

# DSMS<sup>1</sup> Investment in support of Satellite Constellations and Formation Flying

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## Abstract

*Over the years, NASA has supported unmanned space missions, beyond earth orbit, through a Deep Space Mission System (DSMS) that is developed and operated by the Jet Propulsion Laboratory (JPL) and subcontractors. The DSMS capabilities have been incrementally upgraded since its establishment in the late '50s and are delivered primarily through three Deep Space Communications Complexes (DSCC's) near Goldstone, California, Madrid, Spain, and Canberra, Australia and from facilities at JPL. Traditionally, mission support (tracking, command, telemetry, etc) is assigned on an individual-mission basis, between each mission and a ground-based asset, independent of other missions. As NASA, and its international partners, move 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) Integrated communications architecture for Mars exploration, including relays on science orbiters and dedicated relay satellites to provide continuous coverage for orbiters, landers and rovers. JPL is developing an architecture, as well as protocols and equipment, required for the cost-effective operations of such an infrastructure.*
- (2) Internet-type protocols that will allow for efficient operations across the deep-space distances, accounting for and accommodating the long round-trip-light-time. JPL is working with the CCSDS to convert these protocols to an international standard and will deploy such protocol, the CCSDS File Delivery Protocol (CFDP), on the Mars Reconnaissance Orbiter (MRO) and on the Deep Impact (DI) missions.*
- (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 precision constellation missions.*

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

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<sup>1</sup> DSMS – Deep Space Mission System

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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 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 through three DSCC's located near Goldstone, California, Madrid, Spain, and Canberra, Australia and from facilities at and near JPL. Additional facilities at NASA centers (e.g. Ames Research Center), flight contractors (e.g. LMA Denver) and PI's augment this physical layout around the world. In recent years, with the establishment of CCSDS Space Link Extension (SLE) standards, support is being expanded to cover cross-utilization between NASA and non-NASA antennas and control centers [2].

Traditionally, DSN mission support is assigned on a one-mission-one-ground-antenna basis<sup>3</sup>. Allocation is via discrete units, "passes", where each pass is a contact (or a set of contacts within a non-interrupted antenna assignment) between a single mission and a single ground antenna, to conduct mission-required tracking, command, telemetry, and DSN science<sup>4</sup> functions. The process of scheduling (and rescheduling) passes is the main operational process that requires balancing between the requirements of the supported missions; after that initial allocation, the DSN supports one mission largely independent of the support provided to other missions.<sup>5</sup>

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 briefly 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 enumerate 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 is changing the communications infrastructure in two respects. While the near-term approach is to increase the effectiveness of ground-based assets<sup>6</sup> via the broad application of MSPA techniques [3], the longer-term change is

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<sup>3</sup> 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

<sup>4</sup> 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.

<sup>5</sup> While availability of antennas is the key factor forcing coupling between missions competing for support, other restricted resources may also force secondary coupling that needs to be resolved.

<sup>6</sup> 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.

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. This capability will be replicated twice at each DSCC, thus each DSCC will be able to support through MSPA four spacecraft, with two antennas (in addition to one-antenna-one-spacecraft support with the other antennas). 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 telemetry processors where the telemetry is recovered and sent to the respective mission operations centers. While current plans are for 2-MSPA (2 spacecraft sharing one antenna), the evolving DSMS architecture allows to easily expand MSPA capability to support additional spacecraft, simply by installing additional processors.

Sharing an antenna imposes a modest set of restrictions that must be addressed in the planning of operations. The two key MSPA restrictions are the availability of a single uplink, and the requirement that the spacecraft RF characteristics are "matched". The single uplink limitation requires that the missions share use of the uplink, either through scheduling, or by selecting protocols and frequency plans that allow for near-real-time sharing, e.g. by identifying the target spacecraft 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 spacecraft RF characteristics is that not only must the spacecraft reside inside the same antenna 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<sup>7</sup>.

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 straightforward; 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) is likely to become more attractive.

The longer-term solution to communications infrastructure needs is to augment the point-to-point support with relay-based support via an effective network. With the high cost of on-board telecom equipment, designating one, or few, missions to serve as relays for communications to Earth is more cost effective than requiring each mission to communicate directly to Earth. The simplest model is for a tight constellation, where the distances between spacecraft are significantly shorter than those between the constellation and Earth. In such a case, one may equip just one spacecraft with the expensive antenna, power supplies, power amplifiers, etc needed for communications to Earth. The other spacecraft in the constellation can utilize the much simpler, and less expensive, communications equipment needed for inter-spacecraft communications.

An early version of this approach to communications from a constellation will be operational starting in December 2003. The Mars Exploration Rovers (MERs) will have the ability to communicate directly to earth, but will use relay through the Mars Global Surveyor (MGS) and Mars Odyssey (MO) missions to enable higher data returns. In particular, the MERs

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<sup>7</sup> For example, all the DSN 34m BWG antennas are being upgraded to allow simultaneous reception of signals in the X and Ka-bands.

will rely on the MGS/MO relay to cover the Entry-Decent-Landing events, where communications directly to earth is extremely difficult.

The current Mars communications architecture is described in [4] and illustrated in Figure 1. The architecture relies on an internationally-supplied set of communications satellites to provide incrementally increasing coverage to assets at Mars. 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. In the interim, missions will continue to rely on the relaying capabilities that are carried by science-centric satellites.

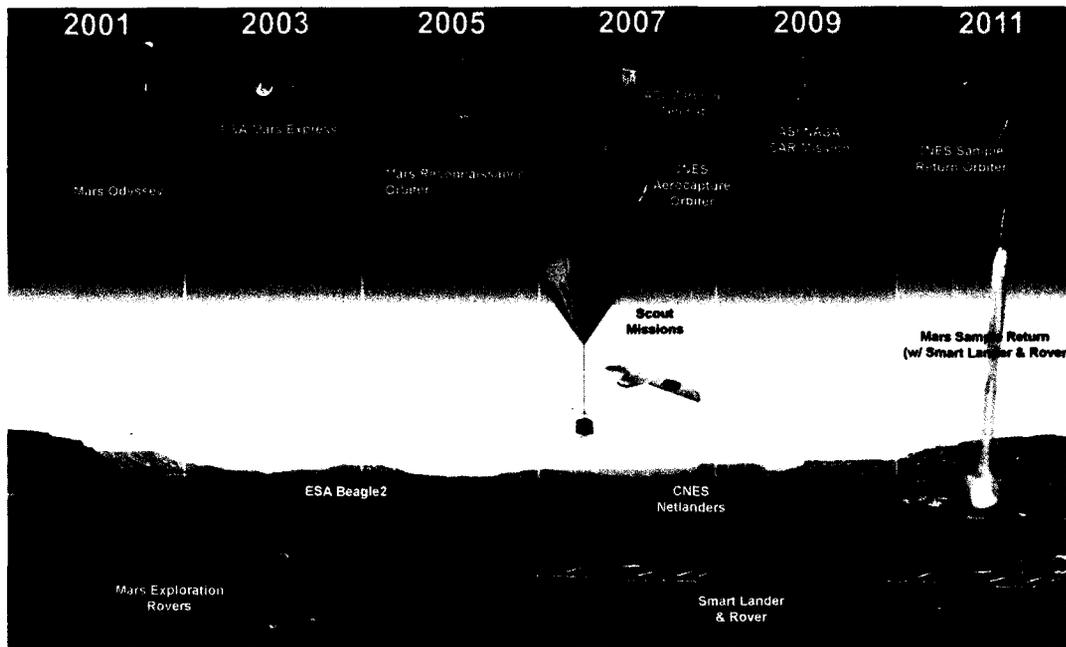


Figure 1 – Mars Communications Architecture

The use of inter-spacecraft 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<sup>8</sup>. 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.

### 3. INVESTMENT IN DEEP SPACE PROTOCOLS

For near-earth constellations, Internet, or Internet-like, protocols 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 spacecraft) making two-way communications with standard Internet protocols impractical.

<sup>8</sup> While communications between deep space missions and earth is migrating to higher frequencies (e.g. 8.4 GHz and 32 GHz) to reduce the space loss, Mars missions communicate with the relay in UHF band.

Each bit is precious. With the long 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 be carefully weighed.

Physical limitations on connectivity. Imagine the simplest case of a rover on Mars trying to communicate to earth via an orbiter around Mars. Because of visibility limitations on the rover-orbiter and orbiter-Earth connections, 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.



Figure 2 – Long-term vision – Constellations at multiple locations

JPL is leading the CCSDS effort to develop a variant of the Internet that can be applied to both the links between the spacecraft and Earth and the inter-spacecraft links [5]. The plan is to have these protocols established as international standards, under the sponsorship of the CCSDS. Given the long RTLT, the protocols will make heavy use of file transfer protocols. A key standard, CFDP, will be used operationally to support MRO and DI. Figure 2 shows a configuration where multiple constellations exist and the CCSDS protocols underlay the communications intra- and inter-constellation.

#### ***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 [6].

Navigating with radio-metric data requires very careful modeling of both the spacecraft and the ground equipment. Both are difficult to calibrate - systematic biases change often with the equipment configuration, temperature, etc. 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-

spacecraft 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

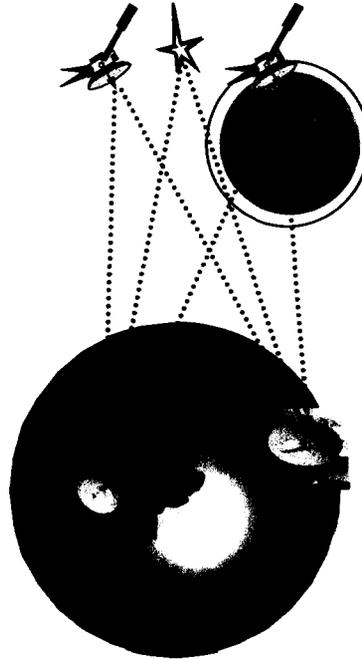


Figure 3 - DDOR Configuration

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 spacecraft 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 spacecraft 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 remaining random effects is minimized - typically to 15 minutes for a measurement, compared to hours for a comparable ranging pass. The only major limitation is the requirement that the spacecraft signal 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 spacecraft, but from integrating observations from instruments on several spacecraft. The formations can be tight, e.g. SIM (or the original plan for 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. DSMS is participating in the development of techniques and equipment to meet these requirements, through investment in technology in the VLBI, GPS, and optical areas.

## 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. JPL is migrating some of the mission operations to multi-mission teams, where a team shares operations of multiple missions with a common thread, e.g. a constellation around Mars. This shared-team-shared-tools approach is 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, utilization of shared operations teams is likely to increase.

JPL is also investing in on-board autonomy because the long RTLT makes joystick operations impractical for deep space missions. The balance between ground-based operations and on-board autonomy is likely to shift toward the spacecraft.

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## ACRONYMS

BWG	Beam Wave Guide
CCSDS	Consultative Committee for Space Data Standards
CFDP	CCSDS File Delivery Protocol
DI	Deep Impact
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
mbps	Mega Bits Per Second
MER	Mars Exploration Rover
MGS	Mars Global Surveyor
MO	Mars Odyssey
MRO	Mars Reconnaissance Orbiter
MSPA	Multiple Spacecraft Per Antenna
NASA	National Aeronautics and Space Administrations
PI	Principal Investigator
RF	Radio Frequency
S/C	Spacecraft
SLE	Space Link Extension
TT&C	Tracking, Telemetry and Command
RTLTL	Round Trip Light Time
VLBI	Very Long-baseline Interferometry