DSMS (DEEP SPACE MISSION SYSTEM) INVESTMENT IN SUPPORT OF SATELLITE CONSTELLATIONS AND FORMATION FLYING

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Abstract

Over the years, NASA has supported unmanned space missions through a Deep Space Mission System (DSMS) that is developed and operated by the Jet Propulsion Laboratory (JPL) and its subcontractors. The DSMS capabilities have been incrementally upgraded since its establishment in the late '50s and are delivered from three Deep Space Communications Complexes (DSCC's) near Goldstone, California, Madrid, Spain, and Canberra, Australia and from facilities at JPL. Traditionally, mission support is assigned on an individual-mission basis - tracking, command, telemetry and so forth, each contact ("pass") is between a single mission and a single ground-based antenna, independent of other missions. As NASA, and its international partners, is moving toward flying full constellations and precision formations, the DSMS is developing plans and technologies to provide the requisite support. The key activities under way are:

(1) Communications infrastructure around Mars, including lower-orbit and "stationary" satellites, to provide continuous coverage for orbiters, landers and rovers. JPL is developing architecture, as well as protocols and equipment required to operate such infrastructure in a cost-effective way.

(2) Internet-type protocols that will allow for efficient operations across the deep-space distances, accounting and accommodating the long round-trip-light-time. JPL is working with the CCSDS to convert these protocols to an international standard.

(3) Techniques to perform cross-navigation between spacecraft that fly in a loose formation. Typical cases are cross-navigation between missions that approach Mars and missions that are at Mars, or the determination of a baseline for missions that fly in an earth-lead-lag configuration.

(4) Techniques and devices that allow the precise metrology and controllability of tight formations for missions such as ST-3 and ST-5.

In this paper we discuss the four classes of constellation/formation support with emphasis of DSMS current status (technology and implementation) and plans in each area.

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1. INTRODUCTION

Over the years, NASA has supported unmanned space missions through the DSN [1], developed and operated by JPL and it subcontractors. In recent years, JPL has expanded the scope of the DSN to include multi-mission ground systems as well as multi-mission operations support infrastructure - the expanded entity is named DSMS. The DSN support is delivered from three DSCC's located near Goldstone, California, Madrid, Spain, and Canberra, Australia and from facilities at and near JPL, as shown in Figure 1. For the DSMS, additional facilities at NASA centers (e.g. Ames), flight contractors (e.g. LMA Denver) and PI's augment this physical layout around the world.

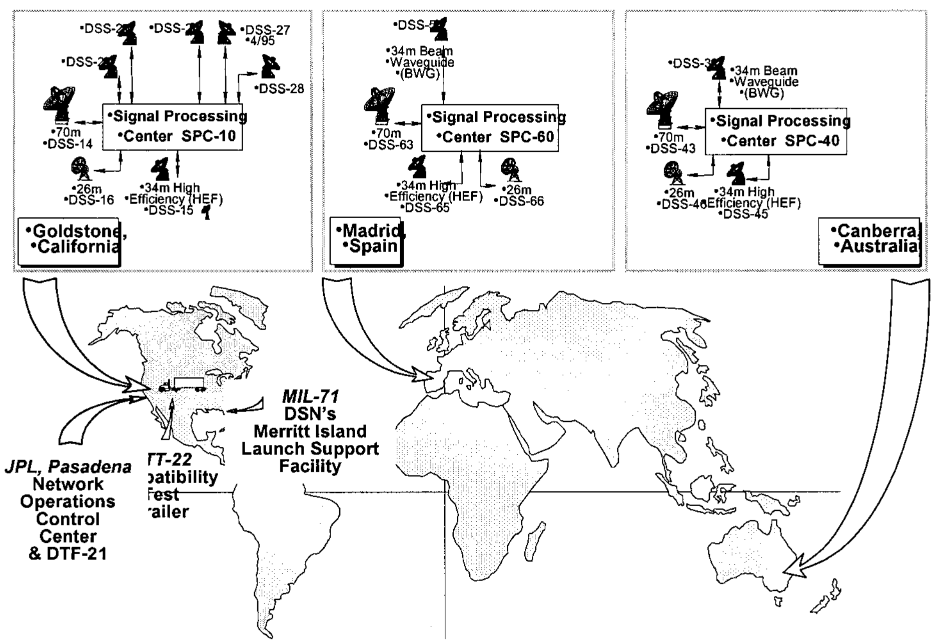

Figure 1 - Key DSN facilities

Traditionally, DSN mission support is assigned on a one-mission-one-ground-antenna basis[2]. DSN support is allocated in discrete units denoted "passes", where each pass is a contact between a single mission and a single ground antenna, to conduct mission-required tracking, command, telemetry, and DSN science[3] functions. The process of scheduling (and rescheduling) passes is the only operational process that requires balancing between the requirements of the supported missions; after that initial allocation, DSN support of one mission is independent of support provided to other missions.

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[2] There are three notable exceptions to the single-mission-single-ground-antenna rule. The first exception is arraying, where multiple antennas are arrayed to collect the signal from a single mission. The second exception is three-way operations where two antennas are used to support a single spacecraft - one for uplink and one for downlink. The third exception is MSPA, discussed further in Section 2

[3] In addition to the traditional TT&C functions, the DSN antennas are used for direct science acquisition, either in a stand-alone mode, or as part of a constellation. Direct science is acquired in the areas of radio astronomy (including VLBI), radio-science and planetary radar.

The one-mission-one-ground-antenna support was an effective solution when there were few deep space missions flying and they were in different areas of the sky, making cross support impractical. This is no longer the case - the evolving plans of NASA and its international partners increasingly deploy mission constellations as both a cost-effective way to focus resources on a specific target (e.g. for Mars exploration) and a tool to greatly increase science acquisition (e.g. interferometric search for planets around stars). This evolution is driving a remarkable change in the methods the DSMS uses to deploy and allocate resources.

In sections 2-4 we address the changing scope of the communications and navigation function of the DSMS, required to support satellite constellations and formation flying. In section 5 we discuss how the DSMS leverages its experience in precision VLBI and GPS technologies to meet requirements for highly accurate metrology and controllability of some formation flying missions. Finally, we briefly comment on other changes to the mission operations environment that would benefit the emerging constellation/precision-flying environment.

2. INVESTMENT IN COMMUNICATIONS INFRASTRUCTURE

To effectively support constellations, NASA [2] is changing the communications infrastructure in two respects. While the near-term approach is to increase the effectiveness of ground-based assets[4] via the broad application of MSPA techniques, the longer-term change is the gradual deployment of communications / navigation trunk lines in areas of space where many spacecraft are expected to exist, initially around Mars.

By 2003, JPL will have MSPA capability deployed at all the DSCC's, with an initial capability to support two spacecraft with a single antenna. In MSPA operations, a single antenna receives the signals from two (or more) spacecraft that are in the same antenna beam. The signals are then routed to different processors, recovered independent from each other and sent to the respective mission operations centers. From the mission's viewpoint, the sharing of a single antenna poses a modest set of restrictions that must be addressed in the planning of operations. While current plans call for up to 2 spacecraft sharing one antenna, the evolving DSMS architecture allows to easily expand MSPA capability to support additional spacecraft, simply by installing additional processors

The two key MSPA restrictions are the availability of a single uplink, and the requirement that the S/C RF characteristics are "matched". The single uplink requires that the missions coordinate use of the uplink for commanding, e.g. by identifying the target S/C in the command header. The missions must also coordinate one-way/two-way operations to assure that the downlink signals from the participating missions do not interfere with each other. The restriction on S/C RF characteristics is that not only must the spacecraft reside inside the same beam, but also their downlink RF characteristics must allow simultaneous reception by a single ground antenna. Thus, the signals must be matched to either a single RF feed, or to one of the multiple-feed combinations supported by some DSN antennas[5].

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[4] The DSN antennas are the most expensive physical assets of the DSMS. They are very large (up to 70m diameter), fully-steerable, with very sensitive receivers, and high power transmitters, required for deep-space TT&C. Maximizing use of these assets, e.g. via MSPA, is crucial to maintaining the cost-effectiveness of space operations.

[5] For example, all the DSN 34m BWG antennas are being upgrades to allow simultaneous reception of signals in the X and Ka-bands.

The DSMS is exploring methods to transmit multiple uplink signals with the same transmitter, providing distinct uplink to the missions sharing MSPA, and distinct downlink RF signals. The technical issues are rather straight forward; from an operations viewpoint the benefit is less clear - splitting the uplink power between several frequencies allows more independence between the supported missions but reduces the power available to each mission. This in turn will require longer uplink periods and increase the cost of operations team to support the longer uplink periods. With the advent of spacecraft transponders with digital on-board frequency synthesizers and auto-acquisition, uplink sharing (while keeping downlinks separate) may become feasible in the near future.

The longer-term solution to communications infrastructure needs is the development of trunk lines. With the high cost of on-board telecom equipment, it appears that designating one, or few, missions as relays for communications to Earth would be cost effective. The simplest model is for a tight constellation, e.g. ST-3, to equip just one spacecraft with the expensive antenna, power supplies, power amplifiers, etc needed for communications to earth. Then, the other S/C in the constellation can utilize the much simpler, and less expensive, communications equipment needed for inter-spacecraft communications.

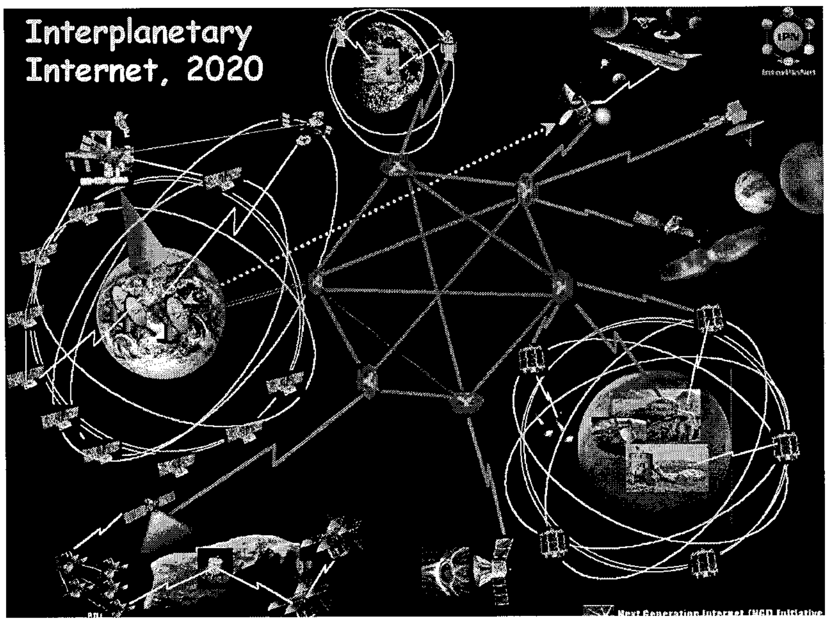

Figure 2 - Vision of NASA Interplanetary Internet

NASA incorporated communications relay satellites in the recently [3] published Mars plans from both NASA and international partners. The design, production, deployment, and operations methodologies of these satellites are largely extensions of the mature capability of government and commercial relay satellites near earth. For example, an early plan that JPL developed [4] included both a low-orbit satellite constellation, and high altitude stationary satellites, similar to the geostationary satellites parked above the equator.

The use of inter-S/C links as elements of the deep space communication scheme offers two interesting side benefits. The first is that the less demanding link budget allows conduct of communications at lower frequencies and simplifies the pointing requirements on the spacecraft[6]. The second benefit is that the RF link used for inter-vehicle communications can also be used for inter-vehicle navigation and spacecraft position-keeping functions, as discussed further in [5].

3. INVESTMENT IN DEEP SPACE PROTOCOLS

For near-earth constellations, protocols similar, or the same, as those used for the Internet can be used. For these protocols, there is a wide choice of providers and devices from commercial sources and a wealth of experience. Deep space communication protocols cannot use the standard Internet protocol without modifying them to accommodate the unique deep space communications environment:

Long RTLT. Deep space communications involves very long RTLT (17-22 hours for the Voyager S/C at present distance) making two-way communications with standard Internet protocols impractical.

Each bit is precious. With the large propagation distances, and low power on the spacecraft, deep space data rates are very low compared to terrestrial and low-earth constellation data rates - KBPS vs. MBPS. The use of that limited bandwidth for protocol overhead must to be carefully weighed.

Physical limitations on links. Imagine the simplest case of a rover on Mars trying to communicate to earth via an orbiter around Mars. Because of visibility limitations, this may occur via two sessions, separated by minutes or hours - the first between the rover and orbiter, the second between the orbiter and Earth. Restricting the protocols to require two-way communications between Earth and rover (via an orbiter) will impose a severe scheduling load.

JPL is leading an Interplanetary Internet working group [6] that is developing a variant of the Internet that can be applied to both the links between the spacecraft and Earth and the inter-spacecraft links. The plan is to have these protocols established as international standards, under the sponsorship of the CCSDS.

Given the long RTLT, the Interplanetary Internet will make heavy use of file transfer protocols. A key standard, CFDP, has been prototyped in both the DSMS ground system and on STRV and will be flight-tested in late 2000.

4. INVESTMENT IN CROSS-NAVIGATION

Deep space navigation was historically based on tracking of a single spacecraft at a time. This was accomplished with combinations of radio-metric (ranging and Doppler) and optical methods. When flying satellite constellations, cross-spacecraft navigation adds powerful elements to the navigator's tool kit. The most exciting near-term improvement is the upcoming use of DDOR [7].

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[6] In contrast, communications between deep space missions and earth is migrating to higher frequencies, to reduce the space loss. For Mars missions communication with the relay is baselined at UHF band while communications to Earth is baselined at X-band.

Navigating with radio-metric data requires very careful modeling of both the spacecraft and the ground equipment. The latter is difficult to calibrate - systematic biases change often with the equipment configuration. In addition, because the radio-metric measurement is radial in nature, it is rather inaccurate in the plane-of-sky direction (perpendicular to the Earth-S/C radial direction), hence long integration times - often a full pass - are required to reduce the random errors to acceptable levels. Recall that the required fidelity of the radio-metric data is extraordinary - required trajectory accuracy for orbit insertion is measured in 10's of km, at distances of over 300,000,000 km for Mars missions

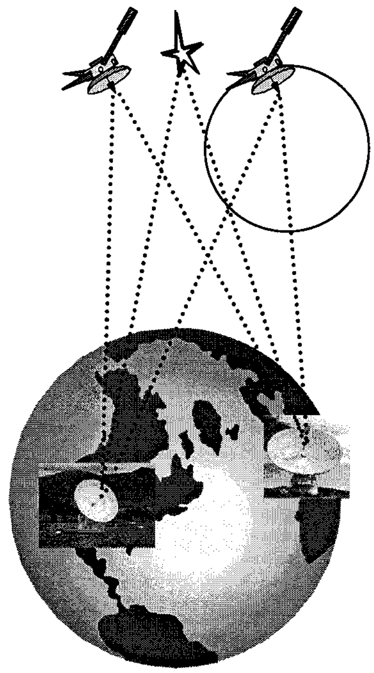

Figure 3 - DDOR Configuration

DDOR offers an effective fast measurement that greatly improves accuracy for the plane-of-sky dimension. The DDOR configuration, shown in Figure 3, relies on two ground antennas and two S/C that are in the same area of the sky (it can also use a spacecraft and a Quasar instead of two spacecraft). In a typical case, one orbits Mars, while the other is approaching Mars. The doubly differenced nature of the measurements virtually eliminates the biases associated with both the spacecraft and the ground equipment. The integration time to reduce the random effects is minimized - typically to 15 minutes for a measurement, compared to 8 hours for a comparable ranging pass. The only major limitation is the requirement for the S/C signal to span a large bandwidth - this is usually accomplished by having tones placed 10-20 MHz away on either side of the RF carrier.

DSMS is planning on deploying a DDOR capability at all the DSCC's by 2003, with primary use for the Mars missions.

5. INVESTMENT IN PRECISION METROLOGY AND CONTROLLABILITY

The investments discussed in Sections 2-4 benefited the scientific mission of NASA (and other international agencies) primarily via improving the cost effectiveness of space exploration.

Formation flying enables also a new class of missions, where the science product is derived not from a single instrument (or multiple instruments), on one S/C, but from integrating observations from instruments on several spacecraft. The formations can be tight, e.g. ST-3, or widely spaced, e.g. STEREO, or CLUSTER. The requirements on metrology and controllability vary: for some formations, routine radio-metric navigation and thruster control are sufficient, others require high-precision metrology and controllability. The latter class of applications and investment in techniques and equipment are further discussed in [5].

6. CONCLUSIONS

In this paper we have focused on the DSMS investments aligned with the support of satellite constellations and formation flying. JPL is also addressing the more general evolution in the methodology of mission operations, downstream from the DSN antennas. There are two fundamental changes that are emerging: the management of a constellation with a single operations team and the evolution of on-board autonomy.

Deep Space mission operations used to be conducted in mission-unique control centers. For Mars's missions, JPL has established a single team that handled multiple missions - the crosscutting theme is the similar operational environment and tracking needs. This shared-team, and shared tools, approach was highly effective in coordinating between the missions, e.g. sharing DSN resources and navigation functions, and controlling/reducing the mission operations costs, even for a modest constellation. As constellation size grows, the shared team will be further expanded, unifying operations across more missions.

In the long-term, JPL in investing in a unified MDS that will be the baseline flight S/W (with the corresponding ground components) for the JPL deep space missions. A key feature of MDS is extensive on-board autonomy, critically significant for deep space missions because the long RTLT makes joystick operations impractical. JPL is exploring use of MDS for non-JPL missions as well.

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ACRONYMS

CCSDS	Consultative Committee for Space Data Standards
CFDP	CCSDS File Delivery Protocol
DDOR	Delta Difference of Range
DSCC	Deep Space Communications Complex
DSMS	Deep Space Mission System
DSN	Deep Space Network
GPS	Global Positioning System
JPL	Jet Propulsion Laboratory
KBPS	Kilo Bits Per Second
LMA	Lockheed Martin Astronautics
MDS	Mission Data System
MBPS	Mega Bits Per Second
MSPA	Multiple Spacecraft Per Antenna
NASA	National Aeronautics and Space Administrations
PI	Principal Investigator
RF	Radio-Frequency
S/C	Spacecraft
STRV	Space Technology Research Vehicle
TT&C	Tracking, Telemetry and Command
RTLT	Round Trip Light Time
VLBI	Very Long-baseline Interferometry