impact of Laser Communications on Future NASA Missions and Ground Tracking Stations

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SUMMARY

NASA's past missions used RF communications to relay scientific data from space observation platforms to the ground. Over the years increasing demands have been placed on those systems, resulting in significant development of the technology. Future missions, however, will require substantially more communications capabilities, while restricting the size, mass or other parameters of the equipment to provide it. These pressures are forcing mission planners to investigate other technologies like optical communications. in this paper the needs of the future missions, both near-Earth and deep-space, will be discussed. Next, the systems being considered for optical communications, both at the spacecraft and at the ground, will be described. Supporting developments that will aid in the realization of these systems are then described, followed by a description of two recent systems level demonstrations.

Summary of Mission Needs

Present-day Earth-orbital missions utilize (he NASA Tracking and Data Relay Satellite System (TDRSS) for returning space-acquired data to the ground. The data is transmitted from (usually) low-altitude satellites to a geosynchronous TDRSS satellite and then transmitted to the ground at White Sands, New Mexico. However, many missions are already finding it necessary to use alternate methods for communications. Missions like SAMPEX, and other missions in the SMEX series have chosen to request direct-to-ground service from the Deep Space Network, a network developed primarily for deep-space missions, rather than incur the cost of the TDRSS user terminals. Also, missions like the SIR-C Freeflyer and other high data rate multi-spectral radar and imaging missions will require more data relay than can be scheduled or provided by the TDRSS network. Furthermore, the short contact times for direct-to-ground data dumps force the data rates to grow even larger, requiring more data throughput capacity than is available (at RF frequencies) from spectrum regulatory bodies. For such missions, the small size, mass and projected cost, coupled with the lack of regulatory restrictions, makes optical communications an extremely attractive alterative for providing service. Additionally, data rates into the Gbps region can be supported with modest-sized (approximately 1-meter diameter) ground-based reception stations.

Deep-space missions are also anxious to utilize the benefits of optical communications. Past missions like Voyager, Magellan, Ulysses and Galileo, as well as the Cassini mission currently under development, have employed RF communications wavelengths. The communications antennas for these systems have been in the 3-5 meter diameter range and have substantially dominated the architecture of the entire spacecraft. Reception of the signals from such spacecraft is accomplished using very large 34-meter and 70-meter diameter radio telescopes. Over the past 30 years the RF communications capabilities of these systems have improved by **12** orders-of-magnitude through improvements in larger antennas, higher power transmitters, shorter RF communications wavelengths, improved microwave systems, coding and antenna arraying. It appears that there is little room for significant additional improvement.

Yet the budgetary pressures on the space science program have dictated a new class of smaller, lighter weight and (hopefully) more frequent deep-space missions. Where missions weighing several thousand kg and large enough to fill the entire Space Shuttle bay were developed in the past, now weight limits in the 1.50-500 kg range, with multiple spacecraft launches on small expendable' launch vehicles, are required. Indeed, studies of the Pluto Flyby mission have had to be re-scoped and redone due to the realities of decreasing targets for mass, power and size of the spacecraft. These reductions have decreased the data-return rate capabilities of the mission (even with the new Ka-band frequency technology) to a mere 270 bps. For such missions, the decreased size and mass of optical communications, along with increased channel capacity, are becoming attractive characteristics. For example, a recent study for the Pluto Flyby mission concluded that a data rate of nearly 5 kbps could be achieved using a spacecraft terminal that was 40% of the mass of the RF terminal and which required no additional electrical power. The message is clear that NASA needs to decrease the size, mass and overall resource impact of its spacecraft communications equipment, while maintaining the throughput of the communications channel as high as possible,

But minimizing the impacts (and hence the cost) of the spacecraft communications terminals is not the only requirement. It is not valid to decrease the capability of the spacecraft system, only to make up the difference by increasing the costs of the ground tracking systems. These days, missions operations costs are becoming major factors in the overall project costs, and mandates have been issued to decrease those costs as well. Currently, the Deep Space Network (DSN) consists of a world-wide network containing 70-meter, 34-meter, 26-meter and 1 1-meter diameter RF stations. The costs to operate these stations are proportional to the size of the antenna and the amount of support time the project requests. Budgetary constraints require that missions minimize both of these,

Optical Communications Systems

In this section some developments that will enable optical communications to be used on these future missions will be described,

OCD Development Program

During the past two years JPL has been developing a laboratory-qualified engineering model of an Optical Communications Demonstrator (OCD). It is based on a simplified system architecture. 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 to package the CCD/Camera readout electronics, and the Tracking Processor Assembly, the assembly which determines, filters and conditions the tracking error signals for actuation of the steering mirror and the coarse pointing gimbal. 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 equipment,

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,

Ground Reception Systems

The ground tracking stations for optical communications will be quite different from the RF systems. For supporting Earth-orbital missions, optical telescopes in the 0.6-1.5 meter range will be adequate, In many cases, even smaller-sized apertures would be adequate to support the communications link requirements if it weren't for atmospheric turbulence-induced signal intensity fluctuations (scintillations). By using telescopes in the above range, adequate aperture averaging is afforded to smooth out those scintillations. Telescopes in this diameter range are widely used and are commercially available.

For longer-distance links from deep space, larger telescopes requiring significant non-recurring development will be required, Initial short-term demonstrations can be supported by existing astronomical telescopes in the 1-3 meter diameter range, such as those at JPL's Table Mountain Facility, or those at Air Force facilities like the Starfire Optical Range or the Air Force Maui Optical Station. However, even larger systems will be required for longer-term and longer-range mission support.

Studies of the requirements for such telescopes commenced in the mid 1980's. The first task was to bound the aperture diameter size, as this had the biggest implication on cost. A cost modeling study was completed which examined historical data on telescope costs, and an analytical model for the cost of a telescope as a function of the diameter and image blur size (a measure of aperture surface quality) was developed. Next the relationship between communications performance benefit (relative to an X-band RF system) was calculated based on the diameter and blur size of the telescope. These two models were then combined to yield an overall performance benefit-vs-cost model. That model showed that a significant increase in performance could be achieved for photon bucket apertures up to 10-meters in diameter without a large increase in cost, but that going beyond 10-meters caused costs to rise sharply. Accordingly, a 10-meter diameter reception station, consisting of a segmented primary with approximately 1-meter diameter hexagonal segments and an overall blur diameter (in angular space) of 100 μrad was baselined.

Unlike astronomical observatories which only view at night, an optical communications facility must be called on to track spacecraft at day and night, occasionally at relatively small solar exclusion angles. This raised the question of whether or not shielding of the telescope optics from the sun was desired (or necessary). Early designs considered a structure called an integral sunshield. The concept involved a bundle of hexagonal tubes, each "tube" having a cross section the same as the primary segments. This would permit the overall size of the sunshield to be kept small while maintaining a large "tube" length-to-diameter ratio. Concerns surfaced, however about the trapped solar heating and the resulting turbulence (and more significantly thermal distortions) that would result therefrom. At this time, no final decision has been made concerning the sunshield.

Studies have also been performed concerning ground station deployment. Recently, the Ground-Based Advanced Technology Study (GBATS) examined network deployment concepts involving linearly dispersed networks of stations around the world, and compared them to networks of regionally-clustered stations. Comparisons were made on the basis of cost for providing 24-hour spacecraft geometric line-of-sight and enough site diversity to get adequate statistical availability. The study concluded that a network of 6 ground stations, spaced uniformly around the equator (or at reasonably small latitudes above or below) was the most cost-effective arrangement.

Although operational tracking of spacecraft has been, and is expected to continue for some time, from the ground (for cost reasons), space-based reception systems will eventually be used. Accordingly, JPL contracted for two definition studies for a Deep Space Relay Satellite System (11 S1<SS), The study contractors were directed to examine both RF and optical technologies, but both concluded early in the study that RF systems with adequate improvement over the present ground-based systems were not economically viable. As access to space becomes more routine, we can expect serious consideration will be given to orbiting deep-space optical reception stations.

Supporting Developments

Atmospheric Visibility Monitoring Program

The performance of space-to-ground optical communications links depends very strongly on the attenuation effects of the atmosphere, most notably from clouds. 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 depl eyed 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 of validated atmospheric visibility models.

Laser Transmit ters and Narrow-band Filters

Significant work has also been preformed on the development of lasers and narrow-band optical filters. JPL pioneered the development t of the diode-pumped, matched-cavity Nd:YAG laser in the mid 1980's and has expanded that technology to the point where 3.5 Watts of single mode green (second harmonic) and 11 Watts of fundamental (1.06 micron) output have been obtained. Additionally, JPL has sponsored work at the New Mexico State University to demonstrate optical filters that have high throughput (>75%) and extremely narrow bandwidths (< 1 Ghz).

Demonstrations

Finally, along with studies and technology developments, it is often necessary to perform system-level demonstrations. This section describes some of those activities.

GOPEX

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

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The uplink beams in the GOPEX demonstration were intentionally broadened out to accommodate atmospheric beam tilting. However, longer-distance links will require more narrow beams that are pointed much more precisely. Accordingly, a series of uplink transmissions to corner cube reflectors on the Moon was performed, both without and with artificial laser guide star atmospheric compensation. Improvement in the retro-reflected beam intensity was observed using adaptive compensation, although the amount of increase was less than expected. Studies are continuing to determine the reasons.

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