Deep Space Representation

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Abstract: **The Deep Space Network (DSN) is a world wide network of large antennas and communication facilities, located in California, Spain, and Australia, that supports interplanetary spacecraft missions. It also performs radio and radar astronomy observations for the exploration of the solar system and the universe, and supports selected Earth-orbiting missions. DSN is part of the NASA Jet Propulsion Laboratory (JPL). Similar networks are run by Europe, Russia, China, India, and Japan.**

I. INTRODUCTION

DSN currently consists of three deep-space communications facilities placed approximately 120 degrees apart around the Earth. They are:

- The Goldstone Deep Space Communications Complex (35°25′36″N 116°53′24″W) outside Barstow, California.
- The Madrid Deep Space Communication Complex (40°25′53″N 4°14′53″W), 60 kilometres (37 mi) west of Madrid, Spain; and
- The Canberra Deep Space Communication Complex (CDSCC) in the Australian Capital Territory (35°24′05″S 148°58′54″E), 40 kilometres (25 mi) southwest of Canberra, Australia near the Tidbinbilla Nature Reserve.

Each facility is situated in semi-mountainous, bowl-shaped terrain to help shield against radio frequency interference. The strategic 120-degree placement permits constant observation of spacecraft as the Earth rotates, and helps to make the DSN the largest and most sensitive scientific telecommunications system in the world.

The DSN supports NASA's contribution to the scientific investigation of the Solar System: It provides the vital two-way communications link that guides and controls the unmanned interplanetary space probes, and brings back the images and new scientific information these probes collect. All DSN antennas are steerable, high-gain, parabolic reflector antennas. The antennas and data delivery systems make it possible to:

- Acquire telemetry data from spacecraft.
- Transmit commands to spacecraft.
- Upload software modifications to spacecraft.
- Track spacecraft position and velocity.
- Perform Very Long Baseline Interferometry observations.
- Measure variations in radio waves for radio science experiments.
- Gather science data.
- Monitor and control the performance of the network.

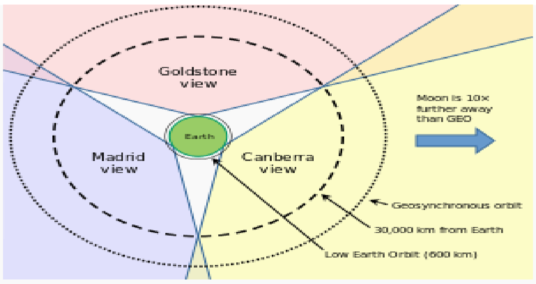

Fig 1: Deep Space

View from the Earth's north pole, showing the field of view of the main DSN antenna locations. Once a mission gets more than 30,000 km from earth, it is always in view of at least one of the stations.

Tracking vehicles in deep space is quite different from tracking missions in low Earth orbit (LEO). Deep space missions are visible for long periods of time from a large portion of the Earth's surface, and so require few stations (the DSN has only three main sites). These few stations, however, require huge antennas, ultra-sensitive receivers, and powerful transmitters in order to transmit and receive over the vast distances involved.

Deep space is defined in several different ways. According to a 1975 NASA report, the DSN was designed to communicate with "spacecraft traveling approximately 16,000 km (10,000 miles) from Earth. JPL diagrams state that at an altitude of 30,000 km, a spacecraft is always in the field of view of one of the tracking stations.

The International Telecommunications Union, which sets aside various frequency bands for deep space and near Earth use, defines "deep space" to start at a distance of 2 million km from the Earth's surface.

This definition means that missions to the Moon, and the Earth–Sun Lagrangian points L_1 and L_2, are considered near space and cannot use the ITU's deep space bands.

Other Lagrangian points may or may not be subject to this rule due to distance.

II. DSN AND THE APOLLO PROGRAM

Although normally tasked with tracking unmanned spacecraft, the Deep Space Network (DSN) also contributed to the communication and tracking of Apollo missions to the Moon, although primary responsibility was held by the Manned Space Flight Network. The DSN designed the MSFN stations for lunar communication and provided a second antenna at each MSFN site (the MSFN sites were near the DSN sites for just this reason). Two antennas at each site were needed both for redundancy and because the beam widths of the large antennas needed were too small to encompass both the lunar orbiter and the lander at the same time. DSN also supplied some larger antennas as needed, in particular for television broadcasts from the Moon, and emergency communications such as Apollo 13.

Excerpt from a NASA report describing how the DSN and MSFN cooperated for Apollo.

Another critical step in the evolution of the Apollo Network came in 1965 with the advent of the DSN Wing concept. Originally, the participation of DSN 26-m antennas during an Apollo Mission was to be limited to a backup role. This was one reason why the MSFN 26-m sites were collocated with the DSN sites at Goldstone, Madrid, and Canberra. However, the presence of two, well-separated spacecraft during lunar operations stimulated the rethinking of the tracking and communication problem. One thought was to add a dual S-band RF system to each of the three 26-m MSFN antennas, leaving the nearby DSN 26-m antennas still in a backup role. Calculations showed, though, that a 26-m antenna pattern centered on the landed Lunar Module would suffer a 9-to-12 db loss at the lunar horizon, making tracking and data acquisition of the orbiting Command Service Module difficult, perhaps impossible. It made sense to use both the MSFN and DSN antennas simultaneously during the all-important lunar operations. JPL was naturally reluctant to compromise the objectives of its many unmanned spacecraft by turning three of its DSN stations over to the MSFN for long periods. How could the goals of both Apollo and deep space exploration be achieved without building a third 26-m antenna at each of the three sites or undercutting planetary science missions?

The solution came in early 1965 at a meeting at NASA Headquarters, when Eberhardt Rechtin suggested what is now known as the "wing concept". The wing approach involves constructing a new section or "wing" to the main building at each of the three involved DSN sites. The wing would include a MSFN control room and the necessary interface equipment to accomplish the following:

1. Permit tracking and two-way data transfer with either spacecraft during lunar operations.
2. Permit tracking and two-way data transfer with the combined spacecraft during the flight to the Moon.
3. Provide backup for the collocated MSFN site passive track (spacecraft to ground RF links) of the Apollo spacecraft during trans-lunar and trans-earth phases.

With this arrangement, the DSN station could be quickly switched from a deep-space mission to Apollo and back again. GSFC personnel would operate the MSFN equipment completely independently of DSN personnel. Deep space missions would not be compromised nearly as much as if the entire station's equipment and personnel were turned over to Apollo for several weeks.

III. ANTENNAS

Fig 2: 70 m antenna at Goldstone

Each complex consists of at least four deep space terminals equipped with ultra-sensitive receiving systems and large parabolic-dish antennas. There are:

- One 34-meter (112 ft) diameter High Efficiency antenna (HEF).
- One or more 34-meter (112 ft) Beam waveguide antennas (BWG) (three operational at the Goldstone Complex, two at the *Robledo de Chavela complex* (near Madrid), and one at the Canberra Complex).
- One 26-meter (85 ft) antenna.
- One 70-meter (230 ft) antenna (70M).

Five of the 34-meter (112 ft) beam waveguide antennas were added to the system in the late 1990s. Three were located at Goldstone, and one each at Canberra and Madrid. A second 34-meter (112 ft) beam waveguide antenna (the network's sixth) was completed at the Madrid complex in 2004.

In order to meet the current and future needs of deep space communication services, a number of new Deep Space Station antennas need to be built at the existing Deep Space Network sites. At the Canberra Deep Space Communication Complex the first of these antennas is currently nearing completion, and a second has begun construction. The first of the new antennas is scheduled to come online in September 2014, and the second in 2016.

IV. CURRENT SIGNAL PROCESSING CAPABILITIES

The general capabilities of the DSN have not substantially changed since the beginning of the Voyager Interstellar Mission in the early 1990s. However, many advancements in digital signal processing, arraying and error correction have been adopted by the DSN.

The ability to array several antennas was incorporated to improve the data returned from the Voyager 2 Neptune encounter, and extensively used for the Galileo spacecraft, when the high-gain antenna did not deploy correctly.

The DSN array currently available since the Galileo mission can link the 70-meter (230 ft) dish antenna at the Deep Space Network complex in Goldstone, California, with an identical antenna located in Australia, in addition to two 34-meter (112 ft) antennas at the Canberra complex. The California and Australia sites were used concurrently to pick up communications with Galileo.

Arraying of antennas within the three DSN locations is also used. For example, a 70-meter (230 ft) dish antenna can be arrayed with a 34-meter dish. For especially vital missions, like Voyager 2, the Canberra 70-meter (230 ft) dish can be arrayed with the Parkes Radio Telescope in Australia; and the Goldstone 70-meter dish can be arrayed with the Very Large Array of antennas in New Mexico. Also, two or more 34-meter (112 ft) dishes at one DSN location are commonly arrayed together.

All the stations are remotely operated from a centralized Signal Processing Center at each complex. These Centers house the electronic subsystems that point and control the antennas, receive and process the telemetry data, transmit commands, and generate the spacecraft navigation data. Once the data is processed at the complexes, it is transmitted to JPL for further processing and for distribution to science teams over a modern communications network.

V. NETWORK LIMITATIONS AND CHALLENGES

Fig 3: 70m antenna in Robledo de Chavela,Community of Madrid, Spain

There are a number of limitations to the current DSN, and a number of challenges going forward.

- The Deep Space Network is something of a misnomer, as there are no current plans, nor future plans, for exclusive communication satellites anywhere in space to handle multiparty, multi-mission use. All the transmitting and receiving equipment are Earth-based. Therefore data transmission rates from/to any and all spacecrafts and space probes are severely constrained due to the distances from Earth.
- The need to support "legacy" missions that have remained operational beyond their original lifetimes but are still returning scientific data. Programs such as Voyager have been operating long past their original mission termination date. They also need some of the largest antennas.
- Replacing major components can cause problems as it can leave an antenna out of service for months at a time.
- The older 70M & HEF antennas are reaching the end of their lives. At some point these will need to be replaced. The leading candidate for 70M replacement had been an array of smaller dishes, however more recently the decision was taken to expand the provision of 34 BWG antennas at each complex to a total of 4.
- By 2020, the DSN may be required to support twice the number of missions it was supporting in 2005. The 2007–present global economic crisis has limited the number of new missions somewhat. However, due to decay and lack of replacement of the existing antennas increased mission support will continue to be an ongoing problem. New spacecraft intended for missions beyond geocentric orbits are being equipped to use the beacon mode service, which allows such missions to operate without the DSN most of the time.

VI. THE DSN DATA TYPES

The DSN is an extremely complex facility, but it becomes more easily comprehensible if you recognize its seven data types, as a context for learning about DSN subsystems, and how they relate to each other. In the past, each of these seven data types was associated with a separate DSN system. Today, thanks to the Network Simplification Program, these have been consolidated into two DSN systems: Uplink (The Uplink Tracking and Command Subsystem, UPL) and Downlink (The Downlink Tracking & Telemetry Subsystem, DTT).

Here is a brief discussion of the DSN data types that are processed in the UPL and DTT:

1. FREQUENCY & TIMING DATA TYPE, F&T

Any computer system, whether desktop or super computer, has an internal clock that directs every step of the computer's operations. F&T is the DSN's "internal clock." With precision and accuracy that are at the forefront of world class frequency and timing science, the Frequency & Timing Subsystem is essential to nearly every part of the DSN, enabling the other six data types to exist.

At the heart of F&T are four frequency standards of which one is prime and the other three are backups. These include the hydrogen masers and cesium frequency standards. The master clock assembly produces time codes using the frequency standard as a reference. Every subsystem across the DSN, and nearly every assembly have an input of F&T

data in the form of a reference frequency and/or time codes. Those subsystems having time code inputs interface via time code translators, TCTs.

F&T synchronization is managed among all three DSCCs and JPL by keeping track of offsets in fractions of microseconds resulting from comparison of local F&T data with reference pulses received from Global Positioning System, GPS, satellites.

2. TRACKING DATA TYPE, TRK

The TRK data type includes Doppler, ranging, predicts, and DSN antenna control.

Measurement of the Doppler shift on a spacecraft's coherent downlink carrier allows determination of the line-of-sight component of the spacecraft's velocity. Routine measurement precision is on the order of fractions of a millimeter per second.

Ranging tones uplinked and transponded by a spacecraft enable navigators to determine an average distance to and from the spacecraft, with a routine precision of about one meter.

Navigators use Doppler and range measurements to determine a spacecraft's trajectory, and to infer gravity fields of bodies that affect the spacecraft. Navigation team members create ephemeris files that the DSN uses to generate antenna pointing predicts and frequency predicts for uplink and downlink. Predicts are sent to DSN sites to enable acquisition and following of the spacecraft.

3. TELEMETRY DATA TYPE, TLM

The word Telemetry is derived from the Greek "tele" (far off), and "metron" (measure). A spacecraft produces digital data to represent engineering measurements, such as the temperatures of parts of the spacecraft, and science data, such as images from its cameras. The spacecraft places symbols on its radio frequency downlink to represent the ones and zeroes that make up this data. The DSN Downlink Tracking & Telemetry subsystem recreates the spacecraft's digital data bit for bit by recognizing the downlinked symbols and decoding them. DSN then delivers the TLM data to the flight project for display, distribution, storage, and analysis, supporting spacecraft engineering managemnt and eventual publication of scientific results

4. COMMAND DATA TYPE, CMD

Flight projects send digital data to the spacecraft via the DSN Uplink Tracking & Command subsystem. Like telemetry-in-reverse, digital bits generated by the flight project are sent as CMD data to the spacecraft, which is able to recognize the bits as either flight software to load into it n-board computers, or as commands to control the spacecraft's activities.

5. MONITOR DATA TYPE, MON

MON data reports on the operation and performance of the DSN itself. The DSN Network Monitor & Control subsystem (NMC) collects data from assemblies throughout its subsystems. This MON data is used in various locations: within the DSCC to watch and control its own activities; at the Network Operations and Control Center at JPL for managing and advising DSN operations, and in flight projects to help with realtime coordination of operations. Flight projects typically select a subset of MON data to distribute and store along with TLM data to provide indications of, for example, the strength of the spacecraft's signal as received by DSN at any given time.

6. RADIO SCIENCE DATA TYPE, RS

RS experiments use the spacecraft radio and the DSN together as a science instrument. RS investigators remotely control equipment in the DSN such as the Radio Science Receivers, RSR, to capture and record data on the attenuation, scintillation, refraction, rotation, Doppler shifts, and other direct modifications of a spacecraft's radio signal as it is affected by the atmosphere of a planet, the sun, moons, or by structures such as planetary rings or gravitational fields.

Unlike the closed-loop receivers used by TRK and TLM, RS uses open-loop receivers and spectrum processing equipment. Rather than lock onto one discrete frequency, the open-loop equipment can observe a range of frequencies.

The JPL Radio Science System Group has an informative website.

7. VERY LONG BASELINE INTERFEROMETRY DATA TYPE, VLBI

VLBI can be applied to a number of investigations. Two or more widely separated DSN stations observe the same spacecraft, or a quasar, at the same time, using open-loop receivers, and record their data. The recorded

data is taken to a special-purpose computer called a correlator for processing to produce a cross-correlation fringe pattern. Further analysis can precisely determine the relative position of the antennas. This investigation is called geodesy. With the antenna positions known precisely, VLBI can precisely determine the position of a spacecraft. VLBI can also produce synthetic aperture results such as images of astronomical objects.

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