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) of the order of 100 Gbps 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 tools required to permit telemetry at near-infrared wavelengths. We describe such a system, and enumerate the hurdles that will have to be overcome to make it a reality.

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 five orders of magnitude. Readout times can be of the order of seconds. The amount of information gathered by a typical 2048 by 2048 element array with 16 bits per pixel and readout once per second can approach 100 Mbps. A tiling of such arrays will be mounted in the focal plane of the Next Generation Space Telescope (NGST), 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-hour day. These short transmission sessions would require data downloading rates another two orders of magnitude faster, particularly since transmission rate reserves are needed in case the ground stations become inaccessible for a day or two and several days' worth of data has to be downloaded at one time. This suggests the need for telemetry systems capable of channel capacities, or transmitting rates, of the order of 100 Gbps. But current telemetry systems are orders of magnitude too slow to accomplish the task.

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 U. S. National Academy of Sciences has recognized the problem (National Research Council, 2001), 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 one or two 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, 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 letter, we propose to 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 (Mecherie, 2001). The European Space Agency (ESA) has recently demonstrated near-infrared laser communication between the SPOT-4 and Artemis orbiting satellites (European Space Agency, 2001). 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).

Section 2 of this letter 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. A 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 (National Telecommunications and Information Administration, 2002). A carrier frequency leap of a factor of a thousand is needed to reach near-infrared frequencies where telluric absorption is low.

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. At high mountain tops, the atmosphere transmits with an efficiency $> 70\%$ in several portions of both these bands.

While much of the emphasis on near-infrared telemetry focuses on the transmitter onboard a spacecraft, a functional system also requires sufficient onboard memory, electrical power to enable transmission, a working optical link, and ground receiving stations on a few well-separated mountain tops around the globe to assure telemetry downlinks at different times of day as the 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 GB of memory, or up to $\sim 6 \times 10^{11}$ 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, onboard data storage will not be a significant limitation a decade from now.

A potential advantage of near-infrared telemetry systems will be their economy. The energy required to transmit one 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.

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 one year, in close proximity to Earth.

3.1. Onboard 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 meter 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, narrow-band 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-meter telescope transmitting 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 arc second. This produces a 3 km sized footprint on the ground. With a 10-meter receiving telescope on the ground, roughly one 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-meter 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 0.1 seconds of arc – 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 the 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.

Currently, near-infrared lasers are limited to an optical transmission power of ~ 5 milliwatt, or $\sim 3 \times 10^{16}$ photons per second 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 per second, 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. 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 0.6 arc seconds. Using adaptive optics, the image size can be decreased to less than 0.15 arc seconds (Close et al., 2002a, 2000b). However, it may be useful to defocus the beam to about 0.15 arc seconds to mitigate the effects of beam wander over the entrance aperture of the receiving fiber. The 0.15 arc second spot size for a focal ratio f/4 beam, matched to the acceptance angle of a fiber, is of the order of 30μm in diameter, whereas the *mode field* diameter, i.e. the diameter of the transmitting portion of the fiber, is $\sim 10\mu$m. 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 et al, 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 $\sim 10\,\mu$m diameter diffraction limited Gaussian beam, which is fed into the transmitting telescope.

Alternatively, power 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 as many as 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 onboard the spacecraft with a DWDM system will be able to transmit ~ 25 photons per bit 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 onboard is assured through the use of redundant laser diodes.

3.2. The Mountain-Top Receiving Station

The mountaintop receiving telescope amplifies the incoming beam by means of a further EDFA, demultiplexes the DWDM signals using a grating, 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 guarantees 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, a signal-to-noise ratio $S/N > 1$ can be achieved. For a bit rate equal to the bandwidth, the minimum number of photons per second 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 per second 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 per second. If the transmission rate is to be 100Gbps, the bank of 40 lasers needs to emit 5×10^{18} photons per second, 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 due to 2.5×10^{12} photons per second at 1550 nm is $\sim 3.2 \times 10^{-7}$ Watt (cf Becker et al., 1999, Figure 8.2).

The problems raised by atmospheric turbulence can also be overcome in other ways. InGaAs receivers with bandwidths of 2.5 Gbps and typical active diameters of 55μm are now commercially available. The large active areas of these receivers and their better match to faster (lower focal-ratio) optical systems make direct detection possible. In principle, the entire incoming signal can be imaged onto a single detector even in the presence of atmospheric turbulence producing image sizes up to ~ 0.5 arc seconds. In practice a grating or other device first splits a 40-channel 100 Gbps DWDM signal into 40 separate 2.5 Gbps channels, each imaged onto a separate detector. While the loss of photons between the spacecraft and receiving detector can be reduced by an order of magnitude in this way, commercially available InGaAs detectors have sensitivities $\sim$ 19dB poorer than an ideal quantum detector. Use of such detectors would thus require raising spacecraft transmission power roughly to a total of ~ 5 Watt, achievable using one or more EDFAs in the spacecraft transmitter. Cooled detectors with higher sensitivities would considerably lower this power requirement.

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 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.

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