X-523-68-470
PREPRINT

NASA TM X- 63541

INTERFERENCE SUSCEPTIBILITY OF SATELLITE 136 MHz TELEMETRY LINK

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NOVEMBER 1968

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-523-68-470

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Contract No. NAS5-9243

November 1968

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ABSTRACT

Radio frequency interference (RFI) susceptibility measurements have been made on a satellite 136 MHz telemetry radio link utilizing a pulse coded, split phase type (PCM/PM) modulation. Both co-channel and adjacent-channel types of interference have been simulated, representing RFI from other satellites and VHF voice amplitude modulated (AM) interference from aircraft, both being typical of that experienced by the NASA space tracking and data acquisition network (STADAN). Signal-to-interference (S/I) receiving system thresholds have been established, and a VHF receiver preselector-type filter system has been developed to reduce RFI.

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INTRODUCTION

STADAN ground stations at times experience radio frequency interference (RFI), due to the appearance of two or more interfering satellites having overlapping 136 MHz emission spectrums, located simultaneously within view of a given ground station antenna. In order to determine the susceptibility characteristics of a 136-138 MHz band telemetry link, experiencing this type of RFI, various experimental susceptibility tests were performed on a simulated satellite-to-earth 136 MHz band telemetry data link representative of that utilized by the National Aeronautics and Space Administration's (NASA) Space Tracking and Data Acquisition Network (STADAN).

Both co-channel and adjacent-channel interference threshold levels have been established for a typical pulse code modulation/phase modulation (PCM/PM) 136 MHz telemetry link.

Interference threshold levels were determined by injecting both DESIRED and INTERFERENCE satellite signal levels into the radio frequency (RF) link. The DESIRED signal, or the one being tracked, was of PCM/PM split-phase format with a 5 kHz square-wave baseband modulation. This is equivalent to a PCM bit rate of 10 K bits/s alternately modulated with "0" and "1." The maximum phase deviation was maintained at about 1 radian to provide sufficient carrier power for phase lock.

The INTERFERENCE was first unmodulated (CW carrier); and later modulated with a PCM format similar, but not coherent with, the DESIRED signal. A pulse code frequency modulation (PFM) INTERFERENCE source was also tested. Test data was obtained for coincident DESIRED and INTERFERENCE carrier frequencies, and for these two carriers off-set in frequency by a known amount. These cases thus simulate a number of possible satellite interference situations in STADAN.

Spectrum analyzer graphs, showing power level vs frequency, were also obtained for both simulated and actual satellite signal sources. The off-band spurious emission levels were measured and compared with established Goddard standards.[1]

The STADAN Diversity Telemetry Receiving System was also tested to determine its susceptibility to adjacent-channel interference such as that caused by the VHF aircraft AM voice communication band from 118.00 MHz to 135.95 MHz. The bit error probability (BEP) of a PCM split-phase data signal has been measured as a function of simulated aircraft interference frequency, and the receiver input signal-to-interference (S/I) ratio. A VHF preselector-type filter system has been developed for the 136 MHz telemetry receiver to eliminate degrading effects of aircraft RFI, and to reduce effects of in-band satellite interference. Filter performance test results are also described.

TEST RESULTS

PCM/PM

The 136 MHz simulated RF link (Figure 1) utilized two Dynatronics type PCM simulators, one channel of a 2-channel General Dynamics/Electronics Diversity telemetry receiver, an Electrac Model 315 demodulator, and a PCM bit comparator. This type equipment is now utilized in the STADAN network.

The initial test run had an unmodulated CW INTERFERENCE source of power level, I, and a PCM DESIRED signal of unmodulated power level, S, initially set to -125 dbm (decibels below 1 milliwatt) that is just above receiver thermal noise threshold where the signal-to-noise ratio, SNR = +4 dB. The PCM bit error rate (BER) was read from a counter by an operator, and the corresponding bit error probability (BEP) plotted as a function of the signal-to-interference (S/I) ratio; with "I" as the independent variable (Figure 2). The INTERFERENCE carrier frequency, f_I, was superimposed, or coincident with the DESIRED satellite signal carrier frequency, f_S.

The Figure 2 data reveals negligible degradation in the BEP, above the 2.5×10^{-2} noisy threshold level (i.e,, where SNR = +4 dB), for a coincident CW interference source when $S/I \geq +20$ dB (i.e., desired signal 20 dB greater than interference). This means that a satellite CW beacon signal, on the same assigned carrier frequency, will not interfere with another satellite's PCM/PM telemetry signal if the received CW beacon level at the ground station is 20 dB, or more, below the RF level of the data channel.

The high 2.5×10^{-2} BEP threshold results from high system thermal noise existing near receiver threshold, being a worst-case condition. This measurement validates a previous assumption[2] that "an interference condition is defined as existing when the heuristic equality $S/I \leq +20$ dB holds." This value is currently employed in the computer-automated RFI prediction program for STADAN satellites.

The following two susceptibility tests were subsequently run where both the INTERFERENCE and DESIRED simulated satellite signal sources were PCM/PM types with the Electrac demodulator being phase-locked to the DESIRED signal carrier frequency. The Electrac post-detection filter bandwidth was 50 kHz and the receiver pre-detection bandwidth 100 kHz.

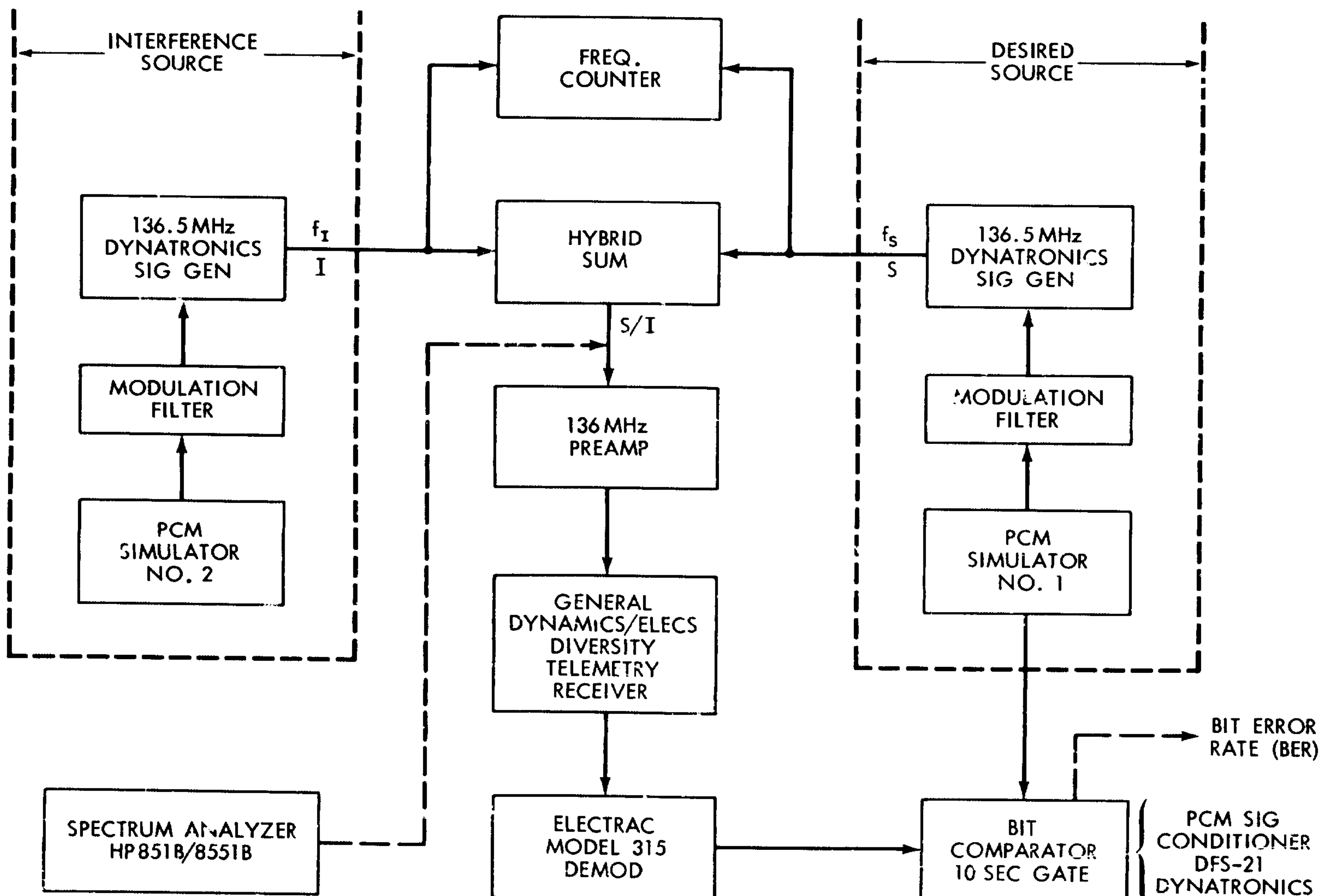


Figure 1. Block Diagram, Simulated Satellite 136 MHz Interference Test Hookup

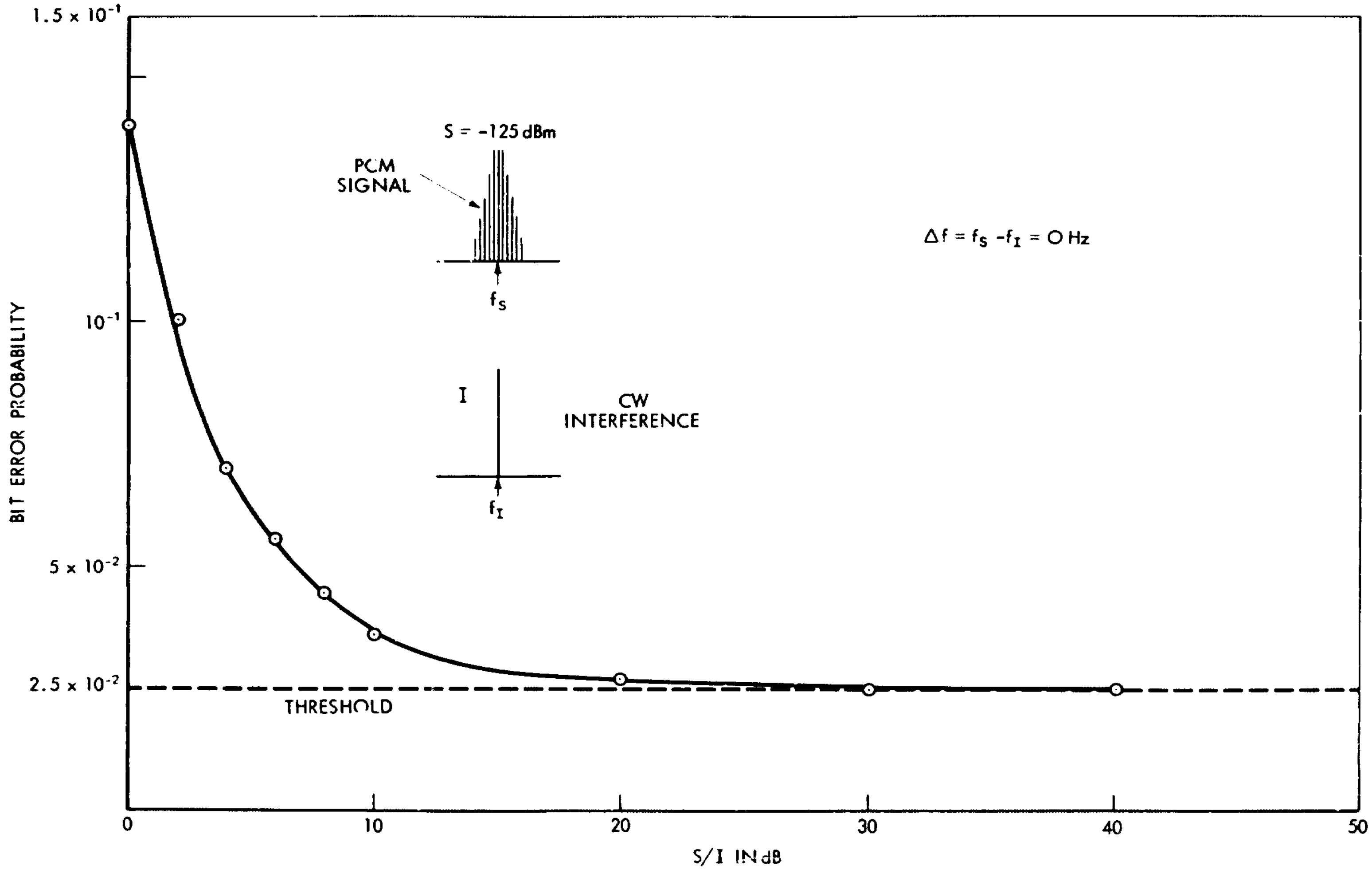


Figure 2. PCM/PM Bit Error Prob. vs S/I for CW Interference

Two sets of curves were obtained (Figures 3 and 4) wherein BEP was measured as a function of S/I ratio, and carrier frequency separation, Δf. The INTERFERENCE carrier frequency, f_I, and unmodulated reference power level, I, were the independent variables. BEP was measured for both noisy (Figure 3) and clean (Figure 4) values of the data signal power level, S, as a function of carrier frequency separation, Δf, and the signal-to-interference ratio, S/I. Similar results were obtained for both cases except the BEP threshold floor is lowered for the clean signal.

The data in Figures 3 and 4 reveals that almost negligible degradation occurs in BEP when the signal-to-interference ratio approaches S/I ≥ +20 dB, even for the worst case where Δf = 0. This is also true both WITHOUT (Figure 3) and WITH (Figure 4) pre-modulation filtering. Figures 3 and 4 also show that the most pronounced change in BEP occurs only for small values of Δf ≤ ±50 kHz,

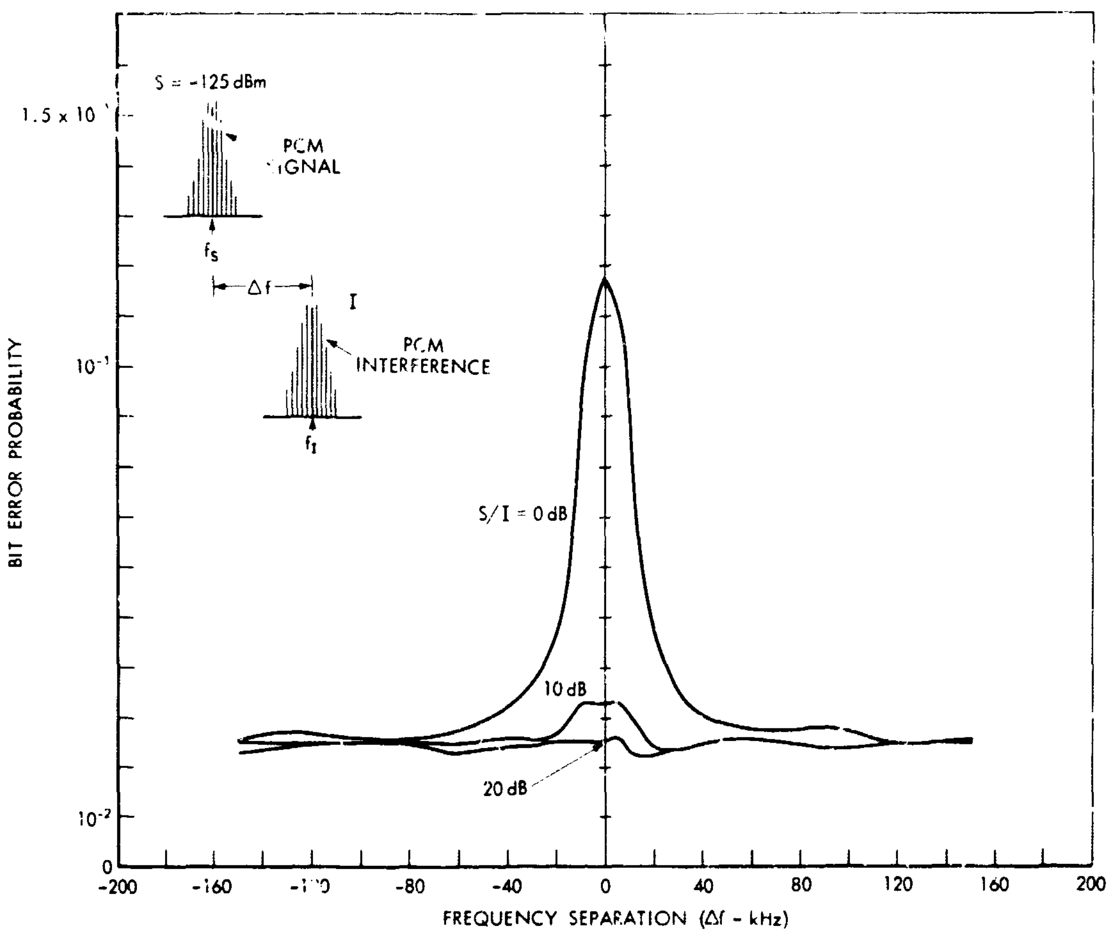


Figure 3. Bit Error Prob. vs Frequency Separation, Δf, <u>Without</u> Modulation Filtering

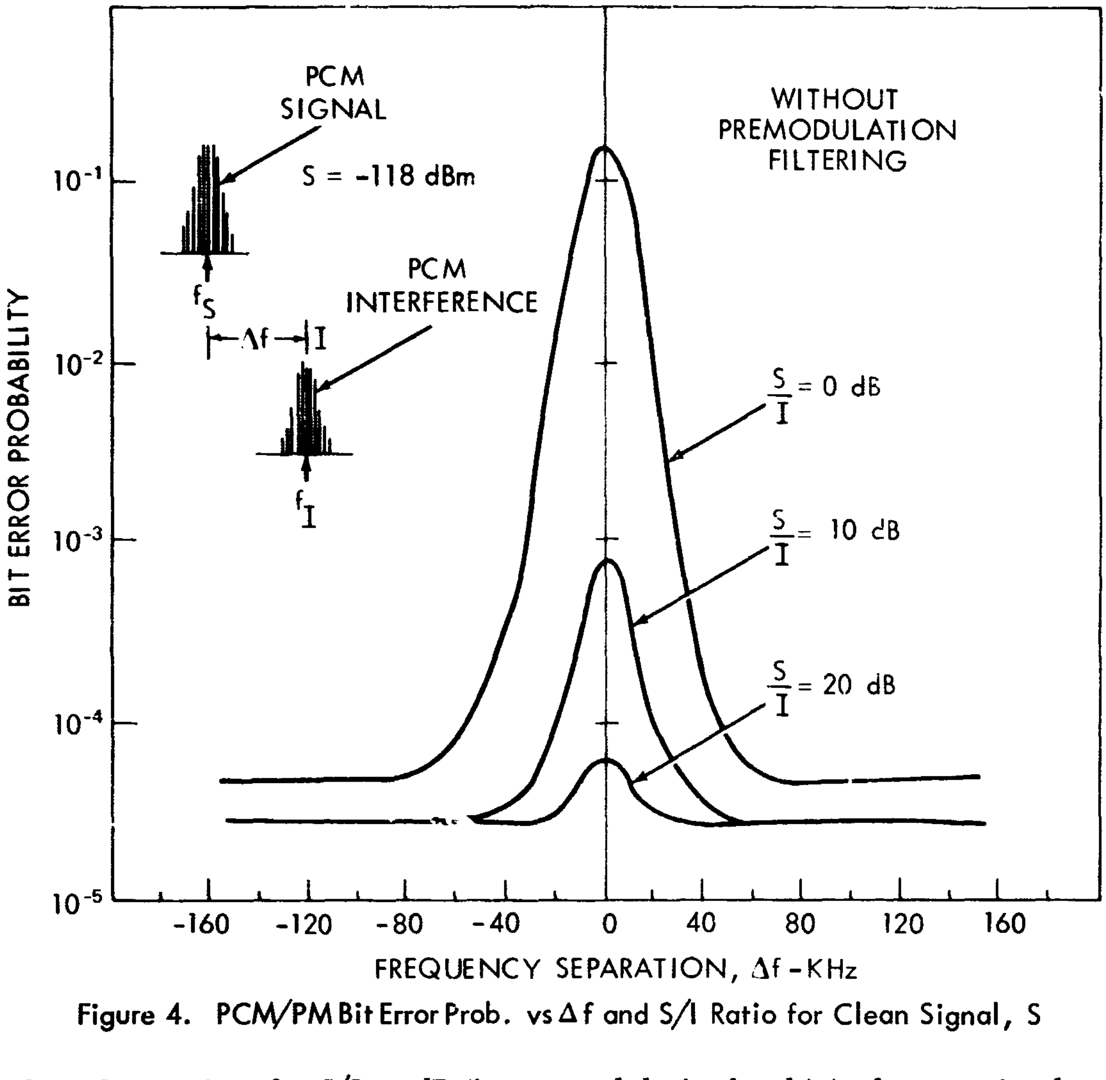


Figure 4. PCM/PM Bit Error Prob. vs Δf and S/I Ratio for Clean Signal, S

about the carrier, for S/I = 0 dB (i.e., equal desired and interference signal levels). It is thus seen that the criterion for low interference, S/I ≥ +20 dB, also applies to two PCM/PM signals as well to a PCM/PM data signal having an unmodulated INTERFERENCE source.

The spectral purity of the unmodulated CW carrier signal, provided by the Dynatronics signal source (Figure 1), is shown in the Figure 6(a) spectrum measured with a spectrum analyzer. The observed off-band spectral purity is about 10 dB below required Goddard standards[1] (e.g., spurious emission only 50 dB, instead of 60 dB down, from unmodulated carrier); however, the Dynatronics source was satisfactory for these interference tests since the spurs were too far from the carrier frequency to affect BEP (i.e., farther than 50 kHz above and below carrier).

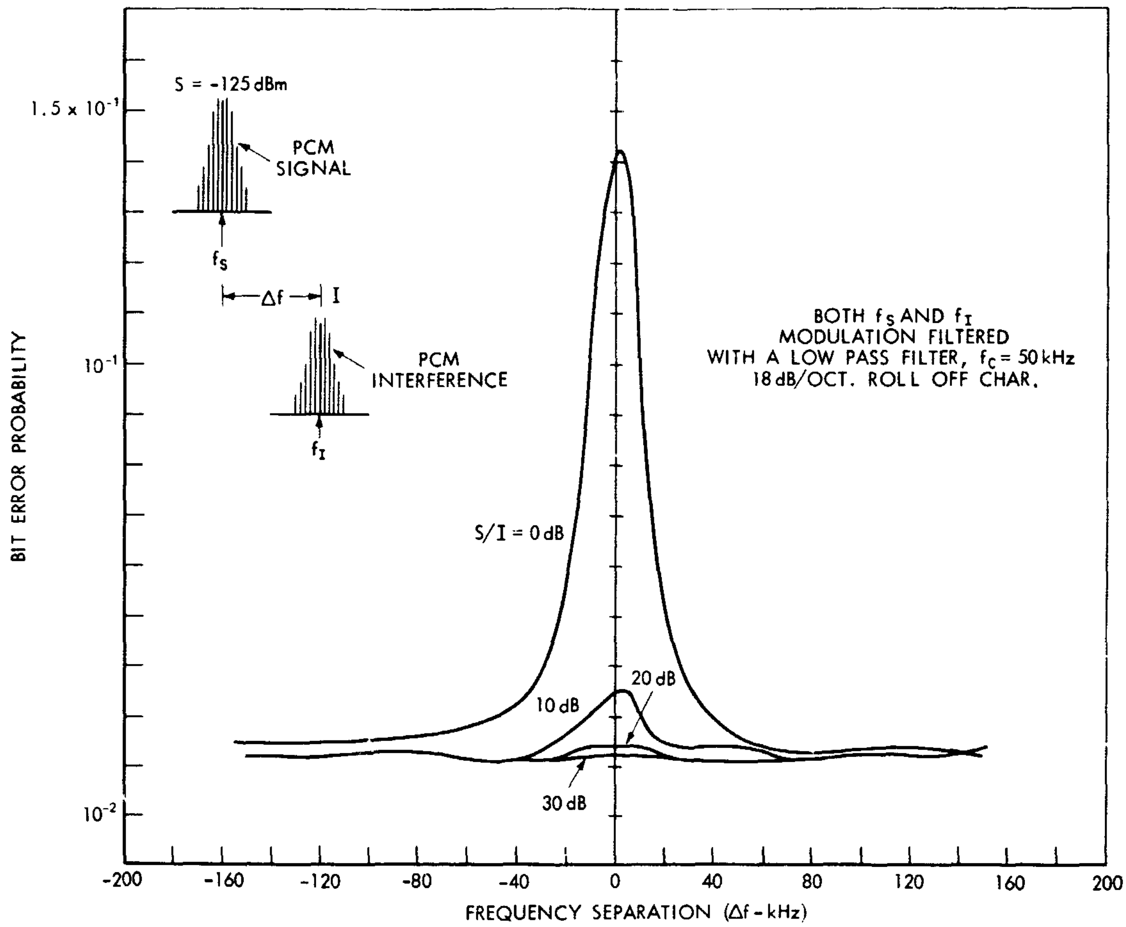
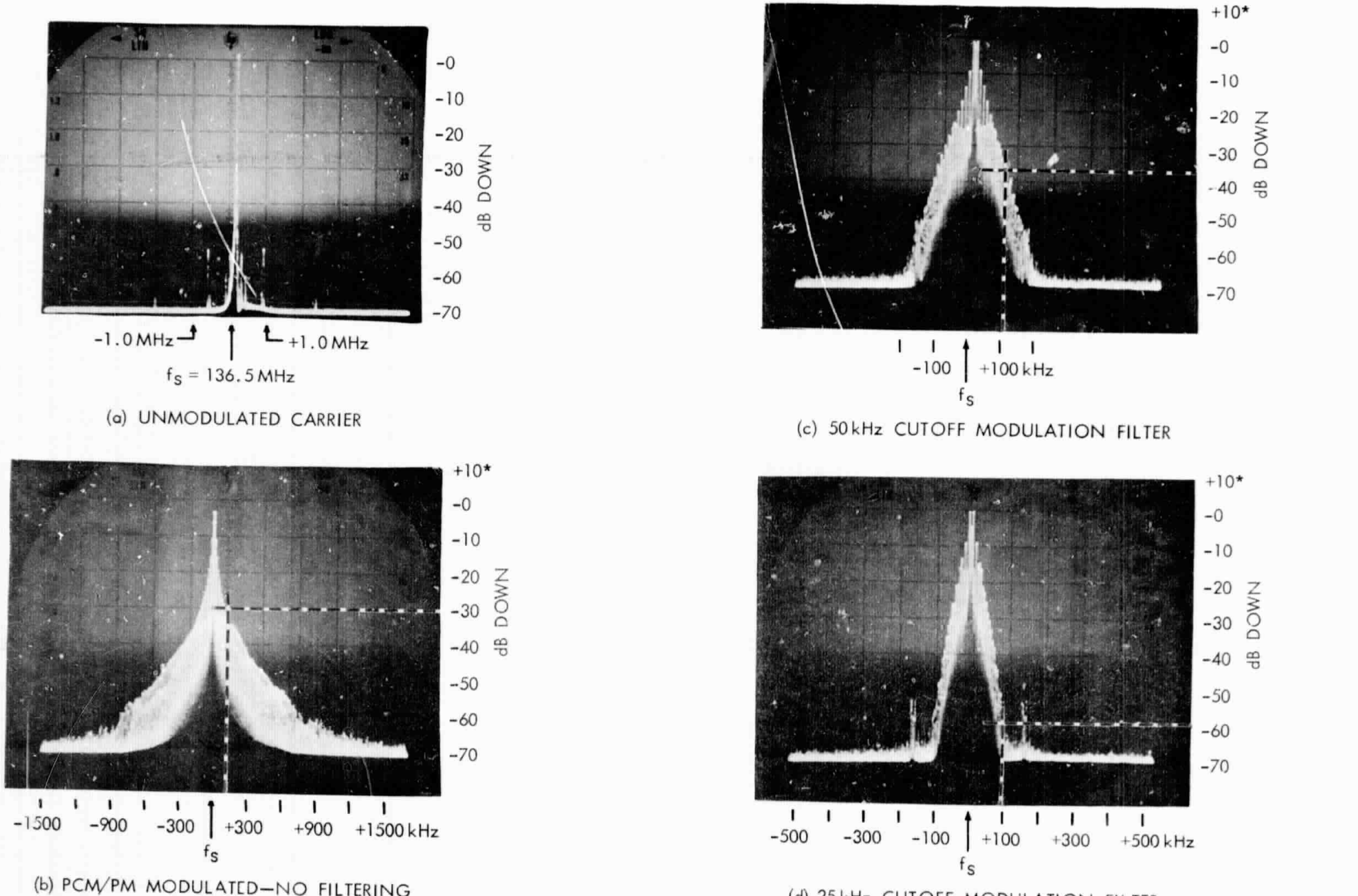


Figure 5. Bit Error Prob. vs Frequency Separation, Δf, With Modulation Filtering

Figures 6(c) and 6(d) also show how spacecraft pre-modulation filtering helps reduce off-band spurious emission compared to the unfiltered case in Figure 6(b). For example, a low-pass 50 kHz cut-off filter reduces the unfiltered spurious emission, at f_S ±100 kHz, from a value of -29 dB down to -35 dB for the filtered case. A narrower 25 kHz cut-off pre-modulation filter further reduces the spurious emission level, at f_S ±100 kHz, down to -60 dB which meets the Goddard standard.[1]

Additional spurious emission tests were performed wherein the off-band modulation level of the interference source was varied for a constant off-set frequency separation, Δf, between the DESIRED and INTERFERENCE carrier frequencies (Figure 7). This test simulates an interference condition wherein a PCM/PM INTERFERENCE signal carrier level is at a high-level and its off-band, adjacent-channel modulation level, I′, is of comparable level with the



(a) UNMODULATED CARRIER

(b) PCM/PM MODULATED—NO FILTERING

(c) 50 kHz CUTOFF MODULATION FILTER

(d) 25 kHz CUTOFF MODULATION FILTER

Figure 6. 136 MHz PCM/PM Signal RF Spectrum

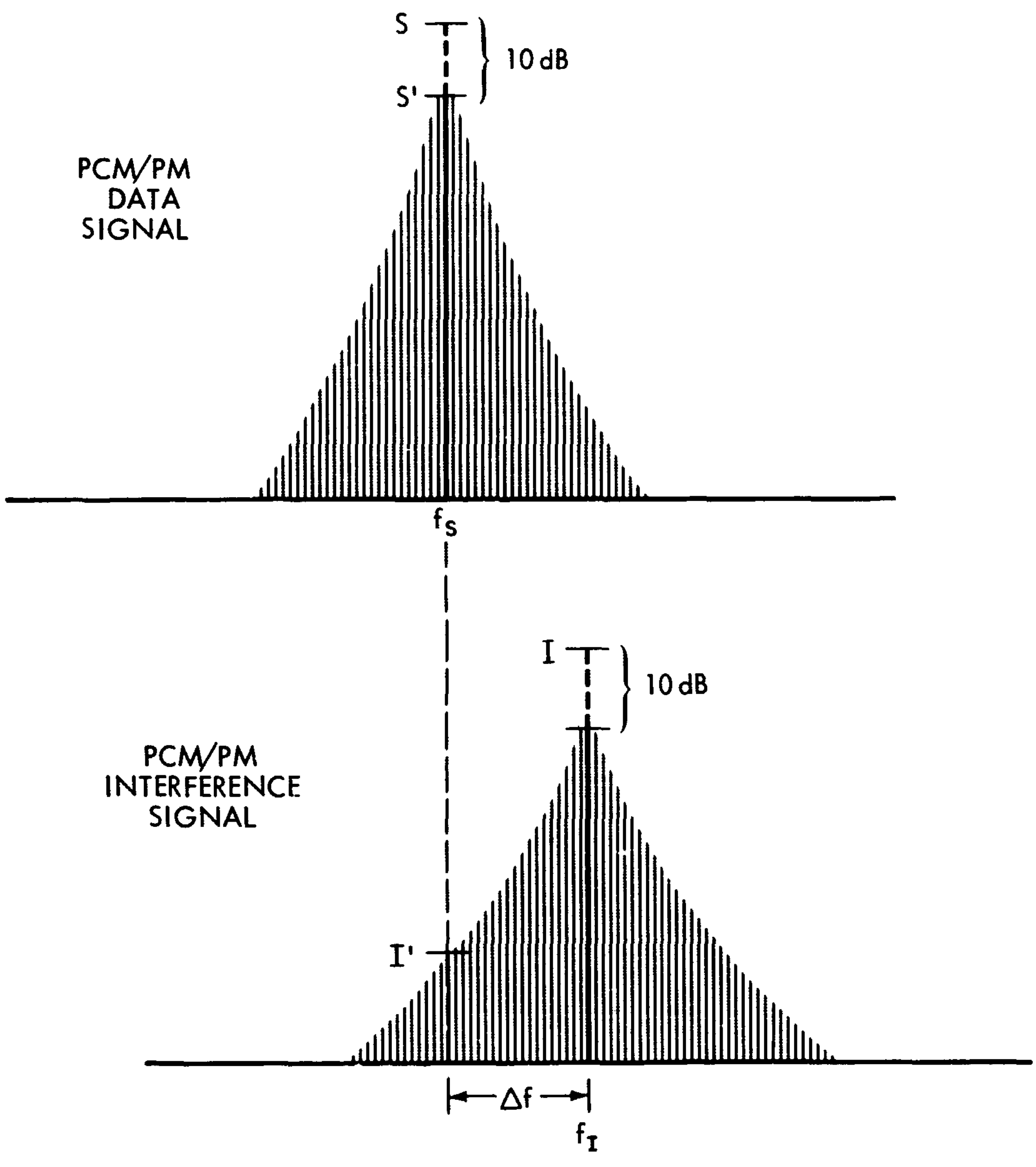


Figure 7. Spectrum Relationship for Spurious Emission Interference Tests

DESIRED data carrier level. For example, if $S' = -130$ dbm, and $I' = -124$ dbm, this condition obviously would cause RFI.

The DESIRED data signal carrier level was set to $S' = -130$ dbm, and the off-band interference level, I', was the independent variable. The ratio S'/I' is plotted as a function of PCM/PM bit error prob. (BEP) in Figure 8 for $\Delta f = 100$ kHz. S' is the reduced carrier level, depending on modulation index, and I' is the interference spurious level.

When the value of $S'/I' = 25\,dB$ is reached (Figure 8), the PCM/PM bit error prob. (BEP) begins degrading from the threshold level corresponding to an error probability of 2×10^{-4} at a SNR = +8.2 dB. The 25 dB value is in reasonable agreement with the data in Figures 2 - 5, inclusive, as well as the Figure 8 value of somewhat over 10^{-1} BEP for $S'/I' = 0\,dB$. The emission spectrums of the DESIRED and INTERFERENCE signals, for Figure 8, are represented by Figure 6(c).

Premodulation filtering in the spacecraft transmitter considerably reduces off-band emission, as illustrated in Figure 6, and is thus effective in reducing adjacent-channel satellite RFI. The BEP of the PCM data signal was obtained (Figure 9), as a function of premodulation filter bandwidth cutoff frequency, f_c, to determine how narrow f_c can be made without significantly increasing the BEP. Figure 9, curve (2), shows that the minimum is $f_c \cong 2.5\,BR$, where BR is the bit rate, corresponding to $f_c = 25$ kHz for BR = 10 K bits/s. A premodulation filter, with $f_c \cong 2.5$ BR, would be very effective in reducing off-band emission as illustrated by comparing Figures 6(b), for no filtering, with Figure 6(d) for $f_c = 25$ kHz. Curves (1), (2) and (3) in Figure 9, were made for a constant receiver IF bandwidth; curve (4) showing the BEP improvement over curve (1) by reducing the IF bandwidth to match the spacecraft premodulation filter bandwidth (i.e., $2f_c$ = IF bandwidth). The value of Δf = 30 kHz, in Figure 9, represents the assigned channel spacing for two spacecraft transmit spectrums[1], each 30 kHz wide.

Additional tests were also run wherein the interference source in Figure 1 was a pulsed frequency phase-modulated (PFM/PM source. These results were quite similar to those obtained for a PCM/PM interference source.

PFM/PM

Simulated satellite interference tests were also conducted for a PFM/PM data signal using continuous wave (CW) and PCM/PM interference sources. The test configuration was similar to that employed in Figure 1 except that the data error was obtained indirectly via the STARS F9 Processor Line (reference 3) instead of an operator reading the error directly as was done for the PCM/PM tests. A prerecorded magnetic tape was the modulating source used to simulate the IMP-F satellite data signal format.

Figure 10 shows that PFM/PM is less susceptible to CW interference, than PCM/PM (Figure 2), for a given S/I ratio. For PCM/PM, the BEP increases

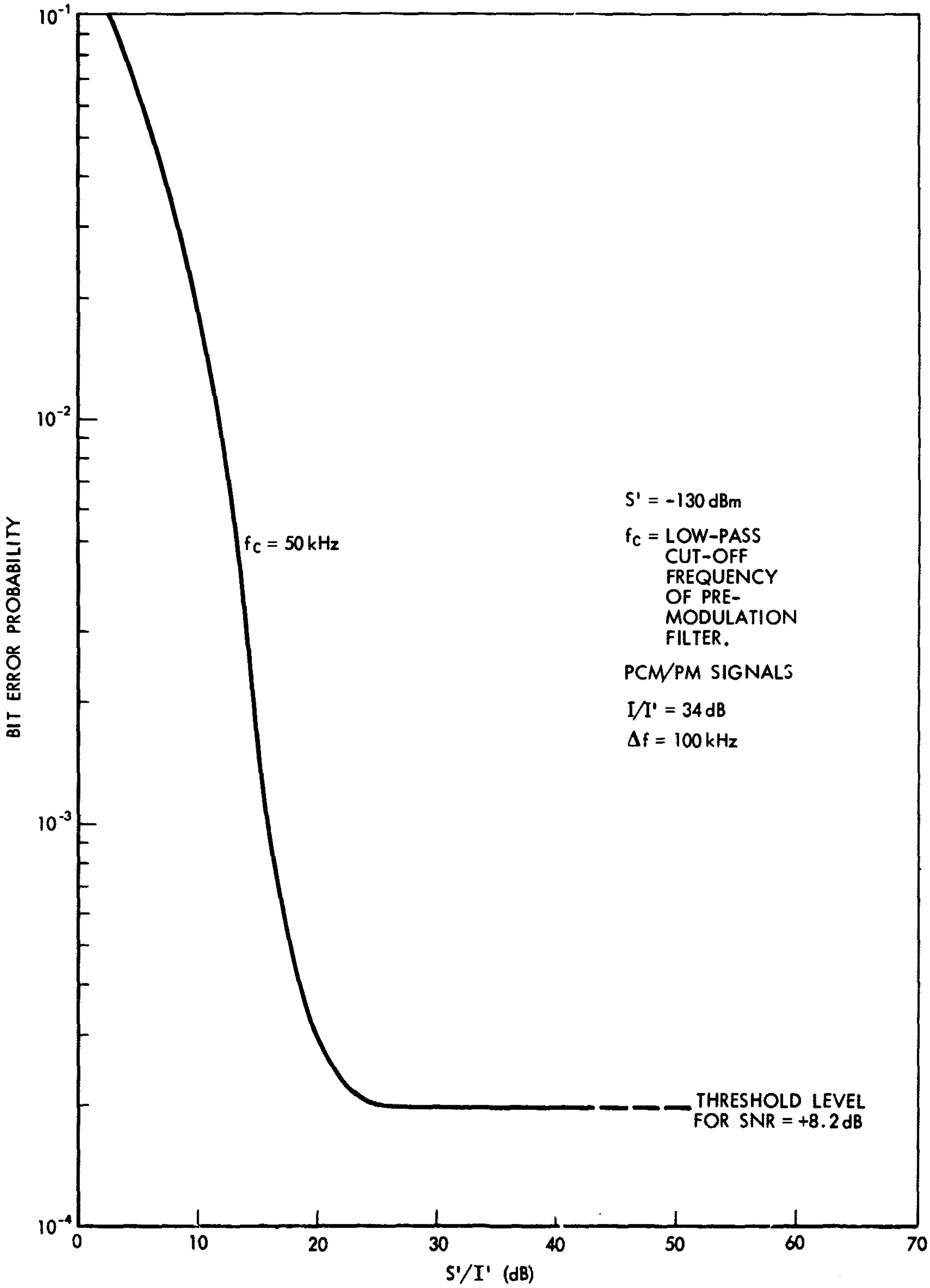


Figure 8. BEP vs S'/I', Spurious Emission Test

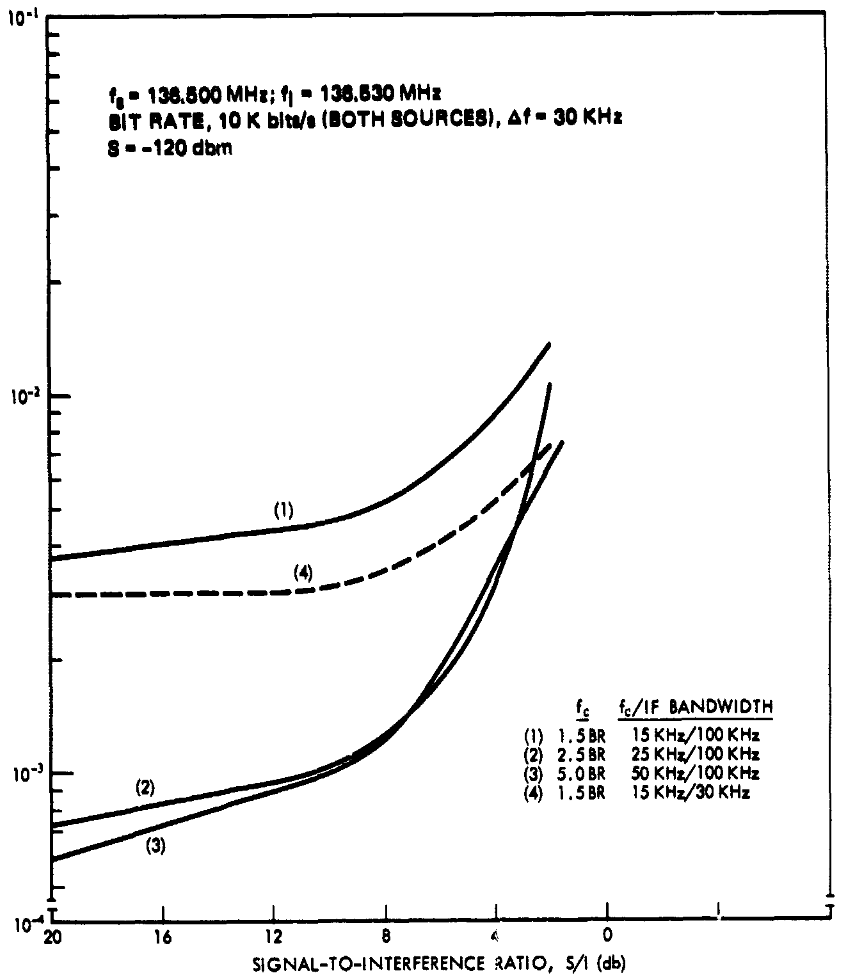


Figure 9. Effect of Spacecraft Premodulation Filter Bandwidth, f_c, Upon PCM Bit Error Probability

at S/I ≤ +20 dB, whereas, the data error starts to increase somewhat below S/I ≤ 0 dB for PFM/PM.

A similar measurement was made with PCM/PM interfering with PFM/PM; in general, the result was similar to that obtained for CW type interference. The PFM/PM interference results were not always repeatable for given conditions, since the data processing computer system threshold sensitivity varied a few decibels, from run-to-run, thereby modifying the effects of the interference.

Satellite Spectrum Signature Measurements

A spectrum signature of the NIMBUS-2 136.950 MHz, 5 watt level, channel was obtained by NTTF personnel during a pass on December 15, 1967 (see

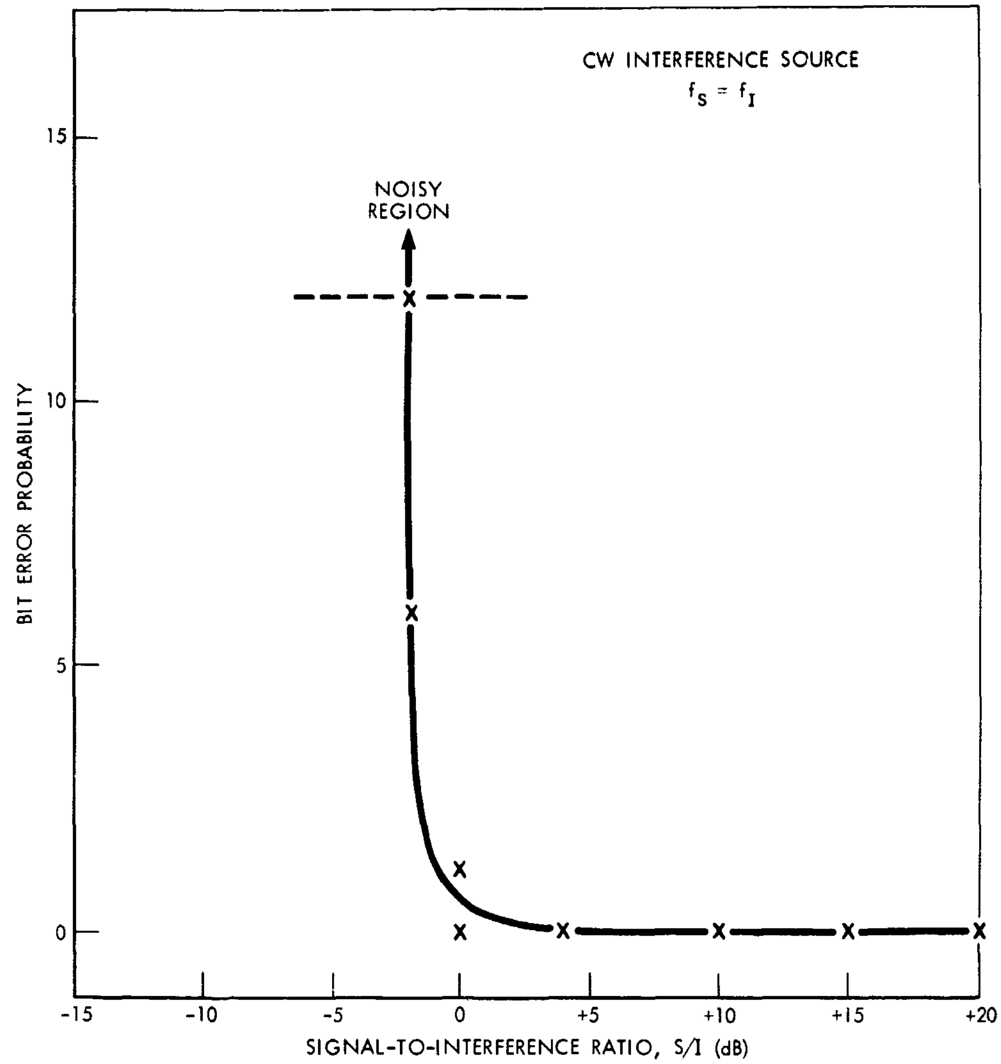


Figure 10. PFM/PM Data Error vs S/I Ratio

Figure 11). This photograph was obtained using a HP 851B spectrum analyzer connected at the 136 MHz preamplifier output from the 9-element yagi antenna.

Figure 11 shows that the N'.MBUS-2 136.950 MHz signal spectrum is contained within a bandwidth of approximately 60 kHz, at points 30 dB down from a value of -110 dBm, which is within Goddard standards.[1]

SIMULATED AIRCRAFT INTERFERENCE TESTS

The STADAN network experiences interference at various times from amplitude-modulated (AM) voice communication signals emitted from aircraft operating

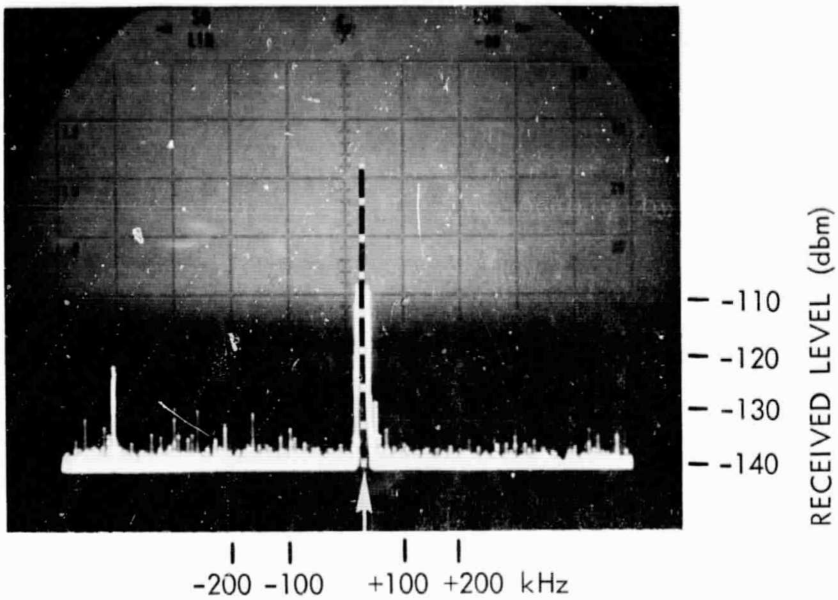


Figure 11. NIMBUS-2 136.950 MHz Channel RF Spectrum Received at NTTF

in the 118.00 MHz to 135.95 MHz VHF band. There are 360 channels, centered at 50 kHz intervals over this band, that are utilized by literally thousands of Federal Aviation Agency, military, and private plane mobile stations. The VHF aircraft channels, located closest to the lower 136.00 MHz bandedge, cause the most difficulty especially when receiving signals from satellites with center frequencies just above 136.00 MHz. Typical examples of reported aircraft interference are listed in Table I for the Rosman, N. C. and Winkfield, England STADAN stations.

The susceptibility of the STADAN Diversity Telemetry Receiver to VHF aircraft RFI has been determined by injecting (Figure 1) an interference power level, I. The Figure 12 BEP was obtained as a function of the interference center frequency, f_I, and the signal-to-interference power ratio, S/I. The telemetry data signal was PCM/PM, split-phase modulated, with a 10 kHz bit rate as was earlier used. The data channel center frequency was f_S = 136.020 MHz, being only 70 kHz higher than the closest aircraft channel centered at 135.950 MHz. The aircraft interference was simulated with a Hewlett Packard Model HP-608D signal generator, 80% AM modulated by a 1 kHz sinusoidal waveform.

Table I
Typical STADAN Station Interference Events Caused by Aircraft

STADAN Station	Date/Time	Satellite Being Tracked		Duration of Interference (Minutes)
		Designation	Telemetry Center Frequency (MHz)	
Rosman, N.C.	17 Nov. '66 (2336 Z)	AIMP-D (1966-58A)	136.020	5
Rosman, N.C.	16 Nov. '66 (2300 Z)	AIMP-D (1966-58A)	136.020	5
Rosman, N.C.	17 Oct. '66 (0525 Z)	NIMBUS-B (1966-40A)	136.500	1
Rosman, N.C.	12 Feb. '66 (0632 Z)	BE-B (1964-64A)	136.17	0.5
Rosman, N.C.	7 Nov. '65 (1945 Z)	OGO-2 (1965-81A)	136.20	1.8
Rosman, N.C.	3 Aug. '64 (2259 Z)	Telstar-2 (1963-13A)	136.05	Lost the Pass
Winkfield, England	15 Nov. '68 (1138 Z)	NIMBUS-2 (1966-401)	136.5	Lost the Pass

The PCM bit error prob. (BEP) increases when $I \geq I_t$, where I_t is the interference threshold value. A typical value is I_t = -112 dbm, for f_I = 135.950 MHz, corresponding to S/I = -10 dB (Figure 12). The aircraft channels below 135.950 MHz, down to 135.700 MHz, group together in the vicinity of $I_t \cong -90$ dbm, corresponding to S/I $\cong$ -32 dB. A preselector-type filter system, to be effective in reducing VHF aircraft RFI, must reduce the receiver input interference power level, I, down to a value $I \leq I_t$.

The Figure 12 data represents a worst-case condition near noise threshold. Other data taken for a cleaner carrier signal S, resulting in lower BEP floor threshold values, shows an increased interference threshold level, I_t, at any given frequency, f_I. The latter case thus requires less preselector filtering than the noisy case.

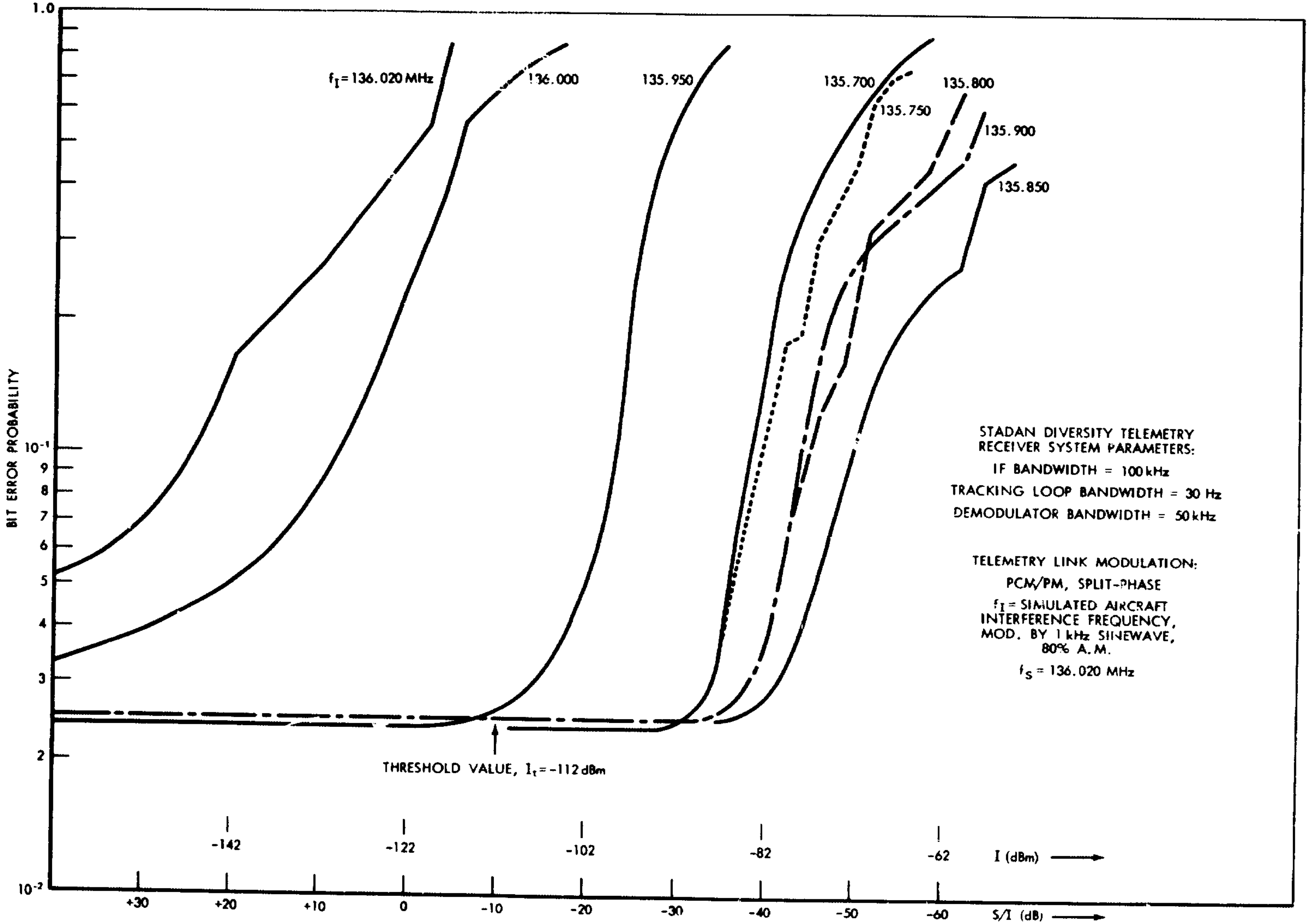


Figure 12. PCM/PM Telemetry Bit Error Prob. vs f_I and S/I

VHF AIRCRAFT INTERFERENCE FILTER MODEL

The VHF band from 118 MHz to 135.950 MHz is a world-wide aeronautical mobile service region, and consequently all STADAN stations are subjected to this type RFI, but some more than others. For example, stations such as Rosman, North Carolina, Fort Myers, Florida, and Winkfield, England (near London airport), that are located close to airports, experience aircraft RFI more frequently than other stations located farther away from airports.

A worst-case interference situation is visualized wherein an interfering aircraft is centered within the main beam of an 85 foot-diameter dish antenna at a distance of only 10 miles (see Figure 13). The aircraft's effective radiated power (ERP) level normally ranges from +10 dBw to +20 dBw (decibels above 1 watt). A maximum received interference power level of $I_{max} \cong$ -22 dbm can exit at the output terminals of an 85 foot dish antenna for an aircraft ERP = +20 dBw. The received -22 dbm interference level will assuredly cause RFI in a telemetry link, tuned near 136.00 MHz, where the received satellite signal level normally ranges from S = -90 dbm to -145 dbm. A preselector filter system is necessary to reduce aircraft interference down to a level $I \leq I_t$.

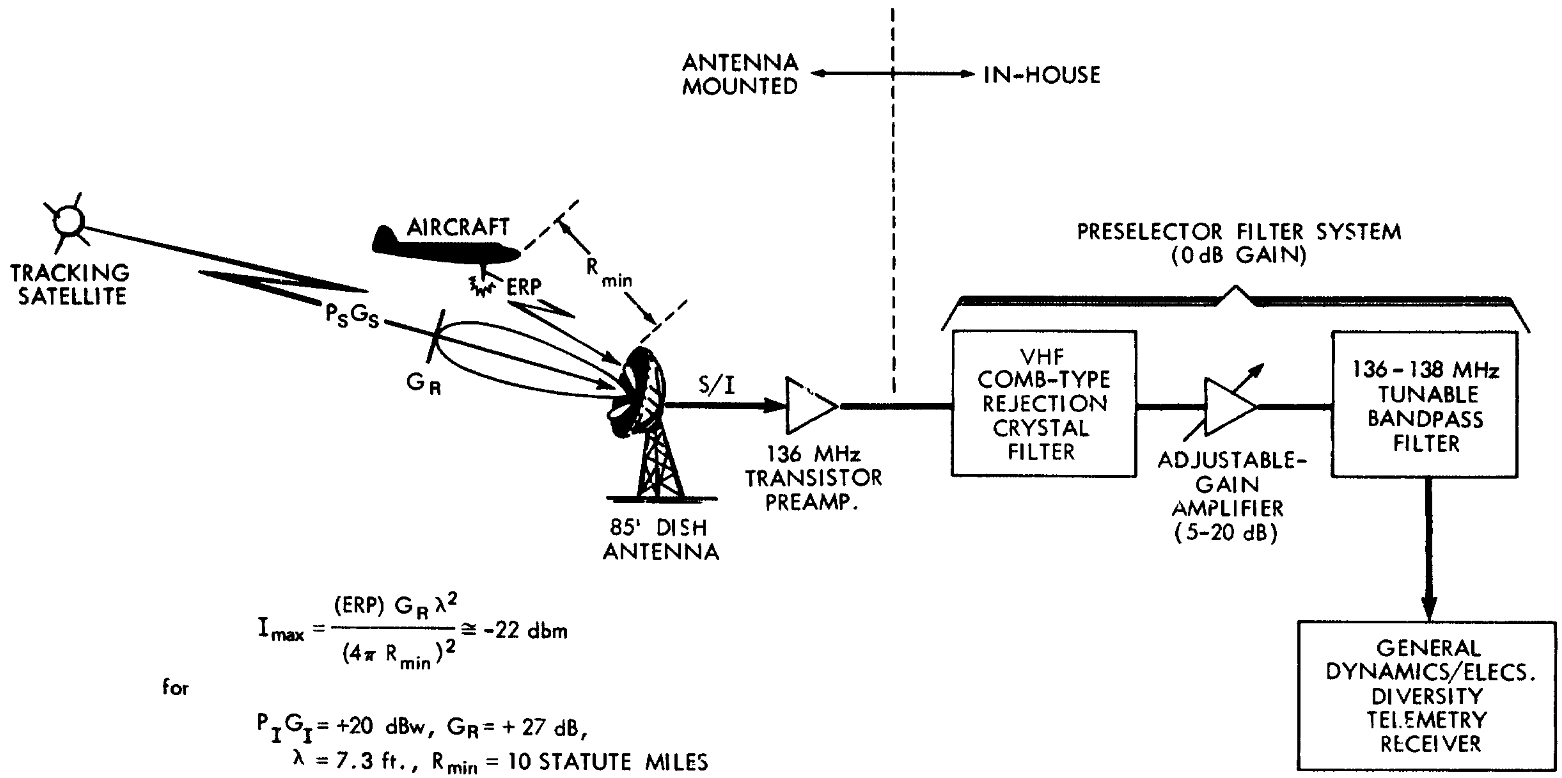
Ideally, a low-loss preselector rejection filter, that rejects interference signals at 135.950 MHz and below, should be located at the antenna output terminals just ahead of the preamplifier. However, the in-band insertion loss of such a filter must necessarily be low, over the 136-138 MHz pass band, to avoid system noise figure degradation.

Unfortunately, the latter constraint precludes the use of a practical filter ahead of the preamplifier On the other hand, a sharp-tuned filter system, located immediately after the preamplifier (see Figure 13), can be extremely effective in reducing aircraft RFI assuming that the received interference power level, I, does not saturate the preamplifier.

The 136 MHz transistor preamplifier, utilized in STADAN telemetry stations, has a linear input-output characteristic (Figure 14) for input signals lower than about -22 dbm, which happens to be the maximum anticipated aircraft interference level (Figure 13). Therefore, it is concluded that the 136 MHz preamplifier will not introduce non-linear products, which if present, would reduce the effectiveness of a post-amplifier filter such as that shown in Figure 13.

The STADAN 136 MHz transistor preamplifier now incorporates a wide band pass, low loss, fixed-tuned helical resonator type filter at its input providing isolation in excess of 100 dB, at 148 MHz, the satellite command transmitter frequency.

A composite interference filter system has been developed (Figure 13) that utilizes a comb-type notch crystal filter matrix to reject aircraft signals, and a tuned, multiple-section, band pass cavity filter that accepts satellite signals in the 136-138 MHz band.



$$I_{max} = \frac{(ERP)\, G_R\, \lambda^2}{(4\pi\, R_{min})^2} \cong -22 \text{ dbm}$$

for

$P_I G_I = +20$ dBw, $G_R = +27$ dB,
$\lambda = 7.3$ ft., $R_{min} = 10$ STATUTE MILES

Figure 13. VHF Aircraft Interference Filter Model

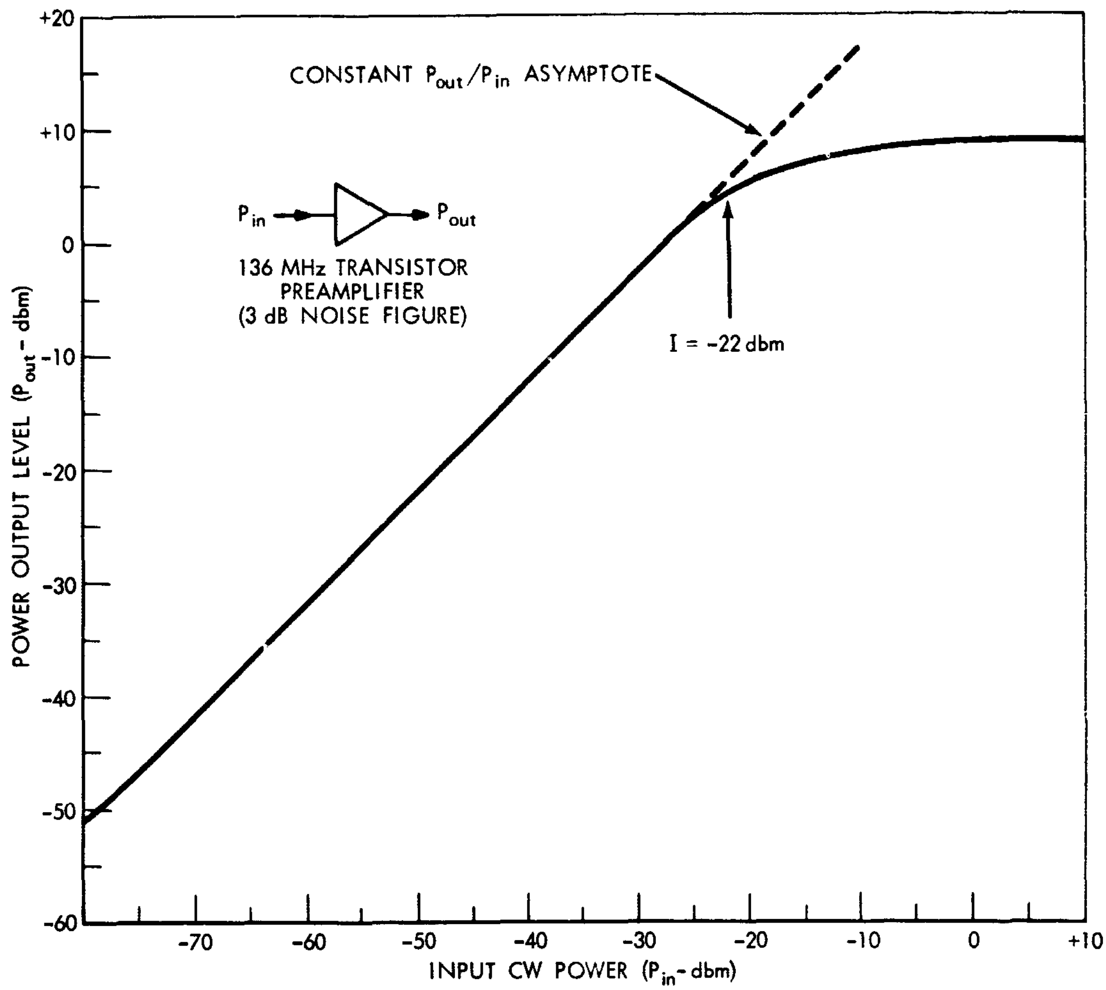


Figure 14. Linearity Characteristic of 136 MHz Transistor Preamplifier

The notch rejection crystals are special AT-cut quartz resonators, operating at the 5th overtone, that are mounted in an HC-25/U type holder. The crystal motional quality Q factor is 40,000 minimum, and various crystals are fixed-tuned and centered on the VHF aircraft channels located closest to the lower 136.00 MHz bandedge. The 20 kHz wide, 30 dB point, bandwidth of each rejection notch is sufficiently broad to reject AM voice modulation, occupying a 6 Hz wide double-sideband spectrum, and to handle the specified 0.005 percent aircraft transmitter center frequency drift. The notch peak attenuation, at the comb filter center frequencies (i.e., 135.95 MHz, 135.90, etc. down to 135.40 MHz), has been selected to yield the desired rejection in conjunction with the lower selectivity skirt of the 136-138 MHz tunable band pass filter (Figure 15). The dashed portions of the Figure 15 response curve represent predicted filter performance; whereas, the solid portions represent measured performance.

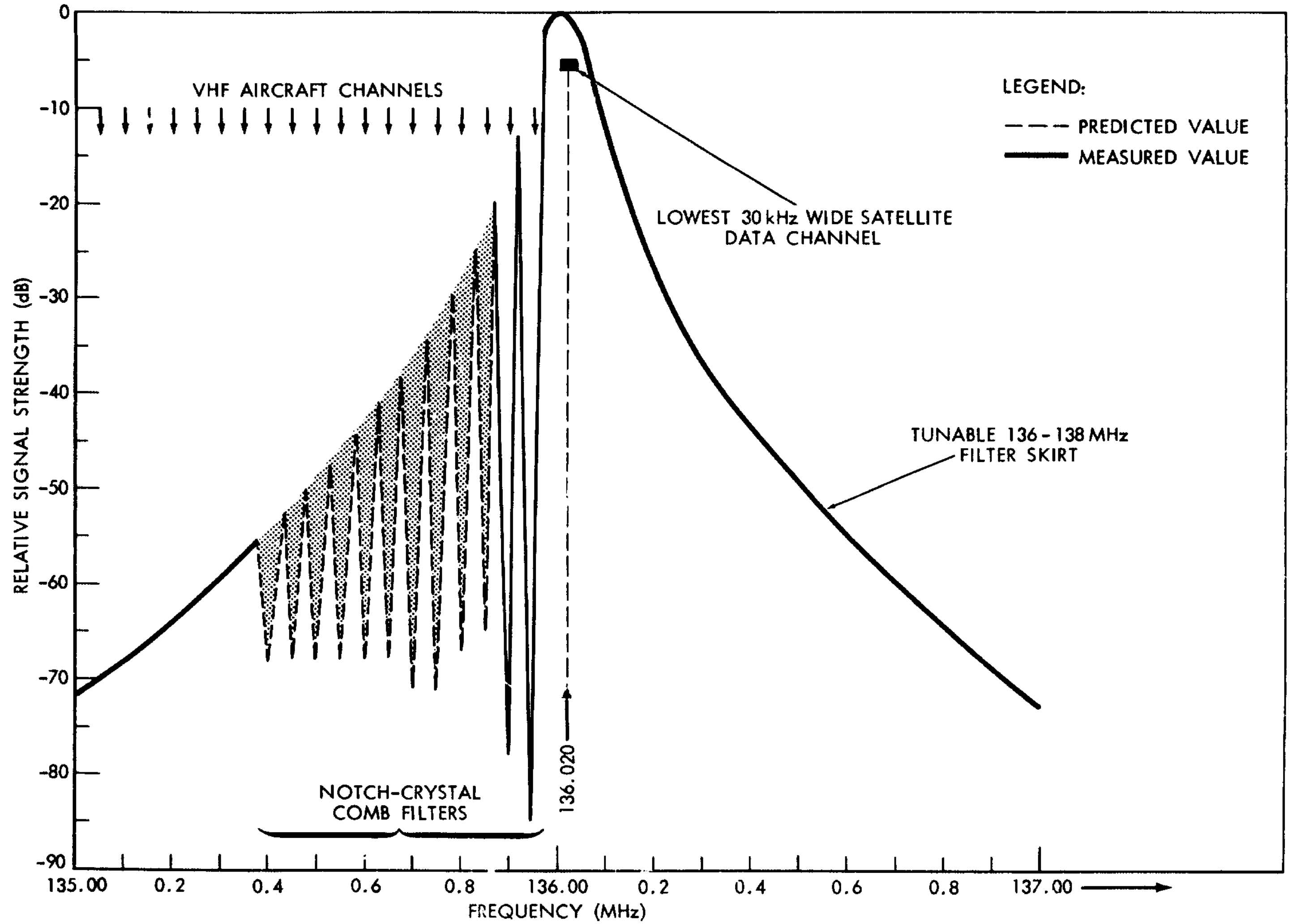


Figure 15. 136-138 MHz Preselector Filter Response, f_o = 136.005 MHz

Figure 15 shows the tunable band pass filter tuned to a center frequency, $f_o = 136.005$ MHz; yet only 55 kHz away, at 135.95 MHz, the composite response is 85 dB down from the value at f_o. This rejection is sufficient to reduce aircraft interference down to a level commensurate with the receiver bit error rate threshold, $I_t = -112$ dbm at 135.95 MHz (Figure 12), when $f_o = 136.020$ MHz. The lowest 30 kHz wide satellite data channel is centered at 136.020 MHz.

The tunable filter pass band has been fixed at a value between 100 kHz to 125 kHz, at the 3 dB down points, that is sufficiently broad to accept a 90 kHz wide data channel; yet is narrow enough to provide additional in-band selectivity. Figure 16 shows the tunable filter centered on the highest telemetry data channel at 137.980 MHz. The additional rejection provided by the notch-crystal comb filter is of course not necessary when the filter pass band is tuned to the upper portion of the 136-138 MHz band.

The basic design of the tunable filter consists of three coupled coaxial resonators forming an equal-element pass band filter. Each coaxial resonator consists of a 4-inch square aluminum cavity with silver-plated coaxial center conductor one-quarter wavelength in electrical length. The unloaded Q of each resonator is 3500, minimum. Continuous tuning of all three cavity resonators is provided with a one-knob front panel control. Accurate phase tracking of the resonators has been maintained to better than 5° at any given freque[illegible] over the pass band for auto-track requirements. A wide band adjustable-gain amplifier compensates for mid-pass band insertion loss making the preselector filter system (Figure 13) "0 dB" gain.

CONCLUSIONS

Radio Frequency Interference (RFI) susceptibility tests have been made on a simulated 136 MHz satellite telemetry link using both PCM/PM, split phase, and PFM/PM type modulations. In general, the data acquisition system PCM/PM threshold performance will not degrade when the receiver input signal-to-interference ratio is $S/I \geq +20$ dB. PFM/PM modulation is somewhat less susceptible to RFI than PCM/PM. For example, a typical PFM/PM system data error will not significantly increase for $S/I \geq 0$ dB.

Spacecraft premodulation filtering considerably reduces adjacent-channel satellite interference by lowering emitted side-band levels. The severity of the premodulation filtering appears limited to a filter bandwidth approximately equal to 2.5 times the bit rate for PCM square-wave modulation; however, this amount of filtering will reduce off band spurious emission by as much as 30 dB compared to the unfiltered case.

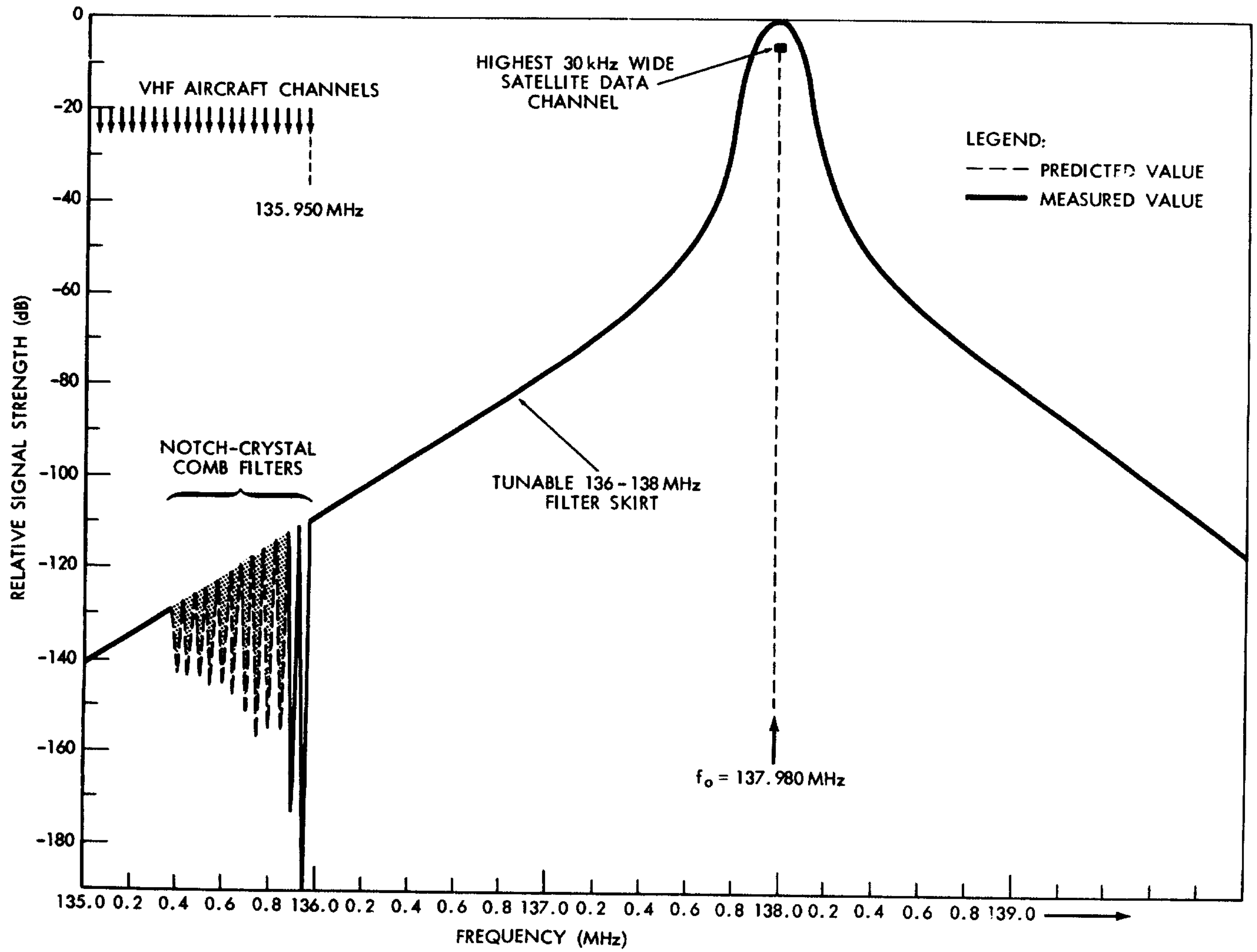


Figure 16. 136-138 MHz Preselector Filter Response, f_o = 137.980 MHz

The susceptibility of a STADAN 136 MHz PCM/PM telemetry receiving system, to simulated VHF aircraft interference, has been determined. An aircraft interference filter model has been developed. A prototype preselector filter system, consisting of a sharply-tuned comb-type notch rejection crystal filter and a tunable band pass filter, has been fabricated and laboratory tested. Additional field evaluation tests of the preselector filter system are planned, for the immediate future, prior to production procurement for STADAN use.

The crystal comb filter technique, for rejecting VHF aircraft interference, is also suitable for use in the Data Relay Satellite System (DRSS) spacecraft. The Figure 13 Preselector Filter System is suitable for autotrack as well as telemetry receiving applications. One (1) filter channel is required for each receiver channel.

ACKNOWLEDGMENT

The helpful suggestions of Dr. Robert J. Coates, Head, Advanced Development Division, Mr. Frank Keipert, of the Information Processing Division, and Mr. John Martin of the STADAN Operations Division, were particularly helpful during the initial planning phases for the PCM/PM susceptibility tests.

The contributions of Mr. Robert Griswold, of the Bendix Engineering Group at the Goddard Network and Training Test Facility (NTTF), were especially helpful during the PCM/PM data-taking phase. Mr. Tom Martin, of the NTTF Bendix Engineering Group, performed a similar function for the PFM/PM tests. Mr. Thomas J. Karras, of the Information Processing Division, was helpful in coordinating the PFM/PM evaluation using the STARS F9 Processor Line.

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