Progress and Plans for the Optical Communications Program at JPL

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ABSTRACT

Recent accomplishments and programmatic changes in direction of the NASA-funded optical communications program at JPL are discussed. The applications for the technology are first described. The systems and technologies for both the spacecraft optical communications terminals and the supporting optical reception infrastructure are covered. Plans for a comprehensive set of systems-level demonstrations are presented, These include early aircraft and ground demonstrations, a proposed mission enhancement experiment in space, and a planned solicitation for the first (mission definition) phase for a flight hardware development and demonstration of the technology in space contract,

1. INTRODUCTION

For the past 14 years NASA has been supporting JPL to develop and demonstrate optical (laser) communications technology and systems, and to perform the deployment planning for its use on future NASA's missions. These activities have, in the past, concentrated on deep-space missions. With the changing emphasis toward smaller and more frequent missions, the evolutionary changes and budgetary pressures emanating from NASA Headquarters, and the importance of industrial collaboration, several modifications to the program directions have been implemented over the past few years. This paper describes the recent accomplishments in the NASA-funded optical communications program at JPL, and presents a vision of where the program is expected to go in the years to come. In the next section we will discuss the expected set of mission applications during the next decade. This will be followed by a description of the progress and plans for the reception networks that will support the NASA portions of those missions. In Section 4 the designs and hardware developments for the spacecraft payload terminal will be summarized, followed in Section 5 by a description of the program's supporting technology developments, In Section 6 we will discuss our plans for system-level demonstrations, followed in Section 7 by an overall summary and conclusions.

2. APPLICATIONS

Important applications for optical communications exist in the NASA community , the commercial arena, and in programs funded by other departments of the government,

2.1 NASA Missions

From a communications systems standpoint, NASA missions can be divided into two basic categories; near-Earth (i.e Earth orbital) missions and deeper-space missions. For the near-Earth missions, there are several generic categories. The first is the data-dump from LEO category, In the past, low-altitude Earth-orbiting spacecraft were provided communications support (in the rf domain) by the Tracking Data Relay Satellite System (TDRSS). However, budgetary pressures on the individual spacecraft projects have made it economically difficult for many of them to afford a LEO to GEO RF link capability. This has forced many of the missions to request a variance, permitting them to dump their data directly to the Deep Space Network (DSN) on the Ground. While solving the immediate needs of the specific mission, the result has been an oversubscription of the DSN, a network that was designed primarily to support deep-space missions, If this trend continues (as it is expected to do) the network will not be able to support all the requests of the user missions and an alternate data-dump downlink capability, with many missions requiring high data rates, will be required. Optical communications is a very attractive technology for this application since the impact of the space-borne terminal on the host spacecraft is minimal and the cost to replicate small-aperture optical ground terminals is quite manageable. Indeed, some of these ground terminals could even be transportable, allowing the network to be reconfigured for more efficient coverage,

Another class of near-Earth missions involves LEO to GEO (or higher-orbit non-GEO) relay satellites, For some applications, the data volume and processing requirements will require collection of the data at a specific point, Such missions might include Earth global sensing where the number of research institutions capable of receiving the raw data is limited, If the data includes high resolution and spectrally separated images, the data volumes can easily be too large for on-board storage and later data dump to a specific ground station. In such cases, linking back through higher-altitude relay satellites will be required, However, as stated before, the user missions are being heavily cost constrained, and are having a hard time affording the rf technology to accomplish such links. In these applications, optical communications is major contender for providing such service.

Also of interest to near-Earth users are GEO-to-GEO crosslinks. NASA has long wanted to close the "zone of exclusion" for low-altitude satellites that use the TDRSS network. Such a capability would be of benefit to the Space Shuttle missions , and could be of even more interest to the Space Station.

There are also several applications in the deep-space mission set. Most of these missions are concentrating on the new generation of micro- or mini-spacecraft, NASA has initiated a program for the Discovery class of small missions and is processing many proposed mission concepts from a large set of proposed missions. Since these missions have severe mass and cost constraints, optical communications could enable many of these missions to meet the size, mass and power constraints without severely limiting the amount scientific data return.

Another class of missions called ACME (Asteroid, Comet, Moon Evolutionary Spacecraft Program) is being defined at JPL, These missions will use advanced technologies (such as laser communications) to enable challenging mission technical objectives while satisfying the micro-spacecraft constraints,

Finally, even though the emphasis is now on small spacecraft systems, there are still expected to be periodic (approximately one per decade) flagship-class missions of the Galileo or Voyager type. Since most of the major solar system bodies have had initial space investigations, the return missions are likely to involve much more in-depth, and hence much more data-intensive, science data gathering. For these missions, optical communications is likely to be a key enabling technology for sensors such as synthetic aperture RADAR anti multi-spectral imaging.

2.2 Commercial Applications

There are a number of multi-satellite, commercial telecommunications networks that have been proposed recently to service mobile, rural and personal communications needs, These are networks like Iridium, Calling, and Globelstar, to name a few, The number of satellites in each of these networks is large and will likely require complex routing anti rerouting of traffic between satellites, Because of the multiplicity, each spacecraft must be severely constrained in terms of mass and cost to keep the launch costs under control. However, this multiplicity also creates opportunities for amortized developments that could significantly alter the economics and technical viability of new services. For such applications, optical communications is expected to play a key role in these, or future versions of these networks,

2.3 Other Governments l Application-&

There are also a lot of commercial opportunities afforded by other government programs, particularly for the Department of Defense. Laser communications is likely to be a significant contender for interconnections between global early-warning satellite clusters, communications satellite grids, tactical network satellites for theater defense, and for air-to-air or air-to-space links from flying command posts.

3. RECEPTION SUPPORT NETWORKS

Many of the NASA applications will require reception-end support, This support will be in the form of either a ground-based reception infrastructure, of a space-based one. Additionally, even the space-to-space applications will likely transition through a technology validation phase where space-to-ground demonstration links will be required, Studies and systems-level planning have been underway for a number of years in these areas,

For the short term, initial demonstrations have been conducted, or are being planned, which make use of existing ground-based optical telescopes. For example, the recently completed GOPEX demonstration used an astronomical telescope at JPL's Table Mountain Facility, as well as an Air Force telescope at the Star{ire Optical Range.[1] Other demonstrations are being planned which use these, or similar telescopes to interact with airborne or flight hardware. This approach is cost-effective since it is usually necessary to do demonstrations to convince the potential users that the technology is adequately mature, but significant resources cannot be obtained from the principle funding sources for those demonstrations without the endorsements of the user community. Using existing facilities costs very little money to create the initial demonstration capability but can yield significant gains in the advocacy area. It is also a very time-efficient way to gain systems-level experience in the technology,

l-he initial systems-level demonstrations will be configured in ways that make them very close to "prototype system" demonstrations for near-Earth applications. Thus, development of similar-sized ground-based terminals that can support the operational needs of the near-Earth applications will follow naturally, However, these demonstrations will only be '(scaled prototypes" for the deep-space applications. As the link range increases, the size of the receiving telescope will increase and the data rates will begin to decrease, Noise mechanisms which often dictate the limits of performance will change. Most deep-space scenarios will require scaling by 6-11 orders of magnitude relative to the near-Earth applications (performance varies as the square of the link range), This dictates that some form of intermediate demonstration vehicle must be created.

At JPL we have been studying for several years the design concepts for a deep-space optical research and development telescope to support such deep-space demonstrations and to provide experience into the systems-level and operational issues of larger reception aperture stations. Initial designs of such a facility considered the use of advanced light-weight composite materials that could produce large aperture, segmented primary mirror structures with reasonably good "photon bucket" aperture efficiency and high thermal stability to withstand day/night solar heating distortions.[2] Preliminary examinations of this technology have indicated that it is not yet cost competitive. Therefore, alternate approaches have been investigated. One approach recently studied is to use a fabrication technique that has been successfully applied to the development of aluminum, large aperture, all-weather submillimeter telescopes.[3] While cost and performance looks promising for nighttime use, more work is required to validate the approach for daytime and daytime/nighttime transition conditions.

Demonstrations of deep-space optical communications to a large aperture ground-based telescope will point the way toward the technology required for an entire global reception network, Initially, this network is envisioned to be ground-based. A study was recently completed to identify candidate global deployments for such a network and to evaluate the resulting performance.[4] The results suggested that a network of 6 linearly spaced stations spread around the world was a reasonable overall choice based on coverage, weather availability and cost.

At some point, however, the network (which could at this point be a single station) is expected to be deployed in Earth-orbit. Just when that should occur is still an open question. To gain some insight into the architecture, expected performance and cost of such an orbiting station, two parallel industry studies were performed.[5-10] Actually, both studies were tasked to evaluate both rf and optical frequencies for use with the orbiting receiving station, However, both contractors concluded by midpoint in the study that if space-borne reception is used, optical was the only viable candidate.[11] I-he studies included examinations of heterodyne reception as well as direct detection, with the latter selected as the favored approach,

4. SPACECRAFT PAYLOAD TERMINALS

Most of the significant effort in this area has been concentrated on the development of an Optical Communications Demonstrator. However, studies have been conducted to show how this technology extrapolates to future micro-spacecraft terminal applications.

4.1.. Optical Communications Demonstrator

In past years, research and development of components and subsystems for spacecraft terminal equipment was carried out at JPL under several NASA sponsoring divisions. Approximately 18 months ago it became possible to aggregate all the space terminal technology development activities into a single development program. This resulting program is the Optical Communications Demonstrator (OCD) program.[12] The OCD program contains an OCD Instrument which is a form, fit and function, but laboratory-environment qualified brassboard of an optical communications spacecraft terminal. It uses a unique “reduced complexity” design that requires only one 2-axis steering mirror and one 2-axis CCD array detector to accomplish uplink beacon acquisition, tracking, return beam point-ahead, and internal transmit/receive co-alignment calibration.[13,14] All of the critical optics are integrated directly into the Telescope Optical Assembly (TOA)[15,16], except the Laser Transmitter Assembly (LXA) which is located remotely for heat dissipation reasons and is fiber-coupled to the TOA.[17]

The OCD Instrument has completed its basic design phase, The tracking system has been breadboarded and tested, the electronics for the tracking detector array have been packaged, and construction of the telescope optics and mechanical assemblies is due to start shortly. Additionally, the LXA has been designed, packaged, assembled and tested. Completion of the entire OCD Instrument is due later this calendar year.

The OCD Instrument is supported by two additional subsystems; one is the Control Terminal which simulates the host spacecraft electrical environment and provides for operational control and display of the OCD Instrument functions, and the other is the Ground Station Simulator, which simulates the receiving terminal at the other end of the link and provides a tracking beacon signal, and the electro-optics for analyzing the OCD Instrument's output optical beam,

4.2 Micro-spacecraft Terminal Designs

The OCD Instrument is intended to be a prototype for a small spacecraft communications terminal. However, the OCD Instrument is not fabricated (due to budgetary constraints) with state-of-the-art lightweight components, nor have ASIC implementations been designed for the electronic circuits. Impacts on future spacecraft (in terms of mass, power, volume etc.) will depend on these embodiments, as well as reasonable technology extrapolations from now to the time of use. Therefore, many application-specific design studies for flight terminal hardware have been performed.[18] These designs have resulted in projections for future deep-space mission flight hardware terminals that vary from below 1 kg of mass to as high as 10 kg, depending on range, data rate and degree of shared equipment. Projections for power consumption varied from below 5 W to as high as 35 W under similar conditions.

5. SUPPORTING TECHNOLOGY

There are a number of key technologies and supporting programs that have augmented the existing space terminal and reception network program elements. This section describes those activities.

5.1 AVM Program

To develop a validated weather visibility model for the atmospheric (primarily cloud outage) impacts on ground-based optical signal reception, a set of three Autonomous Visibility Monitoring (AVM) observatories has been designed, assembled and are in the process of being deployed.[19] These observatories are completely unattended, autonomously operating telescope systems that optically acquire and measure the intensities of stars , both at daytime and nighttime. The stellar powers are measured through a set of 5 filters; the three standard astronomical "1", "R", and "V" filters, as well as narrowband filters centered at the important laser transmitter wavelengths of 532 nm and 860 nm. A sixth filter is also included at 1064 nm, but the signal detection array is not adequately sensitive at this wavelength. Upgrades to the system are planned which will allow this wavelength band to be measured as well.

The first of the observatories has been completed, tested and is in the process of being deployed at JPL's Table Mountain Facility near Wrightwood, CA. The second observatory will be integrated and tested during the Winter of 1994, and will be deployed at Mt. Lemmon, AZ. Plans call for the third unit to be placed in operation on the mountain ridge behind JPL, but it may eventually be deployed to a mountain peak somewhere in New Mexico.

5.2 Lasers

High power-efficiency lasers have also been developed. A diode laser-pumped, Nd:YAG laser with an internal harmonic frequency doubler and acousto-optic Q-switcher was recently developed and tested.[20] The laser, which uses three 10-Watt, fiber-coupled laser-diode-array pump sources, was designed to produce 2 Watts (average) of pulsed, green radiation in a single spatial mode and at a pulse rate of 50 kHz. The unit achieved 3,5 Watts under these conditions, Furthermore, the laser is capable of producing 11 Watts of CW fundamental radiation at 1064 nm with the Q-switch and harmonic doubler removed. This laser is a candidate laser transmitter for higher data rate links from the outer planets,

5.3 Optical Pre amplifiers

The signals from deep space are extremely weak and require large-aperture, sensitive receivers to detect them, Often times the dominant noise in the system is introduced at the detection electronics of the system, In such cases, it is frequently advantageous to amplify the optical signal prior to detecting it on the photo-detector. A study was recently completed where the use of an optically-pumped parametric amplifier (OPA) front-end was evaluated.[21] The study showed that under conditions typical of deep space reception, a 4-6 dB link gain will result, Additionally, the OPA provides a certain amount of front-end optical filtering due to its frequency-selective amplification.

5.4 Optical Filters

Ground-based optical signal reception of signals from space must often be accomplished during the daytime when the background light levels can be very high. For such reception, narrowband optical filters will be needed to reduce the impact of that background light. For this reason, JPL has been sponsoring research and development of such filters at New Mexico State University. The filters are based on a Faraday rotation principle where light passing through a gaseous medium which has been placed in a magnetic field will experience a polarization rotation if, and only if, the wavelength of the light is precisely on resonance with the molecules of the gas. By preceding the cell containing the gas with a polarizer, and following the cell with a 90-degree rotated polarizer, the unwanted light can be blocked. Filter bandwidths as narrow as 1 GHz and with transmission efficiencies as high as 800/0 have been demonstrated.[22,23]

A cesium-vapor Faraday rotation filter operating at 852 nm was recently developed and delivered to JPL for evaluation, A Stark-shifted version of such a filter using rubidium-vapor is now being developed for the doubled Nd:YAG wavelength of 532 nm, and a model for yet another Stark-shifted version at the second harmonic of Nd:YLF (523 nm) has been developed.[24]

6. PLANNED DEMONSTRATIONS

Last year a highly successful optical demonstration was conducted with the Galileo spacecraft.[1] This demonstration was one of a series of planned demonstrations that will validate various aspects of optical communications for space-to-space and space-to-ground applications. This section describes the follow-on demonstrations that are being planned,

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The GOPEX demonstration conducted last year validated that a laser (beacon) beam could be transmitted to a planetary spacecraft based only on the trajectory predicts of that spacecraft, I-he beam transmitted to the spacecraft was intentionally broadened to divergences ranging from 40-120 μrad to allow for the expected atmospherically-induced beam breakup and broadening. The demonstration occurred over ranges up to 6 million km, However, deep-space missions will require beacon transmissions many times farther than this, To transmit over such vast distances, the beams must be much more tightly focussed than the limits imposed by the atmosphere to keep the required laser powers from becoming extremely large. This will require some form of uplink atmospheric compensation,

The objective of the Compensated Earth-Moon-Earth Retroreflector Laser Link (CEMERLL) demonstration is to show that such narrow beams can be precisely transmitted into deep space.[25,26] The demonstration is being conducted in conjunction with the Air Force Phillips Laboratory's Starfire Optical Range, and makes use of recently declassified artificial laser guidestar atmospheric compensation technology, The demonstration uses corner cube arrays left on the Moon by the Apollo astronauts to establish an 800,000 km link, Transmissions will be made to the corner cubes both with, and without, the artificial laser guidestar compensation enabled. When activated, the compensator will remove the higher-order atmospheric aberrations to the beam and will result in substantially stronger returns from the corner cubes, The low-order aberrations of tip and tilt will be compensated by tracking solar-illuminated Lunar features, The demonstration is scheduled for March of 1994,

6.2 Early Aircraft-to-Ground Demonstration

The Optical Communications Demonstrator instrument described in Section 4.1 is being designed for laboratory qualification. However, for not much additional effort and with minimal risk, the **unit could be flown on a** high-altitude **aircraft for an air-to-ground demonstration.** NASA currently operates a fleet of high-altitude research aircraft which includes three operational SR 71's (three more are in storage) and several U2's. Plans are currently being made to fly the OCD Instrument on one of the SR 71 aircraft and conduct a downlink laser communications demonstration at several hundred Mbps to a suitable (existing) ground station. The dernonstration is being planned for early-to-mid 1995.

6.3 Demonstration with the FST

A significant effort was initiated at JPL a couple of years ago to develop a universal testbed for evaluating spacecraft subsystems in an electronically-simulated complete spacecraft environment, This testbed is called the Flight System Testbed (FST). The testbed has the ability to operate with simulated subsystems, or with actual hardware subsystems, and is very useful for examining the interplay between several coupled subsystems. This testbed is expected to be useable by the time the OCD Instrument is developed at the end of 1994. Accordingly, plans are being made to interface the OCD Instrument with the F ST testbed to evaluate its performance in a spacecraft system-level environment. The tests are expected to occur in 1995.

6.4 Proposed Demonstration on SIR C Freeflyer

JPL has developed the SIR C Instrument which will **fly in the Shuttle in** FY94. After two such flights the SAR instrument will be available for other uses. A proposal is being developed by J PL to use this instrument for a SIR-C Freeflyer spacecraft, The freeflyer is anticipated to be launched in FY97 or FY98. However, unlike the Shuttle mission where data can be recorded in flight and processed on the ground later, the freeflyer must transmit its data to the ground. Because of the high data volume collected and the quick overflights of downlink receiving stations, the mission objectives are constrained by the downlink data rates,

This application is a natural for optical communications, In fact, the prototype technology demonstrated in the OCD program, and successfully validated in an SR 71 air-to-ground demonstration, would be capable of sending several hundred megabits per second from the SIR C Freeflyer platform to the ground, The required ground stations would be easy to replicate and relocate as desired since the receiving aperture size would be 0.5 to 0,7 meters in diameter (transportable laser ranging systems exist today with apertures as large as 0.75 meters), The required electrical power and mass of the optical communications terminal would be insignificant relative to the SIR C Freeflyer spacecraft's capabilities.

Discussions have already taken place with the SIR C Freeflyer preproject study team and for the purpose of including a flight-qualified version of the OCD (or similar terminal) on the mission as a mission-enhancement experiment (not critical to the mission but, if successful, would provide a significant enhancement to the overall mission objectives), The response has been very favorable and room has been identified in the spacecraft design for such a terminal.

Demonstration of optical communications technology on the SIR C Freeflyer will be of great benefit to the mission as a long-term mission enhancement, and it is a natural for the laser communications program since it provides the necessary spacecraft host and orbit-insertion launch required to conduct any type of space demonstration of the technology,

6.5 US Industry Development and Demonstration Contract

To demonstrate laser communications technology in space will require the development (in industry) of the space-qualified hardware. One of the objectives of NASA is to stimulate that development in the US industrial base. Accordingly, JPL will soon be issuing an RFP for the first (mission definition) phase contract(s) for a program to develop and demonstrate laser communications technology in space. The program will include one or more flight optical terminals, the host spacecraft, the necessary launch vehicle(s), and the ground-support systems, Considerable latitude will be afforded to the contractors to define the program. The RFP is expected out in the first few months of this year.

7. SUMMARY AND CONCLUSIONS

In this paper the major elements and accomplishments of the NASA-funded optical communications program at JPL have been described. We began by describing the user or applications base for the technology. Next the supporting ground (or space-based) reception infrastructure plans were discussed. We then described the Optical Communications Demonstrator program which is demonstrating and validating the "reduced complexity" design architecture for a space-end terminal. This was followed by a discussion of the supporting technology base, which includes the establishment of a data-supported atmospheric weather model, high-efficiency lasers, reception front-end parametric amplifiers, and narrowband optical filters. Finally, we listed and discussed a set of follow-on systems-level demonstrations that are in preparation, or are being planned. These include a compensated uplink demonstration with the Moon, an SR 71 aircraft-to-ground demonstration link, interfacing the OCD Instrument to the simulated spacecraft environment of the FST, plans for a proposed mission augmentation flight experiment on the SIR C Freeflyer spacecraft, and an impending RFP release for the first phase of a flight hardware development and space demonstration program.

From the material presented herein, as well as developments in the laser communications community throughout the world, it is clear that the question is not "if" optical communications will be used, but "when". We will surely see the realization of such links in, or from, space, this decade,

8. ACKNOWLEDGMENTS

I-he research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. The author wishes to express **his appreciation to the members of the** JPL optical Communications Group, the supporting members from the other JPL divisions and sections, and to the industrial, governmental and university affiliates, that have contributed to the substantial accomplishments discussed in this paper

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