RFI Prevention for Colocated Antennas

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Current baseline design for the Mark IV-A 1985 Deep Space Network (DSN) calls for colocating the antennas of each Deep Space Communications Complex at one site. This article analyzes potential radio frequency interference (RFI) problems related to colocation and outlines the solutions.

I. Introduction

The Mark IV-A configuration of the Deep Space Network (DSN) is currently being designed for implementation by mid-1985. To reduce life-cycle cost and ensure telemetry and radio metric performance, the present baseline design as of October 1980 requires that all the antennas of each Deep Space Communications Complex (DSCC) be located close to the 64-meter antenna, except for Deep Space Station (DSS) 12 at Goldstone. This study examines the following questions: What are the RFI problems introduced by colocation? What are the solutions and concerns?

Section I defines the baseline network configuration, describes the distinct characteristics of colocated antennas, and identifies potential RFI sources and affected functions.

Section II defines the performance criteria as a design goal for RFI prevention, and describes the analytical model to be used for case-by-case analyses of the RFI sources and effects.

Section III gives the results of analysis for each case and suggests requirements where necessary.

Section IV highlights the conclusions.

Section V summarizes the implementation requirements as suggested and identifies antenna tests necessary to reduce the uncertainties in this analysis. Some of these tests are already underway.

A. Baseline Configuration

The configuration is depicted in Fig. 1. At Goldstone, the following antennas will be colocated:

(1) One 64-meter antenna, transmit and receive, supporting deep-space functions.

(2) Two 34-meter antennas, receive only, supporting deep-space functions or near-earth missions.

(3) One 9-meter antenna, transmit and receive, supporting near-earth missions.

DSS 12, however, will stay where it is and not be colocated.

At Canberra and Madrid, all antennas will be colocated, including the 34-meter transmit-receive antenna.

B. Characteristics of Colocated Antennas

For colocated antennas, the distance between antennas are relatively short (hundreds of meters) and the antennas are normally within the line of sight of each other. The colocated antennas under study have diverse operating frequency bands, transmitter power levels, and receiver front-ends as shown in Table 1. These antennas also have to point to deep-space missions, near-earth missions, and radio stars, substantially increasing the chance for a transmitting antenna to radiate to the front of a receiving antenna.

C. Potential RFI Sources and Affected DSN Functions

Potential sources of RFI include:

(1) S-band transmitters at the 64-meter and 34-meter antennas.

(2) S-band transmitter at the 9-meter antenna.

(3) Planetary radar transmitters (S- and X-bands) at Goldstone.

(4) Future X-band transmitter at the 34-meter transmit-receive antenna.

(5) Test signal generators.

(6) External sources.

Functions that may be affected include:

(1) Deep space mission X- and S-band receive for telemetry, tracking, and radio science.

(2) Near-earth mission S-band receive.

(3) X- and S-band very long baseline interferometry (VLBI) for navigation and crustal dynamics.

(4) Search for Extraterrestrial Intelligence (SETI).

(5) Radiometer measurements.

(6) Radio astronomy.

II. Performance Criteria and Interference Model

The possible interference between a potential RFI source and an affected function is analyzed according to the performance criteria given below; a description of the mutual interference model follows.

A. Performance Criteria

(1) No significant degradation due to in-band RFI.

(a) Acceptable RFI level for near-earth receive, measured at input to the low-noise amplifier (LNA):

CW[1] type	< −160 dBm (20 dB[2] lower than the carrier level of a typical high-earth orbiter, ISEE-3)
White-noise type	< −185 dBm/Hz (0.5-dB increase in noise temperature)

(b) Acceptable RFI level for deep-space receive, measured at input to the LNA:

CW[1] type	< −192 dBm (20 dB[2] less than the recommended minimum carrier level for 1-Hz loop)
White-noise type	< −202 dBm/Hz (0.1-dB increase in noise temperature)

(2) No receive system saturation due to out-of-band RFI.

(3) Allow antennas to point as close as 10 degrees to each other, from baseline as short as 200 meters.

These criteria would allow daily support of telemetry, tracking, command, and VLBI (to be discussed later) without appreciable restrictions on the pointing of antennas. Radio science and radio astronomy sometimes need a cleaner RF environment that would require some pointing restrictions or schedule coordination.

B. Antenna Mutual Interference Model

The mutual interference geometry is depicted in Fig. 2 where the two antennas are assumed to be within the line of sight of each other. The RFI power measured at the front end of the receiving antenna in Fig. 2 is related to the RFI source power at the transmitting antenna by the following equation:

$$P_R(f, D, \theta_T, \theta_R) = P_T(f) + G_T(f, \theta_T) - L_D(f, D) + G_R(f, \theta_R) - L_F(f) \quad \text{dBm} \qquad (1)$$

where

f = frequency of the RFI

D = baseline distance between antennas

P_R = received power at LNA input, dBm

P_T = transmitted power at feedhorn output, dBm

[1]Continuous wave, i.e., sinusoidal signals.

[2]To ensure good carrier acquisition and phase tracking performance in the receiver. For comparison, the CCIR criterion is also −192 dBm based on a 1-Hz loop.

G_T, G_R = relative gains of the transmitting and the receiving antennas at the indicated off-boresight angles in Fig. 2, dBi

L_D = path loss, dB

L_F = attenuation in the downlink filter before the LNA, dB

The transmitted power P_T, can be that of a carrier, a sideband, or a harmonic depending on the frequency of interest. The harmonic power and sideband power can be reduced by using proper filters.

The antenna gain in an off-boresight direction, G_T or G_R, depends on the antenna radiation pattern and the pointing angle. The radiation pattern of a 64-meter antenna measured in S-band at 700-meter range is given in Fig. 3. At present, this is the only near-field data available among all antennas. We have adopted for all cases a model that assumes the curve in Fig. 3 for angles larger than 20 degrees off boresight, a relative amplitude of 10 dBi at 10 degrees, and a linear continuation from 10 to 20 degrees. The radiation pattern beyond 20 degrees is relatively independent of antenna size, frequency, and range because it is generated by forward spillovers that are not intercepted by the antenna subreflector. Within 10 degrees at 200-meter range, the relative amplitude increases rapidly since these angles are very close to, or even inside, the cylindrical projection from the antenna reflector dish. To reduce the uncertainties in the model, some tests are being conducted, and more planned, to obtain radiation patterns for the 34-meter and the 9-meter antennas.

The path loss, L_D, is represented by $(\lambda/4\pi D)^2$ where λ is the wave length and D is the baseline distance.

The filter before the low-noise amplifier with effective attenuation L_F is a design choice to reduce the out-of-band radiation that may cause saturation of the amplifier or the receiver in the in-band frequency region.

III. Case Analyses

Each case of RFI source and effect was examined; most were analyzed using Eq. (1). The findings are summarized below. These findings form the basis for the implementation requirements recommended later in the report.

A. Effects of S-band uplinks on X-band downlinks

It is clear from Table 1 that the fourth harmonics of a certain range of S-band transmit frequencies fall in the pass band of the X-band travelling wave maser (TWM) or other X-band, low-noise amplifiers. The interfering signals must be stopped before leaving the transmitting antenna. To date, the fourth-harmonic filters have been implemented in deep-space transmitters, but they do not exist in near-earth transmitters. With proper filtering, the fourth-harmonic power transmitted from any antenna is expected to be reduced to −120 dBm from experience with deep-space transmitters. If this can be assured, the performance criteria is likely to be met even at 10-degree pointing angles, as shown by the link analysis in Table 2. The uncertainties shown in Table 2 represent our current lack of knowledge of the antenna radiation patterns, not the uncertainties of a stochastic nature. If any pointing angle is larger than 30 degrees instead of 10 degrees, it can be observed from Fig. 3 that there would be an additional 20-dB margin in Table 2, and hence almost no risk in not meeting the performance criteria. If the 9-meter antennas are positioned at the north end of the complexes in the northern hemisphere, and at the south end of the complex in the southern hemisphere, the chances for cross pointing would be greatly reduced. Table 2 has not included the white-noise-type RFI because the noise level in the transmitter is usually much lower than the harmonics level. We expect the noise-type RFI to meet the noise-type criteria when the harmonics meet the CW-type criteria.

The VLBI receive system will be sufficiently protected once the stated performance criteria are met. This is because:

(1) Contribution of RFI to the system temperature would be negligible.

(2) Effect of RFI on quasar or spacecraft signals would be negligible due to interferometry and earth doppler.

(3) RFI interaction with station-generated calibration tones would also be negligible. Each tone is expected to have at least −145-dBm power. With CW-type RFI lower than −192 dBm, the phase error would be less than one millicycle even when the RFI spectrum lies within 5 Hz of the calibration tone, an event with very-low probability.

B. Effects of S-band uplinks on S-band downlinks

S-band uplink interference is out-band since transmitted frequencies are below 2120 MHz and receive frequencies are above 2200 MHz (see Table 1). The question is whether the interference would be strong enough to saturate the receive system and cause nonlinearity in the receive frequency band.

The S-band TWM is known to saturate at the power levels shown in Fig. 4. It is seen that the saturation level at a representative transmitted frequency of 2110 MHz is about −25 dBm. The saturation level for an S-band field effect transistor (FET) with a crustal dynamics frequency range (2220 to 2320 MHz) is estimated to be at −55 dBm at the same frequency. The result of a link analysis as shown in Table 3 indicates that for receive systems using a TWM at the front end, either a cryogenic filter (currently being developed at JPL) or a regular room-temperature filter can be used to avoid saturation. However, using a room-temperature filter will add about 3 kelvin to the system temperature. For receive systems using a FET at the front end, room-temperature filters would be necessary.

C. Effects of Planetary Radar at Goldstone

The planetary radar operates at 2320 MHz (S-band) and 8495 MHz (X-band). Current ranging code has a fundamental frequency of 200 kHz, with a bandwidth (through the ninth harmonic) of about 2 MHz. Future fundamental frequency could be as high as 2 MHz, with a bandwidth as great as 20 MHz. The carrier and sideband frequencies are too close to the deep-space receive frequency bands to be effectively separated by filtering.

When the X-band radar is transmitting at 400-kW total power with a 2-MHz fundamental frequency and a 128-bit pseudonoise code, a harmonic line at around 8420 MHz could have a strength of about -45 dBm. This calculation assumes that the klystron roll-off and an exciter filter could achieve about 80-dB attenuation at this frequency. Under this assumption, the X-band RFI from the X-band radar is calculated in Table 2. The effect of the S-band radar on the near-earth S-band reception at around 2275 MHz is calculated in Table 3 based on a similar assumption on transmitted power. It is clear from Table 2 that even at very favorable pointing conditions, the X-band reception at nearby deep-space antennas can not meet the performance criteria. Similar calculations have shown that the deep space S-band receive functions can not satisfy the criteria when the S-band radar is operating.

However, Table 3 indicates that the 9-meter station at Goldstone can receive near-earth signals satisfactorily when the S-band radar is operating. This is possible because the performance criteria for near-earth missions are less stringent and because there would be a small hill blocking the line of sight from the 64-meter antenna if the 9-meter antenna is properly located. The effect of the small hill is estimated according to Ref. 2. This hill would also reduce the fourth harmonic RFI from the 9-meter antenna to the 64-meter antenna.

D. Effects of Future X-Band Uplink

The X-band uplink frequency band is separated far enough from the X-band downlink to prevent any interference. This separation is already planned in the microwave and the exciter designs. Furthermore, X-band uplink will not produce any harmonics that would interfere with the K_u-band downlink currently under study at JPL.

E. Effects of Test Equipment Leakage

When test equipment operates at downlink frequencies, any leakage of enough power could interfere with the live downlink. Proper shielding is needed to contain leakage to about -120-dBm CW level and about -135-dBm/Hz noise level in the downlink frequency bands.

F. Effects on Radiometer Measurements

RFI of CW type cannot affect radiometers since radiometers only measure wideband noise power. Noise-type RFI could interfere, but the criteria given above will ensure that any increase of system temperature be lower than 0.1 dB. This is acceptable for current purposes of water-vapor radiometers and noise-adding radiometers.

G. Effects on SETI and Radio Astronomy

The Search for Extraterrestrial Intelligence (SETI) instrument is currently in its conceptual design stage. It is already clear that the extra-wide frequency band of interest to SETI (1 to 25 GHz) requires special measures. The prevention of any transmitted signals in this frequency range (including all transmitters given in Table 1) from either saturating the low-noise amplifier or contaminating the actual signals received from the sky will be necessary. Band-reject filters may therefore be necessary to prevent receiver saturation. Software or other means must be used to separate and delete the transmitted frequencies from the received signal spectrum. Since these frequencies are predictable, it should be possible to identify them as known RFI for deletion. Detailed solutions and alternatives are being studied by the SETI team.

While the performance criteria for RFI prevention would serve to protect the integrity of most of the present radio astronomy observations, they do not guarantee nondegradation of the RF environment at all times. From a radio astronomy standpoint, any degradation, even satisfying a set of more stringent criteria, would still compromise the potential of DSS 14 as a versatile, increasingly sensitive instrument for single-dish radio astronomy observations.

H. External RFI

We must continue to monitor the external RFIs and coordinate with external transmitting sources as we do now, especially at Goldstone. The RFI from satellites or high-flying airplanes will affect the receiving antennas to relatively the same extent whether the antennas are colocated or not. But more effort may be necessary to coordinate with low-altitude transmitting sources around Goldstone since the DSS 14 site at Goldstone is not protected by hills from the east and the west. On the other hand colocation of antennas could probably make monitoring and coordination easier.

IV. Conclusions

When the requirements in the next section are implemented we expect that the performance and operation of telemetry, tracking, command, and VLBI systems to be essentially unaffected by RFI. The radio science system and the radio astronomy operations may sometimes need a cleaner RF environment that must be assured by antenna pointing precautions and possibly schedule coordinations.

Operational schedule of the planetary radar at Goldstone must be coordinated with the downlink functions in the same frequency band at the nearby 34-meter stations. DSS 12 and DSS 13 will remain unaffected by the radar. The 9-meter antenna at Goldstone could also be relatively unaffected if it is properly located.

The SETI observations will be affected if one of the colocated antennas is used. Band-reject filters will be necessary to prevent receiver saturation. RFI prediction, identification, and rejection schemes will be needed to delete the intracomplex RFI. Alternative solutions are being studied by the SETI team.

V. Recommendations

A. Recommended Implementation Requirements

(1) Implementation of filters.

  (a) Fourth-harmonic filters for GSTDN transmitters.

  (b) Exciter filters for Goldstone radar.

  (c) Downlink filters at 34-meter and 9-meter antennas.

(2) Location of 9-meter antennas to minimize RFI.

(3) Transmitting and receiving antennas not to point within 10 degrees of each other, with more restrictions on special occasions.

(4) Schedule restriction on Goldstone radar and colocated 34-meter antennas.

(5) Deletion of dual-frequency uplink capability at 9-meter antennas to eliminate intermodulation products.

(6) Control of test-signal leakage.

(7) SETI to have filters to prevent saturation and software to identify and reject known RFI.

(8) Predictions, to trace and predict the intracomplex RFI from the transmitters, based on antenna pointing predictions. These predictions would be necessary for scheduling SETI observations or those radio astronomy and radio science experiments, that are more sensitive than the performance criteria given in Section II.

(9) Continued frequency coordination to prevent external RFI.

B. Recommended Tests

(1) Near-field (about 200-meter range) antenna radiation patterns for 64-meter and 34-meter antennas, at S-band and X-band.

(2) Mutual interference between antennas at current conjoint site as a function of pointing angles, at S- and X-band.

(3) Radiation patterns of the 9-meter antenna (S-band and fourth harmonic) and the power level of its fourth-harmonic radiation.

(4) Planetary radar sideband power and terrain effect measurement.

The first two tests are on-going at the conjoint stations in Australia. The last two tests are still being planned.

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References

1. Bathker, D. A., *Predicted and Measured Power Density Description of a Large Ground Microwave System*, Technical Memorandum 33-433. Jet Propulsion Laboratory, Pasadena, Calif., April 1971.
2. International Telephone and Telegraph, *Reference Data for Radio Engineers*, Chapter 28, H. W. Sams & Co., 1968.

Table 1. RF characteristics of receive systems and transmitters

Receive system	Frequency range, MHz	System temperature, K, and front-end amplifier
Deep-space receive		
Spacecraft S-band	2290 to 2300	20, TWM[a]
Spacecraft X-band	8400 to 8440	20, TWM
VLBI		
S-band	2265 to 2305	20, TWM
X-band	8400 to 8500	20, TWM
Crustal dynamics		
S-band	2220 to 2320	150, FET[b]
X-band	8200 to 8600	160, FET
Near-earth missions		
S-band	2200 to 2290[c]	150, FET or PARAMP
SETI wideband	1 GHz to 25 GHz	15 to 35[d]

Transmitter	Frequency range, MHz	Maximum power, kW
Deep-space transmit		
S-band, 20 kW (64 m, 34 m)	2110 to 2120	20
S-band, 100 kW (64 m)	2110 to 2120	100
Goldstone planetary radar		
S-band	2320[e]	400
X-band	8495[e]	400
X-band, 20 kW (34 m)	7145 to 7190	20
Near-earth missions		
S-band, 20 kW (9 m)	2025 to 2110[c]	20

[a] Travelling-wave maser.

[b] Field effect transistor.

[c] Future high earth-orbiter missions (starting from AMPTE) will use 2225 to 2275-MHz range for downlink and 2050 to 2095-MHz range for uplink.

[d] Design for the wide-band, low-noise amplifier is still being studied.

[e] Ranging sidebands (up to 9th) will extend to ±20 MHz.

Table 2. X-band RFI link analysis

Parameter	Fourth harmonics effect on 64 m and 34 m		Planetary radar effects on 34 m	
	Assumption	Effect, dB	Assumption	Effect, dB (8420 MHz)
P_T	20 kW, filtered	−120 dBm CW	400 kW, filtered	−45 dBm CW
G_T	10 deg	+10 ±5	90 deg	−15 ±5
L_D	200 m	−97 ±3	200 m	−97 ±3
G_R	10 deg	+10 ±5	90 deg	−15 ±5
L_f	None	0	None	0
P_R		−197 ±13 dBm		−172 ±13 dBm
Criteria		−192 dBm CW		−192 dBm CW

Table 3. S-band RFI link analysis

Parameter	Planetary radar effect on 9-m		Saturation due to out-band RFI	
	Assumption	Effect, dB (2275 MHz)	Assumption	Effect, dB (2110 MHz)
P_T	400 kW, filtered	−45 dBm, CW	20 kW	73 dBm, CW
G_T	90 deg	−15 ±5	10 deg	+10 ±5
L_D	640 m	−96 ±3	200 m	−86 ±3
G_R	10 deg	+10 ±5	10 deg	+10 ±5
L_f	None	0	Cryogenic or room temp.[a]	−45 or −75
Hill		−40 ±10	None	0
P_R		−186 ±23 dBm		−38 ±13 dBm cryogenic or −68 ±13 dBm room temp.
Criteria		−160 dBm CW		−25 dBm CW (TWM) or −55 dBm CW (FET or PARAMP)

[a]3-kelvin noise penalty.

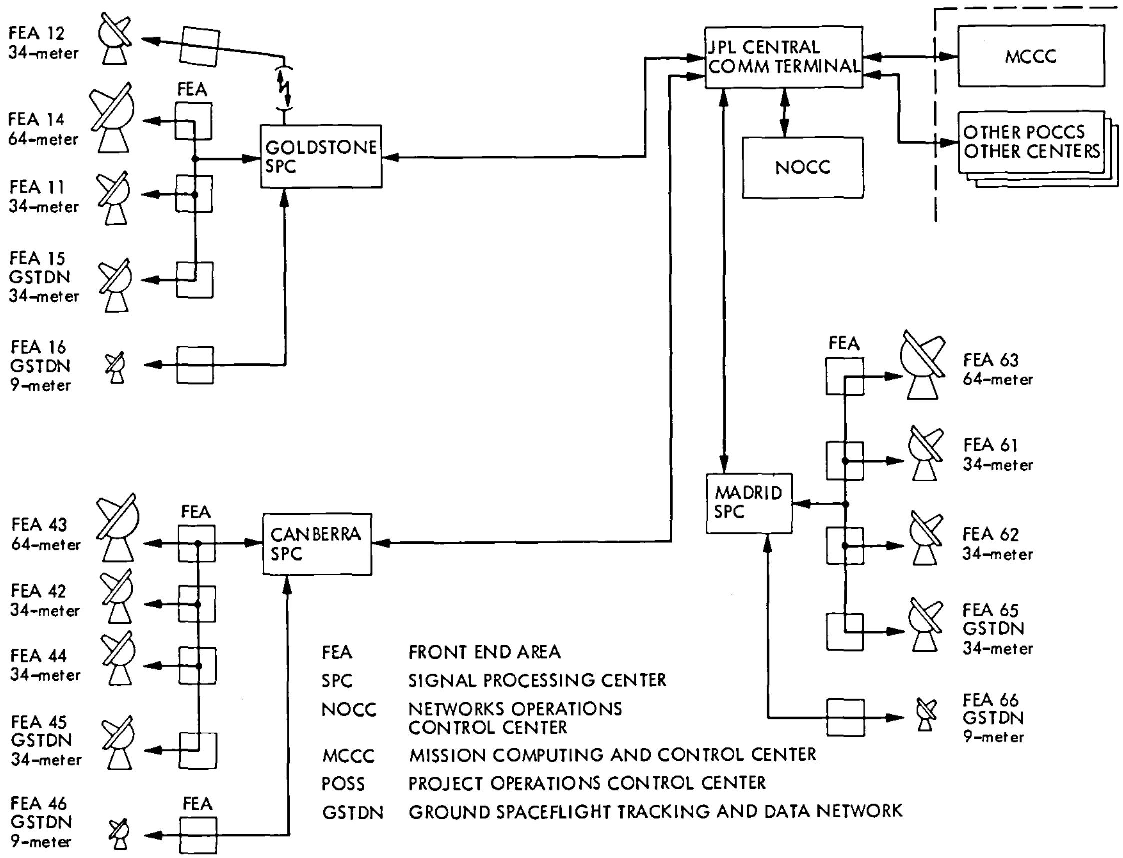

Fig. 1. Mark IV-A 1985 DSN baseline configuration

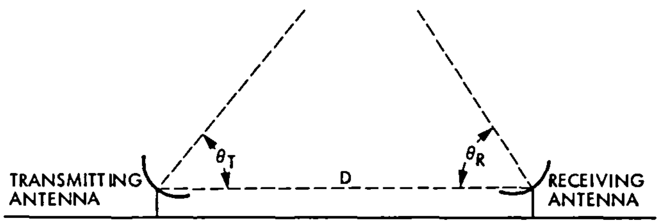

Fig. 2. Antenna mutual interference geometry

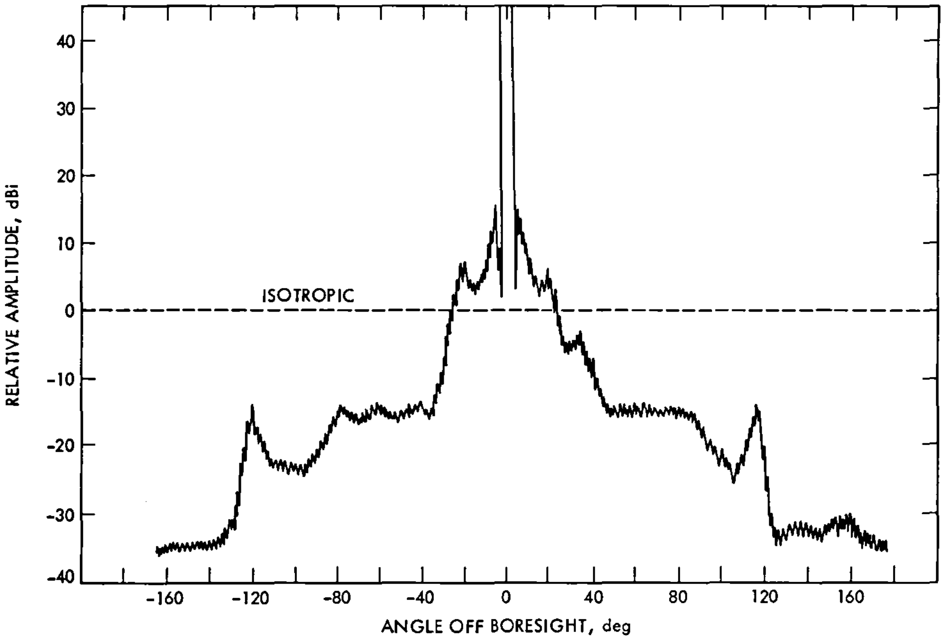

Fig. 3. Measured azimuth pattern of the 64-m advanced antenna system at Goldstone, Calif.; 2115 MHz, range = 700 m (from Ref. 1)

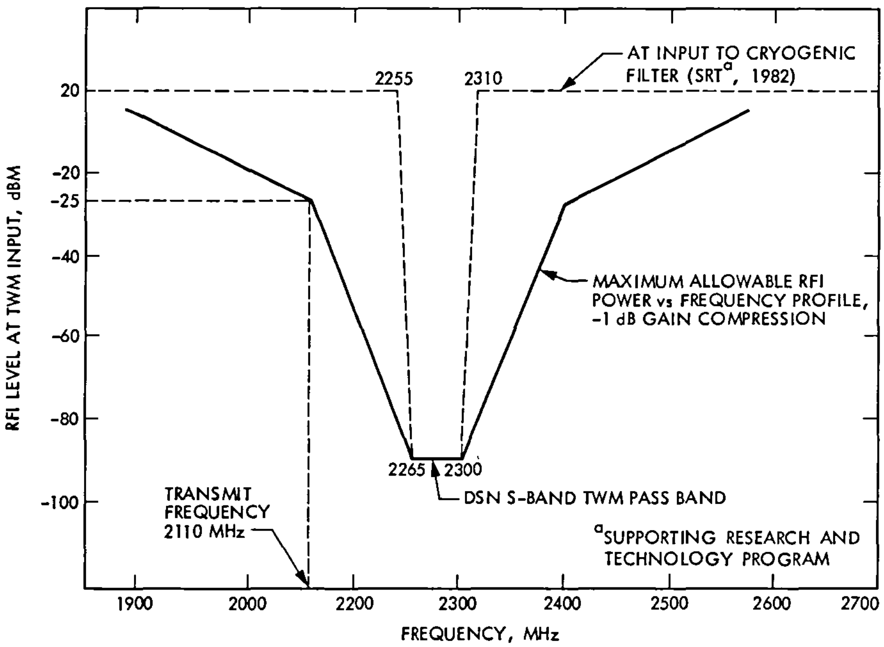

Fig. 4. S-band TWM saturation power level vs frequency