THE FUTURE OF NASA'S DEEP SPACE NETWORK AND APPLICATIONS TO PLANETARY PROBE MISSIONS

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ABSTRACT[1]

NASA's Deep Space Network (DSN) has been an invaluable tool in the world's exploration of space. It has served the space-faring community for more than 45 years. The DSN has provided a primary communication pathway for planetary probes, either through direct-to-Earth links or through intermediate radio relays. In addition, its radiometric systems are critical to probe navigation and delivery to target. Finally, the radio link can also be used for direct scientific measurement of the target body ("radio science").

This paper will examine the special challenges in supporting planetary probe missions, the future evolution of the DSN and related spacecraft technology, the advantages and disadvantages of radio relay spacecraft, and the use of the DSN radio links for navigation and scientific measurements.

One of the main purposes of the participation of the DSN at this meeting is to learn about any special needs from the planetary probe community. We encourage scientists and mission designers to become more actively involved in helping with future DSN planning, and would be pleased to work with them to help develop the best communication, navigation, and radio science systems for probe mission concepts.

1. THE CHALLANGES TO SUPPORTING PROBE MISSIONS

Although all deep space communication and navigation is challenging, planetary probe missions are even more so for a number of reasons:

- Probes tend to be severely power-limited, with the probe battery capacity limited by mass, volume, and thermal constraints.
- The gain of a probe's communication antenna can be restricted by atmospheric dynamics, the lack of pointing capability, and mass constraints.
- Probes are often short-lived, requiring a large volume of science data to be communicated in a short time.
- Probes must often endure extreme environments or atmospheric turbulence, placing additional stress on the communications system.
- The target body's atmosphere can attenuate communication signals. On the other hand, this absorption can provide information on the atmospheric constituents.
- Probes often require a precise location and trajectory at the atmospheric entry point, requiring advanced navigation techniques.

2. FUTURE PLANS FOR THE DSN

Probe missions often require the sensitivity of the large DSN 70m antennas (one at each of the DSN's three sites: Goldstone in California, Madrid in Spain, and Canberra in Australia), but these antennas are now more than 40 years old. Between now and 2020, NASA plans to add new 34m antennas to the DSN so that each DSN site will have at least four such antennas. This will provide a backup capability to each 70m antenna for communications at X-band (8.4 GHz), since multiple 34m antennas can be combined to receive a spacecraft's downlink, synthesizing an antenna aperture equivalent to the sum of the individual an-

[1] The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

tenna areas. Uplink will be provided with a single 80 kW transmitter on one of the 34m antennas, resulting in transmitted power equivalent to a DSN 70m antenna with its 20 kW transmitter.

Fig. 1. DSN 34m Beam Waveguide Antennas at Goldstone, California

With this capability in place, missions can continue to rely on robust 70m-level support. In addition, all these new antennas will have Ka-band (32-Ghz) capability, which can provide a factor of ~4 communications performance improvement over X-band [1].

Future DSN plans also call for additional capabilities to be added to the DSN including:

- More 34m antennas so that the 70m antennas can be decommissioned from routine use.
- New back-end DSN signal processing allowing communication downlinks up to 150 Mbps and uplinks up to 25 Mbps,
- New coding and modulation schemes providing a factor of ~5 in performance, and
- New Disruption-Tolerant Networking (DTN) [2] protocols to allow assured communications and autonomous use of relay links.

NASA has also invested in advanced spacecraft communication capabilities. As a result, several missions are already flying Ka-band systems. Prototype coding and modulation systems have been demonstrated on the ground. NASA is in the process of developing a new generation of spacecraft transponders based on its new software-defined radio (SDR) standard.

The overall communications improvement possible over today's systems is exhibited in Fig. 2, although all these advances may not apply to planetary probes.

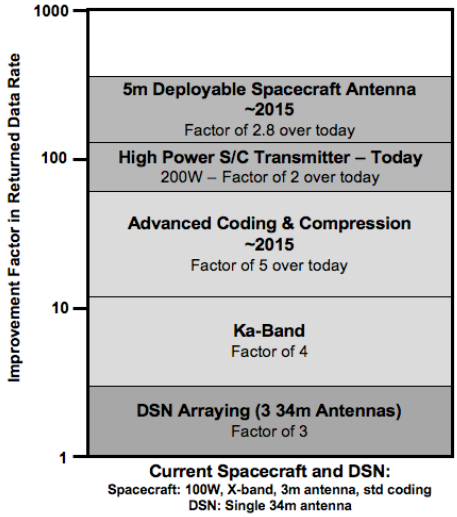

Fig. 2. Possible communication improvements

3. CHOICES FOR THE OVERALL COMMUNICATION SYSTEM

There are two possible communication options for probe missions: direct-to-Earth or through a relay spacecraft. The DSN has had experience with both systems.

3.1. Direct-to-Earth

By communicating directly to Earth, a mission can save the cost of the relay but data volumes will be limited and the probe may have to include a potentially much larger onboard communication system. For missions relatively close to the Earth (e.g., Venus) this may a logical choice. Direct-to-Earth communication is more difficult for the outer planets, due both to the enormous distances and radio signal absorption in their atmospheres.

The DSN can receive signals from deep space at S-band (~2.2 GHz), X-band (~8.4 GHz) and Ka-band (~32 GHz). The X- and Ka-bands are the "workhorse" frequencies for the DSN. The DSN has S-band capabilities on its 70m antennas and on a small number of its 34m antennas only. In the current plan, the DSN will have a more limited S-band capability in the future, especially after the 70-m antennas are replaced (~2025). S-band support has been made more difficult lately due to the tendency for nations to dedicate more of this band for other uses – notably mobile services. DSN S-band performance is particularly degraded in Madrid for this reason.

The DSN has supported frequencies lower that S-band in the past – as low as UHF (~400 MHz). However,

there is no legal protection for DSN spectrum use below S-band. Recent studies at Goldstone have indicated a large amount of potential interference. Though it is technically feasible for the DSN to support probe missions at these frequencies, a successful mission would depend on mitigation of this interference.

Direct-to-Earth techniques can be quite useful even for more distant targets. In the case of the Cassini/Huygens Titan probe, relay communications were supplemented with direct-to-Earth radio science by eavesdropping on the radio signal sent from the probe to the relay spacecraft. Although the DSN was not used to receive the probe signal, the DSN's Radio Science Receivers (RSRs) were transported to selected radio astronomy facilities to acquire these science measurements.

The DSN's standard communication receiver supports the telecommunications and navigation functions and provides accurate radio-metric measurements. It is, however, limited in the minimum required received signal level and has a threshold below which it loses lock. It also is limited in the signal dynamics and can lose lock if the frequency shift is either too high or too fast.

The RSR, on the other hand, is an open-loop receiver that does not lock on the incoming carrier. It digitizes and captures the spectrum in a pre-selected bandwidth for post processing by the user to better extract precision information. In the process, it is not limited by the signal to noise ratio or frequency dynamics in the same manner as the tracking receiver. Designed for radio science experiments that typically require ultra-high phase stability as well as experiment configurations where the signals are weak due to absorption, refraction or other effects or can experience high Doppler shifts or accelerations.

The RSR records the received signal so that the telemetry or radio science data can be extracted in non-real-time. In the Huygens case the telemetry signal was too weak to be recovered this way. More recently, the DSN has developed a portable version of the RSR, which makes observations at non-DSN antennas easier.

Fig. 3. DSN Portable Radio Science Receiver (RSR)

We assume that the probe will be equipped with a low gain antenna – with essentially no gain. With this assumption, communications performance is nearly frequency-independent, at least in a vacuum. Direct-to-Earth data rates for various probe distances were calculated for the IPPW meeting in 2006 [3]. They assume a probe with a 25W X-band transmitter and a 4 dBi antenna. The results shown in Table 1 are based on these calculations and modified to show the expected performance for the currently planned DSN configuration. We have shown a column for arraying a DSN 70m antenna with five 34m antennas. This is a possible DSN configuration ~2025. Though missions should not rely on scheduling this many DSN antennas at a time, this may be possible for short periods of special scientific interest, such as probe descents. For comparison, the Table also shows the performance that may be possible using the Square Kilometer Array (SKA), the planned next generation radio astronomy observatory. All these numbers are approximate – they are based on a model of Jupiter's atmosphere, including atmospheric absorption for a probe at a depth of 10 Bars assuming a 45° zenith antenna angle of transmission from the probe.

Ground Antennas	SKA	DSN 70m	DSN 70m + 5 34m's
Venus (0.3 AU)	1.3 Mbps	11 Kbps	26 Kbps
Venus (2.4 AU)	21 Kbps	180 bps	400 bps
Mars (0.6 AU)	340 Kbps	2.9 bps	6.4 Kbps
Mars (2.6 AU)	17 Kbps	150 bps	340 bps
Jupiter	4.1 Kbps	35 bps	80 bps
Saturn	1.1 Kbps	10 bps	23 bps
Uranus	330 bps	3 bps	6 bps
Neptune	130 bps	1 bps	2 bps

Table 1. Direct-to-Earth link performance

Clearly, communications performance will be quite limited for the outer planets – even using the SKA. Hence, a strategy that employs relays for communication supplemented by ground antennas for radio science may be preferred if the additional cost of a relay spacecraft is within the mission budget.

3.2. Relay Links

The use of a relay spacecraft can greatly improve the performance of a probe communications link. Relay links using the DSN have been employed with much success, including the Galileo Probe at Jupiter [4]; the Cassini/Huygens probe at Saturn; and many Mars missions.

Relays are an integral part of the international Mars exploration strategy. They have provided many advantages [5] including:

- Increased data return – Nearly all data from the Mars Exploration Rovers (MER) has come through relays, allowing ~10 times the data volume as the direct-to-Earth link on the Pathfinder mission in the first 90 days alone.

- Increased energy efficiency – Relays intended to serve multiple missions enable low-cost mission concepts since spacecraft do not have to carry heavy and power-intensive communication systems. MER was between 10-100 times more efficient in energy per bit than an equivalent direct-to-Earth link mission would have been, and the Phoenix (PHX) mission was accomplished with no direct-to-Earth capability.

- Increased connectivity – relays enable interactive operations in-situ. PHX had up to 10 relay contacts per Martian day.

- Better critical event telemetry – Relays allow the capture of telemetry data during high-risk mission phases, including entry, descent, and landing.

- Improved radio-based navigation – in situ spacecraft can use radio metric observables from the relay links.

For probe missions, the advantage of increased connectivity can be quite important. Without a relay, the mission design has to ensure line of sight between the probe and the Earth during communications. This constraint is more easily managed if there is a relay spacecraft.

Probe missions can use either one-way or two-way (bidirectional) communication with a relay. In the one-way case, data is simply sent from the probe to the relay where it is either stored or immediately sent to Earth. In the two-way case, there can be feedback on the communication link. Standard protocols, such as DTN, can guarantee assured data quality without the need for complex schemes (such as multiple transmissions or oversampling of science data) and without human intervention.

Table 2 shows some future possibilities for data returned from a probe through a relay. The performance is limited by the relay's direct-to-Earth communications system. For this example, we have assumed a relay system that is equivalent to the Mars Reconnaissance Orbiter (MRO). The data rates denoted with asterisks are higher than the relevant allocated bandwidth for deep space, which would require increased power to fit the transmitted data within the required bandwidth or a temporary relaxation of the bandwidth restrictions for the limited lifetime of the probe.

	Data Rate Today		Data Rate ~2020		Data Rate ~2030	
Spacecraft Capabilities	3m Antenna X-Band 100 W Transmitter		3m Antenna Ka-Band 180 W Transmitter Advanced Coding		5m Antenna Ka-band 200 W Transmitter Advanced Coding	
DSN Antennas	1 x 34m	3 x 34m	1 x 34m	Equiv to 3 x 34m	1 x 34m	Equiv to 7 x 34m
Venus (0.3 AU)	*80 Mbps	*240 Mbps	*575 Mbps	*1.7 Gbps	*1.8 Gbps	*8.9 Gbps
Venus (2.4 AU)	1.3 Mbps	3.8 Mbps	9 Mbps	27 Mbps	28 Mbps	139 Mbps
Mars (0.6 AU)	20 Mbps	*60 Mbps	140 Mbps	430 Mbps	440 Mbps	*2.2 Gbps
Mars (2.6 AU)	1 Mbps	3 Mbps	7.7 Mbps	23 Mbps	24 Mbps	120 Mbps
Jupiter	240 Kbps	740 Kbps	1.8 Mbps	5.3 Mbps	5.5 Mbps	27 Mbps
Saturn	70 Kbps	210 Kbps	510 Kbps	1.5 Mbps	1.6 Mbps	7.8 Mbps
Uranus	20 Kbps	60 Kbps	140 Kbps	430 Kbps	440 Kbps	2.2 Mbps
Neptune	8 Kbps	24 Kbps	56 Kbps	170 Kbps	170 Kbps	870 Kbps

Table 2. Relay link performance
* indicates data rates that are higher than the bandwidth allocations

4. NAVIGATION USING THE DSN

Planetary probe missions will likely depend on radiometric measurements as primary data types for developing navigation and trajectory solutions. The principal data types are Doppler, ranging, and angular measurements using techniques such as delta differenced one-way ranging (ΔDOR) [6].

The goal is to deliver the probe spacecraft to the desired atmospheric entry point and trajectory with an acceptable degree of error.

Accuracy can be increased substantially if there are other spacecraft at or near the target body. In this case, the DSN can perform differential radio measurements between the existing spacecraft (whose orbit or position is likely very well known) and the probe spacecraft. These measurements eliminate many common error sources, including effects near the target and near the Earth, resulting in increased precision [7].

It is also possible to increase navigational accuracy by adding non-DSN assets to the measurement. The DSN has successfully co-observed spacecraft for navigation purposes with antennas of other space agencies and with radio astronomy facilities.

Even if precise atmospheric delivery is not essential to a probe mission, it will still be desirable to determine the probe's path a-postiori, as well as to track its trajectory within the target's atmosphere.

5. SCIENTIFIC MEASUREMENTS WITH RADIO LINKS

Planetary atmospheric probes have used the radio communication links to provide additional science data. These measurements have most often focused on atmospheric dynamics by monitoring the velocity or position of the probe during its trajectory through an atmosphere. By modelling the response of a probe to changes in atmospheric motion, key data on general circulation, vertical structure, and turbulence can be obtained.

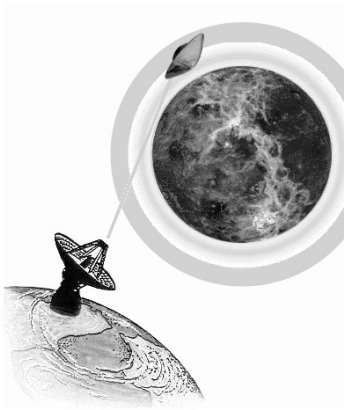

Fig. 4. Probe radio science

Position and velocity measurements of the probe depend on precision measurements of the phase of the radio signals transmitted by the probe on either direct-to-Earth links or relay links. This requires that both the probe transmission of the signal and its reception on the Earth or a relay spacecraft be controlled by stable frequency references, either onboard ultra-stable oscillators or an atomic clock at a DSN station on Earth, whose stability might be transferred to the relay spacecraft by radio link.

Probe velocity measurements require measuring the change in signal phase with time, the signal Doppler shift, providing a determination of the velocity component along the signal path. This has been done successfully for probes in the atmospheres of Venus (Venera [8] and Pioneer 10 probes [9], Vega balloons [10]), Jupiter (Galileo probe [11]), and Titan (Huygens probe [12]), with signal reception either on the Earth or on relay spacecraft. For the Galileo and Titan probes, the experiment design included both direct-to-Earth and relay links to simultaneously obtain two components of velocity information (although for the Titan probe the link to the relay spacecraft failed). An additional component of velocity information can be obtained through Earth-based VLBI measurements, as has been successfully done for the Pioneer 10 and Vega balloons at Venus and the Huygens probe at Titan. These VLBI measurements provide velocity information in the plane-of-the-sky and require signal reception at multiple Earth antennas. Probe position information can be obtained by modelling the velocity information, but improved results are possible from VLBI measurements, which require that the probe transmit over a range of frequencies (e.g., as with the Vega balloons and the Huygens probe).

Sometimes probes transmit at frequencies that are not supported by the DSN, requiring the use of radio astronomy observatories if Earth-based reception is desired. When radio observatories are employed, transport of versatile DSN Radio Science Receivers to these sites, as was done for the Huygens probe, can offer key scientific advantages.

In some cases signal absorption by atmospheric constituents influences the choice of frequency. In the outer planets ammonia is a strong absorber, leading to the choice of lower frequencies than standard DSN bands. However, signal absorption can be useful scientifically for determining the atmospheric density of molecular species, as was done for ammonia during the Galileo probe descent [13].

6. THE MILLION MILE SCREWDRIVER

The DSN can be used to perform in flight tests of probes or relays. This was accomplished by ESA in the case of the Cassini/Huygens mission [14]. The DSN was used to emulate the Huygens signal to the Cassini relay radio. It was this test that uncovered a critical design flaw in the relay radio, resulting in eventual changes to Huygens trajectory and ultimately saving the probe mission.

This ability to test and implement solutions remotely has often been referred to as the “million mile screwdriver.”

7. UNDERSTANDING THE SPECIAL NEEDS OF THE PLANETARY PROBE COMMUNITY

DSN planning is an ongoing activity. In order to develop plans for the future, we need to understand the missions that the DSN will be supporting.

The current DSN plan is based on the mission model as it is currently understood. However, the set of possible future DSN-support missions is constantly evolving.

Periodically, as in the case of this meeting, there are opportunities for intense first-hand interaction of mission concept developers. Both the DSN and the mis-

sion community benefit from these interactions and, as a result, both can hone their plans.

The authors encourage the planetary probe community to interact with the DSN planners to make their needs known and to learn how the DSN's planned capabilities can help enable their missions.

8. CONCLUSION

The DSN has embarked on a new phase of development that will ensure substantial capabilities for decades to come. Many of these capabilities are directly applicable to planetary probe missions, in both direct-to-Earth and relay communication systems.

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