Optical Communication Subsystem for the X2000 Series of Planetary Missions

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ABSTRACT

NASA has started a major new Advanced Deep Space System Development (a.k.a. X2000) Program at JPL. The objective of this program is to develop and space-qualify (in a total system environment) advanced, cutting-edge technologies for the next generation of deep-space exploration missions. The targeted mission sets include the Fire and Ice missions (Pluto Express, Europa Orbiter, and Solar Probe), the Champollion comet mission, and the robotic (and eventually human) missions to Mars. The program will develop, qualify and integrate these technologies into a set of defined deliverables that will be demonstrated in the JPL Flight System Testbed. The first major deliverable is scheduled for completion at the end of FY'2000, with subsequent deliverables completed at approximately 2-3 year intervals thereafter. One of the key technologies selected for development under this program as part of the first deliverable is optical communications.

Although designed initially around the Europa Orbiter mission conditions, the optical communications subsystem will be capable of providing expanded data rates from a variety of planetary mission applications. Development of the system has commenced based on detailed studies conducted in FY'97. The laser communication terminal contains a 30-cm diameter telescope, redundant focal plane array detectors, redundant uplink data detectors, and a pair of diode-pumped solid-state laser transmitters. This terminal is also multi-functional. In addition to laser-communication, it is also capable of narrow-field/high-resolution science imaging, laser-altimeter returned-signal detection, optical imaging for final approach spacecraft navigation, and transmission and reception of navigational ranging signals.

This paper will describe the architecture, design, expected performance and development plan for the optical communications flight terminal, as well as the flight mission applications that such a terminal could support.

INTRODUCTION

NASA (Code S) has initiated a significant technology development program at JPL called the Advanced Deep Space System Development Program (ADSSDP); also known as the X2000 Program. The program has been structured with a series of significant deliverables. The first major delivery (Del #1) is due around the end of the year 2000. The applications target for Del #1 is primarily a set of deep-space missions (e.g. Europa Orbiter, Pluto Express, Solar Probe, or Mars missions). For the purpose of concentration, the Europa Orbiter mission was taken as the representative mission. However, extensions to the other applications have also been considered. Several key enabling or enhancing technologies were selected to be included in the first delivery development. Optical communications was one of those selected technologies.

This paper describes a program to develop a deep-space optical communications terminal flight engineering model for the X2000 program. We begin by describing the X2000 program, including the definition of a "reference mission design". Then, we discuss the functional requirements for the optical communications system that will be developed thereunder. This leads to the generation of specific performance requirements. We then discuss the general architecture of the optical communications terminal design, followed by a description of the program development plan.

THE X2000 PROGRAM

In the past technologists have, from time to time, developed technologies only to find that they were not adopted by the flight mission designers, while the mission designers, on the other hand, found that they had to use outdated technologies as the new ones had not been adequately developed. The primary reason for this situation is that there still existed a developmental gap between the two disciplines. The technologists were developing technologies that they "thought" the mission designers needed, yet there was still a significant development (and required funding) gap, to carry the "delivered" technology to what the mission designers really required. Additionally, the technologists frequently needed solid end-user endorsements for their specific technologies to justify award of the required development resources. Thus, closing this developer-user gap would be mutually beneficial to both; allowing the end-user to get what he/she really needs and providing the programmatic justifications for the development funding.

The Advanced Deep Space System Development Program (ADSSDP), (a.k.a. X2000 Program) recognized this chasm and has been organized to close this gap. The program has been designed around a series of discrete system deliveries. The first of these deliveries is scheduled for the 2000 time frame.

Subsequent deliveries will occur at approximately 2-3 year intervals thereafter. Each delivery will contain the development of a set of several high-payoff technologies. While not a flight mission in itself, X2000 is designing these technologies for a specific customer base, and through the vehicle of a reference flight mission "design". This approach brings together the various technical disciplines of a spacecraft mission environment (e.g. mission design, propulsion, attitude control, power, avionics, thermal, etc.), as well as those representing the ground support infrastructure, with the technology developers so that not only the functional performance of the specific technology is considered, but the flight system and ground interfaces as well. The customer base for the first delivery consists of the Ice and Fire missions (Europa Orbiter, Pluto Express, and Solar Probe), the Mars program, and the Champollion comet mission. The reference mission for Delivery #1 is the Europa Orbiter mission. It should be pointed out that the actual Europa Orbiter mission design team is not constrained by the details of the "reference mission design" being performed under X2000. However, there is frequent interaction between the two design teams.

Although it is very desirable to have each developed technology apply to all missions in the customer base, it is recognized that this may not always be practical or economical. However, a reasonable overlap with the customer set needs, and compatibility with the reference mission design, are required. Several key technologies were selected for development as part of Delivery #1, including highly-integrated avionics, milli-Newton thrustors, new light-weight composite structures, and a new stellar compass. One of the selected technologies is spacecraft-to-earth optical communications

Figure 1 shows a diagram of the reference mission design for Delivery 1 (Europa Orbiter reference point). The propulsion module is the dominant feature for the design, with the payload portion setting on top. The optical communications transceiver is located at the left of the payload. Figure 2 shows an exploded view of the reference model payload.

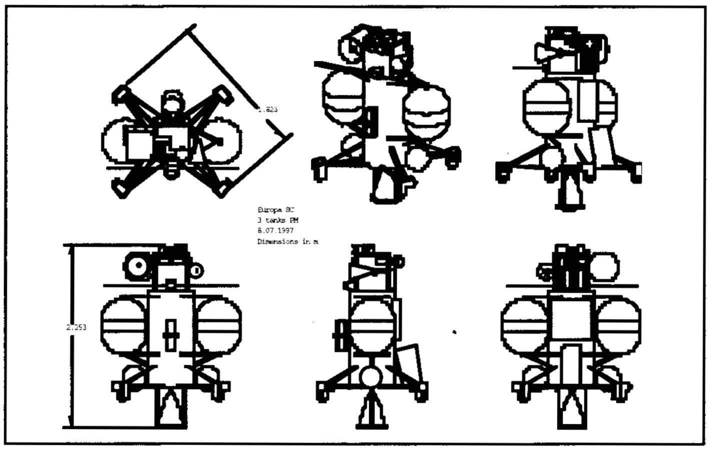

Figure 1. X2000 reference mission spacecraft layout

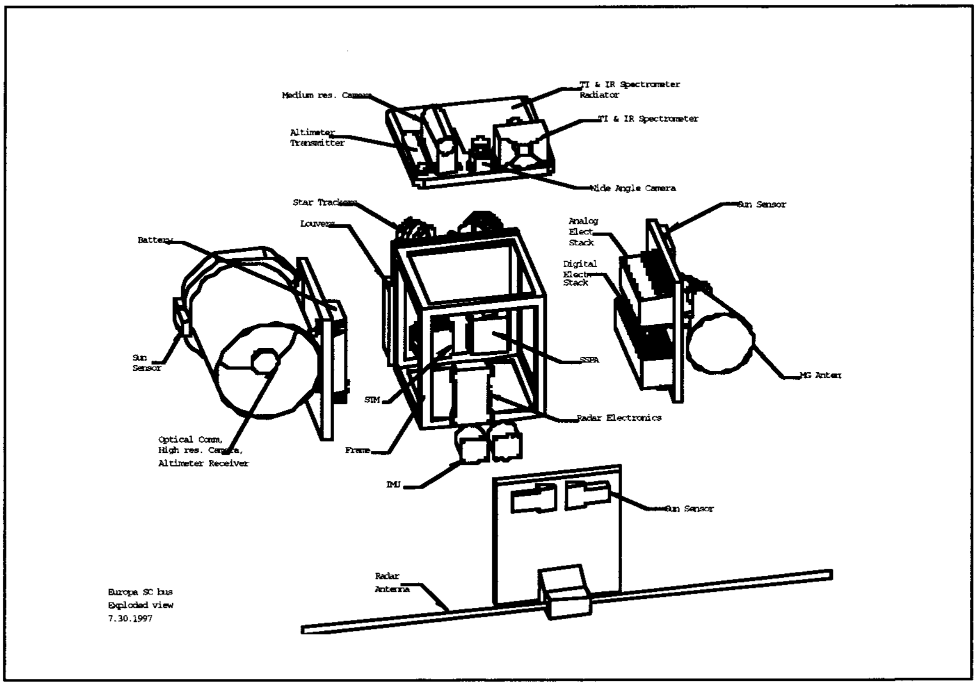

Figure 2. Exploded X2000 reference mission payload

OPTICAL COMMUNICATIONS TERMINAL REQUIREMENTS

The primary objective of the optical communications terminal is to provide the capability to return more space-acquired science and engineering data back to the Earth than is possible with the conventional radio-frequency technology, and to do it with less impact on the host spacecraft. However, to do this, it must be consistent with the general needs of the spacecraft missions. In this section, we identify the general mission requirements, and then summarize the optical communications terminal functional and design requirements. Table 1 shows the general communications requirements for the X2000 Reference mission.

There are several communications modes being considered, The primary (science-return) mode is optical communications for both uplink commanding and for downlink data transfer. To accomplish this, the spacecraft attitude control system must be in the "precise control" mode, maintaining the attitude of the spacecraft within a 2 mrad wide deadband cycle. *(We note that if the actual Europa Orbiter Project - as opposed to the reference mission- does select optical communications for its mission, it may consider it as a secondary "mission enhancement" capability rather than prime).*

There are two mission modes that do not require such precise attitude control. One of them is the "beacon" mode. In this mode, a simple "one-of-four-tone" beacon signal is transmitted from the spacecraft to the ground. These tones are used to alert ground controllers when the spacecraft needs a

Function	Requirement
Primary Link	Lasercomm (both uplink and downlink)
When Comm Coverage Requested	Lasercomm first, then RF, if unsuccessful cycle back and forth
Multi-functionality	Combined telecom with narrow-field science imaging , optical navigation & ranging reception will be performed
Emergency Communications mode	Via RF Link
Beacon Communications Mode	Via RF Link
Near Earth Communication	Via RF Link
Operation Mode S/C Attitude	
- Control	$\leq +/- 1$ mrad (3 σ)
- Knowledge	$\leq +/- 0.75$ mrad (3 σ)
Beacon / Emergency Mode S/C	
- Attitude Control & Knowledge	≤ 18 mrad
Emergency Mode S/C Attitude Recovery	to ≤ 18 mrad
Operation Time at Planet/Planet's Moon	30 Days Min
Data Storage Available	2 Gbytes, 8 bits/byte
Doppler Measurement Data	Not available
Navigation data from Optical Comm System	- Optical ranging - Onboard optical nav. imaging

Table 1. Reference Mission Telecom Requirements

specific level of service. The other mode is the emergency communications mode. Emergency communications is accomplished at a very low data rate and is primarily used for recovering from anomalous conditions. Both the beacon and emergency communications modes are assumed to use a simple RF communications system and can be operated with a significantly relaxed (18 mrad) attitude control deadband cycle. *(Again, the actual flight project may do otherwise of the RF link is prime).*

The reference mission also assumes a very short primary missions data return time while at Europa (at a distance of 6 AU). This is due to the very significant radiation levels that are present around Jupiter. The short mission time, and the limited data storage, drive the required data rates to higher values. These higher data rate transmissions will be accomplished over the optical communications link. Note that the reception of these signals must be during both daytime and nighttime on the earth.

The functional and design requirements for the optical communications terminal (used for the high-data-rate communications) are shown in Table 2.

Parameter	Requirement
Maximum Range	6 AU
Earth Reception	During both Earth day-time and night-time
Data Rate	≥ 80 kbps
Modulation Format	8-bit PPM (Pulse Position Modulation)
Allocated DC Power	≤ 35 W
Allocated Weight	≤ 12 kg
Desired BER	10^{-6} (coded) for science & telemetry
Link Margin	≥ 3 dB
Pointing Reference for Downlink	- Sun-lit Earth image for ranges > 1AU - Uplink Laser Beacon when < 1AU
Tracking Loop Update Rate	≥ 2 KHz

Table 2. Functional and design requirements for optical communications terminal

It is first noticed that the terminal will serve several functions, enabled by virtue of its primary telescope and focal plane detectors. In addition to command reception and downlink data transmission, it must also receive and retransmit two-way navigational ranging pulses. These help mission controllers determine the current location and expected trajectory of the spacecraft. Additionally, the optical communications telescope can be used for narrow-field imaging. Such imaging can be performed to enhance science data return, or it can be used view target bodies relative to the stellar background, thereby providing ground control navigators with additional navigation information.

The data rates planned in the reference mission are 80, 160, 240 and 320 kbps. These rates are much higher than the typical 10 kbps or so possible with reasonable-sized RF systems, and they are enabled by using Pulse Position Modulation (PPM) with matched Reed-Solomon (R-S) coding for error control. A 2 kbps uplink capability is planned for occasional command uploads. It likewise will use PPM modulation and R-S coding.

Perhaps the most interesting item is the method of providing a reference for downlink beam-pointing control. When the distance from the Earth to the spacecraft is less than 1 AU (1 AU is the mean distance from the Sun to the Earth), an uplink laser beacon signal will be received and tracked. However, as the spacecraft moves beyond 1 AU distance, the system will revert to tracking the solar-illuminated Earth image. This provides a "free" beacon signal, although there are certain times of the year when this beacon is not available (i.e. when the Earth is in front of the Sun). Finally, the optical communications system must have the ability to track out base platform motions from the spacecraft in order to keep the downlink beam on the Earth receiver. The tracking loop sensor must have an update rate that is high enough to allow the loop to compensate for the highest frequency jitter components. The current baseline for the update rate is 2 kHz.

ARCHITECTURAL SYSTEM DESIGN

The design to satisfy these requirements is shown in Figures 3 and 4. Figure 3 shows an isometric view of the flight terminal. It contains a 30-cm telescope used for both transmit and receive functions. Under the telescope is the necessary beam control optics, steering elements and detectors. The control and processing electronics are located under the beam-control optics (out of sight in the figure).

Figure 4 shows a block diagram of the system. The terminal is made up of three main parts; the Optical System Assembly (OSA) which includes the telescope, optics and detectors; the Electronics Processor Assembly (EPA), containing all the detector control electronics, modulation and demodulation electronics, and the necessary terminal control functions; and the Laser Transmitter Assembly (LTA) which contains all the components needed for the diode-pumped, Nd:YAG lasers transmitters. The shaded items represent functionally-redundant subassemblies.

The design of the terminal is based on the design of the Optical communications Demonstrator (OCD), an earlier-developed laboratory engineering model terminal [Ref. 1-6]. Light from the beacon signal, or the target science image if used in the science imaging mode, is received by the telescope (shown by the clear arrow), passed by beamsplitters 1 and 2 (BS1 and BS2), and is detected by the Focal Plane Array (FPA). If receiving the beacon, the position of the beacon signal on the FPA determines the orientation of the telescope. Uplink command or ranging signals are received by the telescope, passed by BS1 but deflected by BS2 to the slow-speed Beam Mirror Assembly (BMA) and then to the Uplink Detector Assembly (UDA). Transmitted optical energy from the Laser Transmitter Assembly (LTA) is sent to a high-speed BMA for fine-beam steering, is deflected off BS1, and passes out the telescope in the desired direction. A small portion of the transmit signal passes through beamsplitter BS1, and, after retro-reflection back to it, is deflected through BS2 and detected by the FPA.

Images detected by the FPA are read into the EPA where a signal processor handles the data. If received in the science imaging mode, the data is formatter and sent to the spacecraft data storage system via the high-speed 1394 bus. If in the communications mode, the beacon signal is processed to determine the transmit pointing corrections (based on the location of the beacon, a small portion of the transmitted beam, and any point-ahead information received from the spacecraft control computer) and adjusts the BMA as appropriate. The EPA's signal processor may also periodically send beacon images to the spacecraft processor for calibration purposes.

Data received by the UDA is A/D converted and the resulting signal is applied to the uplink PPM demodulator. However, if the uplink signal is a ranging pulse (i.e. when the system has been placed in the ranging mode), the detected pulse is sent directly to the LTA to trigger a downlink pulse. Demodulated uplink data is sent to a formatter, whereupon it is relayed via the 1394 bus to the spacecraft control computer. Data to be sent to the ground is received by the data formatter in the EPA via the 1394 bus, and is sent to the PPM modulator. The modulated signal is then applied to the LTA.

The EPA also supports some necessary housekeeping functions These include high-speed clock signal generation, residual power conditioning and health and status monitoring.

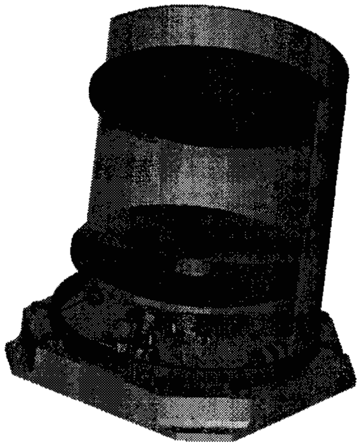

Figure 3. Optical Terminal

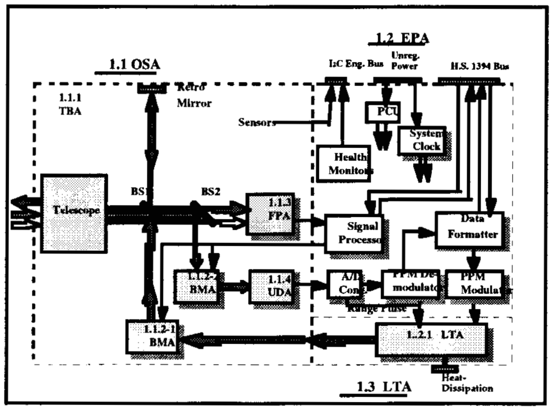

Figure 4. Terminal Block Diagram

PROGRAM DEVELOPMENT PLAN

The development of the X2000 optical communications terminal was initiated in October of 1997, with scheduled delivery to the X2000 project in April of 2001.

In the first year, four risk-reduction developments will take place. The first is the development of an End-End Communications Breadboard. This will functionally demonstrate the signal modulation, demodulation, and temporal synchronization functions for both the uplink and the downlink, as well as the turn-around ranging function. Interface with the breadboared will be via the 1394 interface, where CCSDS-formatted data will be passed to the breadboard for handling. The second is a breadboard to demonstrate the Earth-image tracking function. This breadboard will include the FPA, BMA and breadboard control electronics, as well as Earth-image and straylight simulators. The third is the development of an engineering model of the LTA, and the fourth will be evaluation of candidate BMA's. Along with these risk reduction tasks, the initial design of the overall system will commence.

In the second year, the detailed design of the terminal will commence. This will make use of the results of the risk-reduction activities performed in the first year, and will extend those designs to flight-qualifyable packaging. Fabrication, integration and alignment will take place in the third year, followed by functional and flight-environmental testing. A test station previously developed by JPL [Ref. 7-8] will be modified to support the program. In April of 2001, the system will be delivered to the X2000 project for testing in an simulated flight-environment.

CONCLUSIONS

The X2000 program will provide a programmatic umbrella under which a number of new technologies will be developed to the level that flight missions can more easily adopt the development products. Optical communications is one of those technologies. The terminal technology developed in this program will have a multiplicity of uses, including uplink and downlink communications, two-way ranging, and science imaging. By developing the system in a "reference flight mission" environment, the development activities can be tailored to the relevant environment, and will provide a more closely aligned product to the mission planners. A set of four risk-reduction developments will be pursued in 1998, with full development and environmental qualification of the entire system by April of 2001.

ACKNOWLEDGMENTS

The research described in this report was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors would like to express their appreciation to the X2000 study and development team members who have contributed to the definition of this system architecture.

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