A LASER DOWNLINK FOR SMALL SATELLITES USING AN OPTICALLY MODULATING RETROREFLECTOR

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Abstract

This paper presents an earth-satellite-earth laser downlink system which is compact, simple, and low-power enough to be considered for use on very small satellites. Presented here is the design, feasibility study, and results from preliminary "proof of concept" testing of the critical components.

I. Introduction

For many small satellite applications it would be desirable to have a downlink system which is extremely low-power and compact. In addition, there exist possible "fly-along" scenarios where scientific instrumentation would be allowed on larger satellites which are primarily dedicated to other uses, ie. plasma probes flying on a low orbit communication satellite. For this type of mission the additional requirements would include non-interference with the host satellite, and most importantly non-consumption of the host's downlink bandwidth.

It was with this sort of mission in mind that we have performed this design study for a laser communication system tailored to these unique specifications. This system will keep the vast majority of the space, weight and power required for a satellite communications system off the spacecraft by using a ground laser and a spacecraft mounted retroreflector/optical modulator (See Figure 1). The

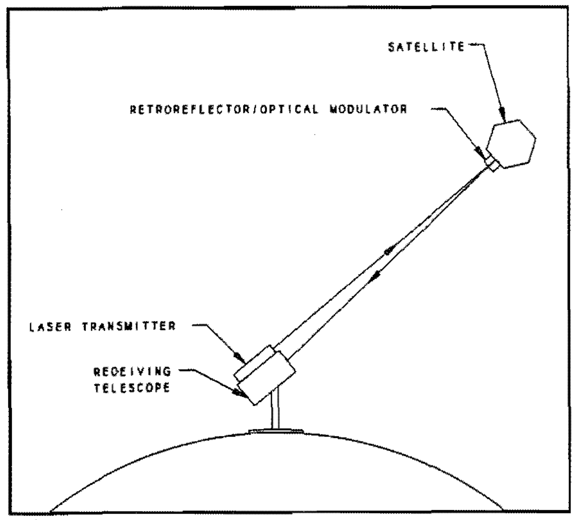

Figure 1

optical modulator is a high speed ferroelectric liquid crystal (FLC) device which acts as a controllable light valve. Some limited uplink capabilities will be allowed through modulation of the ground-to-satellite beam, which will be received by small silicon detectors on the retroreflector assembly. The system will be able to be entirely isolated from the host spacecraft, and require none of the host's radio frequency downlink bandwidth.

The complete system will also include a buffer memory which will hold enough data for several downlink passes, control circuitry which will decode the uplink commands and driver circuitry which will modulate the retroreflector

Table 1
System Specifications

Weight < 3 kg
Size < 15 cm x 40 cm diam
Power < 6 watts
Downlink
Rate = 50 Khz
Capacity = 10-20 Mbits/day
Photons/bit = $3.7x10^3$
Transmitter duty = 45%

assembly with the data. Preliminary testing of the FLC optical modulator has shown that 50 Kbaud data rates are feasible, which for satellites in 250 to 500 km orbits, with orbital inclinations near the latitude of the ground station, are expected to yield a total downlink capability of 10 to 20 Megabits per day. Other, faster FLC devices are being designed, which could increase the data rate by a factor of approximately 5.

II. System Overview

Table 1 gives the proposed general specifications for this system.

Data will be sent in packets of 150 to 300 bits per packet depending on the satellite's range. This is necessary in order to allow the transmitter to be pulsed, avoiding the effects of atmospheric backscatter. Once the tracking station has locked onto the satellite, the transmitted beam will be modulated with a begin transmission/packet length command. When the control system decodes this command, it will modulate the appropriate data packet on those retroreflector/optical modulator assemblies which received this command. The transmitted beam pulse will only be long enough to allow this single packet to be sent. The timing will be chosen such that the atmospheric backscatter background due to the interaction of the transmitted beam and the atmospheric aerosols will have ceased before the return beam is received.

Figure 2 gives a block diagram for this system.

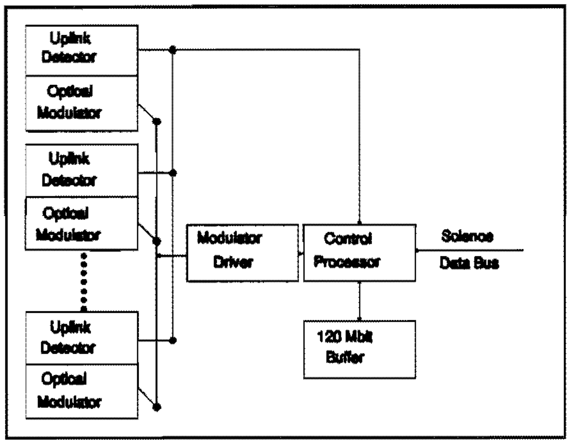

Figure 2

The individual components are:

Satellite mounted retroreflector\optical modulator & detector

Figure 3 is a conceptual drawing of the retroreflector/ optical modulator assembly, made up of seven modulator/ detector sub-assemblies. The retroreflector is a standard hollow device, constructed of three flat mirrors assembled into a mutually orthogonal inside corner.

The modulator is a high speed ferroelectric liquid crystal device reported by

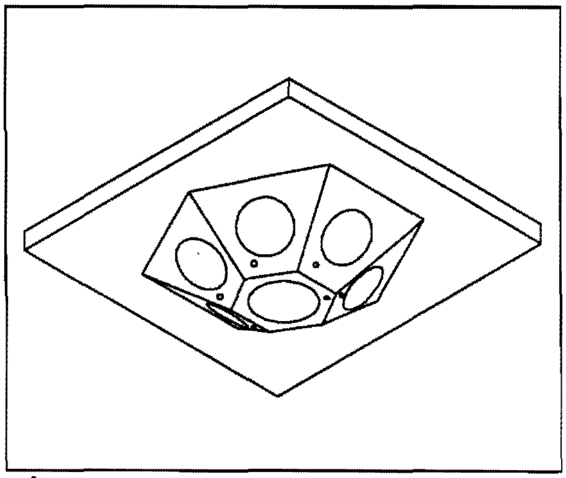

Figure 4

Pagano-Stauffer, Johnson, et. al. at the University of Colorado at Boulder[1], and is manufactured commercially by Displaytech Inc. of Boulder. The device operates as a $\lambda/2$ plate. An applied electric field causes the FLC molecules to rotate, which varies the transmission of the plate. A sample device was obtained on loan from Displaytech, and in-house testing has shown the suitability and limitations of this device.

Characteristics of the Displaytech LV050AC Light Valve

The Displaytech LV050AC Light Valve was tested using a visible laser, silicon detector, and square wave generator. The device as received from the factory is optimized for the visible, so a HeNe laser (632.8 nm wavelength) was used. The flight system will use a custom device which will be optimized for the 840 nm band.

The voltage used to drive the modulator was a simple ± 10 volt square-wave with a nominally 50% duty cycle, although some improvement in performance was noted at other duty cycles during high speed operation. The absolute

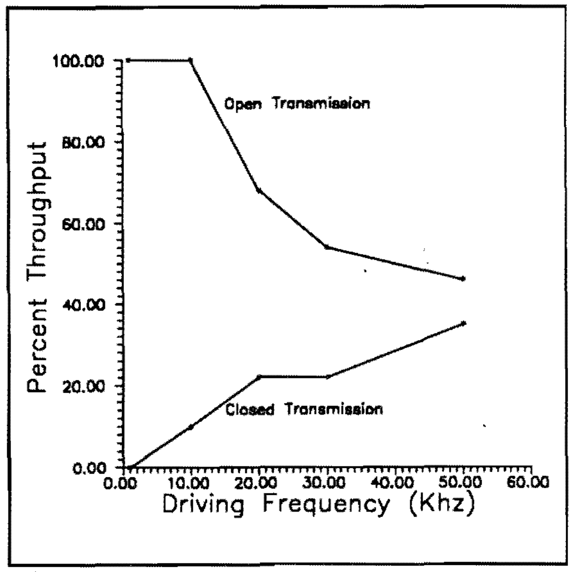

Figure 3

throughput, open and closed throughput as a function of modulating speed, and throughput as a function of entrance angle were measured.

The absolute optical throughput was measured at greater than 80% for modulating speeds of less than 1 khz. Figure 4 shows the open-state transmission, closed-state transmission, yeilding percent modulation as a function of frequency, showing that the light valve is operational at modulating frequencies over 50 khz.

Our tests have shown that the throughput of the light valve falls off by less than 20% as off axis angles approach 45°, showing the suitability of this device to the wide acceptance angles required in this application.

Satellite control system/data buffer

The control system will be capable of storing 120 Megabits of science data from the host experiment, and passing the data to the optical modulator when the uplink gives the "send data" command. The uplink beam will be of sufficient power density that simple silicon detectors will be used for uplink reception, and no optics will be required. The controller will be able to command the modulator to send the appropriate length of data packet, and the placement of the uplink detectors will make it possible to modulate only those FLC's which are illuminated by the laser.

Transmitter

The transmitter consists of a 10 Watt solid state CW laser operating at 840 nm, into a laser collimator of 4-inch aperture. These devices are available off-the-shelf quite inexpensively, and are simple to set up and maintain. 840 nm was chosen as the operating wavelength because of the availability of high-power solid state lasers, availability of detectors and other optical materials, and the attenuation, scatter and background characteristics of the atmosphere.

Receiver

The ground receiver system will be a large aperture (1-meter class) telescope co-aligned with the laser transmitter, and a direct detection detector system. Direct detection laser receiver systems have been designed and tested[2] which can provide data rates of 10 Mbits per second, at error rates of 10^{-9} errors per bit, at photon flux levels of less than 200 photons per bit. The system detailed in reference 2 is a fairly simple solid state avalanche photo-diode based system, which is very similar to that which will be required for this application.

A narrow band optical filter will be incorporated in the detector design to block out of band background.

Ground tracking requirements will be on the order of 50 μrad pointing precision, at tracking rates of about 25 mrad per second. This is well within the capability of off-the-shelf components.

III. System Model

The considerations for a model of this system are:

Beam attenuation due to atmospheric absorption/scatter

A personal computer adaptation of the Air Force Geophysics Laboratory's LOWTRAN atmospheric model (PCTRAN) was used to model the beam transmission through the atmosphere. The model used was that of midlatitude summer, rural aerosol, with light cirrus clouds. This yielded a total attenuation of 35% at 840 nm. Using the principle of reciprocity, this would apply equally for the upward and downward beams, yielding a total atmospheric throughput of 0.42.

Beam attenuation due to beam spread/diffraction

For the complete beam path, there are three sources of beam spread; transmitter aperture diffraction, retroreflector aperture diffraction, and beam spread due to atmospheric turbulence. Beam spread due to aperture diffraction is assumed to be Fraunhofer, and is calculated as[3];

$$\Theta=\frac{2.44\lambda}{D}\,[rad]$$

where D is the effective aperture, and λ is the laser wavelength.

Beam spread due to atmospheric turbulence is taken to be 0.5 arc-seconds for absolute best seeing[4]. In this case we have taken worst-case seeing to be 10 times this, or 5 arc-seconds.

Beam spread causes the total signal to be attenuated by the ratio of the beam diameter at the plane of the receiving optic to the diameter of the receiving (or retroreflecting) optic. Assuming a 4-inch transmitter aperture, 5 arc-seconds of atmospheric beam spread, a 3-inch diameter retroreflector, and a 500 km altitude satellite at a range of 1000 km, attenuation in the upward beam will be;

$$UpAtten=\frac{D_r^2}{((\Theta_a+\Theta_t)*Range)^2}$$

where;

D_r = diameter of retroreflector

Θ_t = diffraction due to transmitter aperture

Θ_a = atmospheric beam spread

Range = distance to satellite

The attenuation factor for the upward beam is calculated to be $2.9\text{x}10^{-6}$.

Attenuation in the return beam (neglecting any diffraction due to the 1-meter receiving telescope) will be due to a combination of the upward beam spread and the effects which will cause the downward beam to spread;

$$DnAtten=\frac{D_t^2}{((\Theta_t+2\Theta_a+\Theta_r)*Range)^2}$$

where;

D_t = diameter of receiving telescope = 1-meter

Θ_r = diffraction at 3-inch retroreflector aperture

The attenuation factor for the return beam is calculated to be $1.1\text{x}10^{-4}$. The total attenuation due to beam spread is the product of these;

$$\tau_{bs}=UpAtten*DnAtten$$

This yields a total beam spread attenuation of 3.2×10^{-10}.

The ground-to-satellite beam spread is also the tracking requirement for the ground system, in order to keep the satellite in the beam. This is approximately 50 μrad. Tracking simulations have been run for two satellites in appropriate orbits for ground tracking from Logan, Utah: MIR and LACE. The maximum tracking speed required is estimated to be on the order of 25 mrad per second, and the satellites were estimated to be within trackable range and elevation angle for approximately 11 minutes per day for MIR, and 15 minutes per day for LACE, in 3 to 4 passes.

Attenuation due to throughput of optical system elements

Another source of beam attenuation is the throughput of each of the elements in the optical system. Table 2 lists each of these, and the resulting system efficiency.

Total Link Attenuation

The total link attenuation for this system is given by;

$$\tau_s=\tau_a*\tau_{bs}*\tau_o$$

Where;
τ_a = the atmospheric attenuation
τ_o = the throughput of the optical system

This is calculated to be 1.0×10^{-11} for the open state of the modulator, and 6.0×10^{-12} for the closed state.
The resulting number of total photons per bit is given by;

$$BitFlux=\frac{P_0\frac{\lambda}{hc}\tau_s}{Baud}$$

Where;
P_0 =laser power(10 Watts)
h = Planck's constant
c = speed of light
Baud = 50×10^3 bits/sec

The number of actual signal photons per bit is the difference between the number of photons per bit for the open modulator and that of the closed modulator. This is calculated to be 3.7×10^3 photons per bit.

IV. Atmospheric effects

The atmosphere will have other effects on the laser beam. These other effects include scintillation, backscatter, and beam wander.

Scintillation

Optical beams which pass through the atmosphere will experience scintillation, or fluctuations in transmission, commonly called "twinkling" when applied to starlight.

Table 2
Optical Throughput

Beam Expander	
Throughput	≈ 0.95
Diffraction	≈ 0.84
Retroreflector	
FLC (two passes)	
'Open' State	≈ 0.37^2
'Closed' State	≈ 0.28^2
Retroreflector	≈ 0.96
Diffraction	≈ 0.84
Receiver	
Telescope	≈ 0.96
Detector	≈ 0.90
TOTAL SYSTEM THROUGHPUT	
'Open' State	≈ 0.076
'Closed' State	≈ 0.044

Measurements[5] have shown that this is a low frequency phenomenon, with mean frequencies below 1 Khz.
Yura & McKinley[6] have

modeled this as cells of turbulence "locked-in" the steering winds which occur between 5 & 20 kilometers. Application of this model assuming two passes through the atmosphere, steering wind speed of 27 m/sec, and a zenith angle of 60 degrees yields an irradiance variance of;

$$\sigma^2=N[C1\left(\frac{V}{27}\right)^2+C2]\,\lambda^{-\frac{7}{6}}\sec\Theta^{\frac{11}{6}}$$

Where;
$C1 = 7.42\text{x}10^{-2}$
$C2 = 4.45\text{x}10^{-3}$
V = speed of steering winds
Θ = zenith angle
N = number of passes through atmosphere

For these assumptions, σ^2 is calculated to be 0.686. This result is then used to calculate the fraction of time that a signal will fade or surge beyond a certain level. This is calculated as;

$$frac(i\geq i_0)=\frac{1}{2}[1-erf\frac{F_0+0.5\sigma^2}{\sqrt{\sigma}}]$$

Where;
erf = the error function
F_0 = the fade/surge level (chosen as 6 db)

This yields a fade/surge fraction of 0.10, which predicts that the signal will be within ±6 db of the median signal level 90% of the time. This is a worst case calculation, as the effects of aperture averaging over the 1-meter aperture receiving telescope will actually improve the signal stability.

Backscatter

A laser beam passing through the atmosphere will be attenuated by scattering. A fraction of this scatter will be directed back into the transmitter/receiver aperture, constituting a strong in-band background signal, which will have some fade/surge characteristics caused by the same mechanism as scintillation. At 840 nm the primary scattering mechanism is Mie scattering[7] which is caused by aerosol particles in the atmosphere.

A simplified model of the backscatter can be derived using the volume scattering and volume attenuation coefficients for sea level, and assuming that they fall off exponentially with altitude, as the aerosol pressure does. The single scattering LIDAR equation[8] can be modified for the continuous case;

$$Bscatter=P_0A_r\int_0^R\frac{\beta(R)}{R^2}e^{\int_0^R\alpha(r)\,dr}dR$$

Where;
$\beta(R)$ = aerosol scatter function
$\alpha(r)$ = aerosol extinction function
A_r = receiving telescope area

This model yields a backscatter background of $7.8\text{x}10^{10}$ photons, which is orders higher than the signal level, so we are planning to use a pulsed/packet communication technique at an appropriate pulse length such that the backscatter background will have faded before the return beam is received. This technique has successfully been accomplished before (see reference 5).

Background

The laser wavelength of 840 nm was chosen to be at a wavelength long enough that Rayleigh scattering of solar radiation could be neglected, and of a wavelength short enough that thermal radiation from the atmosphere could be neglected. LOWTRAN modeling of the daytime atmosphere has shown that for all scenarios where the atmosphere has sufficient transparency to allow this communication system to operate, solar background will be minimal. The ground tracking system will, of course, have to be able to keep the telescope from tracking across the sun.

Beam Wander/Bending

Atmospheric turbulence will also cause a beam to wander or bend in a time-varying fashion. The effect is much worse for near-zenith than for more horizontal paths. This effect has been shown[9] to be approximately 20 μrad for a horizontal path through the atmosphere, and 200 μrad for a vertical path. Another group of experimenters[10] estimated their experiment's combined beam wander and telescope jitter to be 50 μrad for 30 to 60 degree zenith angles.

Inspection of some actual beam wander data[11] indicates that there is a short period (<0.5 sec) beam wander in both the horizontal and vertical paths of approximately 50 μrad. In addition to this, the data shows a long period (≈120 sec) beam wander of approximately 20 μrad in the horizontal path, and approximately 200 μrad in the vertical path.

The worst-case model that we have calculated yields a beam spread of approximately 50 μrad in the ground-to-satellite beam. This is appropriately sized to contain the short term wander. The beam expander can be adjusted to compensate for better atmospheric conditions, to keep the beam spread near 50 μrad.

The long term wander may limit the ability of the ground tracking station to fully track satellites as they pass directly overhead, or may change the optimum ground station location for a given satellite, to one for which the satellite does not pass higher than a zenith angle of 30 degrees. Either scenario would reduce the amount of data which could be collected per day.

Another possibility which we are investigating is that of active tracking to eliminate the long-term beam wander problem. There is sufficient signal, if a separate tracking telescope and detector system is used, to allow active tracking of the satellite return beam. The detector would be a 4-element silicon array, behind an 8-inch telescope. The detector would be synchronized to the transmitter to eliminate backscatter, and would integrate the received signal. This active tracking system would also be able to compensate for beam refraction as the satellite is tracked near the horizon.

V. Conclusions

This design study has introduced a simple, efficient, light-weight communication system for small satellite and "fly along" mission use. The somewhat limited data downlink capacity does not make it the perfect communication system for all missions, but we believe that there exist missions for which this system is suitable. The light-weight, efficient nature of the spacecraft system has its drawbacks, however, in the increased size and complexity of the ground station. This probably indicates that the system is best suited for data communications to a group of satellites.

VI. References

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