EARTH-SPACE LEOSAT COMMUNICATION USING OPTICAL FREQUENCIES

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ABSTRACT

This paper introduces the concept of a high bit rate burst type communications system as a means of increasing the communications throughput on LEO spacecraft. The discussion concerns the use of optical frequencies due to the decrease in size, weight and prime power of LEO satellite communication packages at these wavelengths. The penalty is an increase in pointing and tracking complexity. An example link design is presented.

Introduction

As Low Earth Orbit SATellite (LEOSAT) technology advances, these spacecraft are becoming increasingly complex and able to perform multiple functions while maintaining small dimensions. The present generation of LEOSATs have very limited communication capacity, and together with the periodic invisibility of a satellite in low earth orbit, their utility is lower than geostationary satellites. One method to increase the capacity of space based communications platforms is through the use of higher frequencies. This trend leads naturally to the optical portion of the frequency spectrum. This paper examines the feasibility of employing an optical communications package on a LEOSAT and discusses the issues involved. Optical satellite communications have the potential to provide higher capacity links than can be obtained at VHF and UHF frequencies.

The major advantage of moving to optical frequencies for LEOSAT links is that antenna size and weight are greatly reduced when the wavelength is in micrometers rather than fractions of a meter as at VHF and UHF. Since the dimensions of most LEOSATs are on the order of one to two meters or less, it is difficult to fit high gain VHF or UHF antennas with dimensions of many meters onto such spacecraft. At optical frequencies, antennas with dimensions of hundreds of wavelengths can be implemented with very small lenses. However, the beamwidths produced by these high gain antennas are very narrow, with consequent problems of pointing the beam with sufficient accuracy. Nevertheless, the advantages of moving to optical frequencies are considerable and well worth investigating for use in store and forward LEOSAT communication systems.

Optical LEOSAT Considerations

The proposed link scenario is shown in Fig. 1. We consider a LEOSAT at 765 km altitude with multiple beams pointed at the earth. This configuration forms a push-broom effect along the surface of the earth. We will adopt this geometry to simplify the pointing and tracking requirements as well as the stability requirements on the satellite. With this system the multiple beam transmitter can be made to swivel with the motion of the spacecraft as it flies over a target. This will increase the dwell time on a particular earth station site. The channel consists of free-space except for the last 20,000 meters which consists of the turbulent atmosphere.

Sufficient margin can be built into the link with today's technology to compensate for clear sky turbulence, but rain and cloud blockage will result in link unavailability. Thus an optical link from a LEOSAT is highly intermittent and best suited to "mail box" applications. In such an electronic mail service, the satellite collects data from users as it orbits the earth and then retransmits them to the required destination. Recent developments in mass storage devices make it possible to store large volumes of data on the spacecraft.

As another application, consider a remote sensing satellite in low orbit collecting image data. The amount of data generated by imaging systems is tremendous. This is the driver for much of the work on image compression techniques. Image compression always causes a loss of information content. If the bit rate of the link can be increased sufficiently then image compression may become unnecessary at best, or at least reduce the demand for larger and larger compression ratios.

The Atmospheric Channel

The use of higher frequencies, and, in the extreme, optical frequencies, on LEOSATs will permit information to be transmitted at far greater bit rates than are currently possible. If the channel conditions between the spacecraft and the ground were the same at all frequencies then the increase in bit rate would be a linear function of the increase in frequency. Such is not the case however. At carrier frequencies in the millimeter wavelength range (above 30 GHz) weather, particularly rain, adversely affects the link. As the wavelength decreases further the molecular components of the atmosphere begin to scatter and absorb signal energy. This phenomenon is always present (that is why the sky is blue) but is particularly troublesome when the aerosol particles take the form of water droplets and ice crystals, specifically clouds.

Other mechanisms also come into play. The refractive index of the atmosphere is a function of temperature. Temperature gradients in the path of the signal will cause the refractive index of the path to be a random quantity along the path. Further, this random channel is not constant with time. Temperature gradients are the cause of wind and hence cause atmospheric turbulence. These turbulence effects produce scintillation of the received signal power and a wavefront at the receiver aperture that is spatially uncorrelated, and also cause the apparent angle of arrival of the signal energy to vary randomly with time.

With all of these processes affecting the received signal, it is safe to predict that optical communication through the atmosphere will not be one hundred percent reliable and predictable. Yet when the link exists extremely high data rates are achievable. The result is a burst-type communications channel. Terrestrial free-space links have been demonstrated that carry information at Giga bit per second rates ($>10^9$ bps). Safren[1] has shown that the effects of atmospheric turbulence on an earth-space link can be accounted for with extra link margin of only a few tenths of a dB, dependent on the size of the collecting aperture.

Cloud Outage

Cloud cover statistics, as shown in Fig. 2 [2], indicate that the average cloud cover over most of CONUS is generally less than 50%. There is some seasonal variation and some notable exceptions, for example the north western United States. The premise is that the information to be transmitted is not time critical. If the link can not be completed on this orbit then perhaps the link will be available on the next pass. When the link is completed the data rate is several orders of magnitude greater than available today.

The utility of LEOSAT platforms can be increased if they possess the ability to transfer information at higher rates. LEO remote sensing satellites can currently collect more information than they are capable of down-loading in a single pass. For example, the present generation of LEOSATs for store and forward communications have data rates of typically 9.6 kbps. If the average connect time for a LEOSAT pass is 10 minutes then, ignoring overhead, the number of bits which can be transmitted at 9.6 kbps in this time frame is approximately 5.76×10^6 bits. At 1.0 Mbps it takes less than six seconds to transmit this much data (5.76 seconds to be exact). If the optical link is available for only 1 minute in a pass then the amount of data transmitted will be ten times greater than the RF 9.6 kbps link.

Pointing Acquisition and Tracking

With currently available semi-conductor laser output power, antenna gains on the order of 80 dB to 100 dB are required to obtain suitable link performance. The beamwidth, θ, is related to the gain, G, of a diffraction limited antenna as:

$$G \doteq \frac{30{,}000}{\theta^2}$$

where θ is in degrees.

From this relationship it can be seen that the beamwidths are on the order of one hundredth of a degree or less. Beamwidths of this magnitude will produce footprints on the ground with diameters less than 200 meters. The acquisition problem is to locate the receiver aperture within this 100 m to 200 m diameter spot. The object of the pointing and tracking hardware is the direct and focus the incoming beam energy onto the active area of the photo-detector.

One possible solution to the acquisition problem is to include an RF beacon on the satellite. The footprint of this beacon can be set to look ahead of the approaching optical spot(s). This beacon would serve to announce the approaching arrival of the LEOSAT as well as to relay information concerning its location, possibly obtained from a small GPS receiver on board the LEOSAT. (A GPS receiver suitable for LEOSAT integration has been developed by Texas Instruments.[3]) This would serve a dual purpose on a Earth Observing Satellite (EOS) mission of assisting with the data collection processes. In other words, the inclusion of a GPS receiver could easily be a part of the LEOSAT for mission specific purposes. Once the satellite to earth downlink is established, the uplink to the satellite can be established.

This RF beacon arrangement can also assist with the transmitter tracking by the receiver. As the position information is received from the RF beacon, it can be fed to the tracking system as an aid. The pointing and tracking hardware can maintain link connection through techniques similar to those proposed for the optical intersatellite link scenario. In these systems, the incoming communications beam is used to determine mispointing error through the use of a quadrant photo-detector. It is conceivable that the use of a photo-detector array, instead of a quadrant detector, may be preferable . This would provide a wider field of view and again lessen the tracking requirements.

Optical LEOSAT Link Description

The down-link consists of an optical transmitter on the satellite and an optical receiver on the ground. A similar uplink is required for the bi-directional "mailbox" system. The major components of the optical transmitter are an optical antenna (telescope), an optical signal source in the form of a semi-conductor laser diode or diode array and its associated electronics. On the ground, the major receiver components are the optical telescope used as a receive antenna and the receiver electronics.

The satellite stability can be assumed to be comparable with current technology. These specifications are[3]:

knowledge ± 0.05 degrees each axis
control of ± 0.5 degrees each axis
stability of ± 0.02 degrees per second

The complexity of the pointing and tracking hardware required is dependent on the beamwidth (ie. the gain) of the transmit and receive antennas as well as the velocity and altitude of the spacecraft. In short, the narrower the beam, the more severe are pointing requirements. In order to dwell at a single spot on the earth's surface from a 765 km altitude while traveling at 7 km/s, the maximum rate of change of the look angle is roughly 0.5 degrees per second. The ability to do this with a .001 accuracy is within the reach of current technology.

Ground Station Requirements

The non-coherent optical receiver is a photon counting device. The receiving telescope focuses the incoming electromagnetic energy onto a photo-detector. The optical detector converts incident energy into electrical current. The photo-detector of choice is an avalanche photo-diode (APD) due to it superior weak signal performance. This is a specially engineered photo-diode that is operated in a reverse biased state. The electron-hole pairs generated by the incident number of photons (n) experience an avalanche multiplication through multiple collisions in the intrinsic region of the device. The end result is a greater number of electrons out (m) of the device than the number of photons incident on the device. The amount of average gain inherent in the device is a function of the reverse bias voltage. The gain of the device $G=\frac{m}{n}$ is a statistical quantity due to the random nature of the collision process. These statistics were first documented by McIntyre[4] and Conradi[5]. In other words the desired signal has noise like properties in of itself. The ultimate sensitivity of an optical receiver is determined by the smallest signal current that can be detected out of the photo-detector. This minimum detectable current is limited either by the thermal noise in the receiver circuits following the detector (characterized by the system noise temperature) or by the shot noise out of the photo-detector.

The input to the receiver consists of signal photons (n_s) as well as photons from background radiation sources (n_b). For the space borne receiver the field of view of the antenna is filled with the earth. This is modeled as a black body radiator at 300 K when viewing the dark planet and a 600 degree body when viewing sunlit clouds. The terrestrial receiver will see background radiation due to sunlit clouds in the worst case. This is again modeled as a blackbody at 600 K. The terrestrial receiver looking up at the nighttime sky will collect far fewer background photons. The number of background photons can be found to a first approximation from:

$$n_b = \frac{A_e S}{hf} \cdot \delta f$$

where:

n_b = number of background photons per second
A_e = effective aperture of the receive antenna
S = the flux density of the source based on Planks formula for blackbody radiation
h = Plank's constant: 6.626×10^{-34} J·s
f = the optical frequency
δf = the bandwidth of the receiver optics

The value used in the example link design that follows is $n_b = 1 \times 10^{10}$ photons/second, representative of daylight conditions.

The problem of acquiring the narrow beam from a spacecraft moving at speeds of 7 to 8 km per second is a driving factor in much the system design. Experiments have been conducted and others are planned [6,7] to acquire, track and measure optical signals from space. Most of these trials have used a very wide aperture receive telescope (~1 meter diameter) with sophisticated and expensive tracking and pointing hardware at the ground station. To become viable, an optical LEOSAT ground station must be able to use a small diameter receive aperture and the barest minimum of tracking and acquisition hardware. The smaller the receive aperture, the wider the beam width. This is good, for it relieves pointing and tracking requirements. On the other hand, the wider the field of view the more likely the receiver will find the sun radiating directly onto the detector. This would saturate the receiver. Further, the amount of signal power is directly proportional to the effective area of the receive aperture. This is the classic trade-off for power limited free-space links: antenna gain verses pointing and tracking requirements.

Example Link Design

P_T	0.0 dBW	1 W Peak power: Diode Array at 500 mW average Power [9]
L_T	– 0.5 dB	Loss in transmit optics
G_T	91.3 dB	Gain transmit antenna: 1 cm diameter
L	– 261.0 dB	Free space loss. Distance: 765 km
G_R	91.3 dB	Gain receive antenna: 1 cm diameter
L_R	– 0.5 dB	Loss in receiver optics
P_R	– 79.4 dBW	Power received
P_{req}	– 98.5 dBW	Power required. 10^{-6} BER (300 photons/pulse)
Margin	19.1 dB	

An example link design is shown above. This link is for a 1 Mbps downlink from a LEOSAT at a 765km altitude. The photodetector is a silicon APD with the link operating at a nominal 0.850 micron wavelength. This wavelength is easily obtainable with today's GaAlAs semiconductor lasers. The transmit power is 1 W peak representative a diode array.

The modulation used in this link is Binary Pulse Position Modulation (BPPM). The BPPM signal consists of a binary word divided into two slots. If the pulse arrives in the first slot then the data sent was a "1". If the pulse arrives in the second slot then the data sent was a "0". PPM formats have been shown to be superior to OOK in free-space optical signaling.[8] The optimum receiver for PPM is one that forms a comparison of the signal strength received in each of the two slots and makes a decision by choosing the slot with the greatest signal. This eliminates the need for a threshold determination and can be easily implemented with a delay line and a comparator. The minimum required power is based on the work of Safren[1].

The 1 cm diameter antennas have a 3 dB beamwidth of approximately .0047°. This results in a spot diameter of approximately 63 meters. The path loss shown is for a distance corresponding to a ninety degree elevation angle. Assuming the horizon is at a 10° elevation angle, the satellite will be approximately 2300 km away. This change in distance adds another 9.6 dB to the path loss. The margin then becomes 9.5 dB when the satellite is at the horizon. This margin and the margin above are what remains before accounting for atmospheric losses and fading.

Conclusions

Using optical frequencies for LEOSAT communications links eliminates competition for scarce RF spectrum, and offers the possibility of substantially increased data rates compared to the current generation of UHF/VHF satellites. A number of problems arise which must be solved in practical links. Notably in achieving the required pointing accuracy of the satellite and earth station antennas due to the very narrow beams while communicating through a highly intermittent channel.

References

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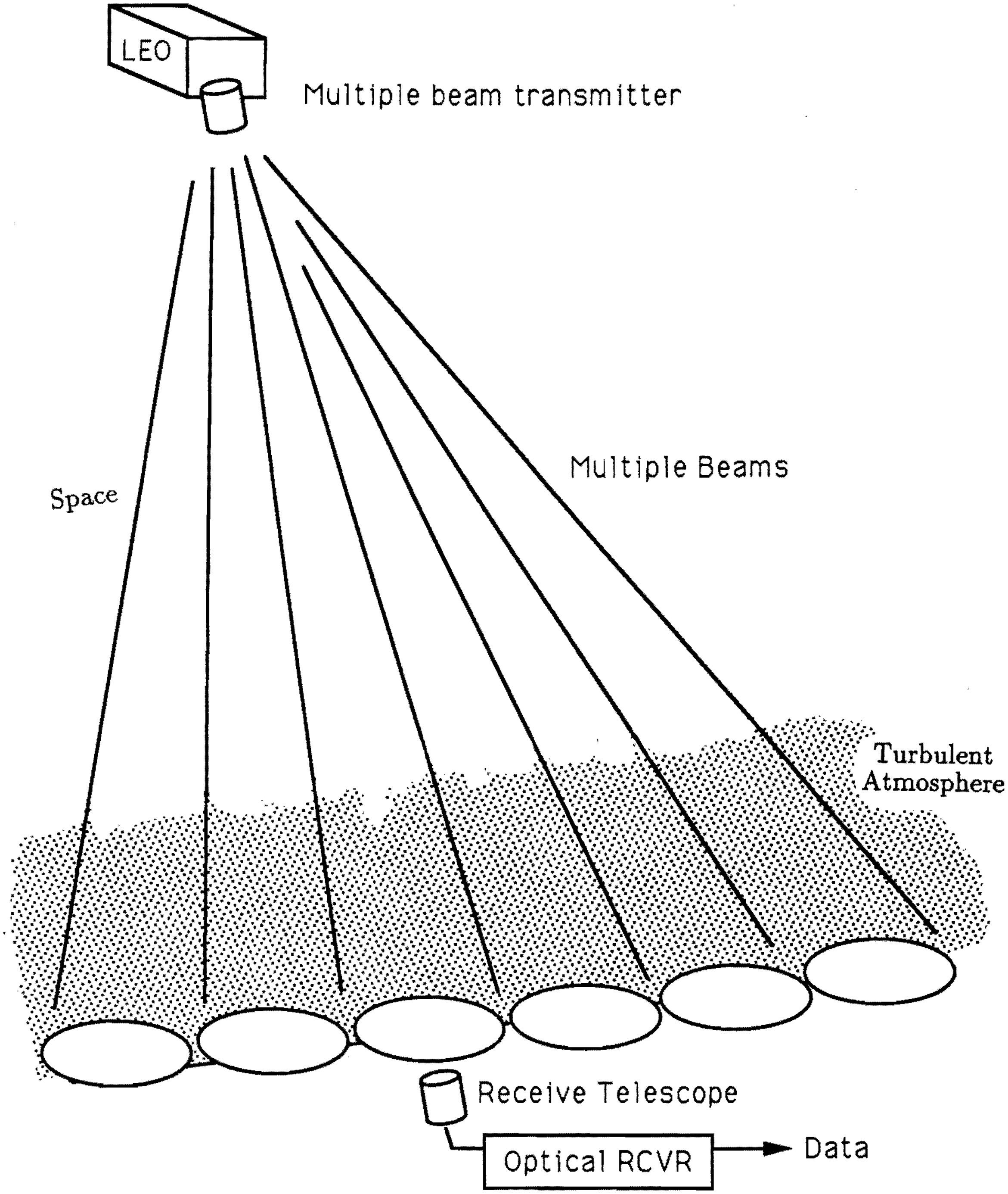
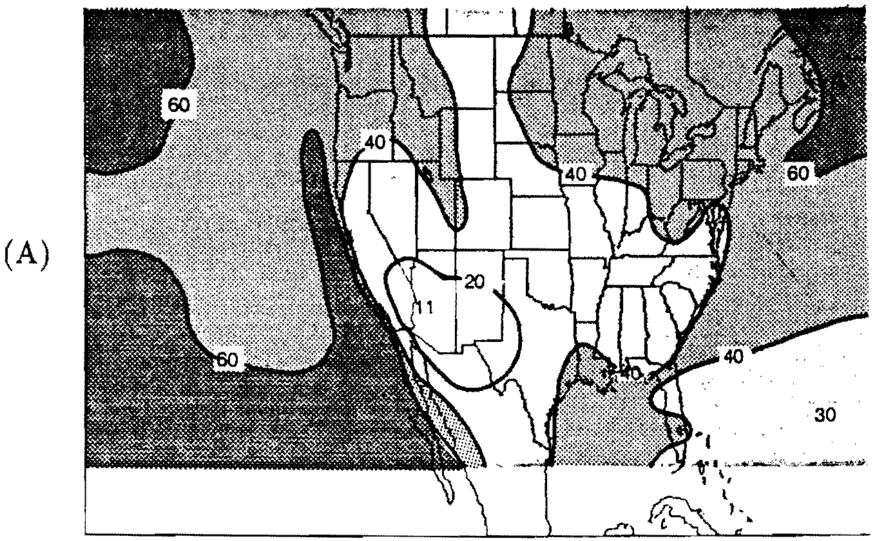
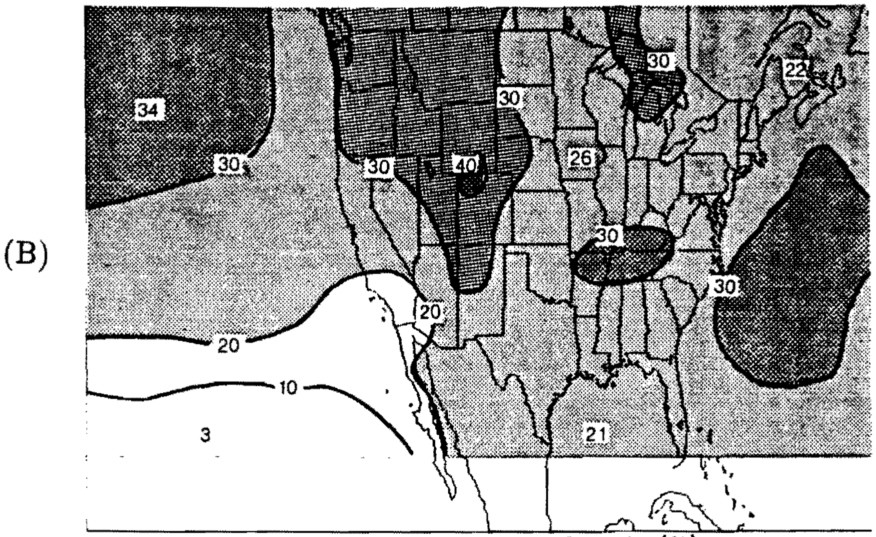


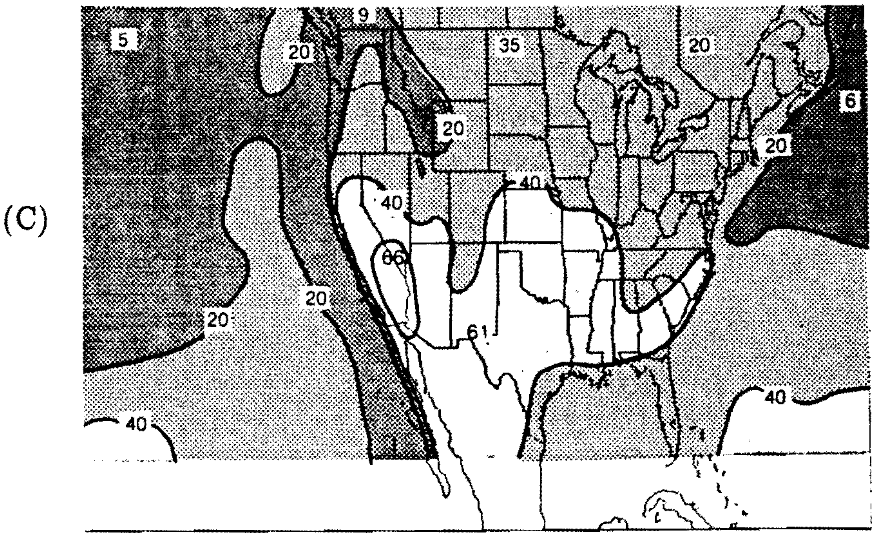
Figure 1.
Possible Optical LEOSAT Scenario



Probability of Opaque Cloud Cover (%)



Probability of Cirrus Clouds (%)



Probability of Clear Sky (%)

Figure 2.

The geographical distributions of (A) cloudy, (B) cirrus, and (C) clear sky conditions fror October 1985 through October 1987. (From Reference 2)