Optical Tracking Telemetry and Commanding (TT&C) For Small Satellites

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Abstract

This paper presents information on the current state of technology and potential subsystem and operational concepts to allow the use of low power optical communication systems to perform tracking, telemetry and commanding (TT&C) for small satellites.

The mantra of 'smaller, faster, better (& cheaper)' has been realized, at least partially, for many aspects of small satellite design, construction and operations. Most small spacecraft systems have become smaller, lighter and more power efficient while offering greater performance. Unfortunately, one area that has not followed this general trend is TT&C. In many ways, this situation takes on greater significance due to the successes in other areas relating to processors, memory and sensor capability. Technology improvements in these areas have increased the capabilities of small satellites to collect, process and store data on-board the satellite to such a point that the ability of the spacecraft to generate data has outpaced its ability to communicate it to the ground. One approach to resolving this situation is to make use of optical communications technology for TT&C.

Introduction

This paper provides an overview of the current activities in optical systems relating to tracking, telemetry and commanding for application to small satellites in low and medium earth orbits.

The first section provides a description of the current trends in small satellite performance effecting the needs for communications and TT&C. It addresses how current practices for TT&C are lagging behind other areas of spacecraft improvement and may be the limiting factor in performance of future missions.

The second section provides a generic description of optical systems for communications and how their performance compares with more conventional RF systems for tracking, telemetry and commanding.

The third section provides a summary of recent developments and current activities with application to optical satellite communications and TT&C.

The fourth section provides a description of a conceptual system for low cost, higher performance TT&C using optical approaches.

Small Satellite Performance Trends

While there has been some debate over the merits of "Smaller, Better, Faster", there is little argument about the fact that the ability of small satellites to collect and process data has increased significantly in recent years, largely driven by increasing performance of data storage and processor technology. Since Moore's Law[*] is expected to hold true for the next decade, increases in performance in electronics based spacecraft system can also be expected to continue. Figure 1 shows the Semiconductor Industry Association projections on the increase in technology performance expected for the next decade.[1]

One significant trend to note is the increases in the density of memory. This directly translates to increases in onboard data storage. While the spacecraft recorder technology typically lags the memory technology by 2 years, the storage capabilities can be expected to double every two years with no increase in size or power consumption.[2]

TELEMETRY

For the purposes of this paper, telemetry includes payload downlink data in addition to spacecraft state-of-health (SOH) data. The payload data will be the driving requirement, for the reasons stated above and the expectation that downlinked SOH data needs are not expected to increase by significant amounts. Due to increased processing capability to support autonomous operations, the amount of SOH data may actual reduce. However, since the SOH data volumes are so small compared with payload data volumes, this extra capacity, if available, will not offset the increased needs for the payload data. Increased processing capability may also allow for better real-time data compression, however, it is the opinion of the author(s) that this increased capacity will also not be sufficient to offset the increased data volume.

Given current and projected trends in spacecraft communications, it becomes apparent that the spacecraft downlink will create a data bottleneck that

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[*] Moore's Law was authored by Gordon Moore, one of the founders of Intel, and it states that the density of transistors for integrated circuits continues to double every 18 months.

will ultimately limit the performance of the satellite, unless the downlink rate can be increased commensurate with the increase in the data generation and storage rates.

Unfortunately, the current method for transmitting downlink data, using RF communications, cannot be increased enough to support the future needs. The capacity of a channel, such as a RF downlink, to transmit information is given by Shannon's theorem:

$$C = W \log_2 \left(1 + \frac{S}{N} \right)$$ Eq. 1

where

C is the channel capacity in bits per second
W is the channel bandwidth
S is the signal power
N is the noise power in the channel (including receiver generated noise)

This equation suggests the approaches to increasing the downlink channel capacity are to 1) increase the transmission bandwidth, 2) increase the signal power, 3) reduce the channel noise, 4) combinations of the above.

Unfortunately, these approaches have limitations. The available bandwidth is dictated by a number of issues including international frequency assignments and spectrum management concerns.

The signal power can be increased through increased transmitter power and/or increased transmit antenna gain. Unfortunately, the ability to increase both these parameters on small satellites are limited and more so for nano- and picosats. Increased transmitter power requires more power allocated to communications at the expense of other onboard systems or by increasing power generation capability on the satellite, with the need for additional solar cells, increasing mass, cost and potentially creating more challenging thermal design requirements. Antenna gain is a factor of the area and the frequency (or wavelength). Increasing antenna area will also be limited by the size and mass constraints.

This situation becomes more complicated when considering such applications as nanosats and picosats, with extremely limited size and power generation capacities.

COMMANDING

For the purposes of this paper, commanding includes all data uplink requirements for the spacecraft, with the exception of communication

satellite traffic. Current systems offer commanding rates on the order of kilobits/sec.

For the most part, the trends for commanding do not appear to be significant drivers. This is partially due to pre-loaded commanding sequences and greater reliance on autonomous operations.

However, higher rate commanding would provide advantages in specific circumstances. In cases with large uploads, such as software patches, higher uplink rates would minimize the time required and the resource loading on TT&C networks. Covert or burst commanding capabilities may also be desireable for a number of sensitive industrial imaging and government managed spacecraft.

TRACKING

Tracking is the process of determining (and maintaining) knowledge of the position of the satellite. The need for increased accuracy or precision of spacecraft position knowledge will be driven by several trends. The first is the increased performance of sensors. This, in turn, will drive the need for geo-location accuracy improvements. The second trend that may drive requirements to increasing levels of performance is the move to clusters of satellites in proximity. Precise knowledge of absolute and relative position will be essential to maintain these formations.[3]

While GPS technology may address most of the initial needs in this area, this approach will not achieve the necessary accuracy for all applications, at a reasonable cost. Significant improvements beyond the current 50 to 100m standard position accuracy and the 1 to 20 m precision position accuracy (authorized users only) will not be achievable without modifications to the GPS signal.[4]

Another consideration is that GPS is of limited use by spacecraft in orbits beyond the GPS constellation.

Optical Systems Technology

The use of optical systems for spacecraft TT&C may provide several ways of increasing overall system performance. The attractive characteristics of optical communications over RF technology are:

- Antenna Gain and Directionality - These antenna characteristics are a function of the ratio between the wavelength and the antenna aperture size. Since optical wavelengths are more than 3 orders of magnitude shorter than RF, this corresponds to 60 dB of greater gain for a given aperture size.
- Bandwidth - The information bandwidth of a signal is a fraction of the carrier frequency

(typically 1/10th for RF systems). Since optical signals range for this application range from 194 THz (1550 nm) to 563 THz (532 nm), this allows many GHz of information bandwidth to be carried on optical carriers.

- Lack of Regulatory Constraints - Optical frequencies are not regulated by the ITU (or anyone else). This eliminates the need for coordination, with regulatory agencies.
- Minimization of Interference - The high directionality of optical signal reduces interference, since an interference source needs to be in the LOS to be detectable.
- Components - Virtually all the required components, such as high efficiency lasers, detectors and modulators are available as COTS.

The use of optical technology for communications is well established in terrestrial fiber optic systems routinely carrying data at rates in excess of 2.48 Gbps. The idea of using optical systems for spacecraft communications is not new. The idea of using optical crosslinks between communications satellites has been around for many years. NASA JPL has also explored the use of optical laser communications for supporting deep space missions.[5,6] However, the mission requirements, available funding and infrastructure to support deep space missions offers little to the support of earth orbiting spacecraft in general. This is primarily due to the relatively low data rates (under 500 kbps and under 100 kbps in most cases) acceptable to the deep space community, since this provides orders of magnitude increase in performance over RF systems.

Optical approaches do have considerations and constraints that need to be considered or addressed in practical systems. These include:

- Eyesafety - The human eye is subject to damage from optical energy at visible and near infrared wavelengths.
- Pointing, Acquisition and Tracking (PAT) - The high directionality of the optical system requires higher performance PAT than RF systems. Platform jitter caused by other spacecraft components must also be mitigated.
- Weather and Other Atmospheric Effects - The optical signals can be greatly attenuated by atmospheric and weather effects, such as clouds, precipitation and scintillation effects.

Eyesafety can be addressed by either using inherently eyesafe wavelengths (greater than 1300 nm) or efforts must be taken to limit the optical

power density to a value below the damage threshold by spreading the signal power (defocusing).

PAT has advanced to levels of performance that now make laser communications systems feasible. Passive and active platform vibration dampening has improved dramatically due to the technology push for large optics in space. This technology is transferable to small platforms. High speed electronics and fast steering mirrors have allowed high precision pointing and line of sight stabilization to remove jitter.

Weather effects can be mitigated by careful site selection and/or geographic site diversity using multiple ground sites. Weather, especially cloud coverage, is a local effect. Experiments by JPL have determined that 5 sites separated by 100 miles each will provide over 99% probability of cloud free line-of-sight to support optical communications activities. It should also be noted that Ka and higher frequency RF systems also considered for this application also suffer from atmospheric and weather degradation.

Spacecraft Optical Systems Status

SPACECRAFT TERMINALS

Several spacecraft terminal designs that could be used to support TT&C currently exist. A significant driver for the development of the more advanced recent designs is the prospect of LEO communication systems, such as Teledesic/Celestri, which include laser communications crosslinks as part of the baseline design. Since this represents a large potential market with a need for hundreds to thousands of terminals in a complete constellation, much effort has been made for developing designs that will result in low cost terminals when made in production quantities. This creates an opportunity for low cost, high data rate systems that can be applied to small satellite TT&C for a cost on par with current spacecraft transponders.

Some of the existing terminal designs either flying or waiting to fly are:

- Semiconductor Intersatellite Link EXperiment (SILEX)
- Space Technology Research Vehicle 2 (STRV-2) Terminal
- Ball/LCI Optical InterSatellite Link (OISL) Terminal

SILEX is a European experiment consisting of a LEO and a GEO terminal. The LEO terminal, PASTEL, is hosted on Spot IV. The GEO terminal, OPALE, will be hosted on ARTEMIS (launch in 2000).. This system will provide 50 Mbps LEO to GEO and 2 Mbps GEO to LEO using 819 nm and 847 nm, respectively. Both terminals are configured with 25 cm apertures. The lasers are direct intensity modulated with 120 mW output power to cover a nominal distance of 45000 km. The terminals are also equipped with 700 mW beacon laser.[7]

STRV-2 is an experimental package built by JPL for flight on the DoD Space Test Program small satellite TSX-5. The laser terminal was built by AstroTerra under contract to BMDO. The terminal is 31.5 lbs, consumes ~56 W in standby and 95 W in operations. Data rates up to 1.24 Gbps over distances of 1600 km (sat-to-sat) and 1700 km (sat to gnd - 16" gnd terminal). The transceiver uses a 5.4" primary aperture and weighs 19.5 lbs, the mount is 1.4 lbs, electronics box is 10.6 lbs. The STRV-2 ground terminal concept is to use a 16" commercial telescope, such as a Meade or Celestron for the receiver and 3 10" telescopes operated in parallel for the transmitter. This approach is used to spread the transmit signal over the aperture area to eyesafe levels and overcome atmospheric scintillation.[8]

AstroTerra has a second design for a higher performance transceiver. This design has an 8" x 8" x 12" envelope, weighs 20 lbs and is expected to consume 50W under full operations. This terminal is designed for 2.48 Gbps at a range of 5000 km. It can support either near-IR diode lasers or Er fiber amplifiers at 1550 nm. In quantity, they project a cost of $300K per unit (100 quantity).[8]

Ball Aerospace has several families of terminal designs. Size, weight and power are scaleable according to spacecraft and communications constraints. Currently, Ball is in a CRDA with the Air Force Research Lab in Albuquerque, NM to fly the OISL terminal design in conjunction with the DoD Space Test Program for technology demonstration purposes.

SATELLITE LASER RANGING

The most significant development in the area of SLR systems is the development of the SLR2000. The SLR2000 is a NASA/GSFC program to develop an inexpensive, full automated, eyesafe satellite ranging system. In this context, inexpensive implies a component cost of $300K, with a fully assembled and tested operational system, including pad, structure, etc. for $500K (in quantity 8). The SLR2000 is intended to provide autonomous, unmanned laser satellite ranging with an expected single shot range precision of approx. 1 centimeter and a normal point precision of better than 3 mm. The system uses a 532 nm signal (frequency doubled Nd:YAG). It includes a 50 cm aperture and is daylight operable for satellites up to GPS altitude.[9]

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MODULATING RETRO-REFLECTORS

A retro-reflector, often referred to as a corner-cube, is an optical device that redirects an incoming signal back along the direction of incidence. The addition of a mechanism that shutters the aperture of the retro-reflector creates a device that can be used to modulate the signal, as shown in Figure 2. The state of the art of modulating retro-reflectors has progressed considerably over the last few years. The advent of ferro-electric liquid crystals (FLCs) and the technology to produce Micro-Electro-Mechanical Systems (MEMS) make new electro-optical systems available. The most significant development has been the increase in the switching speeds that now allow data to be sent at tens of kilohertz up to multi-megahertz with very low power consumption. The technologies used for these devices are:

- Ferro-electric liquid crystal (FLC) - Switches the polarization by reversing the polarity of the bias voltage.
- Multiple Quantum Well Device (MQW) - Switches resonance to pass or reject optical beam by electro-absorption.
- Atomic Absorption Cell (AAC) - Quantum Electronic filter.
- Frustrated Total Internal Reflection (FTIR) - Passes or reflects on one side of solid corner cube surface
- MEMS Spoiled Corner Cube - Diffuse or specular surface reflection on one surface of retroreflector.
- Switchable Gratings (PLZT) - Uses piezo-electric transducers to momentarily create diffracting surface on one surface of retroreflector.

The current activities in this area are summarized in Table 1. The MQW approach developed at NRL appears to be the most promising due to its low power requirements and higher data rates.[10] This technology has been ranked by the DoD Space Experiments Review Board (SERB) and may be flown by the Space Test Program within the next few years. Other technologies may not be suitable for long term exposure to space environments. Liquid crystal technology is sensitive to ultraviolet and gamma radiation. However, this technology may still suitable for short term and/or low altitude applications.

Conceptual Optical System for TT&C

This section presents several ideas for consideration for using optical systems for spacecraft TT&C.

TELEMETRY

For small satellites, a laser terminal, such as the one used in the STRV-2 and its AstroTerra follow-on can provide a means of transmitting data at rate up to and beyond 155 Mbps from space to ground. Since the spacecraft is unlikely to need full-duplex communications at these rates, reduction in size, power, mass and cost should be achievable with a modification to provide for a transmit-only design.

For LEO satellites, this approach is compatible for use with ground terminals with aperture sizes on the order of 10 to 16 inches. For higher altitudes, larger apertures and/or higher power laser sources will be required.

For nanosats and picosats, with lower expected data rates, a modulating retro-reflector may provide a highly effective means of supporting communications, with either a ground-based terminal or even another spacecraft equipped with a laser transmitter and appropriate detector technology. Since the carrier signal is transmitted to the spacecraft, it allows for communications without the need to mount a transmitter, with its large power draw, on the spacecraft bus. The ground terminal need to support this application is consistent with a system intended for satellite laser ranging. A side-benefit of this approach is that the return signal can also be used for laser ranging while simultaneously supporting communications.

TRACKING

There are both passive and active modes of operations for supporting tracking. The passive mode is to operate using conventional satellite laser ranging techniques. The performance of the SLR2000 is beyond the needs for most satellite TT&C applications. The authors believe that a lower performance system, (e.g., < 1 meter), which still exceeds the capabilities of RF ranging and tracking systems and on-board GPS will be achievable at a fraction of the cost of the SLR2000.

The active modes use a laser transmitter on board the satellite. The transmitter can be keyed when a signal is received at the satellite or based on synchronized timing, with the time of flight used to determine the range. Since each signal only makes a one-way trip rather than the 2-way trip required for

the passive ranging, the improved signal strength allows for higher accuracy in less time.

COMMANDING

Since commanding requires a lower data rate, it is practical to combine the laser ranging capability with the ability to transmit commands using a simplified laser transmitter. For satellites equipped with a laser terminal, a simplified receiver can be used sharing an aperture with the transmitter. However, a detector circuit mounted on the spacecraft without the need for additional optics could suffice for low data rate reception. This approach could be considered for any satellite as a back-up to RF commanding.

GROUND TERMINAL NETWORKS

The ground terminal to support optical TT&C is based on amateur astronomy equipment, including Meade and Celestron telescope and fiber coupled CCD imagers also used by the amateur and professional astronomy community. The opto-electronics used for lasers, modulators and detectors is also available as off-the-shelf technology courtesy of the terrestrial fiber communication industry. A higher performance mounting system with rapid slew and settle will be required. While not used in amateur astronomy, such mounts are commercially available and are used in other applications, such as lidar.

The development and use of remote controlled, small telescope installations connected via the Internet are also becoming widespread in the astronomy community. This can be used as an operational model for a network of low-cost, remotely controlled, geographically diverse optical TT&C terminals. Such a system is expected to be cost competitive with a conventional RF TT&C system, with added benefits of higher data rates and the prospect of additional contacts under clear sky conditions.

Acknowledgements

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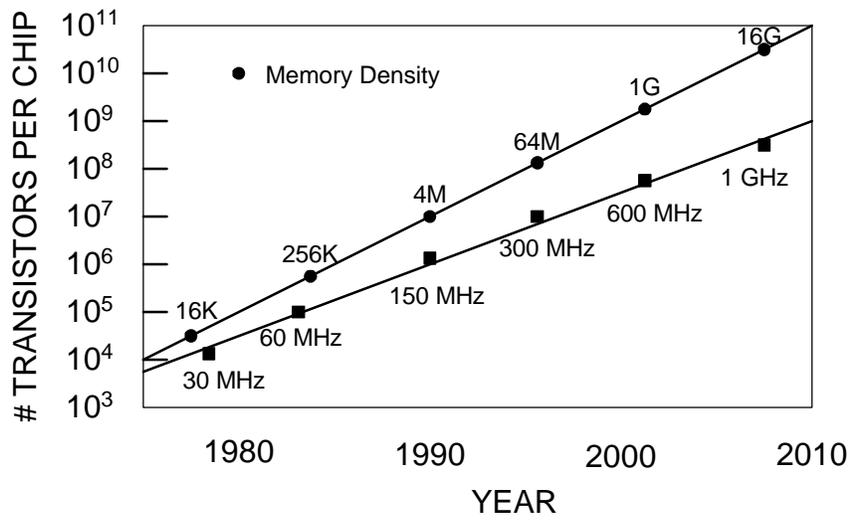
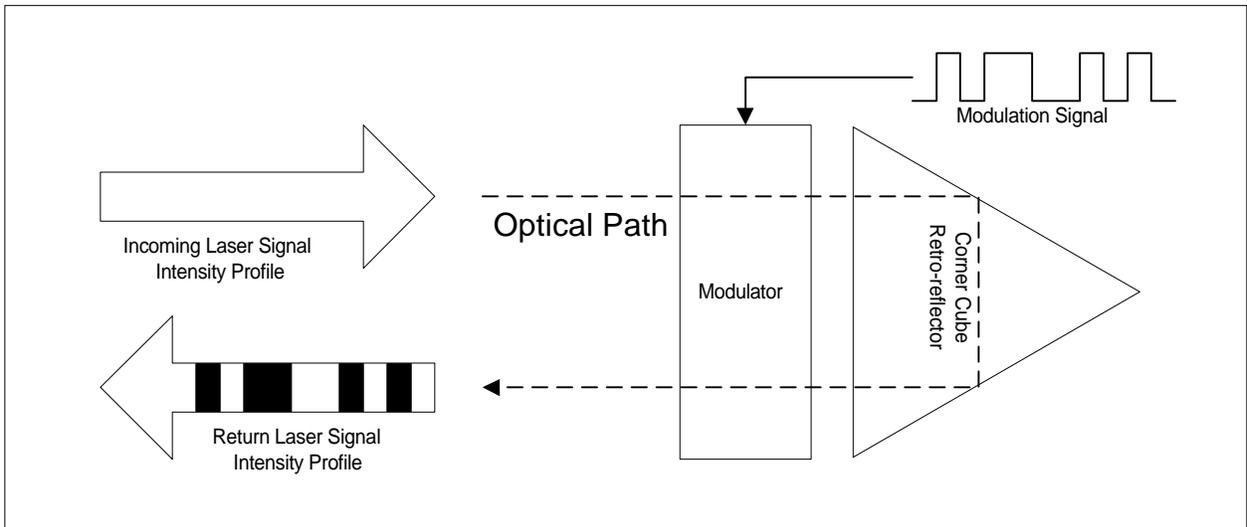**Figure 1: DRAM and LOGIC Density as a Function of Time**

Figure 2: Generic Modulating Retro-Reflector Example

Table 1: Modulating Retro-Reflector Current State of the Art (as of 7/99)

Device	Researcher	Clear Aperture Size	Voltage/Power	Bandwidth
FLC	D. Mansell (Logicon RDA)	5 cm	± 20 V/ 0.5 W	50 kHz
FLC	C. Swenson (Utah State)	5 cm	± 5 V	20 kHz
MQW	C. Gilbreath (NRL)	0.5 cm	5-20 V/ 50-150 mW	< 9 MHz
AAC	J. Thomson (Mission Research)	1 cm	± 5 V	200 kHz
FTIR	B. Galagan (Former Soviet Union)	2 cm	150 V	200 Hz
MEMS	M Oren (Foster Miller)	TBD	TBD	1 MHz (goal)
PLZT	H. Jiang (NZ Technologies)	0.4 cm	75 V/ 3 W	100 kHz