Low-Cost Approaches to Deep Space Missions

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Introduction

The past decade has brought about a radical transformation in NASA's planetary exploration program. At the beginning of this decade, NASA was focused on the Cassini mission to Saturn. Following on the heels of the successful Voyager and Galileo missions, Cassini represents the culmination of an evolution towards successively larger, more complex, and more expensive spacecraft. The Cassini spacecraft weighs in at over 5 metric tons, and carries an entry probe and a sophisticated suite of sensors supporting 27 different science investigations enabling a comprehensive scientific investigation of Saturn with a single spacecraft. The cost of this spacecraft exceeded $2B, including the cost of the large Titan IV launch vehicle.

During Cassini development, NASA realized that it could no longer afford these "flagship" missions, and the agency moved aggressively towards a "faster, better, cheaper" design philosophy of focused science goals and simpler, rapidly-developed spacecraft, allowing much more frequent launches of smaller, lower-cost missions. The Mars Global Surveyor, launched in November 1996, is an example of this new paradigm. Developed in less than 3-years, MGS is only one-fifth the mass of Cassini, and only cost on the order of $220M. The reduced spacecraft mass allows use of the smaller, lower cost Delta launch vehicle. Currently in orbit about Mars, MGS carries a focused suite of six science instruments that are currently returning high-resolution remote sensing of the Martian surface.

The future calls for continued even more aggressive mass and cost targets. Examples of these next-generation goals are embodied in the Mars Micromission spacecraft concept, targeted for launch in 2003. With a mass of only 200kg, this lightweight bus can be tailored to carry a variety of payloads to Mars or other inner-planet destinations. The design of the Micromission spacecraft enable them to be launched at extremely low cost as a secondary "piggyback" payload. The Mars Microsatellites could achieve recurring spacecraft costs of well under $50M.

Three key elements contribute to enabling these dramatic reductions in deep space mission costs:
- First, technological advances lead to miniaturization of spacecraft components and overall cost reduction while increasing capability. Rapid-cycle-time missions do not

have the luxury of developing a lot of critical path technologies; rather, sustained technology programs must deliver mature technologies that can be quickly picked up by new missions.

- Second, standardization leads to low-cost multi-mission solutions, allowing significant re-use. Standards help to enable flexible interoperability between missions and even between different space agencies. And early, well defined space system standards guides industry towards providing "plug-and-play" solutions in an open, competitive marketplace.
- Third, faster mission development cycles demand a design methodology that supports and enables rapid infusion of new technologies and on-the-shelf commercial solutions into complete spacecraft and mission solutions.

While this paper will focus on how NASA is driving down the cost of its planetary missions, these same principles apply equally well to Earth-orbiting missions.

Technology

To develop the technologies needed for reducing the cost of future deep space missions, NASA has created the Deep Space Systems Technology Program, also known as "X2000". The goals of X2000 are to achieve dramatic technology breakthroughs, enable low-cost missions, develop a science-driven architecture, and support progressive spacecraft miniaturization. A key focus of the program is on miniaturized avionics subsystems. Roughly every three years, X2000 makes a major delivery of new spacecraft systems based on aggressive technology developments. The X2000 first delivery, slated for 2001-2002, will deliver a complete spacecraft avionics package with a mass of roughly 50 kg, requiring 85 W of power. These avionics will be quickly infused into near-term missions such as New Millennium ST-4, Europa Orbiter, and Pluto Express. Delivery 2, scheduled for 2004-2005, will reduce avionics mass to only 5 kg, in support of next-generation microspacecraft. Delivery 3, in the 2008 time frame, will further reduce avionics mass to 1 kg, continuing towards the goal of "spacecraft on a chip". Underlying these deliveries is an ongoing long-term research and development program carried out by the JPL Center for Integrated Space Microsystems (CISM) in partnership with selected industrial partners. The X2000 deliveries will be defined by, and built around, technologies emerging from the ongoing CISM research.

NASA is developing new spacecraft communications technologies with the dual goals of increasing data return and reducing mission costs. A key thrust currently is migrating from today's X-band (8 GHz) deep space communications frequency to a higher Ka-band (32 GHz) frequency. The fourfold increase in communications performance at Ka-band, relative to X-band, can be used to increase mission data return or, alternatively, to reduce the size, mass, and cost of spacecraft telecommunications system components. JPL's Telecommunications and Mission Operations Directorate (TMOD) has established a roadmap for moving to Ka-band that encompass both flight and ground technologies. Key flight technologies include miniaturized Ka-band deep space transponders, efficient power amplifiers, and novel new lightweight Ka-band antennas. On the ground, the

challenge is to achieve high aperture efficiency and low receiving noise temperature on our very large Deep Space Network (DSN) antennas. The DSN's new 34m beam waveguide antennas have been designed to support Ka-band reception. New Indium Phosphide HEMT low-noise amplifiers have been developed with module noise temperatures below 10 K. And technologies like the Ka-band array feed and the deformable flat plate mirror are being developed in order to add efficient Ka-band reception to the large 70m DSN antennas. Several deep space missions have already validated the benefits of moving to higher frequencies: Ka-band technology demonstrations are currently in progress with Mars Global Surveyor and New Millennium DS1, while the Cassini mission will use Ka-band operationally as part of its radio science experiments.

While these specific technologies are aimed at deep space, the same principles are driving the earth-orbiting spacecraft community to explore migrating to Ka-band to achieve extremely high communications bandwidth with small, low-mass, low-power systems.

As our spacecraft become more and more autonomous, and the level of onboard computing power increases, software becomes more sophisticated, more complex, and more important in terms of spacecraft cost and capability. While we think of today's spacecraft as a spacecraft bus with some control software added on, tomorrow's spacecraft might be better described as a few million lines of code with a computer processor and some science instruments added on. The Mission Data System (MDS) is a new development effort within NASA to develop next-generation flight software, and on a larger scale to establish an end-to-end flight-ground software architecture for highly autonomous, low-cost mission operations. Central to MDS is the concept of system or subsystem state, coupled with models that describe how a system's state evolves. MDS establishes the notion of a "Goal-Achieving Module", or GAM, to control the system state. By giving the spacecraft specific goals, which can be defined as desired constraints on the system's future state, the GAMs can autonomously do the job of determining and executing the detailed sequence of events needed to satisfy that goal. Not only does the goal-based approach lead to lower-cost mission operations, by eliminating the labor-intensive generation of detailed spacecraft operations sequences, it also enables new classes of space missions that require rapid on-board decisions that don't allow ground-in-the-loop decision-making over long-round-trip-light-time deep space links.

Standardization

International space standards are developed under the auspices of the Consultative Committee for Space Data Systems (CCSDS). The CCSDS, operating under the umbrella of the International Organization for Standardization (ISO), establishes standards for Space Data Communications, Space Information Interchange, Space Mission Cross Support, and Space Navigation. Member agencies include; Agenzia Spaziale Italiana (ASI), the British National Space Centre (BNSC), the Canadian Space Agency (CSA), Centre National d'Etudes Spatiales (CNES), Deutsche Zentrum Fuer Luft- Und Raumfahrt (DLR), the European Space Agency (ESA), Instituto Nacional De

Pesquisas Espaciais (INPE), the National Aeronautics And Space Administration (NASA), the National Space Development Agency Of Japan (NASDA), and the Russian Space Agency (RSA). In addition, there are a large number of Observer Agencies, Liaison Agencies, and over 100 industry-based Associate Members.

Standard multi-mission services are crucial to minimizing the overall cost of NASA's mission set. In the past, with very infrequent planetary launches, NASA could afford to develop custom interfaces for communications and mission operations for each new mission. But in an era of launching 6-12 deep space missions per year, this approach is no longer tenable. Rather, NASA has defined a standard set of multi-mission services to which new projects can subscribe. NASA's Space Operations Management Office has established a Service Catalog which defines these standard services and the interfaces missions must meet to use them. Individual missions will submit Service Requests via the web; these requests are automatically evaluated, scheduled, and executed. This approach allows the development of standard services with the goal of minimizing NASA's costs across the entire mission set. Understanding the costs of standard service units helps drive intelligent investment decisions for new flight-ground services. Individual missions with unique service requirements are required to pay for the development of those capabilities, while missions which can adapt to standard services benefit from low service costs.

The key to successfully establishing low-cost standard services is the definition of a layered space operations architecture with clear, well-defined interfaces at each layer. Similar to the ISO layers that make up the Internet protocol, space communications and operations services are delivered over a layered end-to-end flight-ground architecture that starts at the physical layer and proceeds through a network layer, a transport layer, a data services layer, and a mission services layer. This "stack" provides clean interfaces, allowing technology evolution within a given layer while maintaining the overall architecture and operability with other layers. Data and mission services are defined and developed to operate seamlessly across the entire flight-ground system. For example, navigation applications can be implemented on the ground or on the spacecraft, depending on the needs of each individual mission.

While past missions have mostly represented simple point-to-point links between a single spacecraft and Earth, the future mission set includes more complex network topologies. Examples of these topologies are; constellations of small spacecraft collaboratively carrying out interferometric observations, microspacecraft released from a mother ship to land on small bodies like asteroids and comets, and intensive *in situ* exploration of targets such as Mars, incorporating multiple spacecraft and a dedicated constellation of telecommunications relay and navigation satellites. Building on the success of the Internet in changing the way information flows at Earth, NASA is embarking on establishing an Interplanetary Internet for information flow across this solar system network.

The success of the current Internet is largely a result of the well-designed layered architecture that was defined early on. This layered architecture, coupled with

appropriate communications protocols and interface definitions, has supported several decades of technology evolution, allowing revolutionary increases in communications bandwidth to be inserted while maintaining high-level application-layer interfaces. In much the same way, the Interplanetary Internet will establish a layered architecture for deep space communications, with IP-like protocols tailored to work over deep space links characterized by long round trip light times, low signal levels, and intermittent connectivity. The Interplanetary Internet will support reliable file transfer over planetary distances, much like the terrestrial File Transfer Protocol (FTP), greatly simplifying mission operations by eliminating the bit- and packet-level processing that is done today.

Rapid Design Methodology

The ability to move rapidly and efficiently from initial mission concepts to an integrated spacecraft and mission operations system is essential in driving down mission costs. At JPL, a development infrastructure and set of product development processes have been established to support this lifecycle. The Project Design Center provides an environment for future mission concept studies and early investigation of design trade spaces. A concurrent engineering team representing each critical spacecraft subsystem and mission element staffs the PDC. Working together through shared databases of available components, the team can quickly develop mission point designs with mass, power, and cost estimates. As missions enter development phase, the JPL Design Hub Facility and associated model-based design processes are utilized to rapidly develop spacecraft subsystems. Finally, the Flight System Testbed provides a unique development and test environment, where a mission can start with a fully software-simulated spacecraft and gradually integrate real hardware as it is developed. The FST allows early system-level definition, early flight software development, and early system-level testing as subsystems are developed.

An Example

NASA is currently exploring a novel concept for extremely low-cost missions to Mars and other inner solar system targets. Commercial launch vehicles used to launch communications satellite payloads into geosynchronous transfer orbits (GTOs) offer opportunities for low-mass secondary payloads. For example, the Ariane 5 spacecraft provides a secondary payload adapter ring, called the Ariane Structure for Auxiliary Payloads (ASAP); a spacecraft designed to fit on one quadrant of this ring, with a mass of 200 kg or less, can be placed in GTO at extremely low cost in this piggyback mode. The spacecraft can then be parked in a translunar orbit until the optimal time for the Earth-to-Mars transfer orbit, at which time a powered Earth flyby puts the microsatellite on an interplanetary trajectory.

This low-cost microsatellite approach draws upon the various themes we have discussed. Advanced miniaturized spacecraft technologies are critical in fitting into the challenging ASAP mass and volume envelopes. Standardized interfaces help ensure low recurring cost; our goal is to design a common microsatellite bus that can be quickly tailored to

multiple mission applications. One of these applications is as a building block for the Mars Network, a proposed constellation of spacecraft at Mars providing breakthrough telecommunications relay and navigation services for robotic and, ultimately, piloted mission to the Martian surface. JPL's Project Design Center has already conducted rapid design trade studies to validate the technical viability of this concept, and a rapid development approach will be crucial to delivering a microsatellite that can be flown in this low-cost mode for the 2003 Mars launch opportunity.

Conclusions

Through a combination of advanced technology, standardization, and rapid design methodologies, NASA is dramatically reducing the cost of its deep space missions. The dividend of this progress is that NASA will be able to fly much more frequently, broadening the range of planetary exploration and increasing the rate at which we can explore our solar system and the universe beyond.

These same principles apply equally well to Earth-orbiting missions, be they government-sponsored science missions or market-driven commercial spacecraft. As we enter the 21st century, these new low-cost approaches will truly open the door of space exploration and space enterprise to the entire world community.

Acknowledgments