OVERVIEW OF THE NASA/JPL LASERCOM PROGRAM

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ABSTRACT

The NASA-funded optical communications program being conducted at JPL is described, The spacecraft transceiver terminal developments, a test infrastructure for assessing the performance of future space terminals, an atmospheric visibility monitoring program, some recent systems-level demonstrations, and a communications technology roadmap for planetary missions over the next 25 years are presented.

1. INTRODUCTION

Communications demands for spacecraft are ever-increasing and the technology required to satisfy those link demands often dominates the architecture of the spacecraft structures. This has been true for some time on military and NASA missions, and more recently has become a driver for many proposed commercial satellite networks, Accordingly, NASA has been developing optical communications technology so that future missions can satisfy those demands with much less impact on the space platforms, or the launch vehicles required to lift them off the Earth's surface. Studies, technology development, systems design and deployment planning for this technology have been underway at NASA's Jet Propulsion Laboratory for the past 18 years [1,2].

In this paper the optical communications space terminal technology being developed to address these applications will be described. Next, the development of a test stand to evaluate this such spacecraft terminals is described. Following this, a program to gather detailed statistics on the cloud-cover outages for space-to-ground links will be described, including the data distributions that have been produced from those data. Finally, a roadmap for how this technology can augment or enable deep-space missions of the future will be described.

2, OPTICAL SPACECRAFT TERMINAL DEVELOPMENT

The centerpiece of the NASA spacecraft technology development is the Optical Communications Demonstrator (OCD) program [3]. This program is developing an engineering model of a flight terminal capable of returning kbps to Mbps from the planets, or Mbps- Gbps from high-Earth-orbit to the ground. The system uses a "minimum-complexity" architecture that uses only one detector array and one fine steering mirror to accomplish beacon signal acquisition, tracking, transmit beam pointing, and transmit/receive co-alignment (with point-ahead to accommodate cross velocity). Tracking of the beacon signal is accomplished by using a windowed sub-frame readout from the detector array.

Initial development of the concept involved setting up a tracking system breadboard in the laboratory. This was followed by a contract with 20/20 Systems Inc. to package the CCD/Camera readout electronics, and the Tracking Processor Assembly (TPA) , which determines, filters and conditions the tracking error signals for actuation of the steering mirror (and the coarse pointing gimbal at a lower bandwidth). The is based on a Texas Instruments TMS320C40 DSP processor. A coarse-pointing gimbal was ordered from API Inc. and is scheduled for delivered to JPL in early February 1997,

The Telescope Optical Assembly (TOA), which houses ail the optics, telescope, beamsplitter and steering mirror, has been designed and fabricated. Requirements for the optics were generated, the optics were procured, and subsequently aligned in the TOA housing based on a documented alignment procedure, The TOA was then mated, aligned and tested with the Tracking Detector Assembly which houses the CCD array and custom readout electronics. The combined TOA/TDA assembly currently has a mass of 5.7 kg.

Other supporting electronics such as the Power Conditioning Unit and the Control Terminal (used to simulate the host spacecraft) have been completed. A preliminary version of the software for the controller has been generated, integrated with the controller and processor, and is being evaluated.

Figure 1 shows a sketch of the entire communications terminal. The system consists of a single transmit/receive telescope, a fiber-optic coupled transmit laser assembly, and a separate control processor. All of the optics are located in the telescope assembly. A coarse pointing gimbal assembly is not needed except in mission applications where separate pointing of the terminal relative to the spacecraft is required, The telescope aperture size is 10 cm,

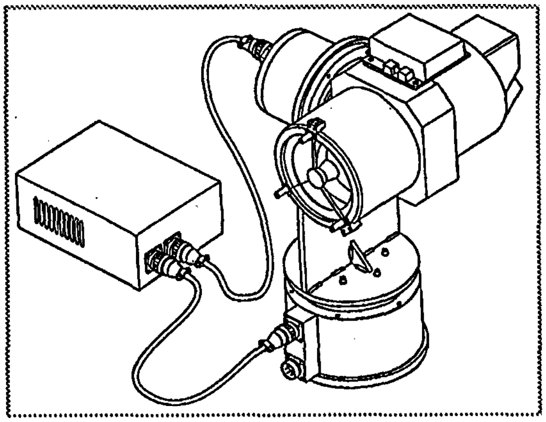

Figure 1. Diagram of the Optical Communications Demonstrator

The OCD is currently undergoing system-level testing. Current estimates of the complete system mass and power (excluding the coarse-pointing gimbal) are 8 kg and 30 W respectively.

3. LASERCOM TEST AND EVALUATION STATION

To evaluate the performance. of the OCD, it is necessary to provide a testing infrastructure that provides the requisite beacon signal and makes quantitative measurements of the terminal under test. This is being accomplished using the Lasercom Test and Evaluation Station (LTES). Although initially designed for evaluation of the OCD, the LTES can be easily adapted for operation with other lasercom terminals.

The LTES provides a calibrated beacon signal for use by the terminal being evaluated. Since the beacon laser is fiber-coupling to the LTES, it can be easily changed to accommodate other terminals.

The LTES receives the transmitted optical signal from the unit under test, and converts the signal to the far-field equivalent for performance measurements. Measurements that can be made include transmit beam divergence, spatial transmit tracking jitter, transmit Strehl ratio, and total transmit power. The modulation on the transmitted signal can be detected and used to measure signal distortion and bit error performance, The LTES can be programmed to alternately provide and then interrupt the beacon signal so that spatial acquisition time statistics of the terminal under test can be measured. Acquisition time statistics are accumulated be measuring individual acquisition times to 1 ms accuracy. The LTES also has a wavemeter to verify the optical signal wavelengths.

Figure 2 is a photograph of the LTES. The large mirror in the upper left of the photo is the input aperture (capable of handling up to 20 cm diameter beams). The downstream optics are used to transform the beam into signal for making the required measurements. The rack of equipment on the right supports the measurement of the various signals. The computer controller can be programmed for automated performance measurement taking and the resulting data is stored and graphically displayed for analysis.

Figure 2. Photograph of the LTES

The LTES is undergoing final calibration, after which it will be used for evaluating the OCD terminal.

4. ATMOSPHERIC VISIBILITY MONITORING

The performance of space-to-ground optical communications links is strongly influenced by the atmospheric conditions in the vicinity of the ground receiving station. The most significant impact comes from the attenuation (and occasional extinction) due to clouds. Some data exists on average clear weather vs. cloudy weather probabilities [4], However, to completely characterize an optical link, one would really like to have a detailed probability model for the cloud-induced optical signal attenuations.

Recognizing this, JPL began several years ago to develop and deploy a set of three atmospheric visibility monitoring (AVM) observatories [5]. These observatories contain autonomously-operated 30 cm telescopes that measure the intensity of bright stellar sources on the ground and from those measurements determine the attenuation of the signal due to the atmosphere, Each of the observatories measures the stellar intensity through a set of 5 spectral filters; two narrowband filters centered at 532 nm and 860 nm, respectively, and three astronomical wideband filters known as the "I", "R' and "V" filters. A third narrowband filter centered at 1064 nm is also included, but the sensitivity of the system detector must be upgraded before it can be used.

The observatory equipment is housed in a roll-off roof dome to protect it during storms, A weather instrument tower monitors weather conditions and closes the dome when conditions (rain, snow, high wind, excessive humidity) exceed trigger levels. During these times, the observatory bookkeeps the condition as infinite atmospheric attenuation, Each observatory has a stored star catalog and when conditions permit, opens its dome and searches for stars in its list, If a star is not observed, the atmospheric attenuation is again bookkept as atmospheric extinction. When a star is located (using its precision telescope pointing mount), intensity measurements are made through the several spectral filters. After completing measurements on one star, the system moves onto the next, Measured stellar intensities, as well as observatory status data are collected and stored on the observatory's computer hard disk, Once each day each observatory establishes connection with JPL via telephone line and its stored data is returned to a central JPL computer for processing.

The three observatories have been developed and deployed in the field. One is located at the JPL Table Mountain Facility (TMF), a 7500 foot elevation site near

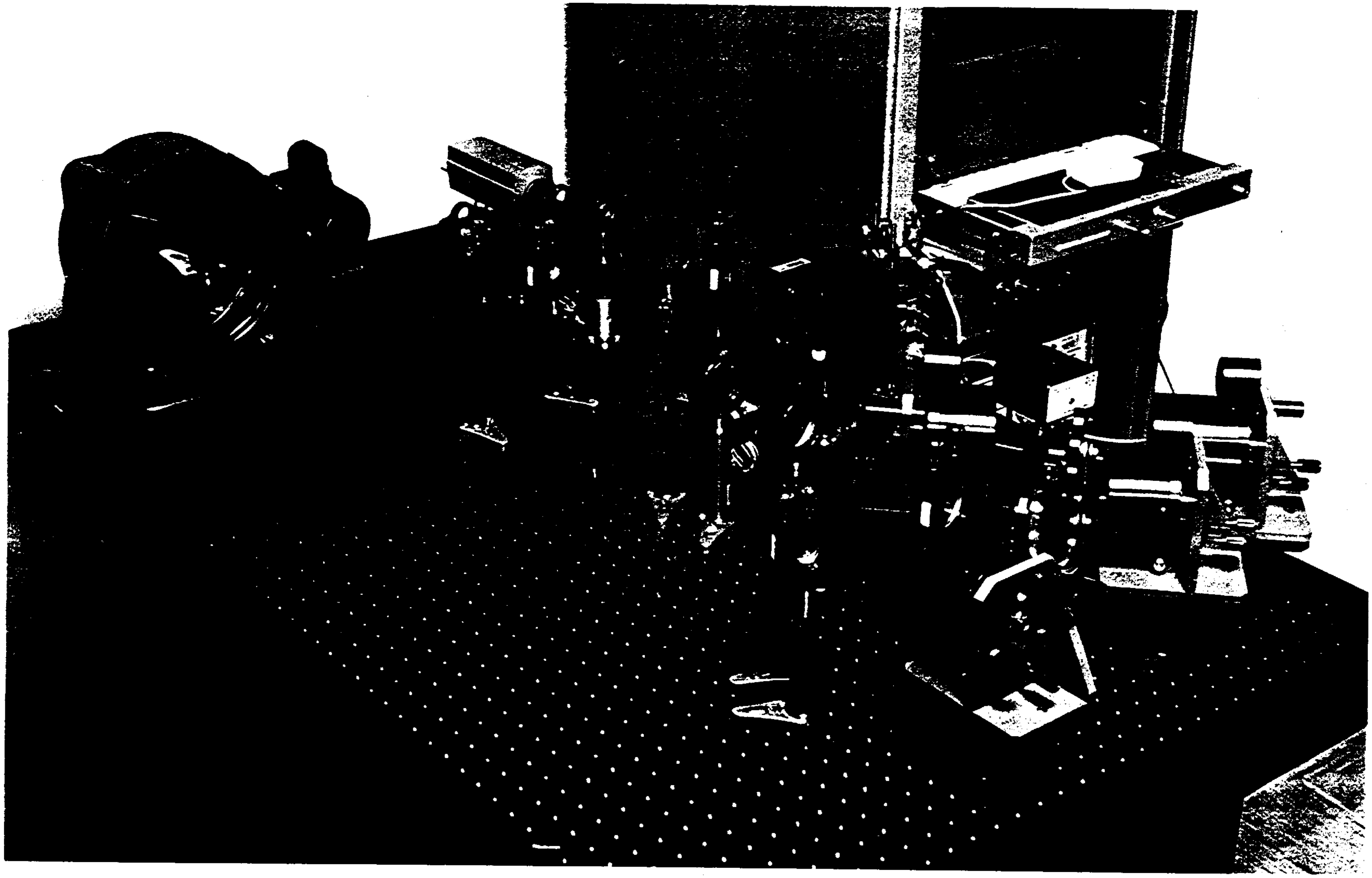

Figure 2

Wrightwood, CA (about 20 minutes northwest of San Bernardino), The second has been installed at an observatory facility at the top of Mt. Lemmon, Arizona, The third was originally set up on the hilltop behind JPL in Pasadena, CA. Recently that unit was relocated to the Goldstone tracking network complex in the desert near Barstow, CA,

Data from the set of observatories, primarily the TMF and Mt. Lemmon sites, have been collected for the several years. These data have been processed into cumulative probability distributions of atmospheric attenuation, A typical plot of such a distribution is shown in Figure 3. This particular plot shows the visibility statistics from the 860 nm and 532 nm narrowband filters for the Table Mountain Facility observatory. The horizontal axis is zenith atmospheric attenuation in dB and the vertical axis is the probability that the atmospheric attenuation was less than or equal to the corresponding value of attenuation on the horizontal axis. The higher atmospheric absorption at the shorter wavelength is clearly seen in the figure. Similar plots have been obtained for the other filter bands and on the other observatories.

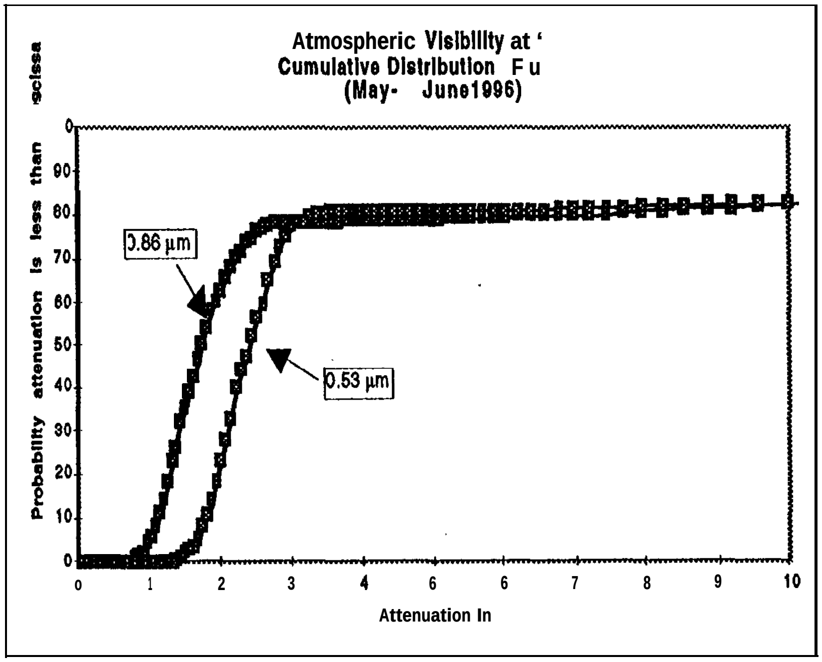

Figure 3. Cumulative probability distributions for the TMF observatory; 860 nm and 532 nm filters.

These plots represent the marginal (single station) probability statistics. The reason for developing three observatories and deploying them in widely dispersed locations is to allow the collection of visibility statistics for a spatially-diverse network (joint probability statistics), It is known that if three stations, each with 70% availability are located in independent weather patterns. the probability that at least one of those stations is cloud-free (attenuation below some reasonable value) is 97%. The system described above was developed and deployed for the purpose of making measurements to validate these joint statistics. Software to produce these joint probability distributions is being developed.

5. SYSTEMS-LEVEL DEMONSTRATIONS

Several significant systems demonstrations of optical communications technology have been conducted recently. Two of those, the Ground-to spacecraft Optical Experiment (GOPEX), and the Ground-to-Orbit Lasercom Demonstration (GOLD) will be described.

In December 1992, an uplink optical communications demonstration was conducted with the Galileo spacecraft (GOPEX) [6]. Laser beams from two ground-based telescopes,

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one at Table Mountain and the other at the Starfire Optical Range, were transmitted to the spacecraft after it returned to Earth for gravity-assist and was speeding on its way to Jupiter. The science imaging camera on the spacecraft was used as the optical detector. By scanning the camera with its shutter open and while being illuminated by the uplink (pulsed) lasers, detections of the individual laser pulses could be recorded. Successful signal detections were obtained at spacecraft distances ranging from 6000,000 km to 6,000,000 km. Measurements made during the demonstration showed significant intensity fluctuations due to atmospheric turbulence. Subsequent data processing showed very good agreement with atmospheric turbulence models.

During the period of November 1995 to May 1996, a second ground-to-space optical communications demonstration was performed, This one was performed cooperative y with the Japanese Ministry of Telecommunications and Posts' Communications Research Laboratory, and involved coordination with both NASDA and NASA. Laser transmissions were sent from the 0.6m telescope at JPL's Table Mountain Facility to the ETS VI satellite and transmissions from the satellite were received at the TMF 1,2 m telescope. Successful transmissions of 1Mbps data were accomplished on both the uplink and the downlink while the satellite was at geosynchronous distances. The results of this demonstration are described elsewhere [7].

6. FUTURE MISSION TECHNOLOGY ROADMAP

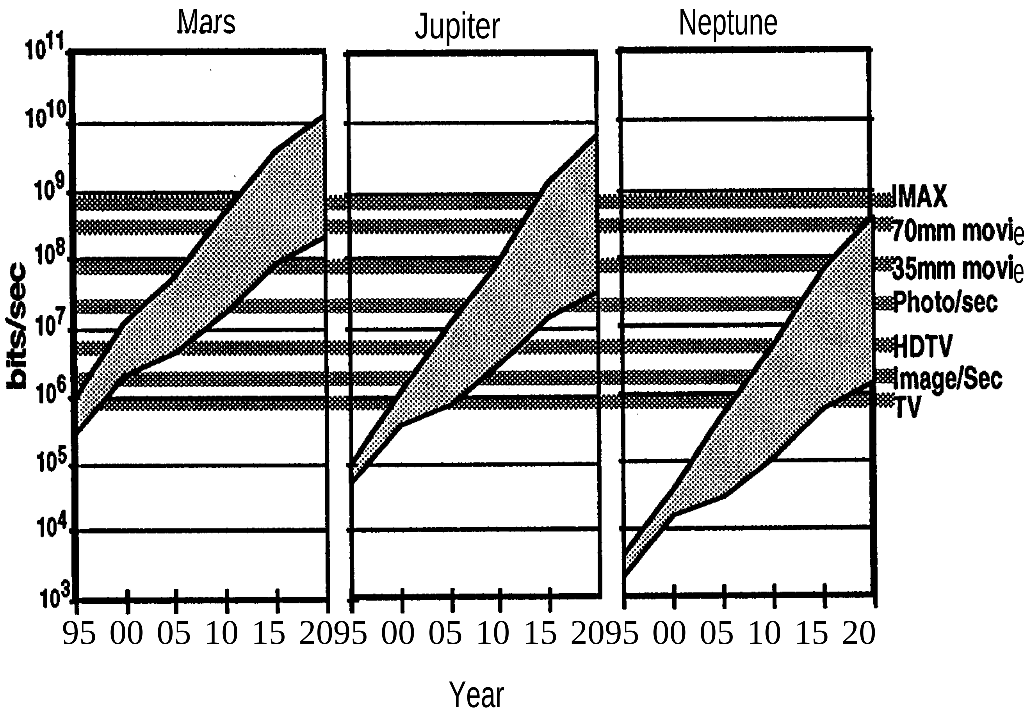
There has been much interest lately in the development of a long range plan for telecommunications within our solar system. Part of the interest stems from a NASA Office of Space Sciences (0SS) planning activity to develop a *roadmap* for the *Mission to the Solar System*, The Jet Propulsion Laboratory (JPL) has been leading this effort for NASA, The roadmap was synthesized over a period of six months with participation from a cross section of the American science community as well as technologists from NASA field centers, academia, and U.S. industry. The roadmap covers robotic exploration for the period of time from now until the year 2020.

NASA realizes that solar system exploration will be an international activity. Foreign space agency plans for planetary missions have been factored into the roadmap activity. There will likely be an international planning activity that will follow NASA's acceptance of the roadmap recommendations.

In addition to developing a set of recommendations to NASA for missions in response to specific scientific questions, roadmap teams examined several of the key enabling technologies. One of these was telecommunications, The focus of the roadmap activity was on space missions within the solar system. However, the work that was performed in the telecommunications area can be extended to far outer planet and longer-distance missions as well.

The Mission to the Solar System roadmap considered many aspects of the telecommunications challenge. The team considered the networking aspects of operating many spacecraft (and landers, rovers, . ..) on a single target body using communications relay satellites orbiting around those bodies, The team also examined the challenge of providing a low cost, low mass, high performance communications capability between the surface elements and a relay satellite. The team spent most of its energy predicting the performance, as a function of time, for the *trunk lines - the* main communications channels between the target bodies and the Earth, rather than the local links between such things as landers and their local relay satellites. The trunk lines represent the hardest problem to solve for outer planet missions and beyond. Two radio-frequency bands (X-band and Ka-band) were considered as was optical communications [8]. This paper deals only with the technology developments considered for the optical communications options of those trunk lines.

The roadmap analysis included an examination of the key technologies required for the trunk lines and their probable availability over the next 25 years. Analyses were performed for three target body communications orbiters: Mars (2.5 AU), Jupiter (6 AU), and Neptune (30 AU.) The results, shown in Figure 4, indicate that in the time frame of the roadmap, we could expect communication bandwidths of more than 1 Mbps at each of these targets - with much greater capabilities at Mars. At the right-hand side of the figure are indications of the kind of data that can be returned from space with such data rates. Such large bandwidths were considered essential to provide a telepresence for the science community and the general public during the exploration, and to lay the infrastructure for subsequent piloted missions,



7. CONCLUSIONS

The NASA-funded optical communications program which is being managed at the Jet Propulsion Laboratory has been described, The primary development elements of this program, the OCD spacecraft terminal development, the LTES test facility, and the AVM data collection program elements, were discussed, Next, two of the recently-completed systems-level demonstrations were covered, Finally, the results of a roadmapping effort in support of the Mission to the Solar System study were described. These results show that very impressive communications bandwidths can be made available to the flight project mission planners in the near future.

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ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. The author would like to express his thanks to the past and present members of the JPL Optical Communications Group, and to the numerous experiment and development collaborators, both domestically and abroad, without who's dedicated efforts these results would not have been achieved. Appreciation is also expressed for the programmatic support of this program from NASA, both from NASA Code S (Dr. Ramon DePaula) and the NASA Space Operations Management Office (SOMO).