Invited Paper

Overview of NASA R&D in Optical Communications

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ABSTRACT

We review the current applications base for the use of free-space optical communications technology. We then describe the NASA programs in the optical communications area addressing those applications areas, in particular, we describe the Laser Communications Demonstration System, an industry-driven program for the space-demonstration of this technology at data rates of at ieast 750 Mbps. We then describe NASA technology development and study activities in support of these applications. Acclivities described include the Optical Communications Demonstrator, a study of an air-to-ground system demonstration, a mission application study for the TO PSAT radar mapping mission, and a program to acquire detailed statistics on atmospheric transmission for space -to-ground links.

1. i NT RODUCTION

Optical communications technology has been advancing at a rapid rate and the applications base appropriate for this technology has been steadily expanding, At one time optical communications was only being considered for the most challenging of deep space links, or for a few specialty iinks for the Department of Defense, in this paper we review the current applications base, and discuss how the NASA optical communications programs, technology developments and system studies are addressing these applications areas, In the next section we will describe the changes that have occurred in the applications base. Following this, we will describe the Laser Communications Demonstration System, a partnership program with industry to address the most pressing needs of that applications base. Finally, we will describe the NASA technology developments and systems studies focused toward demonstrating the maturity and benefits of this technology to the potential users.

2. APPLICATIONS REVIEW

NASA has been working on laser communications since the early 1970's. The principle applications have been the high-rate GEO-GEO and lower data rate deep-space links. At one time, it was believed that optical communications was only applicable to the higher data rate links. With developments in lasers, detectors, pointing systems, and optics, optical communications has begun to encroach on lower data rate links and the crossover between optical and RF technology (if one really exists) has become less definite.

Today, optical communications is being considered for a wide variety of link applications. The emerging set of proposed personal communications satellite networks are considering optical communications for interconnections between satellite nodes. The high volume of data which must be shipped around the world and to the user in commercial remote sensing initiatives is another prime application. And , as these and other networks are tied together in an overall National Information Infrastructure (Nil) or Global Information Infrastructure (Gil), the aggregate data rates and shear data volume are likely to dictate the use of optical.

NASA continues to have applications in the traditional areas (GEO-GEO crosslinks and deep-space return links). However, new application areas are also emerging. With the increased emphasis on smaller, lighter and more cost-effective LEO satellites, it is becoming more and more difficult for the user satellites to justify the cost of relaying data through the Tracking Data Relay Satellite System (TDRSS) as it is currently configured. Thus, lower-cost and lower-impact user satellite terminals, either to the ground or through a new kind of TDRSS, will be required. Next, there are the important missions to planet Earth. Missions like the SIR-C F reeflyer, or the EOS follow-on spectral scanning missions can easily have individual data rates that exceed the current TDRSS capability. Such missions will need either higher data rate links to an advanced TDRSS-like satellite, or will require high-rate downlinks to a set of ground-based collection terminals. additionally, the Space Station, if not initially, is likely to have data volume growth that will require much more capability.

Finally, there are still the analogous requirements for DOD communications capabilities. Connections into and between the Defense Global Grid nodes will become important. And, of course, there are the potential links to/from airborne terminals such as flying command posts.

With this rich set of applications areas, and due to the maturation of the technology, optical communications is expected to be a viable alternative in many of these applications.

3. LASER COMMUNICATIONS DEMONSTRATION SYSTEM

The individual NASA program elements are addressing a variety of these potential applications. One of those programs is the Laser Communications Demonstration System (LCDS). The program was conceived as a paradigm shift. NASA normally develops specifications for equipment it needs for a specific mission, and then contracts with industry to produce that equipment. The requirement for NASA mission hardware are frequently unique, and the quantities required by NASA are almost always small (often only a single flight unit and perhaps a flight spare). This is often a prescription for high cost, unless the NASA requirements just happen to match the specifications of something industry has produced (is producing). The LCDS program took a different approach, and asked industry to consider what it really desired to produce, If industry saw enough economy of scale in a technology close to NASA's needs, then, in theory, it should be less expensive for NASA to either adapt its mission requirements to those already available from industry, or require only minor changes from the industry product line.

With this philosophy in mind, the LCDS program became an industry-driven program. Industry was involved with the formulation of the program, and it participated in the development of the RFP for the program initiation. The objectives of the program are to look ahead and assess the potential applications base for the technology, and then to define a flight demonstration that will, from their perspective, best demonstrate the maturity and applicability of the technology to the appropriate set of applications. The program is to consider the entire demonstration system (optical communications terminals, host spacecraft, launch vehicle(s), ground support system, data collection plans and the demonstration operations. The only technical requirements imposed by NASA were that the demonstration had to have at least one space terminal and the data rate had to be at least 750 Mbps.

At present, the program is in the Phase A/B study phase. The draft RFP was issued in January 1994, and the formal RFP (after inclusion of feedback from industry) was issued in March. Four industry teams responded to the solicitation and in July 1994, two of the teams were placed on contract. One of the teams, headed by Ball Aerospace, has teammates ThermoTrex Corp, Comsat Laboratories, Laser Diode Systems, and Daedalian Technologies, Ltd. The other team is headed by Motorola with Martin Marietta as a teammate. The schedule calls for completion of the Phase A/B studies in May 1995 with a program Non-Advocate Review (NAR), if one is required, the following month, If favorably received at the NAR, the flight demonstration could be operational by 1998.

4. SUPPORTING TECHNOLOGIES AND STUDIES

NASA is also supporting a number of technology developments, system studies and demonstration planning activities. This section describes some of the activities in progress, or completed during the past year,

OCD Development Program

During the past two years JPL has been developing a Laboratory-clualified engineering model of an Optical Communications Demonstrator (OCD). It is based on a simplified system architecture described earlier [1-7]. It uses a single CCD detector array and a single two-axis steering mirror to accomplish the functions of beacon acquisition, tracking, transmit/receive alignment and point-ahead monitoring. The tracking system breadboard was completed and evaluated in the laboratory. This was followed by a contract with 20/20 Systems Inc. to package the CC D/Camera readout electronics, and the Tracking Processor Assembly, 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 course pointing gimbal is from Sagebrush Industries with a ThermoTrex-developed controller. The gimbal and controller were obtained from the Air Force Rome Laboratory through an inter-government-agency loan.

The Telescope Optical Assembly has been designed, both optically and mechanically, and the fabrication drawings for the optics and mechanical support components have been generated. Procurements for the optics have been placed and the machining of the support structures is in progress.

Other supporting electronics such as the Power Conditioning Unit and the Control Terminal (used to simulate the host spacecraft) have been completed. Development of the Ground Station Simulator (GSS), to be used to provide the beacon signal and analyze the output beam from the OCD, was schedule for completion this year but has been delayed until later this year (early FY'96) due to tightening budget limitations. However, the GSS will build heavily on some surplus government obtained from the Air Force Phillips Laboratory after a major program termination.

The current schedule for the OCD development calls for the OCD Terminal (the portion of the program that represents the spacecraft communications terminal) to be completed by the end of FY'95. The GSS will be completed in early FY'96 and will be used in the evaluation of the OCD Terminal.

Air-to-Ground Demonstration Study

A number of mission applications and advocacy-bolstering studies have been completed recently. This section describes the study of a potential optical communications demonstration intended to build confidence in the technology for future Earth-orbiting radar missions such as the SIR-C Freeflyer. Before discussing the study, a brief description of the SIR-C/X-SAR mission is in order.

The Shuttle Imaging Radar- C/S-SAR mission has flown twice on the Space Shuttle Endeavor; once in April 1994 and again in October 1994. The payload is a multi-frequency, active array synthetic aperture radar, The radar provides dual polarization C-band and L-band radars, and a single-polarization X-band radar. The latter of these was provided through the German (DARA) and Italian (ASI) Space Agencies. The first flight mapped 5.6% of the Earth (25.6 million square miles) producing $4.7X10^{13}$ bits of data (equivalent to 20,000 encyclopedia volumes) while the second flight exceeded that with 9% mapped (≈ 25,000 encyclopedia volumes). Additionally, the second flight included passes over areas that had been overflown during the first flight. This allowed for the processing of data from the two flights for a major new "first"; the interferometric combination of data from the two flights, not only at C- and L-bands, but at X-band as well. These processed results permitted detailed height determination and change detection to be performed.

The SIR-C/X-SAR instrument is indeed a highly successful payload and a valuable space asset. Accordingly, NASA has been considering the possible reflight of the instrument as a SIR-C Freeflyer spacecraft by adding the necessary solar panels and infrastructure to make it a self-contained spacecraft. However, unlike the Space Shuttle flights, which used tape recorders for most of the collected data, the SIR-C FF would require a high bandwidth data link. In fact, the extent of the mission coverage objectives would be impacted by the amount of data that could be returned. For this reason, the project management was very interested in the capabilities of optical communications, particularly if the technology could provide very high data rate data dump directly to the ground. However, like most missions that are considering a new technology that has not been proven in space, a convincing system-level demonstration, that could be performed in the near-term, was considered to be pivotal. Additionally, such a demonstration could also have a strong impact on the future missions of NASA's Earth Observation System program, particularly for missions with high data volume instruments like multi-spectral imagers.

Given the near-term demonstration need and the fact that the OCD Instrument was being developed (and although not yet space qualified, was being built with eventual flight qualification in mind), an aircraft-to-ground demonstration was proposed. Interest in such a demonstration was high in the SIR-C project office (at JPL) and at NASA Headquarters, both Code Y (the office responsible for Mission to Planet Earth) and Code O (responsible for Space I-racking and Data Acquisition). Accordingly, resources were made available for a detailed study of the demonstration.

The approach for the demonstration was to use the JPL OCD Instrument as the airborne terminal for flights on both the NASA DC-8 aircraft and then the NASA ER-2 high-altitude aircraft (basically a U-2 aircraft). (The NASA SR-71 vehicle was initially considered, but had to be abandoned for technical reasons). The Air Force Phillips Laboratory was contacted and was interested in providing the Starfire Optical Range's 1.5 meter telescope for the ground tracking terminal, The initial demonstrations would use the DC-8 aircraft where operational personnel could be onboard to verify operation and assist in the initial spatial acquisition, (The DC-8's attitude knowledge was not as accurate as the ER-2 aircraft's knowledge and operator assistance was required. However, assistance only to the level of attitude knowledge of the ER-2 aircraft would be performed). The DC-8 flights would allow for lower-cost initial "shake-down" demonstrations of the entire system. Additionally, the DC-8, flying at a lower altitude than the ER-2, could perform overpasses at higher angular rates, more commensurate with eventual satellite overpasses, This would provide good operational experience for the ground station tracking. The higher-altitude ER-2 flights would then be performed without operator assistance, and at an altitude containing nearly all of the Earth's atmospheric effects.

The demonstration was to consist of an entire end-to-end validation using real radar data. Data tapes of actual SIR-C/X-SAR data, along with the flight and ground recorders used for the SIR-C mission, would be loaned to the demonstration by NASA Code Y. The flight recorder would provide data at rates of 180 Mbps or 225 Mbps (depending *on* how many simultaneous SAR channels were being played back). The recorded data at the ground station would subsequently be played back and processed at the J PL SAR Processing Facility for conversion to images and compared with the images processed from the original (flight) data tapes.

Mounting of the OCD Instrument in the DC-8 would be at the #9 bay window (the one currently used for Airborne Imaging Spectrometer measurements). The OCD would first be mounted on the ER-2's payload interface pallet, and then the pallet would be mounted over the #9 bay window. After the DC-8 flights, the entire pallet/OCD would be transferred to the Q-bay of the ER-2 (located behind and below the pilot's seat).

The demonstration could be performed during the first half of 1996.

TOPSAT Mission Study

Another radar mission is being considered by NASA, The Topographical mapping SATellite (TOPSAT) is a direct descendent to the successes of the SIR-C mission. The primary objective of this mission would be to generate a digital elevation map (DEM) of the entire globe. Additionally, such a mission would be able to detect small changes in the earth's surface due to such things as volcanic eruptions, plate stress bulging, or erosion. One version of this mission would consist of a pair of Earth-orbiting satellites in a 550 km altitude orbit and having a maximum 2 km separation. data from the two SAR radars would be interferometrically connected to do the height mapping. The communications needs of this mission candidate were for a spacecraft-to-spacecraft link and a spacecraft-to-ground link (from either satellite) at 250 Mbps. One additional requirement was that the form factor of the spacecraft must be small to minimize atmospheric drag.

First, as shown in Table 1, the difficulty factor (data rate-distance squared product) for TOPSAT is much less challenging, at least for the TOPSAT crosslink, than most traditional space links. This opens up possibilities for using very simple systems on the spacecraft. In particular, if the transmit beamwidth of the optical communications terminal could be enlarged, the pointing and tracking system could be greatly simplified. If the beam could be increased large enough to encompass the entire pointing uncertainty of the spacecraft, no fine pointing system would be required at all.

	Data Rate * (distance)^2, km^2/S
TOPSAT Crosslink	10^9
TOPSAT Downlink	10^{14}
Typical Earth Xlinks	10^{14}-10^{18}
Deep Space Links	10^{20}-10^{22}

Table 1 - Data rate-distance squared products for TOPSAT and other typical space links

A design study was initiated assuming there was no fine pointing system, and that all pointing of the (4 mrad) beam was accomplished by the coarse pointing system using open-loop control of the coarse pointing gimbal, (The attitude knowledge of the spacecraft was expected to" be about 1 mrad). This structure has the added advantage that no uplink (or crosslink) beacon signal is required to initiate the link, The spacecraft simply points a communications head, consisting of a laser diode and aperture definition lens for transmit and a receiving lens, spectral filter, and avalanche photodetector for the receiver, based on the attitude knowledge of the spacecraft and the resolution (0,25 mrad) of the coarse-pointing gimbal.

The results of the study showed that a 25o Mbps, 2 km crosslink could be established with a 0.5 mm transmitter lens, 320 mW laser diode, and a 1 cm receiver aperture at the other end. With earthshine in the background, the link margin was 24 dB! Even more surprising, if the same terminal were to be pointed at the ground, the 250 Mbps link could be established comfortably to a ground-based 1 -meter diameter reception telescope. The downlink analysis assumed an 1100 km link range (slant range for a 550 km orbit at 30 degree elevation angle), daytime reception of the signal, and a 7 dB loss due to atmospheric attenuation, The resulting margin was 3.2 dB.

The size of the terminal head, assuming full redundancy and excluding the coarse-pointing gimbal, was 4 cm X 5 cm X 6 cm and the mass estimate **was well under a kilogram.**

For slightly more challenging links, it is necessary to add additional complexity, either in the form of increased power or by narrowing the transmit beam divergence, which necessitates some level of fine beam control and, of course, an uplink beacon signal. A terminal design that covers this region of applications and can be built with much less than 5 km of mass has already been reported [8].

Atmospheric Visibility Monitoring Program

The performance of space-to-ground optical communications links depends very strongly on the attenuation effects of the atmosphere. To fully understand the outage statistics of the link , and potential strategies (i.e. spatial diversity) to mitigate them, an accurate data base of atmospheric attenuation is needed. JPL has developed and deployed a system to gather such statistics,

A set of three visibility monitoring observatories designed to track stars and measure the atmospheric attenuation, have been designed and built. The observatories are autonomous and operate under computer control. Each observatory contains a 10 inch telescope, a CCD array detector and a six-position spectral filter wheel. A star catalog in the on-site computer tasks the observatory to search for and acquire stars, and then to make intensity measurements of the stars using the filters, The CCD array is used to measure the intensity using 20 X 20 pixel subarrays. Measurements are made using narrow-band filters centered at 1.06 μm, 0.86 μm and 0.532 pm, respectively, as well as through the standard astronomical '(I", "R", and "V" filters, Data collected at the observatories is stored in files at the site and once each day sent to JPL over commercial telephone lines.

The three observatories have been deployed at JPL's Table Mountain Facility (Wrightwood, CA), Mt Lemmon (near Tucson AZ), and on the hill behind JPL (Pasadena, CA), and are now operational. Data files are sent back to JPL daily and are being used to generate detailed visibility statistics. These statistics will permit the generation validated atmospheric visibility models.

5. CONCLUSIONS

We have described the NASA R+D program in optical communications, We began by reviewing the current application base for the technology. This base has expanded from the traditional NASA and DOD links to an expanded set of commercial and governmental applications. Next we described the Laser Communications Demonstration System, a joint industry/government program intended to reduce the costs of this technology to the government by giving industry a more significant hand in defining the technology base. We then described supporting developments and systems studies. These included the status of the OCD development, a system demonstration using an air-to-ground link, a missions application study of the TOPSAT radar mission, and a developed and deployed system to collect statistics on the optical transmission of the atmosphere for space-to-ground links. These developments, along with similar accomplishments in industry and other government laboratories, should enable significant optical communications demonstrations in the very near future.

6. ACKNOWLEDGEMENTS

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