RECOMMENDATION ITU-R RS.1166-3

Performance and interference criteria for active spaceborne sensors

(1998-1999-2006)

Scope

This Recommendation reflects the performance and interference criteria for spaceborne active sensors in the bands allocated to the EESS (active). The Annex presents the technical bases for development of performance and interference criteria for various types of spaceborne active sensors. The sensor types include altimeters, scatterometers, precipitation radars, synthetic aperture radars and cloud profile radars.

The ITU Radiocommunication Assembly,

considering

a) that spaceborne active microwave remote sensing requires specific frequency ranges depending on the physical phenomena to be observed;

b) that certain frequency bands have been allocated for spaceborne active microwave remote sensing;

c) that these bands are also allocated to other radio services;

d) that performance criteria are a necessary prerequisite to the establishment of interference and sharing criteria;

e) that studies have established measurement sensitivity requirements;

f) that performance requirements for active sensors can be stated in terms of precision of measurement of physical parameters and availability, measured at the satellite, assuming that degradation from other elements in the system will be small;

g) that performance objectives for active spaceborne microwave sensors are a prerequisite for the establishment of the associated interference criteria;

h) that interference criteria are needed to ensure that systems can be designed to achieve adequate performance in the presence of interference, assess compatibility with systems in other services and, if needed, to assist in developing criteria for sharing frequency bands among services;

j) that Annex 1 presents the technical bases for performance and interference criteria based on representative active sensors, *recommends*

1 that the performance criteria given in Table 1 should be applied to instruments used in active sensing of the Earth's land, oceans and atmosphere:

TABLE 1

Frequency band	Performance criteria for remote sensing instruments				
	Scatterometer	**Altimeter**	**SAR imager**	**Precipitation radar**	**Cloud profile radars**
432-438 MHz			Minimum reflectivity of –21 dB		
1 215-1 300 MHz			Minimum reflectivity of –32 dB		
3 100-3 300 MHz		Sea level precision ≤ 3 cm	Minimum reflectivity of –26 dB		
5 250-5 570 MHz	Wind speed ≥ 3 m/s	Sea level precision ≤ 3 cm	Minimum reflectivity of –24 dB		
8 550-8 650 MHz	Wind speed ≥ 3 m/s	Sea level precision ≤ 3 cm	Minimum reflectivity of –21 dB		
9 500-9 800 MHz	Wind speed ≥ 3 m/s	Sea level precision ≤ 3 cm	Minimum reflectivity of –18 dB		
13.25-13.75 GHz	Wind speed ≥ 3 m/s	Sea level precision ≤ 3 cm		Minimum rain rates from 0.7-0.75 mm/h	
17.2-17.3 GHz	Wind speed ≥ 3 m/s			Minimum rain rates from 0.7-0.75 mm/h	
24.05-24.25 GHz				Minimum rain rates from 0.7-0.75 mm/h	
35.5-36 GHz	Wind speed ≥ 3 m/s	Sea level precision ≤ 3 cm		Minimum rain rates from 0.1-0.2 mm/h	–17 dBZ ± 10%
78-79 GHz					–27 dBZ ± 10%
94-94.1 GHz					–30 dBZ ± 10%
133.5-134 GHz					–34 dBZ ± 10%
237.9-238 GHz					–44 dBZ ± 10%

dBZ – "Unit" radar reflectivity used in meteorology which represents a logarithmic power ratio (in decibels, or dB) with respect to radar reflectivity factor, Z, referred to a value of 1 mm^6/m^3.

2 that the interference and data availability criteria given in Table 2 be applied for instruments used for active sensing of the Earth's land, oceans and atmosphere.

TABLE 2

Sensor type	Interference criteria		Data availability criteria (%)	
	Performance degradation	*I*/*N* (dB)	Systematic	Random
Synthetic aperture radar	10% degradation of standard deviation of pixel power	–6	99	95
Altimeter	4% degradation in height noise	–3	99	95
Scatterometer	8% degradation in measurement of normalized radar backscatter to deduce wind speeds	–5	99	95
Precipitation radar	7% increase in minimum rainfall rate	–10	N/A	99.8
Cloud profile radar	10% degradation in minimum cloud reflectivity	–10	99	95

Annex 1

Performance and interference criteria for spaceborne active sensors

1 Introduction

Performance criteria for active spaceborne sensors are needed in order to develop interference criteria. Interference criteria, in turn, can be used to assess the compatibility of radionavigation and radiolocation systems and active sensors in common frequency bands.

This Annex presents the technical basis for development of performance and interference criteria for various types of spaceborne active sensors. The sensor types include altimeters, scatterometers, precipitation radars, synthetic aperture radars, and cloud profile radars.

Although the criteria are based on current and planned space science system designs and associated operating requirements, it is anticipated that future space science systems can be designed to accept at least the same levels of interfering signals and associated spatial and temporal conditions.

2 Altimeters

This section presents information on the performance and interference criteria for spaceborne altimeters in the frequency bands 3.1-3.3 GHz, 5.25-5.57 GHz, 8.55-8.65 GHz, 9.5-9.8 GHz, 13.25-13.75 GHz and 35.5-35.6 GHz.

2.1 Performance criteria

Spaceborne altimeters produce, after data processing, measurement of sea level with a precision of less than 3 cm. The noise level in height measurements from altimeters is around 2-2.4 cm for low sea-states. An increase of 0.1 cm in the height noise due to interference would not materially affect the data and would be acceptable. In other words, a 4% degradation in height noise would be consistent with mission objectives.

A requirement for altimeter missions is acquisition of 90% of all possible data over oceans. The design goal is higher than the minimum requirement and has been established as 95% of all possible data. Observations must be taken as close to the land-sea interface as possible (below 15 km from the land-sea interface, altimeter waveform distortions occur and prevent accurate height estimation). The budget for lost data must accommodate all sources of loss including those due to spacecraft systems, the altimeter instrument, manoeuvres, etc.

The availability requirement for altimetry data is 95%, assuming that the associated individual outages are brief and randomly dispersed over all observation time and areas (i.e. most outages lasting 2 s or less).

The impact of interference that is always present at a given geographical location is much more serious than that of random interference, because measurements can never be obtained from those geographical areas. In that event the requirement for altimeters is to obtain valid data for 99% of all geographical areas of interest.

2.2 Interference criteria

Typical altimeters have link budgets that result in *S*/*N* of 13 dB (except for 35.5-36 GHz altimeters) in the receiver range resolution bandwidth of 39.9 dB/Hz. The altimeter height noise varies as $1 + 2/(S/N)$. For a return signal having a *S*/*N* of 13 dB before interference, the addition of interference causes the following increase in height measurement noise:

Interference level	*S*/*N* (dB)		Degradation (%)	
	Non-white interference	White interference	Non-white interference	White interference
None	13	13	Baseline	Baseline
10 dB below noise	12.6	12.99	1	0.05
3 dB below noise	11.25	12.5	4.5	1
Equal to noise	10	11.5	9	3.8
10 dB above noise	2.6	3	91	82

For 35.5-36 GHz altimeters, atmospheric effects and technological constraints result in a less favourable link budget (*S*/*N* close to 10 dB) and so the sensitivity to interference level is higher, the following values have to be taken into account:

Interference level	*S*/*N* (dB)		Degradation (%)	
	Non-white interference	White interference	Non-white interference	White interference
None	10	10	Baseline	Baseline
10 dB below noise	9.6	9.98	1.7	0.08
6 dB below noise	9.0	9.9	4.2	0.5
3 dB below noise	8.2	9.5	8.4	1.2
1.5 dB below noise	7.7	9.1	11.8	3.8
Equal to noise	7.0	8.5	17	6.9
10 dB above noise	–0.4	0	167	150

Degradation of height measurement noise in excess of 4% will not allow mission requirements to be met. To allow for non-Gaussian interference, the threshold for interference is set at 3 dB below the noise floor. As can be seen, the performance degradation increases sharply for interference levels above the noise floor.

The criterion for harmful interference to altimeters is, therefore, an aggregate interfering signal power level of −117 dB(W/320 MHz) at 13-14 GHz and a level of –119 dB(W/450 MHz) at 35.5-36.0 GHz which would cause an unacceptable increase in the height measurement noise.

In shared frequency bands, availability of altimeter data shall exceed 95% of all locations in the sensor service area in the case where the loss occurs randomly and shall exceed 99% of all locations in the case where the loss occurs systematically at the same locations.

3 Scatterometers

This section presents information on performance and interference criteria for spaceborne scatterometers in the frequency bands 5.25-5.57 GHz, 8.55-8.65 GHz, 9.5-9.8 GHz, 13.25-13.75 GHz, 17.2-17.3 GHz and 35.5-36.0 GHz. It provides performance and interference criteria for active spaceborne scatterometers that can be used to analyse the compatibility of active spaceborne scatterometers and radionavigation and radiolocation systems in these bands.

Unwanted radio frequency emissions reaching the scatterometer's receiver can corrupt the radar’s scatterometer measurement of σ_0, where σ_0 is the normalized radar backscatter coefficient. The amount of degradation will depend on the statistics of the external interference.

3.1 Performance criteria

In scatterometer systems, an estimate of the echo return signal power is made by first measuring the “signal + noise” power (i.e. the echo return plus the system noise contribution), and then subtracting the “noise-only” power (an estimate of the system noise alone, or “noise floor”). The system noise includes thermal emissions from the Earth, as well as those introduced by the antenna, waveguides, and the receiver noise figure. To optimize system performance, the “signal + noise” and the “noise-only” measurements are made over different bandwidths and/or at different times. This strategy relies on the fact that the nominal system noise is inherently white during the measurement sequence (stationary, and with a flat spectral power distribution).

If external interference is present, the new composite background noise is the sum of the interference and the nominal system noise. Depending on the strength, modulation, antenna gain pattern, and geometry of the interfering source, the composite noise may not be white over the measurement sequence. The “noise-only” measurement will then not correspond to the noise of the “signal + noise” measurement and errors in the estimation of σ_0 will result.

The estimated σ_0 error that results from a given “noise-only” measurement error can be quantified with the following equation:

$$\sigma_0 \text{ Error (dB)} = 10 \log [1 + (\alpha - 1) / SNR\, \sigma_0] \tag{1}$$

where:

$SNR\, \sigma_0$ (dB) = 10 log (S/N) = signal-to-noise ratio of the σ_0 estimation process

with:

S: echo return power spectral density

N: nominal noise floor power spectral density (approximately –200 dB(W/Hz) at the scatterometer receiver input for both "fan beam" and "spot beam" antennas)

and

$$\alpha\,(\text{dB}) \;=\; 10 \log \left([N \;+\; (I_{s+n} \,/\, B_{s+n})] \,/\, [N \;+\; (I_n \,/\, B_n)]\right) \qquad (2)$$

with:

I_{s+n}: average power from interfering source in B_{s+n} during the "signal + noise" measurement period

B_{s+n}: "signal + noise" measurement bandwidth

I_n: average power from interfering source in B_n during the "noise-only" measurement period

B_n: "noise-only" measurement bandwidth.

The impact of external interference is most severe for winds with low speed. The lowest wind speed to be measured by spaceborne scatterometers is 3 m/s. Results of computer simulations conducted for non-stationary interference to the NSCAT scatterometer have shown that a maximum value of α (see equation (2)) that will allow performance requirements to be met for 3 m/s wind speeds is 0.7 dB.

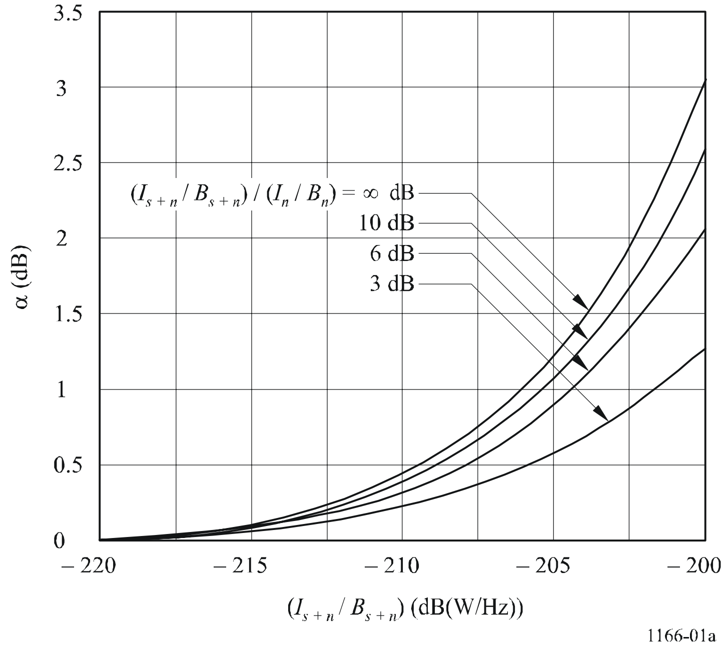
Scatterometers in the future may employ spot beam antennas rather than fan beam antennas as are used for NSCAT. The main differences, besides the antenna pattern, between the two types of scatterometers are the transmitted e.i.r.p. and receive antenna gain. Results of computer simulations conducted for non-stationary interference have shown that a maximum value of $\alpha = 6$ dB (see equation (2)) can be tolerated with the "spot beam" antenna and still meet the performance requirements for 3 m/s wind speeds.

The allowable loss of scatterometer data due to interference from radio frequency stations randomly distributed across the oceans is 5% of the data taken over the global oceans. The allowable loss for systematic interference is 1%. Systematic interference is defined as the loss of coverage at the same points on the oceans for most passes over those points. These maximum allowable losses have been derived from the NSCAT science requirement for measuring 90% of global vector winds over the oceans and taking into consideration other randomly distributed data losses introduced mainly in areas with intense rainfall.

3.2 Interference criteria

Figure 1a is a plot of equation (2) for a scatterometer with a receiver noise floor of N = –200 dB(W/Hz). It shows α as a function of the power spectral density of the interfering signal I_{s+n} / B_{s+n}). Note that different results for α will be obtained depending on how the interference is changing over time or over bandwidth. Figure 1a contains a family of plots for several values of the parameter 10 log $[(I_{s+n} / B_{s+n}) / (I_n / B_n)]$.

FIGURE 1a



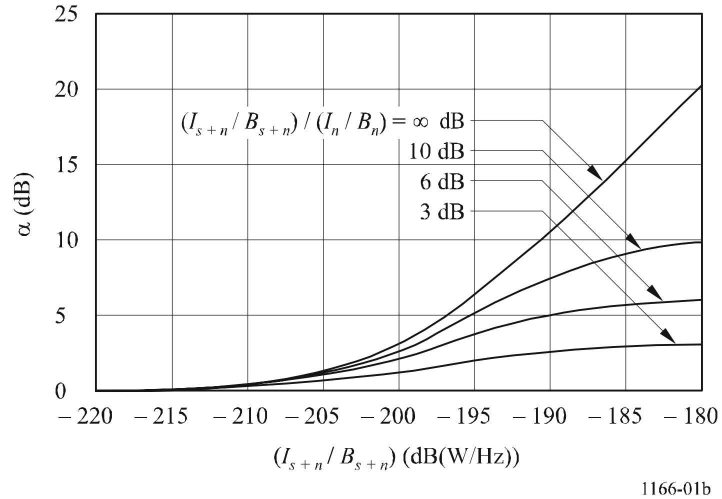
The time separation of the "signal + noise" measurement period from the centre of the "noise-only" measuring period is approximately 0.23 s. During this time the angle from the spacecraft scatterometer to a specific point on the ground will change by approximately 0.1°. Due to the narrow beamwidth of the fan beam antenna (0.42°, 3 dB beamwidth), changes of several dB in received interference levels should be expected as the scatterometer side lobes move through a transmitter beam. Engineering judgement has led to a value of 6 dB as the assumed maximum expected change in 10 log $[(I_{s+n} / B_{s+n}) / (I_n / B_n)]$ during the measurement period. From Fig. 1a, it is therefore concluded that the maximum interference power spectral density that any one of the six fan beam antennas of the NSCAT scatterometer can sustain without degraded measurement accuracy is –207 dB(W/Hz) or –174 dBW over any 2 kHz bandwidth within the 1 MHz bandwidth of the processing channel.

For white-noise like interference, the maximum acceptable interference spectral power density would be approximately −194 dB(W/Hz) at the input of the receiver which translates to an interference criterion of –161 dBW over any 2 kHz bandwidth within the 1 MHz bandwidth of the processing channel.

In the case of non-white noise, the interference criterion for a scatterometer which uses a spot beam antenna can be determined for the worst case assumption of 10 log $[(I_{s+n} / B_{s+n}) / (I_n / B_n)] = \pm\infty$. This situation represents the case in which the interference is present for either the "signal + noise" or the "noise-only" measurement, but not for both simultaneously.

From Fig. 1b it is therefore concluded that the maximum interference power spectral density that the "spot beam" antenna of an NSCAT-like scatterometer can sustain without degradation in the measurement is –195 dB(W/Hz). This requirement must hold for any 10 kHz bandwidth within the overall 1 MHz processing channel.

FIGURE 1b



For white-noise like interference, the maximum interference spectral power density would be approximately –185 dB(W/Hz) at the input of the receiver for a scatterometer with a “spot beam” antenna.

In shared frequency bands, availability of scatterometer data shall exceed 95% of all locations in the sensor service area in the case where the loss occurs randomly and shall exceed 99% of all locations in the case where the loss occurs systematically at the same locations.

4 Precipitation radars

This section presents information on performance and interference criteria for spaceborne precipitation radars in the frequency bands 13.25-13.75 GHz, 24.05-24.25 GHz, and 35.5-36.0 GHz. The performance and interference criteria for active spaceborne precipitation radars can be used to analyse the compatibility of active spaceborne precipitation radars and radionavigation and radiolocation systems in these bands.

4.1 Precipitation radars based upon TRMM

The first spaceborne precipitation radar is the TRMM Precipitation Radar (PR) which was launched in 1997.

Mission objectives and the design of the TRMM PR have been examined in order to develop performance and interference criteria that can subsequently be used to assess the compatibility of the PR and systems in the radionavigation and radiolocation services. Interference criteria are presented for both the level of interference that constitutes harmful interference and for the amount of data loss due to interference that are consistent with meeting mission objectives.

4.1.1 Performance criteria

The science requirement for the TRMM PR is to achieve, after data processing, measurement of rain rates equal to or greater than rain rates of 0.7 mm/h. An increase in measurable rain rate to 0.75 mm/h would not materially affect the data and would be acceptable as a performance criterion.

TRMM will obtain rainfall measurements everywhere within latitudes between ±35° as determined by the inclination of its orbit. Obtaining all potential rain measurements is important, however, measurements in the Inter-Tropical Convergence Zone (ITCZ), which is an area bounded by the Earth's equator and 10° N latitude, and the wide belt area extending from the Maritime continent to the South Pacific (called Australian Monsoon Trough and South Pacific Convergence Zone or SPCZ) are of particular importance. These most important areas are generally bounded by latitudes of 0°-10° N and 50°-180° E and 0°-10° S. Tropical rainfall is critical to distributing water across the Earth. Precipitation is greatest near the equator and more than two-thirds of it falls in the tropics. This precipitation releases energy that helps to power global atmospheric circulation, thus shaping both weather and climate. Tropical rainfall also plays a key role in the sporadic "El Niño" climate anomalies that trigger floods and draughts around the globe. Obtaining multi-year science data sets of tropical and subtropical rainfall measurements is key to understanding how interactions between the sea, air and land masses produce changes in global rainfall and climate. Such measurements can only be obtained by the use of satellites.

With the preceding background, the scientists on the TRMM project have determined that the needed availability of rainfall data is a function of where the rainfall occurs. The most critical area is in the ITCZ and in the vicinity of special "ground truth" sites that are being established in order to correlate the PR data with simultaneous terrestrial measurements. A criterion for loss of data in the ITCZ when interference occurs randomly is 0.2% of the possible data.

4.1.2 Interference criteria

An increase in rain rate measurement from 0.7 to 0.75 mm/h corresponds to a degradation in the system noise level of 10% due to noise-like interference. Therefore, the interference should be 10 dB below the system noise level. Since the system noise level is –140 dBW and the final bandwidth of the PR is 600 kHz, the criteria for the harmful interference level is –150 dB(W/600 kHz). Outside the 12 MHz band between 13.793 GHz and 13.805 GHz, the allowable interference level is much higher due to the band-pass filtering in the receiver; –115 dBW for 13.790-13.793 GHz and 13.805-13.808 GHz, –90 dBW for 13.75-13.79 GHz and 13.808-13.850 GHz, and –70 dBW for 13.85-13.86 GHz. At 35.5-36.0 GHz, the criteria for the harmful interference level is –152 dB(W/600 kHz).

In shared frequency bands, availability of precipitation radar data shall exceed 99.8% of all locations in the sensor service area in the case where the loss occurs randomly.

4.2 Precipitation radars based upon TRMM follow-on

4.2.1 Introduction

In this Annex, technical characteristics, performance and interference criteria of a spaceborne precipitation radar at 35 GHz are provided as another example of the active sensors which will use the 35.5-36.0 GHz band.

4.2.2 TRMM follow-on and 35 GHz band precipitation radar

A TRMM satellite was successfully launched in November 1997 and after that, TRMM has been producing unique and useful global set of data on the rainfall distribution and demonstrating the potential benefits of such data in the field of climate, weather forecast, hydrology, etc. As a successor to the TRMM satellite, a follow-on mission is planned.

To attain a wider latitude coverage compared with 35° of latitude in the case of the TRMM satellite, increasing the observation region and achieving more sensitive measurement are required in the follow-on mission. For these reasons, a 35 GHz precipitation radar as well as a 13 GHz precipitation radar are planned to be onboard the follow-on mission satellite. Table 3 shows the outline of the follow-on satellite.

TABLE 3

Outline of follow-on precipitation radar mission

Purpose	Global measurement of rainfall distribution
Orbit height	400 km (tentative)
Orbit inclination	60°-75°
Onboard sensors	13 GHz precipitation radar 35 GHz precipitation radar Microwave imager, visible/infrared radiometer, etc.

4.2.3 Technical characteristics of the 35 GHz precipitation radar

Table 4 shows technical characteristics of the 35 GHz precipitation radar which is being considered as one of the instruments onboard the follow-on precipitation radar satellite. The main task of the 35 GHz precipitation radar is to make high sensitivity measurements. The goal of the minimum detectable radar reflectivity is at least less than 14 dBZ and the resultant rain rate is less than 0.2 mm/h, which can never be achieved by the 13 GHz precipitation radar. Compared to the 13 GHz precipitation radar, the beam scanning function of the 35 GHz radar would be only a limited one. The antenna beam would be fixed at nadir or scanned within a few degrees from nadir.

TABLE 4

Characteristics of TRMM follow-on 35 GHz precipitation radar (tentative)

RF centre frequency	35.55 GHz
Transmit peak power	200 W
Pulse width	1.67 μs
Pulse repetition frequency	2 627 Hz
Pulse modulation	None
Antenna gain	51.5 dBi
Antenna orientation	Nadir or limited scanning
Antenna diameter	1.2 m (efficiency = 0.7)
Antenna beam width	0.5°
Horizontal resolution	3.5 km
RF transmit bandwidth	14 MHz
Receiver baseband bandwidth	600 kHz
System noise level (NF = 4 dB)	–142 dB(W/600 kHz)
TX/RX feeder loss	2.5 dB

4.2.4 Performance and interference criteria

4.2.4.1 Performance criteria

The percentage of the weak rainfall in the high latitude region is larger than that in the tropical region. Therefore it is necessary to measure the weak rain as much as possible in order to obtain a bias-free estimate of the rainfall distribution statistics over the high latitude region. Measurements of less than 0.2 mm/h rain rate are one of the measurement requirements in the precipitation radar follow-on mission. For this reason, a minimum detectable radar reflectivity of less than 14 dBZ is specified as the performance criteria of the 35 GHz precipitation radar.

4.2.4.2 Interference criteria

The radar reflectivity of 14 dBZ corresponds to 0.15 mm/h rain rate. This value may be degraded to up to 0.2 mm/h. This performance degradation corresponds to a 10% increase of the system noise temperature, or about a 0.5 dB increase of the system noise level. This criterion is essentially the same for the 13 GHz precipitation radar. As for the criterion of the data loss by interference, the same criteria for the 13 GHz precipitation radar could be used for the 35 GHz precipitation radar. Interference criteria for the 35 GHz precipitation radar is summarized as follows:

– permissible interference level: –152 dB(W/600 kHz);

– permissible data loss from interference: 0.2%.

5 Synthetic aperture radars

This section presents information on the performance and interference criteria for spaceborne active imaging radar sensors in the frequency bands 432-438 MHz, 1 215-1 300 MHz, 3 100-3 300 MHz, 5 250-5 570 MHz, 8 550-8 650 MHz and 9 500-9 800 MHz. The performance and interference criteria can be used to analyse the compatibility of active spaceborne imaging radar sensors and radionavigation and radiolocation systems in these bands.

5.1 Performance criteria of SARs

Synthetic aperture radars (SARs) are used in space to typically produce radar image maps of the terrain below as the spacecraft motion creates a synthetic aperture over a typical aperture time of only 0.2-1.5 s Any signals which interfere during this aperture time affect the imaging of that particular feature. Many SARs image mainly land and land/water transitions at the coasts. A finite number of selected sites are chosen by the experimenters to image over a range of look angles as the 1-8 day repeat orbits drifted slightly. Any interference that disrupts data from an experimental terrestrial site during any one of the look angle sequences would adversely affect performance. Another use of SARs is to produce topographic maps which can be used for digital elevation models. Some SARs use repeat pass interferometry in order to produce topographic maps. Interference on either one of the passes would affect the performance adversely. One spaceborne SAR flew a 10-day repeat orbit at 233 km, and collected fixed baseline interferometric SAR data during the ascending passes using 5 250-5 350 MHz and 9 500-9 800 MHz while collecting normal SAR data using the 1 215-1 300 MHz band. A second 5 250-5 350 MHz/9 500-9 800 MHz receive antenna mounted on a boom 30 m from the main antenna collected data simultaneously with the main antenna, and thus provided interferometry data without having to repeat passes. A scanning SAR mode using the 5 250-5 350 MHz band allowed collection of data over a 230 km wide swath, and allowed total coverage between ±60 degree latitudes. Any interference to either of the simultaneously received signals adversely affected the performance of the sensor.

A requirement for SAR imaging or topography missions is acquisition of 99% of the data from selected sites over land or land/ocean transitions. This budget for lost data is separate from other sources of loss such as those due to the spacecraft systems, the SAR instrument, etc.

The availability requirement for SAR data is 99%, assuming that the losses are of short duration and random over data acquisition time and areas. Interference at a given geographical location on a systematic basis is more serious, especially over one of the experimenters' selected sites, where ground truth experiments or validation experiments may be occurring at the same time. Interference at a given geographical location for the scansar topographic missions could create a gap in the global coverage map.

5.2 Interference criteria of SAR

The interference criteria for spaceborne imaging radars have been established as that presented in Table 2. In this Table 2, the interference criteria for synthetic aperture radars is an interference-to-noise ratio (I/N) of –6 dB, which corresponds to a 10% performance degradation of the standard deviation of SAR pixel power.

This interference level may be exceeded upon consideration of the interference mitigation effect of SAR processing discrimination and the modulation characteristics of the radiolocation/ radionavigation systems operating in the band. These levels may be exceeded for percentages of images less than 1% for systematic occurrences of interference and less than 5% for random occurrences of interference;

SAR raw data are processed both in range and azimuth to produce a radar image. A point target return is spread linearly in frequency both in range and azimuth dimensions. The processor correlates the data in both dimensions, and the processing gain typically ranges from 20 to 40 dB for the return echo. Noise and interference signals have much lower processing gains. The receiver noise has nearly 0 dB gain in range. Interference signals at the same input level as the noise, have different processing gains depending upon the waveform modulation type.

5.2.1 Processing gain of noise

The system noise, referenced to the antenna port, consists mainly of the antenna noise and front-end receiver noise. This noise can be modelled as a white, stationary, Gaussian noise process. The processor correlator is essentially a matched filter for the linear FM, or chirp, pulses. The range processing gain for noise is 0 dB. The azimuth processing gain is N^2 for the coherent integration of N returns during a synthetic aperture and N for the noise. There is a synthetic aperture integration time and an appropriate PRF needed to process the pixels to a certain resolution size in azimuth ρ_{AZ} as follows:

$$G_{N_{AZ}} = T_I PRF$$

$$T_I = \frac{\lambda R_S}{v L_{eff}}$$

$$PRF = 1.2 \frac{v}{\rho_{AZ}}$$

where:

G_{NAZ}: azimuth processing gain

T_I: SAR azimuth integration time

PRF: pulse repetition frequency

λ: wavelength

R_S: slant range

v: spacecraft platform velocity

L_{eff}: effective antenna length in azimuth

ρ_{AZ}: azimuth resolution.

As an example, for SAR3 near 9.6 GHz, λ = 0.03125 m, R_S = 535.8 km at 20° incidence angle, v = 7.05 km/s, and L_{eff} =1.56 m, then T_I = 1.52 s. For ρ_{AZ} = 1 m, then PRF = 8 460 Hz, and the azimuth processing gain for noise G_{NAZ} is 41.1 dB.

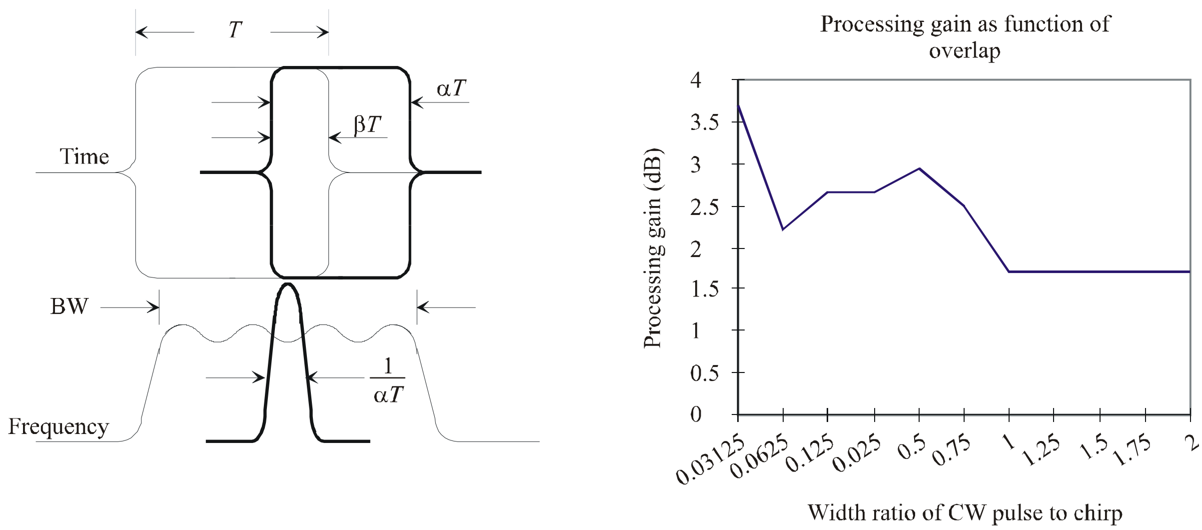
5.2.2 Range processing gain of interference signals

5.2.2.1 Pulse CW interference

Assuming that the RF centre frequency of the interference pulsed CW signals is within the processing band frequency, then the processing gain of interference relative to noise varies with the width of the CW pulse with respect to the linear FM pulse width, and with the percentage of overlapping area as shown in Fig. 2.

FIGURE 2

Time and frequency characteristics of chirp and pulse



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Assuming the interference pulse width is less than the chirp pulse width and is enveloped by the chirp (i.e. $\alpha = \beta$), then the processing gain is shown as a function of the fractional pulse width in Fig. 2.

5.2.2.2 CW interference signals

The RF centre frequency of the CW interference signal is assumed to be in the processing frequency band. For a level of interference signal equal to the noise level, the CW processing gain is 2.3 dB. For each image pixel, this is the same as for a CW pulse with the same width as the chirp pulse, the width ratio is unity.

5.2.2.3 Linear FM interference signals

The interference spectrum is assumed to fall within the processing frequency band, and the interference pulse is assumed to overlap the return echo pulse as shown in Fig. 1.

Let the chirp signal $f(t)$ be represented by the following:

$$f(t) = \mathrm{rect}(t / T_1)\mathrm{e}^{j2\pi f_0 + j\pi\mu t^2} \tag{1}$$

where:

rect(t): rectangle function of unity width

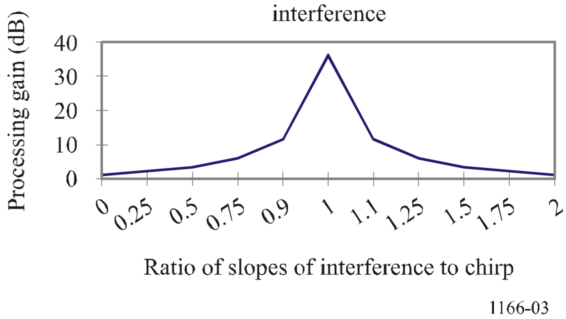
f_0: RF carrier frequency

μ: slope.

The processing gain of the interference pulse varies as the slope ratio $|\mu'/\mu|$ for approximately the same pulse width (i.e. $\alpha = 1$) as shown in Fig. 3. The slope of the interference pulse is μ' and the slope of the radar chirp is μ.

FIGURE 3

Processing gain of linear FM interference



5.2.2.4 Other interference waveforms/modulation

Interfering terrestrial radars have various waveforms/ modulations such as Barker codes, non-linear FM, etc. Each of these may be modelled, and processing gains relative to noise calculated. These modulations are not covered herein. However, even though the range processing gain is not covered herein, the azimuth processing gain still pertains to these pulsed waveforms.

5.2.3 Azimuth processing gain of pulsed interference signals

The SAR azimuth processing is performed through the summation of echo returns as the antenna beam illumination on the ground passes by the target area. For noise, the azimuth processing gain is N, for the integration of N pulses during a synthetic aperture. For interfering pulses, the phasing of the interfering signal within each range window differs from return to return since the terrestrial radar and the SAR have different PRFs. For the interfering pulsed signal, previous analyses using simulations for successive range windows and the summation of returns during a SAR integration interval showed that the instantaneous peak powers for azimuth processed interference pulses vary between 0 dB and 9.5 dB.

5.2.4 Calculation of allowable interference

The allowable interference levels as specified above may differ upon consideration of the interference mitigation effect of SAR processing discrimination and modulation characteristics of the radiolocation/ radionavigation systems operating in the band. The allowable interfering signal power P_I is as follows:

$$P_I = I / N \cdot P_N \cdot \frac{G_{N_{AZ}}}{G_{I_{AZ}}} \cdot \frac{G_{N_{RNG}}}{G_{I_{RNG}}} \qquad (2)$$

where:

- I/N : ratio of the interference-to-noise at the processor output
- P_N : noise power at the antenna port
- $G_{N_{AZ}}$: processing gain of noise in azimuth
- $G_{I_{AZ}}$: processing gain of the interfering signal in azimuth
- $G_{N_{RNG}}$: processing gain of noise in range
- $G_{I_{RNG}}$: processing gain of the interfering signal in range.

The processing gains are the products of the range processing gains and the azimuth processing gains. The range processing gain for interference is normally small, that is, less than 4 dB; however, the azimuth processing gain for interference is normally 20 dB to 40 dB lower than that for noise. For instance, in the case of a wideband SAR at 9.6 GHz receiving interference from an airborne radar, both the radar and the SAR use linear FM pulses with widely different chirp slopes. The SAR chirp slope is 45-450 MHz/ µs and the airborne radar chirp slope is 0.5 MHz/ µs. The ratio of the interfering chirp slope to the SAR chirp slope |µ'/µ| is only 0.001 to 0.01, and from Fig. 3 the corresponding range processing gain is about 2.3 dB. For I/N = –6 dB, P_N = –83.7 dBm, $G_{N_{AZ}}/G_{I_{AZ}}$ = 41.1 dB, and $G_{N_{RNG}}/G_{I_{RNG}}$ = –2.3 dB, then P_I should not exceed –50.9 dBm. Table 5 shows the calculation of processor gains for noise, the minimum desired return echo signal (SNR = 0 dB), and the interfering signal for the case of SAR3 at 9.6 GHz receiving interfering signals from the airborne radar.

TABLE 5

Range and azimuth processing gains for noise, signal and interference for SAR3 at 9.6 GHz

Signal type	Input power (dBm)	Range processing gain (dB)	Azimuth processing gain (dB)	Output power (dBm)
Noise	–83.7	0.0	41.1	–42.6
Minimum desired signal	–151.3	26.5	82.2	–42.6
Maximum acceptable interfering signal	–44.9	2.3	0.0 to 9.5	–42.6 to –34.8

5.2.5 Input/output signal characteristics of SAR operating in the bands 432-438 MHz and 1 215-1 300 MHz

The maximum acceptable interference output signal is equal to the system noise level, or receive antenna noise at the output. Table 6 shows the input/output signal characteristics of the noise, the minimum desired signal, and the maximum interfering signal, allowing for processing gain in range and azimuth. The levels are shown for both the 432-438 MHz band and the 1 215-1 300 MHz band.

TABLE 6

Input/output signal characteristics for SARs in the bands 432-438 MHz* and 1 215-1 300 MHz

Signal type	Input power (dBm)	Range processing gain (dB)	Azimuth processing gain (dB)	Output power (dBm)
Noise	–97.7 (–103.4)	0.0 (0.0)	30.6 (33.0)	–67.1 (–70.4)
Minimum desired signal	–156.5 (–164.2)	28.2 (27.8)	61.2 (66.0)	–67.1 (–70.4)
Maximum acceptable Interfering signal[(1)]	–69.4 (–72.7)	2.3 (2.3)	0 to 9.5 (0 to 9.5)	–67.1 to –57.6 (–70.4 to –60.9)

* The values for the 432-438 MHz band are shown in parentheses.

(1) Applies to non-FM pulsed interference sources with pulse durations of 2 μs or less. The levels vary for other pulse durations by only ± 0.6 dB.

5.2.6 Input/output signal characteristics of SARs operating in the bands 3 100-3 300 MHz and 5 250-5 570 MHz

The maximum acceptable interference output signal is equal to the system noise level, or receive antenna noise at the output. Table 7 shows the input/output signal characteristics of noise, the minimum desired signal, and the maximum interfering signal, allowing for processing gain in range and azimuth. The levels are shown for the postulated radars. For the 5 250-5 350 MHz band, the parameters for the main antenna have been used. However, the topographic interferometry mission may employ a pulse with a width of 66 μs to increase the signal energy and use a boom antenna having a length of only 8 m with LNAs at each stick in elevation in order to reduce the noise level.

For the nominal case, it shows at what level an interfering signal at the input equals the same power of the noise at the respective outputs. At these input levels, there would be no receiver back end saturation, for saturation does not occur for another 18 dB. The receiver front end 1 dB compression point is –22 dBm at the input. The receiver input maximum power handling is +37 dBm. So, the maximum acceptable interference signal is still very much less than needed to saturate or than maximum power handling.

TABLE 7

Input/output signal characteristics for SARs in the band 3 100-3 300 MHz* and 5 250-5 570 MHz

Signal type	Input power (dBm)	Range processing gain (dB)	Azimuth processing gain (dB)	Output power (dBm)
Noise	–96.7 (–99.3)	0.0 (0.0)	24.2 (27.7)	–72.5 (–71.6)
Minimum desired signal	–149.1 (–156.0)	28.2 (29.0)	48.4 (55.4)	–72.5 (–71.6)
Maximum acceptable Interfering signal(1)	–74.8 (–73.9)	2.3 (2.3)	0 to 9.5 (0 to 9.5)	–72.5 to –63.0 (–71.6 to –62.1)

* The values for the 3 100-3 300 MHz band are shown in parentheses.

(1) Applies to non-FM pulsed interference sources with pulse durations of 2 μs or less. The levels vary for other pulse durations by only ± 0.6 dB.

5.2.7 Input/output signal characteristics of SARs operating in the bands 8 550 MHz and 9 500-9 800 MHz

The maximum acceptable interference output signal is equal to the system noise level, or receive antenna noise at the output. Table 8 shows the input/output signal characteristics of the noise, the minimum desired signal, and the maximum interfering signal, allowing for processing gain in range and azimuth. It shows that an interfering signal as low as –74.5 to –75.0 dBm at the input equals the same power of the noise at the output. At this input level, there would be no receiver back end saturation, for saturation does not occur until the input signal reaches –56 dBm at a 60 dB receiver gain. The receiver front end 1 dB compression point is –22 dBm at the input. The receiver input maximum power handling is +37 dBm. So, the maximum acceptable interference signal of –74.5 to –75.0 dBm is still very much less than is needed to saturate or than for maximum power handling.

TABLE 8

Input/output signal characteristics for SARs in the band 8 550-8 650 MHz* and 9 500-9 800 MHz

Signal type	Input power (dBm)	Range processing gain (dB)	Azimuth processing gain(dB)	Output power (dBm)
Noise	–94.0 (–94.5)	0.0 (0.0)	21.8 (21.8)	–72.2 (–72.7)
Minimum desired signal	–145.3 (–145.8)	29.5 (29.5)	43.6 (43.6)	–72.2 (–72.7)
Maximum acceptable Interfering signal(1)	–74.5 (–75.0)	2.3 (2.3)	0 to 9.5 (0 to 9.5)	–72.2 to –62.7 (–72.7 to –63.2)

* The values for the 8 550-8 650 MHz band are shown in parentheses.

(1) Applies to non-FM pulsed interference sources with pulse durations of 2 μs or less. The levels vary for other pulse durations by only ± 0.6 dB.

5.2.8 Interference criteria

The criteria for unacceptable degradation in performance for imaging or topographical interferometric synthetic aperture radars are peak powers of:

432-438 MHz	–109 dBW/6 MHz
1 215-1 300 MHz	–106 dBW/20 MHz
3 100-3 300 MHz	–110 dBW/20 MHz
5 250-5 570 MHz	–111 dBW/20 MHz
8 550-8 650 MHz	–111 dBW/20 MHz
9 500-9 800 MHz	–110 dBW/20 MHz

These criteria apply to non-FM pulsed interference sources with pulse durations of 2 µs or less. For other pulse durations, the criteria varies by only ± 0.6 dB.

5.2.9 Availability criterion

In shared frequency bands, availability of SAR data shall exceed 99% of all geographical locations targeted as selected sites or for global coverage in topographical mapping.

6 Cloud profile radars

This section presents information on performance and interference criteria for spaceborne cloud profile radar sensors in the frequency bands 94.0-94.1 GHz, 133.5-134.0 GHz, and 237.9-238 GHz.

6.1 Performance criteria for 94 GHz cloud profile radar

The objective of a spaceborne cloud profiling mission is to measure the reflectivity profile for all clouds within the field of view with a minimum reflectivity of –30 dBZ.

6.2 Interference criteria of the cloud profile radar

Interference should degrade Z_{min} less than 10% in 95% of the service area. Ten percent degradation in Z_{min} corresponds to an interference-to-noise ratio of –10 dB. This interference criterion corresponds to an interference power level of –155 dBW over 300 kHz.

6.3 Availability criteria of the cloud profile radar

For random interference signals, the interference should degrade Z_{min} less than 10% in 95% of the service area. If the interference signal is not random, it should degrade Z_{min} less than 10% in 99% of the intended service area.