above 156 MHz

1 Analysis of performances related to MMS stations operating in the 156-174 MHz frequency band

Performances of MMS receivers are described in Recommendations ITU-R M.489-2, ITU-R SM.331-4 and ITU-R SM.332-4. Designation of channels by frequencies is specified in Radio Regulations (RR) Appendix 18.

Analysis of relevant ITU-R Recommendations shows that the VHF MMS stations feature the following performances:

– emission class – F3E or G3E;
– frequency band required – 16 kHz;
– frequency separation of channels – 25 kHz;
– polarization – vertical;
– receiver sensitivity – above 2 μV.

As shown in RR Appendix 18 Channel No. 60 is an adjacent channel in the 156-174 MHz frequency band. The ship transmitter stations and receivers of coast stations operate at 156.025 MHz carrier frequency with the bandwidth of 25 kHz. In accordance with the above ITU-R Recommendations the required frequency bandwidth is 16 kHz. Therefore, the MMS coast station receivers would receive interfering signals in the frequency band 156.017-156.033 MHz.

It is obvious that out-of-band emissions produced by space surveillance radars operating in the 154-156 MHz frequency band would be at their maximum in that channel. Therefore only emissions in RR Appendix 18 Channel 60 are taken into consideration hereinafter.

Analysis of information on the MMS stations related to the above ITU-R Recommendations, including Recommendation ITU-R M.489-2, shows that RR Appendix 18 frequency channels are designed for radiotelephony, i.e. they have functions that are technologically similar to mobile service stations operating in the 154-156 MHz frequency band.

Analysis of MS stations performances in the 154-156 MHz frequency band shows that the stations mainly operate using signals in 16 kHz and F3E emission class. The protected field strength of 12 dB(μV/m) is used as a protection criteria for those stations. It should be noted that similar to the field strength for land mobile service the above value is far more stringent than required practically and is used as a coordination threshold. Actually administrations are using less stringent protection criteria for mobile service in the course of bilateral coordination.

2 Assumed performances characteristics of space surveillance radars and MMS stations

For further analysis the radar characteristics reflected in Table 21 were used.

TABLE 21

Space surveillance radar performances used for interference estimation

Parameter	Narrow-band mode	Wideband mode
e.i.r.p. in the horizon direction (dBW)	55	
e.r.p. in the horizon direction (dBW)	53.5	
Antenna gain in the horizon direction (dB)	12	
Pulsed radiation power (dBW)	43	
Pulse duration (ms)	13	3.2
Pulse repetition period (ms)	40.3	9.92
Operation frequency (Hz)	155 999 937	155 687 500
Antenna height (m)	19	
−3 dB antenna beam width (degrees)	5.2	
Polarization	Vertical	

Such space surveillance radar operation frequency was chosen in order to analyse the worst-case interference impact on MMS receivers.

3 Analysis of space surveillance radar emission impact on operation of MMS stations

Radiation spectrum of space surveillance radars is determined by pulsed radiation power (P_i), pulse duration (τ_i) and pulse repetition period (T_i). For the radio pulse sequence under consideration the value of spectral component with number n is calculated using the following expression:

$$A_n = \frac{A\tau_i}{T_i}\left\{\frac{\sin\left(\frac{(\omega_0+\omega_n)\tau_i}{2}\right)}{\frac{(\omega_0+\omega_n)\tau_i}{2}} + \frac{\sin\left(\frac{(\omega_0-\omega_n)\tau_i}{2}\right)}{\frac{(\omega_0-\omega_n)\tau_i}{2}}\right\}$$

where:

$\omega_0 =$ $2\pi f_0$

$\omega_n =$ $2\pi n / T_i$

A : signal amplitude

n : harmonic number.

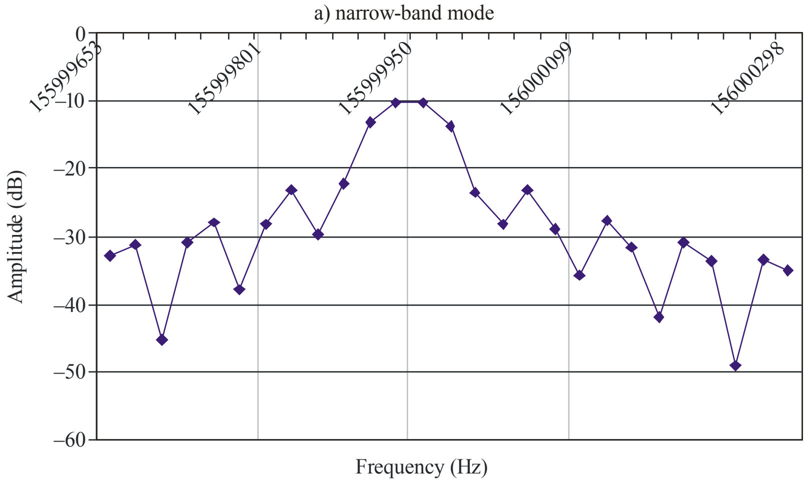
Analysis of the derived expression shows that spectral components of maximum amplitude are concentrated near the radar operation frequency (f_0). Moving away from that frequency, the amplitudes of the spectrum components decrease in line with the rule which is approximated with the following expression:

$$A_n \approx \frac{A\tau_i}{T_i}\left|\sin\left(\frac{(\omega_0-\omega_n)\tau_i}{2}\right) \Big/ \frac{(\omega_0-\omega_n)\tau_i}{2}\right|$$

Figure 18 shows a normalized spectrum of space surveillance radar signal for which characteristics are presented in Table 21.

FIGURE 18

Rated spectrum of a pulsed signal with radio-frequency filing



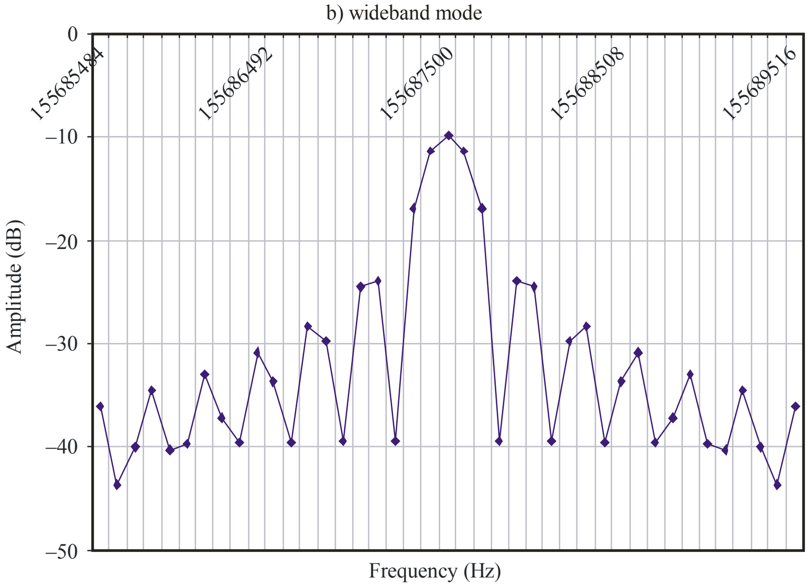


Figure 18a shows the spectrum of a narrow-band signal with Fig. 18b showing the spectrum of a wideband signal. The normalized spectrum of radar signals were used for calculating the power of interference produced by the space surveillance radar transmitter in the 156.017-156.033 MHz.

Analysis of the radar signal parameters presented in Table 21 shows that for the narrow-band signal the span between the spectrum components is 24.813 Hz, while it is 100.8 Hz for the wideband signal. It is obvious that power of out-of-band interference would depend on the amount of interference spectrum components falling into MMS receiver passband and on their amplitudes. Amount of spectrum components falling into the signal band could be derived through dividing the receiver passband width by the span between the spectrum components such as:

$$N = \Delta F_{rec} / \Delta f_n$$

where:

ΔF_{rec}: receiver passband;

Δf_n: span between spectrum harmonics.

Thus, 644 spectrum components of radar narrow-band signal or 159 spectral components of its wideband signal fall into the MMS receiver bandwidth. Out-of-band emission power in the receiver frequency band could be estimated by summing up the powers of radar signal spectrum components falling into the receiver operation passband:

$$P_{int} = \sum_{n=1}^{N} P_n^{int}$$

where:

P_n^{int} : harmonic power for the radar signal with number n.

Summing up the harmonic powers shows that power of interference produced by the radar transmitter in the MMS receiver passband and delivered to the radar antenna input in the narrow-band mode is 3.4 dBW, whereas the power of wideband signal interference produced by the radar transmitter in the MMS receiver passband is −13.5 dBW. Since frequency tuning-out from the radar narrow-band signal carrier in the MMS receiver passband would not exceed 0.02% from the transmitter operation frequency and tuning-out for wideband mode would not exceed 0.2%, it could be assumed that radar antenna gain in the horizon direction in that frequency band is unchanged and equals 12 dB. Thus, out-of-band interference e.i.r.p. is 15.4 dBW for a narrow-band signal and −1.5 dBW for a wideband signal, which corresponds to an e.r.p. of 13.9 dBW for the narrow-band signal and –3 dBW for the wideband signal.

Interference field strength in the vicinity of the MMS receiving antenna was estimated considering signal propagation over land and water paths for 10% of time and 50% of the MMS receiver antenna locations and its height of 10 m.

Analysis of the estimation results shows that narrow-band signal field strength of 12 dB(μV/m) for a completely overland path would be at the distance of 54 km from the radar antenna and it would be at the distance of 90 km for a completely over-water path. For the wideband signals those values are 19.2 km and 28.6 km correspondingly. Thus, the largest values, i.e. 90 km for the narrow-band signals and 28.6 km for the wideband signals correspondingly, could be taken as protection criteria for the MMS receivers. Taking into consideration that estimations conducted using Recommendation ITU-R P.1546-4 for complete over-sea water radio paths yield over-estimated values of field strength provides for conclusions that the protection distances obtained would ensure interference-free operation of MMS stations for paths of any kinds.

It is to be noted that the above-mentioned protection distance would be reduced due to using band-pass filters at the radar transmitter output. The results of studies in effect of additional attenuation in the filter on protection distance values are shown in Table 22.

TABLE 22

Additional filtration of radar signals

Additional attenuation (dB)	10	20	30
Protection distance, narrow-band signal (km)	48	28	16
Protection distance, wideband signal (km)	15	7	4

Analysis of the obtained results shows that usage of band-pass filters at the radar transmitter output to attenuate out-of-band emissions by 30 dB provides for reducing the protection distance up to 16 km. Moreover, usage of band-pass filter in a wideband mode to attenuate by 30 dB additionally provides for reducing the protection distance up to 4 km. The polarization decoupling would reduce protection distance to 0 km.

It is worth noting that the current scenario of deploying the radiolocation radars stipulates their location on land at a sufficient (over 50 km) distance from large areas of water, because such water surfaces near radars could impose significant unpredicted variations of radar signal field mainly due to multipath propagation caused by water obstacles. Therefore it could be stated that the results obtained are in line with the actual scenario of radar usage.

4 Conclusion

The conducted studies show that out-of-band emissions from space surveillance radars operating in the 154-156 MHz frequency band would cause no unacceptable interference to MMS receivers operating in the 156-174 MHz frequency band. Embedding the band-pass filters in the transmitters providing for additional attenuation by 30 dB outside the operation frequency band together with polarization discrimination would ensure feasible operation of radiolocation radars and MMS stations even in the same geographical areas. However, it is important to mention that the given operation scenario would not be practically implemented.

References

Recommendation ITU-R BT.419-3 – Directivity and polarization discrimination of antennas in the reception of television broadcasting.

Recommendation ITU-R F.755-2 – Point-to-multipoint systems in the fixed service.

Recommendation ITU-R F.758-4 – Considerations in the development of criteria for sharing between the terrestrial fixed service and other services.

Recommendation ITU-R M.489-2 – Technical characteristics of VHF radiotelephone equipment operating in the maritime mobile service in channels spaced by 25 kHz.

Recommendation ITU-R M.1461-1 – Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services

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 P.310-9 – Definitions of terms relating to propagation in non-ionized media.

Recommendation ITU-R P.1406-1 – Propagation effects relating to terrestrial land mobile and broadcasting services in the VHF and UHF bands.

Recommendation ITU-R P.1546-4 – Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3 000 MHz.

Recommendation ITU-R SM.331-4 – Noise and sensitivity of receivers.

Recommendation ITU-R SM.332-4 – Selectivity of receivers.

Recommendation ITU-R SM.337-6 – Frequency and distance separations.