Deep Space C^3: High Power Uplinks

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Abstract. The uplink transmitters of the Deep Space Network (DSN) perform three key functions in support of space missions: navigation, command uplink, and emergency recovery. The transmitters range in frequency from S-band to Ka-band, and range in RF transmit power from 200W to 400kW. Future improvements to the uplink transmitters will focus on higher frequency transmitters for high data rate communications, high power X-band uplinks for emergency recovery, and/or in-phase uplink arraying for either application.

INTRODUCTION

The uplink transmitters of the Deep Space Network (DSN) perform three key functions in support of space missions: navigation, command uplink, and emergency recovery. The transmitters are located in Spain, Australia, and the U.S west coast, which allows for 24-hour coverage of all points in the ecliptic region. The communication frequencies range from S-band to Ka-band, and the RF transmit powers range from 200W to 400kW. This paper will discuss the performance requirements that navigation, command uplink, and emergency recovery of spacecraft place on the transmitters, and will forecast how the performance requirements and the transmitter systems are projected to evolve over the next two decades. Table 1 gives an introduction to the present suite of DSN communication transmitter systems. All transmitters except for the 200W system use a single klystron for the final power amplifier stage.

TABLE 1. Deep Space Network Transmitter Systems

	26 meter antenna	34 meter antenna	70 meter antenna
S-band TXR	2kW, 20kW	200W, 20kW	20kW, 400kW
X-band TXR		4kW, 20kW	20kW
Ka-band TXR		800W	

To facilitate simultaneous transmit and receive, the uplink and downlink frequencies are separated by between 5% and 25% depending on the band; for example, the X-band uplink channel frequencies are near 7.2GHz while the downlink frequencies are near 8.4GHz.

NAVIGATION

The Deep Space Network measures the angular position and radial distance of spacecraft. Some navigation techniques require the use of an uplink reference signal transmitted from a ground station such as an ultra-stable reference frequency for Doppler or a sequence of waveforms such as square waves of different periods for range. The downlink signal can be received by the same station ("two-way ranging") or a different station ("three-way ranging") if the light time of travel is too long to make the round trip in a single tracking period.

Range and Doppler

The range is most accurately measured as the round-trip light time (RTLT) from Earth to the spacecraft to Earth, known as two-way range if the same ground station transmits and receives, or three-way range if the receiving ground station did not transmit the original signal. Less accurate measurements are made of the light travel time from the spacecraft to Earth (one-way range) because of the reduced signal quality generated on the spacecraft. Measurements of RTLT locate a spacecraft up to 400,000 miles from Earth (somewhat beyond the orbit of the Moon) to within 1 meter; near the orbit of Mars the uncertainty increases to 1 km at a distance of 150 million kilometers. Matching the received bit string to the known transmitted code permits a very accurate determination of spacecraft range.

The range rate, or spacecraft velocity vector toward or away from Earth, is estimated from the Doppler shift of the received frequency from the spacecraft (which for best accuracy is locked to a stable signal transmitted from a ground station). The phase of the signal is integrated and sampled once per second [1]; 30 to 60 minutes of data points are analyzed for routine tracking, or up to 9 hours of phase data may be accumulated in a single track in a radio science experiment to detect gravity waves. The Deep Space Network meets a performance specification requiring a maximum velocity uncertainty of 0.1mm/sec. [2] The derivative of the range-rate, a spacecraft acceleration vector, is also calculated and has contributed to mapping the gravity wells of Mars and Jupiter.

Angular Position

The angular position of the spacecraft is measured in two ways. Precise antenna pointing control combined with the narrow angular width of the main lobe enables precise location of the source of a received signal. The half-power beamwidth of a 70-m antenna receiving an X-band downlink from the spacecraft is 0.5 milliradians, and the Master Equatorial instrument directs the antenna to the predicted position of the spacecraft with an accuracy of 70 microradians [3]; conically scanning the antenna around the signal source permits active correction and very accurate pointing during a tracking period that may last 8 hours.

More accurate determinations of angular position use various forms of Very Long Baseline Interferometry (VLBI). In particular, Delta-Differential One-way Ranging (Delta-DOR), Figure 1, measures the difference in range to the spacecraft from two receivers with accurately known positions, using a nearby quasar to calibrate the instrumentation delays. Today Delta-DOR measurements of signals emitted by the spacecraft can locate a spacecraft to within 5 to 10 nanoradians. Future improvements in spacecraft signal quality are expected to yield 1-nanoradian accuracy within 10 years.[4] For a spacecraft orbiting Mars, when Mars is near a minimum distance from Earth, 1 nanoradian corresponds to a transverse position uncertainty of 150 meters.

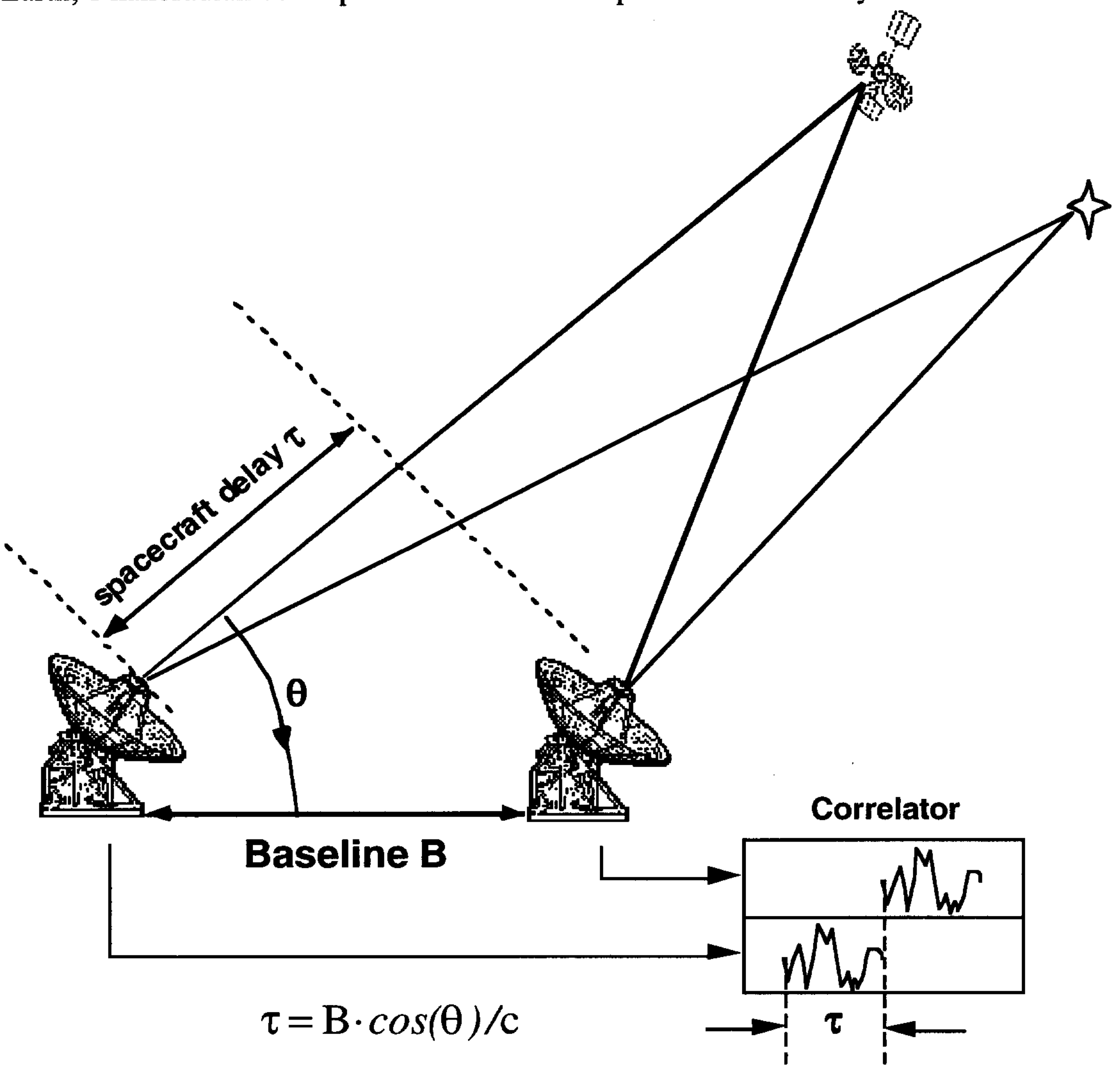

FIGURE 2. Geometry and technique for Delta-Differential One-way Ranging (Delta-DOR). Figure courtesy of Charles Naudet.

Future Navigation Upgrades

Navigation accuracy depends on the quality of signals received from the spacecraft; unfortunately spacecraft platforms lack the thermal stability, power conditioning, and mass allowance to carry highly stable transmitters. Future upgrades to navigation capabilities are focusing on improving the stability of space-qualified oscillators for improved clocking, and on increasing the signal-to-noise ratio of received signals through higher power space-based transmitters and ultra-low noise ground receivers. Navigation requirements are not typically drivers for higher performance in ground-based transmitters.

The most difficult test of spacecraft navigation is entry, descent, and landing on a planet, moon, or asteroid. Aerobraking, the developing practice of using atmospheric friction to reduce a spacecraft's velocity and achieve a desirable low altitude, circular science orbit, also requires precise control of the spacecraft's entry vector. However aerobraking in principle permits a planned program of gradual testing that starts by barely skimming the expected location of the outer atmosphere. Entry, descent and landing requires committing the spacecraft to a course that the onboard software must complete independently. Because light-time delay prohibits active control from Earth, the spacecraft has only on-board altimeter measurements to assist entry, descent and landing. To date nearly all spacecraft have entered the gravity well of a solar system body alone; but, in the future, communication and navigation orbital infrastructure will be pre-placed in those regions of deep space of greatest scientific interest: Mars, possibly one or more of the moons of Jupiter and/or Saturn, and possibly the Earth/Sun Lagrangian points L1 and L2.[†] With these added resources, autonomous spacecraft will perform active 3D navigation using X-band and UHF local links throughout entry, descent and landing.

COMMAND UPLINK

Uplink commanding currently involves transmitting both software commands and software upgrades to the spacecraft. The months or years of travel time (known as the "cruise phase" of the mission) from launch to the initiation of science observations are a busy time for mission software specialists on the ground because funding limitations require that significant elements of mission software development be deferred until after launch. Exploratory missions by definition do not know exactly how measurements will be optimized before the mission commences science operations; hence, missions spend the flight time developing software approaches to many different scenarios, ready for upload as required. The Deep Space Network's three 70-meter antennas can support the standard command rate of 2 kbps out to the edge of the solar system.[‡][5] An additional eight[§] 34-meter antennas can support 2kbps to spacecraft only out to about the orbits of Jupiter and Saturn.[*] Two new NASA initiatives will strain the limits of this capability: missions to the outer planets and autonomous rovers on Mars.

[†] Orbits around L1, between earth and sun, are excellent for solar wind observations; orbits around L2, approximately one million miles beyond earth from the sun, are a cold, quiet zone appropriate for deep space observatories.
[‡] Using the 400kW S-band transmitters to a 1-meter diameter High Gain Antenna on an S-band-equipped spacecraft.
[§] Nine 34-meter antennas will have 20kW X-band uplink as of late 2003.
[*] Using the 20kW X-band transmitters to a 1- meter diameter High Gain Antenna on an X-band-equipped spacecraft.

Command Uplink to the Outer Planets

Project Prometheus is tasked to develop a nuclear-powered ion propulsion system capable of reducing flight times and/or increasing payload mass to the outer solar system. The first application of the new system will be the Jupiter Icy Moon Orbiter (JIMO) presently scheduled for launch in 2011. Other missions to more distant locations (e.g., Saturn, Neptune, etc.) using this system may follow. Some nearer-term, very distant, chemical propulsion missions include Cassini, due to arrive at Saturn in July of 2004, and the New Horizons mission to Pluto and the Kuiper Belt, due to launch in 2006. The long distances associated with all of these upcoming missions tend to stress both the command uplink and emergency recovery capabilities of the DSN – sometimes forcing mission reliance on routine uplink rates of less than 2 kbps and dependence on medium-gain antennas (MGAs) rather than low-gain omnis for emergency recovery (a dependence that makes the spacecraft vulnerable to malfunctions affecting attitude control).

While the 70-m antennas are equipped with 400 kW S-band transmitters that could easily support much higher routine command rates into a spacecraft's high-gain antenna (HGA) at distances beyond Saturn, Uranus, or even Neptune, most deep space missions utilize X-band for their uplinks. At X-band, the 70-m antennas are only equipped with 20 kW transmitters. Hence, they are unable to support a 2kbps uplink (into a 1m HGA) beyond about 23 AU (roughly between the orbits of Uranus and Neptune). Even if the spacecraft were S-band capable, there are safety-related limitations on the power-flux density of the beam that would preclude unrestricted use of the 400 kW transmitter for routine uplink. And, the 70-m antennas are generally already oversubscribed for critical event coverage. Possible upgrades to the DSN for enabling higher uplink rates at longer distances include high power Ka-band uplink, active arraying at X-band, and Ka-band, and optical telecommunications. All these options share the same approach: reducing the beam width of the uplink antenna or mirror to concentrate more of the transmitted power on the spacecraft – all while staying within acceptable near-field power-flux density limits. However, this common approach has an inherent weakness: the main lobe of the antenna, now made narrow by design, must be maintained on the correct vector to the spacecraft with great accuracy. Large antennas suffer greatly from distortion by gravity and wind, the cumulative "main lobe" of an array is relatively narrow and oscillates with variations in the phase of the individual signals, and laser signals are similarly distorted by atmospheric effects. Approaches to active control of the transmitted wavefront are under investigation by several groups at JPL.

Autonomous Rover Navigation

Maximizing science return from assets on the surface of Mars will require that the rovers execute complex scientific and navigational tasks without frequent pauses for earth command uplink. Possible navigation options include:

- Living with the delay by allowing the rover to move only short distances between commands

- Use of orbiters and/or ground-based beacons to provided limited GPS-like capability
- Use of inertial navigation in combination with star/sun sightings and/or above techniques.
- Applying autonomous navigation techniques that are reliant upon visual-cuing.

Because terrain obstacles and associated decision points may occur in time frames much shorter than the two-way light time with Earth, only the last solution truly enables real-time *in situ* exploration. Hence, looking out toward the 20-year horizon, future rover mission concepts are increasingly assuming autonomous navigation with a consequent reduction in the amount of low-level commanding from Earth. However, the rover will usually lack the resources to process photographic and/or radar data from orbital remote sensing assets and/or its own instruments into an appropriate guidance, navigation, and control (GN&C) product. Hence, the orbital remote sensing and/or rover observations must be downloaded to Earth, processed into a GN&C product, and uplinked. Analogy to autonomous systems on Earth suggest that such GN&C products will require an uplink rate of around 200 kbps - 100 times higher than the maximum uplink rate of any previous deep space mission. [6]

Presently, only the three 70-meter antennas can provide sufficient power density at the receiver to support a 200 kbps X-band uplink data rate to Mars orbit. [5] As already mentioned in the outer planets case, a variety of options for supporting higher uplink rates and longer link distances are currently under investigation. One of those options, an in-phase arrayed uplink has been tested with 34m antennas in Apollo Valley, Goldstone. [7] The "spot" where multiple signals are in phase is much smaller than the single-signal illumination area, and it precesses within the single-signal main lobe as the signal's phase difference varies. JPL is currently studying how to allocate the phase coherence requirement among the transmitter subsystems to enable a stabilized wavefront from an arrayed uplink.

EMERGENCY RECOVERY

As alluded to earlier, the 400kW S-band transmitter system on the 70-m antennas is generally used for emergency communication with a spacecraft that is located more than a couple of AU from Earth, has entered a "safe mode" and, for one reason or another, cannot maintain Earth-point well enough to make use of its HGA or MGA. Under such circumstances, the increased power density is needed to get into the spacecraft's low-gain omni-directional antenna at a rate of 7.8125 bps or higher.

Unfortunately, as noted earlier, many recent and planned future missions do not carry S-band receivers, only X-band and, perhaps in the more distant future, Ka-band. This trend results from a combination of strong competition for S-band from ground-

[1] The Small Deep Space Transponder, or SDST, is the communications standard for the most recently launched missions and all missions in the foreseeable future. The maximum bit rate of the SDST is 2kbps; the minimum bit rate that the SDST can process is 7.8bps.

to-ground mobile telephone users, the low data rate of the S-band channels, and competition for the available S-band channels from older spacecraft lacking X-band capability.

A robust X-band emergency uplink capability will be essential for these missions. The present 20kW X-band system on the 70-meter antennas can support the required 7.8125 bps data rate to an omni-directional antenna out to the orbit of Jupiter [5]; extending X-band emergency recovery to Saturn and the rest of the outer solar system will require a higher power X-band capability, perhaps mounted on the 70-m system – with replacement of the 400kW S-band transmitter becoming possible as missions requiring S-band are completed. Other options, including the arraying of uplinks from the 34m antennas, are also under investigation.

CONCLUSION

Future upgrades to the Deep Space Network's ground-to-space transmitter systems will require development of X-band transmitters with 10 to 20 times the power of the current 20 kW system and/or in-phase uplink arraying techniques for the existing transmitters.

ACKNOWLEDGMENTS

Special acknowledgement to David L. Losh, Larry Epp, and Abdur R. Khan for valuable discussions of the uplink arraying effort. The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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