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Satellite Laser Communication With Widely Dispersed Ground Stations

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Abstract
We use a cloud attenuation model derived from key Italsat results to find laser cloud attenuation for satellite-ground links. Gaseous attenuation is included for 2-10 micron attenuation with the aid of a MODTRAN model. New silicon laser developments at 3 microns allow special 10 and 3 micron comparisons. Ten microns are emphasized. High worldwide laser attenuation and relatively low link availability are indicated for latitudes south of Washington, DC.

Link availability is raised with suitable Northern Latitude satellites, such as Earth Observation Satellites. Soviet cloud correlation results indicate that link availability would be raised to acceptable levels with ground sites separated by 100-390 km.

1. Introduction
The Jet Propulsion Laboratory and Kim (1,2) have recognized that optical communication near one micron wavelength can offer significant broadband advantages for satellite to ground communication links. They recognized that optical advantages over conventional satellite frequencies at 12-14 GHz included small size, low cost convenient signal processing, and freedom from government frequency regulations. Laser communication links also hold the promise of high data rate. Satellite-ground links would, however, be complicated by propagation loss and sporadic availability.

Chu and Hogg (3) allowed us to note (4) that 10 micron lasers would have less atmospheric attenuation than 1 micron lasers. The 10 micron attenuation (function of longitude, latitude, and link availability) is available as a Mathematica function (4). The results can be shown as zenith attenuation maps, and we emphasize modest 80% availability here for reasonable link attenuation. We include attenuation, size, and cost features here for a fuller comparison of lasers for satellite-ground links. We combine the Chu and Hogg cloud attenuation results with the discrete atmospheric windows shown by MODTRAN (5). These windows include favorable observations near 2, 3, and 10 microns.

Laser links might be especially useful for sun synchronous Earth Observation Satellites. Landsat 4 and 5 missions were precursors to the valuable missions which may occur for EOS, but we reconsider the 701 km Landsat altitude. Large clouds of space debris were released by the Chinese antisatellite test of January 2007. The average altitude of the debris...
is near 800km, and we suggest new sun synchronous orbits near 1000 km. We show a key equation for required sun synchronous inclination (Appendix A) as a function of semi major axis, and we show the altered inclinations for the new altitudes. We show figures of the new earth observation orbits.

The Chu and Hogg cloud attenuation implied notable advantages for 10 micron lasers relative to the shorter wavelengths. In addition, we use a MODTRAN model to show atmospheric transmittance regions between 1 to 10.6 microns. The combination of Chu and Hogg cloud attenuation with MODTRAN gaseous attenuation is used as a basis for comparisons of laser links. The combination often favors 3 and 10 micron links. The attenuation results are also found to be a strong function of Latitude and Longitude. Worldwide attenuation plots are emphasized for the 10 and 3 micron regions. The shorter wavelengths are indicated to become competitive with 10 micron attenuation at Latitudes greater than 50 degrees north. Communication links at Northern latitudes are especially interesting for EOS because downlinks are concentrated near the poles. The polar EOS tends to have successive repeat passes over Northern ground stations.

The shorter wavelengths also have some intrinsic advantages in size and system cost. Satellite system cost studies as Teichmann (6,7,8) tend to place high emphasis on system antenna gain. More than half of the system cost for optimum system studies was implied to reside in the antenna subsystem to achieve high gain. The shorter wavelength lasers would overcome part of their attenuation disadvantages by achieving high gain at small apertures. We discuss the system cost relations of lasers in the 2 to 10 micron region, and find that 3 micron lasers may be competitive with 10u EOS downlinks at high latitudes.

2. Recent Developments

Recent Silicon Laser Developments

We applied the Chu and Hogg insights to the cloud water content which can be derived from key millimeter wave results of Barbaliscia et al (9,10) by analytical methods (11,12). Ten micron communication links appeared attractive at mid and high latitudes. Also, Frank Hanson (13) had fascinating comparisons of 10 microns and 3 micron links.

Since then (14), important new silicon laser developments have been proceeding rapidly. Bahram Jalali observed that silicon allowed photon-phonon exchange (the Raman Effect) to proceed better than in other materials. He has noted that silicon lasers are promising for 2.3 to 7 micron radiation. Fig. 2-1 is a schematic of the Jalali amplitude as the radiation traverses a silicon light pipe. The amplitude builds rapidly along the length of the silicon.
Satellite Laser Communication With Widely Dispersed Ground Stations

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The Chu and Hogg cloud attenuation implied notable advantages for 10 micron lasers relative to the shorter wavelengths. In addition, we use a MODTRAN model to show atmospheric transmittance regions between 1 to 10.6 microns. The combination of Chu and Hogg cloud attenuation with MODTRAN gaseous attenuation is used as a basis for comparisons of laser links. The combination often favors 3 and 10 micron links. The attenuation results are also found to be a strong function of Latitude and Longitude. Worldwide attenuation plots are emphasized for the 10 and 3 micron regions. The shorter wavelengths are indicated to become competitive with 10 micron attenuation at Latitudes greater than 50 degrees north. Communication links at Northern latitudes are especially interesting for EOS because downlinks are concentrated near the poles. The polar EOS tends to have successive repeat passes over Northern ground stations.

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![Silicon Laser Image Amplifier, as Bahram Jalali](https://www.intechopen.com)

Fig. 2-1. Amplitude v. Length for Silicon Laser, after Jalali May10 – Jalali2.nb.

The effectiveness and reliability of the silicon lasers in the estimated 2.3-7 micron range is a strong inducement for us to include this range of wavelengths for Earth Observation Satellite laser link studies.

Intense Satellite Debris Field Developments
A Chinese anti-satellite test in January 2007 left an enlarged debris field between centered near 800 km altitude. It stretches from 700 km to over 900 km altitude. In addition, a Russian satellite hit a valuable Iridium satellite in 2009 at lower altitude. Therefore, we alter a useful 701 km Landsat orbit to nearly 1000 km altitude. The inclination must also be altered to keep the useful sun-synchronous features. Fig. 2-2 indicates the mean debris field, and Fig. 2-3 the higher orbit required to clear the debris. Appendix A discusses the change in inclination needed for the higher orbit.
Valuable EOS views of Earth include the endangered Arctic region (Fig. 2-4). The coastlines are shown in relief so that visibility regions can be found quickly.

3. Laser Propagation Comparisons

Four decades ago, Chu and Hogg attempted to compare optical communication with infrared communication at 10.6 microns for terrestrial communication. They found that 10 micron signals propagated much better through fog than did the optical communication.
Fig. 3-1 indicates the kind of signal loss they anticipated over a wide range of frequencies. The upper curve indicates loss through 1 km of fog with 0.1 gm/m³ liquid water density, vs Frequency on the abscissa. Note that 10 microns corresponds to 30 THz and the 1 micron region corresponds to 300THz. The fog comparison for this figure indicates about 60 dB and 200 dB loss, respectively, for the two frequencies.

Cloud attenuation can be estimated as a function of worldwide location and desired availability. An 80% availability was used for 10 micron propagation in order to keep propagation loss to reasonable levels. A form of Quad-Diversity was chosen for the ground site to get desired overall link availability. Four sites on the order of 15 km apart were used to approach 98-99% availability. The diversity section below will indicate even higher link availability at hundreds of kilometer separation.

We also add gaseous attenuation here for completeness. A smoothed MODTRAN result is seen as Fig. 3-2. It includes gaseous attenuation for a moderate atmosphere.
The MODTRAN model can be combined with the cloud zenith attenuation model to indicate low attenuation at 10\(\mu\) and 3\(\mu\).

Variations in attenuation for the 10 micron and 3 micron maps may be seen as Figs. 3-3, -4.

The ten micron cloud attenuation varies, as clouds form and dissipate. The attenuation may be described by an exponential probability density function, with high attenuation at the 90\(^{th}\) percentile level. For convenient probability calculations, this may be referred to as the 10 percent exceedance level. Fig. 3-5 shows the intense attenuation that a ground observer would experience by looking straight up (zenith), looking through the clouds. An observer near Miami may experience hundreds of dB attenuation.

Fig. 3-2 Smoothed MODTRAN Transmission v. Wavelength, Microns

Fig. 3-3 10 Micron Attenuation Map  Fig. 3-4 3 Micron Attenuation Map

80% Availability
Many successful systems would require attenuation less than 10 or 15 dB. Lower link availability, as Fig. 3-6, would be required. Fig 3-6 indicates zenith attenuation at 80% availability, and many important ground sites in northern New England (note Boston 42 deg North) may enjoy reasonable attenuation as 10 dB.
Zenith attenuation at 10 microns is notably less than attenuation at 3μ (Fig 3-7).

Fig. 3-6 10μ Zenith Attenuation in Northern Hemisphere 80% Availability [PR=.2] Mathematica Jan22010—nb.

Fig. 3-7 Worldwide 3μ Attenuation Contours, 80% Availability [PR=.2] Jan12010—nb.

The asymmetry in the attenuation contours between the northern and southern hemispheres is apparent in Fig. 3-8. In addition, the attenuation of the southern hemisphere has not been as thoroughly studied as the northern hemisphere.

The 80% attenuation can offer interesting ground sites, but if we let availability standards slip even further to 70%, the area of ground sites expands sharply, as in Figs. 3-9 and -10.

The areas east of Cuba and off West Africa are the only intense propagation loss regions remaining at both 3μ and 10μ in Figs. 3-9 and -10, respectively.
The modest 10 micron attenuation at 80% availability allows attractive communication sites to appear, as Bangor Maine near 10 dB loss and 50dB near Washington DC, as in Fig 3-8. Difficult or untenable attenuation as 80-100 dB is indicated near Charleston, SC.

Fig. 3-8 Worldwide 10μ Attenuation Contours, 80% Availability [PR=.2] Jan12010—nb.

The asymmetry in the attenuation contours between the northern and southern hemispheres is apparent in Fig. 3-8. In addition, the attenuation of the southern hemisphere has not been as thoroughly studied as the northern hemisphere.

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The attractive coverage for 3u at 70% availability extends even further into the Southern Hemisphere for 10u, as in Fig 3-10. Appendix B lists the 10u attenuation equation.

Of course, the limited single link availability we have discussed here is not acceptable for most important communication applications. Key Japanese tests (15) of 1u laser links addressed the question of extending the observed 20% single link availability. They placed laser receiver sites throughout the country, and were delightfully surprised that availability increased to greater than 90%. The Soviets may have anticipated this sharp rise in availability with cloud correlation studies in the early '70s. We will address the Soviet cloud correlation function in Section 4, to imply much better availability when 100-390 km site separation is available.

The ratio of 3micron/10micron attenuation can also be found. The ratio appears useful for estimating where 3 micron lasers could be seriously considered as an alternative to 10 microns. Fig. 3-11 uses the ratio, and draws contours at locations where 3 micron lasers are estimated to be competitive. Regions north of the contours of Fig. 3-6 may be considered as reasonably competitive 3 micron regions. Note that regions north of Labrador and Denmark appear to be a demarcation for 3 micron laser use.

Cost Advantages for 3 Microns

Key satellite system optimization studies (6,7,8) have placed a heavy emphasis on system antenna gain. Further, high gain at small size and cost is emphasized. Lasers can provide this high required antenna gain, but with disadvantages of high propagation loss.

A cost term as $\text{Cost/Bit}=\frac{1}{3}\left(\text{Loss dB} - 20\log F\right)$ was found (5) to include both the loss disadvantages and the gain advantages of a satellite system. This is also closely related to a method of minimizing $(\text{Loss dB} - 20\log F)$ for millimeter wave system. This cost per information bit method can be applied to Fig. 3-6 to find the transition line moves slightly south for the system cost comparisons, as Fig. 3-12.
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![Fig. 3-11 Contours of 10u/3u Attenuation; Transition Contours to 3u at Labrador-Denmark](Mathematica May7—CountryBig.nb)

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$$\text{Cost/Bit} = \left(\frac{\text{loss}}{f^2}\right)^{1/3}$$

was found (5) to include both the loss disadvantages and the gain advantages of a satellite system. This is also closely related to a method of minimizing \((\text{Loss,dB} - 20 \log F)\) for millimeter wave system. This cost per information bit method can be applied to Fig. 3-6 to find the transition line moves slightly south for the system cost comparisons, as Fig. 3-12.
A transition region to 3 microns is now indicated to move south from Labrador to Northern Maine.

**Intense 10μ Attenuation at 90% Availability**

The modest 80% availability attenuation of Figs 3-8 would require ground site diversity for useful communication. Alternatively, one might consider 90% availability for single sites (Fig. 3-13).
Severe 100dB zenith attenuation contours are indicated at Labrador and Denmark if 90% availability is required for single links.

4. Diversity Analysis

Boldyrev and Tulupov (16) developed cloud correlation functions to describe the cloudy/clear relations between two separated ground stations. The correlation functions were compiled from many satellite observations, with large scale characteristics for hurricanes and much smaller sizes for more typical observations. Fig. 4-1 shows correlation function results for a number of different seasons.

Boldyrev and Tulupov recognized that a correlation for all clouds could be represented conveniently by

\[
\text{Cloud correlation} = 0.2e^{-x} + e^{-0.036x} - e^{-0.15x} + 0.8e^{-0.003x} \cos(0.0075x)
\]  

(4-1)

where x= separation, km

Their insight into the importance of the correlation function will next be seen with a description of Pierce’s bivariate exponential probability density function.
Boldyrev’s function can be used as a direct input into a correlated bivariate exponential pdf, and then to develop quantitative results for diversity advantages. We use the form of the correlated exponential pdf as:

$$p(A_1, A_2) = \frac{e^{-\frac{A_1 + A_2}{B(1-r)}} P}{B^2 (1-r)^2} \left(1 - \frac{A_1 A_2}{B^2 (1-r)^2}\right)$$

(4-2)

where $A_1$ and $A_2$ are the rain attenuation (dB) at the 2 sites
$r$= correlation between sites, found from Boldyrev
$B$=standard deviation of the univariate pdf, and
$p$= conditional probability that rain attenuation is observed; as 0.80

![Fig. 4-2. Pierce’s Correlated Exponential pdf; rho=0.8](image)

The double integral on the density function should be evaluated to find the joint probability of exceeding arbitrary attenuation levels. The probability of both sites having attenuation greater than $AR$ (dB) may be functionally shown as Eq. 4-3.

$$P[A_1>AR, A_2>AR]$$

The bivariate function of Fig. 4-3 is defined for all possible weather events, even clear weather at both ground sites. Instead, the exponential density function should be defined for rain events in the 1% to 0.1% range: This is where the exponential pdf has the most relevance. We note again that $PR= -0.1$ corresponds to 90% availability.

The Boldyrev function offers even more promise for ground diversity, however.


\[ P[A1>AR, A2>AR] = \]

\[
\frac{p}{\int_{AR}^{\infty} \int_{AR}^{\infty} e^{-\frac{A1+A2}{B(1-r)}} I_0 \left( 2 \sqrt{\frac{A1A2r}{B^2(1-r)^2}} \right) dA2 dA1}{B^2(1-r)}
\]

(4.3)

The low values of the Boldyrev correlation function \( r \) will be key to finding low probability of attenuation \( AR \). System operators will recognize \( AR \) (dB) as the rain attenuation available with switched diversity, when they can choose the site with the least rain attenuation.

The integral has not yielded to attempts to integrate it exactly, and it turns out to be a very lengthy numerical integration. An upper limit is chosen as (10 B) rather than infinity. The exceedance probability (Eq. 2-3) is abbreviated as \( (pr) \) below.

The result of the double integration can be found as Figures 4-3 and 4-4. Fig. 4-3 shows exceedance probability \( (PR=\log_{10}(pr)) \) v. normalized \( (AR/B) \) and correlation coefficient \( r \). Exceedance probability contours may also be shown as Fig. 4-4 for \( 0<r<1 \).

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The Boldyrev function offers even more promise for ground diversity, however.
The integral can be evaluated numerically even for negative correlation, as occurs at 390 km for the Boldyrev function. Sharp new benefits can be found in the results of Fig 4-5, with the negative correlation in the 200km-390 km interval as specified by Boldyrev.

The joint exceedance probability is seen to take a quantum step down in the 200-390 km region. This means that if one ground site has bad weather, another ground site 200-390 km away probably has good weather. Indeed, one can test this by experience: if you get a blizzard, your cousin 300 km away is likely to have brilliant blue skies. Two widely separated ground sites are not just better than independent sites, but are much better. Fig. 4-5 extends 4-4 to negative correlation, and the sharp change in PR can be seen at correlation $r=-0.2$.

A short approximation for the exceedance probability PR can be found as:

$$\text{Log10[Exceedance]} =
0.131989 - 0.861214 \text{AR} + 0.011358 \text{AR}^2 - 1.69174\frac{1}{2}r^2 - 50(-0.02-r)^2 + 0.083318r + 0.603411\text{AR}r - 0.65129r^2
$$

Where AR is single link attenuation(dB), with standard deviation B=1

$$r=\text{cloud correlation coefficient}
$$

The probability contours may be seen more clearly as Fig. 4-6.
Satellite Laser Communication With Widely Dispersed Ground Stations

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The PR contours can be checked immediately by comparing the PR=-1 and PR=-2 curves. At constant attenuation AR, point (*) at correlation=1 corresponds to point (**) at correlation=0. This is necessary because 0.1 exceedance must correspond to 0.01 at zero correlation. The benefits of negative correlation, as seen by Boldyrev, are seen by further dropping to point 3 (***) at correlation= -0.2. Point 3 shows much better probability, approaching PR=-3 or 0.001 exceedance probability, or 99.9% availability.

Fig. 4-6 Probability Contours v. AR/B, Correlation Coefficient $r$

Mathematica Jan18PROBlistb--.nb.
Fig. 4-7 imposes the Boldyreov correlation function as a function of distance. The cloud correlation function is 1 at $x=0$ and drops to 0 at $x=200$ km. It then drops to negative values for $200<x<390$ km, and exceedance probability $PR$ drops abruptly to give clear advantages over independent sites. With independent sites (correlation=0) a single site outage probability of 20% would drop to 4%, or 96% availability. Site separation as 300-390 km would imply even better availability, from further analysis of Fig. 4-6.

The 80% exceedance (20% availability) of the Japanese experiments would be implied to improve to nearly 85% availability, with an approximate solution of Fig 4-7. The approximate solution is seen as the contours of Fig 4-8. The Japanese experimenters were delighted with results near 90% availability for widely separated ground stations in Japan.
Fig. 4-7 PR v. Attenuation, Distance (km) by Boldyrev and Pierce Mathematica Jan122010—Boldeyrev.nb

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6. Summary

We applied Chu and Hogg’s key cloud attenuation results to Italsat observations (9) and cloud water analysis (11) to estimate worldwide laser attenuation for satellite-ground communication links. Section 3 gave worldwide zenith attenuation estimates for 80% availability, 90% availability, and 70% availability. The equation for cloud attenuation at 70% availability is given in Appendix B. We emphasized 10 micron wavelengths and 80% availability for modest attenuation. Reasonable availability was suggested by using Boldyrev and Tulupov’s negative cloud correlation at large distances, as 200 – 390 km. Section 4 outlined the analysis and anticipated results for dual switched ground sites. Fig. 4-8 anticipated the encouraging current Japanese (15) results: 20% single site availability growing to over 85% at 300 km site separation. Eighty percent availability and zero
correlation at 200 km were indicated to give 96% availability for the dual sites, and 390 km was indicated as notably better. Even better performance should be expected for quad diversity. We addressed possible 10 micron laser reliability issues by considering new silicon lasers in the 3-10 micron range. The cloud attenuation model (1,2) and a smoothed MODTRAN atmospheric transmission model indicated the 3 micron space-ground attenuation as too high except in regions north of Labrador-Denmark. The 3 micron lasers might be well suited to small Earth Observation Satellites with widely dispersed ground sites at far northerly latitudes. Laser space-ground links would be similarly attractive for Molniya satellites and temperate and Arctic ground locations. Indeed, Molniya satellites may avoid a difficult acquisition concern intrinsic to the fast moving EOS. The Molniya satellites would have an additional concern: attenuation would be slightly higher than the zenith attenuation shown here. This has been addressed at the Ka Conference in Naples (4).

Acknowledgements


7. Reference

K.E. Wilson et al, “Overview of the Ground-to-Orbit Lasercom Demonstration,” Free-Space Laser Comm. Tech IX, SPIE, Jan. 1997. The GOLD experiment was intended for ground to GEO communication with the Japanese ETS-VI satellite. Instead, the ETS-VI was stuck in the transfer orbit and only partial data was collected. The 1.024 MB/s links showed 10E-4 BER on the uplink and 10E-5 BER on the downlink.


T.S. Chu and D.C. Hogg, “Effects of Precipitation at 0.63, 3.5, and 10.6 Microns”, Bell System Technical Journal, May-June 1968


Appendix A Required Inclination for Higher EOS Orbit

The typical Landsat 4 orbit, at 701 km altitude, and 98.4 degrees inclination, must be altered for higher altitudes. The method of Osculating Elements shows the rate of change of Right Ascension as

\[
3 J_2 \frac{\mu}{a^3} r^2 (5 \cos^2(i) - 1)
\]

with \(i\) as the inclination, \(a\) as the semimajor axis, and \(\mu\) the Earth gravitational constant.

![Figure A-1 Required Inclination for Sun Synchronous Orbits May17-LS4b.nb](https://www.intechopen.com)

The shift from the Landsat 4 altitude to 1000 km is seen to require almost 99.5 deg inclination.
Appendix B 10 Micron Zenith Attenuation, dB PR=.3

This Mathematica program is available from the author. It gives zenith attenuation maps at 70% availability.

Zenith Attenuation [70\%] =

\[
\text{dB} (B-1) = 0.002092 \times 10^{-10} \times \text{LAT}^2 + 2.2092 \times 10^{-10} \times \text{LAT} + 0.00041968 \times \text{LON} + 2.18986 \times 10^{-10} \times \text{LON} + 2.44557 \times 10^{-10} \times \text{LAT} \times \text{LON} - 0.000011487 \times \text{LON}^2 + 1.0003 \times 10^{-10} \times \text{LAT} \times \text{LON} - 1.38021 \times 10^{-10} \times \text{LON}^2 + 1.38016 \times 10^{-10} \times \text{LON}^3.
\]

Where LON = Longitude, deg East
LAT = N. Latitude
Mathematica [Jan2—Point3.nb]

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This study is motivated by the need to give the reader a broad view of the developments, key concepts, and technologies related to information society evolution, with a focus on the wireless communications and geoinformation technologies and their role in the environment. Giving perspective, it aims at assisting people active in the industry, the public sector, and Earth science fields as well, by providing a base for their continued work and thinking.

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