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Project Report
ATC-92

Effects of Common Band (3500-3700 MHz) Operation of Geostationary Satellites and the FAA Limited-Surveillance Radar

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16. Abstract

The study reported investigates the likelihood of interference by FDM/FM transmissions from geostationary satellites operating in the frequency range 3500-3700 MHz upon proposed FAA limited-surveillance radars operating in the same band. It is concluded, based upon the analysis, that the FAA limited-surveillance radars and the geostationary satellites can function in a common band, 3500-3700 MHz with only slight degradation to the radar coverage.

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FEDERAL AVIATION ADMINISTRATION
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SPECTRUM MANAGEMENT STAFF

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This objective is achieved through the following services:

Planning and defending the acquisition and retention of sufficient radio frequency spectrum to support the aeronautical interests of the nation, at home and abroad, and spectrum standardization for the world's aviation community.

Providing research, analysis, engineering, and evaluation in the development of spectrum related policy, planning, standards, criteria, measurement equipment, and measurement techniques.

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Providing spectrum management consultation, assistance, and guidance to all aviation interests, users, and providers of equipment and services, both national and international.

ENGLISH/METRIC CONVERSION FACTORS

LENGTH

To From	cm	m	km	in	ft	mi	nmi
cm	1	0.01	1x10^{-5}	0.3937	0.0328	6.21x10^{-6}	5.39x10^{-6}
m	100	1	0.001	39.37	3.281	0.0006	0.0005
km	100,000	1000	1	39370	3281	0.6214	0.5395
in	2.540	0.0254	2.54x10^{-5}	1	0.0833	1.58x10^{-5}	1.37x10^{-5}
ft	30.48	0.3048	3.05x10^{-4}	12	1	1.89x10^{-4}	1.64x10^{-4}
mi	160,900	1609	1.609	63360	5280	1	0.8688
nmi	185,200	1852	1.852	72930	6076	1.151	1

AREA

To From	cm^2	m^2	km^2	in^2	ft^2	mi^2	nmi^2
cm^2	1	0.0001	1x10^{-10}	0.1550	0.0011	3.86x10^{-11}	5.11x10^{-11}
m^2	10,000	1	1x10^{-6}	1550	10.76	3.86x10^{-7}	5.11x10^{-7}
km^2	1x10^{10}	1x10^{6}	1	1.55x10^{9}	1.08x10^{7}	0.3861	0.2914
in^2	6.452	0.0006	6.45x10^{-10}	1	0.0069	2.49x10^{-10}	1.88x10^{-10}
ft^2	929.0	0.0929	9.29x10^{-8}	144	1	3.59x10^{-8}	2.71x10^{-8}
mi^2	2.59x10^{10}	2.59x10^{6}	2.590	4.01x10^{9}	2.79x10^{7}	1	0.7548
nmi^2	3.43x10^{10}	3.43x10^{6}	3.432	5.31x10^{9}	3.70x10^{7}	1.325	1

VOLUME

To From	cm^3	liter	m^3	in^3	ft^3	yd^3	fl. oz.	fl. pt.	fl. qt.	gal.
cm^3	1	0.001	1x10^{-6}	0.0610	3.53x10^{-5}	1.31x10^{-6}	0.0338	0.0021	0.0010	0.0002
liter	1000	1	0.001	61.02	0.0353	0.0013	33.81	2.113	1.057	0.2642
m^3	1x10^{6}	1000	1	61,000	35.31	1.308	33,800	2113	1057	264.2
in^3	16.39	0.0163	1.64x10^{-5}	1	0.0006	2.14x10^{-5}	0.5541	0.0346	2113	0.0043
ft^3	28,300	28.32	0.0283	1728	1	0.0370	957.5	59.84	0.0173	7.481
yd^3	765,000	764.5	0.7646	46700	27	1	25900	1616	807.9	202.0
fl. oz.	29.57	0.2957	2.96x10^{-5}	1.805	0.0010	3.87x10^{-5}	1	0.0625	0.0312	0.0078
fl. pt.	473.2	0.4732	0.0005	28.88	0.0167	0.0006	16	1	0.5000	0.1250
fl. qt.	948.4	0.9463	0.0009	57.75	0.0334	0.0012	32	2	1	0.2500
gal.	3785	3.785	0.0038	231.0	0.1337	0.0050	128	8	4	1

MASS

To From	g	kg	oz	lb	ton
g	1	0.001	0.0353	0.0022	1.10x10^{-6}
kg	1000	1	35.27	2.205	0.0011
oz	28.35	0.0283	1	0.0625	3.12x10^{-5}
lb	453.6	0.4536	16	1	0.0005
ton	907,000	907.2	32,000	2000	1

TEMPERATURE

°C = 5/9 (°F - 32)

°F = 9/5 (°C) + 32

EFFECTS OF COMMON BAND (3500-3700 MHz) OPERATION OF GEOSTATIONARY SATELLITES AND THE FAA LIMITED-SURVEILLANCE RADAR

1.0 INTRODUCTION

The International Table of Frequency Allocations designates the 3500-3700 MHz radio frequency band for transmissions by Radiolocation devices and by the Fixed-Satellite Service (FSS). Although there has been little usage of this band for the latter purpose thus far, there is considerable interest on the part of the Intelsat member nations to expand operation to the 3500-3700 MHz band with the introduction of future Intelsat satellites.

In an agreement between the Federal Aviation Administration (FAA) and the National Telecommunications Information Administration, NTIA, the frequency band from 3500-3700 MHz has been reallocated to include Aeronautical Radionavigation as a coequal service with Radiolocation (NTIA Frequency Allocation Table footnote G110). This reallocation was made with the understanding that the FAA limited surveillance radar (LSR)* would be accommodated in the band.

In order to assure that interference effects produced by the FDM/FM transmissions from geostationary satellites** will not render the performance of the proposed limited surveillance radar unacceptable, the MIT Lincoln Laboratory has been tasked to perform the interference analysis reported herein. The results of this analysis will be used in support of the United States' position at the 1979 World Administrative Radio Conference (WARC) in regard to the feasibility of band sharing between systems in the Fixed-Satellite Service and those in the Radiolocation/Aeronautical Radionavigation Service in the 3500-3700 MHz band.

2.0 INTERFERENCE FROM SATELLITE DOWNLINKS TO THE LSR RADARS

The discussion and analysis which follows addresses the effect of geostationary satellite FDM/FM transmissions on the candidate LSR radar receiver/processor. A number of simplifying assumptions are first made as to the

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*A candidate design of the LSR radar was developed as part of a definition study sponsored by the FAA Systems Research and Development Service and is contained in Reference 1.

**The 1971 World Administrative Radio Conference (WARC) established limits on the maximum allowable power flux density (PFD) which satellites can radiate as measured at the earth's surface. In the frequency band 3400 to 7750 MHz, a PFD limit of -152 dBW/m^2/4 KHz (angle of arrival $<5^{\circ}$) has been established.

characteristics of the FDM/FM transmission spectra, and as to the choice of the LSR moving target detector (MTD) doppler processor. Analytic results are then provided for the case defined, and quantitative discussion furnished.

2.1 General

The LSR is a ground-based FAA surveillance radar to be installed at small airports. Surveillance will be required to ranges of 16 nmi (instrumented to 32 nmi) and to altitudes below 10,000 feet, for aircraft of at least 1.0 square meter cross-section which exhibit Swerling-I fading characteristics. Radar system parameters are discussed in paragraph 2.3. The radar is assumed to employ MTD-doppler filter processing, and adaptive linear, constant-false-alarm-rate (CFAR) thresholding in order to limit false alarms due to precipitation and/or noise interference. Although this technique does limit the number of false targets declared per antenna scan by increasing thresholds adaptively, it also reduces system sensitivity to aircraft targets in the same range/azimuth/doppler cell(s). It is the effect of increasing adaptive CFAR thresholds, caused by additive noise when scanning by a geostationary satellite that will be considered in this analysis.

It is also assumed that the satellite Power Flux Density (PFD) at the surface of the earth (LSR-site) will be equal to or less than -128 dBw/m^2/MHz (in one linear polarization) (see Reference 2), and that the effective aperture of the LSR radar antenna will be a maximum of 0.46 m^2 normally occurring at elevation angles between 1.5 degrees and 3.5 degrees.

2.2 Satellite FDM/FM Spectra, Analysis Assumptions

Under conditions of normal traffic loading each satellite transponder may retransmit a multiplexed baseband load of up to 960 4-KHz voice channels with a baseband bandwidth up to 12-3852 KHz. Under these varying load conditions, it is assumed that the allowable power flux density (PFD) at the earth's surface of -128 dBW/m^2/MHz is not exceeded and that the signal will appear to the LSR MTD-doppler processor as random noise. Under conditions of light channel loading ($\approx$24 voice channels) it is assumed that out-of-band noise (0-12 KHz, or greater than 108 KHz) is added to the baseband to sustain "adequate" carrier deviation in support of the PFD limit. In actual satellite operations, however, carrier energy dispersal to meet the PFD limit under conditions of light channel loading, is achieved by the addition of a low frequency, spreading waveform in the transmission from the earth station to the satellite.

The candidate LSR processor will process 32 coherent samples for each range gate (1/8 nmi, 1.544 μsec) while operating at an average pulse repetition frequency of 2500 Hz. In order for the satellite signal to appear as random noise to this processor, the signal must exhibit random phase from sample-to-sample (approximately 400 μsec) over the 32-pulse coherent processing interval (CPI). Under the conditions stated above this is normally the case, and for the purpose of the analysis the signal is assumed to appear as random noise to the LSR processor.

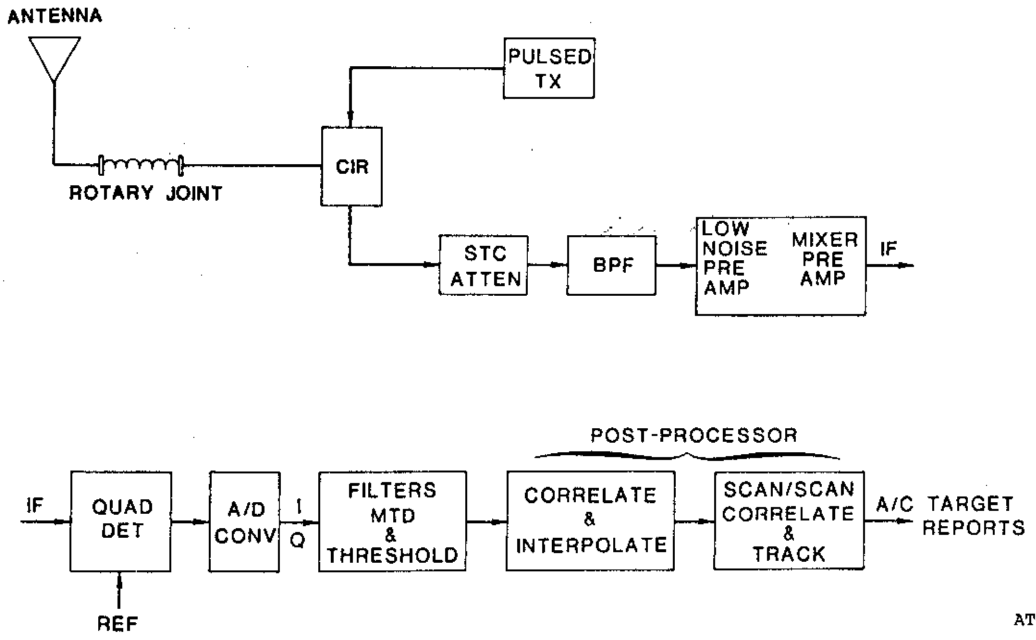
2.3 Analysis

1) LSR Radar System

The LSR radar system as described in Reference 1 may be represented by the block diagram shown in Figure 2.3.1 for purposes of identifying sensor reference ports and loss elements. The parameters of the LSR radar system are listed in Table 2.3-1, and the parameters of the processor are listed in Table 2.3-2. Operation of the MTD-doppler processor is shown graphically in Figure 2.3.2. As is shown in this figure 256 range gates are processed during each CPI (32 pulses), producing outputs for 32 orthogonal filters. Each filter output is compared against a linear CFAR threshold which is computed by summing the magnitudes of 16 gates bracketing the cell of interest (subtracting the value for the cell of interest and one on each side), dividing by 13, and multiplying by 4.875 (for a $P_{F.A.} = 10^{-5}$/cell). Range/doppler/CPI cell magnitudes that exceed the CFAR threshold are declared primitive target reports, and passed on for post-detection processing. The purpose of the MTD post-processor is to filter out noise, clutter, interference and "angel" false alarms, and to output target reports for moving A/C. Experience with experimental Terminal-ASR-MTD systems indicates that approximately 40 noise false alarms per scan can be managed without outputting false A/C target reports, and the needed probability of detection (P_d) for A/C targets must be equal-to-or-greater than 0.75, to insure track acquisition and maintenance. System losses are listed in Table 2.3-3, and are typical of S-band radar systems. The losses are broken into four types as they affect the radar equation computations.

Abbreviations:

A/D CONV	Analog-to-digital Converter
BPF	Bandpass filter
QUAD DET	Quadrature Detector
STC	Sensitivity Time Control
TX	Transmitter
I-Q	In-phase and Quadrature Phase Channel
CIR	Circulator



ATC-92(2.3-1)

Fig. 2.3-1. Functional block diagram LSR radar/processor.

TABLE 2.3-1

Azimuth Beamwidth	3.4°
Pulsewidth	2.0 μs
PRF (average)	2500
Instrumented Range	32 nmi
Antenna Scan Rate	4 sec/15 RPM
Wavelength (λ)	0.0833 m
Transmitter Peak Power (P_t)	100 KW
Antenna Gain (G)	29.2 dB
Receiver Bandwidth (B)	0.56 MHz
Noise Figure (NF)	5.0 dB

TABLE 2.3-2

Coherently Processed Intervals (CPI) per 2-way Beamwidth	2.0
Coherently Processed Points or Doppler Filters (I)	32
CPI's per scan	312
Range Gates	256 (1/8 mi)
Range Azimuth Cells	79872
Range Azimuth Doppler Cells	2.56×10^6
False Alarms per Scan	40
False Alarms per Cell (P_{FA})	1.56×10^{-5}
Probability of Detection (P_D)	0.75

The maximum allowable number of false alarms per scan and the minimum needed probability of detection (P_D) are known from experience with operational trackers and represent conservative values.

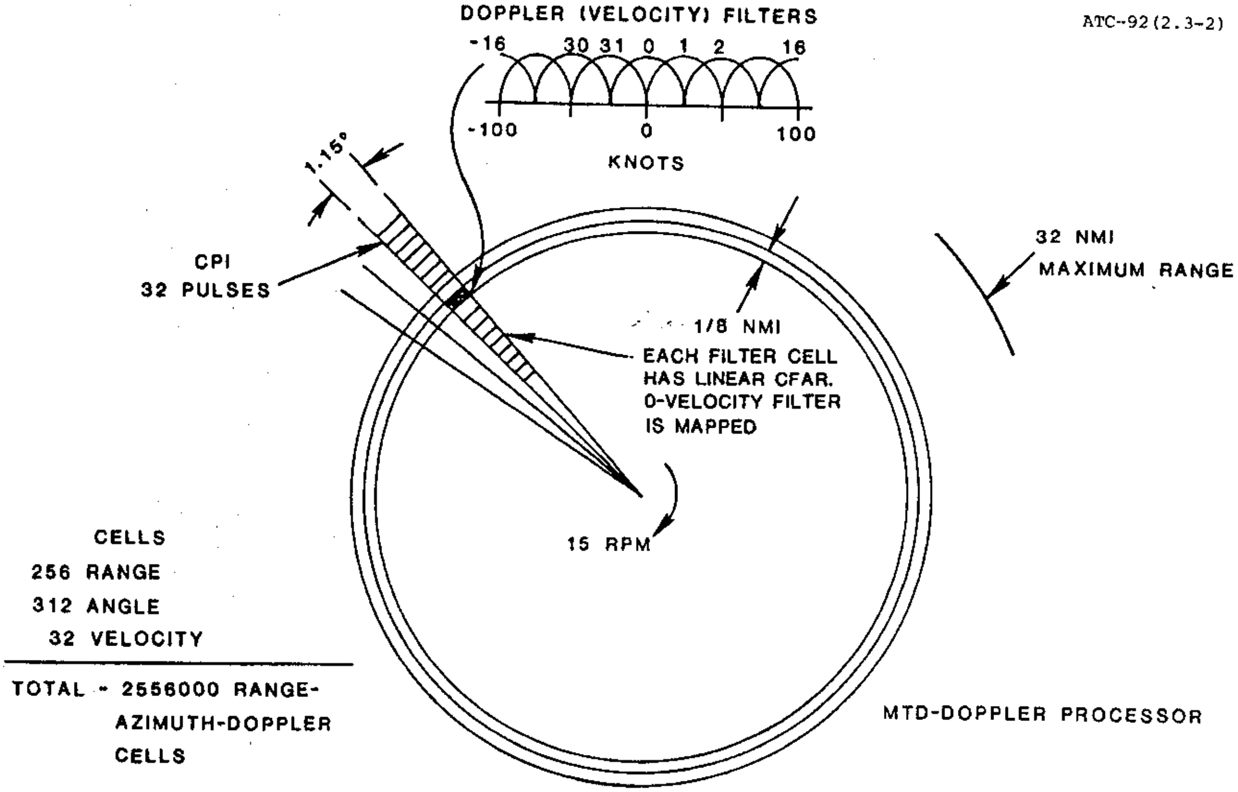


Fig. 2.3-2. Range, doppler azimuth resolution of MTD processor.

TABLE 2.3-3

Processor Losses (L_P)

Pulse Waveform Mismatch	0.5 dB
Range Gate Straddle	0.8
Doppler Weighting	0.9
Doppler Straddle	1.0
Mean Level Thresholding	1.8
	L_P = 5.0 dB

Radar Losses (L_R)

Atmospheric (2-way)	0.5 dB
Circular (2-way)	1.0
Limiter-STC	0.7
Rotary Joint (2-way)	0.4
Waveguide (2-way) 50 ft.	1.0
Azimuth Straddle (2-way)	1.0
	L_R = 4.6 dB

Satellite Losses (L_S)

Circulator	0.5 dB
Limiter-STC	0.7
Rotary Joint	0.2
Waveguide	0.5
Azimuth Straddle	0.5
	L_S = 2.4 dB

Front End Temperature Losses (L_T)

Circulator	0.5 dB
Limiter-STC	0.7
Rotary Joint	0.2
Waveguide	0.5
	L_T = 1.9 dB

2) Computations

a. Antenna Effective Area (A_e)

The effective area of an antenna is given by:

$$A_e = \frac{G\lambda^2}{4\pi} \tag{1}$$

$$A_e = \frac{10^{2.92} \; .0833^2}{4\pi} = 0.459 \text{ m}^2 \tag{2}$$

b. Receiver Effective Temperature (T_R)

The effective noise temperature of an RF amplifier connected to an antenna using a transmission line having a loss L_T is given by:

$$T_R = \frac{T_A}{L_T} + T_L \left(\frac{L_T - 1}{L_T}\right) + 290(NF-1) \tag{3}$$

where T_L is the temperature of the lossy line, and T_A is the noise temperature of the antenna. Since the antenna mostly looks at sky rather than the ground $T_A \underset{-}{\sim} 100^\circ K$. Then:

$$T_R = \frac{100}{10^{.19}} + 290\left(\frac{10^{.19}-1}{10^{.19}}\right) + 290(10^{.5}-1)$$

$$T_R = 795^\circ \text{ Kelvin}$$

c. Received Signal Power vs Range for a one square meter target (σ) referenced to the input of the receiver front end.

$$P_R = \frac{G^2 \lambda^2 P_t \sigma}{(4\pi)^3 R^4 L_R}$$

$$P_R = \frac{10^{2x2.92} \times .0833^2 \times 10^5 \times 1}{(4\pi)^3 \; R^4 \; 10^{.46}}$$

$$= 8.39 \times 10^4 R^{-4} \text{ watts}$$

when R is in meters, or

$$= 7.14 \times 10^{-9} R^{-4} \text{ watts}$$

when R is in nautical miles

P_R is plotted in Figure 2.3-3.

d. Detection Threshold

There are approximately two CPI's per beamwidth. Consequently it is necessary to determine what signal-to-noise ratio $(S/N)_{out}$ is required out of the doppler filter for a 0.75 probability of threshold crossing from either or both CPI's to be declared. The signal-to-noise required is a function of the probability of detection (P_D), the probability of false alarm (PFA) and the correlation of the two target returns. If the radar operates at a constant frequency the cross-section of an aircraft may barely change from one CPI to the next, and the two returns would then have a correlation near unity. However, the scan-to-scan amplitude distribution will be Rayleigh. This is the Swerling I case and has been numerically calculated for several correlation values.[3] A close approximation for the unity correlation case in the area of interest is

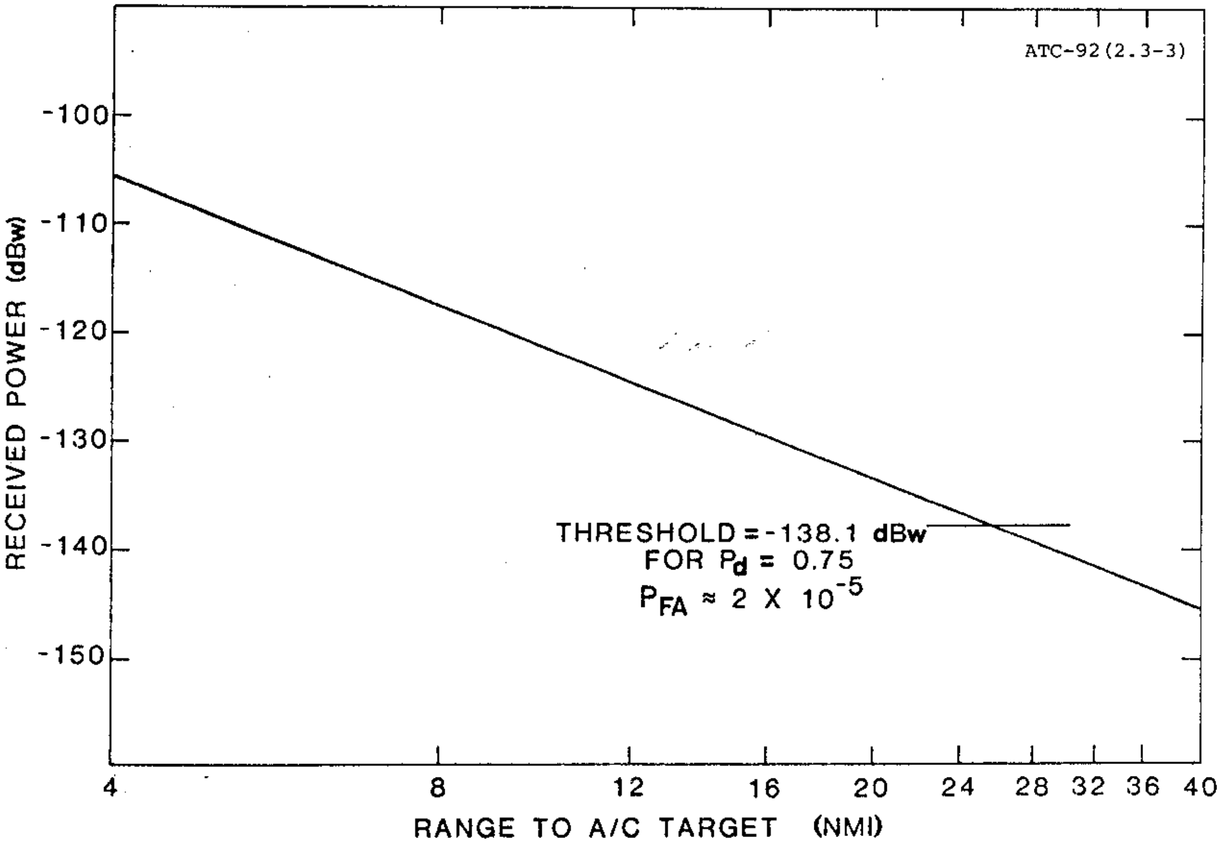


Fig. 2.3-3. Radar signal from A 0 dBsm ($1M^2$) target referred to front-end.

$$(S/N)_{out} \simeq .7\left(\frac{\ln P_{FA}}{\ln P_D} - 1\right)$$

$$(S/N)_{out} = .7\left(\frac{\ln 1.56\times10^{-5}}{\ln .75} - 1\right) = 26.2 \text{ (14.2 dB)}$$

The detection threshold power referred to the receiver front end is therefore

$$P_{Th} = (S/N)_{out} KT_R BL_P/I$$

where K is Boltzmann's constant.

$$P_{Th} = 26.2 \times 1.38 \times 10^{-23} \times 795 \times 5.6 \times 10^{5} \times 10^{.5}/32$$

$$= 1.59 \times 10^{-14} \text{ watts (-138.0 dBW)}$$

The detection threshold (P_{Th}) is indicated in Figure 2.3-3.

e. Satellite PFD to set LSR detection threshold at 0.75 for a 1 m^2 target.

The total equivalent noise temperature (T) at the front end input is the sum of the effective temperature (T_R) and of the equivalent satellite temperature (T_S).

$$T = T_R + T_S = T_R + \frac{P_{FD}A_e}{KL_S}$$

However, at threshold, the total noise temperature is given by the radar equation

$$T = \frac{\sigma G^2 \lambda^2 IP_t}{(4\pi)^3 R^4 KB(S/N)_{out} L_P L_R}$$

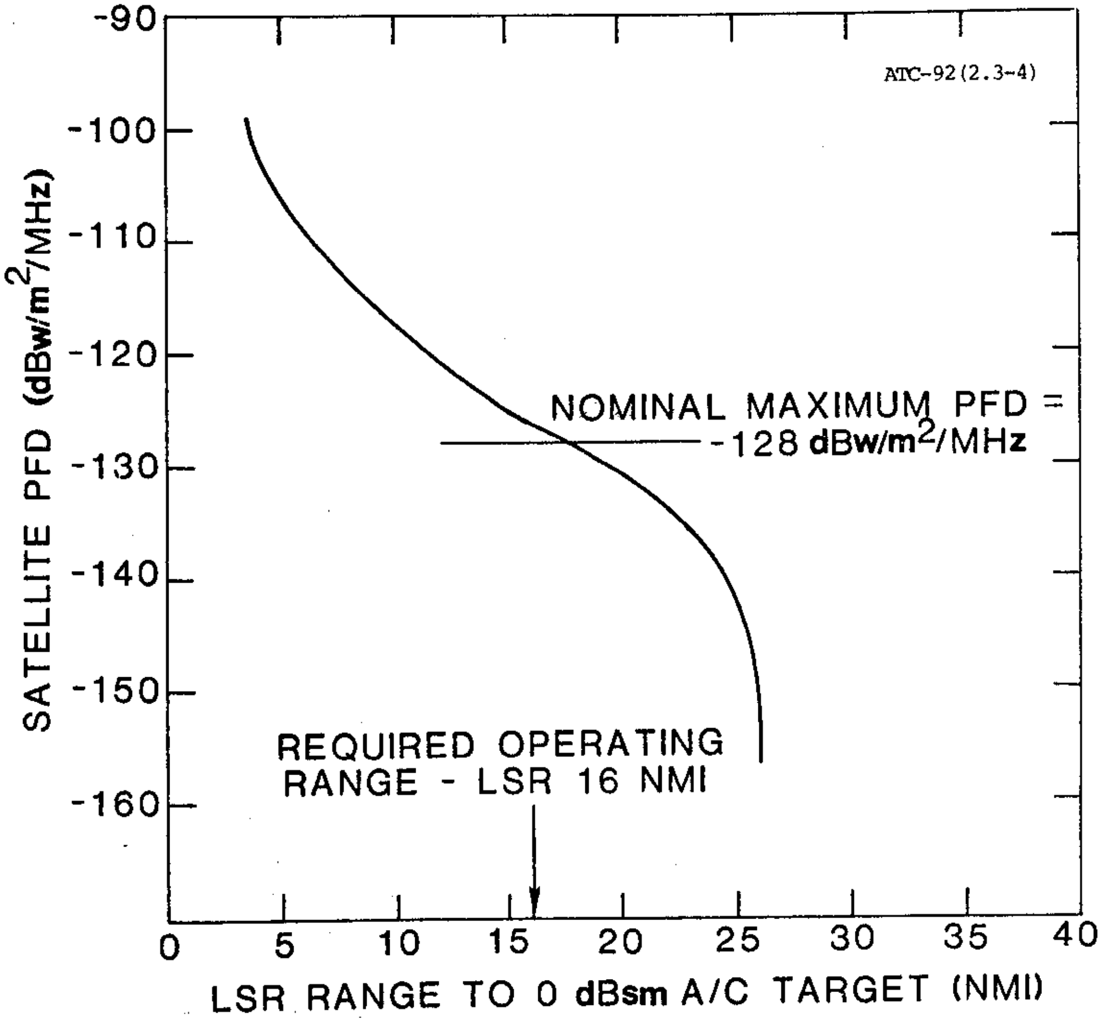


Fig. 2.3-4. Satellite PFD to set LSR detection threshold at .75 for A 1 m^2 target.

Solving for the PFD:

$$\mathrm{PFD} = \frac{L_S}{A_e}\left(\frac{\sigma G^2 \lambda^2 I P_t}{(4\pi)^3 R^4 B (S/N)_{out} L_P L_R} - KT_R\right)$$

This is the PFD needed to keep the radar at threshold.

$$\mathrm{PFD} = \frac{10^{.24}}{.459}\left(\frac{1 \times 10^{2\times 2.92} \times .0833^2 \times 32 \times 10^5}{(4\pi)^3 R^4 \times 5.6 \times 10^5 \times 26.2 \times 10^{.5} \times 10^{.46}} - 1.38\times 10^{-23} \times 795\right)$$

$$= 0.219\ R^{-4} - 4.15 \times 10^{-20} \text{ watts/m}^2\text{/Hz}$$

where R is in meters.

$$= 1.87 \times 10^{-8} R^{-4} - 4.15 \times 10^{-14} \text{ watts/m}^2\text{/MHz}$$

where R is in nautical miles.

This equation is plotted in Figure 2.3-4.

f. Satellite PFD to Raise Threshold by 3 dB.

The satellite power level at the front end is set equal to the front end noise power, or

$$\overline{\mathrm{PFD}}\ A_e B/L_S = kT_R B$$

Therefore,

$$\mathrm{PFD} = \frac{kT_R L_S}{A_e}$$

$$\text{PFD} = \frac{1.38 \times 10^{23} \times 795 \times 10^{.24}}{.459}$$

$$= 4.15 \times 10^{-20} \text{ watt/m}^2\text{/Hz}$$

$$= 4.15 \times 10^{-14} \text{ watt/m}^2\text{/MHz}$$

$$= -133.8 \text{ dBW/m}^2\text{/MHz}$$

g. Satellite PFD to Create False Alarms

The MTD processor is designed to reject rain and ground clutter through the use of adaptive thresholds. These adaptive algorithms will efficiently prevent the occurrence of false alarms from uncorrelated noise such as from the satellite. The only effect the interference will have is to reduce the sensitivity of the radar.

3.0 CONCLUSION

The analysis of the LSR performance when being interferred with by a geostationary satellite emitting FDM/FM signals has been derived from basic radar equations and presented above as a set of parametric curves. The analysis has been based on the following assumptions:

Satellite carrier is deviated sufficiently to appear as random noise to the radar.

The radar main-beam peak points at the satellite each scan.

No frequency separation exists to isolate satellite downlink and radar.

Only one satellite interferes in this band at any given azimuth.

The aircraft targets are in the main elevation beam of the radar at the satellite azimuth.

A specific candidate radar processor is used.

A conservative level of P_d (0.75) at the interference threshold.

Although these assumptions were made in the interests of bounding the task of analyzing the interference problem, they represent conditions likely to be experienced if these systems share the same frequency band. Of course, not all CONUS radars will "see" a satellite in the peak of their elevation patterns. For those cases where the radar does observe a satellite, alternate frequency allocation may be possible. Also, the region of surveillance coverage involved is statistically small, typically being approximately 3 CPI's of a total of 312 and approximately 32 range gates of a total of 256 (≈0.1%). Further, aircraft targets whose flight paths enter this region while they are in-track will be retained, and only those targets not in-track will be affected as they are acquired.

It is concluded on the basis of the above analysis and assumptions that the LSR MTD radars* and Intelsat geostationary satellites can function in a common frequency band, 3500-3700 MHz, with only slight degradation to the LSR surveillance coverage. It is important to note, however, that the LSR is instrumented for coverage to 32 nmi although the operational requirement is to a range of only 16 nmi for a 0.75 probability of detection of a 1.0 square meter aircraft target.

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*A somewhat simpler LSR-MTD processor may actually be used for this FAA surveillance service, possibly one which uses a 16-pulse CPI as opposed to the 32-pulse system analyzed. This will increase the LSR sensitivity to noise interference slightly (≈1.5 dB), but there still appears to be adequate margin, even if authorized satellite PFD levels are used.

REFERENCES

1. "Short-Range Terminal Radar (SRTR) Definition Study," FAA Report No. FAA RD-78-64 dated September 1978.

2. Interagency Agreement No. DOT-FATQWAI-679, Modification No. 14, page 2.

3. D. H. Pruslin, "Second Order Detection Statistics for Fluctuating Targets," Technical Note 1976-1, Lincoln Laboratory, M.I.T. (30 January 1976), DDC AD-B009986-L.