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Radiocommunication Sector of ITU

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(06/2019)

Preliminary results of sharing studies between a 45 MHz radar sounder and incumbent fixed, mobile, broadcasting and space research services operating in the 40-50 MHz frequency range

RS Series

Remote sensing systems

International Telecommunication Union

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REPORT ITU-R RS.2455-0

Preliminary results of sharing studies between a 45 MHz radar sounder and incumbent fixed, mobile, broadcasting and space research services operating in the 40-50 MHz frequency range

(2019)

NOTE – This Report provides necessary information currently available as background to the preliminary agenda item 2.2 for WRC-23 in order for WRC-19 to finalise the agenda for WRC-23.

1 Introduction

This Report provides a static analysis methodology for determining the degree of compatibility between a space-borne 45 MHz radar sounder as described in Recommendation ITU-R RS.2042 and incumbent fixed, mobile, broadcasting, and space research services. It describes analysis methodologies and documents the results of a series of calculations and simulations that have been based upon actual system specifications and operational factors. The Report presents a summary of the preliminary static analyses examining the compatibility between a space-borne 45 MHz radar sounder and incumbent services operating within the 40-50 MHz frequency band.

2 Radar sounder characteristics and operation

2.1 Mission objectives

The spaceborne active sensor operating in the 40-50 MHz range will produce subsurface data with a vertical resolution of 5-7 m, and will have a surface SNR of 66 dB. The orbital mapping campaign is planned to include one month of orbital checkout and eighteen months of scientific data collection. The mission's scientific objectives are: 1) to understand the global thickness, inner structure, and the thermal stability of the Earth's ice sheets of Greenland and Antarctica as an observable parameter of earth climate evolution, and 2) to understand the occurrence, distribution and dynamics of the earth fossil aquifers in desertic environments such as northern Africa and the Arabian peninsula as key elements in understanding recent paleoclimatic changes. Eighteen months of sensor operation is sufficient to collect data in the interested scientific areas with a 5 km nadir track spacing at the equator, using a 548-day (18 months) exact repeat orbit at 400 km altitude. Due to the inherent temporal instabilities in both the ice fields and the aquifers in desertic environments, it is anticipated that there will be follow-on missions with a frequency of one eighteen month scientific mission every ten years.

2.2 Design parameters

The postulated system for the Earth orbiting sounding radar is an earth enhanced duplicate of the Shallow Radar Sounder (SHARAD) which was a Mars orbiting sounding radar operating in the 15-25 MHz frequency range. The resulting radar data will be used in the study of the Earth's subsurface with radar mapping of subsurface scattering layers with the intent to locate water/ice/deposits. The characteristics and orbital parameters of the 45 MHz spaceborne sounding radar are shown in Table 1.

TABLE 1

45 MHz spaceborne sounding radar characteristics

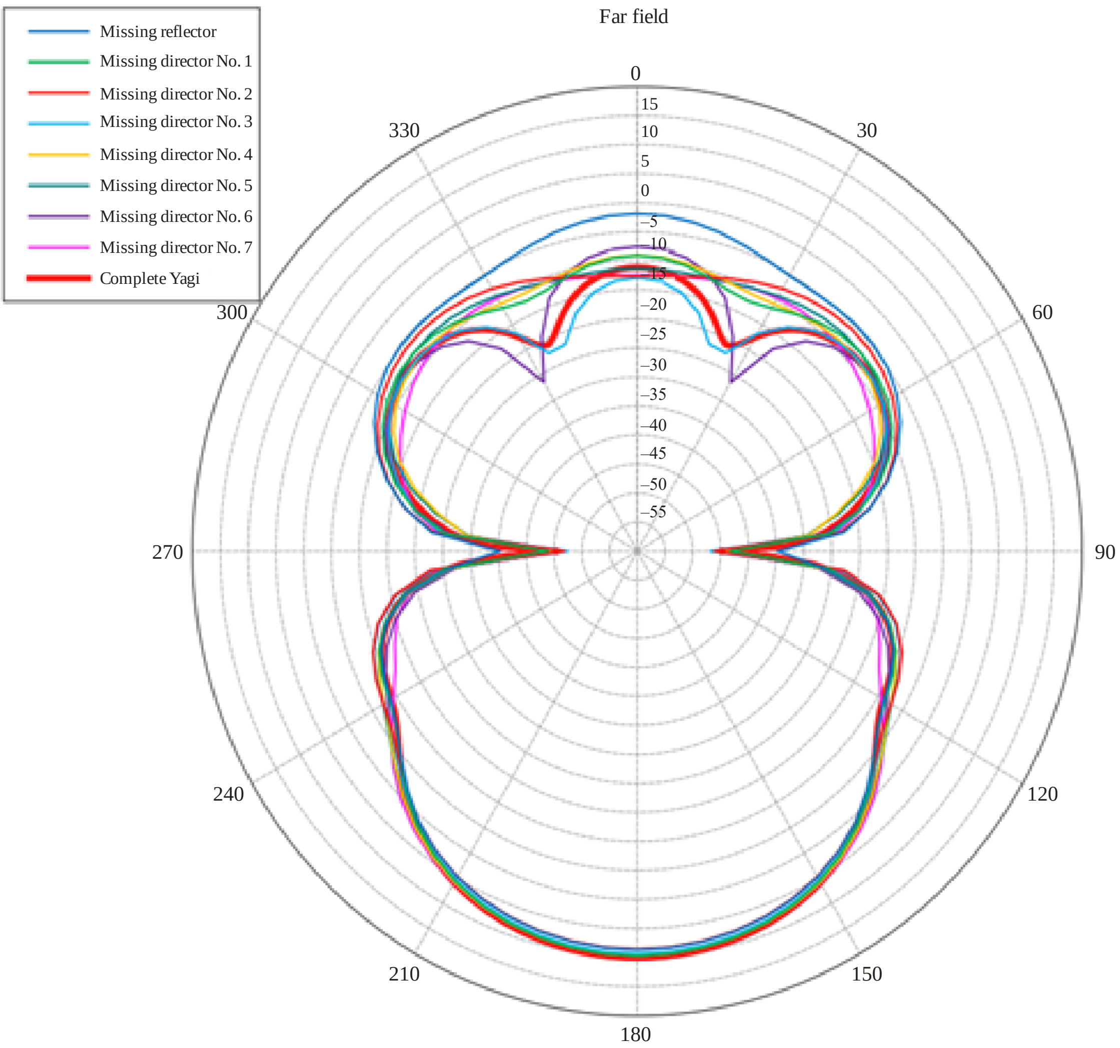
Sensor characteristics	
Parameter	**Value**
Sensor Type	Radar Sounder
Orbit characteristics	
Type of orbit	Circular, SSO[1]
Altitude (km)	400
Inclination (degree)	97
Ascending node LST	004:00
Eccentricity	0
Orbits per day	15.8
Repeat period, days	548
Antenna characteristics	
Antenna type	9 Element Cross Yagi
Number of beams	1
Antenna peak gain (Transmit & Receive) (dBi)	10
Polarization	Circular
−3 dB beamwidth (degree)	40
Antenna beam look angle (degree)	Nadir
Antenna beam azimuth angle (degree)	Nadir
Antenna elevation beamwidth (degree)	40
Antenna azimuth beamwidth (degree)	40
Sensor antenna pattern	See Figure 1
Transmitter characteristics	
RF centre frequency (MHz)	45
RF 3dB bandwidth (MHz)	8
RF 20dB bandwidth (MHz)	10
Transmit peak power (dBW)	20
Pulsewidth (usec)	85
Pulse Repetition Frequency (PRF) (Hz)	1200
Pulse modulation	Linear FM (LFM) Chirp
Receiver characteristics	
RF centre frequency (MHz)	45
Gain (dB)	40-50
SNR, dB	30
LNA bandwidth (MHz)	>100
Final IF filter bandwidth (MHz)	12
System noise figure (dB)	5
Minimum detectable signal level (dBm)	−132
I/N (dB)	−6
Interference threshold level (dBm)	−138
Dynamic range (dB)	<20

1 Sun Synchronous Orbit.

The spaceborne sounding radar antenna is a nine-element cross Yagi antenna with antenna gain of 10 dBi, and beamwidth of 40° in range and azimuth as shown in Fig. 1.

FIGURE 1

Nine-element Yagi antenna pattern



Total gain (frequency = 50 MHz; Phi = 0°)

2.3 Orbital parameters

The spaceborne active sensor will be deployed on a low-Earth orbiting satellite at an altitude of 400 km, at an inclination optimized for a sun synchronous orbit and with an eccentricity less than 0.001. Orbital parameters can be found in Table 1.

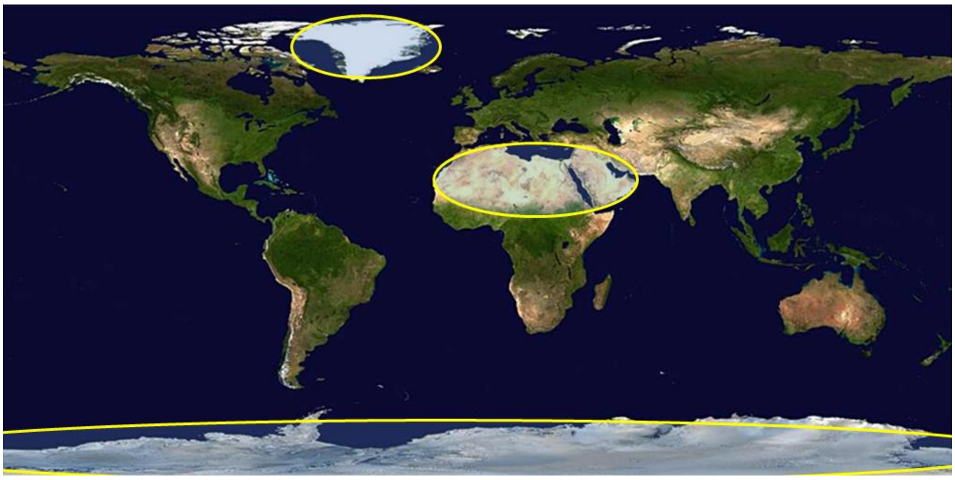
2.4 Operational limitations

The sounding radar is to be operated exclusively over un-inhabited or sparsely populated areas of the ice sheets of Greenland and Antarctica and the deserts of northern Africa and the Arabian Peninsula and will operate for a period not to exceed 10 minutes in duration per 92.7 minute orbit.

Areas of coverage for the proposed regions of operations that depict the geographic area over which the transmitted signal will be propagated are included in Fig. 2.

FIGURE 2

Spaceborne radar sounder coverage



The radar is to be operated only at night-time between the local hours of 3 a.m. to 6 a.m. This period of operation during the day was chosen because ionospheric perturbations to the radar signal are at a minimum during this time period and use of the spectrum by other services is expected to be the lightest.

It is also important to note that this study considers the operational scientific objectives and constraints of the radar sounder described in Recommendation ITU-R RS.2042. The study of this report considered the impact of one operational sounder on the incumbent services allocated in the 40-50 MHz frequency range. Taking into account the high investment cost associated with this type of sensor observations in the 40-50 MHz band, the number of spaceborne radar sounder missions operating simultaneously is expected to remain very few; perhaps only one, or two, in number.

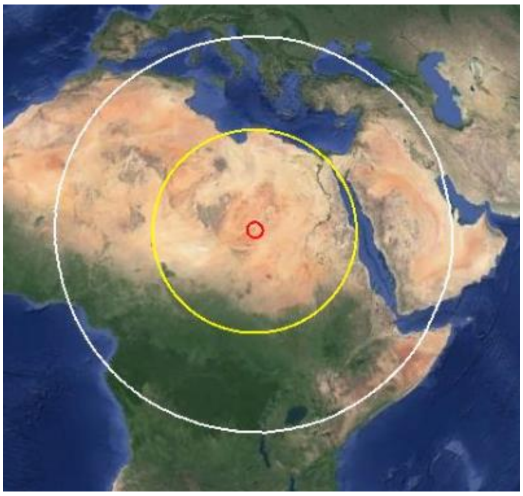
2.5 Pfd and spectral pfd levels at Earth's surface

For the parameters of the sounding radar in Table 1, the power flux-density (pfd) level at the Earth's surface is calculated to be −93.3 dB(W/m^2) at 45 MHz, corresponding to spectral pfd levels of −163.3 dB(W/m^2Hz) at 45 MHz. The antenna orientation will be nadir.

Figure 3 shows the results of a static area analysis based on power and antenna characteristics and provides some insight into the radar sounder's radiated power levels (dBW) as seen at the Earth's surface. Levels within the red circle are −120 dBW or greater, levels between the red circle and the yellow circle vary from −120 to −130 dBW and levels between the yellow circle and the white circle fall between −130 and −150 dBW, levels outside of the white circle will be less than −150 dBW.

FIGURE 3

Radar sounder radiated power at the Earth's surface

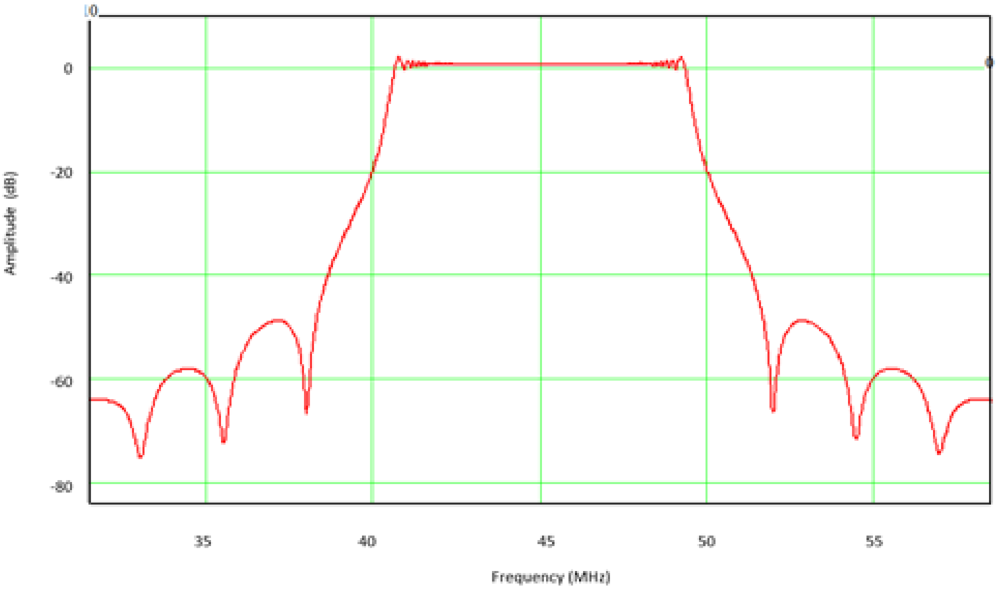


2.6 Emission Spectrum

Figure 4 shows the typical chirp emission spectrum waveform that is expected for the radar sounder operating in the frequency range of 40-50 MHz.

FIGURE 4

Typical chirp emission spectrum



3 Characteristics for services operating in the 40-50 MHz frequency band

3.1 Allocated services within and nearby (±15 MHz) the 40-50 MHz frequency band

Table 2 summarizes the incumbent service allocations within and nearby (±15 MHz) the 40-50 MHz frequency band.

TABLE 2

Allocation summary

Services	Frequency band (MHz)		
	25-40	**40-50**	**50-65**
Standard Frequency and Time	24.99-25.005		
	39.986-40.02		
Fixed	25.01-25.07	40.02-40.98	68-74.8
	25.21-25.33	40.98-41.015	
	26.175-26.2	41.015-42	
	26.2-26.35	42-42.5	
	26.2-26.42	42.5-44	
	26.2-26.35	44-47	
	26.35-27.5		
	26.42-27.5		
	26.35-27.5		
	27.5-28		
	29.7-30.005		
	37.5-38.02		
	38.25-39.986		
Mobile	25.01-25.07	40.02-40.98	68-74.8
	25.21-25.33	40.98-41.015	
	27.5-28	41.015-42	
	29.7-30.006	42-42.5	
	37.5-38.25	42.5-44	
	38.25-39.986	42.5-44	
	39.986-40.02		
Maritime Mobile	25.07-25.21	44-47	
	26.1-26.175		
Radio Astronomy	25.55-25.67		
	37.5-38.25		
Broadcasting	25.67-26.1	47-50	50-68
			68-72
Meteorological Aids	27.5-28		
Amateur/Amateur Satellite	28-29.7		50-54
Space Research	39.986-40.02	39.986-40.02	
		40.98-41.015	
Radiolocation		39.986-40.02	54-68
		42-42.5	68-72

For the purpose of this preliminary analysis, only services that fall within the 40-50 MHz frequency band have been considered. These services include Fixed, Mobile, Broadcasting, Space Research and Radiolocation.

4 Interference levels

4.1 Radar sounder interference criteria

Given that the minimum detectable signal for the radar sounder's receiver is −132 dBm and assuming an I/N of −6 dB, an interference threshold level of −138 dBm was assumed.

4.2 Incumbent services interference criteria

Interference criteria for the incumbent systems operating within the 40-50 MHz band is based on information in relevant Recommendations of the affected services, or has been calculated based upon noise floor levels where the necessary information is not available. The calculation of interference criteria based on noise floor levels is outlined in the following sections.

4.3 Calculation of maximum interference levels

4.3.1 External noise calculation

External noise is a combination of three components: man-made noise, galactic noise, and atmospheric noise. Man-made noise depends on the frequency and the environment, Galactic noise N_{gal} only depends on frequency and Atmospheric noise, N_{atm} depends on frequency, time of day and season. Figure 2 of Recommendation ITU-R P.372-13 provides man-made, galactic and atmospheric noise energy levels as a function of frequency; this figure is reproduced below in Fig. 5. In the quiet receiving sites, Curve C of Fig. 5 applies. However, since Fig. 5 Curve C does not extend to 45 MHz, it is necessary to use the primary equation (13) in Recommendation ITU-R P.372-13 to determine the median value of noise figure in quiet receiving sites as follows:

$$F_{am} = c - d \log f$$

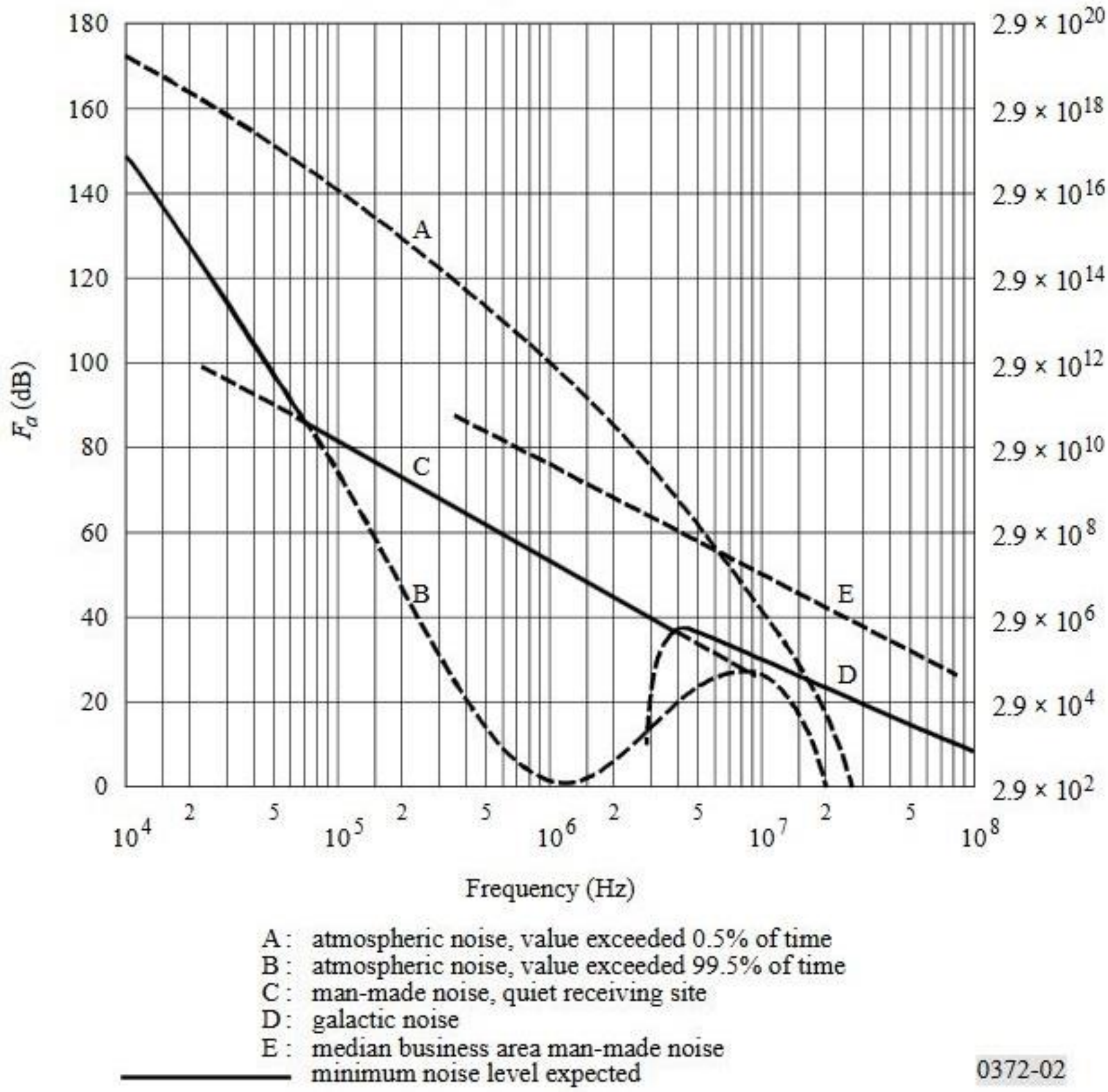
where, from Table 1 of Recommendation ITU-R P.372-13, c = 67.2 and d = 27.7.

The expert working group responsible for Recommendation ITU-R P.372-13 confirmed the appropriateness of the above formula, noting that it was derived from man-made noise measurements taken in 1970. It is likely that man-made noise has increased over time and any such increase will also improve the compatibility between the radar sounder and any incumbent system.

Therefore, at 45 MHz, the median noise figure is 21.4 dB which has then been used in these studies. It should be noted that this quiet receiving site level of man-made noise which is determined from the above formula is greater than the galactic and atmospheric noise at that frequency.

FIGURE 5

Man-made, galactic, and example atmospheric noise energy models
(Noise Figure F_a, and Noise Temperature t_a vs. Frequency)



Man-made, galactic and atmospheric noise figures obtained from Fig. 5 are listed in Table 3.

The noise floor in dBm is derived using the noise figure (equation (2)):

$$N_f = F + 10*\text{Log}\,(B) - 174 \quad (2)$$

where:

F = noise figure (dB)

B = bandwidth (Hz).

Table 3 summarizes the results of the noise floor calculations at 45 MHz.

TABLE 3

Noise components at 45 MHz

Noise component	***Man-made* (*R*ural)**	**Galactic**	**Atmospheric[1] (Exceeded 0.5% of time)**
F(dB)	21.4	18	N/A
Noise floor (dBm/Hz)	−152.6	−156	N/A
Noise floor (dBW/Hz)	−182.6	−186	N/A

(1) Atmospheric noise at frequencies above 30 MHz does not influence the overall noise contribution.

4.3.2 Resulting external noise calculation at 45 MHz

Given the values of man-made, galactic and atmospheric noise one can calculate the resulting external noise using the following formula:

$$N = 10*\log_{10}(10^{(Ngal/10)} + 10^{(Nman/10)} + 10^{(Natm/10)}) \qquad (3)$$

At 45 MHz:

1) man-made noise is equal to −182.6 dBW/Hz for “rural” environments;

2) galactic noise is equal to −186 dBW/Hz;

3) atmospheric noise depends on the brightness temperature, with maximum values occurring during the night and minimum values at midday, when the solar elevation angle is the highest. As indicated in Fig. 5, atmospheric noise does not influence the overall noise contribution at 45 MHz. For the purpose of these calculations atmospheric noise was assumed to be non-existent.

Therefore at 45 MHz the external noise has been determined to be equal to −181 dBW/Hz.

4.3.3 Maximum interference level

Once the external noise N is known, the maximum allowable interference level into a receiver with a bandwidth of B (Hz) is determined from:

$$I_{max} = N + (I/N)_{long\ term} + 10*\log_{10}(B)$$

with:

I_{max} : the maximum allowable interference level in the incumbent service receiver

$(I/N)_{long\ term}$: the long term allowable I/N

N : the external noise value in dBW/Hz, calculated in “rural” and “quiet rural” environments.

The maximum interference level, I_{max}, is derived from the value of the lowest atmospheric noise level. Table 4 provides an estimation of the external noise and the maximum interference levels.

TABLE 4

Service protection criteria: Maximum interference levels for incumbent services within the 40-50 MHz frequency band

Service	*I*/*N* (dB)	Channel bandwidth (kHz)	Maximum interference level (dBW/channel bandwidth)
Fixed	−6	36	−141.4
Mobile	−10	16 (1)	−148.9
Broadcasting	−10	9 (1)	−151.4
Space Research	−6	1	−157
Radiolocation	−6	125	−136

(1) The appropriate value for channel bandwidth used in the calculations for the Broadcasting and Mobile service needs further investigation. Information from expert working groups indicate that values of bandwidth could possibly be larger than those indicated above. This will be investigated in future dynamic studies.

5 Propagation factors for consideration in Dynamic Simulation Analyses

Radio propagation at VHF and UHF on space to earth paths through the ionosphere is subject to attenuation, polarization rotation, amplitude and phase scintillation and ray-path bending. These effects may influence the extent of frequency sharing for satellite services between satellite and terrestrial services and the effects are directly dependent on the electron density (Ne) level in the different layers of the ionosphere. The column integral of *Ne*, the Total Electron Content (TEC), is of special importance. Lower TEC values allow for more sensitive spaceborne radar sounder operation. To achieve these lower values the orbital altitude of the spaceborne sounding radar should be as low as possible and operations should occur at around the time of solar minimum; that is, night-time data acquisitions.

For orbiting satellite systems the effect of time and location variations of irregularities in the ionosphere may be of importance. Equatorial and polar regions will need to be considered when conducting interference and compatibility studies, both in-band and out-of-band, between the radar sounder and incumbent services operating in the 40-50 MHz frequency band. In the Polar Regions, periods of auroral activity also need to be considered for timeframes where there is such activity.

The influence of the magnetic field of the earth has some effect on polarization (Faraday rotation); however, since the spaceborne radar sounder employs circular polarization the difference in interference to the incumbent service receivers resulting from Faraday rotation is negligible.

Table 5 summarizes the propagation factors that need to be taken into consideration when conducting dynamic interference and compatibility analyses along space to earth transmission paths. Derivations of the magnitude of the effects in Table 5 and their relevancy to compatibility studies can be found in Annex 1 to this Report.

TABLE 5

Estimated nominal ionospheric effects at 45 MHz for zenith incident angles of 40 degrees

Effect	Magnitude	Frequency dependence	Relevancy to compatibility studies
Faraday rotation (degrees)	12 973	$1/f$^2	Not Relevant
Propagation delay-phase advance (usec)	25.809	$1/f$^2	Not Relevant
Refraction (milliradians)	< 23.661	$1/f$^2	Can be neglected – See Annex 1
Variation in the Direction of Arrival (Min of Arc)	62.014	$1/f$^2	Not Relevant
Absorption-Polar Cap (only) (dB)	9.83	$\sim 1/f$^2	Consider
Absorption-Auroral+Polar Cap (dB)	12.2	$\sim 1/f$^2	Consider
Absorption-Mid Latitude (dB)	<2.28	$1/f$^2	Consider
Dispersion (ns/MHz)	11 473	$1/f$^2	Not Relevant
Scintillation	Section 4 of Rec. ITU-R P.531-12	Section 4 of Rec. ITU-R P.531-12	Not Relevant

5.1 Faraday rotation

Faraday rotation is a propagation effect that results from the magneto-ionic nature of the ionosphere which impacts linearly polarized signals. A linearly polarized signal can be decomposed into two circularly polarized signals with equal magnitude: left hand circularly (LHC) polarized signals and right hand circularly (RHC) signals. The Earth magnetic field causes the LHC and RHC signals to propagate with two different velocities which results in rotating the plane of polarisation of the linearly polarized signal; this is known as Faraday rotation. The Faraday rotation alters the signal polarisation with the degree of change depending upon the state of the ionosphere. This state varies with the time of day, the seasons, and variations in the sunspot cycle.

Since the radar sounder uses circularly polarized transmissions the interference impact of the radar sounder transmission in relation to the incumbent service receiver will be reduced by 3 dB regardless of the Faraday rotation. It is noted that Faraday rotation will have a somewhat different effect on the vertical and horizontal components of the circular polarization; however, this is considered to be negligible and so the impact of Faraday rotation is disregarded in these studies.

5.2 Group delay and phase advance

The ionospheric refractive index is less than unity which results in a phase velocity (speed of light in vacuum/refractive index) for a sinusoidal that is greater than the speed of light in vacuum (i.e. phase advance). Furthermore, the ionospheric refractive index is frequency dependent which makes the ionosphere dispersive with group velocity less than speed of light and which in turn leads to group delay. Based on Recommendation ITU-R P.531-13, group delay and phase advance in the 40-50 MHz frequency band occur with equal values and opposite signs, and they are directly proportional to the Total Electron Content (TEC) along the propagation path of the sounder signals. Lower TEC values are associated with lower values for the phase advance and group delay. Lower TEC values can be realized by maintaining a low orbit altitude and by operating the sounder at night. Since these factors are inherent in the design and the operational characteristics of the sounder, group delays and phase advance should be considered as a factor when conducting interference and compatibility studies between the sounder and incumbent services operating within the 40-50 MHz frequency band. Phase advance impacts the phase of sounder – carrier phase, and the group delay impacts the information derived from the sounder signals. However, since this sounder study is based on power summation, which does not require phase information, both group delay and phase advance are not required in this study.

5.3 Refraction

The refractive index of the earth's ionosphere is responsible for the bending of radio waves from a straight line geometric path between a satellite and ground.

The maximum plasma frequency of the ionosphere (maximum plasma frequency of ionospheric F2 layer, foF2) does not exceed 15 MHz. Since the 45 MHz sounder is operating at a frequency that is higher than foF2, sounder transmissions propagating in the nadir direction pass through the ionosphere without refraction.

Rays propagating along other directions can undergo refraction due to variation in the refractive index of either the atmosphere or the ionosphere. However, based on Table 1 of Recommendation ITU-R P.834-11, the value of refraction due to variation of the atmospheric refractive index (atmospheric refraction) is very small and can be ignored. Also refraction due to variation of ionospheric refractive index (the ionospheric refraction) is very small and can be ignored. This is reflected in Table 5.

5.4 Atmospheric absorption

At VHF frequencies, observations have shown that typical night-time atmospheric absorption values range from 0.005 dB to 0.02 dB. Given the radar sounder's hours of operation and these low absorption values, one can conclude that atmospheric absorption will have, at best, a minimal effect on the path and can be ignored when conducting dynamic interference and compatibility studies outside of equatorial and Polar Regions. Within equatorial and polar regions absorption has been reported to fall within the range of 0.5 dB to 6 dB and must be considered as a factor in system design and operation and should also be considered when conducting dynamic interference and compatibility studies between the radar sounder and incumbent services operating within the 40-50 MHz frequency band. Annex 2 derives values for absorption at different zenith angles based on Recommendation ITU-R P.531-13, and is the source for the values in Table 5.

5.5 Ionospheric dispersion

The dispersive characteristics of the ionosphere are attributed to the frequency dependent characteristics of the ionospheric refractive index, and can result in the distortion of RF energy pulses that are propagated through it. The dispersion, or differential time delay due to the normal ionosphere, produces a difference in pulse arrival time. The dispersive term for pulse distortion is proportional to TEC. When the difference in group delay time across the bandwidth of the pulse is the same magnitude as the width of the pulse it will-be significantly disturbed by the ionosphere. In addition to pulse distortion by the dispersive effects due to the TEC of the normal background ionosphere, radio pulses are also modified by scattering from ionospheric irregularities. Although dispersion is a factor that needs to be taken into account by systems designers, it does not need to be considered when conducting dynamic interference and compatibility studies between the sounder and incumbent services operating within the 40-50 MHz frequency band.

5.6 Scintillation

Scintillation manifests itself as a variety of rapid variations of amplitude, phase, polarization angle, and angle of arrival of the signals. These variations degrade both the signals emitted by the sounder, and signals intercepted by the sounder. At the power level, which is used in the compatibility study, the signal degradation due to scintillation is reflected as additional attenuation imposed on signal powers. Imposing additional attenuation reduces the interfering signal powers either from the sounder or into the sounder.

5.7 Doppler

Although Doppler shift is an important characteristic that must be taken into consideration when designing a radar sounder, the effects of Doppler shift will not need to be considered when conducting interference and compatibility studies between the sounder and incumbent services operating within the 40-50 MHz frequency band.

5.8 Ducting

Ducting is the worst case of refraction, where the propagating signals undergo total reflection. The propagating signal may be either the sounder signal propagating toward Earth surface or an interfering signal propagating toward the sounder. Based on § 5.3, the impact of refraction can be disregarded within the sounder beam width. Accordingly, ducting cannot occur within the sounder beam width, and it is not required to be accounted for in the compatibility studies.

6 Static analysis methodology

6.1 Radar sounder to incumbent systems

The radar sounder transmitting antenna will be nadir looking and operations, as stated in §§ 2.3 and 2.4, will occur exclusively in un-inhabited or sparsely populated areas of the ice sheets of Greenland and Antarctica and the deserts of northern Africa and the Arabian Peninsula, and, also, operations will occur for a period not to exceed 10 minutes in duration while over those areas of interest.

The analysis methodology is as follows. Maximum interference levels for each of the incumbent systems under study were calculated as described in § 4.3. Signal levels at the incumbent service receiver are derived using equations (4), (5) and (6) below. Frequency dependent rejection and losses due to absorption are to be included in a calculation that will determine the level of interference to the incumbent receiver. The resultant interference signal level will be compared to the maximum incumbent service interference levels as shown in Table 4 to determine if the maximum allowable interference level has been exceeded.

Equations that will be used to derive the interference level from the radar sounder at an incumbent receiver are based upon those that can be found in Recommendation ITU-R SM.337-3 – Frequency and distance separations, and are as follows.

Free Space Path Loss:

$$FSL = 32.4 + 20\log(f) + 20\log(d) \quad (4)$$

where:

f = frequency (MHz)

d = distance (km)

FSL = dB.

Using equation (4) with an operational frequency of 45 MHz at an orbital altitude of 400 km yields a path loss (FSL) of 117.6 dB.

Frequency Dependent Rejection:

$$FDR = K\log(Bt/Br) \quad (5)$$

where:

Br =	receiver 3 dB bandwidth (Hz)
Bt =	transmitter 3 dB bandwidth (Hz)
K=	10 for non-coherent signals, 20 for pulse signals.

FDR is calculated using equation (5), with *K* = 20, as the sounder has a pulsed output. FDR is calculated for each of the incumbent receivers.

Interference Signal Level:

$$Pr = TXp + TXg + RXg - TXL - FSL - Lp - RXL - FDR \quad dBm \quad (6)$$

where:

Pr =	received power (dBm)
TXp =	transmitter output power (dBm)
TXg =	transmitter antenna gain (dBi)
RXg =	receiver antenna gain (dBi)
TXL =	transmit feeder and associated losses (feeder, connectors, etc.) (dB)
FSL =	free space loss or path loss (dB)
Lp =	The *Lp* term includes both miscellaneous signal propagation losses and absorption losses. Miscellaneous losses include fading margin, polarization mismatch, and other losses associated with medium through which signal is travelling. For polar and mid-latitude regions, the absorption loss values calculations are provided in Annex 2 and were equal to 9.83 dB for the Polar Regions, 12.29 dB for Polar Regions during auroral activity, and less than 2.46 dB for the mid-latitude regions. These are calculated loss values for slant path that is 20 degree off-axis from zenith
RXL =	receiver feeder and associated losses (feeder, connectors, etc.) (dB)
FDR =	Frequency Dependent Rejection (dB).

6.1.1 Radar sounder to incumbent systems static analysis results

System characteristics and the propagation effects (absorption losses) were taken into consideration for this analysis which is based upon the methodology that is described in Recommendation ITU-R P.619-1 – Propagation data required for the evaluation of interference between stations in space and those on the surface of the Earth, and Recommendation ITU-R RS.1260-1 Annex 2 Methodology for interference assessment and mitigation. A summary of the results of the static analysis can be found in Table 6.

TABLE 6

Results of static analysis

MidLatitude

Service	Sounder transmitter power (dBm)	Sounder antenna gain (dBi)	Path loss (dB)	Loss due to absorption (mid-latitude) (dB)	Incumbent receiver antenna gain (dBi)	Other losses (dB)	FDR (dB)	Power at incumbent receiver (dBm)	Power at incumbent receiver (dBW)	Maximum incumbent interference level (dBW)	Interference exceedance level (dB)
Fixed	50	10	118	2.3	0	3	47	−109.72	−139.72	−141.40	1.68
Mobile	50	10	118	2.3	0	3	54	−116.76	−146.76	−148.92	2.16
Broadcasting	50	10	118	2.3	0	3	59	−121.76	−151.76	−151.42	−0.34
Space Research	50	10	118	2.3	0	3	78	−140.84	−170.84	−156.96	−13.88
Radiolocation	50	10	118	2.3	0	3	36	−98.90	−128.90	−135.99	7.09

Polar

Service	Sounder transmitter power (dBm)	Sounder antenna gain (dBi)	Path loss (dB)	Loss due to absorption (Polar) (dB)	Incumbent receiver antenna gain (dBi)	Other losses (dB)	FDR (dB)	Power at incumbent receiver (dBm)	Power at incumbent receiver (dBW)	Maximum incumbent interference level (dBW)	Interference exceedance level (dB)
Fixed	50	10	118	9.8	0	3	47	−117.27	−147.27	−141.40	−5.87
Mobile	50	10	118	9.8	0	3	54	−124.31	−154.31	−148.92	−5.39
Broadcasting	50	10	118	9.8	0	3	59	−129.31	−159.31	−151.42	−7.89
Space Research	50	10	118	9.8	0	3	78	−148.39	−178.39	−156.96	−21.43
Radiolocation	50	10	118	9.8	0	3	36	−106.45	−136.45	−135.99	−0.46

Auroral+Polar

Service	Sounder transmitter power (dBm)	Sounder antenna gain (dBi)	Path loss (dB)	Loss due to absorption (Polar) (dB)	Incumbent receiver antenna gain (dBi)	Other losses (dB)	FDR (dB)	Power at incumbent receiver (dBm)	Power at incumbent receiver (dBW)	Maximum incumbent interference level (dBW)	Interference exceedance level (dB)
Fixed	50	10	118	12.29	0	3	47	−119.73	−149.73	−141.40	−8.33
Mobile	50	10	118	12.29	0	3	54	−126.77	−156.77	−148.92	−7.85
Broadcasting	50	10	118	12.29	0	3	59	−131.77	−161.77	−151.42	−10.35
Space Research	50	10	118	12.29	0	3	78	−150.85	−180.85	−156.96	−23.89
Radiolocation	50	10	118	12.29	0	3	36	−108.91	−138.91	−135.99	−2.92

7 Summary

The results of the static analysis show that the transmissions of proposed sounder in the midlatitude regions are slightly higher than the interference thresholds for the Fixed and Mobile services and, for the Radiolocation service, about 7 dB higher than the interference thresholds. For Broadcasting and the Space Research Service, the interference thresholds are not exceeded. In the Polar Regions the interference thresholds for the five services are not exceeded, including times when there is no auroral activity as well as when there is auroral activity. In all three cases (midlatitude, polar and polar + auroral), the two dominating factors are the environmental noise levels in areas where there are assignments in these services, and the impacts of absorption, which is higher in the Polar Regions.

The results of studies indicate that additional more rigorous static and dynamic studies are required to determine if compatibility is feasible between the spaceborne radar sounder and the incumbent fixed, mobile and radiolocation services in the 40-50 MHz frequency range. These studies may, among other factors, include:

– time-of-day and location factors which take into account the infrequent operation of the sounder and the limited areas of operation;
– refinement of noise levels for areas taking into account the incumbent service assignments in the frequency range;
– solar activity fluctuations;
– other seasonal effects; and
– directionality of the radar sounder signal compared to the incumbent services.

Considering the marginal exceedance of the interference threshold for fixed and mobile services (i.e. less than 2.2 dB) these exceedances may be resolvable through refined analyses. In the case of the radiolocation service where an exceedance of protection levels by about 7 dB was found, if this exceedance cannot resolved by the dynamic analysis, some additional mitigation steps may be needed requiring further study. Such follow-on studies should look at these issues and also examine compatibility with services operating in the bands immediately adjacent to the spaceborne radar sounder frequency range of operation.

Annex 1

Derivation of propagation factors

1 Summary

The propagation parameters reported in Table 5 in the main body in this Report are grouped into two groups: one group having parameters linearly proportional to total electron content along the propagation path, and another group having parameters with dependence on ionospheric refractive index profile. The methods used in calculating the propagation parameters of the first group and the second groups are described in §§ 3 and 4 respectively. Also the variation in angle of arrival is among the parameters within the second group. The profile of such a variation is calculated to prove that ducting cannot take place between the transmissions of the radar sounder and the incumbent services.

2 Grouping propagation parameters

The ionospheric propagation parameters reported in Table 5 in the main body in this Report can be gathered into two groups:

- One group having parameters linearly proportional to total electron content along the propagation path; and
- Another group having parameters with dependence on ionospheric refractive index profile.

The ionospheric propagation parameters within the first group are the following:

- Faraday rotation;
- Group Delay (phase advance);
- Absorption (polar cap absorption, auroral absorption, and mid – latitude absorption).

The ionospheric propagation parameters within the second group are the following:

- Refraction;
- Variation in angle of arrival.

3 Calculating propagation parameters within the first group

Each parameter within the first group is linearly proportional to the total electron content (TEC). By labelling TEC as N_T it can be written along a propagation path s as follows:

$$N_T = \int n_e(s)ds \qquad (7)$$

where $n_e(s)$ is electron density (concentration).

In case of Recommendation ITU-R P.531-13, where the systems are deployed above the ionosphere, the integration limits in equation (7) are from 80-2 000 km. Those limits are based on the altitude values used by IRI-2012 (International Reference Ionosphere 2012). For the 45 MHz radar sounder, the total electron content N_{TS} can be written as:

$$N_{TS} = \int_{80km}^{400km} n_e(s)ds \qquad (8)$$

Based on equation (8), the total electron content in case of the 45 MHz radar sounder is equal to the area under the curve of ionospheric electron density profile for heights extending from 80 km to 400 km. In case of Recommendation ITU-R P.531-13, the total electron content is equal the area under the curve from height of 80 km to the height of 2 000 km.

Figures 1 to 3 below depict some examples of ionospheric electron density profiles. For each figure, the height resolution used is 1 km, and both areas are calculated using the numerical trapezoidal rule. Below each figure of Figs 1 to 3, the following are provided:

- Total electron content N_T used in Table 7.
- Total electron content N_{TS} in case of the 45 MHz sounder.
- Ratio R of N_{TS} over N_T:

$$R = \frac{N_{TS}}{N_T} \qquad (9)$$

The three ratio R values reported below Figs 1 to 3 yield an average ratio value R_{avg} of 0.52. Accordingly, each parameter within the first group is multiplied by this average value to bring the parameter value to the sounder altitude of 400 km. Then the frequency dependence $1/f^2$ is used to transfer the value at the radar sounder altitude from 1 GHz, which is used in Table 3 of Recommendation ITU-R P.531-13, to 45 MHz. Such frequency dependence yields a scaling factor F:

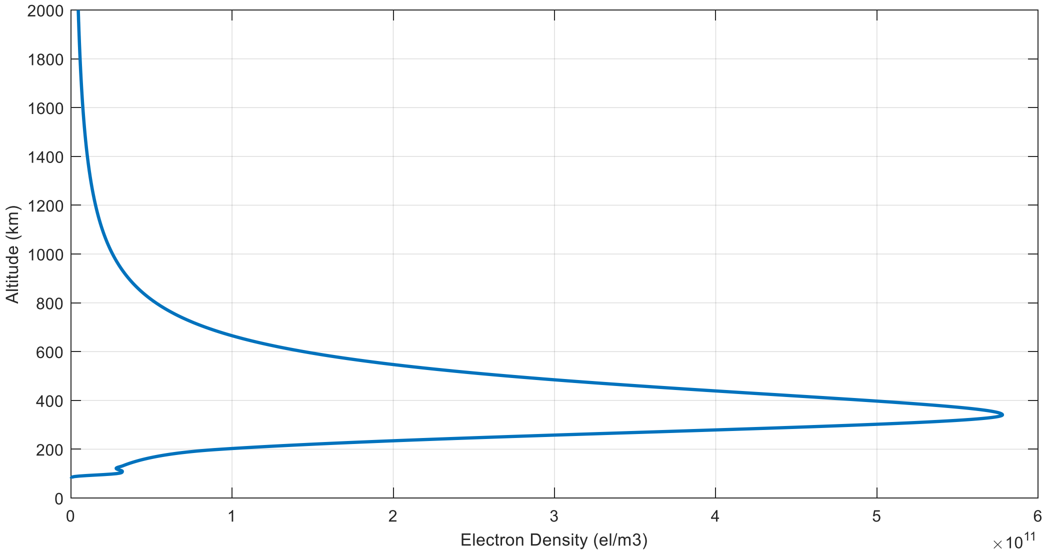
$$F = \left\{\frac{1/0.045}{1/1}\right\}^2 = \left\{\frac{1}{0.045}\right\}^2 = 493.83 \tag{10}$$

In summary to transfer parameters within the first group (Faraday rotation, propagation delay, and attenuation) from Table 3 of Recommendation ITU-R P.531-13 to Table 5, each parameter is multiplied by the following factor:

$$R_{avg} \times F = 0.52 \times 493.83 = 256.79 \tag{11}$$

FIGURE 1

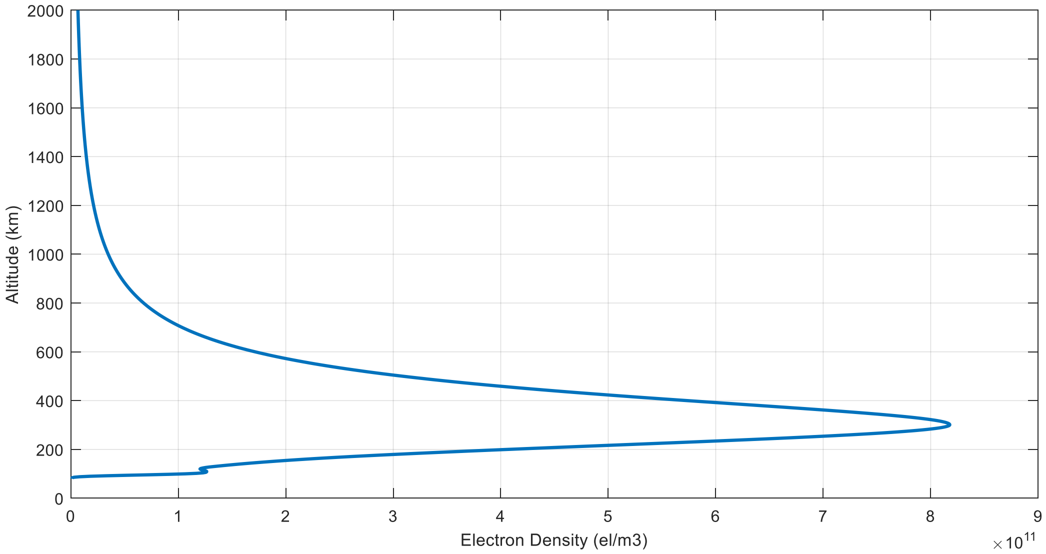
Ionospheric electron density versus height (date = June, 14, 2017, Universal time = 1.5 hour, latitude = 50°, longitude 40°)



Based on this Figure: $R_T = 1.8 \times 10^{17}$ el$/m^2$, $R_{TS} = 8.7 \times 10^{16}el/m^2$, and $R = 0.482$.

FIGURE 2

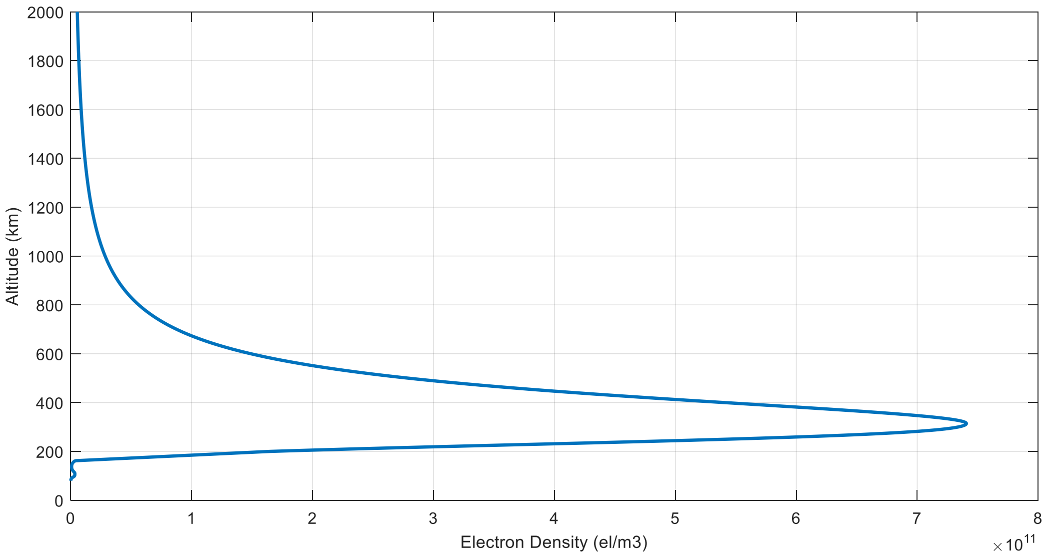
Ionospheric electron density versus height (date = June, 14, 2017, Universal time = 1.5 hour, latitude = 50°, longitude 90°)



Based on this Figure: $R_T = 2.7 \times 10^{17}$ el$/m^2$, $R_{TS} = 1.6 \times 10^{17}el/m^2$, and $R = 0.582$

FIGURE 3

Ionospheric electron density versus height (date = June, 14, 2017, Universal time = 1.5 hour, latitude = 0º, longitude 0º)



Based on this Figure: $R_T = 2.2 \times 10^{17}$ el$/m^2$, $R_{TS} = 1.2 \times 10^{17}el/m^2$, and $R = 0.5561$

4 Calculating propagation parameters within the second group

The propagation parameters within the second group are:

– variation in angle of arrival; and

– refraction.

4.1 Variation in angle of arrival

The variation in angle of arrival in case of the downlink (sounder – Earth) direction can be obtained from the following Snell's law in polar coordinate:

$$(a + h)n(h) \sin \varphi_h = (a + 400)\, n(400) \sin \varphi_{400} \quad (12)$$

In the above, a ($a = 6\,370\ km$) is the Earth radius, $n(h)$ is the ionospheric refractive index at an altitude of h km, and φ_h is the zenith incident angle at the height h. If the elevation angle is used instead of the zenith angle, equation (12) reduces to equation (13) of Recommendation ITU-R P.676-11, and equation (7) of Recommendation ITU-R P.834-7.

The angle difference $\Delta(h)$ gives the variation in angle of arrival at the height h:

$$\Delta(h) = \varphi_h - \varphi_{400} \quad (13)$$

Figures 4 to 6 calculate downlink (sounder-Earth) variations in angle of arrival using the three electron density profiles used in Figs 1 to 3, for a sounder with an incident angle of 30°. In each figure an arrow is added indicating the direction of propagation.

The ionospheric refractive index profiles used in Figs 4 to 6 are based on equation (14).

$$n(h) = \sqrt{1 - \left(\frac{f_c(h)}{f}\right)^2} \quad (14)$$

In equation (14), f is the frequency in Hz ($f = 45\,000$ Hz), and $f_c(h)$ is the electron plasma frequency (critical frequency) at the height h with:

$$f_c(h) = 8.9785\sqrt{n_e(h)} \tag{15}$$

FIGURE 4

Downlink (sounder-Earth) variation in angle of arrival as a function of height for a sounder incident angle of 30° (Electron density profile as in Fig. 1). Based on the Figure $\Delta(80)$ = 1.31°

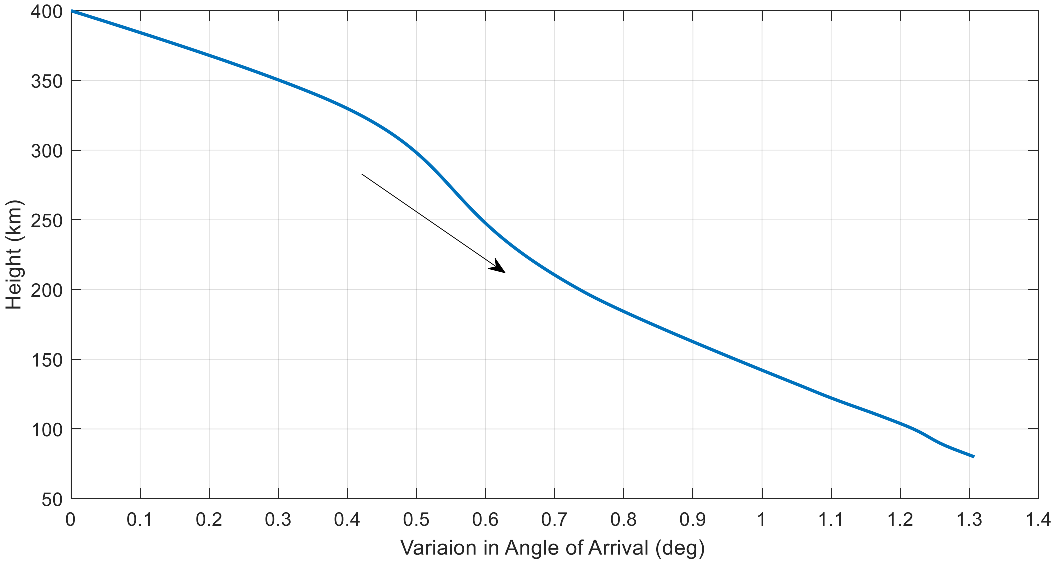


FIGURE 5

Downlink (sounder-Earth) variation in angle of arrival as a function of height for a sounder incident angle of 30° (Electron density profile as in Fig. 2). Based on the Figure $\Delta(80)$ = 1.25°

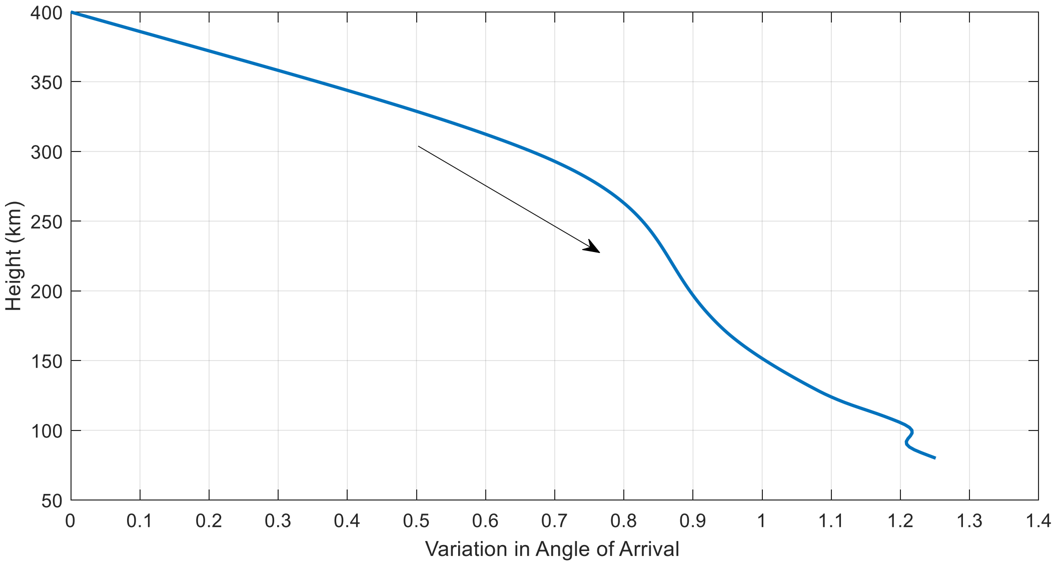
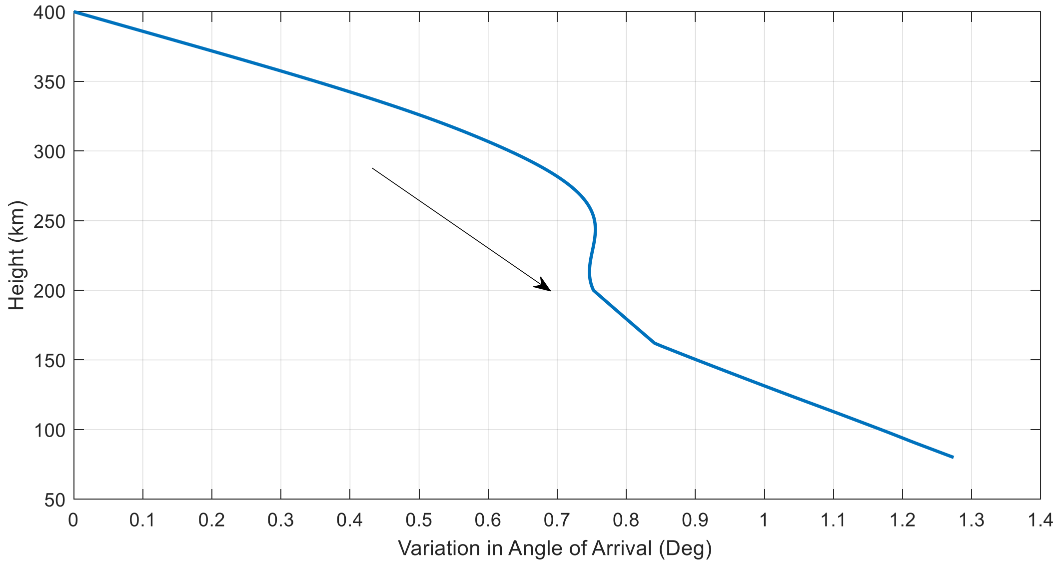


FIGURE 6

Downlink (sounder-Earth) variation in angle of arrival as a function of height for a sounder incident angle of 30°
(Electron density profile as in Fig. 3). Based on the Figure $\Delta(80)$ = 1.27°



Figures 4 to 6, give the following values for downlink (sounder – Earth) variation in angle of arrival $\Delta(80)$ at the lower boundary of the ionosphere: 1.31°, 1.25°, and 1.27° respectively. Those values yield an average variation in angle of arrival of $1.28° = 1.28 \times 60 = 76.8$ minutes.

Also examining Figs 4 to 6, indicates that total reflection and hence ducting cannot take place at any altitude between the radar sounder altitude of 400 km and the lower boundary of the ionosphere of 80 km. At any altitude for total reflection to occur, the variation in angle of arrival should be equal or greater that 60° (90° – the incident angle of 30°). To put this into a mathematical form we write $\sin \varphi_h$ from (3) as:

$$\sin \varphi_h = \left\{\frac{1+400/a}{1+h/a}\right\} \left\{\frac{n(400)}{n(h)}\right\} \sin \varphi_{400} \qquad (16)$$

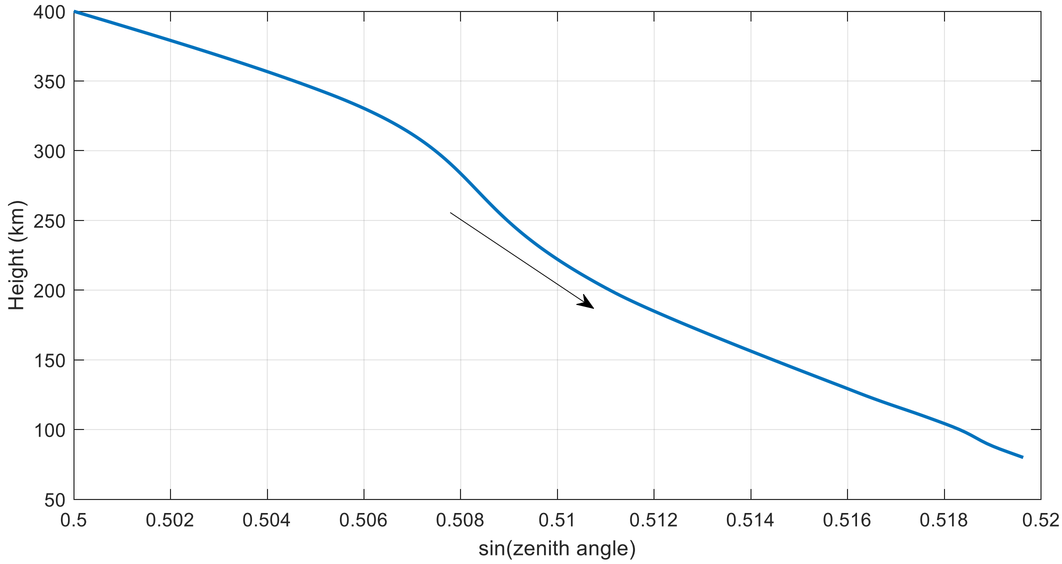
Total reflection (ducting) occurs if $\sin \varphi_h \geq 1$ which can be incorporated into equation (16) yielding the following condition leading to total reflection (ducting):

$$\sin \varphi_h = \left\{\frac{1+400/a}{1+h/a}\right\} \left\{\frac{n(400)}{n(h)}\right\} \sin \varphi_{400} \geq 1 \qquad (17)$$

The above condition cannot be satisfied for a ray propagating from the sounder at $\varphi_{400} = 30°$ as shown in Fig. 7.

FIGURE 7

Downlink (sounder-Earth) sin φ_h versus height (Electron density profile as in Fig. 1)



In case of uplink (Earth-sounder) direction, based on reciprocity, the above results are reversed. This means that the increase in angle of arrival (beam defocusing) depicted in Figs 4 to 6 in downlink (sounder-Earth) direction becomes a decrease (beam focusing) in angle of arrival in the uplink (Earth-sounder) direction. For instance, in Fig. 4, a ray leaving the radar sounder at a zenith angle of 30° reaches the lower boundary of the ionosphere at a zenith angle of 31.31 (30° + 1.31°). On the other hand, as shown in Fig. 8, a ray entering the lower boundary of the ionosphere at a zenith angle of 31.31° reaches the radar sounder at a zenith angle of 30° (31.31° – 30°).

FIGURE 8

Uplink (Earth-sounder) variation in angle of arrival as a function of height for a sounder incident angle of 30° (Electron density profile as in Fig. 4). Based on the Figure $\Delta(400) = -1.31°$

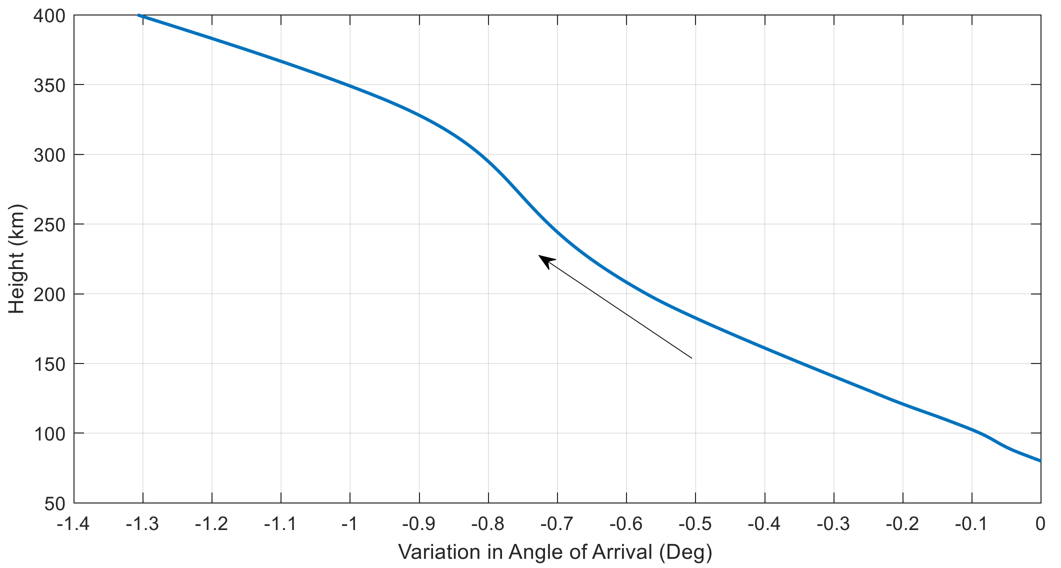


FIGURE 9

Uplink (Earth-sounder) sin φ_h versus height (Electron density profile as in Fig. 4)

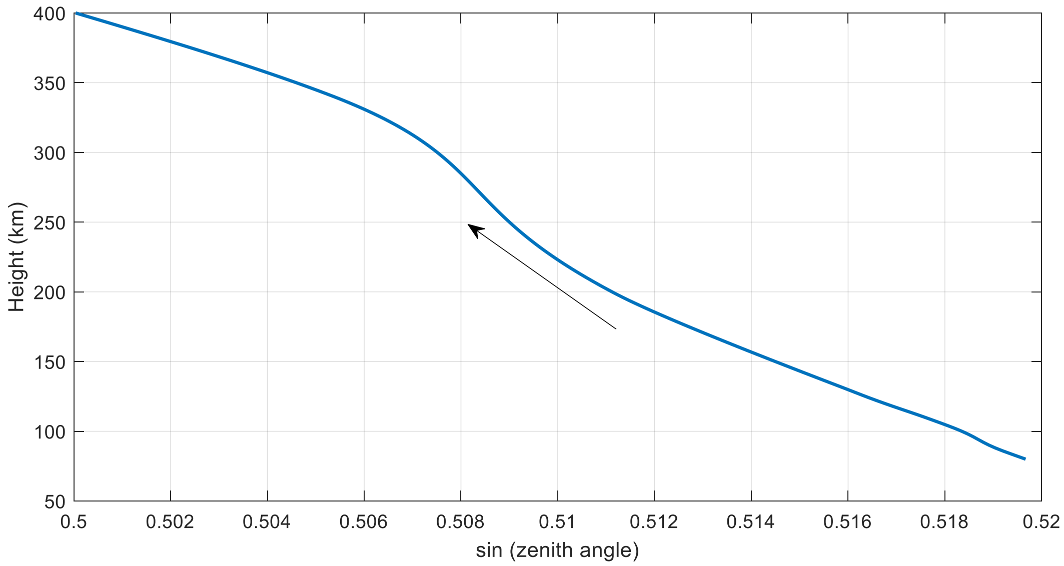


Figure 9 is calculated to prove that ducting cannot occur in case of uplink (Earth-sounder). Figure 9 depicts $\sin\varphi_h$ for a ray entering the lower boundary of the ionosphere at zenith angle of 31.31°. As shown in Fig. 9, along the propagation path $\sin\varphi_h < 1$. Accordingly, along the propagation path total reflection and hence ducting cannot occur. It is worth mentioning that Fig. 9 (uplink) is the same as Fig. 7 (downlink). The only difference between the two figures is the propagation (arrow) direction.

4.2 Refraction

Refraction in downlink (sounder-Earth) direction is caused by the variation in ionospheric refraction index along the propagation path and it is given by:

$$\tau_{dn} = -\int_{80}^{400} \tan\varphi_h \frac{n'(h)}{n(h)}\, dh \qquad (18)$$

In the above $n'(h)$is the first order derivative of the ionospheric refractive index with respect to height. It is worth mentioning that using the elevation angle instead of the zenith angle, equation (18) reduces into equation (5) of Recommendation ITU-R P.834-7.

To facilitate performing numerical calculation of equation (18) the following identity is recalled:

$$\frac{n'(h)}{n(h)} = \{\log n(h)\}' \qquad (19)$$

Then equation (9) is used to write $\tan\varphi_h$ as:

$$\tan\varphi_h = \frac{(a+400)n(400)\sin\varphi_{400}}{\sqrt{\{(a+h)n(h)\}^2 - \{(a+400)n(400)\sin\varphi_{400}\}^2}} \qquad (20)$$

Now introducing (19) and (20) into (18) yields:

$$\tau_{dn} = -(a+400)n(400)\sin\varphi_{400}\int_{80}^{400} \frac{\{log n(h)\}'}{\sqrt{\{(a+h)n(h)\}^2 - \{(a+400)n(400)\sin\varphi_{400}\}^2}}\, dh \qquad (21)$$

The integral in equation (21) is calculated numerically using the electron density profiles used in Figs 1 to 3 yielding refraction values of 5.88, 6.98, and 6.50 mrad. Those refraction values give an average refraction value τ_{avg} of 6.45 mrad in the downlink (sounder-Earth) direction. Based on reciprocity, those refraction values are reversed in the uplink (Earth-sounder) direction. Equation (21) can adapted for calculating uplink refraction τ_{up} through exchanging the radar sounder height by the height of the ionosphere lower boundary, and removing the minus sign yielding:

$$\tau_{up} = (a+80)n(80)\sin\varphi_{80}\int_{80}^{400}\frac{\{logn(h)\}'}{\sqrt{\{(a+h)n(h)\}^2-\{(a+80)n(80)\sin\varphi_{80}\}^2}} \quad (22)$$

In summary, based on reciprocity, refraction effects in the uplink direction are the reverse of the corresponding effects in the downlink direction. No ducting can occur in the uplink direction.

Annex 2

Atmospheric absorption/attenuation

Based on Recommendation ITU-R P.531-13, there are three types of ionospheric attenuation:

– Polar cap absorption (PCA)

– Auroral absorption, and

– Mid-latitude absorption.

The values of the above attenuation are given in Table 3 of Recommendation ITU-R P.531-13 at a frequency of 1 GHz and zenith angle of 30°. Those values are recalled in the Table 7 below.

TABLE 7

Ionospheric attenuation at 1 GHz and zenith angle of 30 degrees

Attenuation Type	**Attenuation value (dB)**	**Frequency dependence**	**Zenith angle dependence**
PCA	0.04	$1/f^2$	$\sec\theta_i$
Auroral + PCA	0.05	$1/f^2$	$\sec\theta_i$
Mid-latitude absorption	< 0.01	$1/f^2$	$\sec\theta_i$

The 45 MHs sounder is a nadir looking sounder with a frequency of 45 MH, and is located at a height of 400 km. The zenith angle within its footprint varies between 0° and 40°.

The following steps can be followed for adapting the above attenuation values for the 45 MHz:

– Transferring the above values from 1 GHz to 45 MHz (0.045 GHz) through multiplying each value by the factor of $\left(\frac{1}{0.045}\right)^2 = 493.8272$.

– After frequency transferring, transfer the attenuation to the sounder location. This can be achieved by multiplying the ratio of the total electron density below the sounder and total electron density of the ionosphere. This ratio may vary between 0.59 to 0.54 depending on the location. The value of 0.54 is used[2].

[2] The lower value is used because it yields lower attenuation values. Lower attenuation values could be used for setting interference criteria and not the higher attenuation values.

– Transferring the attenuation values from the zenith angle of 30° to the nadir incidence direction. This can be achieved through multiplying by this ratio $\frac{\sec 0}{\sec(30*\frac{\pi}{180})} = 0.8660$.

Accordingly transferring the attenuation values in Table 7 for the sounder use at nadir incidence (zero zenith angle) can be achieved through scaling them by the following factor:

$$493.8272 \times 0.54 \times 0.8660 = 230.9334$$

Scaling by the above factor yields the attenuation at zero zenith angle A_0 which can be used for getting the attenuation A_θ at an arbitrary zenith angle θ as follows:

$$A_\theta = A_0 \sec\theta$$

TABLE 8

Ionospheric attenuation between the 45 MHz sounder and Earth surface at three different zenith angles (9°, 20°, 30°)

Attenuation (dB)	A_0	A_{20}	A_{30}
PCA	9.2373	9.8303	10.6663
Auroral + PCA	11.5467	12.2880	13.3330
Mid-latitude absorption	< 2.3093	< 2.4576	< 2.8378