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(05/2015)

Potential interference from the Earth exploration-satellite (active) spaceborne radars operating in the 1 215-1 300 MHz frequency band to the aeronautical radionavigation surveillance radar receivers in the 1 240-1 370 MHz frequency band

RS Series

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REPORT ITU-R RS.2350-0

Potential interference from the Earth exploration-satellite (active) spaceborne radars operating in the 1 215-1 300 MHz frequency band to the aeronautical radionavigation surveillance radar receivers in the 1 240-1 370 MHz frequency band

(2015)

1 Background

From the ITU Radio Regulations' Table of Frequency Allocations and the relevant footnotes, the following services of primary status share the 1 215-1 300 MHz frequency band:

– Radionavigation service (RNS) per footnote RR No. **5.331**: Limited to Aeronautical RNS (ARNS) in 1 240-1 300 MHz for Canada and the United States of America; and RNS in 1 215-1 300 MHz for 75 other countries.

– Radiolocation service (RLS) – 1 215-1 300 MHz.

– Radionavigation-satellite service (RNSS) (space-to-Earth) (space-to-space) – 1 215-1 300 MHz.

– Earth exploration-satellite (active) service (EESS) – 1 215-1 300 MHz.

– Space research (active) service (SRS) – 1 215-1 300 MHz.

– Fixed service and mobile service – 1 215-1 300 MHz for 32 countries, per footnote No. **5.330**.

In the frequency band 1 215-1 300 MHz, EESS (active) and SRS (active) are subject to the limitations of certain Radio Regulations (RR) including Nos. **5.332**, **5.335** and **5.335A**.

– **5.332** In the band 1 215-1 260 MHz, active spaceborne sensors in the Earth exploration-satellite and space research services shall not cause harmful interference to, claim protection from, or otherwise impose constraints on operation or development of the radiolocation service, the radionavigation-satellite service and other services allocated on a primary basis. (WRC-2000)

– **5.335** In Canada and the United States in the band 1 240-1 300 MHz, active spaceborne sensors in the Earth exploration-satellite and space research services shall not cause interference to, claim protection from, or otherwise impose constraints on operation or development of the aeronautical radionavigation service. (WRC-97)

– **5.335A** In the band 1 260-1 300 MHz, active spaceborne sensors in the Earth exploration-satellite and space research services shall not cause harmful interference to, claim protection from, or otherwise impose constraints on operation or development of the radiolocation service and other services allocated by footnotes on a primary basis. (WRC-2000)

In the United States of America, the ARNS surveillance radars are used to detect and track airborne systems to assist air traffic controllers with monitoring and separation of aircraft. These radars operate in the frequency band 1 240-1 370 MHz and operate continuously in all weather conditions.

Proposed spaceborne active sensors in the 1 215-1 300 MHz band include the synthetic aperture radars (SAR) and scatterometers.

In the light of availability of characteristics of the proposed spaceborne active sensors, this Report provides a preliminary study of the potential for interference from these spaceborne active sensors, namely SAR3-6, to the ARNS surveillance radar receivers in the frequency band 1 240-1 370 MHz. The following ITU-R Recommendations will be used as the guidelines in this study:

– Recommendation ITU-R M.1463-3 – Characteristics of and protection criteria for radars operating in the radiodetermination service in the frequency band 1 215-1 400 MHz.
– Recommendation ITU-R M.1461-1 (2003) – Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services.
– Recommendation ITU-R M.1372-1 (2003) – Efficient use of the radio spectrum by radar stations in the radiodetermination service.
– Recommendation ITU-R RS.1280 (1997) – Selection of active spaceborne sensor emission characteristics to mitigate the potential for interference to terrestrial radars operating in frequency band 1-10 GHz.

2 EESS systems characteristics

In this study, the potential interference from EESS (active) SARs 3, 4, 5 and 6 to ARNS surveillance radar receivers is considered[1]. The characteristics of these spaceborne active sensors, operating in the 1 215-1 300 MHz frequency band, are shown in Table 1. Figure 1 includes the typical SAR modes of operation (Stripmap, ScanSAR, and Spotlight), satellite altitude, and range of look angles for SARs 4, 5 and 6.

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[1] SARs 4, 5 and 6 represent different operational modes of a single SAR system.

TABLE 1

Spaceborne active sensors – Characteristics

Parameters	SAR 3	SAR 4	SAR 5	SAR 6
Orbit type	Sun-sync	Sun-sync	Sun-sync	Sun-sync
Orbit altitude (km)	757	628	628	628
Orbit inclination (degrees)	98	97.9	97.9	97.9
Orbit eccentricity	Circular	Circular	Circular	Circular
Local time of node	18:00, ascending	12:00, descending	12:00, descending	12:00, descending
Peak transmit power (W)	3 200	3950	6120	6120
Antenna type	Offset-feed parabolic 15 m diameter, linear array feed	Planar array 2.9 m × 6.0 m	Planar array 2.9 m × 9.9 m	Planar array 2.9 m × 9.9 m
Peak transmit antenna gain (dBi)	35.0	34.7	36.6	36.6
e.i.r.p. peak (dBW)	68.4	70.7	74.5	74.5
Antenna transmit elevation beamwidth (degrees)	20.9	4.3	4.6	4.6
Antenna transmit azimuth beamwidth (degrees)	0.89	2.1	1.3	1.3
RF centre frequency (MHz)	1 215-1 300	1 257.5	1 236.5 1 257.5 1 278.5 Selectable	1 236.5 1 257.5 1 278.5 Selectable
Polarization	Dual/quad, linear H and V	H and V	H and V	H, V, circular, and 45 degrees linear
Pulse modulation	Linear FM	Linear FM	Linear FM	Linear FM
RF bandwidth max (MHz)	78	84[1]	14[2], 28[2]	28[2]
RF pulse width (µs)	78	43-71	37-67	18-43
Pulse repetition frequency (Hz)	2 400	1 620-2 670	1 050-1 860	1 550-3 640
Chirp rate (MHz/µs)	1.0	1.18 to 1.95	14 MHz: 0.21 to 0.38 28 MHz: 0.42 to 0.76	0.65 to 1.56
Transmit duty cycle[2] (%)	18.7	11.5	7.0	6.8
Azimuth scan rate (rpm)	0	0	0	0
Antenna beam transmit look angle (degrees)	30	7.2 to 59	7.2 to 59	7.2 to 59
Antenna beam transmit azimuth angle (degrees)	0	±3.5	0	0

TABLE 1 *(end)*

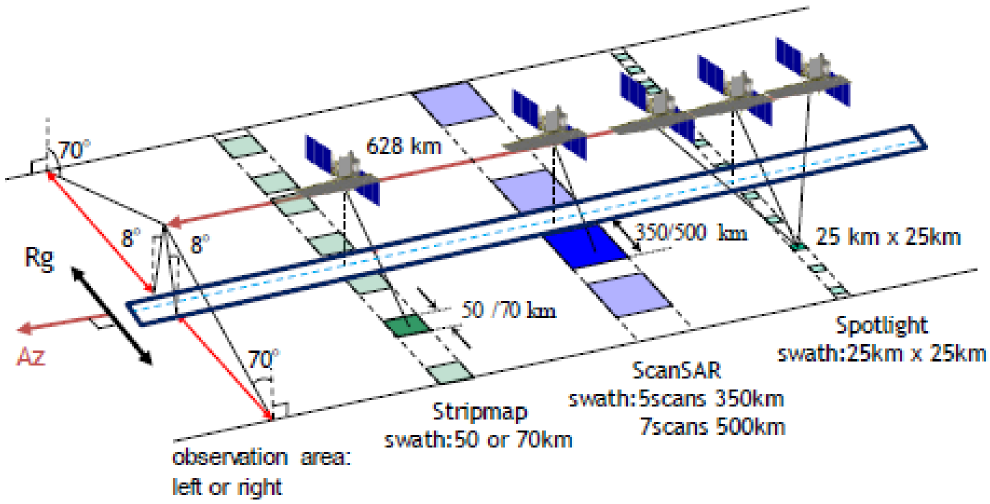
Parameters	SAR 3	SAR 4	SAR 5	SAR 6
Comments	Transmits wide beam in elevation, receives with multiple narrow beams in elevation during receive interval	Transmits beam orthogonal to flight path (azimuth angle of ±3.5 degrees for spotlight SAR observation) at selectable look angle 7.2 to 59 degrees	Transmits beam orthogonal to flight path (azimuth angle of 0 degrees; ScanSAR) at selectable look angle 7.2 to 59 degrees	Transmits beam orthogonal to flight path (azimuth angle of 0 degrees; Stripmap) at selectable look angle 7.2 to 59 degrees

1 Maximum RF bandwidth value shown is occupied bandwidth.

2 Transmit duty cycle value is fixed, using PRF value and RF pulse width value within range of values shown above.

FIGURE 1

Typical SAR modes of operations (SAR-4, 5 and 6)



Tables 2 and 3 show the azimuth and elevation antenna gain equations for SAR3 and SAR4 as a function of off-axis angle. Table 4 shows the azimuth and elevation antenna gain equations for SAR5 and SAR6 as a function of off-axis angle.

TABLE 2

Standard SAR3 antenna gain equations

Pattern	Gain $G(\theta)$ (dBi) as a function of off-axis angle θ (degrees)	Angle range
Vertical (elevation)	$G_V(\theta_V) = 35.0 - 0.18(\theta_V)^2$ $G_V(\theta_V) = 32.6 - 0.05(\lvert\theta_V\rvert - 7)^2$ $G_V(\theta_V) = 33.0 - 2.69(\lvert\theta_V\rvert - 12)^2$ $G_V(\theta_V) = 15.0 - 20.8\log(\lvert\theta_V\rvert) - 0.68(\lvert\theta_V\rvert - 16)$ $G_V(\theta_V) = -30$	$\lvert\theta_V\rvert < 4.0°$ $4.0° \leq \lvert\theta_V\rvert < 11.3°$ $11.3° \leq \lvert\theta_V\rvert < 16.0°$ $16.0° \leq \lvert\theta_V\rvert < 35.0°$ $\lvert\theta_V\rvert \geq 35°$
Horizontal (azimuth)	$G_h(\theta_h) = 0.0 - 15.0(\theta_h)^2$ $G_h(\theta_h) = -18.0$ $G_h(\theta_h) = -13.55 - 23\log\lvert\theta_h\rvert$ $G_h(\theta_h) = -36.5$	$\lvert\theta_h\rvert < 1.1°$ $1.1° \leq \lvert\theta_h\rvert < 1.7°$ $1.7° \leq \lvert\theta_h\rvert < 10.0°$ $\lvert\theta_h\rvert \geq 10.0°$
Beam pattern	$G(\theta) = \{G_V(\theta_V) + G_h(\theta_h)\}$	

TABLE 3

Standard SAR4 antenna gain equations

Pattern	Gain $G(\theta)$ (dBi) as a function of off-axis angle θ (degrees)	Angle range
Vertical (elevation)	$G_V(\theta_V) = 0.0 - 0.38(\theta_V)^2$ $G_V(\theta_V) = 0.0 - 0.544\theta_V - 8.5$ $G_V(\theta_V) = -22.0$	$0° < \lvert\theta_V\rvert < 5.5°$ $5.5° \leq \lvert\theta_V\rvert < 24.75°$ $\lvert\theta_V\rvert \geq 24.75°$
Horizontal (azimuth)	$G_h(\theta_h) = 34.7 - 2.7(\theta_h)^2$ $G_h(\theta_h) = 34.7 - 0.95\,\theta_h - 10.65$ $G_h(\theta_h) = 34.7 - 23.0$ $G_h(\theta_h) = 34.7 - 23.0 - 35\log(\theta_h/38)$ $G_h(\theta_h) = 34.7 - 36.1$	$0° < \lvert\theta_h\rvert < 2.17°$ $2.17° \leq \lvert\theta_h\rvert < 13.0°$ $13.0° \leq \lvert\theta_h\rvert < 38.0°$ $38.0° \leq \lvert\theta_h\rvert < 90.0°$ $\lvert\theta_h\rvert \geq 90.0°$
Beam pattern	$G(\theta) = G_V(\theta_V) + G_h(\theta_h)$	–

Note – These equations cover the worst case envelope patterns with the maximum electric beam steering angle range in both elevation and azimuth directions. As the result, these equations contain some margins against actual antenna patterns. Therefore, the –3 dB beamwidth derived from these equations can be slightly different from the beamwidth (–3 dB) specified in Table 1.

TABLE 4

Standard SAR5 and 6 antenna gain equations

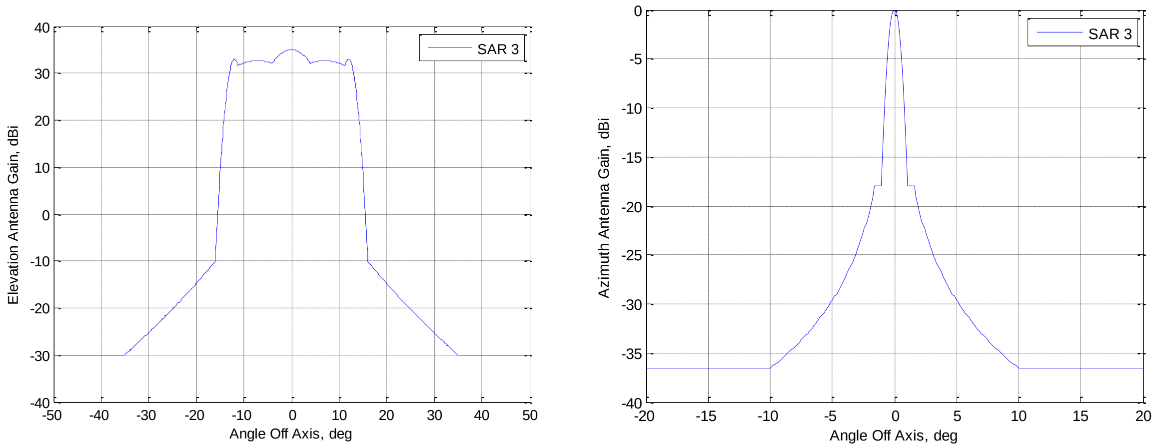
Pattern	Gain $G(\theta)$ (dBi) as a function of off-axis angle θ (degrees)	Angle range
Vertical (elevation)	$G_V(\theta_V) = 0.0 - 0.30(\theta_V)^2$ $G_V(\theta_V) = 0.0 - 0.69\,\theta_V - 7.24$ $G_V(\theta_V) = -26.0$	$0° < \lvert\theta_V\rvert < 6.20°$ $6.20° \leq \lvert\theta_V\rvert < 27.00°$ $\lvert\theta_V\rvert \geq 27.00°$
Horizontal (azimuth)	$G_h(\theta_h) = 36.6 - 7.0(\theta_h)^2$ $G_h(\theta_h) = 36.6 - 1.43\,\theta_h - 12.83$ $G_h(\theta_h) = 36.6 - 25.0$ $G_h(\theta_h) = 36.6 - 25.0 - 34\log(\theta_h/40)$ $G_h(\theta_h) = 36.6 - 36.98$	$0° < \lvert\theta_h\rvert < 1.46°$ $1.46° \leq \lvert\theta_h\rvert < 8.47°$ $8.47° \leq \lvert\theta_h\rvert < 40.0°$ $40.0° \leq \lvert\theta_h\rvert < 90.0°$ $\lvert\theta_h\rvert \geq 90.0°$
Beam pattern	$G(\theta) = G_V(\theta_V) + G_h(\theta_h)$	–

Note – These equations cover the worst case envelope patterns with the maximum electric beam steering angle range in both elevation and azimuth directions. As the result, these equations contain some margins against actual antenna patterns. Therefore, the –3 dB beamwidth derived from these equations can be slightly different from the beamwidth (–3 dB) specified in Table 1.

Figure 2 plots the azimuth and elevation transmit antenna gain patterns as a function of the angle off axis for SAR 3. Figure 3 plots the azimuth and elevation transmit antenna gain patterns as function of the angle off axis for SARs 4, 5 and 6.

FIGURE 2

SAR 3 – Azimuth and elevation transmit antenna gain pattern



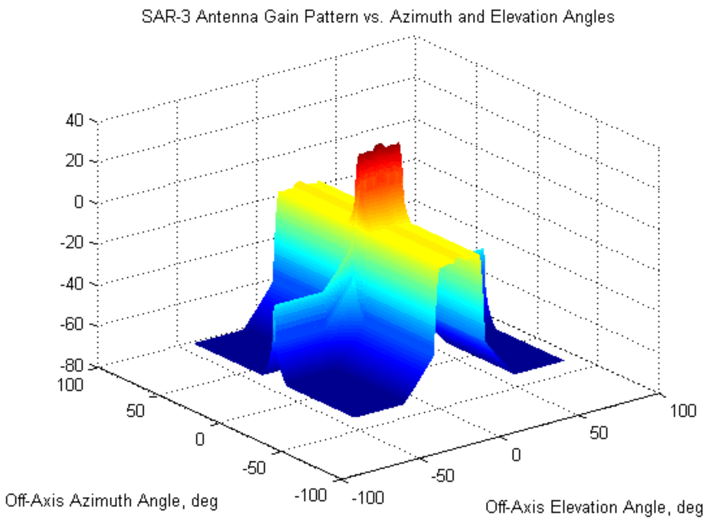


FIGURE 3

SARs 4, 5 and 6 – Azimuth and elevation transmit antenna gain patterns

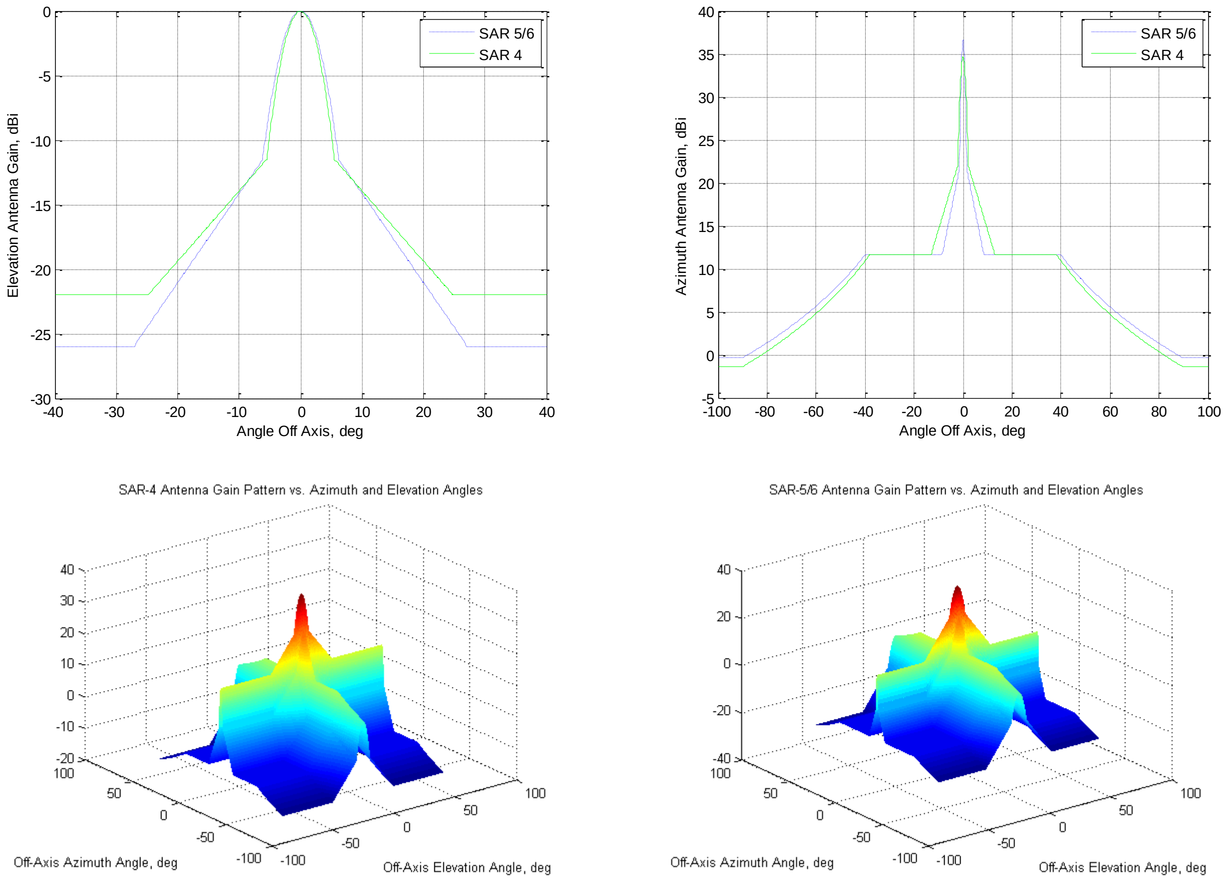
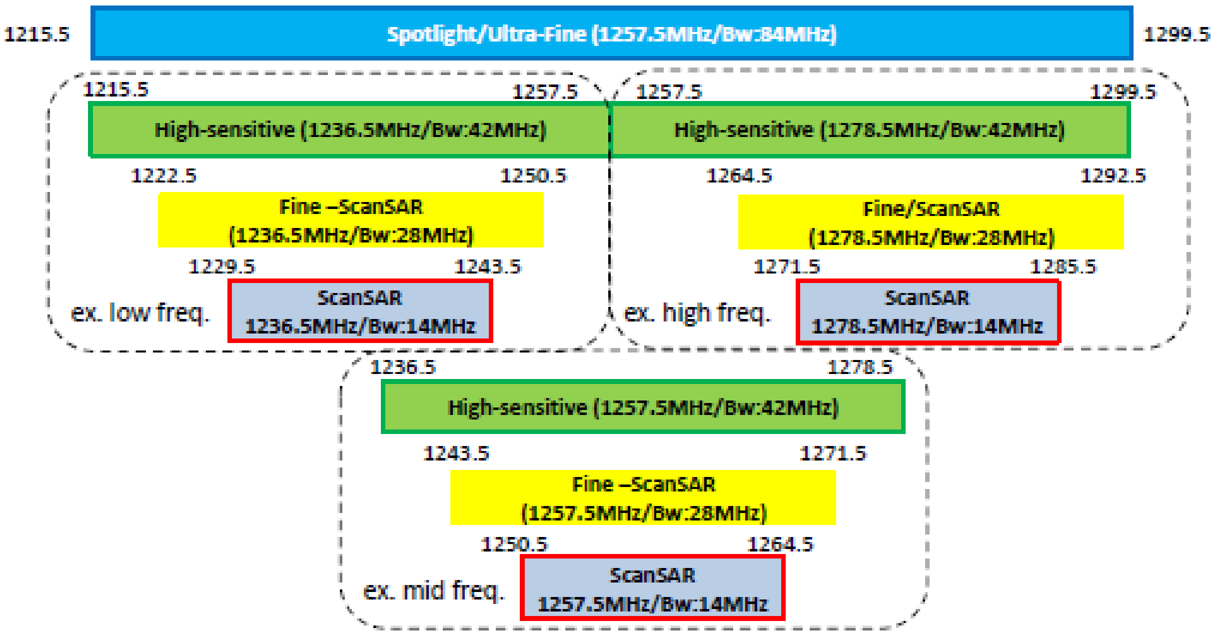


Figure 4 shows the SAR 4, 5 and 6 modes of operations together with the occupied frequency and frequency spans.

FIGURE 4

SARs 4, 5 and 6 modes of operations and frequency spans



3 ARNS surveillance radar characteristics

The ARNS surveillance radars are critical safety-of-life systems used to monitor and to maintain the separation of aircraft. The radars characteristics are provided in Table 5 below, taken from Recommendation ITU-R M.1463-3. Among these radars, this Report only considered effects of EESS (active) emissions on Radar 2 and Radar 8.

TABLE 5

ARNS surveillance radars – Characteristics

Parameters	Radar 1 (system 1)	Radar 2 (system 2)	Radar 8 (system 8)
Peak power (dBm)	97	80	78.8
Frequency range (MHz)	1 240-1 350	1 215-1 390	1 240-1 350
Pulse duration (μs)	2	88.8, 58.8 (Note 1)	115.5; 17.5 (Note 2)
Pulse repetition rate (Hz)	310-380	291.5 or 312.5, average	319, average
Chirp bandwidth	n/a	770 kHz for both pulse widths	1.2 MHz for long pulse
Phase-coded sub-pulse width (μs)	n/a	n/a	n/a
Compression ratio	n/a	68.3:1 and 45.2:1	150:1 and 23:1
RF emission bandwidth (3 dB) (MHz)	0.5	1.09	1.2 MHz
Output device	Klystron	Transistor	Transistor
Antenna type	Horn-fed reflector	Stack beam reflector	Horn-fed reflector
Antenna polarization	H, V, LHCP, RHCP	Vertical, Circular	RHCP; Vertical
Antenna maximum gain (dBi)	34.5, transmit 33.5, receive	32.4-34.2, transmit 33.8-40.9, receive	34.5

TABLE 5 *(end)*

Parameters	**Radar 1 (system 1)**	**Radar 2 (system 2)**	**Radar 8 (system 8)**
Antenna elevation beamwidth (degrees)	3.6 shaped to 44	3.63-5.61, transmit 2.02-8.79, receiver	3.7 shaped to 44 (cosecant squared)
Antenna azimuth beamwidth (degrees)	1.2	1.4	1.2
Antenna horizontal scan rate (rpm)	360º mechanical at 5 rpm	360º mechanical at 5 rpm	360º mechanical at 5 rpm
Antenna vertical scan rate (degrees)	n/a	−7 to +30 in 12.8 or 13.7 ms	n/a
Receiver IF bandwidth (MHz)	0.78	0.69	1.2 MHz
Receiver noise figure (dB)	2	2	3.2
Platform type	Fixed	Fixed	Fixed
Time system operates (%)	100	100	100

[1] The radar has 44 RF channel pairs with one of 44 RF channel pairs selected in normal mode. The transmitted waveform consists of a 88.8 µs pulse at frequency f_1 followed by a 58.8 µs pulse at frequency f_2. Separation of f_1 and f_2 is 82.854 MHz.

[2] This radar utilizes two fundamental carriers, F1 and F2, with two sub-pulses each, one for medium range detection and one for long range detection. The carriers are tuneable in 0.1 MHz increments with a minimum separation of 26 MHz between F1 (below 1 300 MHz) and F2 (above 1 300 MHz). The carrier sub-pulses are separated by a fixed value of 5.18 MHz. The pulse sequence is as follows: 115.5 µs pulse at F1 + 2.59 MHz, then a 115.5 µs pulse at F2 + 2.59 MHz, then a 17.5 µs pulse at F2-2.59 MHz, then a 17.5 µs pulse at F1-2.59 MHz. All four pulses are transmitted within a single pulse repetition interval.

The radar receiver peak, first sidelobe and backlobe antenna gains for Radars 1, 2 and 8 are summarized in Table 6, based on the measured and specified antenna patterns of these radars. Measured radar receiver IF bandwidths at –3, –20 and –40 dB are also shown in Table 6.

TABLE 6

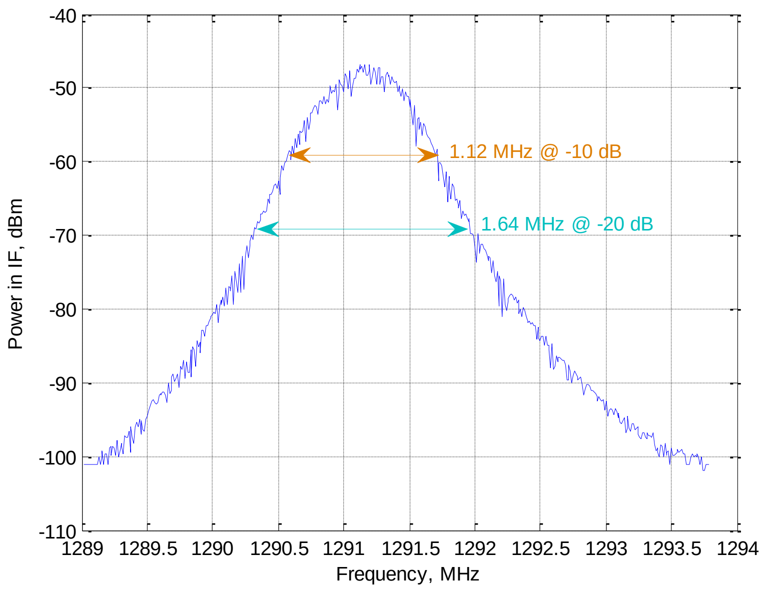
ARNS radar backlobe and first sidelobe antenna gains

Receiver radar antenna	Radar 1	Radar 2	Radar 8
Peak antenna gain	33.5 dBi	38.9 dBi	33.5 dBi
First sidelobe antenna gain from peak antenna gain (measured)	Azimuth: 24.6 dB down Elevation: 27.4 dB down or 6.1 dBi	Azimuth: 35 dB down Elevation: 35 dB down (specifications) or 3.9 dBi	Azimuth: 24.6 dB down Elevation: 27.4 dB down or 6.1 dBi
Elevation backlobe antenna gain from peak antenna gain (measured)	36 dB down or –2.5 dBi	48 dB down or –9.1 dBi	36 dB down or –2.5 dBi
Receiver IF bandwidth, MHz • –3 dB • –20 dB • –40 dB	 0.78 1.64 3.0	 0.69 1.96 3.64	 1.2 2.88 4.26

Figure 5 shows a typical Radar 1 receiver IF frequency response (measured), displaying –10 dB and –20 dB receiver IF bandwidths.

FIGURE 5

Measured IF frequency response of radar 1



4 Interference analysis

Recommendation ITU-R RS.1280 lays out the foundation of the calculation of interference to terrestrial radars – the average interference signal power level, I_R (dBW), received by a terrestrial radar from spaceborne active sensors. This Recommendation suggests that the received signal to noise of the surveillance radars may not be degraded by more than 0.5 dB longer than a single scan time, taken to be 10 seconds. This equates to an interference to noise power ratio of –9 dB at the receiver IF stage. However, in this analysis, an *I/N* of –6 dB is used, which applies to continuous RFI per Recommendation ITU-R M.1463-3.

This Recommendation also suggests that the average interfering signal power level is considered to be of interest in the case of the surveillance radars.

The average interfering signal power level, I_R (dBW), received by a terrestrial radar from one spaceborne active sensor is calculated from:

$$I_R = 10 \log P_t + 10 \log (\tau \, PRF) + G_t + G_r - (32.44 + 20 \log (f\,R)) + OTR - PG \qquad (1)$$

where:

- P_t: peak spaceborne sensor transmit power (W)
- τ: spaceborne sensor pulse width (s)
- PRF: spaceborne sensor pulse repetition frequency (Hz)
- G_t: spaceborne sensor antenna gain towards terrestrial radar (dBi)
- G_r: terrestrial radar antenna gain towards spaceborne sensor (dBi)
- f: frequency (MHz)
- R: slant range between sensor and radar (km)
- OTR: radar receiver on-tune rejection (dB)
- PG: processing gain (dB), rejection of unwanted signals due to radar receiver signal processing (assumed to be zero if not known).

The on-tune rejection term is calculated by:

$$OTR = 10 \log (B_r / B_t) \quad \text{for} \quad B_r \le B_t$$
$$= 0 \quad \text{for} \quad B_r > B_t$$

where:

- B_r : receiver bandwidth
- B_t : bandwidth of the transmitted interfering signal.

It is noted that the effects of pulsed RFI on radar receivers are difficult to quantify and are dependent on receiver/processor design and mode of operation. For these reasons, the radar processing gain should only be accounted for if test measurements are available. When such test measurements are available, Equation (1) simplifies to

$$I_R = 10 \log P_t + G_t + G_r - (32.44 + 20 \log (f\,R)) - PG \qquad (2)$$

Note that the duty cycle factor 10 log (τ *PRF*) and *OTR* terms are not included in Equation (2) since measured processing gain takes them into account.

The radar processing gain of 0 dB is assumed if measurement data is not available as recommended in Recommendation ITU-R RS.1280 and equation (1) with $PG = 0$ is used.

Table 7 shows the SAR-3, 4, 5 and 6 test data sets that were performed on Radar 2. The signals from SAR-3, 4, 5 and 6 with the specified pulse width were injected into the RF front-end of the radar. For each data set, a total of 240 targets, each simulated by fixed-amplitude pulses, were independently generated and the interference results were determined, based on the radar probability of detection. For SAR-4, 5 and 6, there are 6 test data sets that were performed for each mode of operation (spotlight, high sensitive, fine, ScanSAR 14 MHz and ScanSAR 28 MHz) due to the variable pulse widths and pulse repetition frequencies of each mode of operation. For SAR-3, only one test data set was performed since SAR-3 only operates in a single mode with a fixed pulse width.

TABLE 7

SAR-3, 4, 5 and 6 test data sets

Mode	Data set	1	2	3	4	5	6
Spotlight (SAR4)	Pulse width (µs)	45	50	55	60	65	70
High sensitive (SAR6)	Pulse width (µs)	25	30	40	50	55	60
Fine (SAR6)	Pulse width (µs)	16	20	25	30	35	40
ScanSAR 14 MHz (SAR5)	Pulse width (µs)	40	45	50	55	60	65
ScanSAR 28 MHz (SAR5)	Pulse width (µs)	40	45	50	55	60	65
SAR3 78 MHz	Pulse width (µs)	78					

For each mode of operation, the test results from all 6 data sets were averaged and the *I/N* level that corresponds to a measurable reduction in probability of detection for the radar was determined. Figure 6 is a plot of the SAR-3, 4, 5 and 6 interference impact on Radar 2 for five modes of SAR-4, 5, and 6 operation (spotlight, ScanSAR 14 MHz, ScanSAR 28 MHz, high sensitive, and fine) and the one SAR-3 mode of operation. From Fig. 6, Radar 2 can tolerate an *I/N* of +16 dB for SAR-3, +7 dB for SAR-5 ScanSAR 14 MHz, +14 dB for SAR-5 ScanSAR 28 MHz, +16 dB for SAR-4 spotlight and SAR-6 fine, and +17 dB for SAR-6 high sensitive.

Hence, the radar processing gains, relative to the interference protection level of –6 dB (Recommendation ITU-R M.1463), are as follows for Radar 2: +22 dB for SAR-3, +13 dB for SAR-5 ScanSAR 14 MHz, +20 dB for SAR-5 ScanSAR 28 MHz, +22 dB for SAR-4 spotlight and SAR-6 fine, and +23 dB for SAR-6 high sensitive. For Radar 8, a radar processing gain of 0 dB is used in the interference analysis since there is no measurement test for this radar.

FIGURE 6

SAR-3, 4, 5 and 6 interference effects on Radar 2

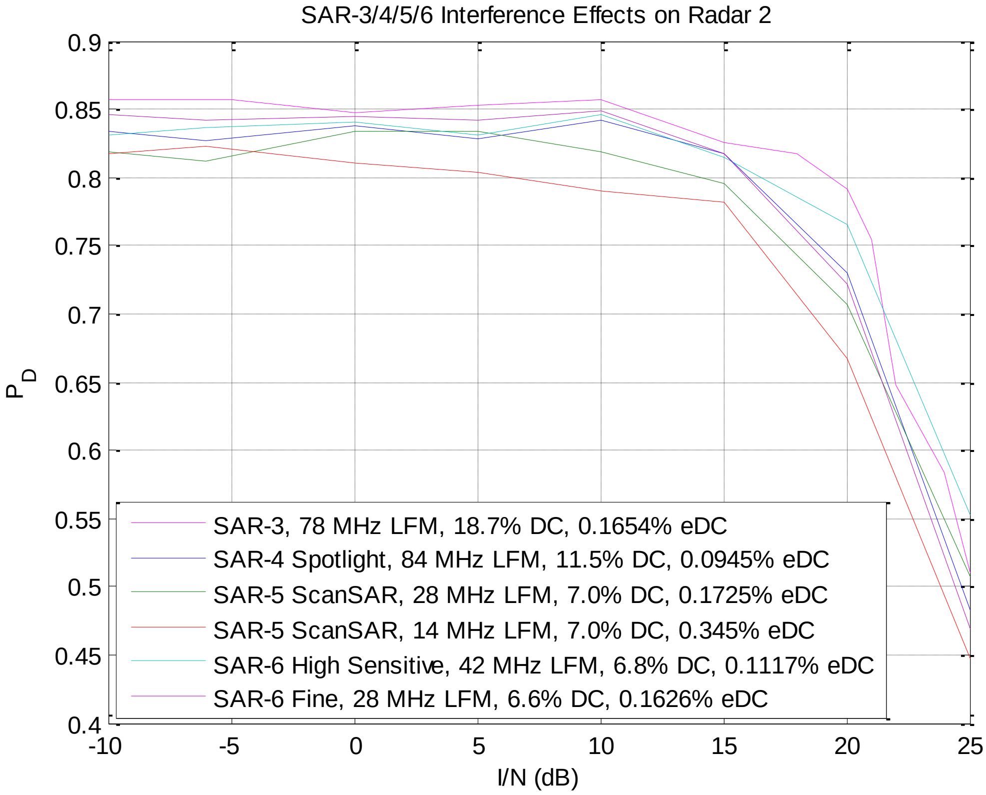


Figure 7 plots the SAR off-axis angle versus the ground system elevation angle. Since the upper limit of Radar 8's elevation fan beam is about 44 degrees, the upper edge of the SAR elevation beam can only be 40 degrees or less in order to avoid main-beam to main-beam antenna coupling. For SAR-4/5/6, the half elevation beamwidth is about 5.5 degrees, hence the maximum look-angle is about 34.5 degrees. For SAR-3, the half elevation beamwidth is about 16 degrees, hence the maximum look-angle is about 24 degrees. For all of these SARs, main-beam to main-beam antenna coupling is not likely with look-angles specified above.

FIGURE 7

SAR off-elevation main beam vs. radar elevation main beam

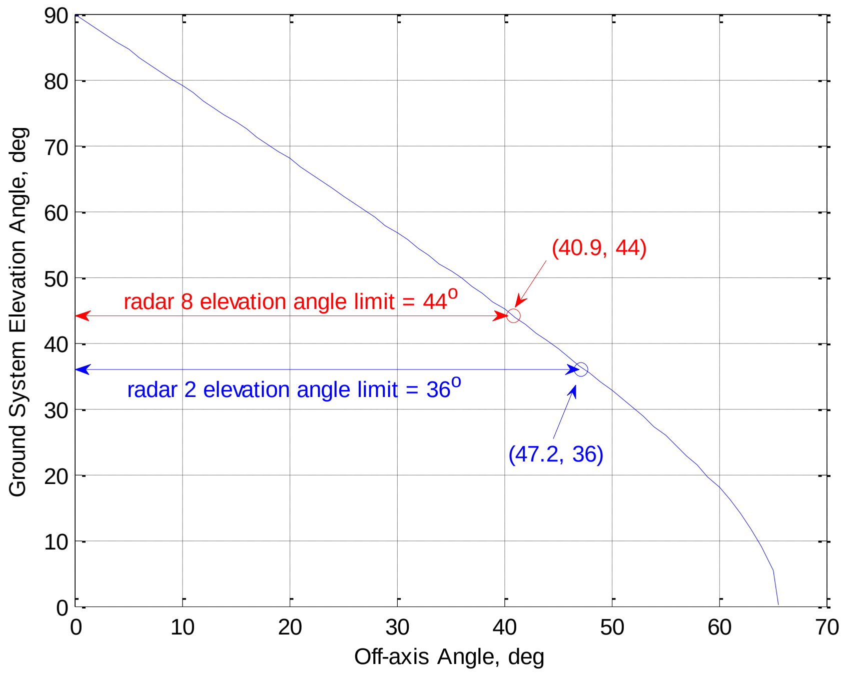


Table 8 shows the interference analysis from the spaceborne sensors (SARs 3, 4, 5 and 6) to the ARNS surveillance Radar 2 and Radar 8 receivers.

TABLE 8

SAR-3, 4, 5 and 6 RFI to ARNS surveillance Radar 2 and Radar 8 receivers

	SAR-3	**SAR-4 spotlight**	**SAR-5 ScanSAR**	**SAR-6 fine**	**SAR-6 high sensitive**
Centre frequency (MHz)	1 257.5	1 257.5	1 278.5	1 278.5	1 278.5
SAR bandwidth (MHz)	78	84	14 28	28	42
Frequency range (MHz)	1 215-1 300	1 215.5-1 299.5	1 271.5-1 285.5 1 264.5-1 292.5	1 264.5-1 292.5	1 257.5-1 299.5
Pulse width (μs)	78	43-71	37-67	18-43	22-62
PRF range	2 400	1 620-2 670	1 050-1 860	1 550-3 640	1 100-3 000
Pulse duty cycle (%)	18.7	11.5	7.0	6.6	6.8
Radar Rx IF (–3 dB) bandwidth (MHz)	0.69	0.69	0.69	0.69	0.69
Portion in radar (%)	0.885	0.82	4.93 2.46	2.46	1.64
Effective duty cycle, eDC (%)	0.1654	0.0945	0.345 0.1725	0.1626	0.112
Radar 2/radar 8 processing gain, *PG* (dB)	+22 / 0	+22 / 0	+13 / 0 +20 / 0	+22 / 0	+23 / 0

TABLE 8 *(end)*

	SAR-3	**SAR-4 spotlight**	**SAR-5 ScanSAR**	**SAR-6 Fine**	**SAR-6 high sensitive**
a) Radar 2/ radar 8 receiver noise[1], *N* (dBW)	–143.6 / –140	–143.6 / –140	–143.6 / –140	–143.6 / –140	–143.6 / –140
b) Radar protection criteria[2] (dB)	–6	–6	–6	–6	–6
c) Per service apportionment[3] (dB)	–4.8	–4.8	–4.8	–4.8	–4.8
Max radar 2/radar 8 interference allowed, $\{I_{IPC} = a) + b) + c)\}$ (dBW)	–154.4 / –150.8	–154.4 / –150.8	–154.4 / –150.8	–154.4 / –150.8	–154.4 / –150.8
RFI exceedance[4], I_R/I_{IPC} (dB)	Figure 4-8	Figure 4-4	Figure 4-5	Figure 4-6	Figure 4-6

1 Recommendation ITU-R M.1461-1 (2003): radar receiver noise, *N* (dBm) = −144 dBm + 10 log B_{IF} (kHz) + *NF*. For Radar 2, *N* = −144 + 10 log (690) + 2 = −113.6 dBm or −143.6 dBW. For Radar 8, *N* = −144 + 10 log (1200) + 3.2 = −110.0 dBm or −140.0 dBW.

2 Radar receiver protection level from Recommendation ITU-R M.1463, *I/N* = –6 dB.

3 In Canada and the United States of America, the frequency band 1 240-1 300 MHz is shared by ARNS, RLS, EESS (active) and SRS (active). The RNSS is not currently authorized in the 1 240-1 300 MHz band in the United States of America but it is included in the per service apportionment since this band is internationally allocated to the RNSS. The SRS is excluded from the per service apportionment since SRS transmit beams do not point towards the Earth. Hence, per-service apportionment to protect ARNS systems is –4.8 dB, assuming equal apportionment among the EESS (active), RNSS and RLS.

4 The Radar 2/Radar 8 backlobe antenna gains (−9.1/−2.5 dBi respectively) are used to compute the average interference signal power, I_R (dBW), received by a terrestrial radar from spaceborne active sensors. For radar *PG* = 0, $I_R = 10 \log P_t + 10 \log (\tau\, PRF) + G_t + G_r – (32.44 + 20 \log (f\, R)) + OTR – PG$ as defined in equation (1). For radar $PG \neq 0$, $I_R = 10 \log P_t + G_t + G_r – (32.44 + 20 \log (f\, R)) – PG$, where radar *PG* took into account the effective duty cycle, eDC = $(\tau\, PRF\, B_r / B_t)$, in the measurement test. Interference exceedance occurs when $I_R/I_{IPC} > 0$ dB.

Figure 8 plots the SAR-4/5/6 satellite-ground tracks for 14 orbital periods, each period of 97.27 minutes. There are 6 ground tracks going through the contiguous United States of America (CONUS) each day (3 from northeast to southwest and 3 from southeast to northwest).

FIGURE 8

SAR-4/5/6 ground tracks for 14 orbital periods

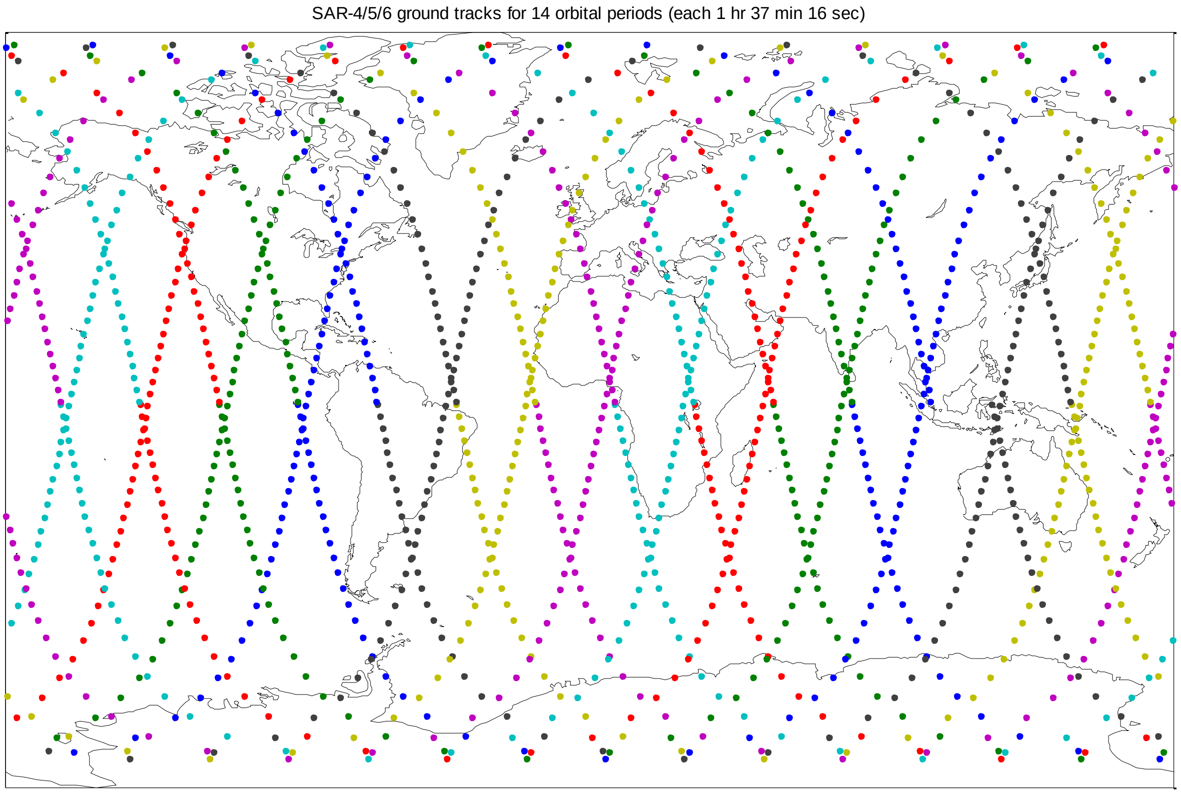
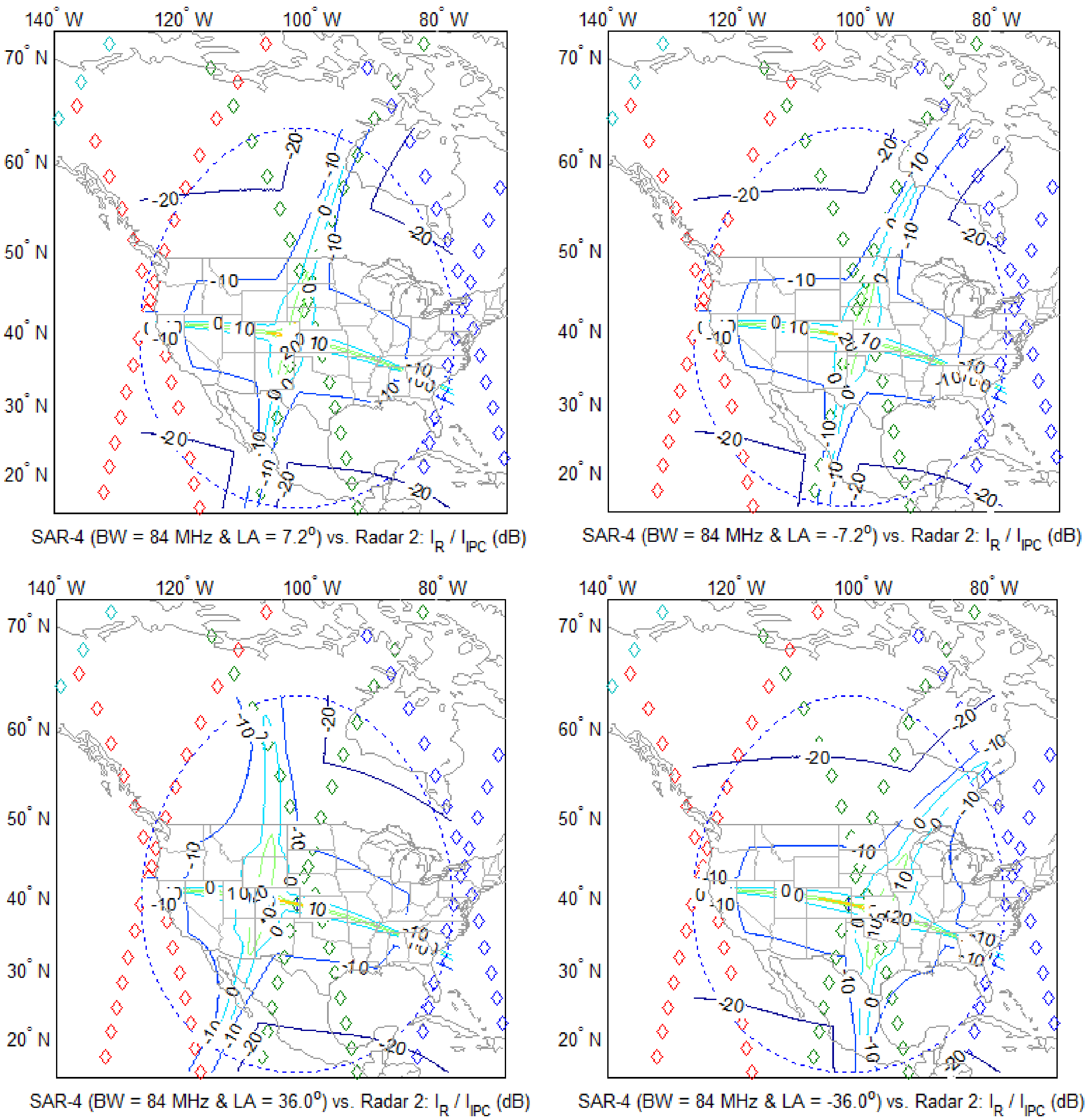


Figure 9 shows iso-contours of I_R/I_{IPC} in dB for SAR-4 and radar 2/radar 8 on the surface of the Earth for SAR-4 look-angles of ±7.2º and ±36º and the satellite line-of-sight (LOS) coverage region (dotted blue line of 0.1 degree elevation angle). In these plots, the regions where I_R/I_{IPC} is greater than 0 dB represent areas where SAR-4 interference exceeds the N −10.8 dB threshold (protection criterion of I/N = −6 dB plus −4.8 dB per service apportionment factor). Satellite position points (diamond shape) projected on the surface of the Earth are 1-minute apart. As shown in Fig. 9, SAR-4 can illuminate a radar for more than 8 minutes in a single ground track. Similarly, Figs 10 and 11 show the I_R/I_{IPC} regions for SAR5/6, respectively, with various look-angles vs. radar 2 and radar 8. The emission footprints of these SAR modes are large relative to the surveillance volume of the ARNS radars and can simultaneously illuminate multiple radars for minutes. In both cases, the temporal duration when I_R exceeds I_{IPC} depends on the ground location of the radar relative to the space sensor ground track and heading.

FIGURE 9

SAR-4 with various look-angles vs. radar 2 / radar 8: I_R/I_{IPC} (dB) regions



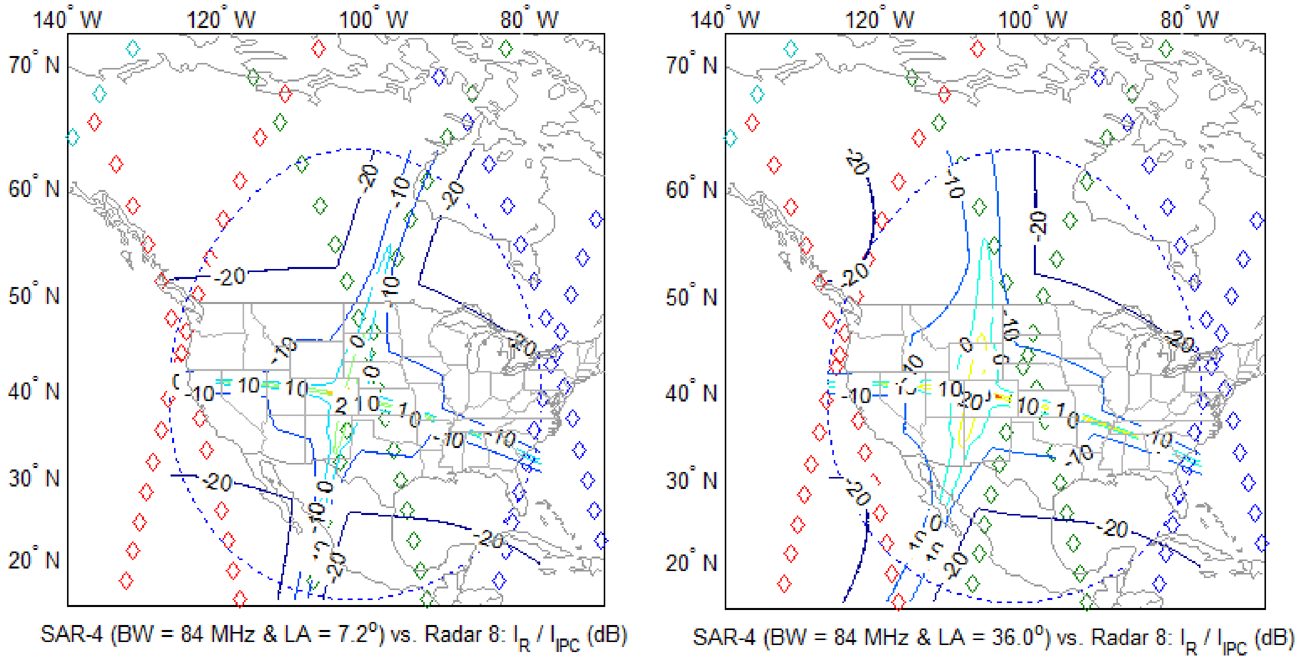
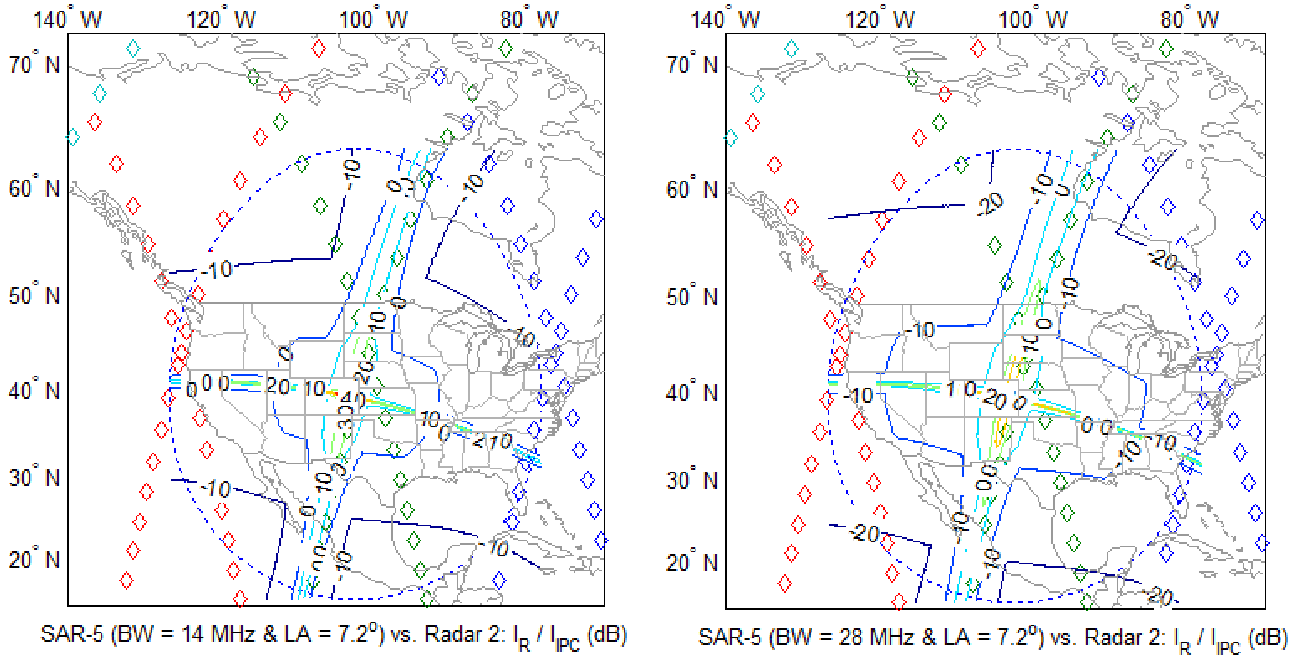
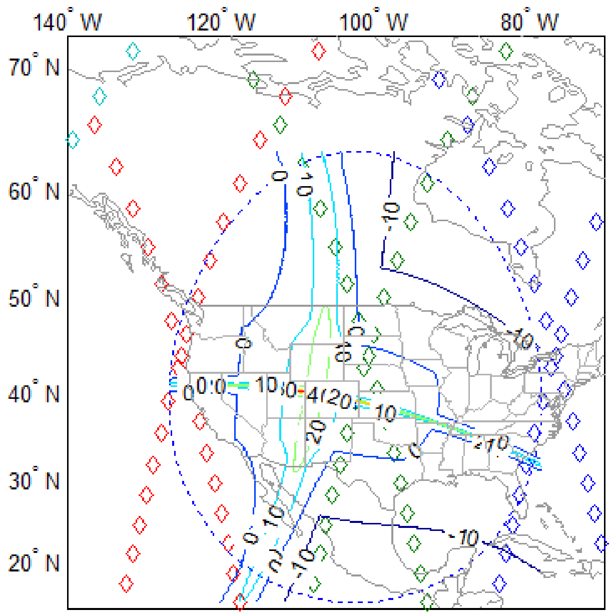


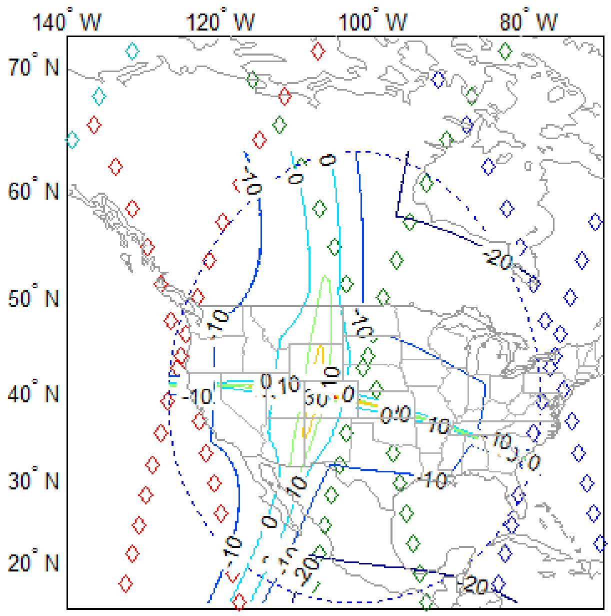
FIGURE 10

SAR-5 with various look-angles vs. radar 2 / radar 8: I_R/I_{IPC} (dB) regions

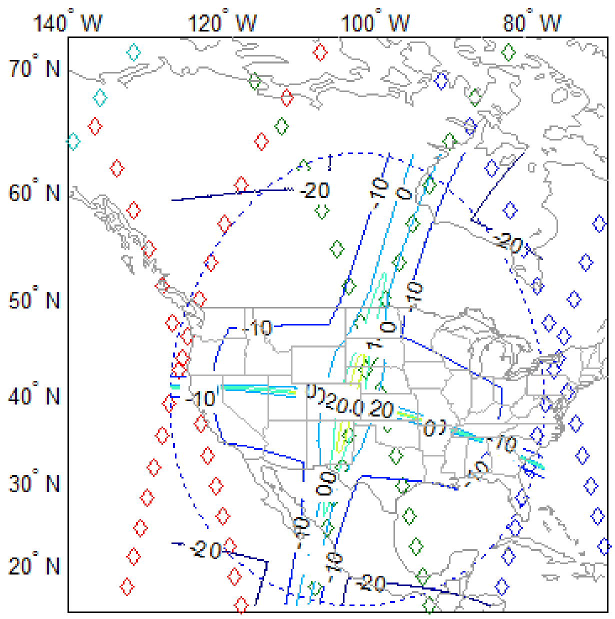




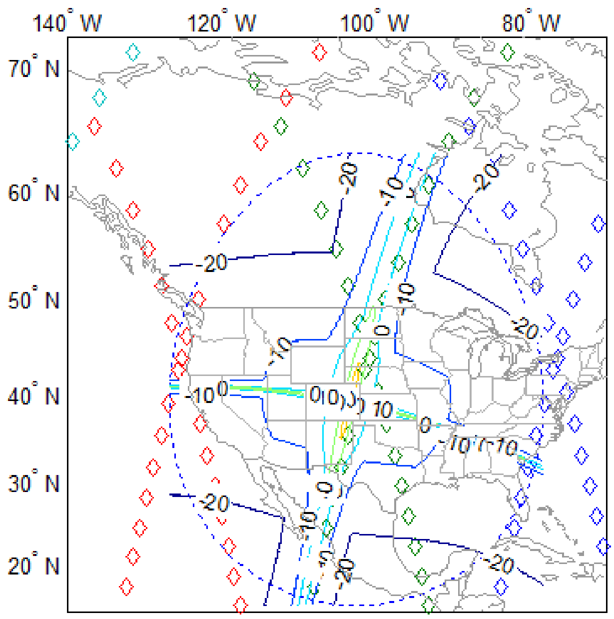
SAR-5 (BW = 14 MHz & LA = 36.0°) vs. Radar 2: I_R / I_{IPC} (dB)



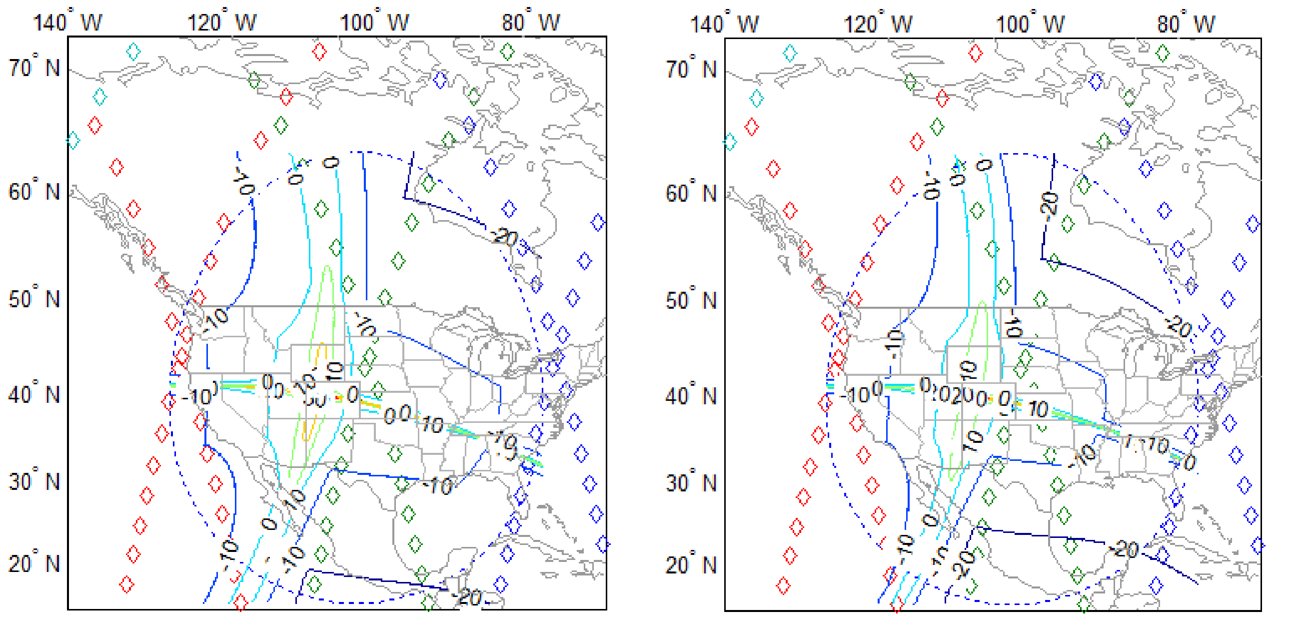
SAR-5 (BW = 28 MHz & LA = 36.0°) vs. Radar 2: I_R / I_{IPC} (dB)



SAR-5 (BW = 14 MHz & LA = 7.2°) vs. Radar 8: I_R / I_{IPC} (dB)



SAR-5 (BW = 28 MHz & LA = 7.2°) vs. Radar 8: I_R / I_{IPC} (dB)

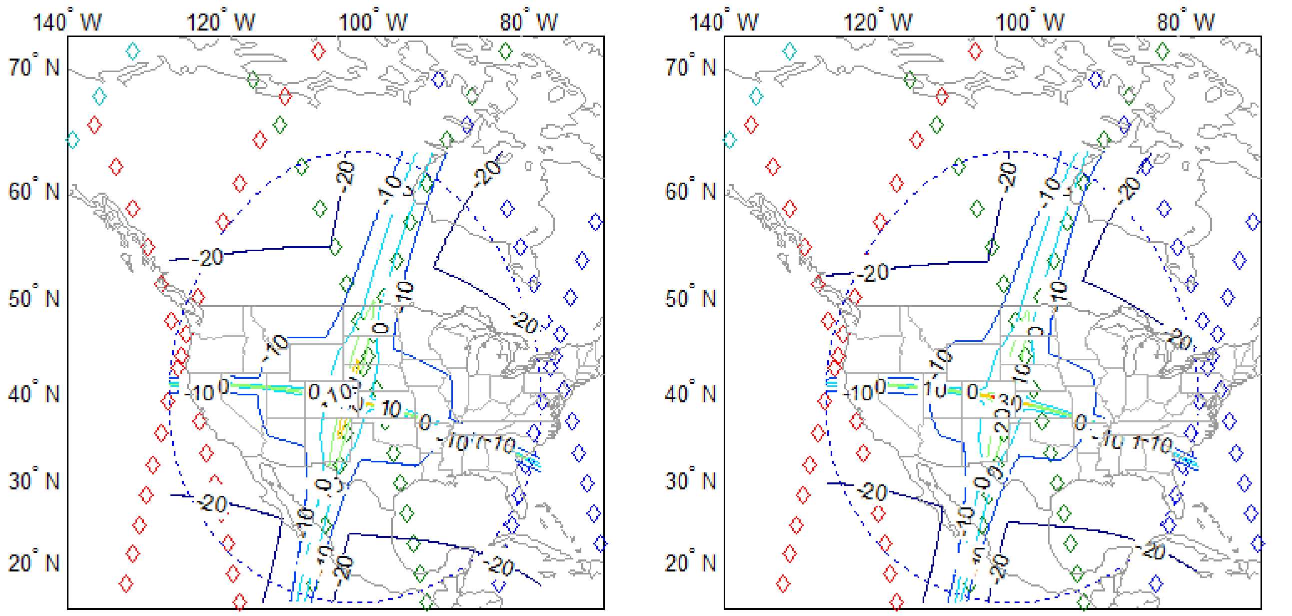


SAR-5 (BW = 14 MHz & LA = 36.0°) vs. Radar 8: I_R / I_{IPC} (dB)

SAR-5 (BW = 28 MHz & LA = 36.0°) vs. Radar 8: I_R / I_{IPC} (dB)

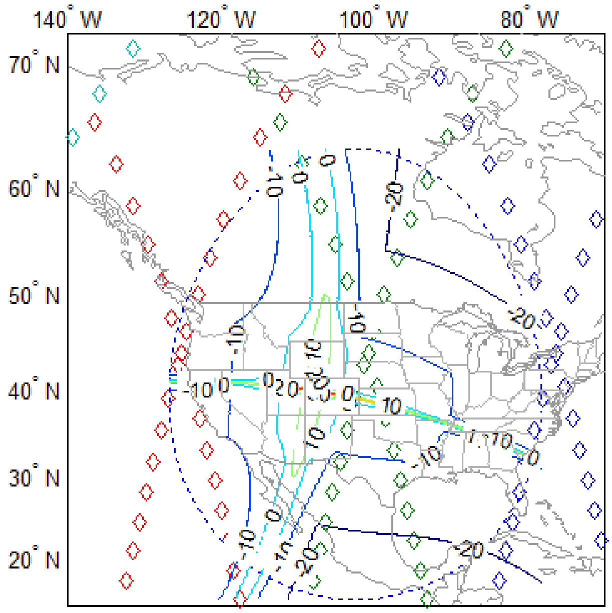
FIGURE 11

SAR-6 with various look-angles vs. radar 2 / radar 8: I_R/I_{IPC} (dB) regions

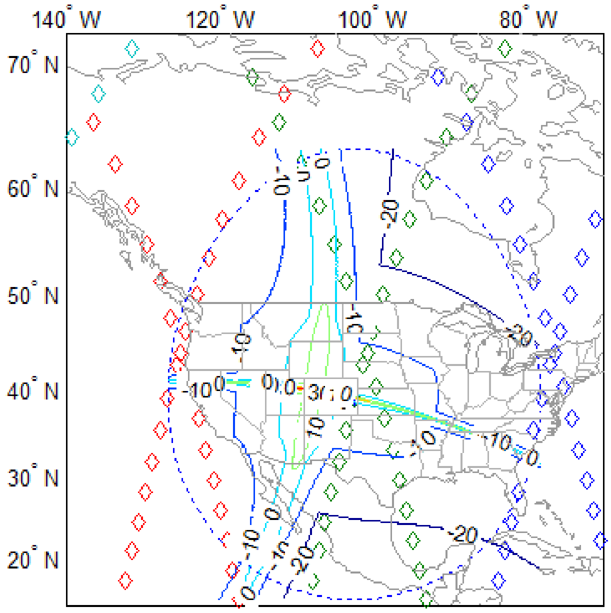


SAR-6 (BW = 28 MHz & LA = 7.2°) vs. Radar 2: I_R / I_{IPC} (dB)

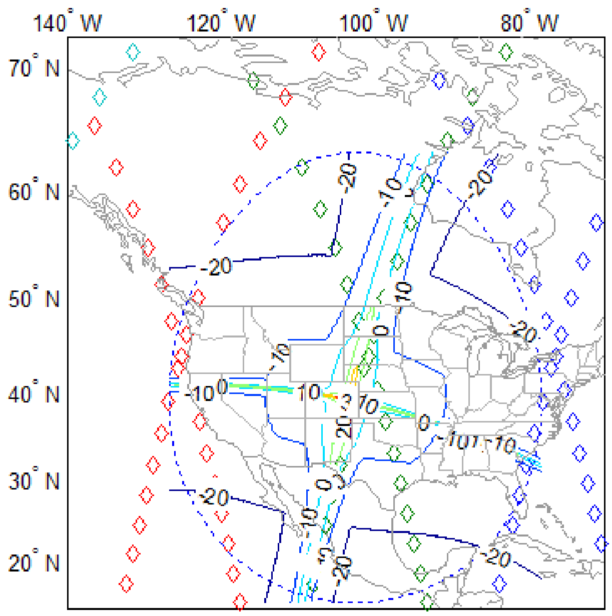
SAR-6 (BW = 42 MHz & LA = 7.2°) vs. Radar 2: I_R / I_{IPC} (dB)



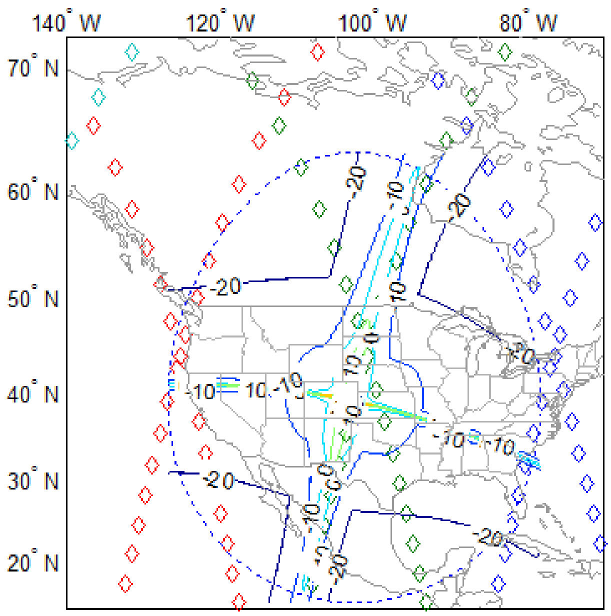
SAR-6 (BW = 28 MHz & LA = 36.0°) vs. Radar 2: I_R / I_{IPC} (dB)



SAR-6 (BW = 42 MHz & LA = 36.0°) vs. Radar 2: I_R / I_{IPC} (dB)



SAR-6 (BW = 28 MHz & LA = 7.2°) vs. Radar 8: I_R / I_{IPC} (dB)



SAR-6 (BW = 42 MHz & LA = 7.2°) vs. Radar 8: I_R / I_{IPC} (dB)

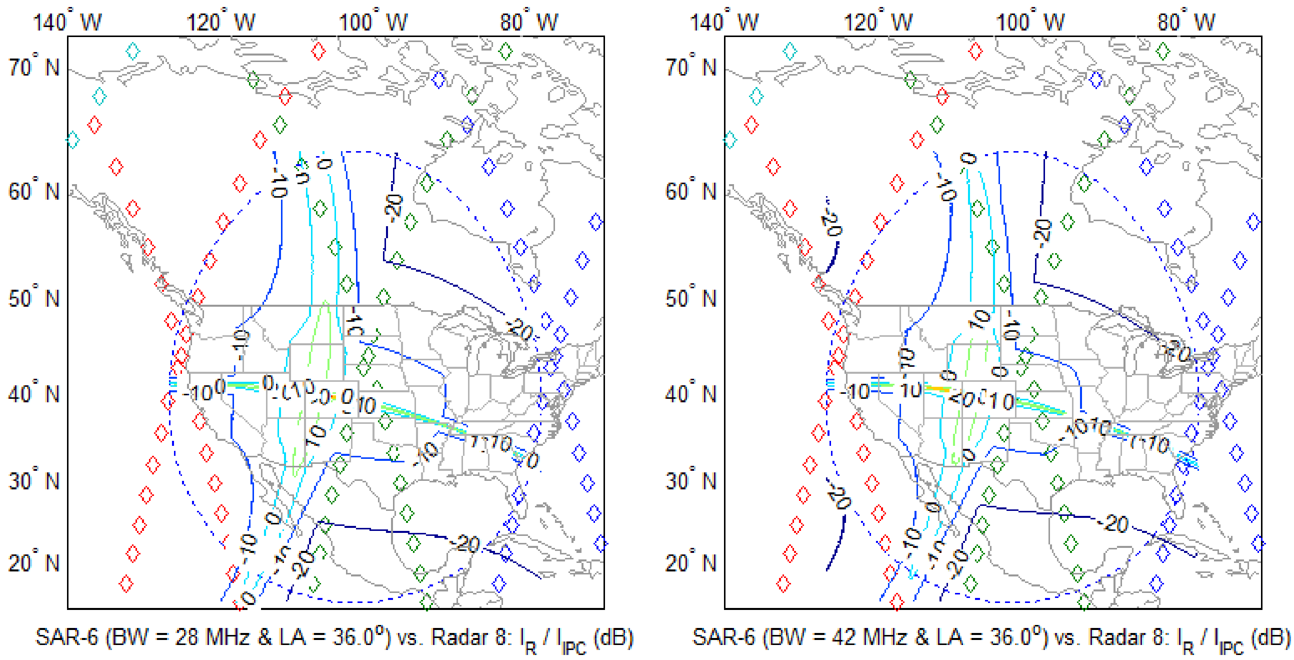


Figure 12 plots the SAR-3 satellite-ground tracks for 14 orbital periods, each period of 99.97 minutes. The SAR ground track can pass over a contiguous territory multiple times per day. For example, there are 6 ground tracks going through the contiguous main land of the United States of America each day (3 from northeast to southwest and 3 from southeast to northwest).

FIGURE 12

SAR-3 ground track for 14 orbital periods

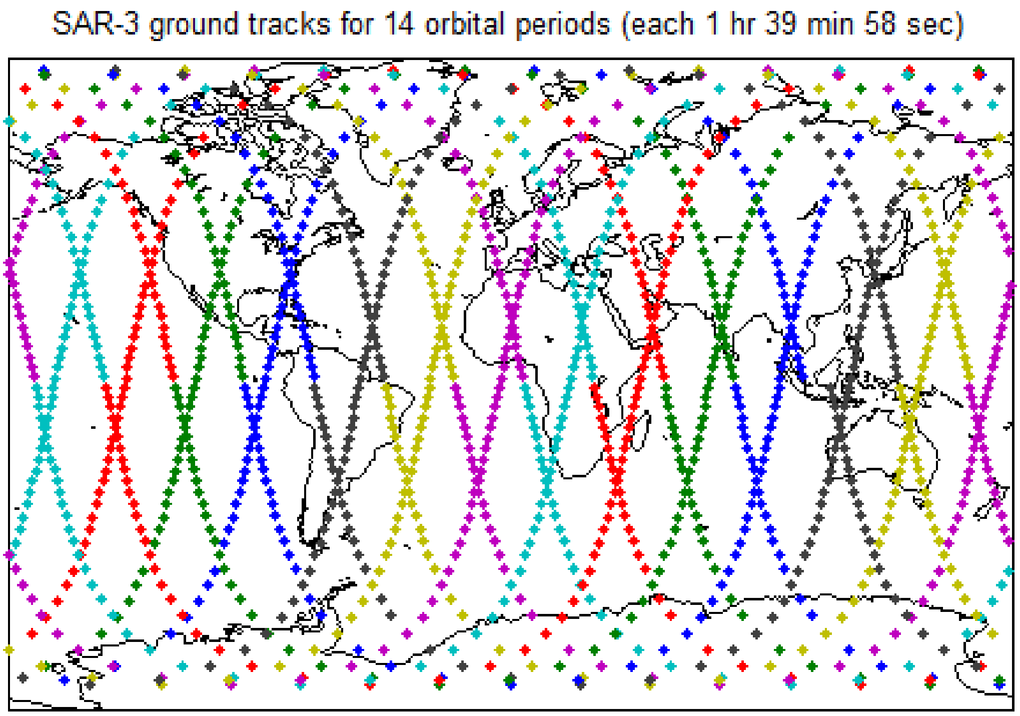
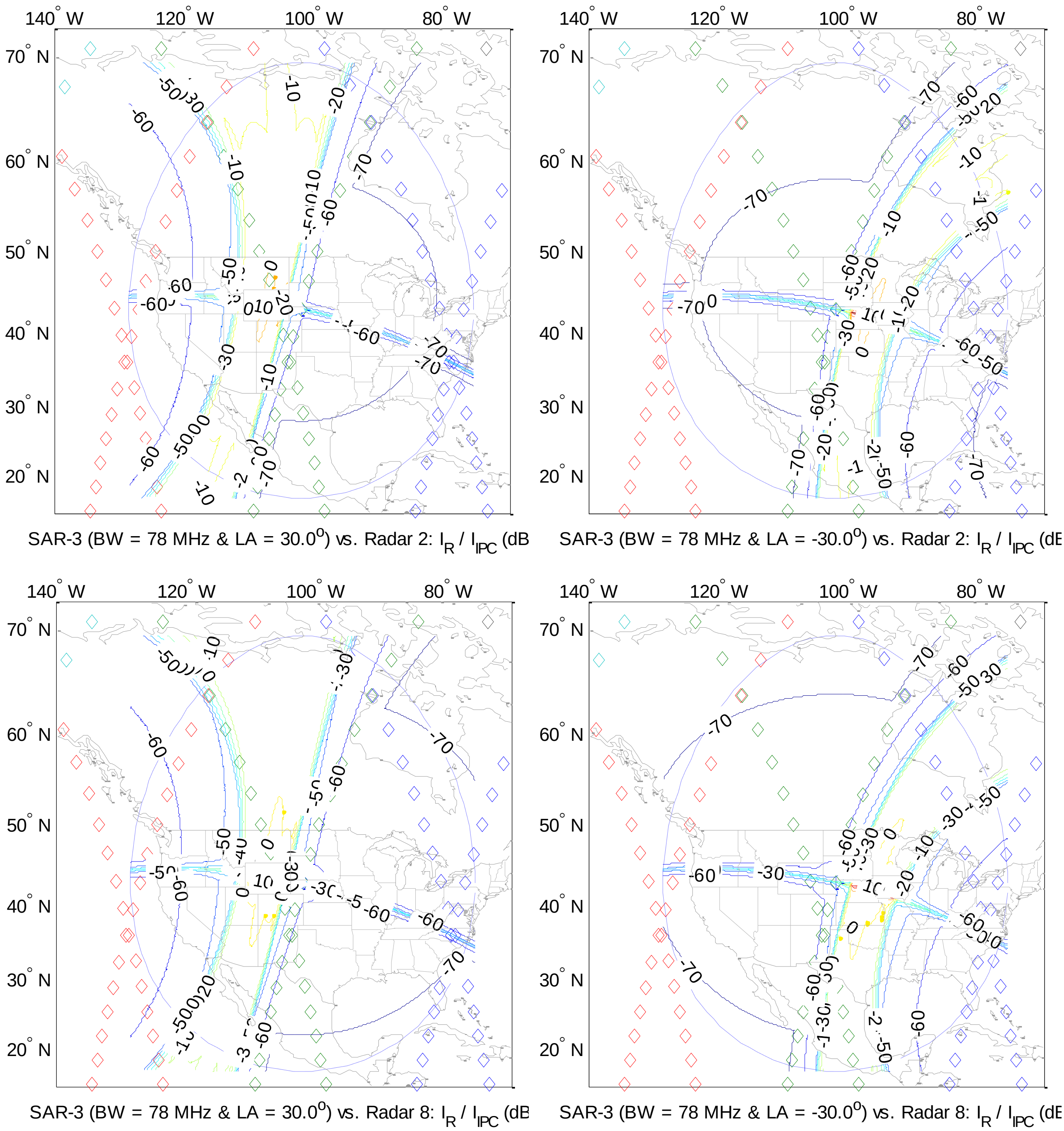


Figure 13 shows iso-contours of I_R/I_{IPC} in dB for SAR-3 and Radar 2/Radar 8 on the surface of the Earth for look-angles of ±30.0° and the satellite LOS coverage region (dotted blue line of 0.1 degree elevation angle). Satellite position points (diamond shape) projected on the surface of the Earth are 1-minute apart. Once again, the regions where I_R/I_{IPC} is greater than 0 dB represent areas where

SAR-4 interference exceeds the N−10.8 dB threshold (I/N of −6 dB plus −4.8 dB per service apportionment factor). As shown in Fig. 13, SAR-3 can illuminate a radar for a few minutes in a single ground track. These regions are large relative to the surveillance volume of the ARNS radars and can simultaneously illuminate with multiple radars for minutes.

FIGURE 13

SAR-3 with various look-angles vs. radar 2 / radar 8: I_R/I_{IPC} (dB) regions



5 Interference mitigation techniques

The following interference mitigation techniques are proposed to help alleviate the potential interference:

– limit the SAR look-angle to no more than 34.5 degrees from the SAR-4/5/6 antenna boresight and to no more than 24 degrees from the SAR-3 antenna boresight;

– coordinate with other EESS (active) operators in the 1 215-1 300 MHz frequency band to avoid simultaneous antenna sidelobe overlap;

– operate SAR-5 ScanSAR with a 28 MHz bandwidth since the 14-MHz bandwidth SAR-5 ScanSAR has a higher level of interference than other SARs;

– operate certain SAR modes only in portions of the 1 215-1 300 MHz band where interference is acceptable to systems in all primary services in this frequency band;

– lower the e.i.r.p. of SARs;

– reduce the antenna sidelobe levels of the SARs;

– lower the SAR effective duty cycle.

6 Conclusion

The results in this study show that a single EESS (active) system, SAR-3/4/5/6, can exceed an *I/N* of −10.8 dB (ARNS protection criterion *I/N* of −6 dB plus a per service apportionment factor of −4.8 dB). In some cases, a single EESS (active) system emissions can also exceed an *I/N* of −6 dB, which would cause interference to ARNS radars in the frequency band 1 240-1 300 MHz. The analysis followed Recommendation ITU-R RS.1280 using EESS (active) antenna patterns with two principle plane cuts. It also assumed a constant ARNS radar antenna elevation gain representing the backlobe level of the antenna elevation gain; independent of the elevation angles of EESS (active) signals into the radar antenna. The interference level into these ARNS radars will be higher when considering multiple EESS (active) simultaneous illuminations. One or more of the suggested interference mitigation techniques can potentially be used in combination, as described in § 5, to reduce or eliminate the potential for interference.