Wireless optical transmission of fast ethernet, FDDI, ATM, and ESCON protocol data using the TerraLink laser communication system

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Abstract. The TerraLink laser communication (lasercom) system was developed as a cost-effective, high-bandwidth, wireless alternative to fiber optic transmission. The advantages of lasercom over fiber optic cabling are primarily economic. However, free-space lasercom is subject to atmospheric effects, such as attenuation and scintillation, which can reduce link availability and may introduce burst errors not seen in fiber transmission. The TerraLink transceivers use large receive apertures and multiple transmit beams to reduce the effects of scintillation. By designing the lasercom link with sufficient margin for atmospheric attenuation and scintillation, a bit error rate (BER) of 10^{-9} or better can be achieved. Since we designed the TerraLink transceivers to be eye-safe at the transmit aperture, each system is range-limited. Link power budgets for the TerraLink systems are presented, and link margin data are shown that quantitatively describe how the effective laser link range varies in different weather conditions. Since the TerraLink transceivers act as simple repeaters, they are protocol-independent. Examples of TerraLink installations transmitting wireless fast ethernet (125 Mbits/s), fiber distributed data interface (FDDI) (125 Mbits/s), asynchronous transfer mode (ATM) (155 and 622 Mbits/s), and Enterprise Systems Connection (ESCON) (200 Mbits/s) protocol data are presented. [S0091-3286(98)00812-5]

Subject terms: laser communication; infrared; link budget; scintillation; ethernet; fiber distributed data interface; asynchronous transfer mode; ESCON.

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1 Introduction

Free-space laser communication (lasercom) can provide a line-of-sight, wireless, high-bandwidth, communication link between remote sites. Data is transmitted by modulated laser light in a fashion similar to fiber optic cable transmission. Instead of a contained glass channel, however, the laser beam travels through the atmosphere. Laser communication has many advantages over other wireless technologies, such as microwave or rf spread spectrum. These advantages include much higher data rates (presently 622 Mbits/s with plans for 2.5 Gbits/s in the future) and increased security because of the laser's narrow beam (see Fig. 1), which makes detection, interception and jamming very difficult. Because of its superior security, lasercom is ideal for the wireless transfer of financial, legal, military, and other sensitive information. Another major advantage of lasercom over rf is that no Federal Communications Commission (FCC) licensing or frequency allocation is required. In some large urban areas or near airports, it is very difficult or impossible to obtain frequency allocation for microwave transmission. Laser communication terminals are also portable and quickly deployable, which make them ideal for disaster recovery and temporary installations. The advantages over fiber optic cabling are primarily economic. In most cases, laser communication is an attractive alternative to the prohibitive cost of trenching the streets to lay fiber, the logistical complexity of obtaining right-of-way permits, or the recurrent costs of leasing fiber lines. The primary disadvantage of free-space laser communication is its vulnerability to atmospheric effects such as attenuation and scintillation, which can reduce link availability and may introduce burst errors. The narrow transmission beam also makes alignment of the laser communication terminals more difficult than the wider beam rf systems. This paper quantifies the effects of weather and scintillation on the availability of laser communication. It is important to understand these limitations to effectively use laser communication as a point-to-point wireless connectivity tool.

2 TerraLink Laser Communication System

TerraLink* lasercom systems can provide a full-duplex, protocol-independent communication link at data rates up to 230 Mbps at ranges up to 8 km, and at 622 Mbps at ranges up to 3.5 km (Ref. 1). Diode lasers are used to transmit the data and the detector is an avalanche photodiode (APD) or a p-i-n detector. All TerraLink models are eye-safe at the transmit aperture. The TerraLink transceivers use multiple transmit beams and large receive apertures to reduce the effects of scintillation.[2,3] Autotracking isavailable to compensate for building sway. A serial computer

*TerraLink is a trademark of AstroTerra Corporation.

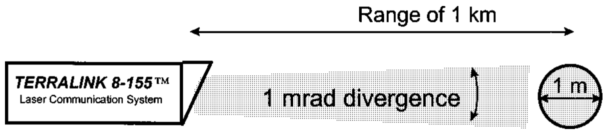

Fig. 1 Narrow beam of the TerraLink laser communication system. The narrow beam makes laser links a very secure means of communication. It is very difficult to detect, intercept, or jam the transmitted signal; however, the narrow beam also produces alignment difficulties. A 1 mrad divergence (which is the divergence of the TerraLink 8 series) produces a spot size of 1 m in diameter at a range of 1 km.

interface provides laser output power and receive signal strength information. There are presently six TerraLink models of which three were used for this study. The TerraLink 4-155 system provides a line-of-sight laser link between sites up to 2 km apart in clear weather. The data rate is adjustable from 10 to 230 Mbps. The TerraLink 4-155 has separate 4 in. diameter transmit and receive apertures. The TerraLink 8-155 uses a single 8 in. diameter aperture for both transmit and receive (see Fig. 2). The maximum clear weather range is 8 km. To avoid optical crosstalk within the single aperture, separate laser wavelengths are used for transmit and receive (780 and 852 nm). A CCD camera, integrated with an external spotting scope with a field of view of 6 deg, is used for initial alignment. Fine alignment is achieved using an internal CCD camera with a field of view of 1.5 mrad. The alignment gimbal is motorized and controlled by a serial computer interface, enabling remote alignment. RS-422 serial cables and RG-59 video coaxial cables can be strung from the TerraLink unit on the rooftop to a control room inside the building, enabling periodic realignment from the comfort of the control room (instead of the roof). Once aligned, autotracking can be incorporated to compensate for building sway. The divergence of the transmit beam is 1 mrad. The TerraLink 8-622 system is presently the only commercial wireless system capable of transmitting data at OC-12 speeds of 622 Mbps. The optics are similar to the TerraLink 8-155, with a single 8 in. diameter aperture for both transmit and receive paths. The maximum clear weather range is 3.5 km.

The technology for the TerraLink laser communication system was fostered from the Ballistic Missile Defense Organization (BMDO) sponsored LEO satellite laser communication program developed at AstroTerra Corporation[4,5] (San Diego). The Space Technology Research Vehicle (STVR)-2 satellite laser communication terminal (see Fig. 3) is scheduled to launch in May 1999. It will carry a mid-wave infrared (MWIR) camera along with the lasercom terminal and other experimental payloads. Collected MWIR data will be transmitted down via lasercom as part of the STRV-2 experiment. The satellite transceiver is designed to communicate to a ground terminal at a maximum data rate of 1.0 Gbps (two channels at 500 Mbps). Each channel has four 1 in. transmit aperture lasers, and are separated by right and left circular polarization. The receive aperture is 5.5 in. in diameter. The lasercom transceiver is designed for satellite-to-ground ranges of 600 to 1800 km. The ground station will consist of three 12 in. transmit apertures and a single 16 in. diameter receive aperture.[6] The ground station will be the baseline for a future terrestrial laser communication unit with a maximum range of 50 km and maximum data rate of 2.5 Gbps.

3 Terralink Link Budget

The laser power link budget for the first generation (1996) TerraLink 8-155 as a function of link range (1, 4, and 8 km) is shown in Fig. 4. The average power leaving the transmit aperture is measured to be 20 mW (13 dBm). The minimum average power required at the detector to give full modulation depth at 155 Mbits/s is 25 nW (-46 dBm). This specification is baselined for a bit error rate (BER) of 10^{-9}. The loss due to mispointing error is estimated to be 3 dB. Receiver optical losses were measured to be 9 dB. The geometrical spreading loss is simply the ratio of the surface area of the receive aperture to the surface area of the transmit beam at the receiver. Since the transmit beam spreads constantly with increasing range at a rate determined by the divergence, the geometrical spreading loss depends primarily on the divergence and the range:

$$\text{Geometrical spreading loss} = \frac{\text{Surface area of receive aperature}}{\text{Surface area of transmit beam (at range } R)} = \frac{\mathrm{SA}_R}{\mathrm{SA}_T + \pi/4(\theta R)^2} \quad (1)$$

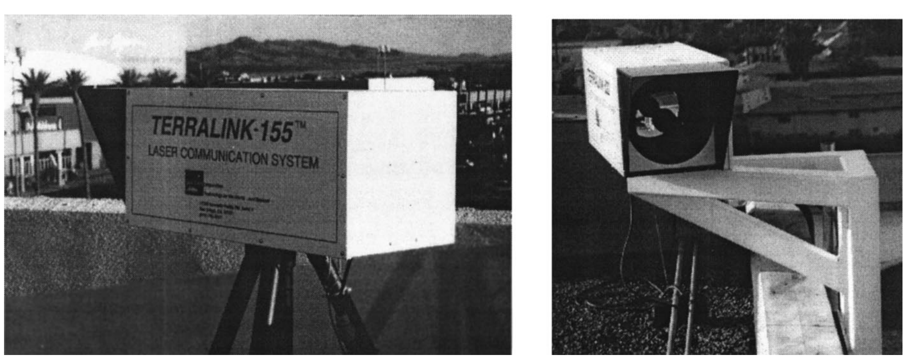

Fig. 2 TerraLink 8-155 transmitting 155 Mbps asynchronous transfer mode (ATM) during the 1996 Networld+Interop trade show in Las Vegas (left). The front view (right) shows the single 8 in. diameter aperture used for both transmit and receive. Maximum clear weather range is 8 km and data rates are adjustable from 1.5 to 230 Mbits/s. Computer-controlled alignment and autotracking are included as optimal features.

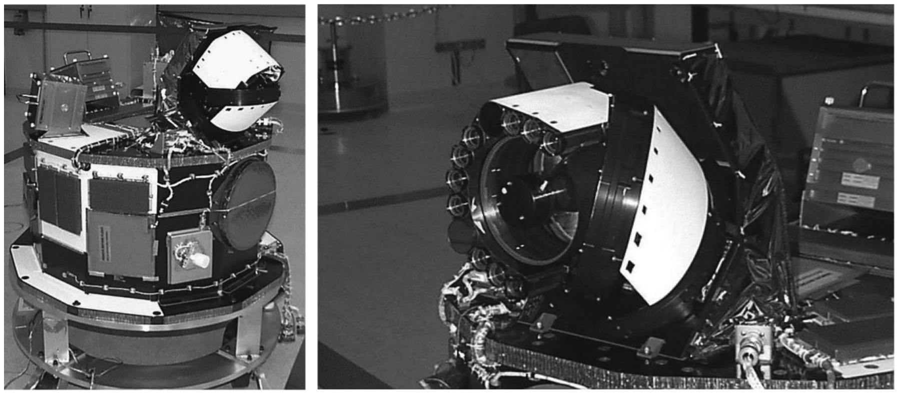

Fig. 3 AstroTerra/BMDO laser communication terminal mounted on the STRV-2 satellite top deck (left) and close-up of the lasercom satellite transceiver (right). It is housed in a two-axis gimbal with a 5.5 in. receive aperture and 8×1 in. transmit and 2×1 in. beacon apertures. The maximum data rate is 1.0 Gbits/s (two channels at 500 Mbits/s) and the LEO to ground range is 600 to 1800 km. The lasercom transceiver is 13.5 in. tall×11 in. wide×13 in. deep. Including electronics, payload weight is 31 lb and peak power consumption is 90 W.

where

SA_R = 0.005 m^2 for the TerraLink 4 and 0.025 m^2 for the TerraLink 8

SA_T = surface area of the transmit aperture =0.005 m^2 for the TerraLink 4 and 0.025 m^2 for the TerraLink 8

θ = divergence=3 mrad for the TerraLink 4 and 1 mrad for the TerraLink 8

R = range in meters.

As the range increases, the losses due to geometrical spreading increase (15 dB for 1 km, 27 dB for 4 km, and 33 dB for 8 km for the TerraLink 8-155).

What remains in the link budget is the margin for losses due to atmospheric effects. Atmospheric effects can be broken into two broad categories: losses due to atmospheric attenuation and losses due to atmospheric turbulence. The latter category is also broadly called scintillation, but also includes laser beam wander and laser beam spreading. The margins for scintillation losses through an 8 in. aperture were determined experimentally from a previous study.[1] As expected, the scintillation fade margin, which was baselined for a BER of 10^{-9}, was observed to increase with range (4 dB for 1 km, 6 dB for 4 km, and 9 dB for 8 km). The TerraLink multiple transmitter design reduces the required scintillation link margin compared to single transmitter products.[3] What remains in the link budget after removing the empirical scintillation fade margin is the

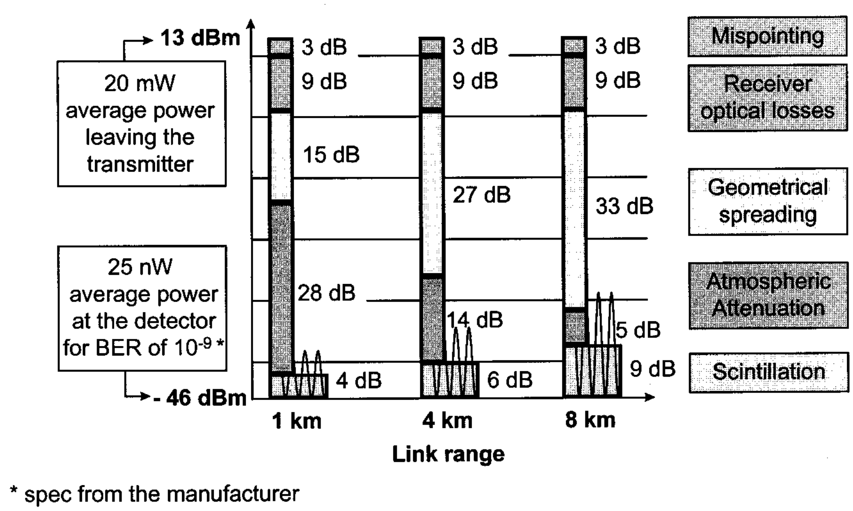

Fig. 4 Link budget for the early revision of the TerraLink 8-155 as a function of link range. The average power leaving the transmitter is 20 mW. Losses due to mispointing (3 dB) and receiver optical losses (9 dB) are constant for all ranges. As the range increases, the losses due to geometrical spreading increase. The margin for scintillation losses through an 8 in. receive aperture was empirically determined from a previous study[1] and also increases with range. The remaining margin is leftover for atmospheric attenuation. A continuous plot of allowable losses due to atmospheric attenuation as a function of link range is shown in Fig. 7 in Section 5.

margin for allowable atmospheric attenuation. This margin for allowable atmospheric attenuation decreases with link range (28 dB for 1 km, 14 dB for 4 km, and 5 dB for 8 km). Combining this margin for atmospheric attenuation with weather information determines the link range and availability of the TerraLink lasercom system. The determination of the maximum clear weather range for each TerraLink model is explained in Section 5. A more detailed description of the effects of the atmosphere on laser beam propagation is presented in the next section.

4 Atmospheric Effects on Laser Beam Propagation

Atmospheric effects on laser beam propagation can be broken down into two categories: attenuation of the laser power and fluctuation of laser power due to laser beam deformation. Attenuation consists of absorption and scattering of the laser light photons by the different aerosols and gaseous molecules in the atmosphere. Laser beam deformation occurs because of small-scale dynamic changes in the index of refraction of the atmosphere. This causes laser beam wander, laser beam spreading, and distortion of the wavefront or scintillation.

4.1 *Atmospheric Attenuation*

The attenuation of laser power in the atmosphere is described by Beer's law[7]:

$$\tau(R)=\frac{P(R)}{P(0)}=e^{-\sigma R}, \tag{2}$$

where

$\tau(R)$ = transmittance at range R

$P(R)$ = laser power at R

$P(0)$ = laser power at the source

σ = attenuation or total extinction coefficient (per unit length).

The attenuation coefficient is made up of four parts:

$$\sigma=\alpha_m+\alpha_a+\beta_m+\beta_a\,, \tag{3}$$

where

α_m = molecular absorption coefficient

α_a = aerosol absorption coefficient

β_m = molecular or Rayleigh scattering coefficient

β_a = aerosol or Mie scattering coefficient.

Aerosols include finely dispersed solid and liquid particles, such as water droplets, ice, dust, and organic materials. Aerosols vary is size from a few molecules to 20 μm in radius. The important atmospheric molecules that have high absorption in the IR band include water, CO_2, ozone, and O_2. There are transmittance windows in the absorption spectra of these atmospheric molecules. We selected laser wavelengths (780 and 852 nm) that fall inside these windows, so atmospheric and aerosol absorption are negligible.[7] Molecular or Rayleigh scattering varies as λ^{-4} (where λ is the wavelength) and is small at these near-IR laser wavelengths. Therefore, aerosol or Mie scattering dominates the total attenuation coefficient.[8] Attenuation due to Mie scattering is a function of the visibility and laser wavelength[7]:

$$\sigma=\beta_a=\frac{3.91}{V}\left(\frac{\lambda}{550\ \text{nm}}\right)^{-q}, \tag{4}$$

where

V = visibility in kilometers

λ = wavelength in nanometers

q = the size distribution of the scattering particles

= 1.6 for high visibility ($V>50$ km)

= 1.3 for average visibility (6 km $<V<$ 50 km)

= $0.585V^{1/3}$ for low visibility ($V<6$ km).

The decibel loss per kilometer for different visibility conditions in Table 1 are derived from the attenuation coefficients calculated using Equation (4). Laser communication outages due to the attenuation of laser light can be a serious problem during times of heavy fog.

4.2 *Atmospheric Turbulence (Dynamic Laser Beam Deformation)*

Occasional bursterrors of the order of 1 ms or less occur during laser communication transmission primarily due to small-scale dynamic variations in the index of refraction of the atmosphere. Atmospheric turbulence (i.e., wind) produces temporary pockets of air with slightly different temperatures, different densities, and thus different indices of refraction. These air pockets are continuously being created and then destroyed as they are mixed. Data can be lost due to beam wander and scintillation as the laser beam becomes deformed propagating through these index of refraction inhomogeneities. The significance of each effect depends on the size of these turbulence cells with respect to the laser beam diameter. If the size of the turbulence cells is larger than the beam diameter, the laser beam as a whole randomly bends, causing possible signal loss if the beam wanders off the receiver aperture (see Fig. 5). More commonly, if the size of the turbulence cells is smaller than the laser beam diameter, ray bending and diffraction cause distortions in the laser beam wavefront.[7] Small variations in the arrival time of various components of the beam wavefront produce constructive and destructive interference, and result in temporal fluctuations in the laser beam intensity at the receiver. These fluctuations in receive power are similar to the twinkling of a distant star (see Fig. 6). The constant mixing of the atmosphere produces unpredictable turbulent cells of all sizes, resulting in received signal strength fluctuations that are a combination of beam wander and scintillation. Scintillation fluctuations occur on a time scale comparable to the time it takes these cells to move across the beam path due to the wind. Scintillation fluctuations can be reduced by using either multiple transmit beams or large receive apertures, both of which are incorporated in the TerraLink system.[2,3]

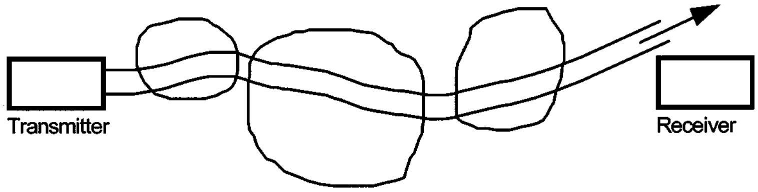

Fig. 5 Laser beam wander due to turbulence cells which are larger than the beam diameter.[7]

5 Margin for Allowable Atmospheric Attenuation and Effective Link Range

Figure 4 shows the margin for allowable atmospheric attenuation at three discrete link ranges. A continuous plot of allowable losses due to atmospheric attenuation as a function of link range is shown as the gray area under the curve in the top plot of Fig. 7. The effective link range and availability of the TerraLink 8-155 laser communication system depends on this margin for atmospheric attenuation and the local weather conditions. Since the laser wavelengths used in the TerraLink (780 and 852 nm) are just outside of the visible spectrum (400 to 700 nm), we would expect the laser light to be attenuated in a fashion similar to visible light. Weather conditions that affect one's ability to see at a distance, such as fog, snow and heavy rain, should affect the performance of a laser communication system. Also plotted in the top chart of Fig. 7, over the atmospheric attenuation curve, are straight lines that correspond to levels of constant visibility or attenuation. The decibel loss per kilometer attenuation coefficient at 780 nm for each visibility is shown in Table 1 (attenuation at 852 nm is slightly less). These were calculated assuming Mie or aerosol scattering as the dominant factor in the atmospheric attenuation [see Eq. (4)]. As visibility decreases, attenuation increases and thus the slope of the line increases. Table 1 also shows the International Visibility Code (IVC), which correlates weather condition with a visibility range.[9] For example, haze is defined as when the visibility is between 2 and 4 km. The IVC weather conditions are also displayed in the upper chart. The intersection of the visibility/attenuation lines with the TerraLink 8-155 margin for atmospheric attenuation curve determines maximum link range for that particular visibility/attenuation level. These intersection points are plotted in the bottom chart of Fig. 7, which results in a link range as a function of the visibility curve for the TerraLink 8-155. The solid gray portion indicates the possible link ranges for each visibility. Since clear weather is defined as a visibility of 10 to 20 km, the maximum clear weather range for the TerraLink 8-155 is 8 km. As the visibility decreases, the effective maximum link range decreases. The values for effective link range in weather is displayed in Table 1. Heavy fog can significantly decrease the availability and link range of laser communication equipment.

The effects of precipitation on the effective link range of the TerraLink 8-155 are shown in Fig. 8 and Table 1. Measured values of attenuation coefficient as a function of average rain rate[10] were incorporated into the top chart of Fig. 8 and Table 1. As the rain rate increases, the effective link range decreases. However, even in the heaviest rain (cloudburst 100 mm/h), the maximum link range is still over 1 km (as compared to the heaviest fog, which limits the link range to 100 m). Attenuation by fog is significantly greater than attenuation by rain at these near IR wavelengths. This is because the fog droplet radius (5 to 15 μm) is of the order of the laser wavelengths, compared to rain droplet sizes[10] (200 to 2000 μm). This is not the case for microwave transmission, where the carrier wavelength is closer to the size of a rain drop. Thus the attenuation of microwaves by rain has a greater effect than attenuation by fog.[10] The effect of snow is between rain and fog.[10] Table 1 summarizes the effects of weather and precipitation on the maximum link range of the TerraLink 8-155. For the shorter link ranges (less than 5 km), the visibility is consistently slightly less than the effective link range. As a general rule of thumb, if you can see the other side of the link, the TerraLink 8-155 has enough margin to overcome atmospheric attenuation and maintain the laser link.

Availability of the TerraLink systems can be estimated from the visibility versus link range charts in Fig. 7 and from regional historical visibility data. Historical visibility data is available for most airports in the world.[11] While the quality and consistency of this visibility data can be questioned, we believe that most of the visibility data is of good enough quality to produce realistic predictions of availability. The table in Fig. 9 shows examples of the historical tabulated visibility data from hourly observations for Las Vegas, Nevada (good visibility), San Diego, California (average visibility), and St. John's, Newfoundland (poor visibility).

The greater than or equal to 4 mile visibility point is used as an example of how the availability as a function of link range curves are determined. From the table in Fig. 9, the visibility is 4 miles or greater 99.8% of the time in Las Vegas, 92.8% of the time in San Diego, and 77.3% of the time in St. John's. A visibility of 4 miles (6.4 km) corresponds to a maximum link range of 5.9 km for the Ter-

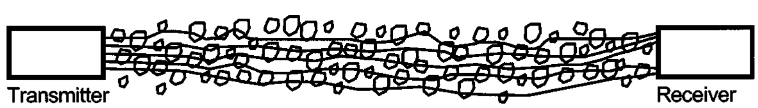

Fig. 6 Scintillation or fluctuations in beam intensity at the receiver due to turbulent cells that are smaller than the beam diameter.[7]

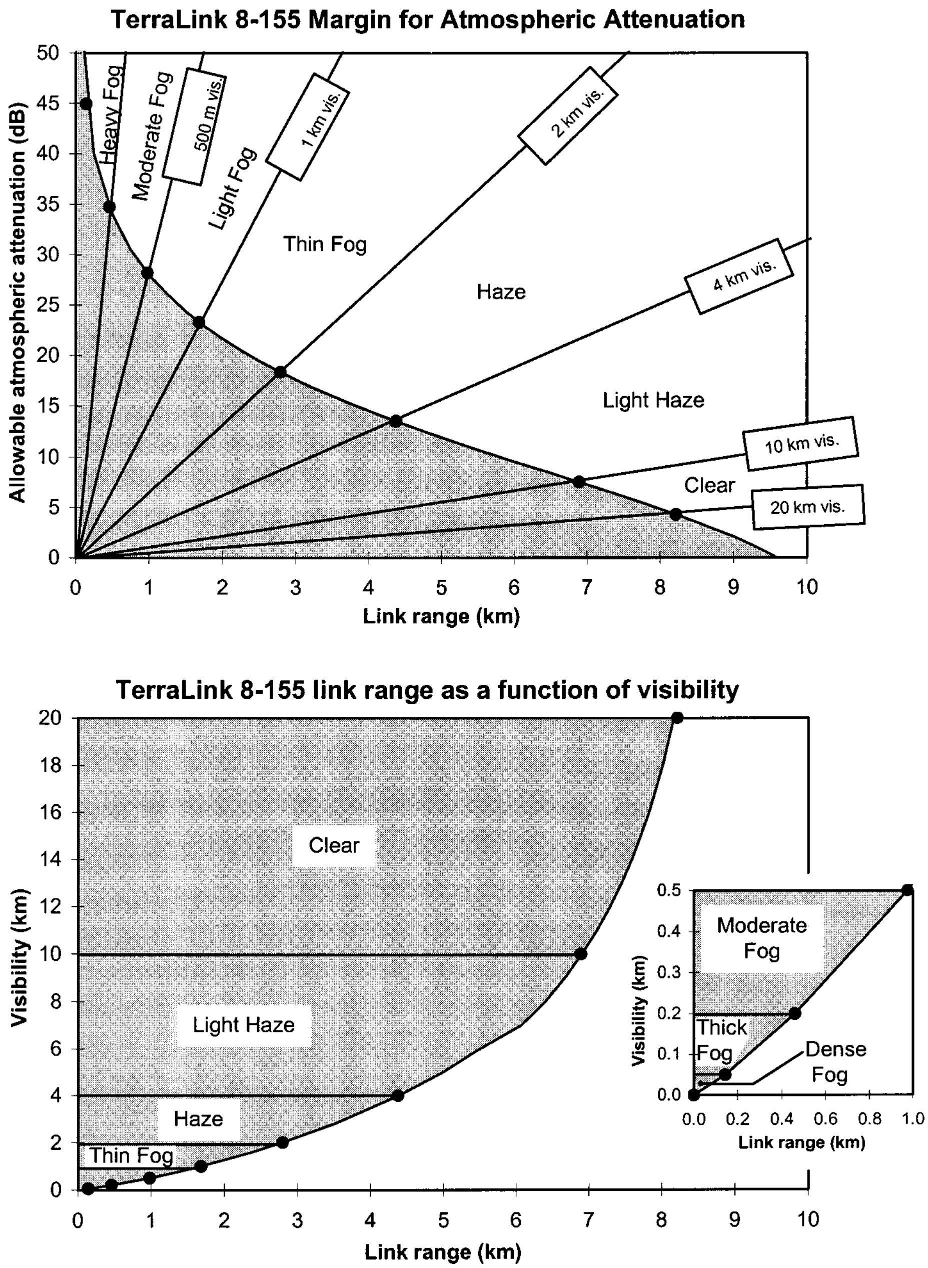

Fig. 7 (top) TerraLink 8-155's allowable margin for atmospheric attenuation as a function of link range (gray area). Straight lines are decibel loss per kilometer in different visibility conditions assuming losses are due to only Mie scattering. The intersection of the straight line with the atmospheric attenuation curve indicates the link range for that particular weather condition. For example, in clear weather the visibility is 20 km. This intersects the atmospheric attenuation curve at 8 km, indicating an 8 km clear weather range. (bottom) TerraLink 8-155's link range as a function of visibility (gray area). The intersection points from Fig. 3 as plotted for visibilities from 0 to 20 km. As the visibility decreases, the effective link range decreases. As a general rule of thumb, for the short ranges, the link range is approximately equal to the visibility. If you can see the other side of the link, the TerraLink 8-155 lasercom link is operational.

raLink 8-155 (based on the visibility versus link range curve in Fig. 7). The percentage frequency visibility can now be considered the percentage of availability or the percentage of time that the TerraLink 8-155 should have enough margin to maintain a link at a range of 5.9 km. All the visibility percentages are converted to link range values using the lower curve in Fig. 7 for the TerraLink 8-155, and the resulting availability versus link range curves are shown in Fig. 9 for the three cities. These availability curves indicate the minimum percentage of time that the TerraLinks will be operating at a BER of 10-9. Since the air over Las Vegas is clear (visibility⩾10 miles) 99.1% of the time, the availability of TerraLink 8-155 system is close to 100% for all link ranges. Las Vegas, Phoenix, El Paso, and similar dry desert cities are ideal for laser communication because of their consistently clear air. San Diego's TerraLink avail-

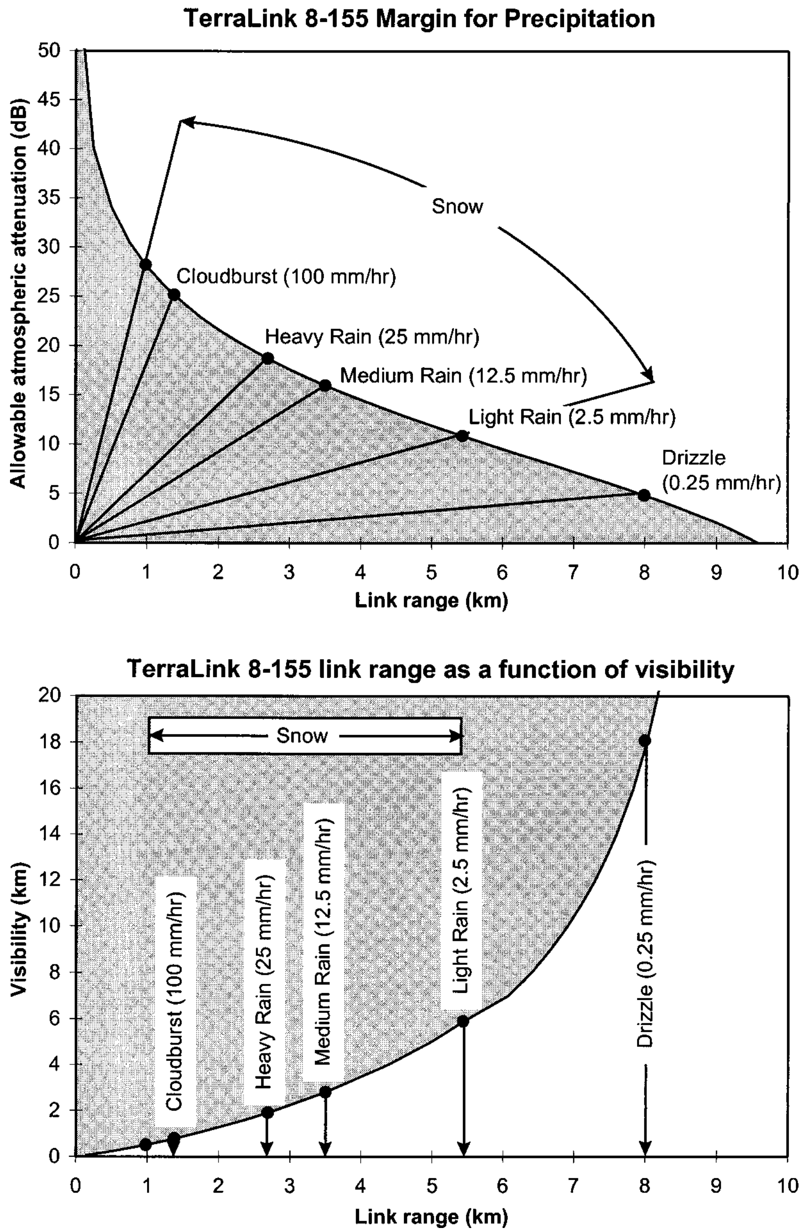

Fig. 8 (top) TerraLink 8-155 margin for precipitation attenuation and (bottom) maximum link range as a function of precipitation.

ability curves are more typical of most U.S. cities with a little visibility-restricting weather. In San Diego, the TerraLink 8-155's performance slowly degrades as the maximum link range is approached. The St. John's, Newfoundland, availability curves are pushed down very low because of very poor weather and visibility. Laser communication would not work well in these areas unless the ranges are very short or the application can handle some downtime. We are presently collecting availability data for the different TerraLink systems to verify the accuracy of these availability curves. Since we are conservative in our link budgets, we believe actual TerraLink performance will be above these availability curves. However, it is very important to educate possible users of laser communication systems about the potential downtime of their laser link due to poor visibility weather.

6 Applications of Free-Space Lasercom in Remote Network Connectivity

The TerraLink lasercom transceivers were designed to be simple full-duplex repeaters of the digital serial data to and from the switch or router via fiber. On the transmit side, the fiber is connected to the TerraLinks with a standard multimode fiber transceiver, which converts the input optical signal to an electrical signal. The electrical signal is then amplified by a laser driver that provides the current to modulate the laser diode. The modulation scheme is simple

Table 1 TerraLink 8-155 International Visibility Code weather conditions[9] and precipitation[10] along with their visibility, decibel loss per kilometer attenuation and maximum TerraLink 8-155 link range.

Weather condition		Precipitation	mm/hr	Visibility	dB loss/km	TerraLink 8-155 Range
Dense fog				0 m		
				50 m	-315.0	140 m
Thick fog				200 m	-75.3	460 m
Moderate fog				500 m	-28.9	980 m
Light fog		Cloudburst	100	770 m	-18.3	1.38 km
				1 km	-13.8	1.68 km
Thin fog	Snow	Heavy rain	25	1.9 km	-6.9	2.39 km
				2 km	-6.6	2.79 km
Haze		Medium rain	12.5	2.8 km	-4.6	3.50 km
				4 km	-3.1	4.38 km
Light Haze		Light rain	2.5	5.9 km	-2.0	5.44 km
				10 km	-1.1	6.89 km
Clear		Drizzle	0.25	18.1 km	-0.6	8.00 km
				20 km	-0.54	8.22 km
Very Clear				23 km	-0.47	8.33 km
				50 km	-0.19	9.15 km

on-off keying. On the receive side, the modulated light hits an APD or p-i-n detector, which turns the optical signal back into an electrical signal. For data rates of 100 Mbps or greater, clock recovery is applied to the signal to square up the digital data because the pulses of laser light become slightly distorted after traveling through the atmosphere. This signal is then fed into a fiber transceiver, which sends the signal down a fiber to the other switch or router. Each TerraLink has a transmitter and receiver, thus providing full-duplex wireless communication. Other than the clock recovery, the TerraLinks were designed to behave just as if a pair of fiber optic cables was strung though the air between the two buildings. Since the TerraLink transceivers act as simple repeaters, they are protocol-independent. To demonstrate their true protocol independence, examples of TerraLink installations transmitting wireless fast ethernet (125 Mbps), Fiber Distributed Data Interface (FDDI) (125 Mbps), asynchronous transfer mode (ATM) (155 and 622 Mbps), and Enterprise Systems Connection (ESCON) (200 Mbps) protocol data are shown.

6.1 *Fast Ethernet Installation*

The San Diego County Water Authority (SDCWA) needed a high-speed fast ethernet connection between two of its buildings in downtown San Diego. Trenching fiber optic cable was not a solution because they planned to move out in 2 yr. The range between the two buildings was 61 m. There was a preexisting wireless rf system in place between the buildings, but it could provide only 2 Mbps of bandwidth. TerraLink 4-155s were installed in September 1997. Although the specified maximum data transfer rate of fast ethernet is 100 Mbps, 4b/5b encoding increases the actual line data rate to 125 Mbps. Once the clock recovery was set to 125 Mbps, the lasercom units behaved as if fiber was laid between the two buildings, connecting their 3COM SuperStack fast ethernet switches. At 61 m, the designated margin for scintillation is 5 dB and the remaining margin for atmospheric attenuation is 35 dB. For this short range, the predicted minimum availability using the TerraLink 4-155s was 99.5% using the methods described in Section 5. After initial installation, the link was tested using the GigaBert-660 Bit Error Rate Tester in the midafternoon, when the effects of scintillation are the greatest.[12] The bit error rate test (BERT) confirmed a good link with a BER of $<10^{-10}$.

6.2 *FDDI Installation*

Star Telecommunication needed to expand their high-speed FDDI LAN across the street at their Santa Barbara facilities. Because of Santa Barbara's strict regulations on altering or blemishing city streets and infrastructure, Star Telecommunications was prohibited from trenching fiber across the street or installing a large antenna microwave link. To stay within city building ordinances, custom mounts were designed to enable the TerraLinks to be placed on the roof in an unobtrusive location, while maintaining the line of sight between the two buildings. One building contained a

% Frequency of Visibility (miles) from Hourly Observations[11]

Visibility (miles)	>=10	>=6	>=5	>=4	>=3	>=2.5	>=2	>=1.5	>=1.25	>=1	>=3/4	>=5/8	>=1/2	>=5/16	>=1/4	>=0
Las Vegas	99.1	99.6	99.7	99.8	99.8	99.9	99.9	99.9	99.9	99.9	100	100	100	100	100	100
San Diego	54.1	85	89.3	92.8	95.2	96	97.3	98	98.1	98.6	98.8	98.8	99.1	99.2	99.4	100
St. Johns	60.6	71.4	74.3	77.3	80.7	81.6	84.9	86.6	87.1	89.4	91.2	91.5	93.5	94.4	96.6	100

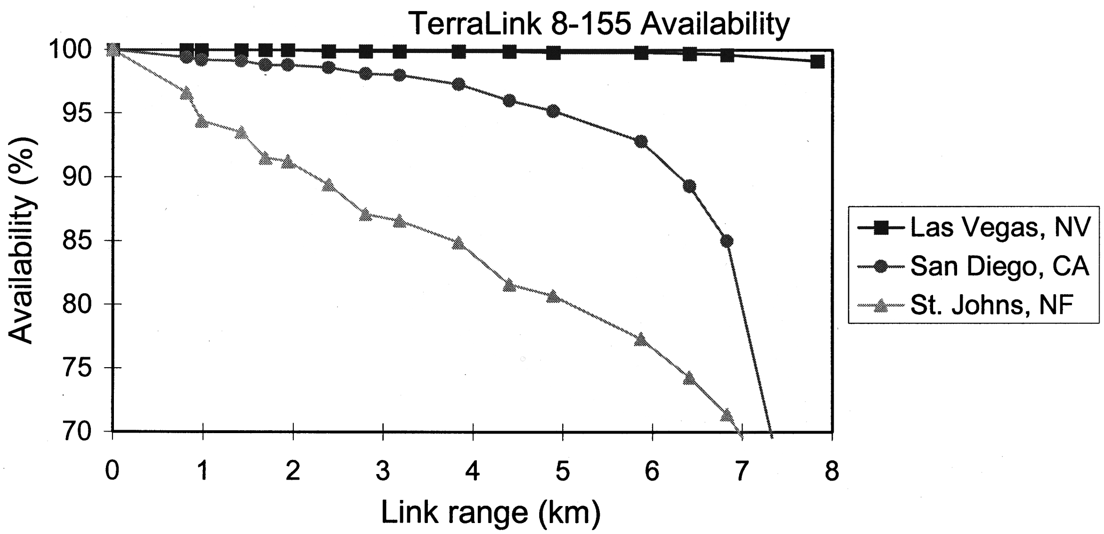

Fig. 9 (top) Historical tabulated visibility data used to calculate the TerraLink availability curves below. The data is percentage frequency of visibility in miles from hourly observations and is available for most airports in the world.[11] For example, the visibility is greater than or equal to 3 miles 99.8% of the time in Las Vegas, Nevada, 95.2% of the time in San Diego, California, and 80.7% of the time in St. John's, Newfoundland. (bottom) TerraLink 8-155 availabilities for Las Vegas (good visibility), San Diego (average visibility), and St. John's (poor visibility). These availability as a function of link range curves were calculated from visibility versus link range curves (see Fig. 7) and historical visibility data. They are baselined for a BER of 10^{-9}.

CISCO 7315 router and the other building housed a Catalyst 5000 switch. The FDDI data rate is 100 Mbits/s. Just as with fast ethernet, FDDI adds 4b/5b encoding, which increases the line data rate to 125 Mbps. The distance between the two buildings is 500 m. At 500 m, the TerraLink 4-155 has 5 dB of scintillation margin and 18.75 dB of atmospheric attenuation margin, and a predicted minimum availability of 99% for Santa Barbara. The BER measured following initial installation was $<10^{-10}$. The TerraLink 4-155 was able to provide Star Telecommunications with a fast and effective solution to their need for high-speed network connections to accommodate its rapid growth without disturbing the historic land and buildings where the company is located. They have been very satisfied with the uptime of the laser link and will be using new TerraLinks to extend their FDDI ring to two more recently acquired buildings.

6.3 *SONET OC-3 and OC-12 ATM Installation*

Kaiser Permanente's Technology Evaluation and Support Department (Pasadena, California) acquired a TerraLink 8-155 for OC-3 ATM wireless connectivity and a TerraLink 8-622 for OC-12 ATM wireless connectivity. This hospital's immediate applications for testing the TerraLinks included remote telemedicine for the timely transfer of large image files such as digital x-rays, and detailed medical video conferencing. The link range was 750 m, with each building housing FORE Forerunner ATM switches. For the TerraLink 8-155 at 750 m range, the designated scintillation margin is 5 dB and the remaining atmospheric margin is 30 dB, resulting in a predicted availability in Pasadena of 99%. The TerraLink 8-622 has the same 5 dB for scintillation margin, but has 22 dB for atmospheric margin because the detector requires more light for full modulation depth at 622 Mbps. For the wireless OC-12 link, the minimum predicted availability was 98.5%. Initial error rates after installation were $<10^{-11}$ for both data rates. Monitoring of the OC-3 link with error analysis software associated with the ATM switch indicated a daily pattern of increased errors. Measurements of misalignment due to building flexure indicated that an active tracking system was necessary to maintain a solid link (more details of this are presented in Section 7). The buildings were five and seven stories tall but were built structurally soft for seismic reasons. Tracking was installed and the daily error patterns were eliminated. After the tracking was installed, further spot error rate testing using an SONET protocol analyzer measured the error rate in loopback mode as 2×10^{-10} over the course of 10 min. The TerraLink 8-622 OC-12 unit was installed in April 1998. We believe this is the first time OC-12 ATM data has been transmitted wirelessly in a production computer network. Continual error monitoring of this link indicate that scintillation still causes zero to 4 burst errors per day. The burst errors vary in duration from 16 ns (10 bits) to 80 μs (50,000 bits). The overall BER is 2 to 3×10^{-9}.

6.4 *ESCON Installation*

Saudi Business Machines needed to provide an international banking customer with high-speed connectivity for their FDDI and ESCON† mainframe protocol systems. Government regulations required the bank to keep redundant records of customer transactions on two mainframes, one in their head office and one in their data recovery center, which were located approximately 2.2 km apart in the city of Riyadh. Unfortunately, fiber cabling was not readily available. Since a single company controls fiber installation in the area, the time for completion of a fiber run can be long—sometimes more than two years. Licensing restrictions in Saudi Arabia precluded the use of microwave or spread spectrum solutions. The most practical, secure solution was to connect the bank's FDDI and ESCON mainframe systems with free-space laser communication systems. However, IBM's ESCON protocol (data rate of 160 Mbps, line rate of 200 Mbps after 8b/10b encoding) is designed to run over fiber-optic cabling and has very low tolerance for errors ($<10^{-12}$), which is lower than the TerraLink's 10^{-9} baseline error rate. To verify if the TerraLink lasercom units were compatible with the ESCON tolerance for errors, testing of the TerraLink system was performed at the IBM Large Scale Computing Test Facility located in Poughkeepsie, New York. Two TerraLink 4-155 units were configured for 200 Mbps (the TerraLink 4-155 has electronics identical to those of TerraLink 8-155s, which were used in the actual installation). Testing was done at 4.5 and 10.7 m indoors. Neutral density filters were used to simulate the effects of atmospheric attenuation, but could not replicate the dynamics of scintillation. ES/9000‡ mainframes similar to the ones in Saudi Arabia were used in the simulation. Serial channel activity monitors (SCAMs) were used to log single bit errors as well as code violation errors. For the short range, no BER over threshold was found for four hours of testing. Measurement of the waveform out of the TerraLink was compared to the waveform out of an ESCON channel fiber. The waveforms were very similar except for at most 100 ps of jitter. An overnight test at the longer range produced some bit errors, but these were determined to be related to damage of one of the optical units during shipping. This testing indicated that the TerraLink lasercom transceivers were compatible with the ESCON protocol at the physical layer. This testing was also the first time ESCON data has been transmitted over a free-space wireless optical channel.

Installation in Riyadh had some unusual environment challenges, since the ambient daytime temperature inside the weather enclosure can reach 150°F in the summer, well beyond the operating specifications of the TerraLink electronics. Since two links were required (FDDI and ESCON), a pair of TerraLinks were required on each side. It was possible to place the two units on each side very close to each other (within 1 m) enclosed within a single air conditioned structure without fear of interference or crosstalk because two wavelengths are used by the TerraLink 8-155 (780 and 852 nm). Remote monitoring and adjustment of alignment indicated that these buildings were also subject to daily motions. The buildings were 10 and 8 stories tall, but were structurally stiffer than the Pasadena buildings because of no seismic hazards. Tracking was later installed to avoid daily manual corrections to alignment. Since the initial installation, the FDDI link has been recently upgraded to an OC-3 ATM link. All that was required was an adjustment of the clock recovery rate to 155 Mbits/s and ATM wireless connectivity was established. For this link range of 750 m, the TerraLink 8-155 had 5 dB of scintillation fade margin and 21 dB for atmospheric attenuation. This resulted in a minimum predicted availability of 99%. This installation has met and exceeded the ESCON protocol low BER specification. The very good lasercom error rate is attributed to the generally good atmospheric conditions in the desert climate.

7 Advantage of Tracking to Maintain Laser Link Connectivity

As mentioned in Section 1, the TerraLink transmit laser beam's divergence is very narrow (1 mrad for the TerraLink 8 series and 3 mrad for the TerraLink 4 series). The narrow laser beam is great for security purposes, but makes initial alignment and maintaining alignment critical issues. The mispointing allowance is 0.3 mrad for the TerraLink 8 series and 0.5 mrad for the TerraLink 4 series. Initially, TerraLink units are finely aligned to each other when they are installed. Because of the small mispointing allowances, it does not take much movement to mispoint a unit and thus break the laser link. Even if TerraLink terminals are installed on stable, stiff platforms mounted directly into a building's structure, the transceivers are still subject to misalignment if the building sways or flexes. Thermal expansion and contraction of a building over a day or heavy winds can result in significant building sway. New buildings in Southern California or other seismically active areas are especially vulnerable to building sway because they are designed to be able to withstand seismic activity by flexing. If building motion continually mispoints the TerraLink units, an active tracking mechanism becomes necessary to maintain alignment.

A case study of building sway was performed at the Kasier Permanente Technology Evaluation and Support Department in Pasadena. Two TerraLink 8-155 units were installed between two of Kaiser's buildings to provide ATM wireless connectivity (recently, these units have been upgraded to the TerraLink 8-622 to provide 622 Mbits/s OC-12 ATM connectivity). The link range was 750 m. The TerraLink units use a CCD camera for alignment purposes. When properly aligned, the CCD camera (which has a field of view of about 1.5 mrad) displays a centered spot from the other transceiver. The centroid of this spot was monitored over a period of 3 days. The results of centroid motion are plotted as the two upper lines in Fig. 10. The centroid motion was converted to milliradian movement away from the center. The data shows a distinctive pattern, which cycles every 24 hours. The maximum displacement from center is between 0.25 and 0.3 mrad. Also recorded during this time were SONET and ATM cell errors, which are

†ESCON is a registered trademark of IBM Corporation.

‡ES/9000 is a registered trademark of IBM Corporation.

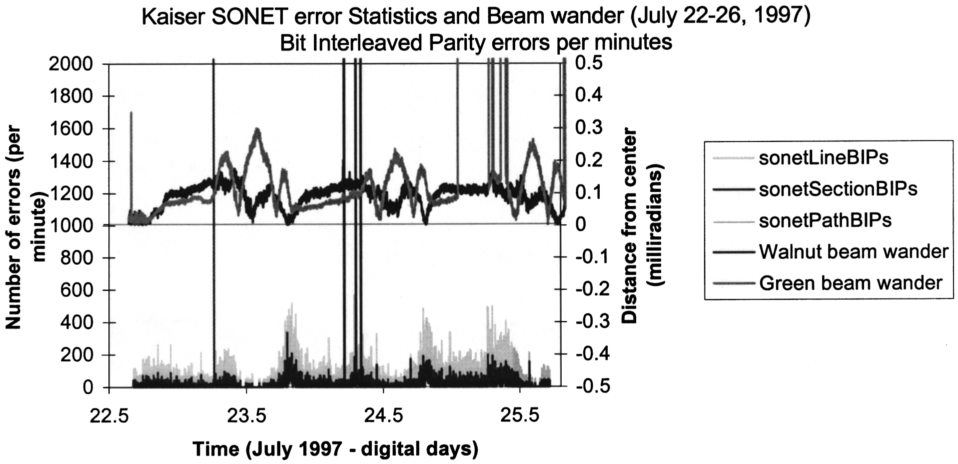

Fig. 10 (top curves) Mispointing due to building sway recorded over 3 days in Pasadena, California. The building sway shows a 24 hour cyclical period with a maximum mispointing of 0.3 mrad (750 m range). (lower curves) SONET packet errors per minute over the same 3 days. The errors also show a 24 hour cyclical period and are mostly due to a combination of mispointing and scintillation.

plotted on the bottom portion of Fig. 10. The number of errors per minute also had a cyclical pattern, which repeated itself every 24 hours. The time of maximum error did not correlate directly to time of maximum misalignment. It seemed to occur in the early evening, ruling out scintillation as the only cause of the errors (except for the large peak of errors in the middle of the last day). Most likely, the peak errors were due to a combination of misalignment and scintillation. If the TerraLink units are slightly misaligned, the outer portion of the beam is generally weaker and more subject to scintillation effects. An autotracking mechanism that keeps the centroid of the spot centered on the CCD camera was subsequently installed at Kaiser. The tracking system moves motors on the outer gimbal of the unit, to accurately point the beam. The errors in Fig. 10 were with a TerraLink 8-155 before tracking. The unit has since been upgraded to a TerraLink 8-622. Since slow tracking has been installed, the BER has decreased significantly from what is shown in the graph in Fig. 10 to a much more acceptable BER of 2 to 3×10^{-9}.

8 Conclusions

The transmission of high-speed computer network data, normally channeled through fiber optic cable, has been successfully demonstrated using free-space laser communication. Free-space laser communication is subject to atmospheric effects, such as attenuation and scintillation, which can reduce availability and introduce burst errors. It is important to understand the effects of weather on the performance of the laser link. Characteristics of the optical design of the TerraLink lasercom system have reduced the effects of atmospheric scintillation and have increased link margins, thus greatly increasing the availability or uptime of the laser link. Accurate estimates of these higher laser link availability can be calculated from link budgets and historical local visibility data. In addition, tracking technology has nullified the effects of building movement, which was a major cause of misalignment or downtime in the past. The net effect is that, in most cases, lasercom availability can be 98% or greater. Case studies of the successful remote wireless optical transmission of fast ethernet, FDDI, ATM, and ESCON data were presented. In these situations, ideally fiber optical cabling would have been the first choice. However, because of economical or logistical reasons fiber was not possible, so free-space lasercom was the solution. In each case, there was no noticeable difference in performance by using laser communication. We are not suggesting that laser communication is the perfect replacement for all fiber installations. We are suggesting that, because of significant improvements to the reliability and cost of free-space lasercom equipment, it can be now considered a serious, and in some cases a very attractive, alternative to fiber. Lasercom can also provide a reliable and cost-effective backup to existing fiber optic infrastructure.

9 Future Work

Technological improvements to the TerraLink product line include designing lasercom systems that transmit at 1.25 Gbps (for gigabit ethernet: 1.0 Gbps data rate with 8b/10b encoding) and 2.5 Gbps (OC-48) for telecommunication applications. We are also developing larger aperture laser-oom systems, in conjunction with our ground-to-satellite terminal,[6] which will have much longer ranges (25 to 50 km). This will enable laser communication to enter the long-haul telecommunications market.

AstroTerra, in conjunction with the Center for Wireless Communication at the University of California, San Diego (UCSD), is currently installing a high-speed wireless communications network in San Diego using the TerraLink 8-622 transceivers. The network hub is at UCSD, and a total of six links are planned (five of the links are shown in Fig. 11). The LaserNet will provide users with access to OC-12 (622 Mbps) wireless communication and data connectivity. All of these links of various ranges will be continually monitored for availability, scintillation, building sway, visibility and other standard meteorological parameters. This extensive information database will be used to update and improve the accuracy of the TerraLink link budgets and the

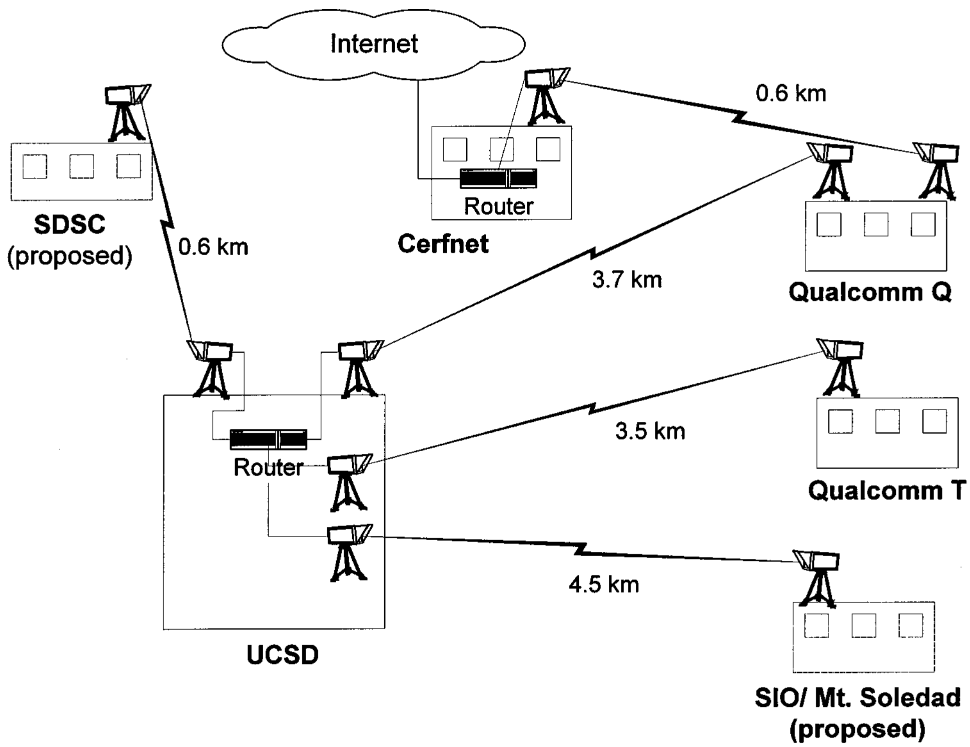

Fig. 11 San Diego LaserNet (not to scale).

availability curves. This data will also be used to achieve a better fundamental understanding of laser transmission through the atmosphere. Present LaserNet research involves determining the effects of the atmosphere on the higher level protocol throughput of computer networks connected with free-space laser communication. This research will enable us to continue to improve our lasercom units not only from a physical layer 1 level, but also from an overall network performance level. Engineering improvements in the design of the TerraLink systems to further reduce the effects of scintillation and improve performance in poor weather will also be tested in the LaserNet. The primary purpose of the San Diego LaserNet is to demonstrate that laser communication is a viable high-bandwidth alternative to fiber optic cabling. This will hopefully lead to a better acceptance of free-space laser communication in the networking and telecommunication industry.

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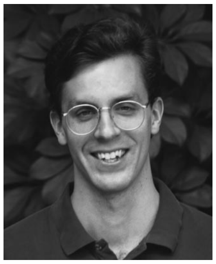

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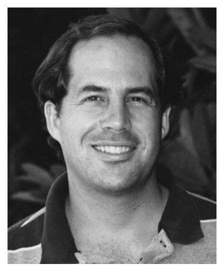

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Casimer DeCusatis: Biography and photograph appear with the special section guest editorial in this issue.