A Method of Optimal Radio Frequency Assignment for Deep Space Missions

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A method for determining optimal radio frequency channels for the Deep Space Network is described. Computer automated routines calculate interference-to-signal ratios over a given mission period and provide a quantitative assessment of the channels which could then be assigned to a new mission. This automated procedure reduces the analysis time considerably and effectively improves upon the accuracy of existing channel assignment techniques.

I. Introduction

The continuously increasing demand for communications channels by the Deep Space Network (DSN) has necessitated the development of more extensive methods of selecting channel frequencies which best minimize the overall potential of mutual interference. Communications channels must be assigned judiciously to new DSN missions with the objective of achieving and maintaining an optimal level of intra-system compatibility. Transmission link and dynamic geometrical parameters which pertain to the spacecraft and tracking station are used in the computations to determine the most suitable channel frequency for both the uplink and downlink transmission modes.

This article presents a method of determining the optimal channel frequencies for new DSN missions.[1,2] A computer model has been developed which calculates the mutual signal degradation between systems as it relates to any given channel assignment. The model utilizes parameters which include the effects of spacecraft position and pointing angles, the modulation schemes, data rates and formats, Doppler shift, and discrete ranging components. An algorithm calculates the optimal frequency for the new mission, a frequency that will have a minimal interference impact on the overall DSN system. The computer program, called the Interference Analysis Program (IAP), is for the most part database driven to provide a high level of automation in the computation.

In the past, there were only a few missions to contend with, and the channel assignment procedure relied heavily on qualitative evaluation techniques. Now with the rapid growth of space research missions, more definitive analyses are needed to ensure efficient use of the DSN frequency spectrum. As the complexity in the analysis increases, there is a concomitant need to improve the accuracy of the analysis and, at the same time, lessen the analyst's dependence on qualitative assessment. The method described in this article effectively reduces the potential for human

[1] J. Gevargiz and C. Ruggier, *DSN Intra-System Spectral Compatibility Analysis, Mars '94 Channel Assignment*, JPL D-7663 (internal document), Jet Propulsion Laboratory, Pasadena, California, July 12, 1990.

[2] D. Bishop, *DSN Inter-System Spectral Compatibility Analysis: CRAF/Cassini Channel Assignment*, JPL D-8797 (internal document), Jet Propulsion Laboratory, Pasadena, California, August 6, 1991.

error and provides a basis for more objective, standardized analysis techniques.

II. Interference Geometry

The criteria for selecting optimal frequencies for a new DSN mission are dependent on the potential for link performance degradation caused within the DSN missions as a whole; that is, performance degradation caused to the existing missions with the introduction of the new DSN mission and, alternately, performance degradation to the new mission caused by the existing missions. This applies to both the uplink and downlink transmission modes.

Figures 1 and 2 show how the interference signal couples to the receiver antenna of a tracked mission for the uplink and downlink modes, respectively. The value R_1 is the range between the Earth station and the tracked spacecraft, SC1, while R_2 is the range between the Earth station and the interfering or interfered-with spacecraft, SC2. The antenna off-axis angle ϕ determines the gain of the interfering signal for the uplink and downlink modes. These trajectory-dependent parameters are used to calculate the mutual interference power spectral density between SC1 and SC2 for any given mission period. The interference-to-signal ratio (ISR) can also be calculated and used as a simple performance factor for evaluating the interference degradation to the DSN.

A. Uplink Interference Mode

From Fig. 1, it can be noted that the uplink signal to SC1 can also couple through the sidelobes of the SC2 antenna and interfere with its received command signal. The absolute interference power level is dependent on the antenna off-axis angle relative to SC2 and the range of SC2.

Typical DSN uplink command signals require only a relatively narrow transmission bandwidth, usually on the order of a few kilohertz. With the narrow-bandwidth requirement and a sufficient guard band between channels, the uplink mode is not considered to be a major factor in determining new channel assignments; however, in some cases, it can significantly impact the accuracy of the overall performance assessment. For this reason, the uplink interference mode is included as an integral part of the channel assignment analysis.

B. Downlink Interference Mode

Referring to Fig. 2, the downlink signal from SC2 is shown to couple through the sidelobes of the ground station receiving antenna which tracks SC1. The level of absolute interference power from SC2 is dependent on the antenna off-axis angle of SC2 with SC1 and the range of SC2.

Unlike the uplink command signals, the downlink signals require a wider bandwidth to accommodate high data rate telemetry and, in some instances, ranging tones which are several megahertz apart. Due to the downlink's wider transmission bandwidth, the signal's power spectrum can spread over a large segment of the frequency band. Consequently, a more stringent approach is needed for the assignment of new channels in the downlink band.

III. Description of the Interference Models

The basic configuration of the IAP analysis models is shown in Fig. 3; this configuration shows a cochannel interference model, an adjacent channel interference model, a Doppler shift model, a frequency optimization algorithm, and a discrete tone analysis model. These models, in turn, are driven by the spacecraft trajectory model and from parameters stored in the mission database. The primary functions of each model are described in the following sections.

A. Spacecraft Trajectory Model

This algorithm calculates the spacecraft range, downlink antenna off-axis angle, and range rate. The trajectory model is driven from a mission database, which contains the spacecraft state vectors and timing data, significant mission event profiles, and the telecommunications parameters required for the uplink and downlink mode analysis.[3]

B. Cochannel Interference Model

Figure 4 illustrates the flow diagram for the cochannel interference analysis between SC1 and SC2. The model calculates the absolute power, power spectral density, and ISR for the case in which the interference signal frequency is coincident with that of the interfered-with signal over the interfered-with spacecraft mission period. This applies to both the uplink and downlink interference mode.

As a first step in the analysis, the total sample of active DSN missions is culled and limited to a sample consisting of only those missions which cause, or are susceptible to, interference in the cochannel mode.

As an example, if isotropic gain of 0 dB is assumed for the spacecraft antenna, from Fig. 2 (downlink mode) the ISR at the ground station is given by

[3] K. Suwitra, "Source Code for the Automated Interference Analysis Program (IAP)" Interoffice Memorandum 3396-92-061, (internal document), Jet Propulsion Laboratory, Pasadena, California, October 19, 1992.

$$ISR = \frac{P(\text{interfering spacecraft})}{P(\text{tracked spacecraft})}$$

$$= \frac{P^d_{C_2} \cdot G(\phi)/L(R_2)}{P^d_{C_1} \cdot G_{\max}/L(R_1)} \quad (1)$$

where

$P^d_{C_1}$ = downlink (d) cochannel transmitted power of SC1 (watts)

$P^d_{C_2}$ = downlink cochannel transmitted power of SC2 (watts)

$G(\phi)$ = off-axis gain of SC2 link, ground station antenna, in the direction of SC2 (ratio)

$G_{\max}$ = maximum ground station antenna gain (ratio)

$L(R_2) = (4\pi R_2/\lambda)^2$ = free space loss for distance R_2 (ratio)

$L(R_1)$ = free space loss for distance R_1 (ratio)

R_1 = range between ground station and SC1 (meters)

R_2 = range between ground station and SC2 (meters)

λ = wavelength of signal (meters)

With the interfering and interfered-with signals in the same frequency band, this expression reduces to

$$ISR = \frac{P^d_{C_2} \cdot G(\phi) \cdot (R_1)^2}{P^d_{C_1} \cdot G_{\max} \cdot (R_2)^2} \quad (2)$$

The antenna off-axis gain $G(\phi)$ is given by the International Radio Consultative Committee (CCIR) antenna reference pattern [1]:

$$\left.\begin{aligned}
&\text{for } \frac{D}{\lambda} \geq 100 \\
&G^*(\phi) = G^*_{\max} - (2.50 \times 10^{-3})\left[\frac{D\phi}{\lambda}\right]^2 \text{ (dB)} \\
&\qquad \text{for } 0 < \phi < \phi_m \\
&G^*(\phi) = G_1 \text{ (dB) for } \phi_m \leq \phi < \phi_r \\
&G^*(\phi) = 32 - 25 \log_{10}(\phi) \text{ (dB)} \\
&\qquad \text{for } \phi_r \leq \phi < 48 \text{ deg} \\
&G^*(\phi) = 10 \text{ (dB) for } 48 \text{ deg} < \phi
\end{aligned}\right\} \quad (3)$$

where

D = antenna diameter (meters)

λ = wavelength (meters)

$G^*_{\max} = 10 \log_{10}(G_{\max})$ = antenna off-axis gain (dB)

$G^*(\phi) = 10 \log_{10} G(\phi)$ = antenna off-axis gain (dB)

ϕ = off-axis angle of the first sidelobe (deg)

G_1 = gain of the first sidelobe $= 2 + 15 \log\left(\frac{D}{\lambda}\right)$ (decibels)

$$\phi_m = \left[\frac{20\lambda}{D}\right]\sqrt{G^*_{\max} - G_1} \text{ (degrees)}$$

$$\phi_r = 15.85\left[\frac{D}{\lambda}\right] \text{ (degrees)}$$

The carrier-to-carrier, data-to-data, and total-power ISR's are calculated and compared to the given interference threshold power ratio. For the carrier-to-carrier mode, the adjusted (after modulation) interfering and interfered-with carriers are compared to a user-defined threshold in decibels. If the threshold is exceeded over the mission period of the interfered-with system, then that mission pair is considered for further analysis. If the threshold is not exceeded, then the data-to-data mode is examined. Similarly, for this mode, the data power of the interfering and interfered-with systems are compared to a user-defined threshold. In the event that user-defined threshold levels are not given, default values are used. Figure 5 illustrates the downlink total power cochannel ISR from Galileo to Cassini versus the days past the launch date of the Cassini mission. This figure also shows the ISR threshold of −20 dB employed in this analysis.

The uplink interference analysis is similar to the downlink analysis with the ISR substituted for the absolute interference power. The received uplink interference power at SC2 is given by

$$\left.\begin{aligned}
P^u_{C_2} &= \frac{P^{GS}_1 \cdot G_2(\phi)}{L(R_2)} && \text{uplink } (u) \text{ cochannel interference power to SC2} \\
P^u_{C_1} &= \frac{P^{GS}_2 \cdot G_1(\phi)}{L(R_1)} && \text{uplink } (u) \text{ cochannel interference power to SC1}
\end{aligned}\right\} \quad (4)$$

where

P^{GS}_1 = ground station (GS) transmitted power to SC1

$G_2(\phi)$ = off-axis transmitted gain of SC1 link antenna, ground station antenna, in the direction of SC2

$G_1(\phi)$ = off-axis transmitted gain of SC2 link antenna, ground station antenna, in the direction of SC1

$L(R_2) = (4\pi R_2/\lambda)^2$ = free space loss for distance R_2 (ratio)

For example, Fig. 6 illustrates the uplink cochannel interference power from Galileo to Cassini versus the days past the launch date of the Cassini mission. The results of the cochannel analysis are then used to eliminate the potential sources of interference from further analysis when for a given interference source,

(1) The absolute power of the uplink interference does not exceed the spacecraft's interference power threshold.

(2) The downlink carrier-to-carrier interference power ratio does not exceed the interference threshold.

(3) The data-to-data interference power ratio does not exceed the interference threshold.

(4) The total-power ISR does not exceed the interference threshold during the entire mission period.

C. Doppler Shift Model

Signals are subjected to Doppler frequency shifts, which although occurring periodically, could cause intolerable interference to the system. The Doppler shift of the interference signal relative to the interfered-with signal is used to calculate the instantaneous changes in the interference power throughout the mission period being analyzed. Maximum Doppler shift is derived from the Doppler rate for each day in the mission period under analysis. The Doppler shift data are then applied as an adjustment factor in the time- and frequency-dependent interference calculations.

The Doppler shift is an important consideration in the channel assignment analysis in that, for some period of time, it can either increase or decrease the degree of isolation between channels.

D. Adjacent Channel Interference Model

Figure 7 illustrates the adjacent channel analysis for a pair of missions (e.g., SC1 and SC2). This model calculates the absolute power, power spectral density, and ISR for the case in which the new DSN link (i.e., SC1), operates on a channel other than that used by the existing DSN mission (i.e., SC2). This procedure is applied to both the uplink and downlink modes.

The adjacent channel interference model is used to calculate the total interference power which couples to the ground station and spacecraft receiver of the interfered-with DSN mission. It can generate plots of the interference power versus time and also provides the basis for the frequency optimization procedure.

The adjacent channel interference analysis constitutes the core of the channel assignment process. Due to the sideband products of a DSN signal, portions of the transmitted power of the interference source will overlap into an adjacent channel user. This interference signal couples spatially, through the antenna sidelobes, and also spectrally, between channels. Interference caused by inadequate frequency spectrum isolation between the band channels is generally referred to as "adjacent channel interference."

In contrast to cochannel interference, the level of the incident adjacent channel interference depends greatly on the rejection properties of the receiver. The problem is that a typical DSN telemetry signal occupies a spectral bandwidth in excess of the channel bandwidth limitation. Sideband products spill over into adjacent channels and can still cause interference, even though separated from other users by several channels.

A method of calculating the interference power incident on a system operating in an adjacent channel is inherently complex. As an example, the typical composite DSN telemetry signal can react to the interference with a loss of carrier lock, a loss of telemetry lock, or a degradation in the output signal-to-noise ratio (increase in the bit error rate). These various forms of link degradation are not necessarily correlated and will depend on the spectral characteristics of the composite interference signal. To overcome these difficulties, a simplified method is needed for modeling the interference components and their effect on the interfered-with system.

1. Spectral Power Envelope Technique. A practical and simple method of calculating adjacent channel interference utilizes the spectral power envelope technique. This technique is used as a worst-case representative model of the interfering signal characteristics.

The spectral power envelope of the interfering signal is constructed using a simple procedure. The procedure de-

fines the signal's power envelope as the upper bound of its spectral power density, limited by the peaks of its spectral components. In the case of the DSN uplink and downlink signals, the power envelope is constrained by the carrier and sideband peak power levels. When the signal's power level, data format, and modulation scheme are specified, a representative model of the spectral power envelope of the composite signal can then be implemented for any particular link.

The spectral power envelope technique is a simplified, first-order approach for the assessment of adjacent channel interference. From the interference geometries and the specified link parameters, the in-band interference power and the ISR are easily calculated. These parameters are applied in the analysis model, as a first step in the evaluation of link performance degradation. Figure 8(a) illustrates an example of the power spectral envelope for missions corresponding to SC1 and SC2. Shown is the spectral power envelope of the interference, $P(f)$, and the harmonics of the interfered-with signal, with the harmonic number labeled $i = 1$, 3, 5, and 7. Also shown in this figure is the interfered-with frequency band, presented as a shaded area labeled $P_I(i)$ for $i = 1$, 3, 5, and 7. The adjacent channel algorithm calculates the interference from mission SC1 to mission SC2 by determining the interference power that falls within the data bandwidth of the subcarrier components of mission SC2, shown as a shaded area in Fig. 8(a). The total adjacent channel interference power P_A, is then given by

$$P^d_{A_1}(i, f_c) = \sum_{j=-N}^{N} \frac{1}{j^2} P^d_{A_1}(i, j, f_c) \qquad (5)$$

where

j = subcarrier harmonic number

i = day number

f_c = channel frequency of mission SC1

$P^d_{A_1}(i, f_c)$ = total downlink adjacent channel interference power from SC1 when operating on channel 18 (f_c)

$P^d_{A_1}(i, j, f_c)$ = adjacent channel interference to the jth subcarrier harmonic of SC2 when SC1 operating on channel 18 (f_c)

Similarly, as shown in Fig. 8(b), the interference to mission SC1 can be calculated using the same algorithm.

An analysis using relative signal power levels is sufficient for conducting the frequency optimization procedure, thereby significantly reducing the complexity of the analysis and the required computer execution time. Although these interference parameters are not, in themselves, sufficient to characterize the actual link performance degradation, they provide a first-order assessment, which satisfies the basic requirements of the analysis.

2. Adjacent Channel Interference Power Calculations. In general, calculation of the interference power $P^d_{A_1}(i, f_c)$ at the interfered-with receiver involves an integration of the total interference power within the receiver's bandwidth. The interference spectral power envelope, P_{spd}, is multiplied with the magnitude squared of the receiver transfer function and then integrated over its spectral bandwidth.

$$P^d_{A_1}(i, j, f_c) = \int_{f_1(j)}^{f_2(j)} P^d_{spd_1}(i, f_c, f) \cdot |H(f)|^2 \, df \qquad (6)$$

where $f_1(j)$ and $f_2(j)$ are the frequency limits of the interference signal within the interfered-with receiver's bandwidth for the jth subcarrier harmonic of mission SC2; $P^d_{spd_1}(i, f_c, f)$, is the spectral power envelope of the interfering signal; and $|H(f)|$ is the magnitude of the receiver transfer function.

For the downlink case, employing the Block III and IV receiver, the receiver bandwidth is referenced to the final IF stage. Similarly, for the uplink case, the typical transponder receiver bandwidth is limited by the predetector filter.

A particularly useful parameter for assessing interference is the ISR. One of the outputs of the adjacent channel interference model is a plot of the aggregate ISR of the new mission and another mission operating in the same frequency band, for some given period of time. As an example, Fig. 9 shows a plot of the downlink adjacent channel ISR for Cassini versus Galileo[4] in the 8-GHz band. This plot shows the periods where the interference levels are expected to exceed the recommended limit.

E. Frequency Optimization Model

An acceptable procedure for determining the optimal channel for a new mission requires an interference analysis that evaluates the overall effect in the DSN as a system,

[4] See footnote 2.

considering both the uplink and downlink telecommunication. This involves the application of some basic analytical calculations, formulation of realistic assumptions, and conclusive evaluation. The automation of the procedure requires implementation of a method which provides a quick and accurate assessment, by which the overall interference impact to the DSN system can be demonstrated parametrically as a function of frequency. Consequently, an optimal channel can be determined without the need for labor-intensive analysis.

The power spectral envelope of the interfering signal within the tracked receiver bandwidth is integrated as a measure of degradation due to interference. The procedure is performed for the uplink and downlink modes, and it takes into account the interference at the SC1 link and the SC2 link (see Figs. 1 and 2), yielding a degradation factor (F_{dgr})

$$F_{dgr} = P^d_{T_1} + P^u_{T_1} + P^d_{T_2} + P^u_{T_2} \qquad (7)$$

where

$$P^d_{T_1} = \sum_{i=1}^{N} P(i)$$

for $P(i) = P^d_{A_1}(i, f_c)$ when $P^d_{A_1}(i, f_c) \geq$ interference criterion.

$$P(i) = 0 \quad \text{otherwise} \qquad (8)$$

where F_{dgr}, $P^d_{A_1}(i, f_c)$, and $P^d_{T_1}$ are, respectively, the degradation factor, the adjacent interference power given by Eq. 5, and the total interference power over the mission period of N days when exceeding the interference criterion.

This process is repeated with the interfering signal placed on all the possible channels to produce a complete set of degradation factors which are interpolated and plotted as a performance degradation curve. The performance degradation curve is calculated for all the DSN mission pairs (SC1/SC2, SC1/SC3, ..., SC1/SCN), and Fig. 10 illustrates an example of the performance degradation curves computed for the Cassini channel assignment. The performance degradation is shown between Cassini (SC1) and some of the existing DSN missions, Galileo, Ulysses, Mars Observer, and the Voyagers.

When all of the degradation curves are assembled into one plot, the result is a frequency optimization curve which indicates the overall trend in degradation to the DSN system across the channel frequency spectrum. The optimization curve is characterized by the outermost peaks, which indicate regions of high levels of interference, and the null values, defined at the intersection of the curves, which indicate regions of relatively low interference. For example, Fig. 10 illustrates the frequency optimization curve for the Cassini channel assignment. The Y-axis represents the daily mutual interference potential, given in "watts·days," whereas the X-axis represents the DSN channel number.

In this example, channel numbers with the lower value on the curve can be considered as viable candidate channels for the Cassini mission. Channels 14, 15, 18, and 19 show corresponding peak values and should be avoided. The candidate channels can then be further assessed for optimization by considering other spectral components, such as ranging and differential-one-way-ranging (DOR) tones. The impact of discrete tones is analyzed using the discrete tone interference algorithm, discussed in the next section. This will ensure that the use of this optimal channel will not cause interference with the introduction of other discrete modulation components.

F. Discrete Tone Interference Analysis and Algorithm

Discrete signal components are known to be other sources of interference that can impact the choice of channel assignment. An analysis of their impact on the interfered-with signal is performed using procedures different from those used for continuous signal component analysis. Among the discrete components of a DSN signal are the special continuous wave (CW) tone signals and the modulation products of the ranging and DOR tones, whose emission spectrum is characterized as a set of harmonically related tones. The frequencies and power levels of these sinusoidal components are easily computed to provide further evaluation of the spectral isolation between channels.

Interference caused by the discrete tones is evaluated in terms of the power ratio of the interfering tone and the interfered-with signal component, and the frequency offset (including Doppler shift) between them. Predefined limits for these two interference criteria will give an indication of whether interference exists.

Figure 11 illustrates the flow diagram for analyzing discrete component interference for DSN uplinks and downlinks. The discrete tone algorithm (DTA) computes the complete set of interference tone frequencies and power levels and tabulates those signal components which lie near the interference tones. Given this information, the analyst can then determine if an intolerable interference situation

exists and whether another channel frequency ought to be examined.

IV. Interference Criteria

A prerequisite for conducting an effective interference evaluation is the establishment of suitable interference criteria. The interference criteria represent thresholds in link parameters and, when exceeded, give an indication of intolerable performance degradation. It can be specified as a numerical value of interference power level, ISR, bit error rate, or another suitable parameter which gives a meaningful indication of the expected degradation in link performance.

The interference criteria used in the analysis are defined as spacecraft-specific interference power limits for the uplink case, and the standard CCIR spectral power density limits for the downlink case. Table 1 shows a sample of the interference criteria used for the DSN tracking station receivers and spacecraft transponder receivers operating in the 2-GHz (S-) and 8-GHz (X-) bands.

The tracking station receiver interference criteria were established through the CCIR to protect the DSN from harmful interference. If the interference signal is assumed to be broadband, its power spectral density received at the threshold level shown in Table 1 will cause an increase in carrier tracking loop noise and, consequently, a degradation of about 1 dB in the output signal-to-noise ratio (SNR). Limitations on the duration of the interference event, as percentages of time, are also specified in conjunction with the interference criteria threshold levels.

The downlink power spectral density limits listed above can be converted to absolute interference power threshold levels with the multiplication of a suitable bandwidth factor. For the Block III and Block IV receivers, a multiplication factor of 10 Hz is used, corresponding to the receiver's most probable tracking loop bandwidth.

Interference criteria threshold levels for the spacecraft are given as absolute power levels and are specified from hardware and link performance considerations. The spacecraft receiver is generally less sensitive to interference than the tracking station receiver. Furthermore, a typical uplink signal occupies far less bandwidth than the downlink signal.

Reference

[1] *Radio Regulations, Appendices 25–44*, Oslo, Norway: Norwegian Telecommunications Administration, pp. AP29-12 – AP29-15, 1982.

Table 1. Interference criteria for DSN tracking station receivers.

Band, GHz	Maximum allowable interference spectral power density, dBW/Hz	Maximum allowable interference spectral power flux density,[a] $dBW/m^2 \cdot Hz$
2.3	−222.5	−255.5
8.4	−220.9	−253.2
13.0	−220.5	−251.7
32.0	−217.3	−239.1

[a] For 70-meter antenna.

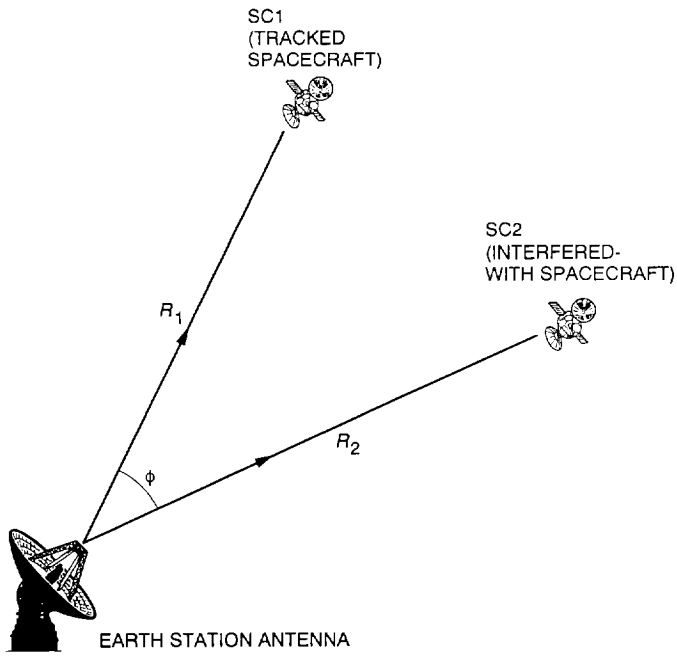

Fig. 1. Interference geometry for uplink.

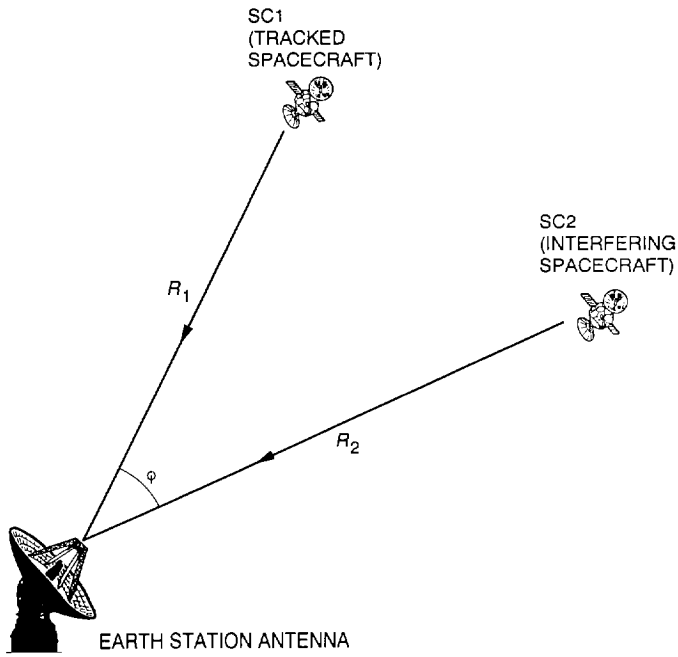

Fig. 2. Interference geometry for downlink.

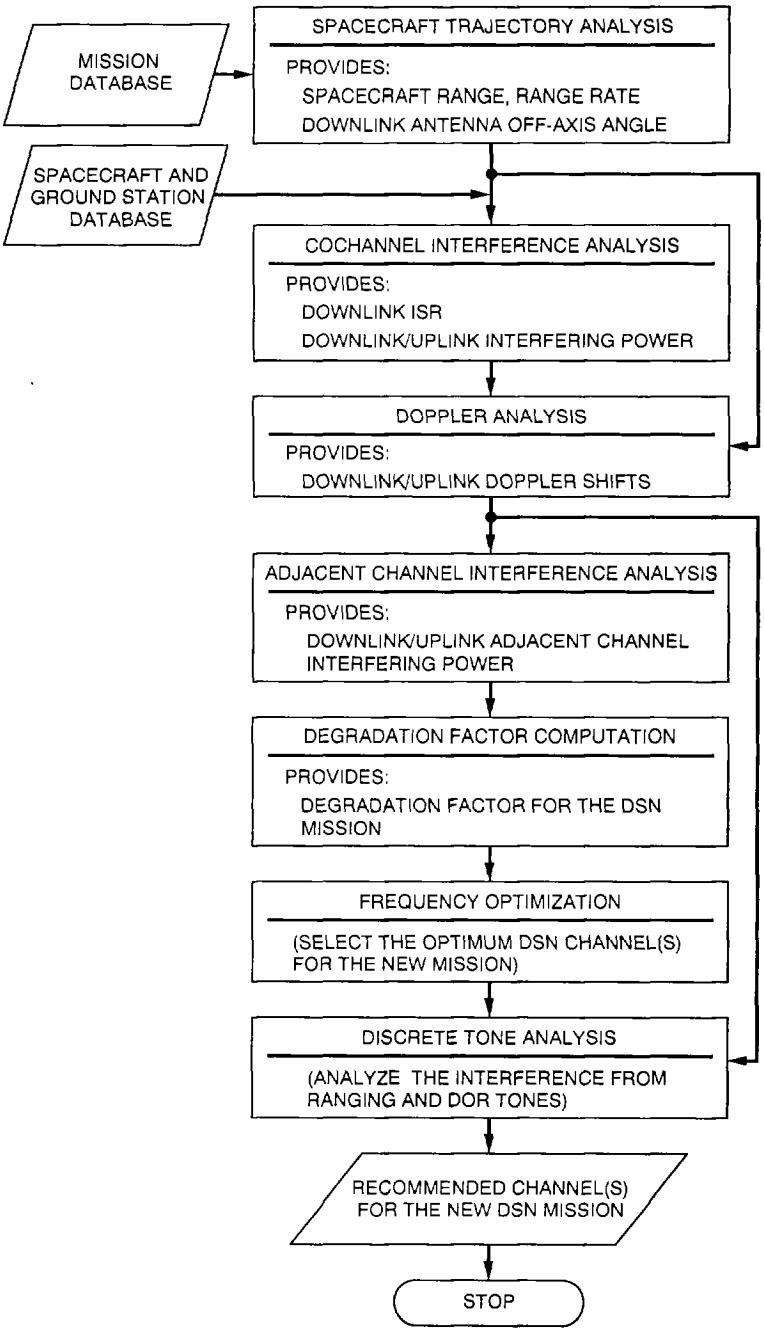

Fig. 3. Block diagram of DSN channel assignment using IAP.

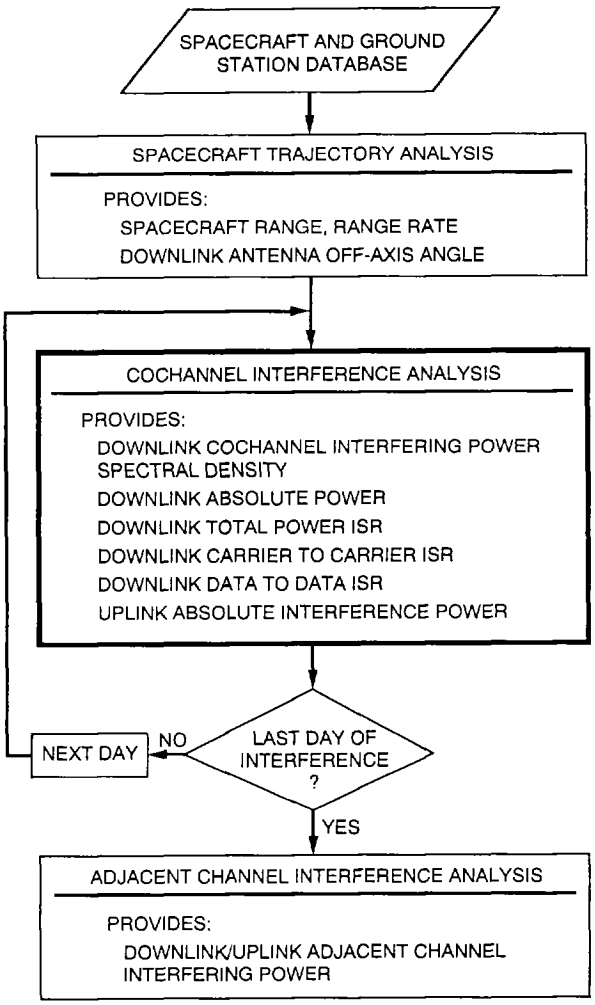

Fig. 4. Cochannel interference analysis.

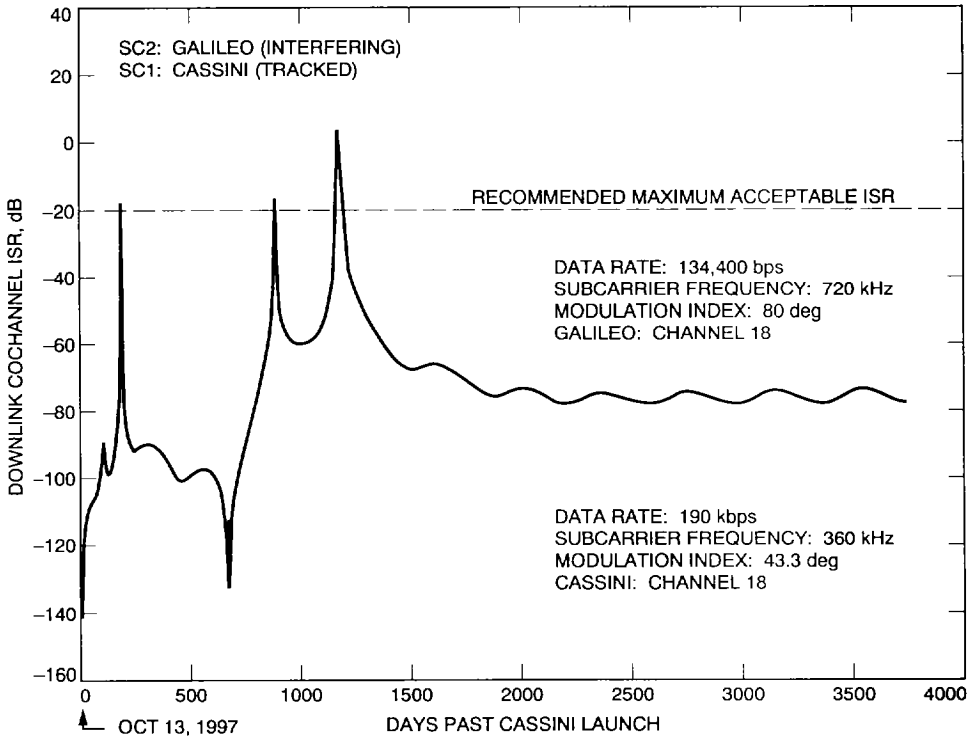

Fig. 5. Downlink total power cochannel ISR from Galileo to Cassini.

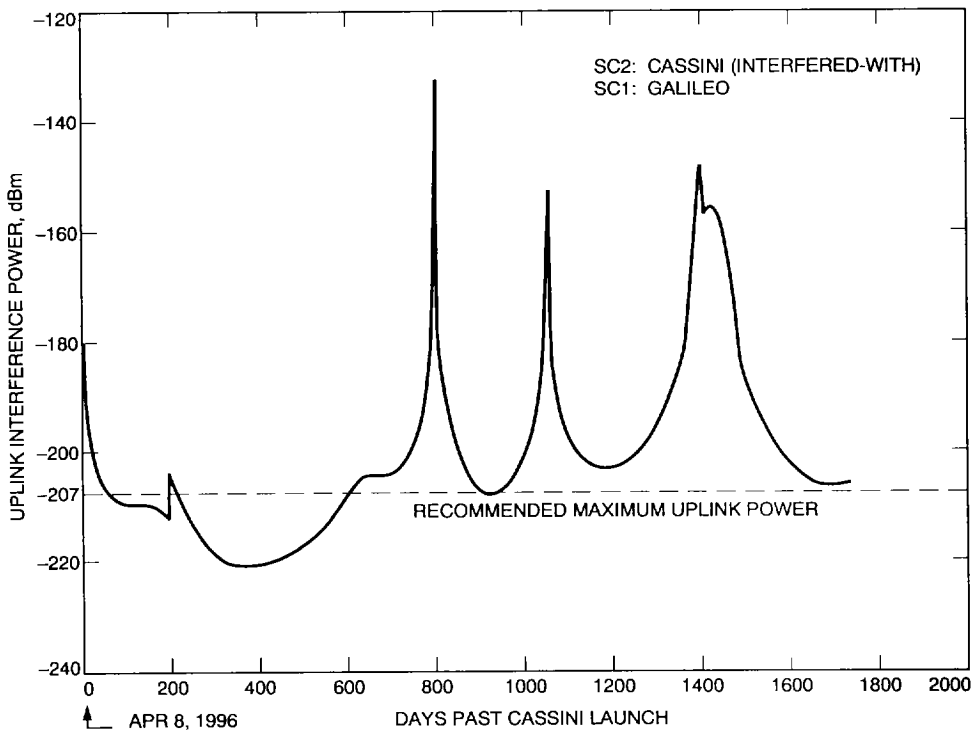

Fig. 6. Uplink cochannel interference power from Galileo to Cassini.

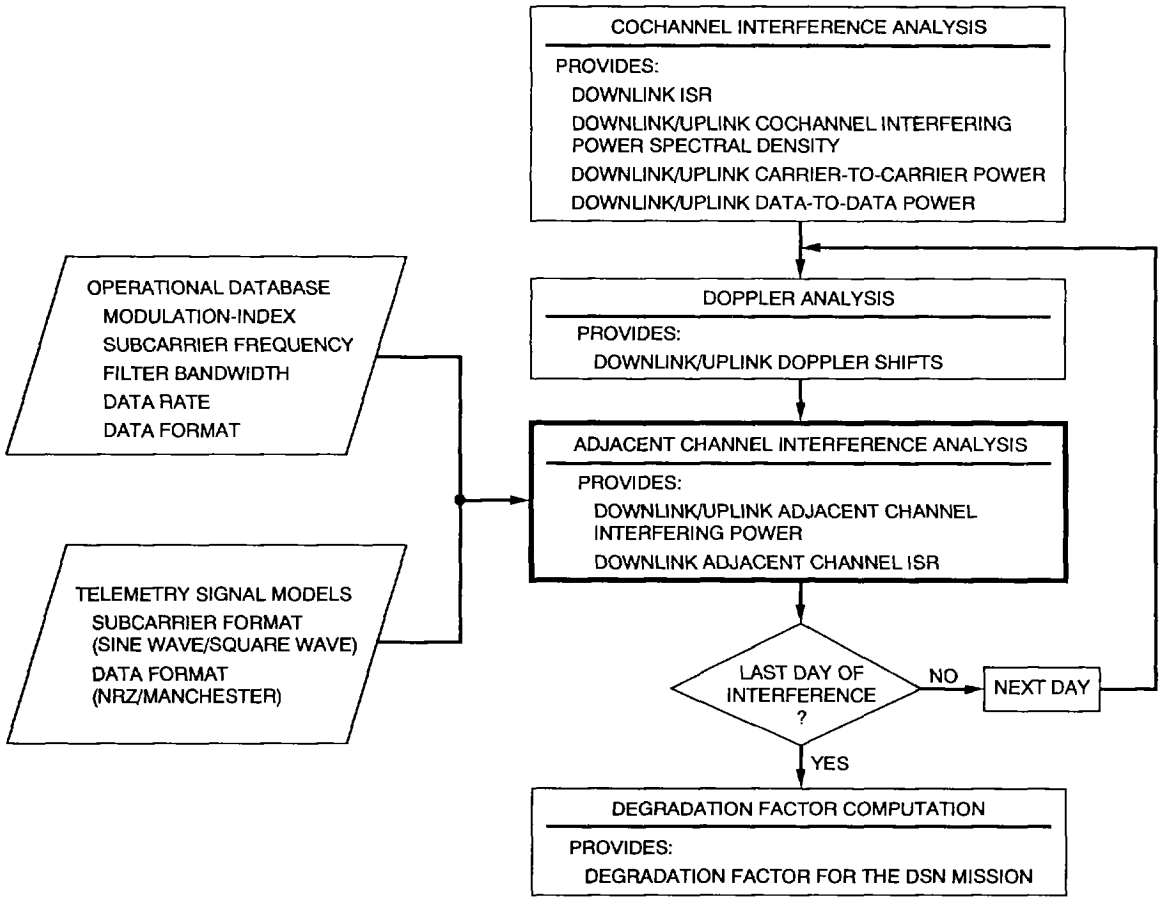

Fig. 7. Adjacent channel interference analysis.

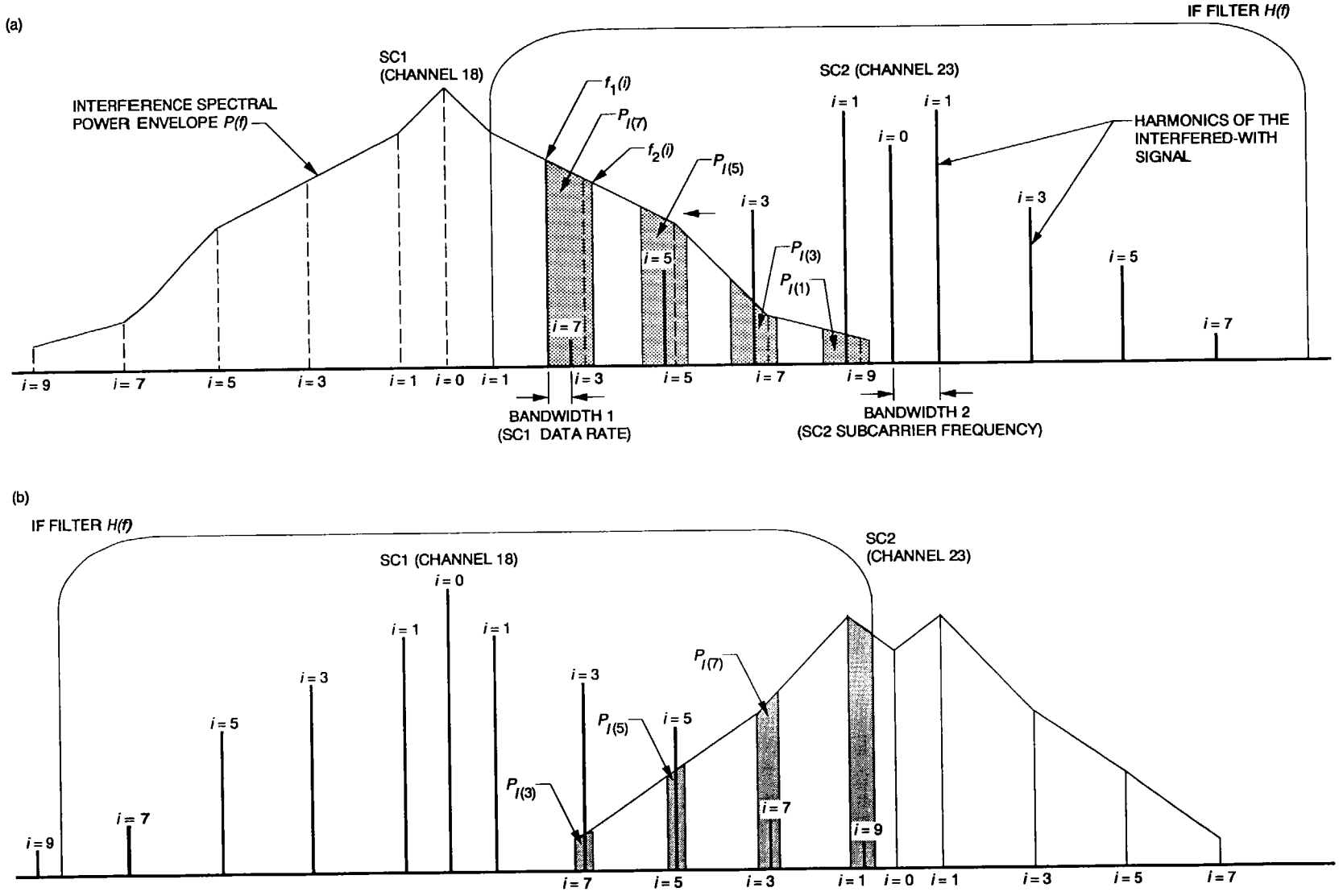

Fig. 8. Interference: (a) from SC1 to SC2 and (b) from SC2 to SC1.

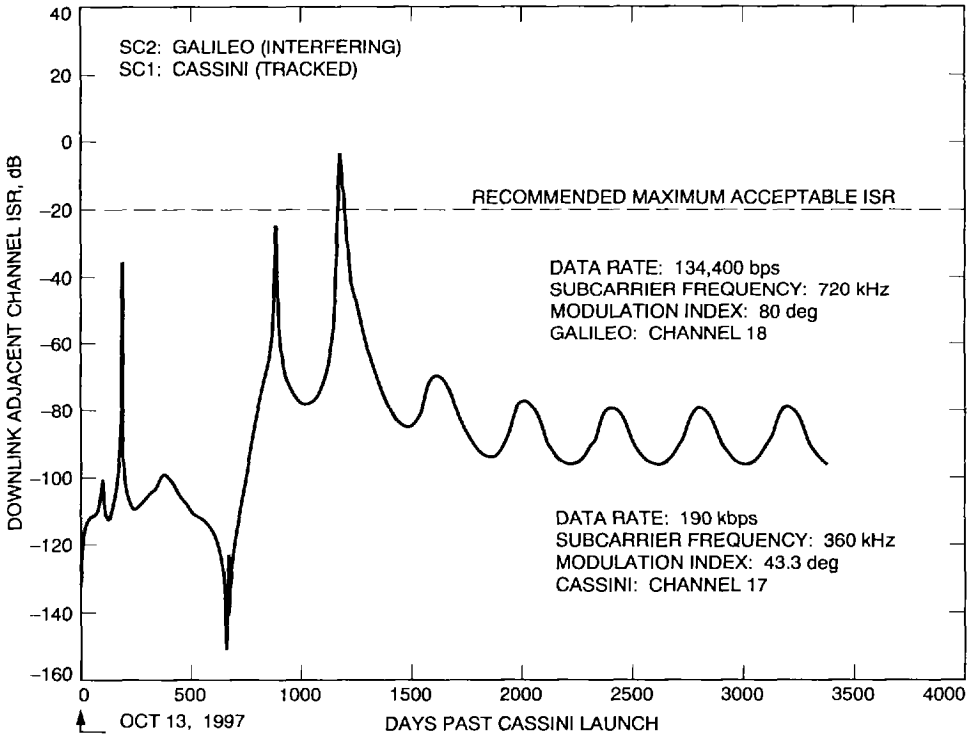

Fig. 9. Downlink adjacent channel ISR for Cassini versus Galileo in the 8-GHz band.

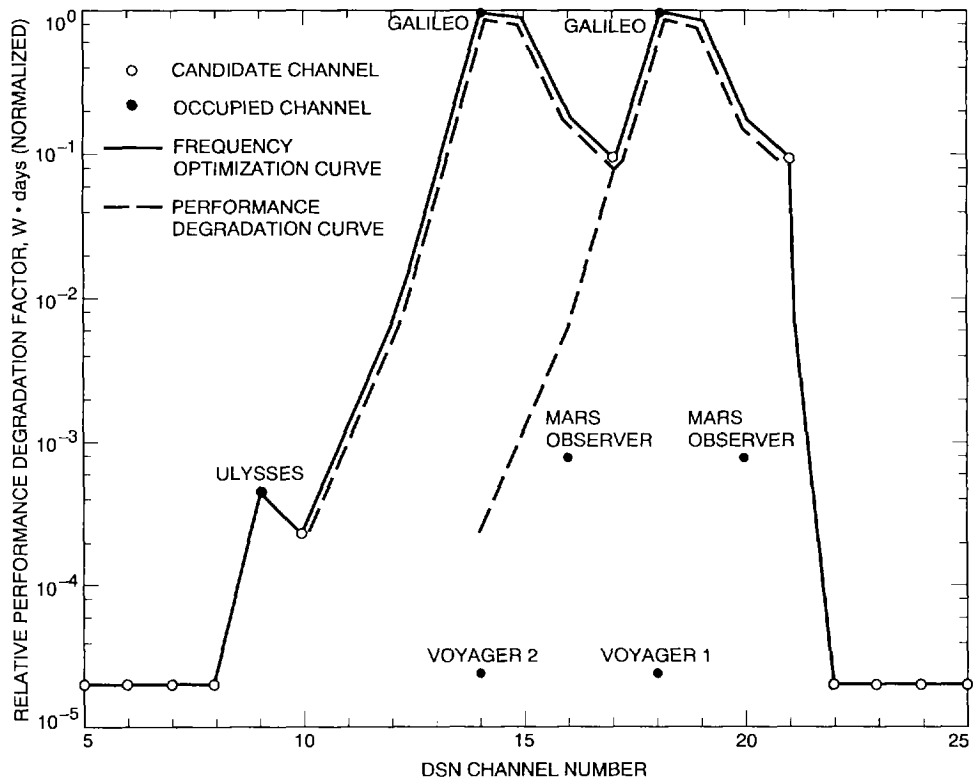

Fig. 10. Frequency optimization curve.

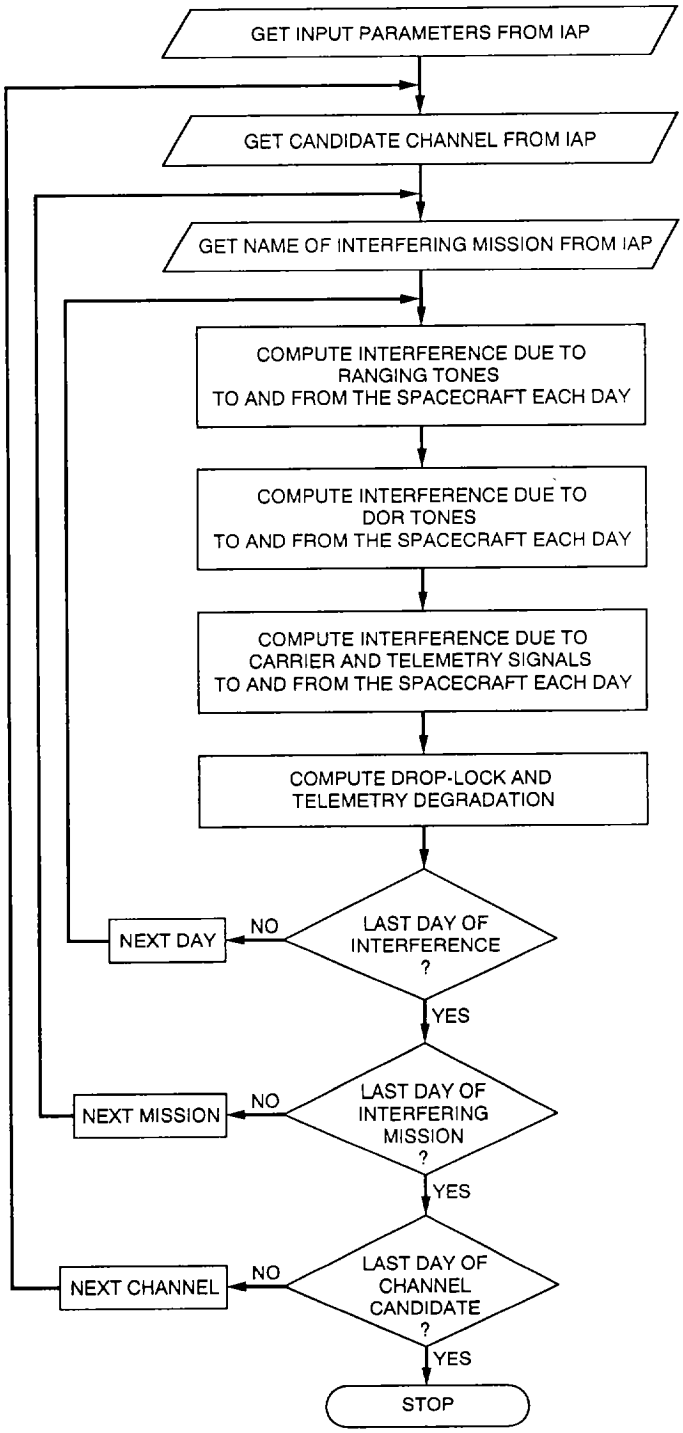

Fig. 11. Block diagram for the discrete tone analysis.