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INTERFERENCE MITIGATION TECHNIQUE USING ACTIVE SPACEBORNE SENSOR ANTENNA IN EESS (ACTIVE) AND SPACE RESEARCH SERVICE (ACTIVE) FOR USE IN 500 MHZ BANDWIDTH NEAR 9.6 GHZ

(SFCG-24 AGENDA ITEM 9.3 "Active Sensors")

Abstract

This document presents an interference mitigation technique using the active spaceborne sensor SAR3 antenna in the Earth Exploration-Satellite Service (active) and Space Research Service (active) for use in a 500 MHz bandwidth near 9.6 GHz.

The purpose of the document is present antenna designs which offer lower sidelobes and faster rolloff in the sidelobes which in turn mitigates the interference to other services from the EESS (active) and SRS (active) sensors.

Introduction

SFCG-23 Agenda Item 9.3 includes, as a topic for consideration by the SWGs, active sensors near 9.6 GHz.

There is WRC-07 Agenda Item 1.3 and Resolution 747 (WRC-03) which considers expanding by up to 200 MHz the existing primary allocations for the EESS (active) and SRS (active) in the band 9500 – 9800 MHz in order to expand the current allocation to a total of 500 MHz bandwidth in the band 9300 – 10000 MHz. EESS (active).

The 9500-9800 MHz band is used by active spaceborne sensors in the EESS (active) and SRS (active) under the provisions of the Radio Regulations. One active microwave spaceborne sensor which has been proposed in this band is the Synthetic Aperture Radar (SAR3). Civilian space agencies have been successfully flying spaceborne synthetic aperture radars in the 9.6 GHz band since 1994. The frequency band used is 9 500-9 800 MHz for which EESS (active) has a primary allocation. WRC-07 Agenda Item 1.3 and Resolution 747 (WRC-03) considers expanding by up to 200 MHz the existing primary allocations for the EESS (active) and SRS (active) in the band 9500-9800 MHz in order to expand the current allocation to a total of 500 MHz bandwidth in the band 9300-10000 MHz. This document herein presents technical characteristics of the active spaceborne sensor SAR3 antenna in the Earth Exploration-Satellite Service (active) for use in a 500 MHz bandwidth near 9.6 GHz and shows the interference mitigation it offers.

Options for wideband active spaceborne SAR sensors

The wideband SAR would provide spatial resolutions to the order of 1 m, requiring up to 500 MHz bandwidth. For a SAR which would transmit linear FM pulses with a bandwidth of 450 MHz, this provides a ground range resolution of 1 m over the look angles of 20 deg to 44 deg. For synthetic aperture radars, in azimuth the resolution in a typical strip map mode is half of the effective antenna length in azimuth. For a SAR antenna size of 50m x 1.4m, the resolution in azimuth in a strip map mode is half of 50m, or 25m. To improve the azimuth resolution to 1m, there are available several techniques and corresponding modes of operation. Fine resolution SAR modes include the spotlight mode, the subarray mode, and the stripmap mode.

The spotlight mode involves "spotlighting" the antenna beam in azimuth by scanning in azimuth as the spacecraft orbits to illuminate a given area for an appropriately long integration time. Since the width in azimuth of the ground illumination beam is only 0.34km to 0.49km depending upon the look angle, 44 to 60 spot beams side-by-side would be needed to image the 20 km swath in azimuth. A total integration time of 95 sec to 178 sec is needed to produce the 1m resolution image over the 20km swath in azimuth. The azimuth beam needs to be scanned from +/- 26 deg to +/- 65 deg in order to spotlight a 20km x 20km area as the spacecraft orbits. Since the subnadir ground velocity is about 7.05 km/sec, the 20km x 20km images would be separated by about 670km to 1255km along the azimuth track. The two other modes allow continuous imaging of 20km strips, but at a cost in power and processing. Since this spotlight mode uses the entire 50m x 1.4m antenna power, the peak power can be lowered by a factor of 10 from the subarray and stripmap modes. Possible characteristics for the spotlight mode are shown in Table 1.

The subarray mode uses subarray processing, whereby the array length in azimuth is subdivided into subarrays, and the individual subarrays receive the return signals simultaneously. The transmit PRF is the lower PRF associated with the 50m length as for the spotlight mode. The effective receive array length in azimuth is the subarray length, such that the antenna beam width in azimuth is broader, corresponding to the shorter subarray length. One could either transmit with one of the subarrays or transmit over all the subarrays and apply a phase spoiling across the array such that the 3 dB width of the azimuth gain pattern is approximately the same as each subarray receive azimuth gain pattern. Two benefits of phase weighting across the entire array is that the peak transmit power of 25 kW can be applied, versus, 1/32 of that power for one of the subarrays. Another benefit is that with the phase spoiling on transmit, the antenna gain pattern in azimuth falls off faster with angle from boresight, thus providing interference mitigation as the sidelobe levels decrease with angle from boresight. This mode allows continuous imaging of 20km strips. Possible characteristics for the subarray mode are shown in Table 1.

The stripmap mode transmits with an effective azimuth antenna length of 2m or less which the SAR processing yields half the effective azimuth length of 1m for azimuth resolution. The transmit PRF is high in order to accommodate the wide Doppler spectrum corresponding to the individual subarray length. The transmit PRF for the stripmap mode is about 32 times that PRF for the spotlight and subarray modes. The corresponding interpulse period (IPP) is then $1/32^{nd}$ of the IPP of the spotlight and subarray modes. One could either transmit/receive with one of the 1.56m subarrays or transmit over all the subarrays and apply a phase spoiling across the array such that the 3 dB width of the azimuth gain pattern is approximately the same as each subarray receive azimuth gain pattern. As before, this yields two benefits by phase weighting across the entire array in that the peak transmit power of 25 kW can be applied, versus, 1/32 of that power for one of the subarrays and that with the phase spoiling on transmit, the antenna gain pattern in azimuth falls off faster with angle from boresight, thus providing interference mitigation as the sidelobe levels decrease with angle from boresight. This mode also allows continuous imaging of 20km strips; however, because of the high PRF needed and the corresponding low interpulse period, the high range ambiguities become prohibitive as the look angle goes above 20 deg to 25 deg. Possible characteristics for the spotlight mode are shown in Table 1.

Modes other than imaging for the wideband SAR include the MTI mode which usually applies a weighting to the antenna pattern in azimuth. However, the SAR modes can also use the weighting in azimuth. Taylor weighting with -50 dB close-in sidelobes causes the mainlobe to broaden by a factor of about 1.5 with a corresponding reduction in gain by about 2 dB. However, the mainlobe falls quickly in angle off boresight down 50 dB and the close-in sidelobes stay below -50 dB relative to the peak gain thus providing interference mitigation with the extremely low sidelobe levels.

TABLE 1
Options for Wideband SAR Modes

Parameter	9.6 GHz 5 kW spotlight		9.6 GHz 25 kW subarray		9.6 GHz 25 kW strip
	20 deg	44 deg	20 deg	44 deg	20 deg
Altitude (km)	506	506	506	506	506
Resolution (m)	1	1	1	1	1
Ground Swath (km)	20	20	20	20	20
Field of View from Nadir (Inc. Angle)	20°	44°	20°	44°	20°
Polarizations	HH	HH	HH	HH	HH
Noise Equivalent σ_0 (dB)	-16	-16	-16	-16	-16
Frequency Range (GHz)	9.3-10.0	9.3-10.0	9.3-10.0	9.3-10.0	9.3-10.0
Bandwidth (MHz)	450	450	450	450	450
Powered antenna width (m)	0.7	1.4	0.7	1.4	0.8
Antenna gain (dB)	54.5	57.5	39.5	42.5	39.5
E.I.R.P (dBW)	88.5	94.5	83.5	86.5	83.5
PRF (Hz)	431	513	431	513	12168
Pulse width (μs)	10	10	10	10	10
RF Power, Peak (kW)	2.5	5.0	25	25	25
RF Power, Average (kW)	0.011	0.026	0.103	0.128	3.04
# of channels	1	1	1	1	1
Data rate (Mbps)	110	234	110	234	3220

Technical characteristics of wideband active spaceborne sensor SAR3 antenna

There are plans for a wideband active spaceborne sensor SAR3, with an improved spatial resolution to the order of 1 m, which would require up to 500 MHz bandwidth. Table 1 presents technical characteristics of active spaceborne sensor SAR3. The SAR3 antenna has a different antenna gain pattern in azimuth on transmit than on receive. In azimuth, the resolution for subarray processing can be improved to one meter. In subarray processing, the array length in azimuth is subdivided into subarrays, whereby individual subarrays receive the return signals simultaneously. The effective receive array length in azimuth is the subarray length, such that the antenna beam width in azimuth is broader, corresponding to the shorter subarray length. The transmit antenna pattern uses all the subarrays and applies a phase spoiling across the array such that the 3 dB width of the azimuth gain pattern is approximately the same as each subarray receive azimuth gain pattern. Two benefits of phase weighting across the entire array is that the peak transmit power of 25 kW can be applied, versus, 1/32 of that power for one of the subarrays. Another benefit is that with the phase spoiling on transmit, the antenna gain pattern in azimuth falls off faster with angle from boresight, thus providing interference mitigation as the sidelobe levels decrease with angle from boresight.

SAR3 Design parameters

SAR3 would transmit linear FM pulses centered near 9.6 GHz, with a pulse repetition rate between 410 and 515 Hz as shown in Table 2. The signal is either vertically or horizontally polarized at transmission and reception, to give one polarization, selectable between HH, or VV. The pulse width is 1-10 microsecond and the range bandwidth is 450 MHz.

TABLE 2

Key spaceborne SAR3 characteristics

SAR3	
Orbit height (km)	506
Orbit inclination (°)	98
Transmit power (W)	25 000
Pulse width (μs)	1-10
PRF (Hz)	410-515
Duty cycle	0.0004-0.005
Average RF power (W)	10-125
Modulation of pulse	Linear FM
RF bandwidth (MHz)	450
Peak antenna gain (dBi)	39.5-42.5

SAR3 would transmit linear FM pulses centered near 9.6 GHz, with a pulse repetition rate between 410 and 515 Hz as shown in Table 1. The signal is either vertically or horizontally polarized at transmission and reception, to give one polarization, selectable between HH, or VV. The pulse width is 1-10 microsecond and the range bandwidth is 450 MHz.

SAR3 Antenna gain pattern

The transmit antenna gain pattern in azimuth for phase weighting across the 50m array is shown in Figure 1. The transmit antenna gain pattern in azimuth for uniform weighting across an individual 1.56m panel is shown in Figure 2. SAR3 uses a planar array antenna. The 50 meter long and 1.4 meter wide planar array consists of transmit/receive (T/R) modules and phase shifters. The antenna is mechanically tilted around 32° from nadir and electronically scanned ±12° about the mechanical position to enable look angles of 20° to 44° from nadir. The antenna beamwidth is 1.1° to 2.3° in elevation. In azimuth, the beamwidth of an individual panel with uniform weighting corresponds to 1/32 of the aperture, or 1.56m, which is 1.15° in azimuth, with an overall gain of 39.5-42.5 dBi. Table 3 shows the equations for the antenna transmit gain pattern with 42.5 dBi peak gain for phase weighting across the 50m antenna. Table 2 shows the equations for the antenna transmit gain pattern with 42.5 dBi peak gain for uniform weighting across an individual 1.56m panel.

Figure 3 shows the antenna gain pattern for the phase weighting across the array and the curve fit to the envelope for angles between -4.5 deg to +4.5 deg in azimuth. Figure 4 shows the antenna gain pattern for the uniform weighting across an individual panel and the curve fit to the envelope for angles between -4.5 deg to +4.5 deg in azimuth.

Figure 5 shows the antenna gain pattern for the phase weighting across the array and the curve fit to the envelope for angles between -90 deg to +90 deg in azimuth. The peak of the gain is +42.5 dBi and the envelope has a floor at -5 dBi. Figure 6 shows the antenna gain pattern for the uniform weighting across an individual panel and the curve fit to the envelope for angles between -90 deg to +90 deg in azimuth. The equations for the uniform weighting pattern are in Table 3.

Figure 7 shows the antenna gain pattern for the Taylor weighting across the array and the antenna gain pattern for uniform weighting across the panel for angles between -90 deg to +90 deg in azimuth. The close-in sidelobes are below -50 dB for this Taylor weighting. Figure 8 shows the antenna gain pattern for the Taylor weighting across the array and the curve fit which is in the Annex 13 of document 7C/146 Liaison Statement To Working Party 8B "WRC-07 Agenda item 1.3, Resolution 747 (WRC-03): Possible extension of the existing primary allocations to the earth exploration-satellite service (active) and the space research service (active) in the band 9 500-9 800 MHz" for angles between -90 deg to +90 deg in azimuth. This curve corresponds to equations for SAR3 in Table 5.

FIGURE 1
Spaceborne SAR3 phase weighting transmit (solid line for phase weighting across array) and uniform transmit (dashed line for uniform weighting across panel) antenna gain patterns at 9600 MHz (-9 deg to +9 deg)

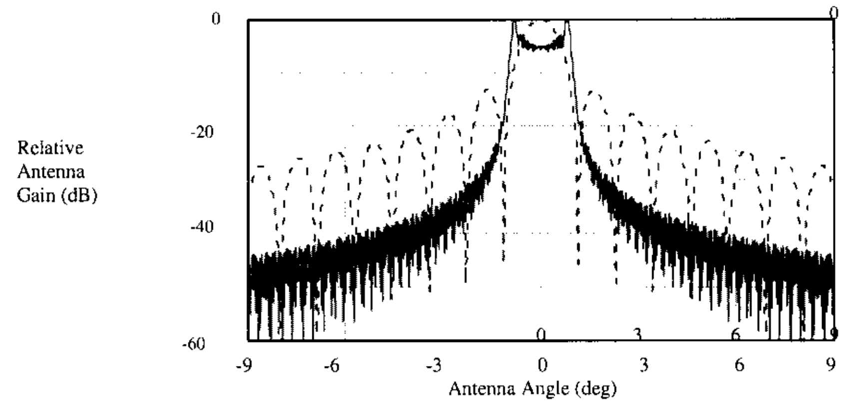


FIGURE 2
Spaceborne SAR3 phase weighting transmit (solid line for phase weighting across array) and uniform transmit (dashed line for uniform weighting across panel) antenna gain patterns at 9600 MHz (-1.5 deg to +1.5 deg)

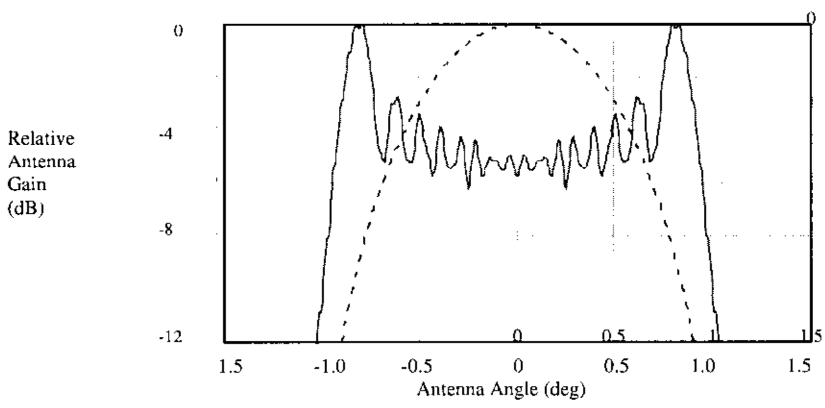


FIGURE 3
Spaceborne SAR3 phase weighting transmit (solid line for Phase weighting of array), phase weighting envelope curve fit (short dashed line), at 9600 MHz (-4.5 deg to +4.5 deg)

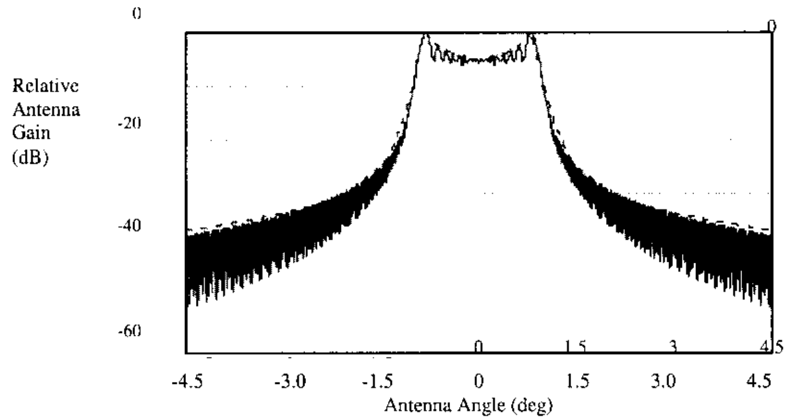


FIGURE 4
Spaceborne SAR3 uniform transmit (solid line for uniform weighting of panel), uniform weighting envelope curve fit (short dashed line) at 9600 MHz (-4.5 deg to +4.5 deg)

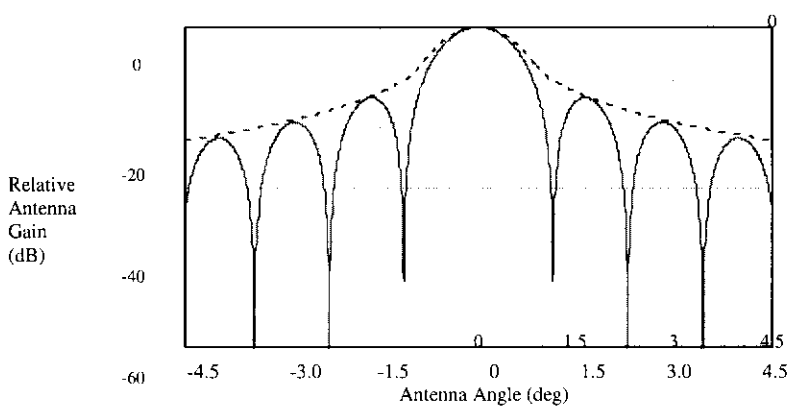


FIGURE 5

Spaceborne SAR3 phase weighting transmit (solid line for phase weighting of array with peak gain of 42.5 dBi), phase weighting envelope curve fit (short dashed line with -5 dBi floor) at 9600 MHz (-90 deg to +90 deg)

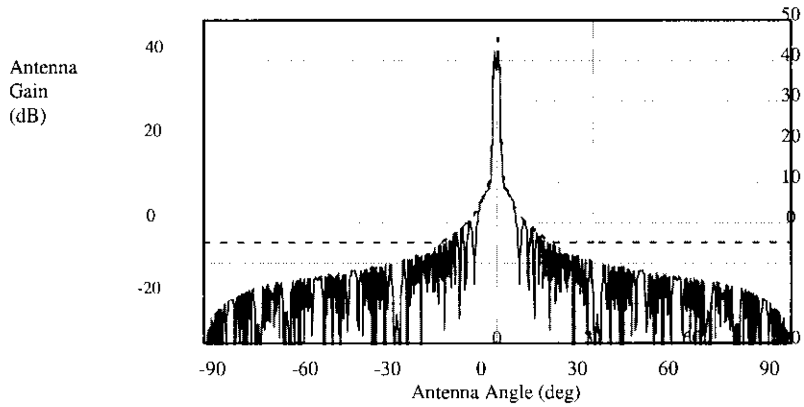


FIGURE 6

Spaceborne SAR3 uniform transmit (solid line for uniform weighting of panel), uniform weighting envelope curve fit (short dashed line) at 9600 MHz (-90 deg to +90 deg)

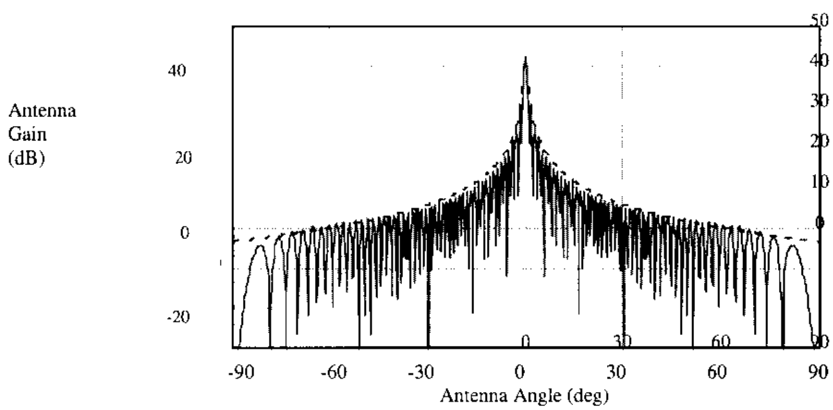


FIGURE 7

Spaceborne SAR3 Taylor weighting transmit (solid line for Taylor weighting of array), uniform weighting transmit (short dashed line for Uniform weighting) at 9600 MHz (-90 deg to +90 deg)

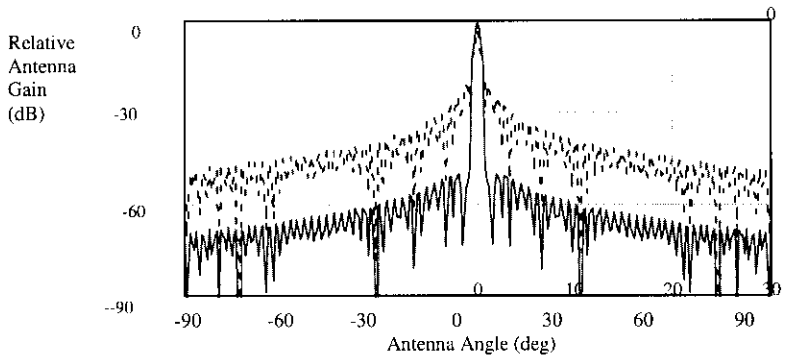


FIGURE 8

Spaceborne SAR3 Taylor weighting transmit (solid line for Taylor weighting of array), envelope curve fit from Table 2 with -48 dB floor (short dashed line) at 9600 MHz (-90 deg to +90 deg)

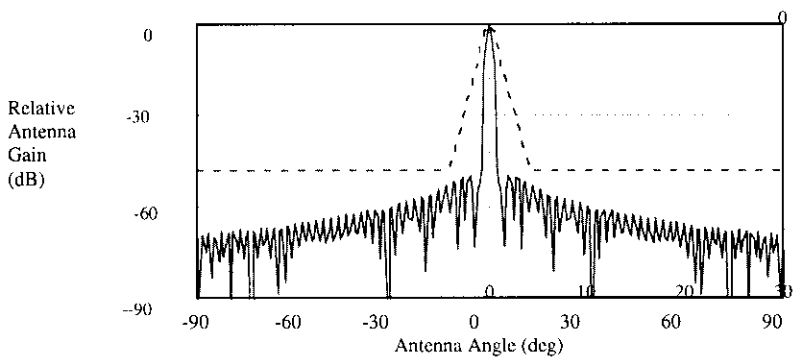


TABLE 3
Spaceborne SAR3 antenna gain pattern at 9600 MHz with Phase Weighting Across Array

Pattern	Gain $G(\theta)$ (dBi) as a function of off-axis angle θ (degrees)	Angle range
Vertical (elevation)	$G_v(\theta_v) = 42.5 - 9.92(\theta_v)^2$ $G_v(\theta_v) = 31.4 - 0.83\ \theta_v$ $G_v(\theta_v) = 10.5 - 0.133\ \theta_v$	$0° < \theta_v < 1.1°$ $1.1° \leq \theta_v < 30°$ $\theta_v \geq 30°$
Horizontal (azimuth)	$G_h(\theta_h) = -5.02 + 6.42(\theta_h)^2$ $G_h(\theta_h) = -873.6 + \text{sign}(\theta_h)\ 2922.3\ \theta_h - 3211.1(\theta_h)^2 + \text{sign}(\theta_h)\ 1154.2(\theta_h)^3$ $G_h(\theta_h) = 61.27 - 97.8 \mid \theta_h \mid + 26.8(\theta_h)^2$ $G_h(\theta_h) = -25.18 - 17.9 \log \mid \theta_h \mid$ $G_h(\theta_h) = -47.5$	$0° < \theta_h < 0.77°$ $0.77° \leq \theta_h < 0.95°$ $0.95° \leq \theta_h < 1.8°$ $1.8° \leq \theta_h < 17.66°$ $\theta_h \geq 17.66°$
Beam pattern	$G(\theta) = \{G_v(\theta_v) + G_h(\theta_h), -5\}$ max	

TABLE 4
Spaceborne SAR3 antenna gain pattern at 9600 MHz with Uniform Weighting Across Panel

Pattern	Gain $G(\theta)$ (dBi) as a function of off-axis angle θ (degrees)	Angle range
Vertical (elevation)	$G_v(\theta_v) = 42.5 - 9.92(\theta_v)^2$ $G_v(\theta_v) = 31.4 - 0.83\ \theta_v$ $G_v(\theta_v) = 10.5 - 0.133\ \theta_v$	$0° < \theta_v < 1.1°$ $1.1° \leq \theta_v < 30°$ $\theta_v \geq 30°$
Horizontal (azimuth)	$G_h(\theta_h) = 0.0 - 9.07(\theta_h)^2$ $G_h(\theta_h) = -8.832 - 18.85 \log \mid \theta_h \mid$	$0° < \theta_h < 1.0°$ $\theta_h \geq 1.0°$
Beam pattern	$G(\theta) = \{G_v(\theta_v) + G_h(\theta_h), -5\}$ max	

TABLE 5
Spaceborne SAR3 antenna gain pattern at 9600 MHz from Annex 13 of 7C/146

Pattern	Gain $G(\theta)$ (dBi) as a function of off-axis angle θ (degrees)	Angle range
Vertical (elevation)	$G_v(\theta_v) = 42.5 - 9.92(\theta_v)^2$ $G_v(\theta_v) = 31.4 - 0.83\ \theta_v$ $G_v(\theta_v) = 10.5 - 0.133\ \theta_v$	$0° < \theta_v < 1.1°$ $1.1° \leq \theta_v < 30°$ $\theta_v \geq 30°$
Horizontal (azimuth)	$G_h(\theta_h) = 0.0 - 9.07(\theta_h)^2$ $G_h(\theta_h) = +1.9 - 12.08\ \theta_h$ $G_h(\theta_h) = -48$	$0° < \theta_h < 1.15°$ $1.15° \leq \theta_h < 4.13°$ $\theta_h \geq 4.13°$
Beam pattern	$G(\theta) = \{G_v(\theta_v) + G_h(\theta_h), -5\}$ max	

Technical characteristics of terrestrial radar system

The system G3 in Table 6 is fixed at 0 deg elevation with a beamwidth of 0.81 deg in elevation so that as SAR3 looks down at 50 deg inclination angle, the system G3 would see SAR3 about 40 deg in the elevation sidelobes, which would be approximately in the 48^{th} sidelobe for a 0.81 deg beamwidth, at an antenna gain of -4 dBi in the sidelobes, for uniform illumination, whereas, the actual illumination probably has amplitude weighting in elevation which gives a faster rate of sidelobe decrease.

TABLE 6

Technical characteristics of beacon and ground-based radars[(1)]

Characteristics	System G3
Function	Tracking Radar
Tuning range (MHz)	9 370-9 990
Antenna polarization	Linear
Antenna main beam gain (dBi)	42.2
Antenna elevation beamwidth (deg)	0.81
Antenna azimuth beamwidth (deg)	1.74
Antenna horizontal scan rate	Not Specified
Antenna horizontal scan type	Sector: ± 45 deg (phase-scanned)
Antenna vertical scan rate	Not Specified
Antenna vertical scan type	Fixed at 0° elevation
Antenna height	100 meters
Receiver IF 3 dB bandwidth (MHz)	1
Receiver noise figure (dB)	Not Specified; 5 dB assumed
Minimum discernible signal (dBm)	−107

1. Characteristics of radar systems taken from PDNR in Document 8B/36, Annex 3 (Chairman's Report)

Receive Power Profiles at Terrestrial Stations

The SAR3 interference power profiles into G3 will be calculated as the satellite flies past a given terrestrial station G3. The first profile will be that obtained by using the phase weighting across the entire 50 m length of the antenna, and the second profile will be obtained by transmitting from a single subarray with the same peak eirp.

The SAR interference power at the terrestrial radar station was calculated using equations (15) and (16) in Annex 1 of ITU-R Recommendation M.1461-1 (Annex 13 of document 7C/146) as follows:

$$I_{sar} = 10 \cdot \log P_{t,sar} + G_{t,sar} + G_r - L_T - L_R - (32.44 + 20 \cdot \log(f \cdot R)) - FDR_{IF} \text{ dBW}$$

where:

$P_{t,sar}$ = SAR peak transmitter power (Watts)

$G_{t,sar}$ = SAR antenna gain in direction of radar station (dBi)

G_r = radar station antenna gain in direction of SAR (dBi)

L_T = insertion loss in the transmitter (dB)

L_R = insertion loss in the radar receiver (dB)

f = radar station receive frequency (MHz)

R = slant range between SAR and radar station (km)

FDR_{IF} frequency dependent rejection, where:

$$FDR_{IF} = OTR + OFR$$

For this study, co-frequency operation is assumed, therefore off-frequency rejection (OFR) = 0.
For pulsed CW and phase-coded pulsed signals, the peak on-tune rejection (OTR) factor is given by:

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

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

where:

B_R = receiver 3 dB bandwidth (Hz)

B_T = transmitter 3 dB bandwidth (Hz).

For chirped pulsed signals, the peak OTR factor is given by:

$$OTR = 0 \qquad \text{for } B_C / (B_R^2\, T) \leq 1$$

$$OTR = 10 \log (B_C / (B_R^2\, T)) \qquad \text{for } B_C / (B_R^2\, T) > 1$$

where:

T : = chirped pulse width (s)

B_C = transmitter chirped bandwidth during the pulse width, T (Hz).

This analysis did not consider atmospheric or insertion losses.

The interference-to-noise ratio can be calculated by the following formula:

$$I/N = I_{SAR} - N_{Radar\ Receiver}$$

where:

I/N: Interference-to-noise ratio at the detector input (IF output) (dB),

$N_{Radar\,Receiver}$: radar receiver inherent noise level (dBm),

$N = -114$ dBm 10 log BIF (MHz) NF,

and:

BIF : receiver IF bandwidth (MHz),

NF: receiver noise figure (dB).

The SAR3 characteristics are shown in Table 2. For this example of interference from SAR3 into G3, the pulse width is 10 microsec, and the peak antenna gain is 42.5 dBi.

The interference levels from SAR3 into G3 as the SAR3 orbits over the fixed location of system G3 at 44 deg look angle from the SAR3 is show in Figure 7 over 2 minutes of orbit time.

The interference threshold assumes an I/N of -10 dB. Using uniform weighting across an individual panel, the SAR is above the threshold about 118 sec; whereas, using phase weighting across the array, the SAR is above the threshold about 14 sec. For this example, the phase weighting technique provides interference mitigation and reduces the amount of time the SAR interference is above the terrestrial radar's threshold by a factor of over 8.

The interference levels from SAR3 into G3 using the gain equations from Annex 13 of 7C/146 as the SAR3 orbits over the fixed location of system G3 at 44 deg look angle from the SAR3 is show in Figure 8 over 2 minutes of orbit time.

The interference threshold assumes an I/N of -10 dB. Using uniform weighting across an individual panel, the SAR is above the threshold about 118 sec; whereas, using the gain equations from Annex 13 of 7C/146, SAR3 is above the threshold about 9.5 sec. For this example, this gain pattern provides interference mitigation and reduces the amount of time the SAR interference is above the terrestrial radar's threshold by a factor of over 12.

FIGURE 7

Interference levels at terrestrial radar G3 from SAR3 (using phased weighting across array or uniform weighting across panel) at 506 km orbital altitude

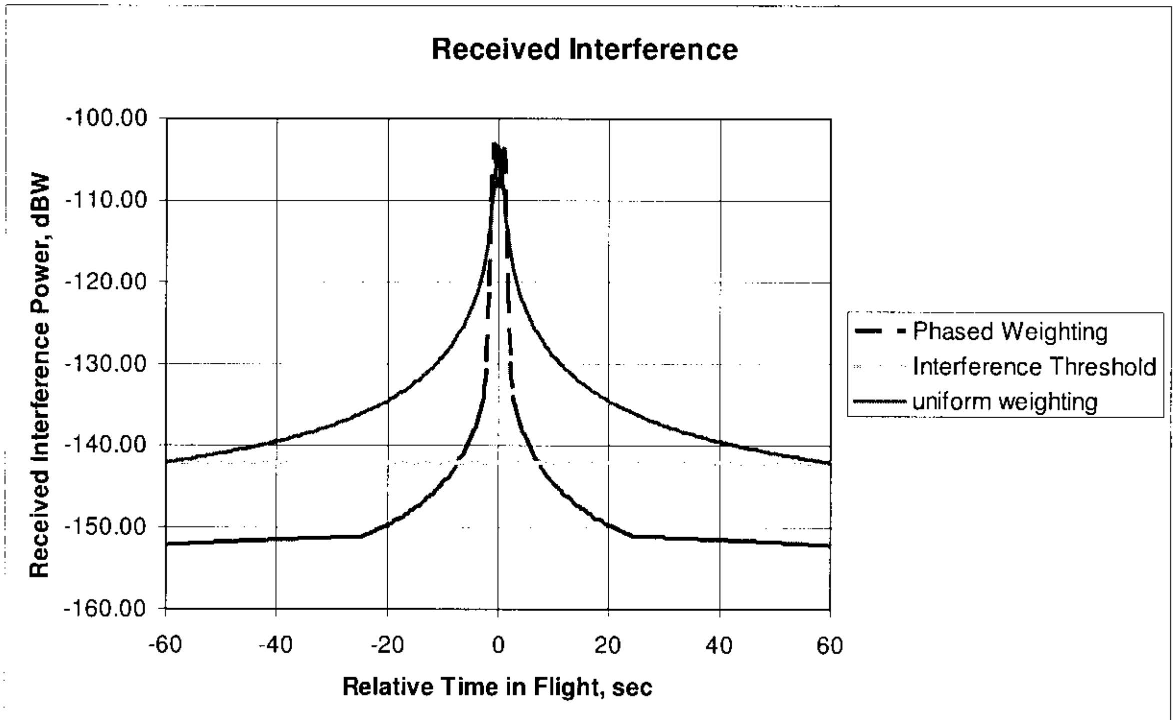
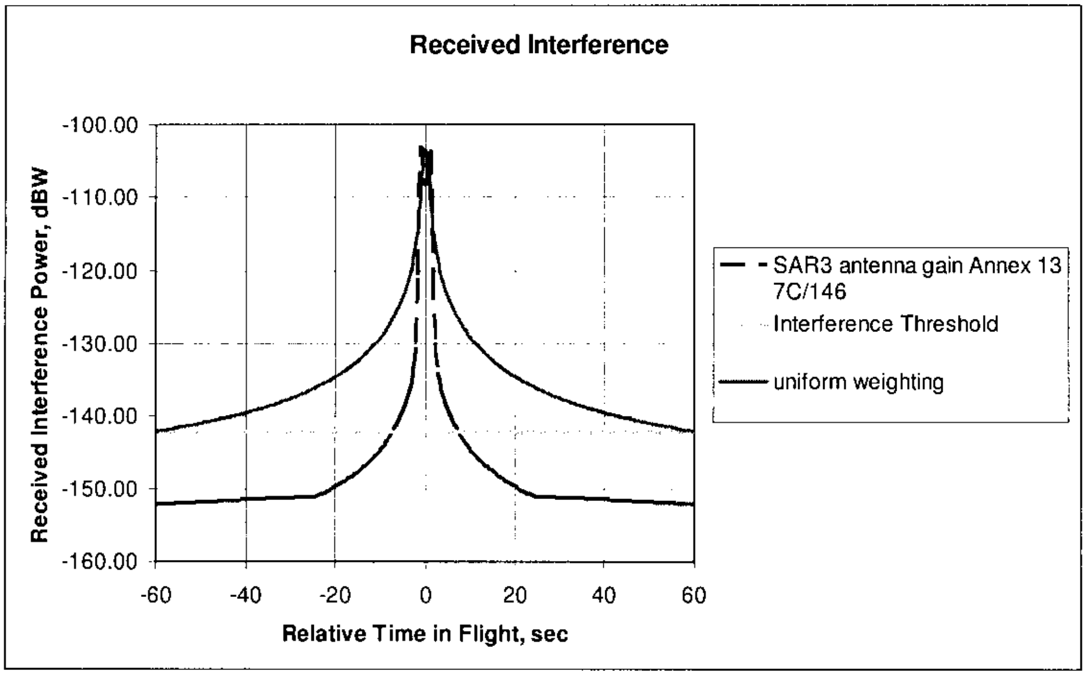


FIGURE 8

Interference levels at terrestrial radar G3 from SAR3 (using gain equation from Annex 13 7C/146 and uniform weighting across panel) at 506 km orbital altitude



Conclusion

SFCG-25 Agenda Item 9.3 includes, as a topic for consideration by the SWGs, active sensors near 9.6 GHz. The interference mitigation technique using phase weighting across the wideband SAR3 antenna array is presented in this document for consideration in the studies supporting the WRC-07 Agenda Item 1.3 and the SFCG-25 Agenda item 9.3.