SYSTEM MODEL FOR A LOW DATA RATE FULL DUPLEX OPTICAL COMMUNICATIONS LINK BETWEEN EARTH AND LEO

D. A. Hazzard, J. A. MacCannell, G. Lee, E. R. Selves, D. Moore, J. A. Payne, C. D. Garrett, N. Dahlstrom, and T. M. Shay
New Mexico State University

ABSTRACT

We present a novel communications link concept. This system offers the potential of low data rate full-duplex communications between earth and LEO. We will present a detailed link model for this system.

KEY WORDS

Circular polarization keying, optical communications.

INTRODUCTION

We present a model for an earth to low-earth-orbit optical communications system; the planned experiment is called Lightweight Optical Wavelength Communications without A Laser in space (LOWCAL.) The LOWCAL system modeled herein is designed to offer very a lightweight, low power consumption, low data rate communications link from LEO satellites. The system utilizes a novel architecture for a free-space optical communications link. This link provides full-duplex communications on a single beam, utilizing a novel concept that we have named the "Lightwire" concept. In addition, this system utilizes a novel data format for free-space optical communications. The current proposed application is a ground to LEO link. The concept however, is generally applicable to other free-space optical communications systems as well.

In this system, the laser and the downlink receiver are both located on the ground. The optical elements located on the spacecraft are the retro-modulator and a simple uplink receiver. Data rates on the order of 10-kbps are currently possible without taxing the current laser or modulator technology. In fact, the transmitter laser for such a system is a semiconductor device. The envisioned system would include a Faraday Anomalous Dispersion Optical Filter (FADOF) in the receiver to allow 24-hour operation of the system. The FADOF is an ultra-high background rejection optical filter developed at New Mexico State University. The FADOF is a key element in this system since it essentially keeps the skylight from reaching the receiver while transmitting 80% of the signal photons. Without a FADOF in the receiver the transmitted laser power would need to be increased by a factor of 10 for the link to be feasible for daylight operation.

We present a simple feasibility model for the LOWCAL experiment that provides an estimate of the performance capability and identifies the major system tradeoffs. In our model we have calculated the required downlink receiver aperture, transmitter laser power, retro-modulator aperture, and both the downlink and the uplink signal-to-noise ratios. We have also taken into account the atmospheric distortions in our model. We will first discuss the analysis of the downlink and then we will analyze the uplink.

THE LOWCAL DOWNLINK

Nearly all of the optical communications experiments to date have utilized either On-Off Keying (OOK) or various coherent optical communications keying (PSK or FSK). We chose to employ for the first time Circularly Polarization Keying (CPK) for our system. A block diagram of the system is shown in figure 1. The diode laser system transmits a constant average power beam to the spacecraft. The transmitted beam is directed through a quarter-wave plate (*l*/4 in figure 1) that will convert the linearly polarized laser beam into a circularly polarized beam. The laser beam is then directed through the aperture-sharing element (ASE) that is literally a mirror with a hole in it. The purpose of the aperture-sharing element is to separate the transmitted and returned beam paths. The transmitted

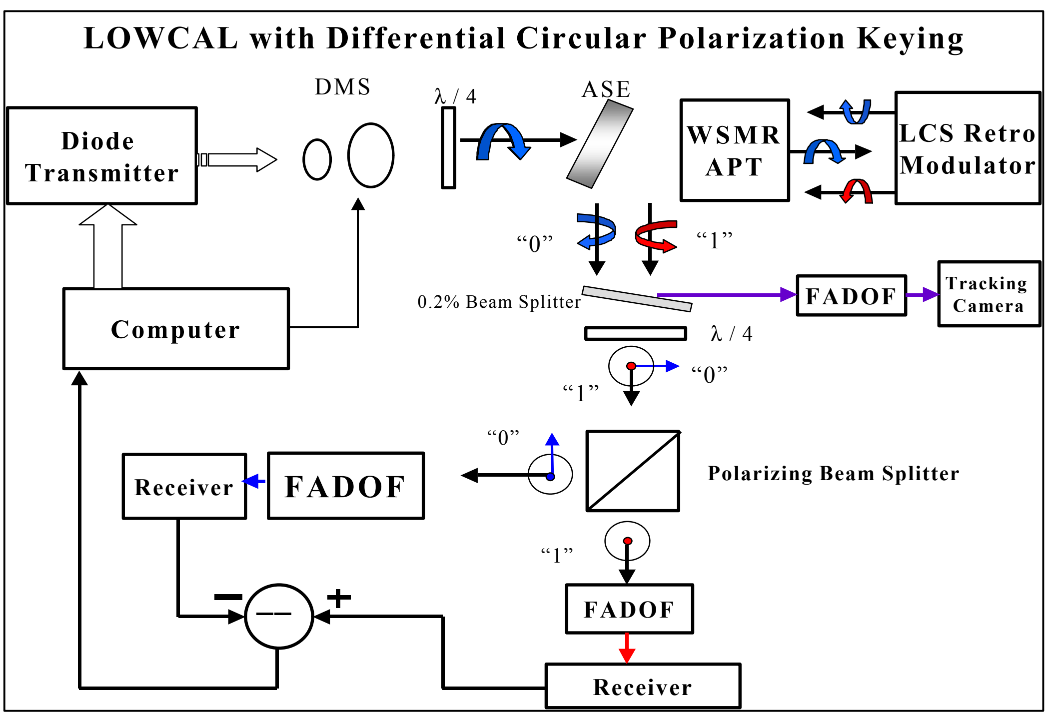

Figure 1.

beam directed through the hole in the mirror to the White Sands Missile Range Advanced Pointer and Tracker (WSMR APT) and then to the spacecraft. In circular polarization keying (CPK) the binary data is encoded in the polarization of the return beam. At the spacecraft a liquid crystal (LCS) retro-modulator will flip the right-handed polarized light into left-handed for a "1". For a "0" the incident polarization is left unchanged. The liquid crystal retro-modulator acts exactly like a corner cube reflector, that is the retro-modulator directs the beam incident on the spacecraft directly back to the transmitting telescope. Then the WSMR APT collects the downlink signal and directs the signal to the aperture-sharing element (ASE). The downlink signal is reflected by the ASE and directed to a beam splitter that sends 0.2% of the signal through a FADOF to the telescope's active tracking camera. Most of the return signal passes through the beam splitter to the receiver quarter-wave plate ($l/4$) which converts the left and right-hand circular polarized light into two orthogonal linear polarizations. The linear polarizations are then separated in the polarizing beam splitter shown in figure 1. Thus the end result is the photons that constitute the "0's" are sent to one FADOF and photo-receiver and the photons that constitute the "1's" are sent to another FADOF and photo-receiver. The final step is these two signals are subtracted, hence this new format is differential circular polarization keying (DCPK).

Two additional advantages of CPK are that we can retrieve non-zero signals for both state and therefore we can detect the presence of both "0's" and "1's". If V_1 is subtracted from V_0, because $V_0 = -V_1$ at the threshold detector, the voltage difference between the high and low has doubled. Thus we have increased the signal-to-noise ratio by an additional 6-dB compared to what the signal-to-noise ratio would have been for the more conventional On-Off Keying (OOK). In summary, DCPK is actually a 2-channel form of OOK, where for DCPK we are detecting the difference between the signal in the two circular polarizations. Thus our downlink is sensitive only to the average power received on each channel; this will be utilized later. The other advantage of this is that since we always have some power returning we can split off a few percent of the return signal and use that as our tracking error loop signal with an intensified camera. CPK and DCPK are the first novel technical features of this system.

SIMPLE DOWNLINK MODEL

Now we are going to model our LOWCAL experiment. During the communications mode it is desirable to utilize a narrow transmit beam (~ 20-μradians) since this maximizes the power incident upon the spacecraft for a given transmitter power. According to the Shuttle Flight Dynamics Information Officer (FIDO)[1], the typical ephemeris uncertainty is approximately 1/3-milliradian. While it is possible to mechanically scan the WSMR APT, it is difficult to obtain an open loop pointing accuracy of more than ± 100-μradians. This is about 10 times the communications mode beam width; therefore this was not an acceptable

acceptable solution. Thus we will operate the system in two modes: first an acquisition mode, and secondly, as soon as the signal is acquired, we will switch to the communications mode. To ensure rapid tracking convergence the acquisition mode transmitted beam will be wide (~ 2/3-milliradian) and a long receiver integration time will be used. In the communications mode, the transmitted beam will be narrow (~20-μradians) and the integration time short to allow data rates of up to 10-kbps. Therefore the link equation for this system must be analyzed in both modes, the communications and the acquire mode.

RECEIVED SIGNAL

The link equation for this system is

$$\text{Margin} = P_{\text{laser}} - L - P_s - M_{\text{scintillaton}} \quad (1\text{-}1),$$

where $P_{\text{laser}} = \text{trasmitted laser power}$,

$P_s = \text{received optical signal power}$,

$M_{\text{scintillaton}} = \text{optical scintillat ion margin}$ (5-dB according to Dr. Keith Wilson of JPL),

L = total link loss, excluding the scintillation losses.

The 5-dB optical scintillation margin provided a BER of ~ 10^{-3} to 10^{-4} in the recent GOLD experiment[2]. The sum of the modulator efficiency loss, L_{mod}, the atmospheric propagation loss, L_{atm}, the telescope loss, L_{T}, and the FADOF transmission loss, L_{FADOF}, add up to 9.3-dB. The signal intercept efficiency loss, L_{SIE}, is given by

$$L_{SIE} = -10\log\left(\frac{A}{R^2 \cdot \Delta\Omega}\right) \quad (1\text{-}2),$$

where A = receiver area,

R = distance from the emitter to the receiver (between 300 and 600-km in a typical LEO[2]),

= solid angle subtended by the transmitted beam.

In the acquire mode the uplink solid angles are, $\Delta\Omega_{\text{acquire}} = 3.6\times10^{-7}$ sr and $\Delta\Omega_{\text{comm}} = 4\pi\times10^{-10}$ sr. Furthermore, the divergence of the return beam, θ_{return}, will be limited either by the atmosphere to 10-μradians or by the diffraction of the transmitter optics, greater than $1.22\lambda/D$ (lower cost optics will have larger beam divergence.)

Using the 60-cm diameter WSMR Advanced Pointing Telescope as the receiver, and a 2-inch retro-modulator, the total round trip signal intercept efficiency losses are 85 and 110-dB for the communications mode and acquisitions modes, respectively. Note that the 25-dB difference in losses between the communications and acquire signal intercept losses is due only to the difference in beam divergences for the two modes. The wider acquisition mode signal is determined by the shuttle downtrack position uncertainties in the acquire

The expression for received optical signal power for the LOWCAL system is

$$P_s = 10\log\left(\frac{P_L}{\text{mW}}\right) - L - M_{\text{scintillation}} \quad (1\text{-}3),$$

where L = total optical link loss, given by

$$L = L_{\text{SIE}} + L_{\text{mod}} + L_{\text{atm}} + L_{\text{T}} + L_{\text{FADOF}} \quad (1\text{-}4).$$

NOISE ANALYSIS

The signal shot Noise Equivalent Power, NEP_{shot}, is given by

$$\text{NEP}_{\text{shot}} = \sqrt{\frac{hc}{l\,h} P_s} \quad (1\text{-}5),$$

where h = Planck's constant,

c = speed of light,

h = quantum efficiency of the photodetector,

l = wavelength,

P_s = received signal power.

The solar noise that is transmitted through the receiver and FADOF is given by

$$P_{\text{sky}} = \frac{¶L_e}{¶l} \cdot \Delta\Omega_{\text{trans}} \cdot A_{\text{receiver}} \cdot \Delta l_{\text{FADOF}} \cdot T_{\text{FADOF}} \cdot h_{\text{T}} \quad (1\text{-}6),$$

where $\frac{¶L_e}{¶l}$ = spectral radiance of the blue sky,

Dl_{FADOF} = equivalent noise bandwidth of the FADOF,

T_{FADOF} = signal transmission of the FADOF.

This leads to a Noise Equivalent Power for the sky given by

$$\text{NEP}_{\text{sky}} = \sqrt{\frac{hc}{l\,h} P_{\text{sky}}} \quad (1\text{-}7).$$

This is added to the receiver noise equivalent power, $\text{NEP}_{\text{receivier}}$ and the signal shot noise NEP_{shot}, to give a total noise equivalent power of

$$\text{NEP} = \sqrt{\text{NEP}^2_{\text{receiver}} + \text{NEP}^2_{\text{sky}} + \text{NEP}^2_{\text{shot}}} \quad (1\text{-}8).$$

This assumes that we have an equal probability of receiving a "1" and "0", the receiver threshold voltage is to set $V_1 + V_0 = 0$, and the extinction ratio is 0. Neglecting intersymbol interference for our simple differential circular polarization keying (DCPK) modulation case, the electrical signal to noise ratio, SNR, is given by

$$\text{SNR} = \frac{4P^2_{\text{received}}}{\text{NEP}^2 \cdot \text{BW}} \quad (1\text{-}9),$$

where BW = electrical bandwidth of the signal.

In the case where the extinction ratio is 0.1 the power penalty will be less than 2-dB. Likewise a system where the fraction of the pulse energy that is received within one bit period, $\gamma \geq 0.9$ the power penalty for this will be less than 2-dB. Thus this should not be a major problem. This leads to a requirement that the electrical SNR = 9.6 for a bit error rate of 10^{-6}. Thus the received optical power must be

$P_s = 1.5 \cdot \mathrm{NEP}\sqrt{\mathrm{BW}}$ (1-10).

For our study we will assume the use of a low noise PMT receiver. This receiver has

$\mathrm{NEP}_{\mathrm{PMT}} = 1 \frac{\mathrm{fW}}{\sqrt{\mathrm{Hz}}}$.

In order to properly model the system we must include the solar noise. The solar spectral radiance[3] at 1-micron is

$\frac{\partial L_e}{\partial l} = 10^3 \frac{}{\mathrm{cm}^2 \cdot \mathrm{sr} \cdot}$ (1-11).

The spectral radiance of the blue sky remains roughly constant as long as the detector is pointing at a region of the sky that is 10 degrees away from the sun. The solar noise incident upon the photodetector filtered by a FADOF is given by

$P_{\mathrm{sky}} = \frac{\partial L_e}{\partial l} \cdot \Omega \cdot \Delta l \cdot A_{\mathrm{receiver}} \cdot T_{\mathrm{FADOF}} \cdot h_{\mathrm{T}}$ (1-12),

where WΩ = solid angle of the receiver,

DΔλ = optical bandpass of the FADOF (0.002-nm at 852-nm),

T_{FADOF} = transmission of the FADOF (80% at 852-nm.)

The total noise equivalent power of the blue sky is given by these two equations:

$\mathrm{NEP}_{\mathrm{sky\ comm}} = \frac{1}{3} \frac{\mathrm{fW}}{\sqrt{\mathrm{Hz}}}$ (1-13)

$\mathrm{NEP}_{\mathrm{sky\ aquire}} = 6 \frac{\mathrm{fW}}{\sqrt{\mathrm{Hz}}}$ (1-14)

for the communications and for the acquisition modes, respectively.

The FADOF reduces the blue sky background an insignificant level for both the daylight communications mode, where $\Delta\Omega = 1.26 \times 10^{-9}$ sr, and the daylight acquisition mode, where $\Delta\Omega = 1.2 \times 10^{-6}$ sr. Thus the FADOF gives us the possibility of 24 hours a day operation.

The required signal power during the communications mode is

$P_s \geq 1.5 \cdot 176 \frac{\mathrm{fW}}{\sqrt{\mathrm{BW}}}$ (1-15).

The bandwidth is given by

$\mathrm{BW} = 2 \cdot \mathrm{DR}$ (1-16),

where DR = signal data rate.

The bandwidth is twice the data rate because the laser beam must be off during the signal reception period so that near field aerosol backscattering and backscattering off the telescope optical train doesn't swamp the return signal. Thus the source duty cycle is 50%. At 10-kbps, ~ 82-pW must reach the receiver to ensure the link quality. The higher losses during the acquisition mode can be overcome by integrating over one second so that the acquisition can be completed quickly and the margins for acquisition mode is 4-dB higher than the margin for the communications mode.

DOWNLINK SUMMARY

The results presented in Table I assume a laser transmitter power of 6-dB, a communications data rate of 10-kbps, and an acquisition mode integration time of 1 second.

TABLE I: Electrical Link Margins

	Comm		Acquire	
D_{retro} (in.)	Day	Night	Day	Night
1	-10	-10	-7	-7
2	13.9	13.9	17	17
3	20	20	23	23

This table shows clearly that a 2-inch diameter retro-modulator on board the satellite will close the link handily. In order to use a 1-inch diameter retro-modulator a transmitter laser with about 50 watts would be required. This item is not currently a standard commercial item but a commercial vendor has produced multiple-watt amplifiers at this wavelength in the past, making this option a possibility. The retro-modulator employs wide field lenses to increase its angular acceptance. A wide field-of-view retro-modulator is desirable because it reduces alignment sensitivity of the system. Phillips Laboratory and Utah State University (AF/PL/USU)[4] used nine retro-modulators to achieve a field-of-view of 40^o in their balloon experiments, increasing the weight of the system significantly. Thus we will attempt to design a single retro-modulator that offers a field-of-view of greater than 60^o full angle that is light weight.

COMPARISON TO PREVIOUS RETRO-MODULATED WORK

Currently, the only previous retro-modulator work that has been performed is the AF/PL/USU experiment[4]. A direct comparison of our work to theirs is shown in Table II.

As you can see from the table, our planned experiments should exceed the previous work in a number of categories. First, our platform is the Space Shuttle. Thus our link will be a factor of 10 higher and nearly a factor of 20 further away than the AF/PL/USU experiment. Second, we expect our data rate to be nearly 10 times greater than theirs. Third, our receiver diameter is 0.6-m instead of 1.5-m (telescopes in the 1.5-m range cost considerably more than ours.) The modulator fields-of-view should be identical. The weight of our modulator should be an order of magnitude lower than their 28-kg. Our modulator area will be constant and a factor of 2 to 20 times the effective area of their modulator (their effective modulator area varies with incident angle). We can offer 24-hour operation because of the use of a FADOF in the receiver. Finally, our transmitter power should be nearly identical despite the order of magnitude higher data rate and the fact that our link has to operate over a factor of 20 longer range.

Table II. COMPARISON WITH OTHER EXPERIMENTS

	NASA/NMSU	AF/PL/USU
PLATFORM	Space Shuttle	Balloon
ALTITUDE	320-km	32-km
DATA RATE	10-kbps	1.2-kbps
RECEIVER DIAMETER	0.6-m	1.5-m
MODULATOR FOV	$\pm\pi/4$	$\pm\pi/4$
MODULATOR WT.	1 to 2-kg	28-kg
MODULATOR AREA	20-cm^2	1 to 10-cm^2
24 HOUR CAPABILITY	Yes	No
TRANSMITTER POWER	4-W	5-W

LOWCAL UPLINK

It is desirable to have bi-directional communications for the proposed applications. An obvious means of doing this is to simply time multiplex the uplink and downlink modes. However, we did not want to suffer a reduction in downlink communications, so we developed a novel method for transparent uplinks and downlinks on the same beam.

We have named this the lightwire concept. In this concept, we utilize different modulation schemes for the uplink and downlink. For the downlink, we utilize the DCPK modulation described in the previous section of this paper, but for the uplink we use sub-carrier PSK (SC-PSK) modulation with a small modulation index. The DCPK modulation format detects the difference between the total number of photons received in the two polarizations; because the SC-PSK modulation doesn't change the average transmitted power the two modulation formats are transparent to one another. Hence, the uplink and downlink formats are invisible to each other, so we have full-duplex operation with one laser beam. At the spacecraft the photodetector converts the optical photons into a RF electrical signal and then at that point conventional PSK signal processing is utilized. Figure 2 below illustrates the "Lightwire concept" operating in conjunction with the DCPK format. Note the system operates in two modes: talk and listen. During the talk mode the transmitted beam is on and the receiver is gated off. Hence, we have full-duplex communications on one carrier beam and therefore we named this the "Lightwire concept".

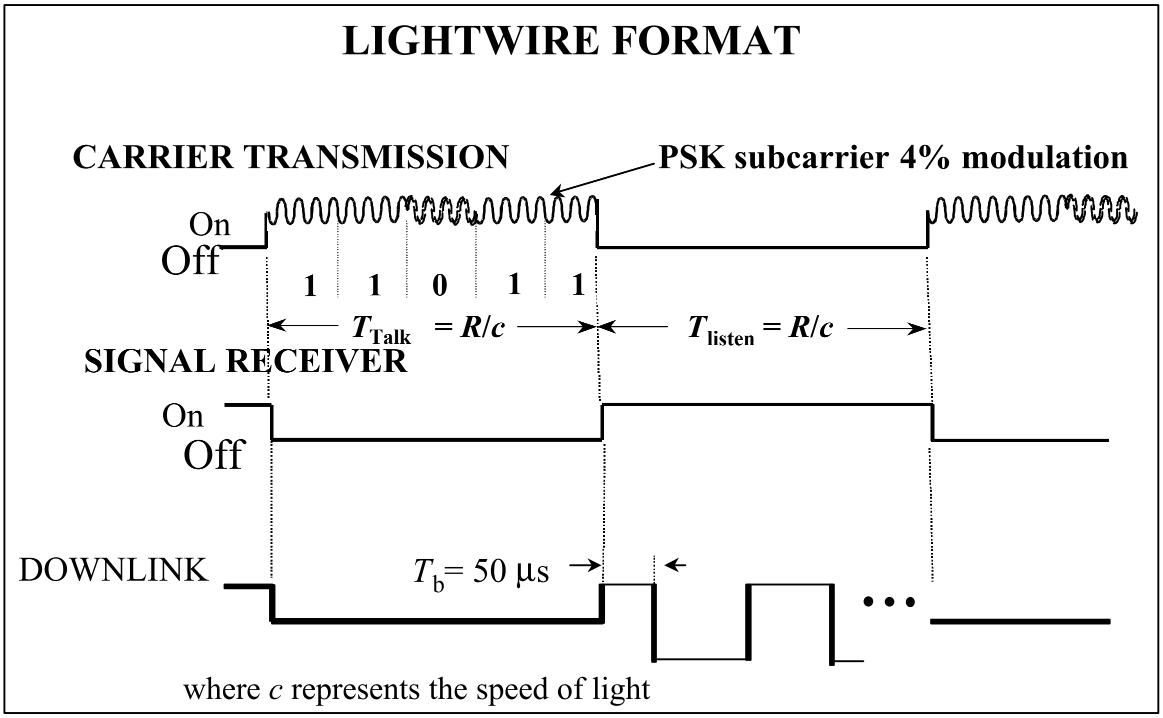

Figure 2.

SIMPLE UPLINK MODEL

The optical power incident upon the spacecraft, P_r, is

$P_r = I_i A_{\mathrm{PD}} \left[1 + m\cos\left(w_{\mathrm{PSK}} t + f(t)\right)\right]$ (1-17),

where P_r = received optical power at the spacecraft,

I_i = intensity incident upon the spacecraft,

m = modulation index,

w_{PSK} = subcarrier frequency,

$f(t)$ = phase of the subcarrier.

The uplink signal-to-noise ratio is

$$\mathrm{SNR} = \frac{\frac{1}{2}\left(mP_r R_{\mathrm{PD}}\right)^2}{2qB\left(P_r R_{\mathrm{PD}} + I_{\mathrm{D}}\right) + \mathrm{RIN}\cdot B\left(P_r R_{\mathrm{PD}}\right)^2 + \frac{4k_B T \cdot B}{R_{\mathrm{L}}} F_t} \quad (1\text{-}18),$$

where q = electron charge,

B = electronic bandwidth,

R_{PD} = photodetector responsivity,

I_{D} = photodetector’s dark current,

RIN = laser relative intensity noise,

k_B = Boltzman’s constant,

T = temperature in degrees Kelvin,

R_{L} = load resistor,

F_t = noise figure of the amplifier.

For a 2-inch diameter photoreceiver the received power, P_r = 5-μW at the spacecraft. Assuming a modulation index, m = 0.04, a photodetector responsivity, R_{PD} = 0.6 amps/watt, a data rate of 10-kHz, a relative intensity noise, RIN = -130-dB/Hz, and a load resister, R_L = 1-MΩ, the signal-to-noise ratio for this SC-PSK uplink is 40-dB.

LASER SAFETY

The worse case laser intensity at the shuttle was calculated and compared to the safe limits for our wavelength and pulse format. We are operating at 852-nm with a pulse-duration of ~ 2-ms and a repetition rate of 250-Hz. The chair of the ANSI Standard Committee on Laser Safety verified that 2-mW/cm^2 is the maximum safe exposure limit. This is to be compared to the worse case calculated intensity at the shuttle is 3-μW/cm^2, when the shuttle is at Zenith and the transmitted laser power is at a maximum. In practice the laser power at Zenith should be reduced by a factor of 10 when the shuttle is at Zenith. In summary, the laser intensity at the shuttle is nearly a factor of 1000 below the maximum ANSI safe exposure limit; hence we will be completely safe.

CONCLUSION

This simple analysis shows that a passive optical communications system that we call LOWCAL can provide a telemetering link to LEO for Zenith angles of $\pm \pi/3$. We should be able to achieve a data rate of 10-kbps over this entire range using a transmitter laser power of about 5 watts. If we elect to only cover Zenith angles of $\pm \pi/6$ then a ½-watt transmitter gives roughly the same performance. The experiment considered using the Advanced Pointing Telescope Facility at WSMR. The use of a FADOF will allow daylight specifications to be within 1-dB. Furthermore, we have presented for the first time the circular polarization keying format for free-space optical communications and the lightwire concept that allows full-duplex communications using a single optical beam. Finally, there is absolutely no eye safety hazard for the shuttle astronauts due to the transmitter laser.

REFERENCES

1. Tracy, William, Shuttle Flight Information Officer, Typical uncertainties if the position updated within 20 minutes of pass.
2. Wilson, K. E., Lesh, J. R., Araki, K., Arimoto, Y., "Overview of the Ground to Orbit Lasercom Demonstration", SPIE Proceedings, Vol. 2990, pp. 23-30, 1997, in Free-Space Laser Communications Technologies IX, G. Stephen Mercherle, Ed.
3. Wolfe, William L., Zissis, George J., Editors, The Infrared Handbook, Third edition, Pp. 3-71
4. Swenson, Charles M., Steed, Clark A., DeLaRue, Imelda A., Fugate, Robert Q., "Low Power FLC-based Retro-modulator Communications System," SPIE Proceedings, Vol. 2990, pp. 296-310, in Free-Space Laser Communications Technologies IX, G. Stephen Mercherle, Ed.