INTERMAP
RADAR COMPATIBILITY
ANALYSIS

INTERMAP™ TECHNOLOGIES

Version 1.21
August 18th, 2008
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DOCUMENT HISTORY

Version	Date	Comment / Description of Change	Author
1.00	February 15th, 2008	Initial draft	Martin Lange
1.10	February 28th, 2008	Added: Compliance with NTIA Spectrum Requirements	Martin Lange
1.20	February 29th, 2008	Added: Example victim system G3	Martin Lange
1.21	August 18th, 2008	Updated: Operational Characteristics Correction: Figure numbering	Martin Lange

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1 INTRODUCTION

1.1 Scope

This analysis describes in detail the characteristics of Intermap´s radar systems STAR-3 through STAR-6, used for mapping surveys. The typical operational characteristics are based on averaged numbers from the survey operations, carried out in 2007 over Europe. By combining the systems characteristics and the operations characteristics the power density patterns on the ground are calculated. As the flight pattern follows a regular grid scheme, the emission footprint can be translated into a time distribution of interference power levels. At the end of this analysis an example calculation demonstrates the expected interference for a specific ground based radar system, selected from an ITU-R document.

1.2 Definitions, Acronyms, and Abbreviations

Line / flight line.............. Planned, straight trajectory for an aircraft for data acquisition, defined by mission planning

Pass .... Actual flight along a planned flight line

Reflight .... Second or third pass along a planned flight line

2 AIRBORNE SENSOR, TECHNICAL CHARACTERISTICS

The following section describes in detail the characteristics of the Intermap interferometric STAR radar systems. In order to allow a direct comparison of systems, the table of technical characteristics is adapted from recommendation ITU-R M.1796, table 2.

Table 1

Characteristics	STAR-3	STAR-6	STAR-4	SATR-5
Function	Interferometric SAR imaging			
Platform (note 1)	Learjet 36		Beechcraft King Air 200 T	
Platform velocity [m/s]	200		105	
Tuning range [MHz]	9 605			
Modulation	Linear FM pulse			
Peak power into antenna	4.5 kW (note 2)			
Pulse width [µs]	22.6			
Pulse repetition rate [pps] (note3)	1800		1890	
Duty cycle	0.04 typical 0.05 maximum			
Pulse rise/fall time [µs]	0.1/0.1			
Output device	Traveling wave tube			
Antenna pattern type	Pencil (azimuth) Fan (elevation)			
Antenna type	Slotted array			
Antenna polarization	Horizontal			
Antenna main beam gain [dBi]	30.8		25.9	
Antenna elevation beamwidth [degrees] (note 4)	14.3		22.3	
Antenna azimuthal 3 dB beamwidth [degrees]	1.4		3.1	
Antenna horizontal scan rate	Not applicable			
Antenna horizontal scan type	Side looking, 90 deg to flight direction, selectable left or right			
Antenna vertical scan rate	Not applicable			
Antenna vertical scan type (note 5)	Fixed tilt angle			
Antenna side lobe levels (1^{st} azimuth side lobe)	13.2 dBi at 2.1 degrees		-0.7 dBi at 5.5 degrees	

Antenna height	Aircraft altitude (typically 11.000 m)	Aircraft altitude (typically 7.300 m)
Receiver IF 3 dB bandwidth [MHz]	167	
Receiver noise figure [dB]	4.1	
Minimum discernible signal [dBm]	Not specified	
Total chirp width [MHz]	135	
RF emission bandwidth [MHz]		
- 3 dB	127	
-20 dB	144	

note 1:

Figure 1. Learjet 36 (STAR-3, STAR-6)

Figure 2. Beechcraft King Air 200 T (STAR-4, STAR-5)

note 2:	Transmitter output peak power:	69.2 dBm	8.3 kW
	losses to antenna:	2.7 dB	
	peak power into antenna:	66.5 dBm	4.5 kW
note 3:	The pulse repetition rate is adjusted to the velocity of the aircraft.		
	Learjet, STAR-3 and STAR-6:	9 pulses per meter	
	King Air, STAR-4 and STAR-5:	18 pulses per meter	
note 4:	Elevation beamwidth:		
	Learjet, STAR-3 and STAR-6:	14.3 deg (3 dB beamwidth)	
		30 deg (over a 11 dB linear slope)	
	King Air, STAR-4 and STAR-5:	22.3 deg (3 dB beamwidth)	
		30 deg (over a 8 dB linear slope)	
note 5:	Boresight depression angle		
	Learjet, STAR-3 and STAR-6:	28.5 deg	
	King Air, STAR-4 and STAR-5:	29.3 deg	

3 COMPLIANCE WITH NTIA SPECTRUM REQUIREMENTS

Reference: NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management (Red Book), Section 5.5

Applicable Criteria: Criteria B, Section 5.5.2

System Parameters:	F_o	9605 MHz	operating frequency
	B_c	135 MHz	bandwidth of frequency deviation
	t	22.6 µs	emitted pulse duration
	t_r	> 0.1 µs	emitted pulse rise time
	t_f	> 0.1 µs	emitted pulse fall time
	P_t	+15.2 dBm / kHz	spectral density
	B(-40 dB)	±138 MHz	emission mask width at –40 dBc
	B(-60 dB)	±1382 MHz	emission mask width at –60 dBc

3.1 Measured Spectra

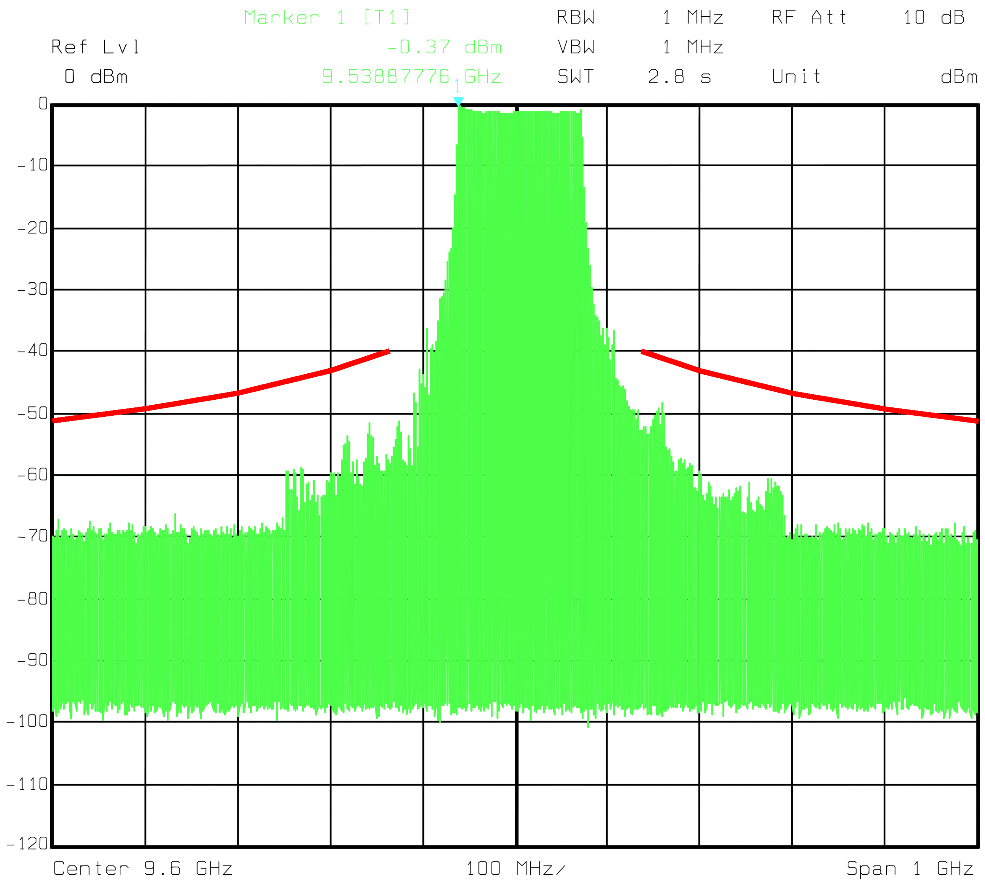


Figure 3. Spectrum of wanted emission, compliant with the NTIA emission mask.

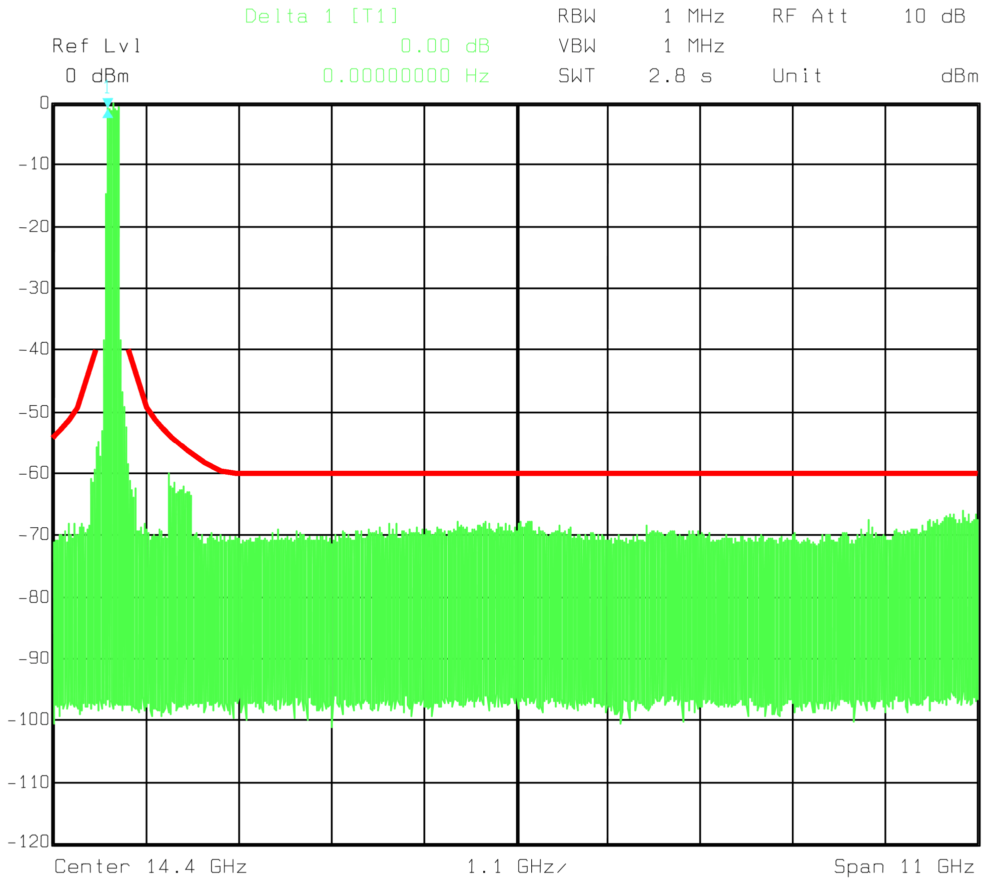


Figure 4. Spourious and harmonic signals, compliant with the NTIA emission mask

4 OPERATIONAL CHARACTERISTICS

All platforms are operated in mapping mode, where the flight lines are arranged in a grid pattern. The final map is mosaiced from data of the parallel flight lines (primary lines). Typically every 100 km orthogonal lines (tie lines) are acquired for control of the primary lines.

RF power is transmitted on a flight line only when data is acquired. Basically every line needs to be acquired only a single time. However in case of turbulences the aircraft trajectory can deviate from the planned flight line beyond specified limits, requiring a reflight. After three passes, a line is accepted in any case and if necessary, the sections of good data are patched together.

Definitions:
- line: planned aircraft trajectory
- pass: actual flight along a line
- reflight: second or third pass along a line

Number of passes = number of lines + number of reflights

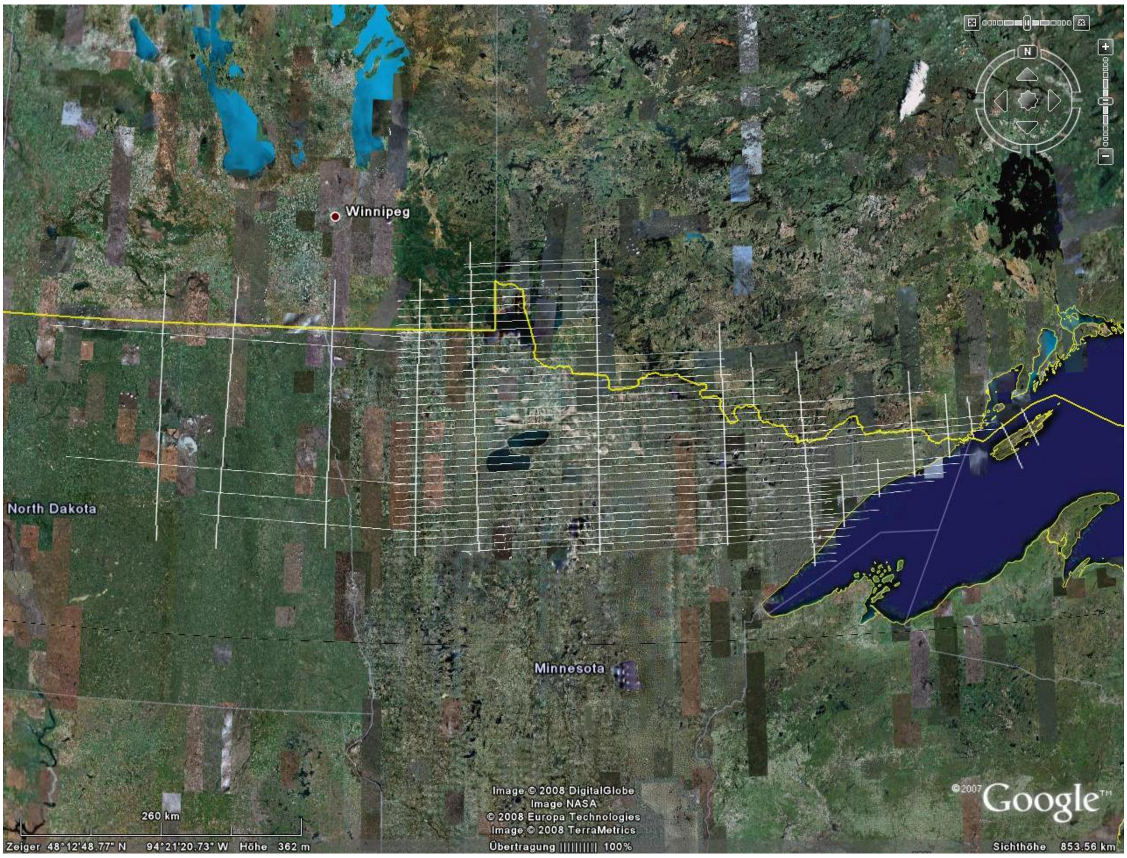


Figure 5. Typical pattern of planned flight lines for data acquisition, respectively RF transmission, area shown: 920 x 740 km

Table 2

Characteristics	STAR-3	STAR-6	STAR-4	SATR-5
Platform	Learjet 36		Beechcraft King Air 200 T	
Line spacing [km]	11		7	
Reflight statistics line flown one times two times three times	 62 % 26 % 12 %			
Average number of passes required to acquire 100 lines (including reflights)	150			
Average number of passes per day (note 1)	6			

5 CALCULATION OF INTERFERENCE POWER LEVELS ON THE GROUND

This section combines the technical characteristics of the airborne radar sensors and their typical operational characteristics, in order to calculate the interference power levels and their distribution over time for a fixed point on the ground. The results of this calculation will allow an easy but still accurate evaluation of the compatibility of Intermap´s STAR radar sensors with a specific other radar system.

5.1 Definitions

Power levels: In the following all power levels are peak power levels. Operating with a duty cycle of typically 4 %, the average power levels of all STAR radar sensors are 14 dB lower than the given peak power levels.

Antenna patterns: In order to avoid disturbing oscillations in the figures, caused by nulls of the side lobes, for all calculations the envelope of the antenna patterns is used.
Consequently in the side lobe range, the following calculations represent a worst case scenario. In average the observed interference levels from side lobes will typically be 5 to 10 dB lower than calculated. All antenna pattern envelopes are derived from measured patterns.

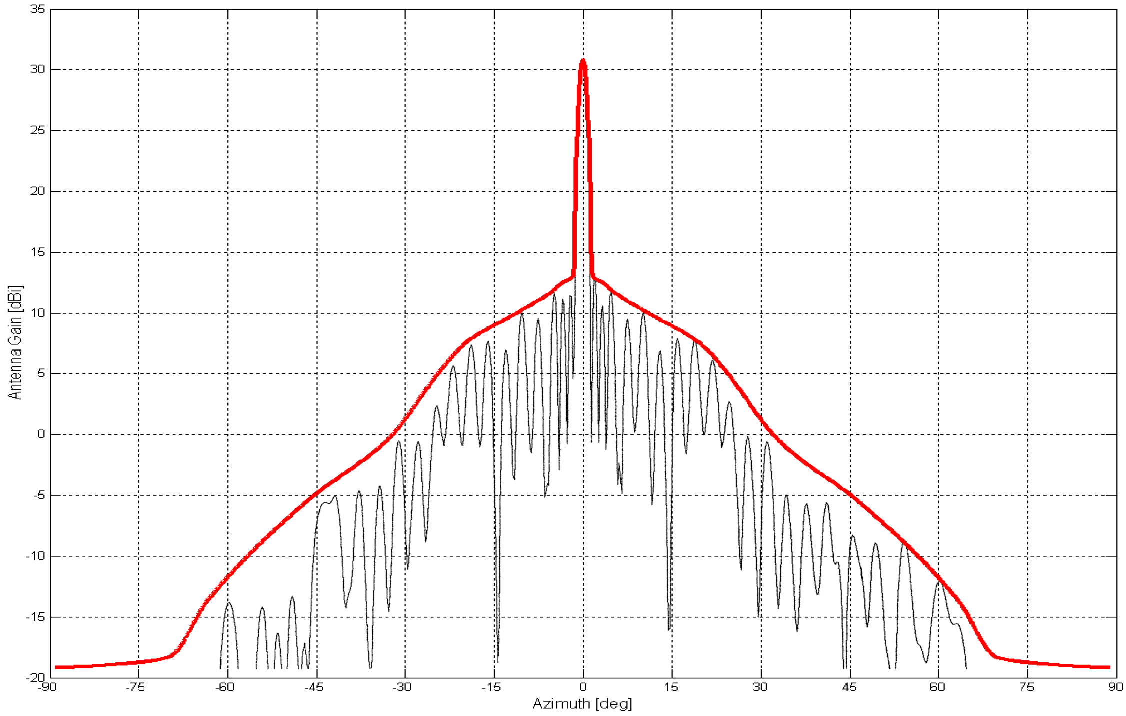
I_{ref}/N and reference receiver: In order to translate the spatial power density on the ground from STAR radar sensors into an *I/N* ratio where the interference power is related to thermal noise, a reference receiver has to be introduced. For simplicity a 0 dBi antenna has been chosen as the reference receiver. At a reference frequency of 9 600 MHz the effective aperture is 0.78 cm^2. For a specific victim receiver I/N can be easily derived from I_{ref}/N.

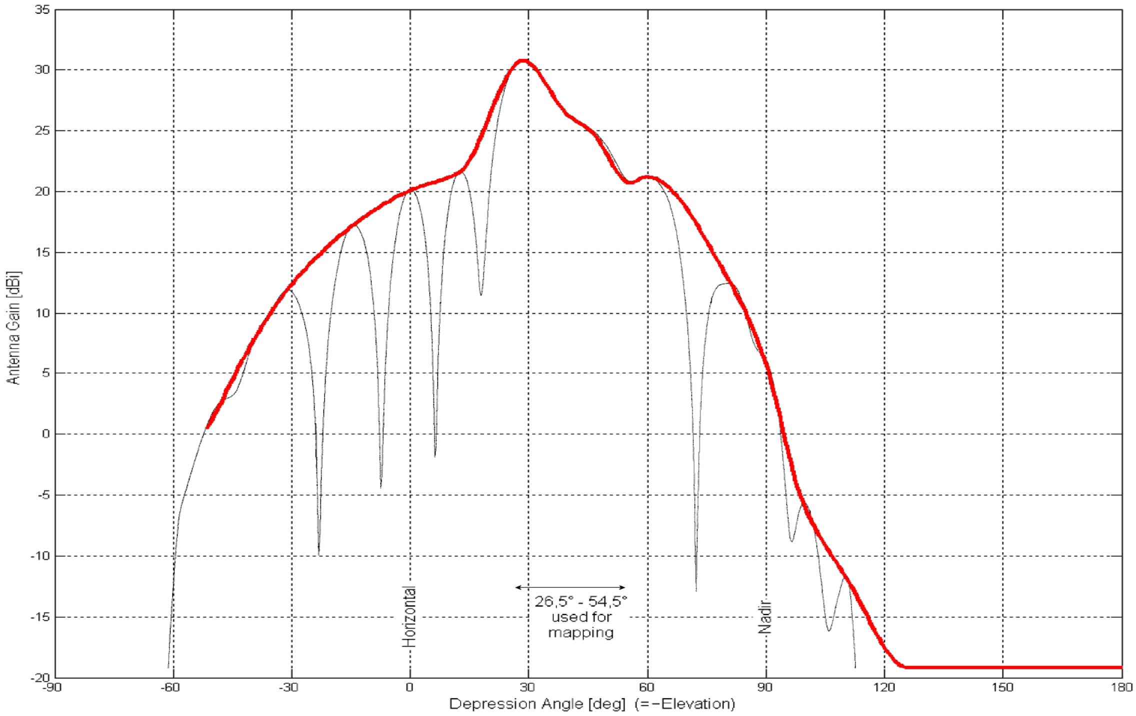
$$I/N = I_{ref}/N + G_I - NF - OTR$$

where:

- I/N = interference-to-noise power ratio [dB] (for the victim radar receiver)
- I_{ref}/N = interference-to-noise power ratio [dB] (calculated for the 0 dBi reference receiver)
- G_I = antenna gain of the victim radar [dBi] (in direction of the interfering STAR radar)
- NF = noise figure of the victim radar system [dB]
- OTR = on-tuned rejection factor [dB] (describing the how much of the 135 MHz STAR signal bandwidth falls into the victim receiver bandwidth)

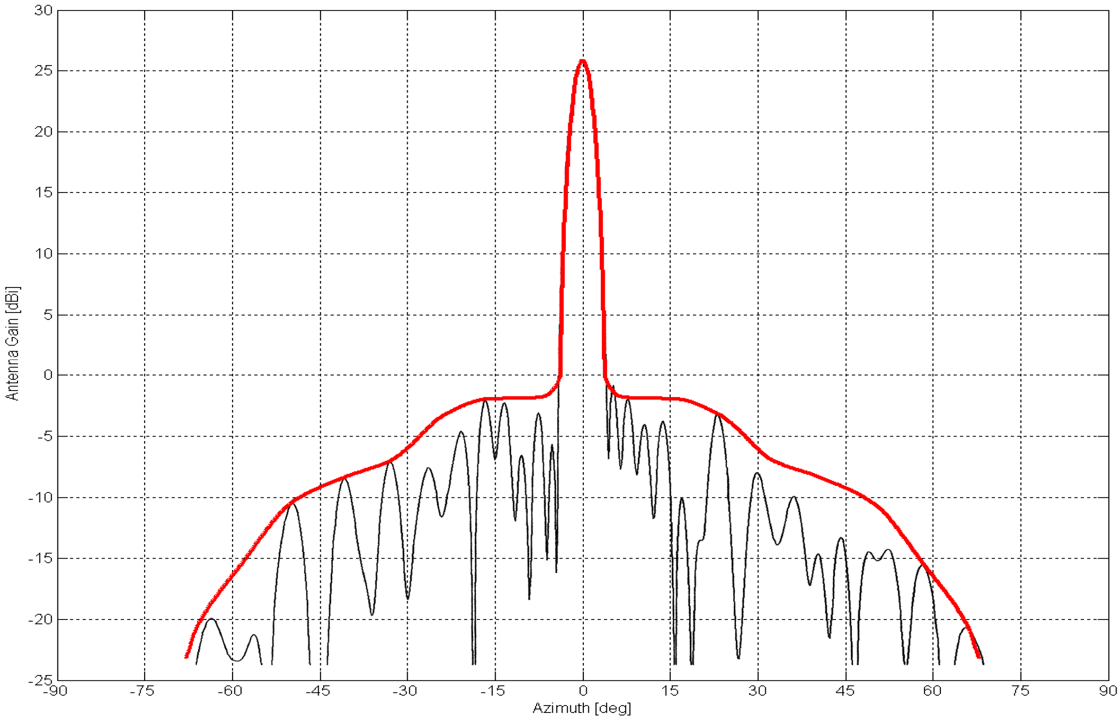
5.2 Antenna Patterns for STAR-3 and STAR-6 (Learjet)

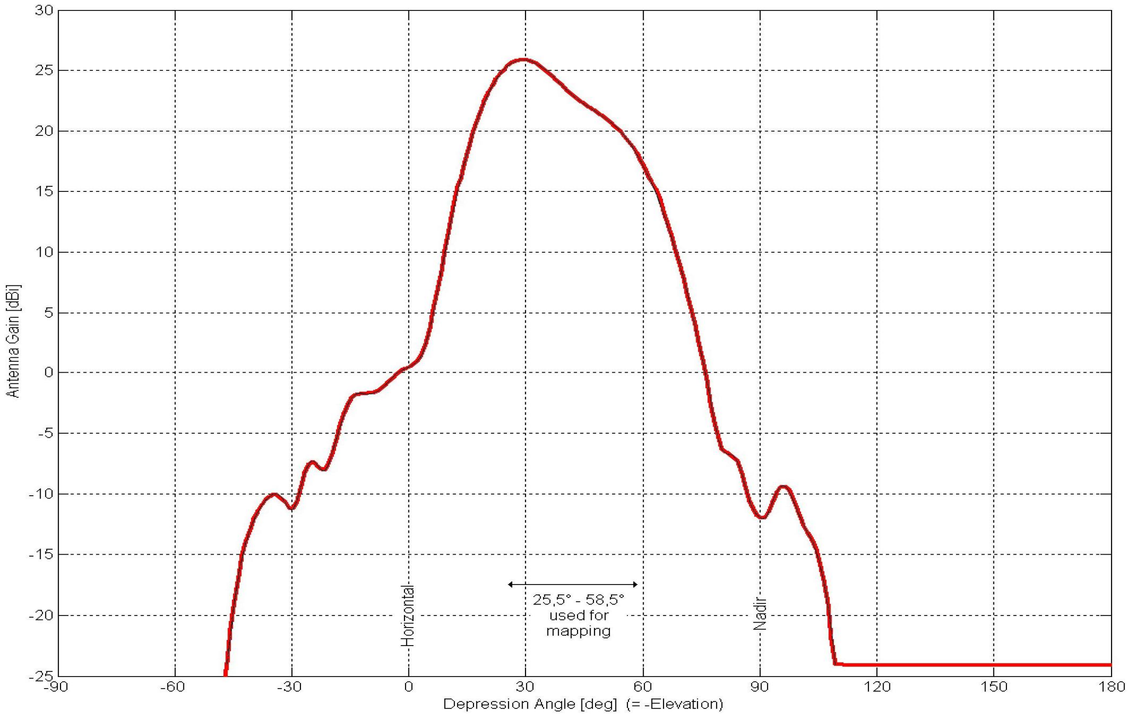




Figures 6 and 7. Solid line: Antenna pattern envelope, used for the I_{ref}/N calculation.

5.3 Antenna Patterns for STAR-4 and STAR-5 (King Air)





Figures 8 and 9. Solid line: Antenna pattern envelope, used for the I_{ref}/N calculation.

Because of the different antenna design, the STAR-4 and 5 elevation pattern show no sharp minima and the envelope is practically identical to measured pattern.

5.4 Interference Power Density Footprint

As a first step for determining the level of expected interference from STAR radar systems, the power density footprint is calculated from the antenna pattern envelopes, the antenna boresight direction and the aircraft operating altitude.

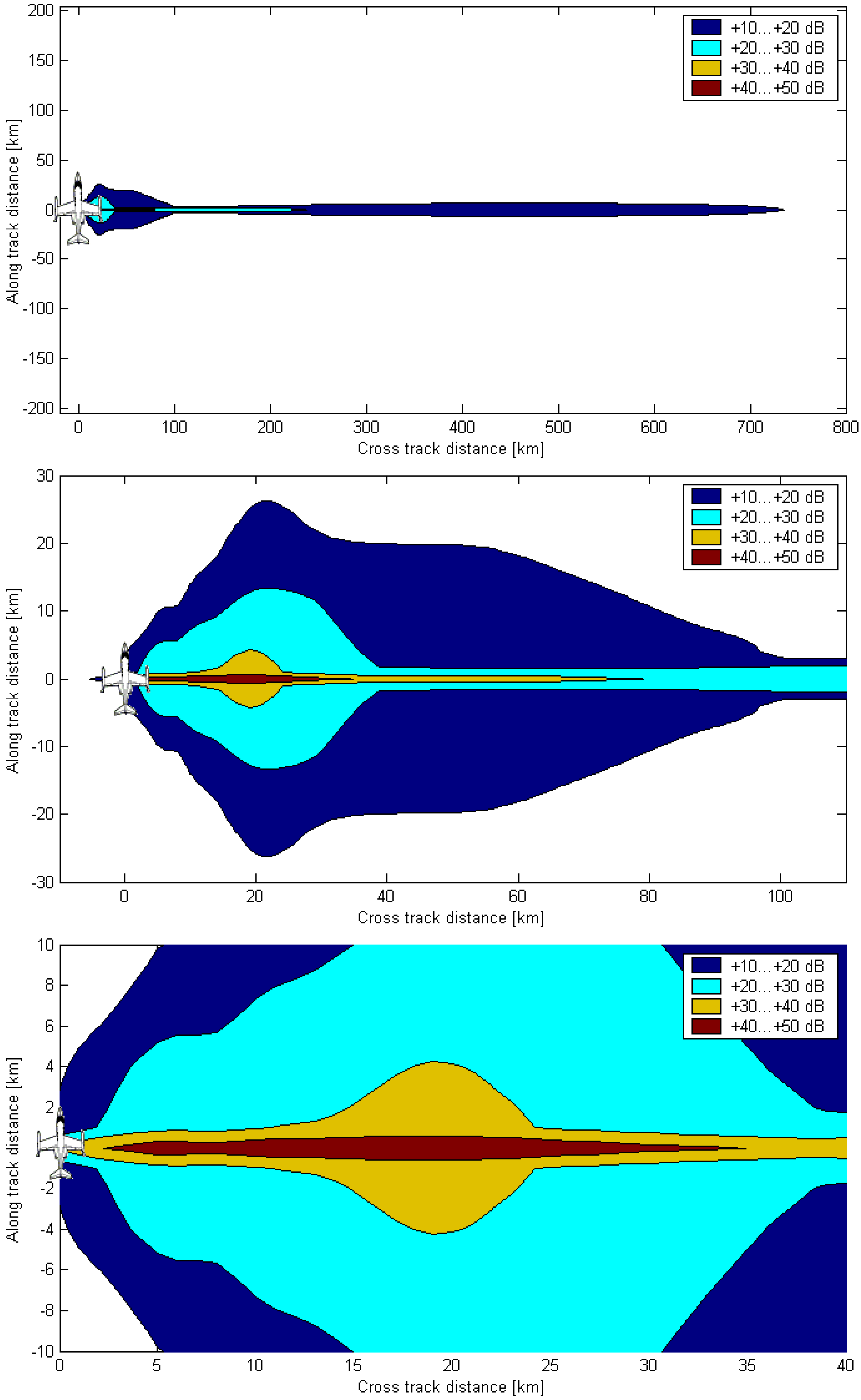
For better interpretation, the power density levels are normalized to I_{ref}/N, which is the power ratio of the interference signal on the ground, received with a 0 dBi omni-directional antenna (reference receiver), relative to the thermal noise power within the emission signal bandwidth.

$$I_{ref}/N = \frac{P_d \cdot A_0}{N_T(Bw)}$$

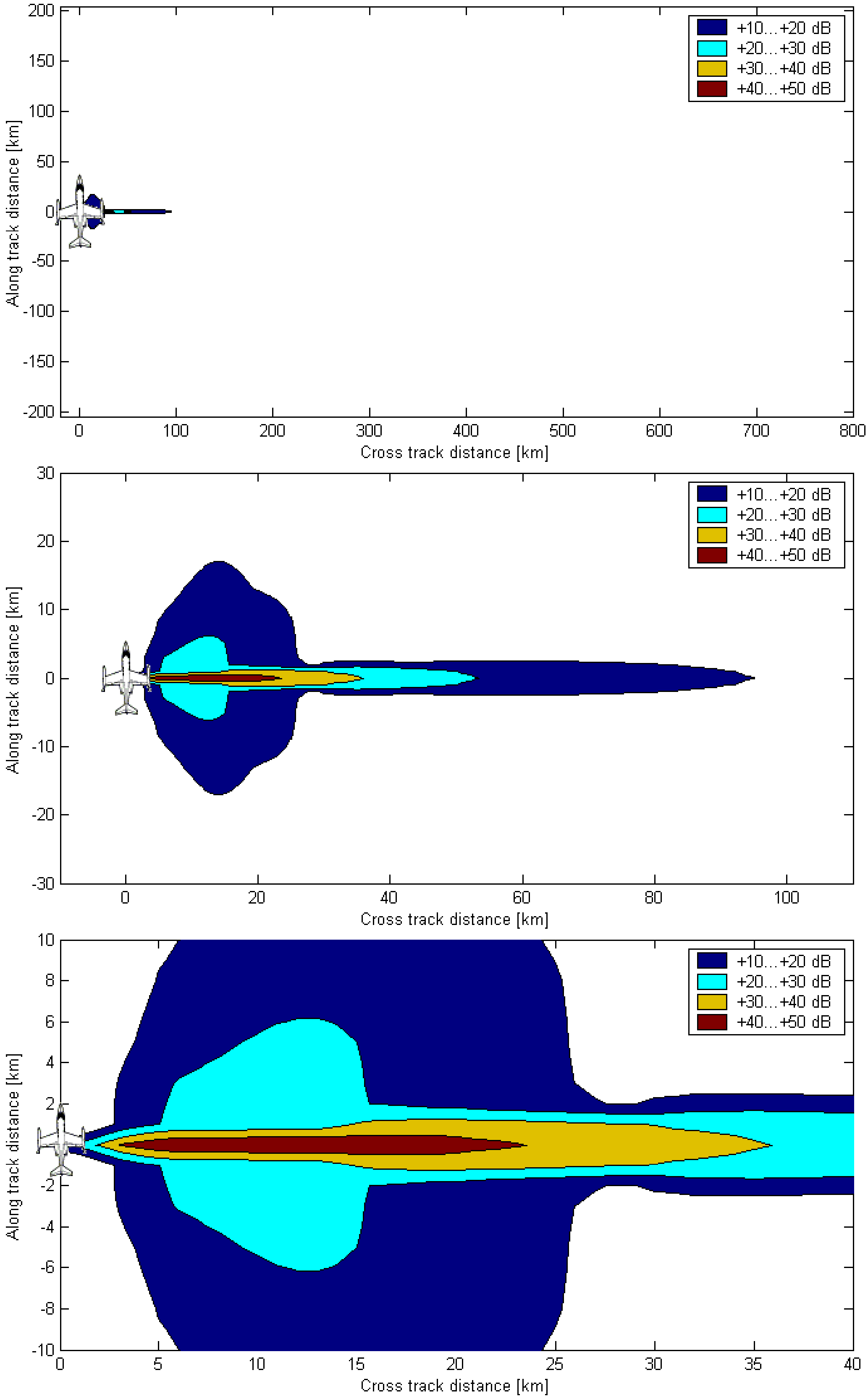
where

I_{ref}/N	=	interference-to-noise power ratio [dB] (calculated for the 0 dBi reference receiver)
P_d	=	interference power density on the ground [dBm / m^2]
A_0	=	effective aperture of a 0 dBi antenna (reference receiver) [m^2] (in this case, at 9600 MHz: 0.78 cm^2)
Bw	=	135 MHz, emission bandwidth of the STAR radar systems
$N_T(Bw)$	=	thermal noise within the emission bandwidth [dBm] (in this case: –92.6 dBm with –114 dBm / MHz)

In the following figures the aircraft is flying South to North, with the antenna pointing to the East. The range of interference is also limited by the distance to the horizon, which is for the Learjet 374 km and for the King Air 305 km.



Figures 10 to 12. Footprint of interference power level above thermal noise (I_{ref}/N) in different scales for range for STAR-3 and STAR-6 (Learjet)



Figures 13 to 15. Footprint of interference power level above thermal noise (I_{ref}/N) in different scales for range for STAR-4 and STAR-5 (King Air)

6 EXPECTED INTERFERENCE LEVELS VS. TIME

Combining the spatial distribution of the emitted power on the ground with the operational characteristics of the aircrafts leads to the distribution of the expected interference levels over time.

As the aircraft is operating along its mission pattern of lines, a fixed point on the ground experiences interference levels which are cross sections through the emission footprint (figures 10 to 15). The cross sections are in flight direction and separated by the typical line spacing of 11 km for the Learjet, respectively 7 km for the King Air.

In the figures below, the horizontal axis shows each flight line of the mission describing a cross section through the emission footprint. Line number 0 is defined as the flight which passes exactly over the victim radar.

The vertical axis shows the total duration of interference during a pass, for different normalized power levels I_{ref}/N.

Examples for the Learjet (figure 16):

- Line number 10 is a flight, passing the victim radar in a distance of 110 km (10 x 11 km).
- A total of 21 flight lines will show interference levels of I_{ref}/N of 20 dB and above.
- When the aircraft acquires flight line number 15, it will pass in a distance of 165 km and interfere for 39 sec at levels I_{ref}/N >= 10 dB and for 22 sec at levels >= 20 dB.

Interference through the antenna main lobe is short in time but wide in range, while interference through side lobes will be observed for longer durations, but only at lower power levels and only within a short range, and in reality, with higher fluctuations, when nulls in the azimuth pattern are crossed.

For the Learjet radars in practice the interference will cut off at the horizon which is in a distance of 373 km, equivalent to flight line number 34.

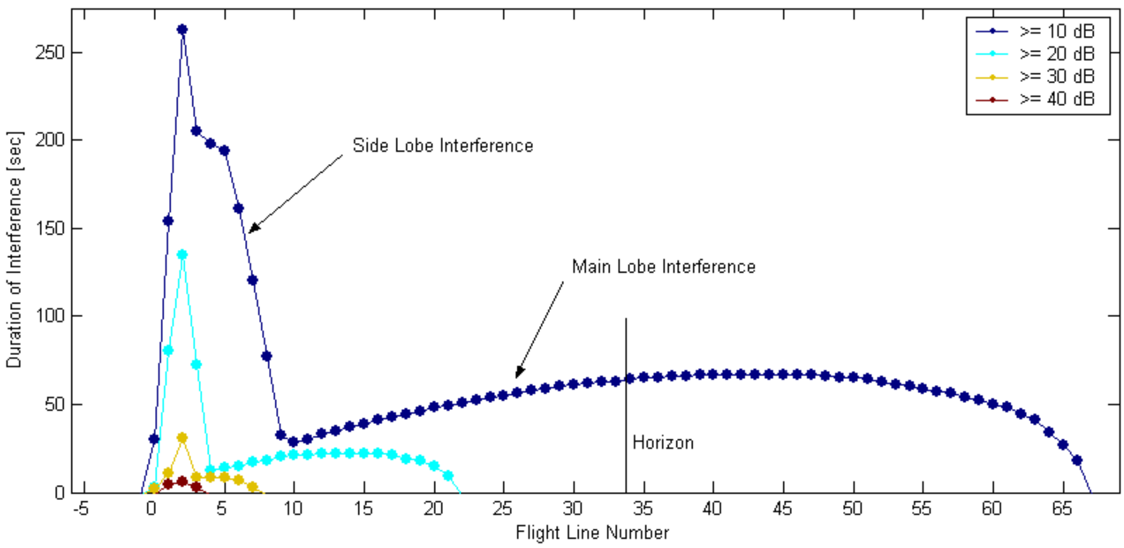


Figure 16. Duration of interference at levels I_{ref}/N vs. flight line number for STAR-3 and STAR-6 (Learjet)

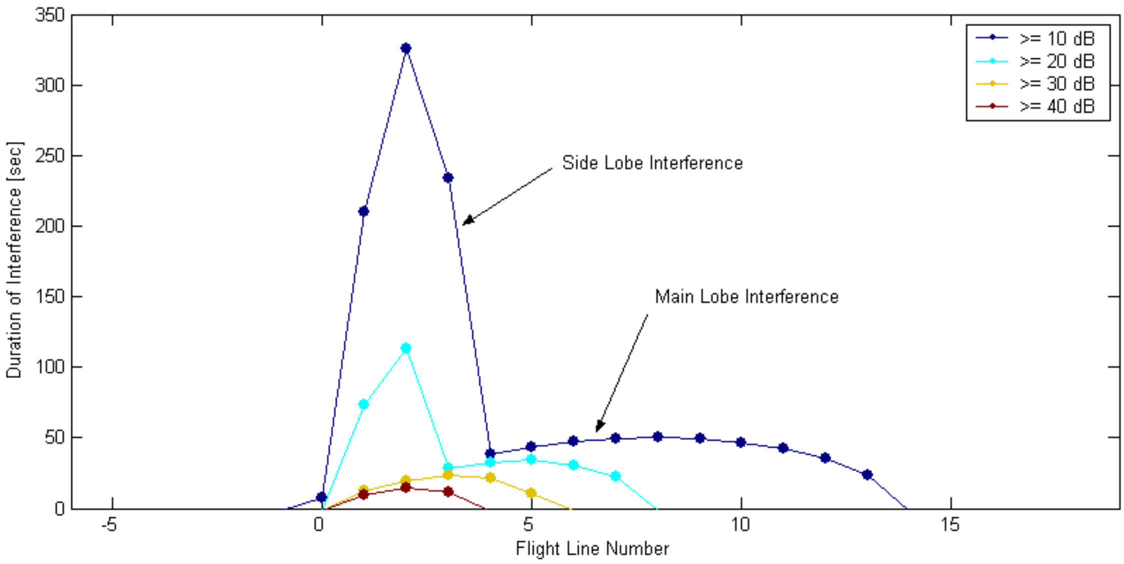


Figure 17. Duration of interference at levels I_{ref}/N vs. flight line number for STAR-4 and STAR-5 (King Air)

Table 3 finally summarizes the interference durations for different ranges of I_{ref}/N. While figures 16 and 17 show the planned flight lines, the table below also takes into account for 50 % reflights, typically encountered in mapping surveys. The nominal overall time period over which the interference is distributed is determined by the average number of six passes per day.

Table 3

Characteristics	STAR-3	STAR-6	STAR-4	SATR-5
Platform	Learjet 36		Beechcraft King Air 200 T	
Total number of lines with interference levels I_{ref}/N >= 10 dB	66 lines = 99 passes (with reflights) (including lines beyond the horizon)		13 lines = 20 passes (with reflights)	
Total survey period in which interference I_{ref}/N >= 10 dB can be observed	16.5 days		3.3 days	
I_{ref}/N level	Total duration of interference for a specific location on the ground			
>= 10 dB	1.88 hours		30.0 minutes	
>= 20 dB	15.5 minutes		8.30 minutes	
>= 30 dB	1.95 minutes		2.13 minutes	
>= 40 dB	19.5 seconds		51.0 seconds	

Remarks:

- The power levels I_{ref}/N refer to the peak power of the STAR radar systems and do not take into account the typical duty cycle of 4 % (-14 dB).

6.1 Example calculation for interference of a specific victim radar

This example calculation will demonstrate the I/N levels and durations, received by a specific victim radar.

Radar system:	G3 (from table 3 from Rec. ITU-R M.1796 'Characteristics of and protection criteria for terrestrial radars operating in the radiodetection service in the frequency band 8 500 – 10 500 MHz')
Radar type:	ground based tracking radar
Tuning range:	9 370 – 9 990 MHz
Antenna main beam gain:	42.2 dBi
Azimuth:	1.74 deg beam width
Elevation:	0.81 deg beam width
Receiver IF bandwidth:	1 MHz
Receiver noise figure:	4 dB (assumed)

Case 1: Interference via side lobes of system G3

In this case it is assumed, that the G3 victim system receives the interference signal from all directions with 0 dBi antenna gain. Consequently the duration of interference will be the same as in table 3, and I/N can be calculated from I_{ref}/N as follows:

$$I/N = I_{ref}/N + G_I - NF - OTR$$

where:

- I/N = interference-to-noise power ratio in the radar receiver of G3 [dB]
- I_{ref}/N = normalized interference-to-noise power ratio on the ground from the STAR radar systems
- G_I = omni-directional side lobe gain of the G3 antenna [dBi] in this case: 0 dBi
- NF = noise figure of the G3 radar system [dB] in this case: 4 dB
- OTR = on-tuned rejection factor [dB] in this case: -21 dB (1 MHz / 135 MHz)

I/N for interference via side lobes of the system G3 is calculated by

$$I/N = I_{ref}/N - 25 \text{ dB}$$

Table 4: System G3, *I/N* levels for interference via side lobes

Characteristics	STAR-3	STAR-6	STAR-4	SATR-5
Platform	Learjet 36		Beechcraft King Air 200 T	
Total survey period in which interference listed below can be observed	16.5 days		3.3 days	
I/N level	Total duration of interference for system G3 over the entire survey			
>= -15 dB	1.88 hours		30.0 minutes	
>= -5 dB	15.5 minutes		8.30 minutes	
>= +5 dB	1.95 minutes		2.13 minutes	
>= +15 dB	19.5 seconds		51.0 seconds	

Case 2: Interference via main lobe of system G3

In this case it is assumed, that the G3 victim system receives points at the STAR radar system and receives interference with its main beam gain. In this case the probability of pointing at the interfering STAR system has to be calculated. Assuming the antenna pointing is independent from the aircraft movement, the probability of pointing the main beam to the STAR system is 2 / (linear Antenna gain). The factor of 2 arises from the fact that the G3 antenna is pointing always up and never below the horizon.

In this case the probability of a G3 main beam interference is 2 / 16 596. The durations of interference are reduced by this factor. As in table 5 the durations of interference will become quite small, a better way of describing the interference is to calculate the number of received STAR emission pulses.

I/N can be calculated from I_{ref}/N as follows:

$$I/N = I_{ref}/N + G_I - NF - OTR$$

where:

- I/N = interference-to-noise power ratio in the radar receiver of G3 [dB]
- I_{ref}/N = normalized interference-to-noise power ratio on the ground from the STAR radar systems
- G_I = main lobe gain of the G3 antenna [dBi] in this case: 42.2 dBi
- NF = noise figure of the G3 radar system [dB] in this case: 4 dB
- OTR = on-tuned rejection factor [dB] in this case: -21 dB (1 MHz / 135 MHz)

I/N from interference via the G3 antenna main beam is calculated by

$$I/N = I_{ref}/N + 17 \text{ dB}$$

Table 5: System G3, *I/N* levels for interference via the antenna main beam

Characteristics	STAR-3	STAR-6	STAR-4	SATR-5
Platform	Learjet 36		Beechcraft King Air 200 T	
Total survey period in which interference listed below observed	16.5 days		3.3 days	
I/N level	Total duration of interference for system G3 over the entire survey			
>= 27 dB	734 pulses = 0.41 seconds		204 pulses = 0.11 seconds	
>= 37 dB	101 pulses = 0.056 seconds		57 pulses = 0.030 seconds	
>= 47 dB	13 pulses = 0.007 seconds		15 pulses = 0.008 seconds	
>= 57 dB	2 pulses = 0.001 seconds		6 pulses = 0.003 seconds	