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Laser Telemetry to Increase Astronomical Downlink Capacities

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ABSTRACT. Astronomical space missions currently on the drawing boards anticipate arrays of 10^9 pixels with high sensitivity and dynamic range, as well as short readout times. Telemetry rates (channel capacities) on the order of 100 gigabits per second will be required to transmit to ground the wealth of data these missions will generate. The fiber telecommunications industry has developed most of the basic components required to permit telemetry at near-infrared wavelengths. But a complete system will urgently have to be prepared for use on currently envisioned missions. We describe such a system and enumerate the hurdles that will have to be overcome to make it ready on time.

1. INTRODUCTION

A challenge to astronomical space observatories, today, is the enormous rise in data rates. Increasingly large detector arrays often with many millions of pixels are in common use. These arrays have exhibited progressively higher sensitivities and dynamic ranges that have enabled exquisitely high spectral, spatial, or time resolution. Many space missions now on the drawing boards make use of a tiling of such arrays and could ideally gather data at rates of several gigabits per second (Gbps). This becomes clear on considering that the dynamic range per pixel on many types of arrays covers 5 orders of magnitude. Readout times can be on the order of seconds. The amount of information gathered by a typical 2048 × 2048 element array with 16 bits per pixel and read out once per second can approach 100 Mbps. A tiling of such arrays will be mounted in the focal plane of the *James Webb Space Telescope* (*JWST*), and future missions for optical/ultraviolet astronomy anticipate arrays of 10^9 pixels.

The accumulated information will need to be periodically telemetered to ground, usually in brief intervals, since the limited number of available ground stations have to sequentially interrogate many different spacecraft in significantly different types of orbits in the course of a 24 hr day. A typical requirement for a 10^9 pixel array with a dynamic range of 16 bits per pixel would be a readout every 10 s, corresponding to a data-gathering rate of order 1.6 Gbps. If the on-target duty cycle is ∼2/3 of the available time, and the spacecraft is assigned a data downloading slot of a half-hour every 24 hr, it would need to transmit back to Earth at a rate ∼30 times higher than the on-target data-gathering rate, or at a rate of ∼50 Gbps. In general one needs to count on occasional failures in transmission, which would require downloading 2 days' worth of data at one time if there had been a transmission failure on a previous day. To avoid losses of data due to inadequate downloading capacity, this would require a data downloading rate of 100 Gbps. But current telemetry systems are roughly 2 orders of magnitude too slow to accomplish the task.

Even today, the limitations are clearly apparent. Munari (2001) has pointed out that available telemetry rates will lower the spectral dispersion capabilities of *GAIA*, even though high dispersion would be a decided advantage for obtaining accurate radial velocities. Long-range plans currently under discussion for an optical/ultraviolet successor mission to the *Hubble Space Telescope* are similarly going to be limited by existing telemetry. Arrays of 10^9 pixels foreseen for such a mission are only a modest extrapolation beyond the $16\text{k} \times 16\text{k} = 2.56 \times 10^8$ pixel arrays currently being built for OmegaCAM, the survey camera for the VLT Survey telescope at Paranal (Valentijn, Deul, & Kuijken 2001). Many other examples of instrumental capabilities being thwarted by low telemetry transmission rates could be cited.

To overcome this difficulty, a number of technical problems will need to be solved, requiring the efforts of a wide variety of experts in telecommunications. The recent decadal report of the US National Academy of Sciences has recognized the prob-

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lem (National Research Council 2001, p. 46), but given the importance not only to the astrophysical community, but also to the geophysical, meteorological, climatological, and Earth resource disciplines, substantial resources should be invested to rapidly develop the necessary techniques. Unless a solution to the mounting telemetry problem is soon found, it will become a throttling bottleneck in the decade ahead.

Many observers have placed their hopes on data compression to deal with this communications problem. On currently planned missions the projected data-gathering rates already exceed the transmission rate by 1 or 2 orders of magnitude. But data compression works well only when the registered data has a high signal-to-noise ratio (S/N). For noisy data, compression has only limited advantages. In particular, where observations are marred by varieties of cosmic-ray glitches or other unpredictable sources of noise, data compression tends to work only when substantial portions of the data are discarded. Experience has shown that the losses imposed by noise spikes can be minimized if they can be identified and characterized and their range of influence (memory effect) on detector sensitivity, amplifier gain, and other instrumental parameters clearly defined (Starck et al. 1999). Often, much of the data can then be cleaned and saved. This is the current situation in far-infrared astronomical observations from space, where bulk germanium detectors sustain frequent cosmic-ray hits. There, considerable gains would be possible if all the data were transmitted to ground and then carefully examined and cleaned. A high-speed data link would permit such downloading and processing.

In this paper, we examine the steps required to make a system with a transmission rate of 100 Gbps a reality. Recent advances in the development of near-infrared laser communications suggest that telemetry in the near-infrared provides the greatest promise (Reyes et al. 2002). The European Space Agency (ESA) has just demonstrated near-infrared laser communication between the *SPOT-4* and *Artemis* orbiting satellites (Tolker-Nielsen & Oppenhäuser 2002). The initial tests used experimental data rates of 50 Mbps with an error rate of less than 10^{-9}. Transmission rates a factor of 10^3 higher do not require fundamental technology changes. In addition, attempts to test space-to-ground laser communications with data rates of 1 Gbps are already underway (Kim et al. 2001), and a variety of military projects are also under investigation.[2]

The new feature of our paper is to describe a systems approach that will make laser telemetry a reality at the time that astronomical missions now on the drawing boards, with projected data-gathering rates requiring orders of magnitude more rapid telemetry downlinks, will be coming on-line. The approach we are taking minimizes the substantial costs that will be involved while addressing the critical areas that require immediate attention if such a system is to be ready in time.

Section 2 of this paper describes a technical approach to the telemetry problem. Section 3 goes into some depth on a specific common problem, namely, telemetry transmission from the second Lagrangian point, L2. A short final section lists our conclusions.

2. TECHNICAL APPROACH

The constraint on existing radio-telemetry systems is available bandwidth. Data transmission rates are directly proportional to transmission bandwidth, which never exceeds a small fraction of the carrier frequency, the frequency of the electromagnetic wave that the transmitted data modulates. Telemetry systems based on radio transmission now are reaching toward bandwidths of order 8 GHz, but substantially higher bandwidths are not likely to emerge at radio frequencies because carrier frequencies cannot be significantly increased. At carrier frequencies higher than 300 GHz, atmospheric gases strongly absorb and prevent transmission from space to ground. This is why current international allocations for transmission between Earth and space only range up to 275 GHz.[3] A carrier frequency leap of a factor of a thousand is needed to reach near-infrared frequencies where telluric absorption again becomes low and the atmosphere transmits well.

Fortunately, much of the technology required for near-infrared telemetry has already been developed for fiber telecommunications. Optical fibers currently operate at near-infrared wavelengths in the 800–900 nm (multimode) and the 1250–1650 nm (single-mode) bands. On high mountaintops, the atmosphere transmits with an efficiency of more than 70% in several portions of both these bands.

While much of the emphasis on near-infrared telemetry focuses on the transmitter on board a spacecraft, a functional system also requires sufficient on-board memory, electrical power to enable transmission, a working optical link, and ground receiving stations on a few well-separated mountaintops around the globe to assure telemetry downlinks at different times of day as Earth rotates. These different requirements need to be analyzed.

A data-gathering rate of 1 Gbps accumulates $\sim 10^{14}$ bits of information in the course of a day. Commercially available solid state memories store up to ~128 Gbytes of memory, or up to $\sim 10^{12}$ bits. An increase by a factor of ~200 in memory capacity will, therefore, be needed, roughly corresponding to the memory increase in individual storage units seen over the past 15 years. If this growth rate in available memory is sustained, on-board data storage will not be a significant limitation a decade from now.

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[2] D. M. Pepper 2002, Multi-functional True-Time-Delay Optical Steering System: Steered Agile Beams (http://www.darpa.mil/mto/stab/kickoff/stab_hrl.pdf).

[3] National Telecommunications and Information Administration (NTIA) 2002, Manual of Regulations and Procedures for Federal Radio Frequency Management (the *Red Book*), chap. 4. This manual can be found at http://www.ntia.doc.gov/osmhome/redbook/redbook.html or http://www.ntia.doc.gov/osmhome/redbook/CHP04.pdf (especially pp. 70–91, where both the international and US allocations for the highest frequency channels are listed).

High memory capacity is a crucial component of the laser telemetry system. Without it, the system fails. If one cannot store sufficient data on board to transmit when periodically interrogated from the ground, the high-capacity telemetry equipment will be of little use. A systems approach matching capabilities at each link in the chain is essential.

A potential advantage of near-infrared telemetry systems will be their economy. The energy required to transmit 1 bit of information can drop in proportion to the increase in carrier frequency. Each bit of information requires the transmission of at least one photon, and this carrier photon requires an energy $h\nu$, where h is Planck's constant and ν is the carrier frequency. However, for a transmitter (telescope) of aperture D, the telemetry beam diverges into a diffraction-limited angle $\theta_D \sim \lambda/D = cD/\nu$, where λ is the wavelength of the carrier and c is the speed of light. This means that for increasing carrier frequency the footprint of the telemetry beam on the ground shrinks in proportion to the frequency. Since the area subtended by the footprint is proportional to ν^{-2}, and the energy per carrier photon is proportional to ν, we obtain a net reduction in required energy per transmitted bit proportional to ν. This assumes that the transmitting antenna on the spacecraft and the receiving antenna on the ground are kept constant in size, independent of carrier frequency. With the emergence of large optical telescopes on the ground, this assumption is not far off the mark. Energy efficiency in this, as in all space applications, is a critical factor. Minimized power requirements save cost and lower complexity.

The transmission link presents different problems for different spacecraft orbits. Telemetry from Earth orbit may be constrained by factors quite different from those facing an astronomical observatory at greater distances.

3. TELEMETRY TRANSMISSION FROM L2

In this section we restrict ourselves to just one type of mission of considerable interest to astronomy. Many astronomical spacecraft now are being readied for launch to the Lagrangian point L2, roughly at a distance of 1.5×10^{11} cm in the anti-Sun direction from Earth. There, the combined gravitational pull of the Sun and Earth keep the spacecraft in an orbit with a period of exactly 1 year, in close proximity to Earth.

3.1. On-Board Transmission System

The near-infrared communications link for such a spacecraft will consist of one or more laser diodes transmitting through a telescope serving as an antenna. Techniques for constructing light-weight, high-quality optical telescopes with an aperture of 1 m have rapidly advanced in recent years, and such telescopes can serve as transmitting antennas to produce the required, well-collimated telemetry laser beam. Direct sunlight must be rejected through a system of baffles, narrowband filters operating at the laser's transmission frequency, and an optical safety shutter, in order to protect the transmitting laser at the telescope's focal point.

A 1 m telescope transmitting at a wavelength of 1550 nm, i.e., a carrier frequency of $\sim 2 \times 10^{14}$ Hz, produces a diffraction-limited beam diverging at 1/3 of an arcsecond. This produces a 3 km sized footprint on the ground. With a 10 m receiving telescope on the ground, roughly 1 photon in 10^5 will be gathered. While this may appear extremely inefficient, it is vastly superior to radio telemetry, which, at a frequency of 100 GHz, produces a footprint roughly the size of the whole Earth and gathers only 1 photon in 4×10^{10} with a 30 m radio antenna. In principle, the net gain of the 1550 nm system could be a factor of 200 in energy efficiency.

The footprint for near-infrared transmission, must be kept well centered on the ground receiving station. This requires the transmitting telescope to point at the receiving station with a pointing accuracy of $0\farcs1$—comparable to the pointing capability of the *Hubble Space Telescope*, whose technology is by now 15 years old. An intermittently transmitted laser beam sent toward the spacecraft from the receiving station on the ground acts as a reference point source to enable the spacecraft to accurately point its telemetry stream at the receiving station. Some computerized "leading" will be required to take into account Earth's rotation during the several second transmission times required to reach a spacecraft at L2. Because sunlight will heat up the telescope, adaptive optics techniques will be needed to maintain both good pointing and compensation for thermal effects. Proposals for phased arrays to replace mechanical beam steering have recently been announced (see footnote 2), but these will require mechanical tolerance stabilities similar to those of a transmitting telescope. Moreover, if phased beam steering over a significant angular sweep is contemplated, wavelength dispersion will severely limit the telemetry bandwidth that can be centered on the ground receiving station.

Currently, near-infrared lasers are limited to an optical transmission power of ~ 5 mW, or $\sim 3 \times 10^{16}$ photons s^{-1} at near-infrared wavelengths. However, because of the sizeable footprint at the receiver, small losses due to atmospheric absorption, and receiver system inefficiencies, only one photon in $\sim 2 \times 10^5$, or 1.5×10^{11} photons s^{-1}, will reach the receiver focal plane. For a transmission rate of 100 Gbps this would yield only 1.5 photons per transmitted bit of information.

It is useful to think of a near-infrared telemetry system as a state-of-the-art fiber transmission system that has been cut at the transmitter and receiver ends. The transmitter is on board the spacecraft, and the receiver is a telescope on a mountaintop. Mountaintop sites with up to 350 cloudless days a year exist. The effects of turbulence normally increase the nighttime image size of a point source to an angular diameter of order $0\farcs6$. Using adaptive optics, the image size can be decreased to less than $0\farcs15$ (Close et al. 2002a, 2000b). However, it may be useful to defocus the beam to about $0\farcs15$ to mitigate the effects of beam wander over the entrance aperture of the receiving fiber. The 0.″15 spot size for a focal ratio ∼f/4 beam, matched to the acceptance angle of a fiber, is on the order of 30 μm in diameter, whereas the *mode field* diameter, i.e., the diameter of the transmitting portion of the fiber, is ∼10 μm. This leads to a further loss of transmitted photons by another order of magnitude, for a total loss of order 2×10^6. This loss would reduce the actual yield to ∼0.15 photons per transmitted bit of information arriving at the receiver.

Two techniques are available to increase this yield. The laser diode output may be amplified by erbium-doped fiber amplifiers (EDFA) or Raman amplifiers, now extensively used in the fiber telecommunications industry (Becker, Olson, & Simpson 1999). For optimum performance at the highest transmission speeds, external modulators are used to modulate the lasers to avoid chirp, a condition in which the drive current changes the refractive index of the material of the laser cavity resulting in a shift of the laser wavelength during modulation. Stable laser wavelengths are achieved using distributed feedback lasers (DFB) in which a grating is incorporated within the laser diode structure. The laser output signals can be optically amplified in an EDFA or a Raman amplifier before entering the fiber leading to the transmitter. This fiber emits a Gaussian beam from a 10 μm diameter beam waist, which is fed into the transmitting telescope. We note, in passing, that military needs for more powerful lasers may eventually provide additional means for increasing laser power.[4]

The bandwidth required for high-speed laser telemetry can be gained through dense wavelength-division multiplexing (DWDM), a technique that currently permits transmission of up to terabits per second along optical fibers (Kartopoulos 2000). Today, DWDM allows 80 lasers each driven at 10 Gbps to be multiplexed at a set of carrier frequencies centered on 1550 nm and separated by just 0.4 nm or 50 GHz. For 100 Gbps telemetry, 40 laser diodes, each transmitting over a bandwidth of only 2.5 Gbps and multiplexed on board the spacecraft with a DWDM system, will be able to transmit ∼25 photons per bit at an effective data rate of 100 Gbps to the ground receiving station with the aid of an EDFA. The EDFA serves to amplify the signals, to overcome any losses in the DWDM and transmitter systems, and to provide a link margin of several decibels (dB). Reliable operation on board is assured through the use of redundant laser diodes.

3.2. The Mountaintop Receiving Station

The mountaintop receiving telescope images the incoming beam into a single-mode fiber, amplifies it by means of a further EDFA, demultiplexes the DWDM signals using gratings, interference filters, or other technology, and images the dispersed radiation onto a series of 40 commercially available high-speed photodetectors. The signal received by each detector is then amplified once more and transmitted to a processing center at a convenient location.

We can readily see that ∼25 photons per bit received at the ground station guarantee transmission with a good signal-to-noise ratio: Any photon amplifier can be thought of as a producer of stimulated emission in response to incident photons. The probability for a single incident photon to induce an emission is proportional to the Einstein coefficient $B(\nu)$. The probability for the amplifier to spontaneously emit an identical photon, however, is given by the Einstein coefficient $A(\nu)$ for a single transmission mode. The relation between the two coefficients is usually written as $A(\nu) = (8\pi\nu^2/c^2)B(\nu)$, where $8\pi\nu^2/c^2$ is the number of possible modes in an isotropic system. For a single mode, however, there are only two polarization states, for each frequency, and $A(\nu) = 2B(\nu)$. As long as more than two photons are incident on the amplifier, per second, per unit frequency interval, $S/N > 1$ can be achieved. For a bit rate equal to the bandwidth, the minimum number of photons s^{-1} required to transmit a bit corresponding to a digit 1 is then $2\Delta\nu$; for a transmitted digit 0, it is zero. So, to transmit $\Delta\nu$ bits per second, the amplifier has to receive at least $\Delta\nu$ photons s^{-1} to achieve $S/N = 1$. For $S/N = 25$ over a bandwidth $\Delta\nu$ we require an incident photon stream of $\sim 25\Delta\nu$. For a total transmission loss rate of order 2×10^6 the photon emission rate at the spacecraft must then be $5 \times 10^7 \Delta\nu$ photons s^{-1}. If the transmission rate is to be 100 Gbps, the bank of 40 lasers needs to emit 5×10^{18} photons s^{-1}, or ∼640 mW, equivalent to ∼16 mW per transmitting laser beam amplified by an EDFA.

At the receiving station, the arriving 25 photons per bit produce ∼20 electrons per bit for a quantum efficiency of 0.8. This leads to an equivalent amplifier input current of 320 nanoamp per mode. The equivalent noise input at the receiver from 2.5×10^{12} photons s^{-1} at 1550 nm is $\sim 3.2 \times 10^{-7}$ W.

Alternative receiver systems can also be considered. A detailed analysis of a pulse position modulated (PPM) laser telemetry system and its ground receiver design has recently been carried out by Biswas et al. (2002) with a single 3 mm diameter near-infrared–enhanced silicon avalanche photodiode and transmission rates only slightly lower than those discussed here. The advantage of such a detector is that it reduces losses incurred in coupling the incoming beam directly into a single-mode fiber. Such a system, however, has to dispense with the use of an EDFA and its associated gain. A number of different detection techniques therefore exist and will need to be investigated to determine an optimum choice.

4. CONCLUSIONS

Today, most of the individual components for near-infrared laser telemetry exist and have been demonstrated to work. Many of them have become available through the efforts of the optical fiber communications industry. Components not yet

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[4] DARPA 2001, Defense Advanced Research Projects Agency Presolicitation Notice, http://www.darpa.mil/baa/baa02-02.htm.

available should become a reality in the decade ahead. Work toward a near-infrared telemetry system, therefore, carries little risk and will rapidly pay for itself in the efficiency with which data will be gathered and transmitted not only in planetary exploration and astrophysics, but also in meteorology, climatological observations, oceanography, and geophysical studies.

A new feature of the system we describe is the use of dense wavelength division multiplexing to provide laser communications from space with sufficient bandwidth to meet currently envisioned needs in the decade ahead. This is an urgent problem. The telemetry chain we describe is, to our knowledge, the first proposed end-to-end system that can be ready in time for the armada of ambitious space missions now planned for launch in the decade ahead.

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