Selection of Frequencies for Deep-Space Telecommunications

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This report explains the procedure used by the Jet Propulsion Laboratory to select and recommend frequencies to be used for deep-space telecommunications. Recommendations are made for missions conducted by the United States and also for other countries or organizations upon request. The report was prepared for the October 1981 meeting of the Space Frequency Coordination Group, held at Oberpfaffenhofen, Federal Republic of Germany. The group included representatives from ten countries and three international organizations, all interested in frequency management issues related to space research.

I. Introduction

As more nations plan to make use of deep-space allocations it becomes increasingly important to cooperate in the selection and assignment of radio frequencies for their new missions. This cooperation is needed to avoid or minimize the possibility of radio frequency interference (RFI) between the telecommunications links of the several missions using each band.

The process used by the Jet Propulsion Laboratory to select frequencies for deep-space missions is described in this report. The process has been used for U.S. missions. It has also been used in response to requests by Japan and the European Space Agency. For appropriate frequency selections to occur, all existing and planned deep-space missions must be considered.

The frequency selection process described in this report deals only with the potential for RFI between deep-space telecommunications links. It does not consider band sharing with other services. It also does not deal with adjacent or harmonic band interference, or with RFI from other spurious emissions.

II. Allocated Bands

The pairs of bands allocated for deep-space telecommunications are shown in Table 1.

III. Channel Plans and Coherence

To provide for orderly selection and assignment of frequencies for deep-space missions, channel plans have been developed within the United States. The plans were based on bandwidth, hardware implementation and frequency ratio considerations. All U.S. deep-space missions utilize frequencies included in the channel plans.

To provide for spacecraft navigation and some types of scientific measurement it is necessary that uplink (Earth-to-space) and downlink (space-to-Earth) transmissions be phase-coherent. This means that the frequency received by the spacecraft transponder must be translated by a fixed ratio and used to control the downlink frequency from the spacecraft.

The requirement for coherence applies between the uplink and downlink frequencies of a band pair. The requirement can also apply to simultaneous transmissions in more than one band pair. Of the four band pairs listed in Table 1, channel plans have been developed for the first two. These plans are shown in Table 2. Table 3 shows the frequency ratios associated with the channel plans.

In Table 2 we see that the channel center frequencies in column 3 lie within the 2290-2300 MHz downlink band. Channel center frequencies in the other bands are a necessary result of the frequency ratios shown in Table 3. A particular channel number, for example channel 17, specifies frequencies in all four bands.

Because of the spacing between allocations and the frequency ratios embodied in the channel plans, some channels in each band are not usable. When complete coherence between the two uplink and two downlink bands is required, the frequencies selected can only be chosen from channels 5-27. Similar channel planning has been proposed for the higher frequency bands. The details of this work are beyond the scope of present frequency selection studies and this report.

IV. The Process of Channel Selection

The selection process is based on calculations and analysis of interference-to-signal power ratios (ISR) as a function of time for each possible pair of missions. The initial calculation assumes that both spacecraft are using the same channel. Co-channel operation is often possible because of the very narrow beams of Earth station antennas and the diverse position and motions of spacecraft engaged in deep space missions.

The worst case ISR is compared to a criterion of acceptable interference. If the ISR meets this criterion for all spacecraft, any channel may be selected. This is true because the co-channel condition was used for the calculation. If the criterion of acceptable interference is not met for the co-channel case, alternatives must be examined. A separate, unused channel may be required. Another possibility is that interference may be acceptable at certain times during each mission.

The ISR calculation is made for each of the two spacecraft in a pair. First, one is assumed to be the desired spacecraft and the other is considered a potential source of interference. The calculation is then repeated for the opposite situation. When separate channels are required, the selection is based on more detailed analysis of the degree of interference, the spectral characteristics of the interfering signals, and the doppler shift caused by relative spacecraft motion.

V. Modes of Interference

The radio frequency signal for deep-space communications normally includes a carrier and one or more sets of data sidebands. Examples of two sets of data sidebands are combined telemetry and ranging signals on a downlink, or combined command and ranging signals on the uplink. When separate data streams are carried on individual subcarriers, there are additional intermodulation products.

Given the necessary frequency relationships, the signals to or from two spacecraft may interfere in one or more of the following ways:

(1) Carrier-to-carrier

(2) Data-to-carrier

(3) Intermodulation product-to-carrier

(4) Carrier-to-data

(5) Data-to-data

(6) Intermodulation product-to-data

These interference modes can occur between uplinks or between downlinks.

In addition, there is a quite different interference mode for the uplink case. Consider the situation where one uplink signal is being transmitted and intended for a particular spacecraft. If this signal is received by another spacecraft and has sufficient strength and the necessary frequency components, it is possible for the receiver in the unintended spacecraft to lock to the uplink signal. This must be avoided if independent operation of the two spacecraft is to be maintained. This interference mode is called one way uplink interference.

In practice, the carrier and the telemetry sidebands are usually the most susceptible to interference between downlinks. The predominant mode for uplinks is the one-way uplink interference.

VI. Interference Protection Ratio

The acceptable ratio of interference to signal power is called the interference protection ratio. The protection ratio used for channel selection purposes is –15 dB, i.e., the maximum allowable effective interference power is 15 dB below the signal power. The signal power refers to the portion of the received signal that is related to a particular function: carrier tracking, telemetry, command, or ranging. A –15 dB ratio will produce negligible effect on carrier tracking performance (Ref. 1, 2), 0.4 dB degradation of telemetry performance and 1.0 dB degradation of command performance, assuming that both the telemetry and command are operating at a symbol error rate of 10^{-5}.

The protection ratio may seem conservative. It is justified by the fact that the frequency selection study usually is performed in a very early phase of a mission when uncertainties exist about many parameters which can affect the interference situation. Additionally, it is a goal of channel selection to provide the safest environment so that mission planners will have maximum flexibility.

The maximum acceptable uplink one-way interference is called the uplink one-way threshold. It is equal to the spacecraft receiver sensitivity. This sensitivity is usually in the range from -155 to -165 dBm. The maximum allowable interference power level as determined by either the protection ratio or the uplink one-way threshold is referred to as the interference threshold. Interference is said to exist whenever this value is exceeded.

VII. Interference Analysis

There are four steps in the interference analysis and channel selection process:

(1) Determine the interference and the signal power levels.

(2) Determine the likely modes of interference: carrier-to-carrier interference, carrier-to-data interference, etc.

(3) Determine the time and duration of potential interference.

(4) Select one or more channels to minimize the potential interference. Avoid potential interference during critical mission events.

To achieve these, it is necessary to have the following information for all the missions involved:

(1) Characteristics of the telecommunication system.

(2) Expected modes of operation as a function of time.

(3) Dates of important mission events.

(4) Orbital elements that specify the mission trajectory.

A complete list and description of the above items are provided in Appendix A.

A computer program has been developed to assist in the calculations needed for interference analysis. This program examines two missions at a time. It accepts as its input a set of orbital elements that completely specify the trajectories of the missions being examined. Based on these orbital elements, it computes for both missions the spacecraft-to-Earth range, the doppler rate, and the angular separation between the two spacecraft. From these data and an assumed fixed e.i.r.p., it then computes the ratio of the total received signal power to the total received interference power (TSIR)[1] and the uplink interference power level as received by the spacecraft. The calculations are made for selected intervals of time during the period of operation that is common for a particular pair of missions.

A. Downlink Interference Analysis

The Earth station receiving antenna is assumed to be pointing at the desired spacecraft and receiving data from it (Fig. 1). Downlink interference occurs when the signal from the other spacecraft exceeds the protection criterion. The downlink TSIR is calculated by the computer program for both missions assuming an equal e.i.r.p. The equations for the computation are:

$$TSIR_1 = G_{MAX} - G(\theta) - 20 \log_{10} (R_1/R_2)$$

$$TSIR_2 = G_{MAX} - G(\theta) + 20 \log_{10} (R_1/R_2)$$

where G_{MAX} is the gain of the receiving antenna in dBi, R is the spacecraft-to-Earth range, $G(\theta)$ is the gain of the receiving antenna in the direction of θ, and the subscripts 1 and 2 refer to the two missions, with 1 being arbitrarily assigned to one mission and 2 the other. The off-axis antenna gain $G(\theta)$ is modeled by the following expressions:

$$G(\theta) = G_{MAX} - (G_{MAX} - 32) \cdot \theta \text{ dB} \quad \text{for } 0^\circ \leqslant \theta < 1^\circ,$$

$$= 32 - 25 \log_{10} (\theta) \text{ dB} \quad \text{for } 1^\circ \leqslant \theta < 48^\circ,$$

$$= -10 \text{ dB} \quad \text{for } 48^\circ \leqslant \theta$$

The next step is to determine the potential modes of interference based on the spectra of the desired signal and the interference. Knowledge of the interference effects on various parts of the system is necessary in this step.

Basically, the interference modes can be determined by finding out which part of the unwanted signal can spectrally interfere with which part of the signal; carrier-to-carrier interference, data-to-carrier interference, etc. An unwanted signal can spectrally interfere with a wanted signal if they are close in frequency. Since the doppler frequency can move the two spectra closer to or farther from each other, it may be necessary

[1]The program calculates TSIR; the protection ratio is usually specified inversely, that is, interference-to-signal.

to consider the doppler effects in determining the modes of interference, particularly when the doppler rate is significant.

The computer program calculates the total interference power. The analyst must consider the amount of interference power that applies to a particular interference mode. The effective interference power of an in-band CW interference is simply equal to the power of the interference. The effective interference power of an interference having a dense spectrum is equal to the power of the interference reduced by a factor equal to the bandwidth conversion factor. The bandwidth conversion factor is defined as the ratio of the bandwidth of the interfered channel to the bandwidth of the interference. The maximum value of the bandwidth conversion factor is unity.

Having determined the interference modes, it is then necessary to calculate the effective interference-to-signal ratio. This ratio can be derived from the total signal-to-interference ratio as follows:

$$EISR = P_W - P_I - TSIR$$

where P_W denotes the power of the wanted signal being interfered with and P_I denotes the effective power of the interference. For example, if the interference mode is carrier-to-data, then the effective interference power is the carrier power of the unwanted signal and the signal power is the power in the data sidebands of the wanted signal.

The effective interference-to-signal ratio can then be compared with the protection ratio. If the protection ratio is exceeded, interference exists. The total number of days for which interference exists is calculated and used as a measure of the amount of potential interference between a given mission pair. This process is repeated for all mission pairs of interest. A detailed step-by-step analysis of the downlink potential interference is provided in Appendix B for a hypothetical system.

B. Uplink Interference Analysis

There are two situations in which an unwanted uplink signal constitutes an interference to a spacecraft. The first is when the effective interference-to-signal ratio exceeds the protection ratio. The second is when the level of an uplink signal as received by a spacecraft exceeds the receiver threshold of that spacecraft for which the uplink signal is not intended. The analysis for the first situation is very similar to the analysis of downlink interference with the exception that the total signal-to-interference ratio is given by a different expression and is the same for both missions. The expression is:

$$TSIR = G_{MAX} - G(\theta)$$

To evaluate the amount of potential interference for the second situation, the power of an unintended uplink as received by a spacecraft located in a direction θ degrees from the main axis of the DSN transmitting antenna is calculated:

$$PU_1 = PT + G(\theta) + 20 \log_{10} \left(\frac{\lambda}{4\pi}\right) - 20 \log_{10} (R_1),$$

and

$$PU_2 = PT + G(\theta) + 20 \log_{10} \left(\frac{\lambda}{4\pi}\right) - 20 \log_{10} (R_2)$$

where PU is the power of the unintended signal, PT is the DSN transmitter output power, $G(\theta)$ is the gain of the transmitting antenna in the direction of θ, λ is the wavelength of the uplink signal, R and the subscripts 1 and 2 are as defined before. The interference power as calculated by the above expressions assumes an isotropic receiving antenna. It is therefore necessary to increase the interference power by an amount equal to the receiving antenna gain before it can be compared to the interference threshold to determine the amount of potential interference.

VIII. Additional Selection Considerations

In the future it may not be possible to select a channel that is completely free of potential interference. This might be the result of many missions sharing a particular band. It will then be necessary to select a channel where the time and severity of interference is such that the most important parts of the affected missions are protected.

Deep-space missions usually have periods of intense activity separated by longer periods of relatively low activity. Interference during the quiet periods will often be acceptable. The potential interference may be strong and virtually destroy successful telecommunications, or it may only cause a slight degradation of performance. The severity of interference therefore affects the choice of channel.

Often, more than one frequency band is used on a mission. The potential interference is usually different for different frequency bands. It may be necessary to examine the potential interference for all frequency bands involved before a selection can be made. Since these frequencies are related to each other by a fixed translation ratio, the resulting channels may be optimal in one band, but not in the other.

IX. Conclusion

The trend of deep-space exploration is toward higher data rates and longer mission life times. Higher data rates tend to require additional bandwidth. Missions with a life time of 10 to 20 years are currently under study. The combination of high data and long life times will increase the opportunity for mutual interference among deep-space missions. The interference analysis and channel selection process described in this paper is a means to minimize such interference and to assure the efficient use of the deep-space frequency spectrum. While the process does not guarantee that a channel or channels completely free of interference can always be found, it does lead to the selection of the best available channel and, equally important, it provides information regarding the resulting potential interference. This information can help mission planners to minimize the effects of the anticipated interference.

References

1. Sue, M. K., "Block IV Receiver Tracking Loop Performance in the Presence of a CW RFI," *TDA Progress Report 42-60, September and October, 1980*, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1980.
2. Sue, M. K., "Telemetry Degradation Due to a CW RFI Inducted Carrier Tracking Error for the Block IV Receiving System with Maximum Likelihood Convolutional Decoding," *TDA Progress Report 42-61, November and December, 1980*, Jet Propulsion Laboratory, Pasadena, Calif., Feb. 15, 1981.

Table 1. Allocations for deep-space telecommunications

Earth-to-Space	Space-to-Earth
2110-2120 MHz	2290-2300 MHz
7145-7190 MHz	8400-8450 MHz
16.6-17.1 GHz	12.75-13.25 GHz
34.2-34.7 GHz	31.8-32.3 GHz

(There are some qualifications affecting these allocations; see the Radio Regulations.)

Table 2. Channel center frequencies

Channel	2110-2120 MHz uplink channel center frequency, MHz	2290-2300 MHz downlink channel center frequency, MHz	7145-7190 MHz uplink channel center frequency, MHz	8400-8450 MHz downlink channel center frequency, MHz	Remarks
1		2290.185185	7147.286265		
2		2290.555556	7148.442131		
3		2290.925926	7149.597994		
4		2291.296296	7150.753857		
5	2110.243056	2291.666667	7151.909724	8402.777780	
6	2110.584105	2292.037037	7153.065587	8404.135803	
7	2110.925154	2292.407407	7154.221450	8405.493826	
8	2111.266204	2292.777778	7155.377316	8406.851853	Channels
9	2111.607253	2293.148148	7156.533179	8408.209876	
10	2111.948303	2293.518519	7157.689045	8409.567903	5-27
11	2112.289352	2293.888889	7158.844908	8410.925927	
12	2112.630401	2294.259259	7160.000771	8412.283950	are
13	2112.971451	2294.629630	7161.156637	8413.641977	
14	2113.312500	2295.000000	7162.312500	8415.000000	fully
15	2113.653549	2295.370370	7163.468363	8416.358023	
16	2113.994599	2295.740741	7164.624229	8417.716050	coherent
17	2114.335648	2296.111111	7165.780092	8419.074073	
18	2114.676697	2296.481481	7166.935955	8420.432097	in
19	2115.017747	2296.851852	7168.091821	8421.790124	
20	2115.358796	2297.222222	7169.247684	8423.148147	all
21	2115.699846	2297.592593	7170.403550	8424.506174	
22	2116.040895	2297.962963	7171.559413	8425.864197	four
23	2116.381944	2298.333333	7172.715276	8427.222220	
24	2116.722994	2298.703704	7173.871143	8428.580248	bands
25	2117.064043	2299.074074	7175.027006	8429.938271	
26	2117.405092	2299.444444	7176.182868	8431.296294	
27	2117.746142	2299.814815	7177.338735	8432.654321	
28	2118.087191		7178.494597	8434.012344	
29	2118.428241		7179.650464	8435.370371	
30	2118.769290		7180.814838	8436.738395	
31	2119.110339		7181.962190	8438.086418	
32	2119.451389		7183.118056	8439.444445	
33	2119.792438		7184.273919	8440.802468	
34			7185.429783	8442.160493	Channels
35			7186.585617	8443.518517	34-39
36			7187.741511	8444.876542	frequencies
37			7188.897375	8446.234566	are estimates
38				8447.592591	only
39				8448.950616	

Table 3. Channel frequency ratios

Band pair	Channel frequency ratio
2110-2120 MHz, 2290-2300 MHz	$\frac{221}{240}$
7145-7190 MHz, 8400-8450 MHz	$\frac{749}{880}$
2290-2300 MHz, 8400-8450 MHz	$\frac{3}{11}$

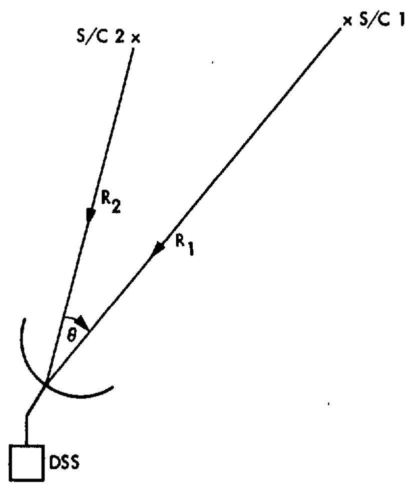

Fig. 1. Downlink interference situation with spacecraft 2 as the interferer

Appendix A

Parameters Needed for Interference Analysis and Channel Selection

I. Information Needed for Detailed Study

Information needed from flight projects in order to perform an interference analysis and subsequent channel selection is detailed in the following paragraphs.

A. Information About the Characteristics of the Telecommunication Systems

(1) Spacecraft antenna gain (for all antennas at their operating frequencies).

(2) Spacecraft transmitter power output (for all possible transmitter modes).

(3) Modulation schemes (including carrier modulation, subcarrier modulation, subcarrier frequencies, number of subcarriers, type of subcarriers, i.e., squarewaves or sinusoids, modulation indices, coding schemes.)

(4) Transmitted data rate or symbol rate.

(5) Number of uplink carrier frequencies, downlink carrier frequencies and their interrelationship.

(6) Frequencies preferred for reasons independent of interference considerations.

(7) Earth receiving station antenna gain.

(8) Spacecraft receiver sensitivity.

B. Expected Modes of Operation as a Function of Mission Phase

These modes are, for example, different combinations of antenna, transmitter power, frequency band, etc.

C. Dates of Important Mission Phases

Dates such as encounter, maneuver, landing, etc., where interference is less tolerable.

D. Mission Trajectory Data

Orbital elements that specify the trajectory of a mission are needed. It is preferred that the orbital elements be provided in the form of classical orbital elements using "Sun Centered, Earth Equator and Equinox of 1950" as a reference frame. The following parameters are needed:

(1) Six classical orbital elements:

Semimajor axis a	Node angle Ω
Eccentricity e	Argument of periapsis ω
Inclination i	Mean anomaly M

(2) Epoch for the above set of elements.

(3) Reference frame used for the above orbital elements. (It is preferred to use "Sun Centered, Earth Equator and Equinox of 1950" as a reference frame.)

(4) Time period for which the above set of elements are applicable.

(5) Launch date.

(6) Arrival date.

(7) Destination.

(8) Expected date for end of mission (EOM).

II. Information Needed for Rough Estimation

Parameters listed in preceding paragraphs constitute a complete set of information needed for frequency selection study. Some of these data may not be available at the early phase of mission design. It is possible, even with an incomplete set of data, to perform a frequency selection study by using typical parameter values or worst-case values, whichever is appropriate. This, however, may place unnecessary restrictions on channel selection. As a minimum, the following parameters are needed for a crude estimation:

A. Characteristics of the Telecommunication Systems

(1) Spacecraft antenna gain.

(2) Spacecraft transmitter power output.

(3) Earth station antenna gain.

(4) Number of uplink and downlink carrier frequencies and their interrelationship.

(5) Frequency preferred for reasons independent of interference consideration.

B. Mission Trajectory Data

In general, all trajectory parameters listed in the previous paragraph are needed. In some special cases where the trajectory of a spacecraft does not consist of any breaks, it is possible to estimate the trajectory by specifying the following parameters:

(1) Launch date.

(2) Arrival date.

(3) Destination.

(4) End of mission date.

Appendix B

Determination of Potential Interference

I. Introduction

This appendix illustrates the necessary steps to determine if potential downlink interference exists. The two spacecraft examined are designated as 1 and 2. Spacecraft 1 is arbitrarily chosen as the wanted spacecraft and the other as the source of interference. Thus, this appendix examines only interference to spacecraft 1 from spacecraft 2. The interference from spacecraft 1 to spacecraft 2 can be obtained by following the same procedures.

II. Assumptions

The hypothetical system used here has the following characteristics:

	Spacecraft 1	Spacecraft 2
Downlink e.i.r.p., dBw	35	30
Antenna gain, dBi	30	25
Telemetry symbol rate, bps	10k	20k
Telemetry subcarrier frequency, kHz	300	300
Telemetry modulation angle, deg	80	40
Number of subcarrier channels	1	1

The doppler frequency and the total signal-to-interference ratio computed by the program are assumed to have the following values:

	Spacecraft 1	Spacecraft 2
Downlink TSIR, dB	0	40
Doppler frequency, kHz	2	1

Both spacecraft are assumed to occupy the same frequency channel.

III. Interference Modes

To determine the interference modes, it is necessary to examine the spectra of the signal and the interference. A sketch of the spectra of these two signals is shown in Fig. B-1. From the sketch, it can be seen that there are two interference modes: carrier-to-carrier and data-to-data. The potential interference for both modes is discussed in the following sections.

IV. Carrier-To-Carrier Interference

To determine if potential interference exists for this interference mode, it is necessary to calculate the power of the wanted signal and the power of the unwanted signal in the carrier channel. The power of the wanted signal in the carrier channel is simply the carrier power of the wanted signal, i.e., the carrier power of spacecraft 1. The unwanted power is the carrier power of spacecraft 2. The wanted and unwanted power can be calculated as follows:

Spacecraft 2 downlink e.i.r.p.	35.0 dBw
Modulation loss (20 log (cos (80°))	-15.2 dB
Wanted power level	19.8 dBw

Spacecraft 2 downlink e.i.r.p.	30.0 dBw
Modulation loss (20 log (cos (40°))	-2.3 dB
Unwanted power level	27.7 dBw

The effective interference-to-signal power is thus equal to:

$$EISR = PW - PI - TSIR$$

$$= 19.8 \text{ dBw} - 27.7 \text{ dBw} - 0 \text{ dB} = -7.9 \text{ dB}$$

which exceeds the protection ratio by about 7 dB. Potential interference to the carrier of spacecraft 1 thus exists.

V. Data-To-Data Interference

To determine if this mode of interference exists it is necessary to calculate the data power of spacecraft 1 and spacecraft 2. These power levels can be calculated as follows:

Spacecraft 1 downlink e.i.r.p.	35.0 dBw
Modulation loss (20 log (sin (80°))	-0.1 dB
Wanted power level	34.9 dBw

Spacecraft 2 downlink e.i.r.p.	30.0 dBw
Modulation loss (20 log (sin (40°))	-3.8 dB
Unwanted power level	26.2 dBw

Since the unwanted signal has a dense spectrum, it is necessary to adjust the unwanted signal power according to the bandwidth conversion factor. The bandwidth conversion factor, B_F, is defined as follows:

$$B_F = \begin{cases} B_w/B_I & B_w < B_I \\ 1 & B_w \geqslant B_I \end{cases}$$

where B_w is the bandwidth of the signal and B_I is the bandwidth of the interference. Since the bandwidth of a data channel is proportional to the data rate, the bandwidth conversion factor can thus be calculated from the following equation.

$$B_F = \frac{(Data\ rate)_1}{(Data\ rate)_2} = \frac{10\text{k}}{20\text{k}} = 1/2 \text{ or } -3 \text{ dB}$$

where the subscripts 1 and 2 refer to spacecraft 1 and spacecraft 2 respectively.

The effective power is thus equal to 26.2 dBw −3.0 dB = 23.2 dBw and the effective interference-to-signal ratio is 23.2 dBw − 34.9 dBw = −11.7 dB. Since this value exceeds the protection ratio, interference to the data channel of spacecraft 1 is said to exist.

VI. Conclusion

The foregoing analysis of a simple hypothetical case serves only as an illustration of the techniques used for interference analysis. Real spacecraft often employ more than one subcarrier channel on the downlink and their spectra are thus more complicated. As a result, interference analysis of an actual system is more involved.

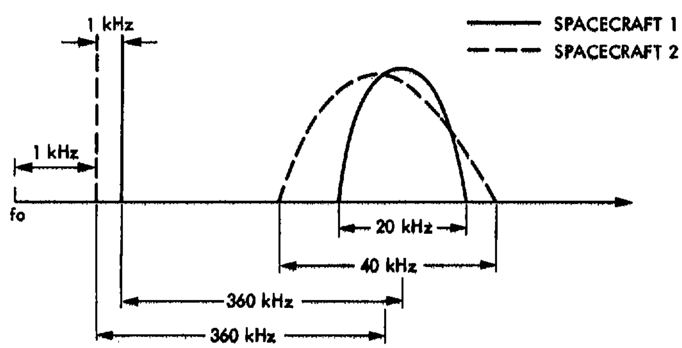

Fig. B-1. Sketch of the spectra of the signal and the interference