DEEP SPACE NETWORK SUPPORT OF SMALL MISSIONS

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Abstract

Spacecraft to be used in future missions supported by the Deep Space Network (DSN) will be much smaller than in previous missions, resulting generally in lower radiated power. These missions are expected to be launched more frequently than previous missions and to require an ever increasing number of tracking hours, while the funds available to track these future missions are declining.

This paper briefly describes the DSN. It then characterizes performance limits of smaller spacecraft and the tracking challenges these limits present, It reviews new techniques and technologies the DSN is developing to meet these challenges. Finally, if recommends guidelines for future missions to follow to most effectively utilize DSN resources.

Introduction

Telecommunications from deep space are made very difficult by extreme ranges from Earth. A mission to Pluto takes the spacecraft more than 30 AU from Earth – for comparison, a spacecraft in geosynchronous orbit has a range of only 0.00024 AU (35784 km). Since received power decreases with the square of range, a spacecraft at Pluto must transmit with an effective power more than ten orders of magnitude greater than that of a spacecraft in geosynchronous orbit in order to generate the same power flux density on the surface of the Earth.

Spacecraft for use in future deep space missions will be much smaller than those in previous missions. Spacecraft size reductions typically require reductions in both antenna aperture and solar array, which result in limits on antenna gain and transmitter power. These reductions consequently lead to reductions in spacecraft Effective Isotropic Radiated Power (EIRP) that severely limit telemetry performance.

Deep space missions are expected to be more frequent in the future. Rather than a few large, all-inclusive Cassini class missions, as in the recent past, there should be many more highly focused missions. Thus not only must tracking resources be provided in such away as to compensate for the poorer performance of future spacecraft, but more missions must be tracked.

The Deep Space Network, operated by the Jet Propulsion Laboratory of the California Institute of Technology for NASA, is the world's premiere network for deep space communications. The DSN is developing and implementing ways of accommodating increased burdens from smaller, more frequent spacecraft.

This paper describes some of the new ways in which the DSN will support future small deep space missions. We briefly review several new developments and present reference materials, including a number of links to mission design information newly available on the World Wide Web.

Some of these new developments are still in an advanced study phase with implementation funding not yet committed. Mission designers are advised to work closely with tile Advanced Missions Program of JPL's Telecommunications and Mission Operations Directorate to become apprised of the current status of such plans and to make their specific requirements known,

The Deep Space Network

The Deep Space Network was constructed to enable communications with spacecraft at extreme ranges. It consists of three complexes of tracking stations with large antennas located around the world at locations approximately 120" apart in longitude near Madrid, Spain; Canberra, Australia; and Goldstone dry lake in the Mojave desert of California. Each complex includes one each 70 m, 26 m and 11 m station; in addition, there are two 34 m stations at Canberra and at Madrid and 6 at Goldstone. The DSN

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configuration as of the end of 1998 is summarized in Table 1.

Each DSN station supports several functions: telecommand, radio navigation, radio science, and telemetry.[2]

The telecommand function begins with the transfer of command data from the flight project to the DSN. The DSN modulates the data onto a subcarrier, translates it to the appropriate RF frequency, amplifies the resultant signal, and transmits it to the spacecraft.

The telemetry function begins with the generation of a telemetry data stream by the spacecraft. This data stream is encoded, modulated onto a carrier (or, if at a low data rate, onto a subcarrier), translated to the appropriate RF frequency, amplified and transmitted to Earth. One or more DSN stations receives the transmission, amplifies it, demodulates if and decodes it, and then routes the data to the project.

Two types of radio navigation are normally employed to determine spacecraft position and velocity: Doppler[3] and ranging. Each of these techniques require the use of a highly stable frequency reference on the spacecraft. This reference can be at the DSN, in which case the frequency for the downlink is derived from the uplink transmission received at the spacecraft. Alternatively, an Ultra Stable Oscillator can be used on the spacecraft. Recent improvements in digital filtering have led to significant improvements in Doppler anti ranging navigation accuracy.[4]

Ant. Size	Location	DSS[1]	S-Band Down	S-Band Up	X-Band Down	X-Band Up	Receiver Type
9 m	Goldstone	17	Yes	Yes	-	-	MFR[2]
11 m	Goldstone	233			Yes	Yes	Sci. At.[4]
11 m	Canberra	33[3]	-		Yes	Yes	Sci. At.
11 m	Madrid	53[3]			Yes	Yes	Sci. At.
26 m	Goldstone	16	Yes	Yes	-	-	MFR
26 m	Canberra	46	Yes	Yes	-		MFR
26 m	Madrid	66	Yes	Yes	-		MFR
34 m	Goldstone	15	Yes		Yes	Yes	Block V
34 m	Goldstone	24	Yes	Yes	Yes	-	Block V
34 m	Goldstone	255			Yes	Yes	Block V
34 m	Goldstone	26			Yes	Yes	Block V
34 m	Goldstone	27	Yes	Yes	Yes	-	MFR
34 m	Goldstone	286			Yes	Yes	Block V
34 m	Canberra	34	Yes	Yes	Yes	Yes	Block V
34 m	Canberra	45			Yes	Yes	Block V
34 m	Madrid	54	Yes	Yes	Yes	Yes	Block V
34 m	Madrid	65			Yes	Yes	Block V
70 m	Goldstone	14	Yes	Yes	Yes	5/00	Block V
70 m	Canberra	43	Yes	Yes	Yes	12/01	Block V
70 m	Madrid	63	Yes	Yes	Yes	5/01	Block V

Table 1. Operational DSN Configuration from 1998 Onwards

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[1] Deep Space Station identifying number.

[2] Multi Function Receiver.

[3] The 11 m stations operate also at Ku-band frequencies: 15250-15350 MHz uplink and 14000-15350 MHz downlink.

[4] Scientific Atlanta receiver.

[5] A K.-band downlink will be added to DSS-25 for New Millennium in 10/98. A low power K.-band uplink will be added for Cassini in 5/01.

[6] Construction and testing of DSS-28 will be completed in 10/00.

The DSN supports two basic types of radio science:[5]

- Precision spacecraft navigation data generated by the DSN can be used to measure planetary mass, mass distributions, and gravity fields. Such data could also be used to detect gravity waves and gravitational redshift.
- During occultations, measurements at the DSN of changes in the signal sent from the spacecraft can be used to study the atmospheric and ionospheric structure of planets and their satellites and to investigate planetary rings.

Upgrades for Galileo

The Galileo spacecraft will go into orbit around Jupiter in December, 1995. It was originally designed to communicate with Earth at X-band through a 4.8 m unfurlable antenna that never opened. All communications must consequently be sent through a pair of S-band low gain antennas. This reduced the EIRP of Galileo by four orders of magnitude from the original design. To compensate so far as possible for this dramatic performance loss, a number of techniques have been developed. Many of these techniques have potential value to the small missions of the future.

Data compression is expected to increase the effective data rate by a factor of 10. Other ground and spacecraft enhancements, including advanced error correction coding and arraying, are expected to increase the effective data rate by another factor of tens

Block V Receiver

The new Block V receivers being installed in the DSN[7] bring significant new capabilities to future small missions, including suppressed carrier telemetry, QPSK telemetry, data-aided carrier tracking, and very narrow band carrier tracking. The minimum carrier loop bandwidth of the Block V is 0.1 Hz.

mall Deep Space Transponder

A survey of future deep space missions previously identified a critical need for a small, relatively inexpensive standard transponder.[8]

The Small Deep Space Transponder (SDST) now under development by Motorola for JPL is expected to be used by most, if not all, new U.S. deep space missions over the decade following the launch of the Cassini spacecraft. It receives at X-band and transmits at both X- and K.-bands. The specifications of this transponder, at the time of publication of this paper, are still under negotiation. It is currently expected to have a carrier tracking threshold of -156 dBm, a tracking loop bandwidth of 30 Hz, and a noise figure of 2.5 dB.

The SDST includes a modulator and a convolutional coder. Its mass will be under 2.5 kg. It will require less than 10 W DC for X/X communications or 13.6 W for X/K_a communications.

Key Spacecraft Operating Modes

Spacecraft telecommunications requirements are frequently driven by just 3 operating modes: command through a Low Gain Antenna (LGA), high rate telemetry through a High Gain Antenna (HGA), and “safing mode” telemetry through an LGA. We examine each of these modes here and consider implications for small missions.

Commanding through LGA

Command link performance is normally limited by the need to be able to command through an LGA at maximum range in the event of an emergency. In such an event, the spacecraft is typically oriented towards the sun, so the gain of the LGA is limited by the need to include Earth within the beamwidth of an LGA pointed towards the sun.

Given the SDST characteristics noted above, a 34 m DSS with a 20 kW transmitter can send commands to a spacecraft at maximum Mars range (2,7 AU) as long as it has an LGA with a gain of at least 7 dB. A 70 m station with a 20 kW transmitter can command this spacecraft about twice as far from Earth.

Emergency Telemetry

Emergency telemetry is typically sent at a very low bit rate, such as 10 bps. To demodulate such telemetry with the coherent tracking techniques normally employed for deep space communications, the carrier signal needs to be recovered at the receiver with an adequate SNR - typically 10 dB or more - and a telemetry margin 3 dB or more is usually desired.

The Block V receiver is capable of receiving carriers using loop bandwidths as narrow as 0.1 Hz. Such a narrow loop bandwidth requires a very stable frequency source at the spacecraft - either a downlink carrier derived from an uplink from a stable ground station oscillator or an Ultra Stable Oscillator (USO) on the spacecraft.

In the event of a spacecraft emergency, a stable uplink frequency reference may not be available. Previous missions have usually had USO which could be used as the frequency reference in such an event. Few future missions, however, are planning to use USOS - instead, they plan to rely on the Auxiliary Oscillator contained within the SDST. The specifications of this oscillator have not been finalized, but it is desired for it to be good enough to permit a tracking loop bandwidth of 3 Hz.

Future missions also plan to have reduced transmitter powers, further reducing performance in this mode. They also frequently want to simplify the spacecraft by reducing fault tolerance requirements - increasing the importance of “safe mode” operations in the event of an on-board failure.

As a result of all these tendencies, emergency telemetry has become a major mission driver. It can drive transmitter power and configuration design.

Future missions may wish to consider Almost Stable Oscillators (ASOs) or USOS to reduce transmitter requirements in this mode.

The Block V receiver’s ability to receive suppressed carriers substantially reduces transmitter power requirements at low data rates. The use of very narrow band tracking loops reduces transmitter power requirements still further.

High rate telemetry through HGA

Several techniques can be used to increase the data rate that can be sent to the DSN from a spacecraft through a High Gain Antenna (HGA). These include arraying, moving to K.-band frequencies, and using advanced coding techniques. The effective data rate can be increased dramatically by using the advanced compression techniques developed for Galileo. These are each discussed briefly below.

Arraying

The DSN has experimented with various arraying techniques to improve overall ground receive system performance by combining multiple apertures.[9] A full spectrum combiner[10] is being installed at Goldstone that will permit the combination of a single 70 m and three 34 m stations. The receive G/T of the combined stations will be equal to the sum of the G/Ts of the individual stations less 0.2 dB (combining loss). This capability can be used for brief, critical mission phases such as planetary flybys. Table 2 shows overall G/T for typical 70 m and 34 m stations and for an array.

DSN Configuration	Typical G/T
Single 70 m	59 dB/K
Single 34 m	53 dB/K
Array of two 34 m	55.8 dB/K
Array of 1 70 m & 3 34 m	61.2 dB/K

Table 2. DSN G/T

K_a-Band

Recent deep space missions have relied upon S-band and X-band communications. K,-band may be the next step. K.-band transmissions from a spacecraft with limited aperture- and DC-power to a Deep Space Station are expected to increase the data rate by 6 dB over X-band transmissions.

The Deep Space Network currently has K.-band receive capability at an experimental 34 m station. This station was used to demonstrate K.-band communications with the Mars Observer spacecraft, and will be used for demonstrations with the Mars Global Surveyor spacecraft to be launched in 1996. A small K.-band transmitter at a 34 m station will be used for Cassini radio science.

The New Millennium program plans to implement a K=-band downlink on its first mission, so the DSN is installing K.-band on an operational basis at a single 34 m station at Goldstone.

While K_a-band appears promising for high rate telemetry, its performance from spacecraft LGAs suffers from many degradations that result in substantially worse performance than from S-or X-band LGAs. As a result, it will not be possible for the DSN to receive K.-band telemetry from an LGA at high ranges (1 AU or more). It should also be recognized that HGA pointing must be tighter at K.-band than at X-band, and that K.-band is very sensitive to rain.

Advanced Coding Techniques

The Galileo mission Is using a feedback concatenated decoder to achieve a Bit Error Rate of 10“7 at a 0.65 dB signal-to-noise ratio.[11] The Galileo concatenated code consists of a (14.1/4) convolutional inner code and a (255,k) variable redundancy Reed-Solomon outer code.

In the past two years, turbo codes have been proposed that promise even better performance with much less complicated decoders.[12] Simulations at JPL[13] recently confirmed some of the performance claims of turbo code proponents. At this time, the DSN has not committed to turbo code implementation, but such codes appear very promising and are the subject of an intensive DSN research effort.

Compression

The Galileo mission was forced to make extensive use of compression to recover from the aforementioned HGA failure. The resultant development, implementation and use of high performance compression algorithms for Galileo has been of great value for other deep space missions.

Galileo uses a block-based lossy image compression algorithm with an 8 x 8 ICT.[14]

The initial resistance of science data customers to compression has been overcome on Galileo by shear necessity. Now that compression has been conclusively demonstrated, the burden of proof is on those who refuse to use it - even when if can dramatically increase science data return and lower spacecraft costs.

Spacecraft Monitoring System

Spacecraft operations in the past have been characterized by frequent downloads of engineering telemetry for monitoring spacecraft health. Large teams of people have been used to analyze the engineering telemetry. In the future, spacecraft are expected to be far more autonomous, requiring fewer downloads of engineering telemetry. On the other hand, mission planners desire frequent spacecraft contacts to assess general spacecraft health and to determine whether additional tracking is required. These frequent contacts could place a large burden on the DSN if the expected large number of missions materialize.

To accommodate these requirements, the DSN is studying the viability of a new spacecraft monitoring system (Fig. 1). The SDST will be able to generate 32 “tones, ” square waves at different subcarrier frequencies, all with a suppressed carrier. These tones are to be used to send discrete messages continuously to a small aperture DSN antenna, each tone representing a single message. In one possible implementation, four tones would represent the following messages:

- The spacecraft is operating nominally and does not require further contact.
- The autonomous system on the spacecraft has identified a problem that requires ground action within two weeks.
- The autonomous system has repaired a problem that the operations team should know more about,
- The spacecraft has data that must be dumped within two weeks or it will overflow memory and be lost,

Each of these tones would be transmitted whenever the spacecraft is scheduled for a contact by the monitor system.

The spacecraft monitoring ground station would receive each spacecraft signal and, if if is a tone, measure the separation between the subcarriers to determine which message was sent, A small antenna can be used, since the received tones can be non-coherently detected using a very long integration time.

This scheme makes it possible to monitor large numbers of spacecraft frequently using an inexpensive station with an aperture far smaller than that of atypical DSN station. Since large integration times can be used, a relatively small EIRP is needed from the spacecraft – less than is otherwise required to receive low rate telemetry at a large DSN station.

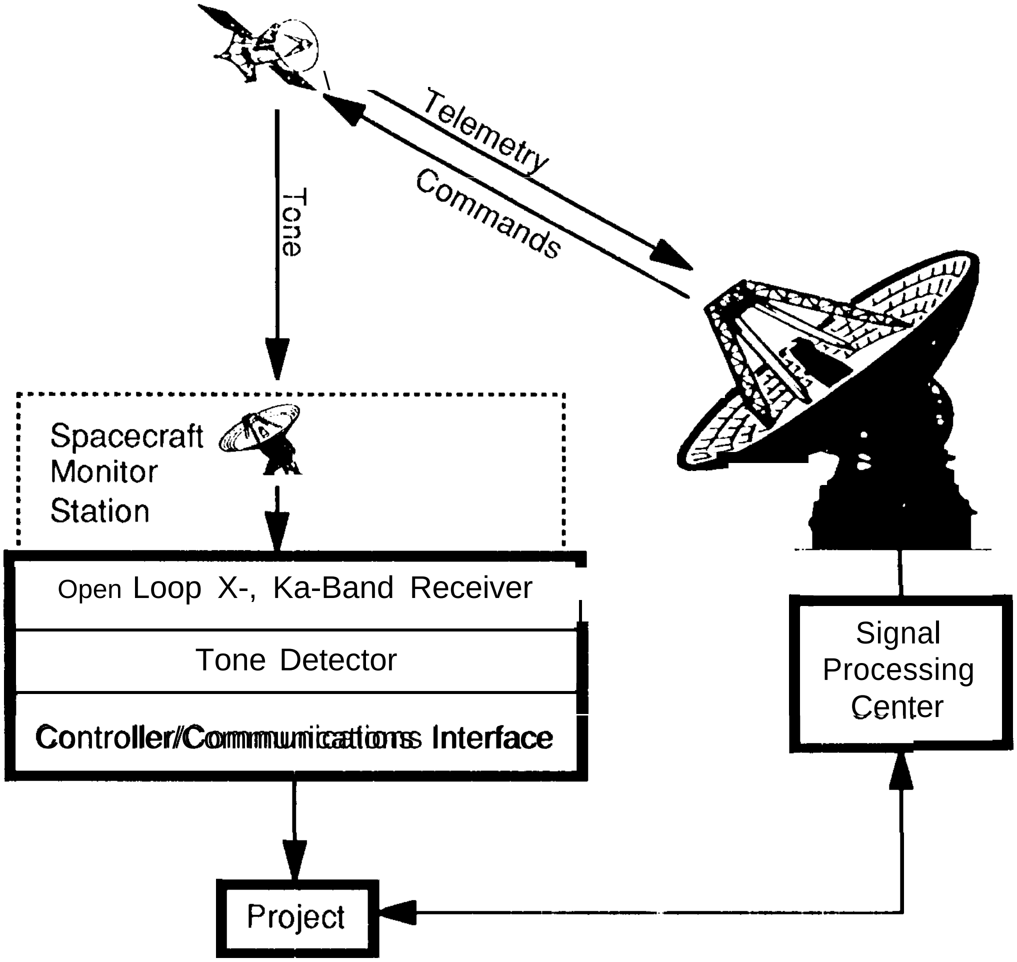

Fig. 1. Spacecraft Monitor System

High Efficiency Data Rate Control

Link performance depends, among other things, on local weather at the receiving station and on ground antenna elevation angle (see Figure 2). In the past, flight projects have used conservative weather models and a small set of fixed data rates - often no more than one during a station pass. K_a-band performance is much more sensitive to both weather and elevation angle than S- or X-band, so optimal performance at K.-band requires frequent variations in data rate throughout any long pass. However, frequent discrete changes in data rate can be counterproductive since the signal must be reacquired after each change.

The DSN is studying the possibility of tracking continuously varying data rate signals without losing symbol loop lock, This would permit the transmission of an optimal data rate at all times. The DSN is also considering development of a short term weather model based on local measurements that will allow the further optimization of data rate. A demonstration of this system is planned by OPSAT in 1997.

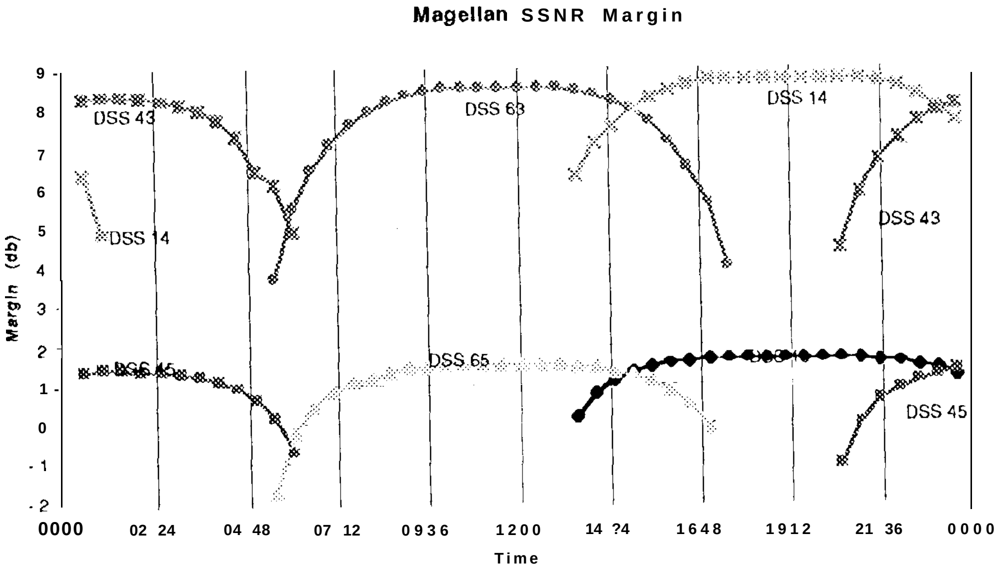

Figure 2. Magellan X-Band Margin at Various Deep Space Stations

Recommendations for Future Missions[15]

To help mission designers understand how to properly utilize the DSN, the Advanced Missions Program of JPL's Telecommunications and Mission Operations Directorate (TMOD) has prepared the following guidelines:

- Adhere to CCSDS recommendations.[16] The Consultative Committee on Spacecraft Data Standards, or CCSDS, is an international body whose members are national space agencies. The CCSDS has developed a set of Recommendations for Space Data System Standards covering telecommand, telemetry, error-detecting and correcting coding, RF and modulation, time codes, high data rates systems, and data base addressing. The DSN urges future missions to follow these recommendations.
- Operate in a "store and dump" mode. DSN ground stations are a limited resource that must be shared amongst many missions. This is much easier to do when spacecraft store their data and dump if at a convenient time, rather than relying on real-time telemetry. Today's reliable Solid State Recorders (SSRs) make this mode of operations efficient for the spacecraft as well.
- Design for scheduling flexibility. Since each DSN station must be shared, designing a mission to be flexible enough to dump data at times when the needed ground stations are available aids in network scheduling and helps ensure that the mission will eventually get all of its data, even in the event of schedule disruptions.

Design for 34 m stations rather than 70 m stations whenever possible. There are only three 70 m stations, but at the end of the decade there will be ten 34 m stations. The 70 m stations utilize old, relatively unreliable hydraulic systems that are subject to failure. Furthermore, the 70 m stations are invariably oversubscribed. It is thus not wise to rely on them any more than absolutely necessary, Use of the 70 m stations should be limited to short-term emergencies and special events, such as planetary flybys.

Operate at X- or K.-band rather than S-band. The S-band frequencies are rapidly disappearing. Far more spectrum is available at X-band than at S-band. Furthermore, there is no performance loss in going to X-band for telemetry; in fact, if an HGA is used on the spacecraft, performance at X-band improves by more than an order of magnitude over that at S-band.

- Use direct modulation for moderate and high data rate telemetry. The Block V receiver is capable of receiving suppressed carrier, directly modulated telemetry. There is thus no longer any reason to use subcarriers for telemetry - at least at data rates of ~ 100 bps or more at which the Costas loop receiver in the DSN can adequately track the carrier even with a 6 dB squaring loss. Subcarriers cause significant expansion of required bandwidth - an increasingly limited resource.
- Do telecommand, telemetry, and ranging simultaneously. These three functions can, and should, be supported simultaneously instead of sequentially to best use limited DSN resources. The SDST is capable of supporting all of these functions simultaneously.

The Advanced Missions Program maintains a World Wide Web site with resources and contacts for mission designers.[17]

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[1] Deep space missions are defined by the International Telecommunications Union Radio Regulations as those which venture 2,000,000 **km or more from** Earth.

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