Impact of Interference on the Receiving Systems of the Deep-Space Network (DSN) Earth Stations Operated by NASA due to Adjacent Band Emissions from Earth Exploration Satellites Operating in the 8025-8400 MHz Band

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Abstract

The Earth Exploration Satellites operating in the 8025-8400 MHz band can have strong adjacent band emissions in the 8400-8450 MHz band that is allocated for Space Research Service (Category-B). The 8400-8450 MHz band is used extensively to support the vital communication and navigation links between a deep-space spacecraft and Earth stations. The unwanted adjacent band emission may exceed the protection criterion established by the ITU-R for the protection of the deep space Earth stations by a large amount and result in harmful interference to the DSN. Although the duration of most interference events is very brief for a typical EESS satellite, the impact on the DSN could be significant and result in severe loss of data for many reasons. This paper will first describe the characteristics of interference from a typical EESS satellite, including the intensity, frequency and duration of such interference. The paper will then discuss the DSN interference susceptibility, including the various components in the receiving systems that are susceptible to interference and the recovery time after a strong interference. Finally, the paper will discuss the impact of interference on science data and missions operations.

1. Introduction

The 8400-8450 MHz band allocated for Space Research Service (SRS) (Category B) space-to-earth is often called the deep-space downlink X-band. This band is used extensively to support the vital communication and navigation links between a deep-space spacecraft and earth stations. Adjacent to the deep-space downlink X-band, the 8025-8400 MHz Earth Exploration Satellite Service (EESS) band is allocated for the downlinks of earth exploration satellites. Because of the proximity of these two frequency bands, the adjacent band emission of EESS satellites can interfere with the sensitive deep-space X-band downlinks. To make the matters worse, the EESS downlinks typically have much higher power flux density than the deep-space spacecrafts, some of which have travel beyond the edge of our solar system.

In this paper, we'll first discuss the characteristics that are unique to the deep-space downlinks and then present the characteristics of the EESS out-of-band interference to the deep-space downlink X-band. The effects of the interference on the deep-space X-band downlinks will then be described.

2. Characteristics of Deep Space Links

The deep-space downlinks have several unique characteristics that are different from the downlinks of spacecrafts and satellites near the Earth. Due to the large distances from Earth and often very limited power resources of the deep-space spacecrafts, the received signals of the deep-space X-band downlinks are usually very weak. To compensate for the low received power and protect the integrity of the data, deep-space tracking stations have large aperture antennas (upto 70 m), sensitive receiver with very low system temperature and the data strong error correction codes, and low data rates (as low as a few bits per second)

are all used to ensure the integrity of the data.

Despite all these measures, the deep-space X-band downlinks generally have very little link margins and are susceptible even to very low-level interference.

Recognizing the extreme sensitivity of the deep-space earth stations and the importance of these links to the success of deep-space missions, the ITU-R established a protection criterion of –221 dB(W/Hz) to protect these earth stations from harmful interference (REC. ITU-R SA. 1157).This protection criterion corresponds to 1 dB increase in the noise floor of the deep-space ground receivers. While such degradation may be acceptable for some of the deep-space missions during some of the mission phases, it can still result in a loss of critical data for some missions. . The deep-space community at NASA has in practice adopted a more stringent criterion to protect deep-space missions from harmful interference, corresponding to 0.1 dB increase in the noise floor, or – 230 dB(W/Hz).

The deep-space unlinks and downlinks are also used for radio science experiments. That is, the characteristics of the deep-space received signal, such as signal strength, phase, etc, are used by scientists to conduct experiments. When an interference event occurs, it is difficult if not impossible for the scientists to determine whether the perturbation of the signal is due to the observed natural phenomenon or an interference event.

In addition, unlike EESS satellites or other satellite services where tracking stations can be located all over the world and often concentrated at high latitudes for near-polar orbits, the deep space tracking stations are usually located in a radio-quiet areas. Their sites are selected so that they can track deep-space spacecrafts continuously, twenty-four hours a day. NASA’s Deep Space Network (DSN) have tracking stations in Goldstone, California, Madrid, Spain, and Canberra, Australia. Other space agencies have their own deep-space tracking networks.

3. Characteristics of EESS Out-of-Band Interference

Because of the large aperture of the deep-space tracking stations, the EESS satellites typically interfere with the deep-space downlink X-band when they fly close to the boresight of the deep-space tracking station antenna. That is, interference occurs when the cone-angle from the deep-space tracking station to the deep-space spacecraft and the EESS satellites is small. With the examples of the potential interfering EESS satellites in [1], the EESS satellites can exceed the deep-space protection criterion as much as 55 dB assuming the deep-space antenna is directly pointing at the EESS satellites and no interference mitigating techniques like the use of transmit filters or directive antennas are used by the EESS satellites. Using the antenna model from ITU-R [2], the excess interference power can by reduced if the EESS satellites do not come within 3.2° of the boresight of a deep-space tracking station and spacecraft that the station is communicating with.

To get a better understanding of the length of interference events from an EESS satellite to a deep-space tracking station when the satellite can come within 3.2° of the tracking antenna's boresight, simulations have been performed. The DSN Goldstone site is selected as the deep-space tracking station receiving X-band downlinks from a spacecraft from Mars. The deep-space spacecraft transmits only when it is above the 6° tracking station elevation mask. The interfering EESS satellite is assumed to be in a sun-synchronous orbit with an altitude of 705 km and an orbit inclination angle of 98.2 degrees. Simulations show that the EESS satellite can potentially interfere with the Mars-to-Earth X-band downlink about 700 sec/year or about thirty-five interference events with an average interference period of twenty seconds each. The effects of each of the interference event on the deep-space X-band downlink can last much longer than the interference period resulting in significant lost of data. Details of how the deep-space X-band downlink may be affected are described in the subsequent section.

4. Description of a Deep Space Receiving System

The instrumentation of the typical Deep Space Station (DSS) is diagrammed in Figure 1. The downlink signal from the antenna is amplified by a cryogenically cooled Low-Noise Amplifier (LNA). Downconversion and demodulation occur within the Downlink Tracking & Telemetry Subsystem (DTT). The detected (but as yet undecoded) telemetry signal from the DTT is sent to decoders (not shown in Figure 1). An intermediate-frequency signal from within the DTT is sent to the Radio Science Receiver (RSR) for the extraction of signal properties of interest to radio science experimenters. Within the DTT, the ratio of the carrier signal power to the noise spectral density is periodically measured. These measurements are sent to the Antenna Pointing Assembly (APA), which produces a scan pattern to be used by the Antenna Control System (ACS). The transmitter is located within the Uplink Subsystem (UPL). Radiometric data, from which the range and the Doppler shift may be inferred, are sent from both the DTT and the UPL to the Tracking Data Delivery Subsystem (TDDS).

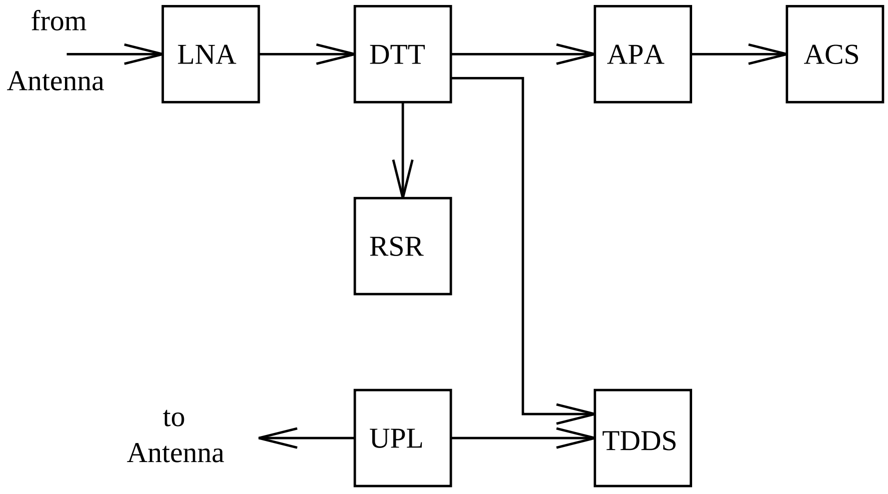

Figure 1: Deep Space Station Instrumentation

At most stations, the LNA that amplifies the signals in the 8400-8450 MHz band is an Indium Phosphide (InP) High Electron Mobility Transistor (HEMT) amplifier [3]. The HEMT amplifier has a 3-dB bandwidth of 490 MHz. At a fewer number of stations, the LNA is a maser [4] with a 3-dB bandwidth of 140 MHz.

The receiver in the DTT is a multiple-conversion superheterodyne receiver [5]. The bandwidth narrows with each succeeding stage. The first Intermediate-Frequency (IF) stage has a center frequency of about 340 MHz and a 3-dB bandwidth of 227 MHz. The second IF stage, which is produced by an upconversion from the previous stage, has a center frequency of 1300 MHz with a 3-dB bandwidth of 110 MHz. The third IF stage has a center frequency of 200 MHz with a 3-dB bandwidth of 72 MHz. The bandwidth of this third IF stage is set by an anti-aliasing filter, whose purpose is to keep interference that lies outside the 72 MHz passband from entering the A/D converter. The analog signal in this third IF is digitized using a sampling rate of 160 MHz, and the remainder of the signal processing in this receiver is digital. Carrier synchronization is achieved within the digital signal processing with a phase-locked loop. This synchronization provides the reference required for coherent demodulation of the carrier. Symbol synchronization and subcarrier synchronization (in the case where a subcarrier is present) are also done in the digital signal processing. The detected baseband telemetry signal is sent out of the DTT to a decoder. The baseband ranging signal (which is present during range measurements) is correlated against a local model, and the relative phase is sent out of the DTT to the TDDS. The measured phase of the downlink carrier, which is needed for a Doppler measurement, is also sent to the TDDS.

A copy of the analog signal in the first IF of the DTT is sent to the RSR [6]. The signal undergoes further downconversion and then digitization within the RSR. The digital signal processing in the RSR is open loop, unlike that of the DTT. The open-loop signal processing of the RSR better preserves the signal amplitude and frequency information, but requires more effort from the user. The data from this receiver is used to search for gravitational waves and to conduct occultation experiments, in which physical properties of a planetary atmosphere can be inferred from the signal properties of a downlink that has passed through the planetary atmosphere.

When tracking a downlink signal in the 8400-8450 MHz band, a DSS antenna is usually pointed using a closed-loop, conical scanning (conscan) technique [7]. The feedback for this closed-loop control comes from the APA, which gets from the DTT periodic measurements of the ratio of the carrier signal power to noise spectral density. In principle, measurements of only the carrier signal power would be needed for closed-loop control of antenna pointing, but the DTT receiver chain uses automatic gain control, as do most superheterodyne receivers, so a measurement of just the carrier signal power would reflect also the variation in receiving system gain. The ratio of the carrier signal power to the noise spectral density, on the other hand, is independent of the receiving system gain. From the periodic measurements supplied by the DTT, the APA produces scan patterns in which the scan center coincides with the direction-of-arrival of the downlink. The scan patterns are sent to the ACS.

5. Susceptibility of a Deep Space Receiving System to RFI

For the purposes of this paper, the susceptibilities of the deep space receiving system are classified into three categories: the gain compression of the LNA, the impairment of carrier tracking due to the presence of a discrete spectral line near the residual carrier, and the elevation of the noise floor due to broadband interference.

5.1 Gain Compression of the LNA

The LNA is designed for linear operation under normal circumstances. However, if a strong interferer is present in addition to the desired signal, the LNA can exhibit nonlinear behavior. Such behavior includes the creation of intermodulation products between the desired signal and the interferer. This means a loss of power to the desired signal, relative to the noise level. The 1-dB gain compression point is the usual measure of the smallest input power that causes a significant amount of nonlinear behavior in an amplifier intended for linear operation. For the HEMT amplifiers, the 1-dB gain compression point is reached when an interfering signal of -63 dBW is present at the input port and inside the 490-MHz bandwidth of that LNA. Some Deep Space Stations use masers for low-noise amplification in the 8400-8450 MHz band. These devices have a smaller bandwidth than the HEMT amplifiers, 140 MHz rather than 490 MHz, but also experience a much earlier onset of nonlinearity. The 1-dB gain compression point of the masers is reached when an interfering signal of -114 dBW is present at the input port and inside the 140-MHz bandwidth of the maser.

5.2 Interference from a Discrete Spectral Line

The most common modulation scheme for deep-space telemetry is phase modulation with less than complete suppression of the carrier [8]. The residual carrier is tracked by a phase-locked loop in the DTT, providing the frequency-and-phase reference needed for coherent demodulation of the carrier and for Doppler and range measurements. In addition, the amplitude and frequency of the residual carrier is measured with great accuracy in the open-loop RSR during radio science observations. A discrete spectral line near the residual carrier can interfere with the DTT carrier tracking loop and also with the RSR measurements.

A discrete spectral line within 0.5 Hz of the residual carrier can significantly degrade the accuracy of the frequency measurement in the RSR. This can happen when the power of the discrete spectral line is not smaller than that of the residual carrier by at least 35 dB.

A discrete spectral line inside the bandwidth of the DTT carrier tracking loop can be a problem for carrier synchronization [9]. The DTT carrier loop bandwidth is an adjustable parameter, typically set within the range 1 Hz to 100 Hz. If the power of the discrete spectral line is 15 dB less than that of residual carrier, then a 10° phase error develops in the loop. This causes a significant degradation in telemetry performance. If the discrete spectral line has a power equal to that of the residual carrier, then the carrier loop will lose phase-lock on the residual carrier, resulting in a telemetry outage.

The effects of a discrete spectral line near the residual carrier that have been discussed above are summarized in Table 1 below. There are other possible negative effects of discrete spectral lines, other than those listed in Table 1. For example, a discrete spectral line near the subcarrier can also degrade telemetry performance. But the DTT receiver and the RSR are most vulnerable to discrete spectral lines near the residual carrier.

Table 1: Effects of a Discrete Spectral Line Near the Residual Carrier
P_{DSL} = power in discrete spectral line, dBm
P_C = power in residual carrier, dBm
Δf = frequency offset of discrete spectral line from carrier, Hz
B_C = carrier tracking loop bandwidth, Hz

Condition	Effect
$P_{DSL} > P_C - 35$ dB, $\Delta f < 0.5$ Hz	loss of frequency stability in RSR measurement
$P_{DSL} > P_C - 15$ dB, $\Delta f < B_C$	10° phase error in DTT carrier tracking loop
$P_{DSL} > P_C$, $\Delta f < B_C$	loss of lock in DTT carrier tracking loop

5.3 Elevation of the Noise Floor

The modulated sidebands of an interferer will often appear as broadband noise to a deep space receiving system. The effect is to elevate the noise floor of the receiving system. This affects all of the following functions: telemetry, Doppler and range measurements, radio science observations, and (closed-loop) antenna pointing. Since deep space radio links, especially downlinks, are often operated with signal-to-noise ratios having very small margins, an elevation of the noise floor by a few tenths of a decibel can represent a significant impairment. The elevation of the noise floor of a deep space receiving system by an EES transmitter is typically short-lived. Figure 2 shows an example of such an event.

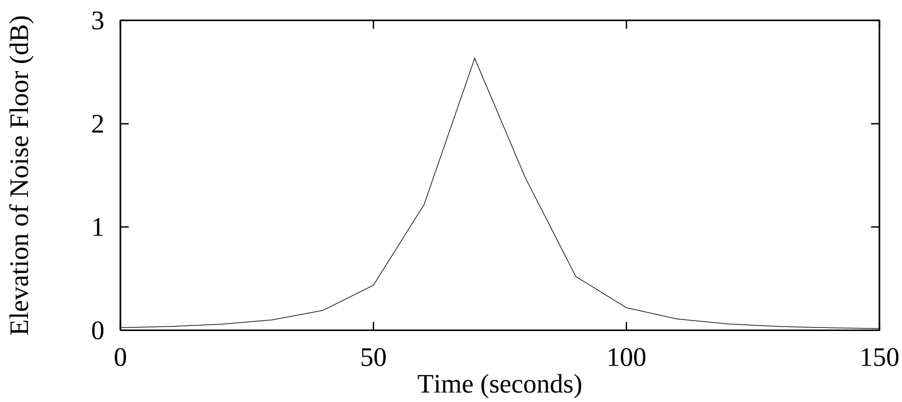

Figure 2: Example Elevation of the Noise Floor

A transient elevation of the noise floor can cause a telemetry outage. The DTT carrier loop can, for example, go out of lock. Worse than that, the conscan tracking of the antenna can fail, causing the antenna to go off-point. This last possibility is discussed in greater detail in the following section.

6. Effects of Lost of Lock of Synchronization Loops on Ranging

In additional to losing telemetry data and science measurements when the synchronization loops become out of lock due to interference, ranging measurements are disrupted. Range measurements are important for orbit determination. A range measurement is made by timing the round-trip or one-way delay of a ranging signal. Due to the typically low signal-to-noise ratio of deep-space ranging, the ranging correlation that determines the round-trip or one-way delay must use a relatively large integration time, often of several minutes duration. If the receiver loses lock, the current range measurement is lost and possibly the next is lost as well. This represents a significant gap in the radiometric data record.

7. Effect of Elevated Broadband Noise on Conscan Pointing

A DSS antenna is typically pointed using a combination of predicts and corrections. The relative motion between a typical deep space vehicle and a DSS antenna is well known. With the aid of predicts, the antenna can, in principle, be programmed to follow the apparent angular motion of the target spacecraft. However, several environmental factors, including wind and tropospheric refraction, cause pointing errors that can only be corrected with closed-loop control. For the 8400-8450 MHz band, the corrections come from conscan.

Each measurement of the ratio of carrier signal power to noise spectral density that is provided to the APA by the DTT is tagged with an out-of-lock indication. When there is an out-of-lock indication, the APA restarts the scan, causing the corresponding correction to be ignored. Because of this built-in precaution, conscan does not fail when the receiver goes out of lock. During an out-of-lock period, the antenna pointing is based on predicts and the last legitimate correction. Normally this will be adequate for the relatively short time required to relock the receiver and reestablish the flow of legitimate conscan corrections.

Problems occur when the measured ratio of carrier signal power to noise spectral density is fast-changing but the receiver does *not* (initially) go out of lock. Even if the scan center coincides with the direction-of-arrival of the downlink and the carrier signal power is constant, the ratio of carrier signal power to noise spectral density will vary due to the presence of a transient broadband interference. The scan period is typically in the range of 30 seconds to 120 seconds [7]. If the noise floor changes significantly during one scan period (as it does in Figure 2), conscan can fail.

Under related circumstances, the failure of conscan has been observed at several DSS antennas. The source of the problem was not an interferer. Rather, it was a transponded signal from the spacecraft being tracked [10]. Under unusual circumstances, a time-varying ranging modulation on the carrier can cause a significant change (during the period of a scan) in the measured ratio of carrier signal power to noise spectral density, even though the scan center coincides with the direction-of-arrival of the downlink. Hence, though the source of the problem was different, the mechanism within the signal processing was the same as outlined above.

8. Reacquisition of Telemetry

If an interference incident occurs that caused the tracking loops to go out of lock, a DSN Earth station operator will need to reset the receiver to reacquire the deep-space downlink signal. If an operator is not present, the receiver will try to reacquire the signal. If the loops are out of track for more than a few seconds, due to the large frequency shift and the narrow bandwidth of the loops, the receiver may never be able to reacquire the downlink signal on its own and the remaining portion tracking pass, which can be several hours long, may be lost. If the deep space station operator recognizes an interference problem, acquisition sequence will have to be reinitiated. Several types of synchronization must be reestablished before detected, decoded bits become available again [11]. The carrier, subcarrier (when a subcarrier is present), and symbol loops in the DTT must all be acquired. Then node synchronization (in a Viterbi decoder) and frame synchronization must be acquired.

Acquisition of the carrier loop requires, in general, the computation of Fast Fourier Transforms (FFT) in order to locate the carrier frequency. This can usually be done quickly, especially if the *a priori* uncertainty in this frequency is small, as it typically is for reacquisition after a brief outage.

Once the carrier frequency has been determined, the process of getting phase-lock in the carrier, subcarrier (when a subcarrier is present) and symbol loops begins. The time required for this is determined by the smallest of the loop bandwidths. Typically, this would be the symbol loop bandwidth, a small fraction of one hertz. The time to acquire phase-lock can be as large as several hundred seconds.

After the carrier, subcarrier and symbol loops are acquired, node and frame synchronization can begin. The two most common classes of coding scheme for deep-space telemetry are turbo codes and serially concatenated convolutional/Reed-Solomon codes.

For turbo coding, frame synchronization can take about four frames to happen, and node synchronization is not a separate process. The turbo codes used for deep space telemetry have frame sizes of 1784, 3568, 7136 and 8920 bits. For a low bit-rate link, this can be time-consuming. For example, a 100-bps telemetry link that employs a 1784-bit turbo code may require 70 seconds for the acquisition of frame synchronization.

For serially concatenated coding, node synchronization is required in the Viterbi decoder and frame synchronization is done by a separate frame synchronizer. Typically, node synchronization in the Viterbi decoder occurs in the time occupied by about 1000 binary symbols. Frame synchronization may take four frames. With a typical interleave depth of five, the frame size is 10200 bits. For example, a 100-bps telemetry link that employs a 10200-bit frame may require 400 seconds for the acquisition of frame synchronization.

The total time for reacquisition of telemetry will be the sum of the time required for the lock of the loops in the DTT plus the time for node and frame synchronization. This total time can be small for high bit-rate telemetry. But for low bit-rates, which are common in deep-space telemetry owing to the severe constraints on downlink signal-to-noise ratio, the total time for reacquisition can be 15 minutes or more.

9. Conclusion

Due to the spectral proximity of the EESS and the deep space X downlink bands, EESS adjacent band emission can interfere with the deep space X downlinks. Since the deep space downlink signal is typically very weak, even a small amount of interference can interrupt the deep space downlink. While it is customary to use fractional interference time to determine the severity of interference problems among EESS satellites, it does not truly represent the interference problem of the deep space downlinks from EESS satellites. The fraction of time that a deep-space X-band downlink is affected by an EESS downlink can be very small. Interference events are typically short and numerous, up to thirty or more each year. For each interference event, which typically lasts a few seconds to thirty seconds, it can take fifteen minutes or more for a deep-space X-band downlink to recover resulting in significant loss of data, assuming a station operator recognizes the problem right away and starts the reacquisition process immediately after the interference event. If the station operator does not realize the receiver is out of lock, the remaining tracking pass, which can last many hours, is lost. In addition to the significant loss of data, each interference event also causes a gap in ranging measurements, each take several minutes to perform, and can cause errors in determining the location of the deep space spacecraft and navigation.

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