Universidad Carlos III de Madrid
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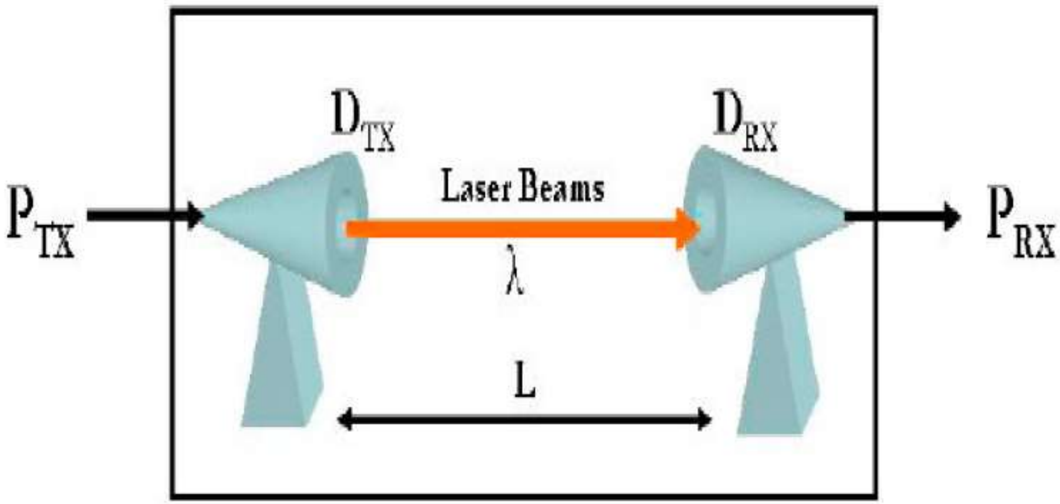
TEMA 8 (Cont.)

TECNOLOGIAS FOTONICAS Y SU APLICACION EN COMUNICACIONES OPTICAS EN ESPACIO LIBRE

FOTONICA

Grado en Ingeniería en Tecnologías de Telecomunicación

1.-INTRODUCCIÓN

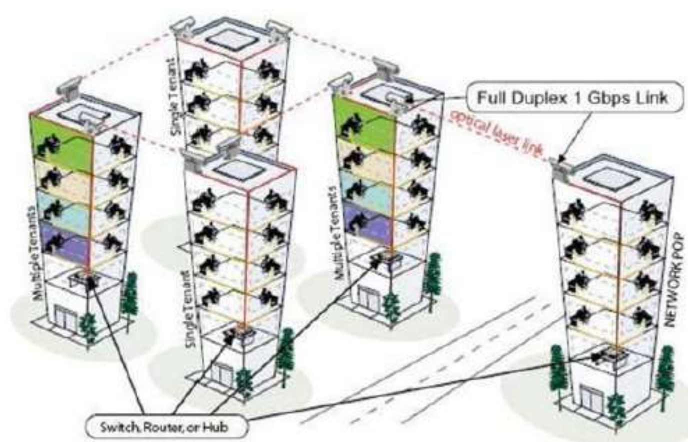


-Láseres de alta potencia

-No se necesitan licencias

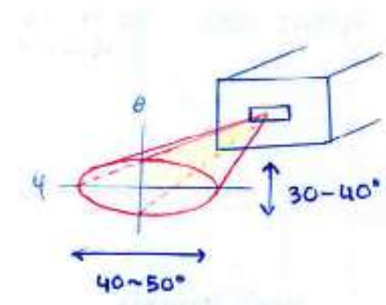
-Aplicaciones:

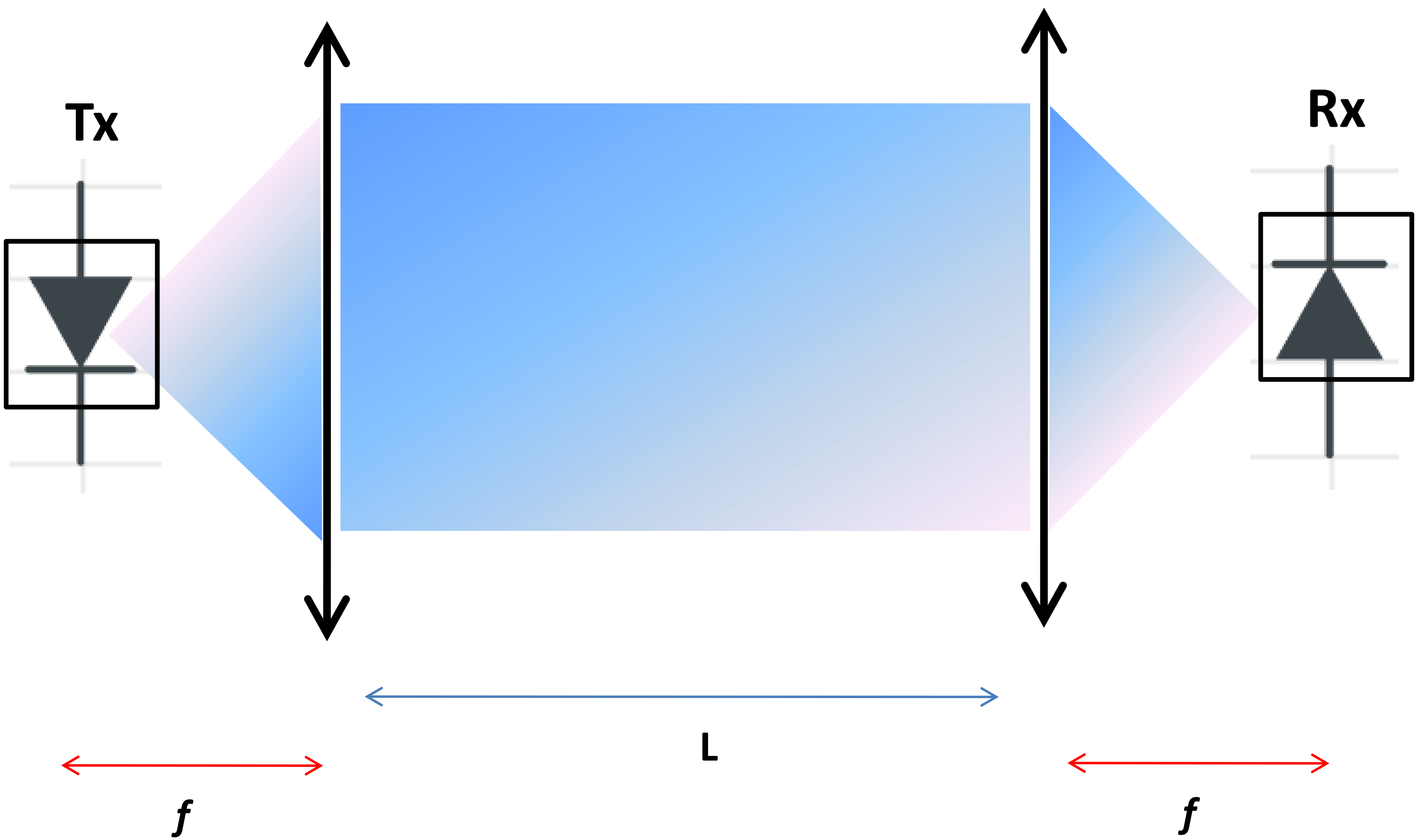
- -comunicaciones satélites
- -control remoto
- -redes en ciudades



2.- ESQUEMA BÁSICO

Fuentes divergentes → lentes colimadoras





3.-FUENTES DE ERRORES

Las lentes NO son un **sistema óptico perfecto**, por lo que llevan asociadas una serie de fuentes de error que **distorsionan el haz de luz**

1. **ABERRACIONES**

   - Aberración Esférica
   - Coma
   - Astigmatismo
   - Distorsión
   - Curvatura de la imagen
   - Aberración Cromática

2. **DIFRACCIÓN**

3.-FUENTES DE ERRORES

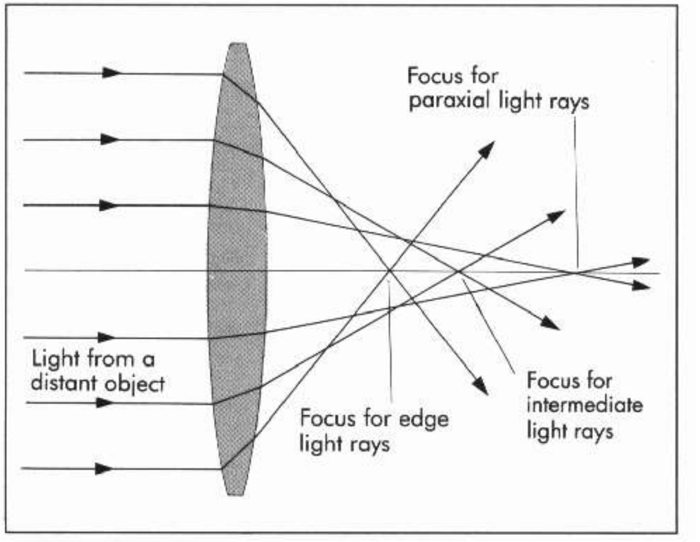
3.1.-ABERRACIONES

Al alejarnos de la óptica paraxial (D↑)

Varios tipos

Aberración Esférica

- Rayos no coinciden en el foco
- Produce una mancha
- Difumina los contornos, pérdida de nitidez

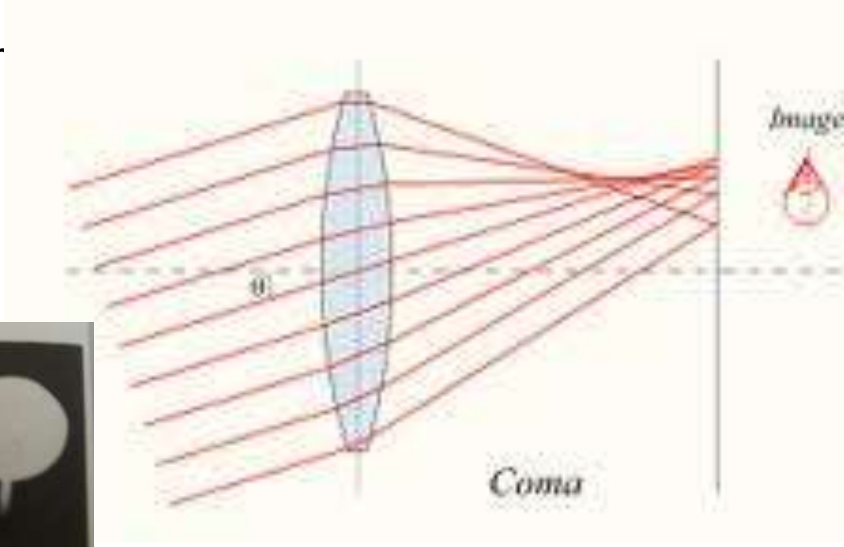


3.-FUENTES DE ERRORES

3.1.-ABERRACIONES

Coma

- Rayos procedentes de una punto fuera del eje no coinciden en el punto imagen.
- Genera una mancha con un plano de sim
- Muy nociva en sistemas de imagen



3.-FUENTES DE ERRORES

3.1.-ABERRACIONES

Astigmatismo

- El haz saliente pierde la simetría esférica por efectos de la lente (variaciones en la curvatura, el índice de refracción, espesor)
- Produce una pérdida de nitidez

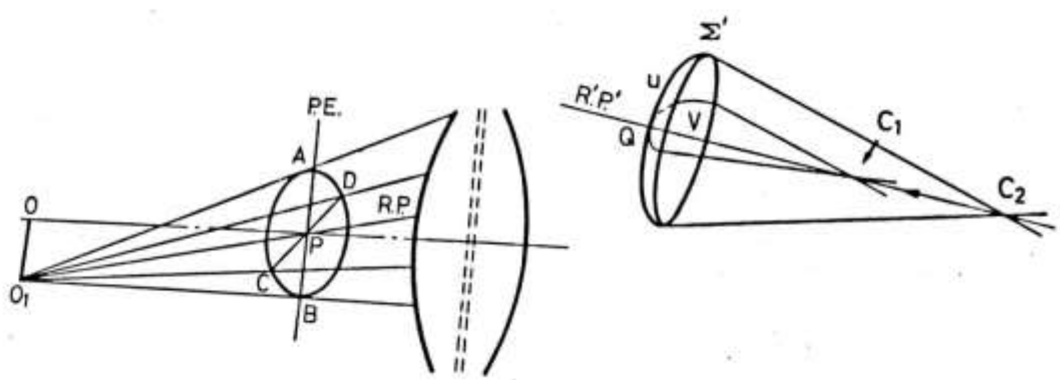


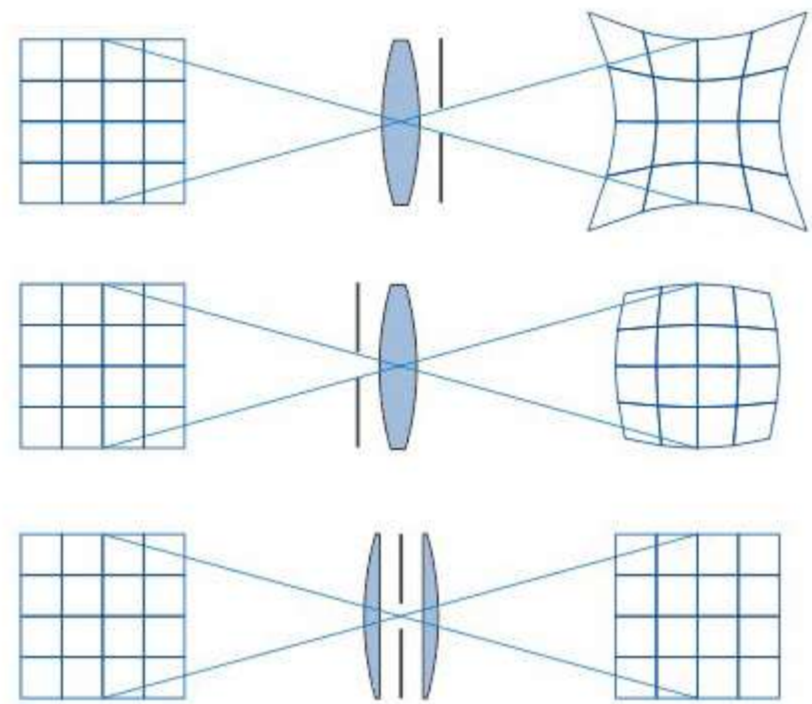
Fig.4.25.

3.-FUENTES DE ERRORES

3.1.-ABERRACIONES

Distorsión

- Producido por un cambio del aumento lateral
- Conlleva una pérdida de semejanza entre el objeto y la imagen

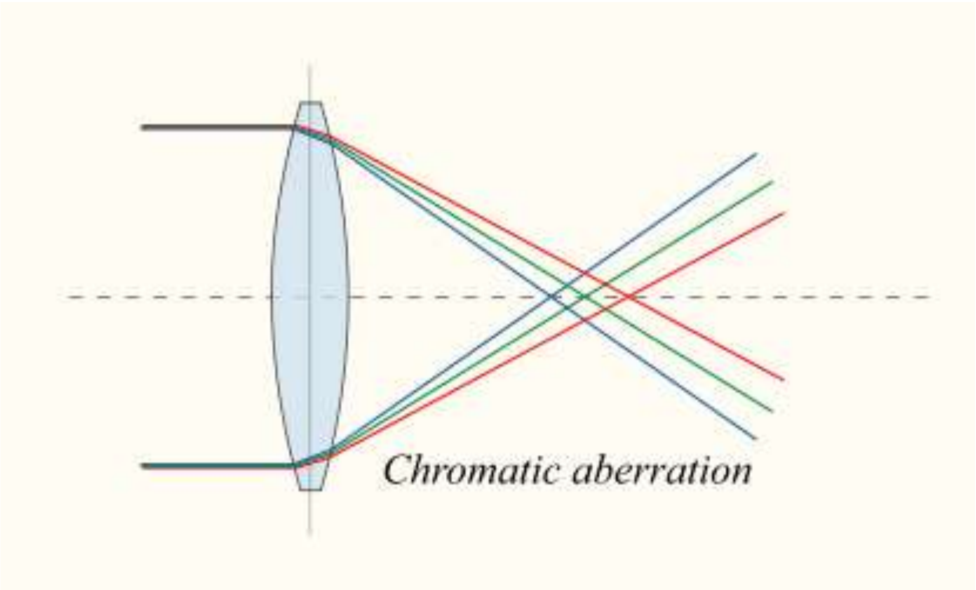


3.-FUENTES DE ERRORES

3.1.-ABERRACIONES

Aberración Cromática

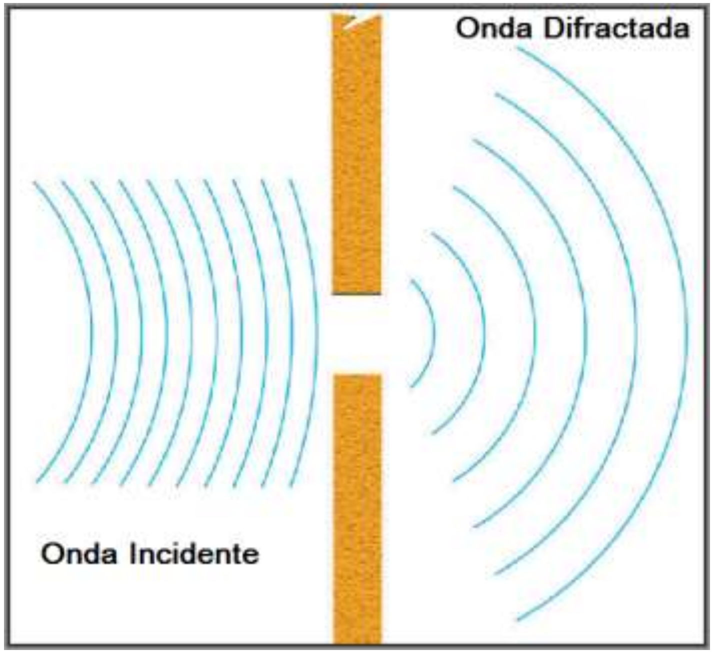
- El índice de refracción de la lente depende de λ
- Cada λ lleva asociada una focal
- Produce una mancha de colores



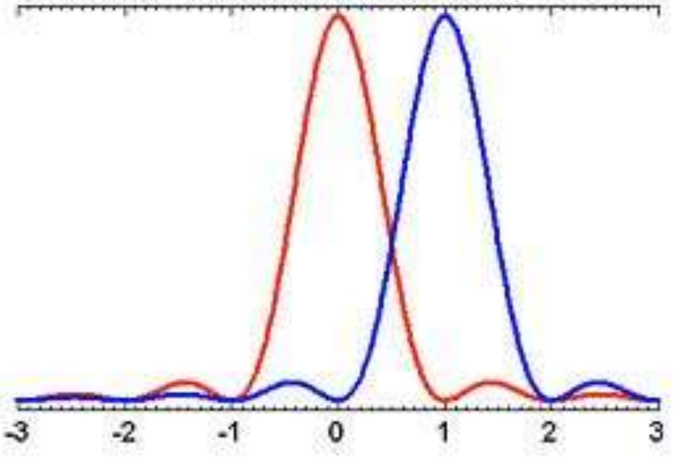
3.-FUENTES DE ERRORES

3.2.-DIFRACCIÓN

- Todo sistema óptico sufre el fenómeno de difracción
- La resolución de todo sistema óptico está limitado por difracción



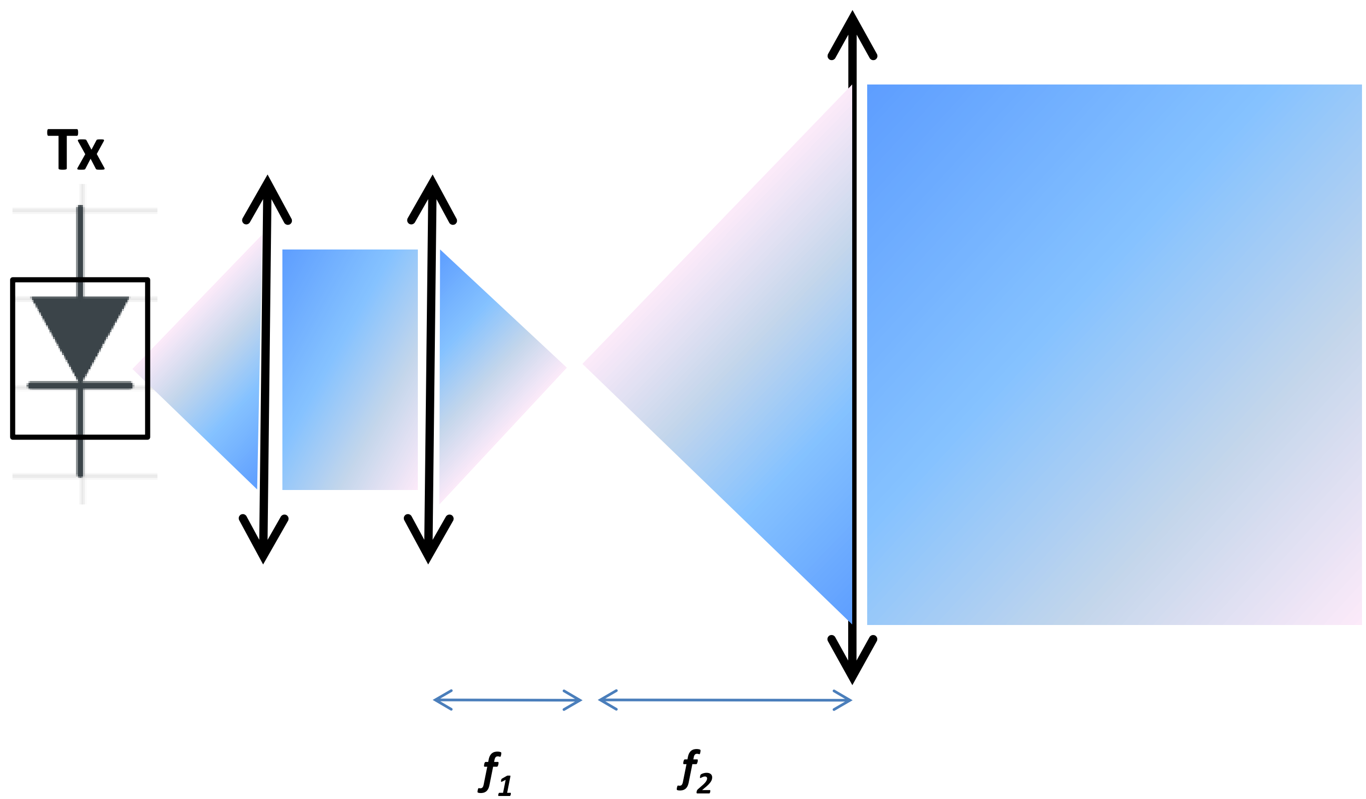
$$\theta = 1.22\frac{\lambda}{D}$$



4.-SISTEMAS ÓPTICOS

4.1.-SISTEMA TELESCÓPICO

- Reduzco la difracción
- Aumento las aberraciones (mayores a mayor pupila de entrada)



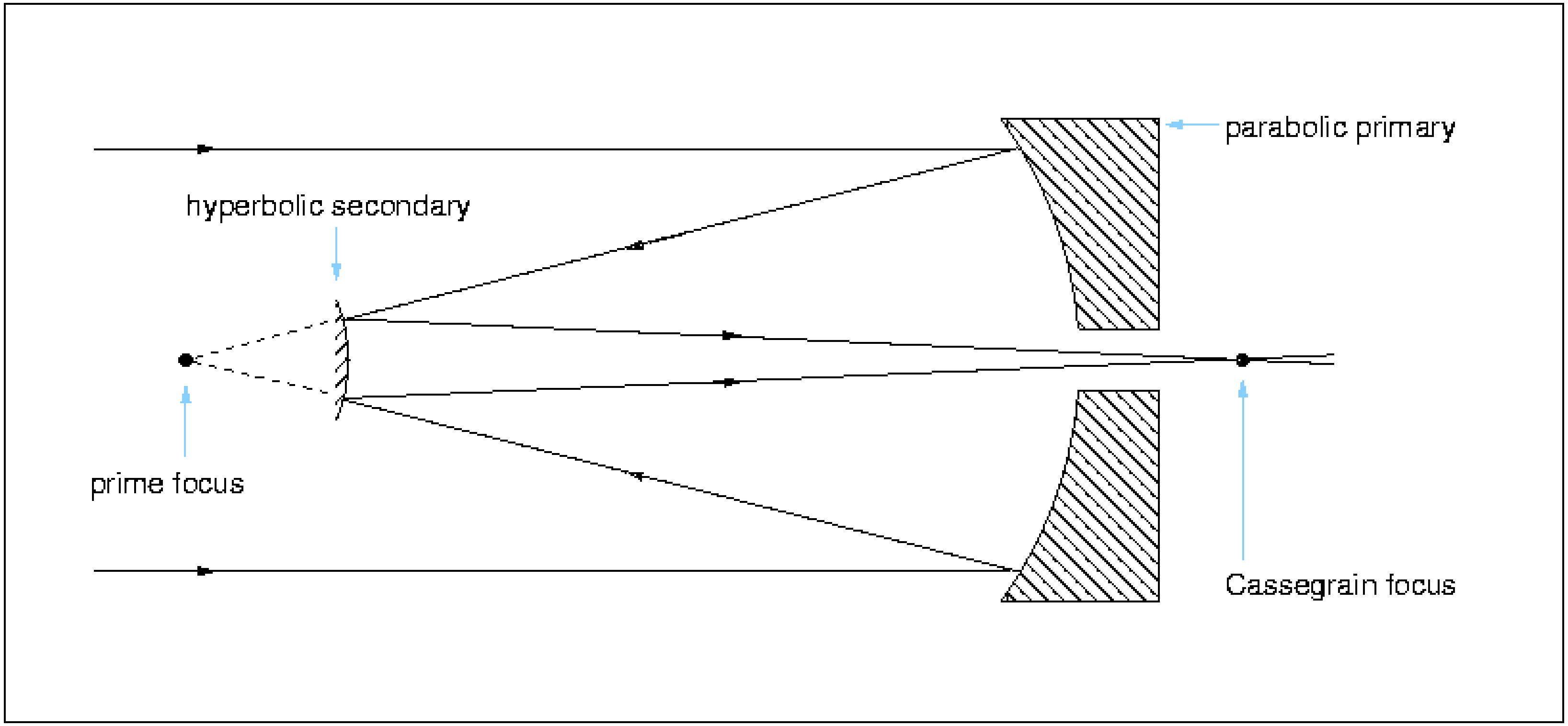
4.-SISTEMAS ÓPTICOS

4.2.-TELESCOPIO CASSEGRAIN

- Usa espejos en vez de lentes

- Menor influencia de las aberraciones (sobre todo cromática)

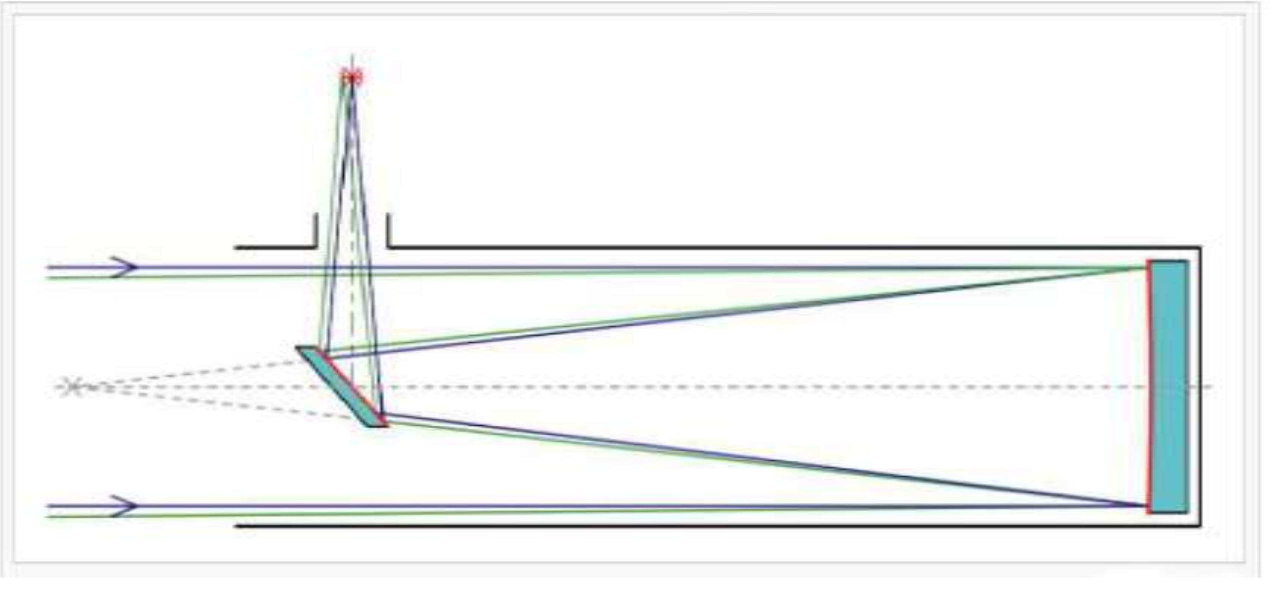
- Reduce los tamaños



4.-SISTEMAS ÓPTICOS

4.3.-TELESCOPIO DE NEWTON

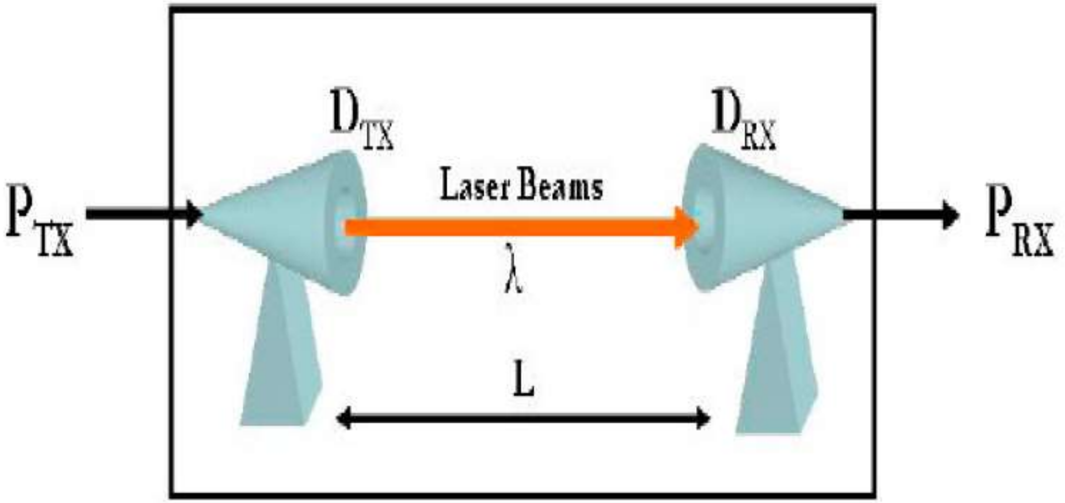
- Usa espejos en vez de lentes
- Ha sido el primer paso realizado por Newton para la creación posterior del Telescopio de Cassegrain para eliminar las Aberraciones Cromáticas.
- Ha sido muy utilizado y se sigue utilizando actualmente en Astronomía.



5.-ENLACES ÓPTICOS EN ESPACIO LIBRE

5.1.-CAMPO LEJANO

Para distancias muy largas (campo lejano) el sistema se puede analizar como el caso de un sistema de antenas de radiofrecuencia.



FÓRMULA DE FRISS

$$P_{Rx} = P_{Tx} \frac{G_{Tx} \cdot G_{Rx} \cdot \lambda^2}{(4\pi \cdot d)^2}$$

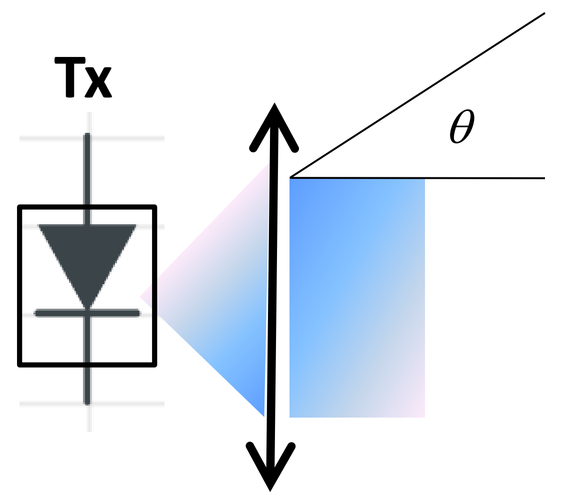
5.-ENLACES ÓPTICOS EN ESPACIO LIBRE

5.1.-CAMPO LEJANO

Relación entre la ganancia de la Antena y la Difracción

$$G = \frac{4\pi}{\lambda^2} A = \frac{4\pi}{\lambda^2} \pi \cdot \left(D/2 \right)^2$$

$$= \pi^2 \left(\frac{D}{\lambda} \right)^2 \approx \frac{\pi^2}{\theta^2}$$



- Una menor difracción implica una mayor ganancia.

5.-ENLACES ÓPTICOS EN ESPACIO LIBRE

5.2.-CAMPO CERCANO

- No es posible aplicar la fórmula de Friis
- Campo Lejano $$d \geq \frac{2D^2}{\lambda}$$
- Es necesario hacer una comparativa entre áreas

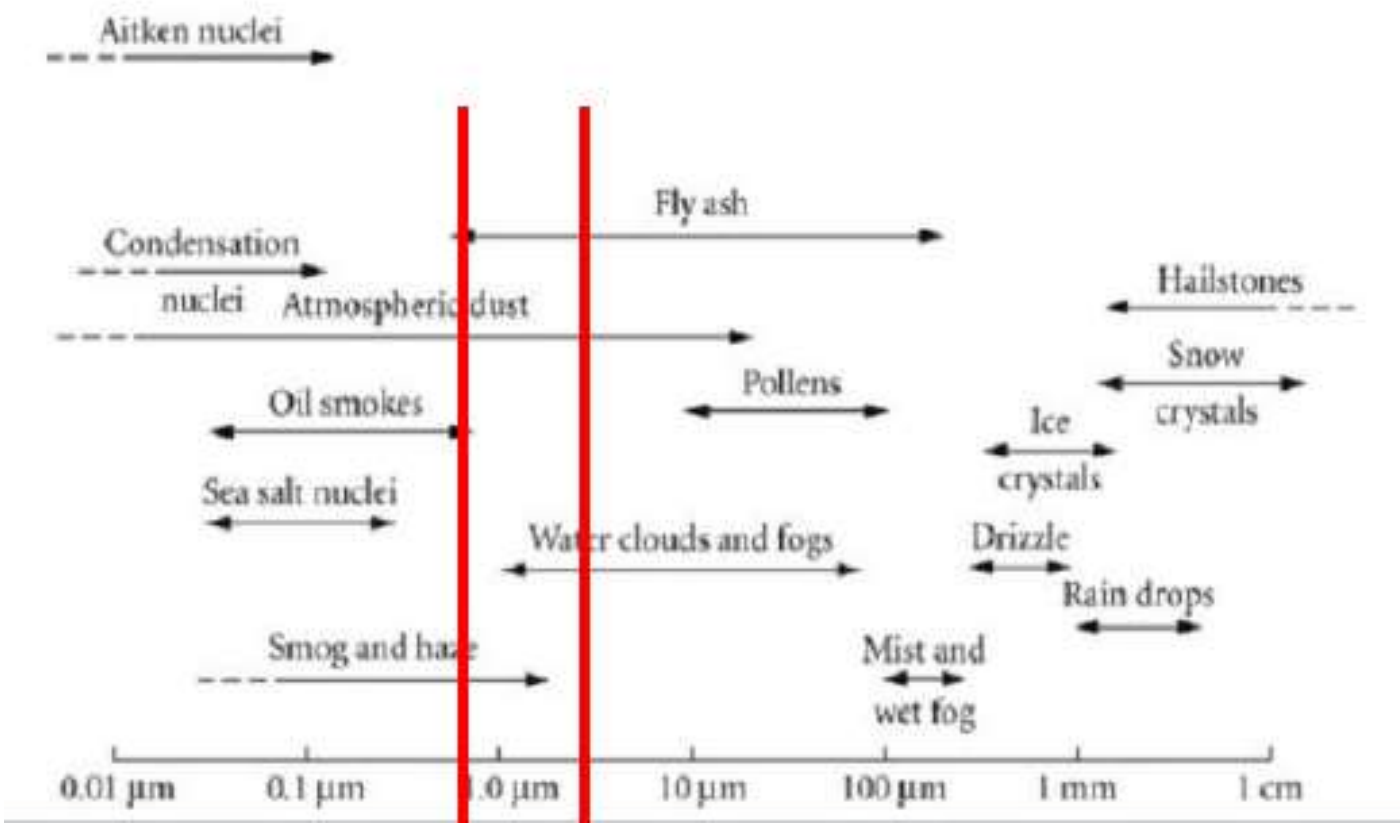
$$\boxed{P_{Rx} = P_{Tx} \frac{A_{Rx}}{A_{Haz}}}$$

- Podemos relacionarlo directamente con la difracción de la forma:

$$P_{Rx} = P_{Tx} \frac{A_{Rx}}{\pi(\frac{\lambda}{D} d)^2} = P_{Tx} \frac{A_{Rx}}{\pi(\theta \cdot d)^2}$$

6.-ATENUACIÓN EN EL ESPACIO LIBRE

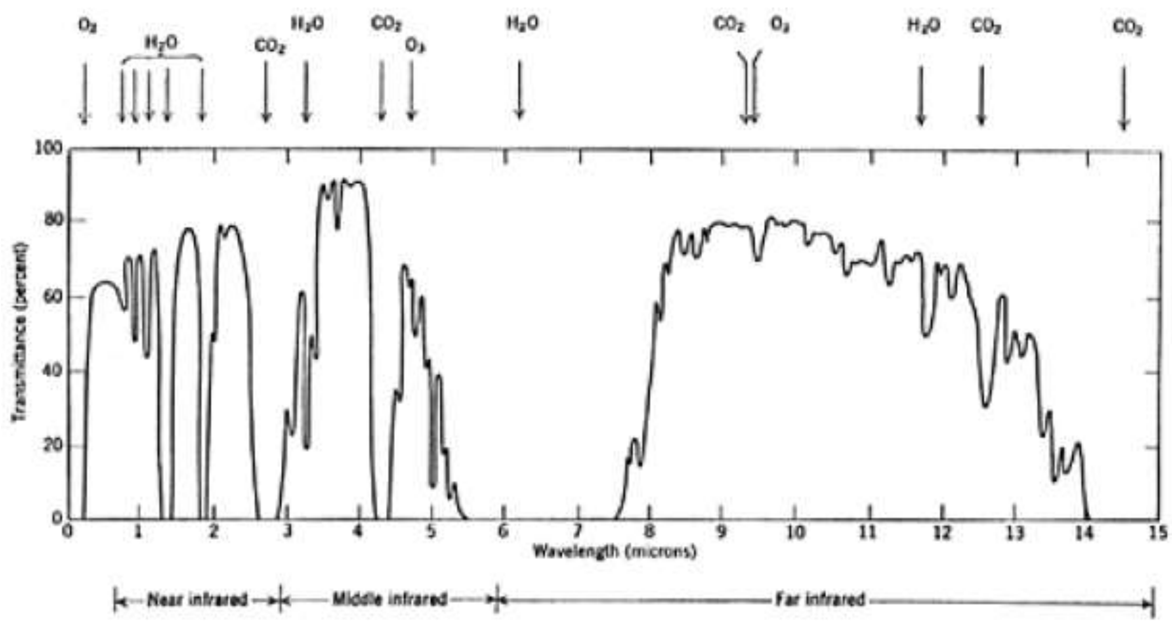
La atenuación en el espacio libre se debe a la interacción de la luz con partículas / moléculas en suspensión (gotas de agua, polvo, aerosoles, etc):



6.-ATENUACIÓN EN EL ESPACIO LIBRE

Los fenómenos que se producen son :

- **Scattering** (Rayleigh/ Mie)
- **Absorción** por la presencia de H_2O, CO_2, O_3
- **Cambios del índice de refracción** de la atmósfera (turbulencias, cambios de presión, cambios de temperatura) → Scintallation



6.-ATENUACIÓN EN EL ESPACIO LIBRE

Una forma de estimar la atenuación es:

$$P_{Rx} = P_{Tx} e^{-\alpha L}$$

donde $$\alpha(dB/km) \approx \frac{17}{V(km)} \left(\frac{0.55}{\lambda(\mu m)}\right)^{q}$$

-donde *V es la visibilidad*

$$-q = \begin{cases} 1.6 & \text{si} \quad V > 50\ km \\ 1.3 & \text{si} \quad 6 < V < 50\ km \\ 0.585V^{1/3} & \text{si} \quad V < 6km \end{cases}$$

Universidad Carlos III de Madrid

FOTONICA

ANEXO

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.

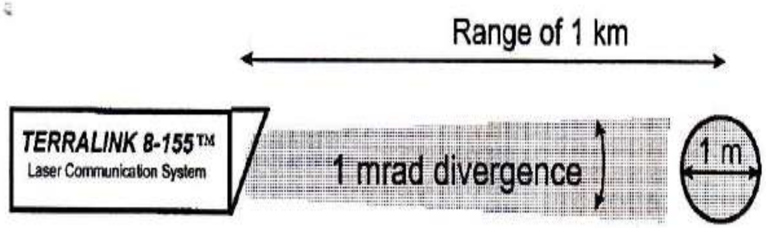


Fig. 1 Narrow beam of the TerraLink laser communication system. The narrow beam makes laser links a very secure means of communication. It is very difficult to detect, intercept, or jam the transmitted signal; however, the narrow beam also produces alignment difficulties. A 1 mrad divergence (which is 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.

nication 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 midwave 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.

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 commu-

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:

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

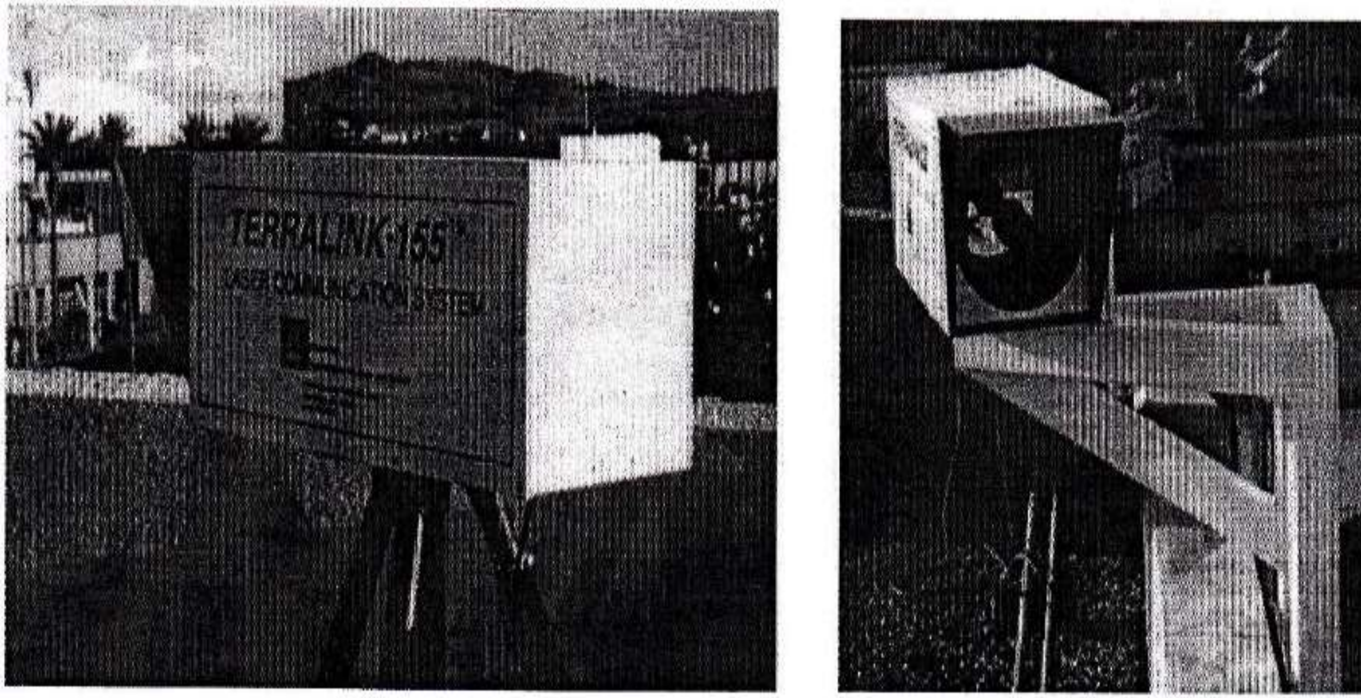


Fig. 2 TerraLink 8-155 transmitting 155 Mbps asynchronous transfer mode (ATM) during the 1996 Networld+Interop trade show in Las Vegas (left). The front view (right) shows the single 8 in. diameter aperture used for both transmit and receive. Maximum clear weather range is 8 km and data rates are adjustable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

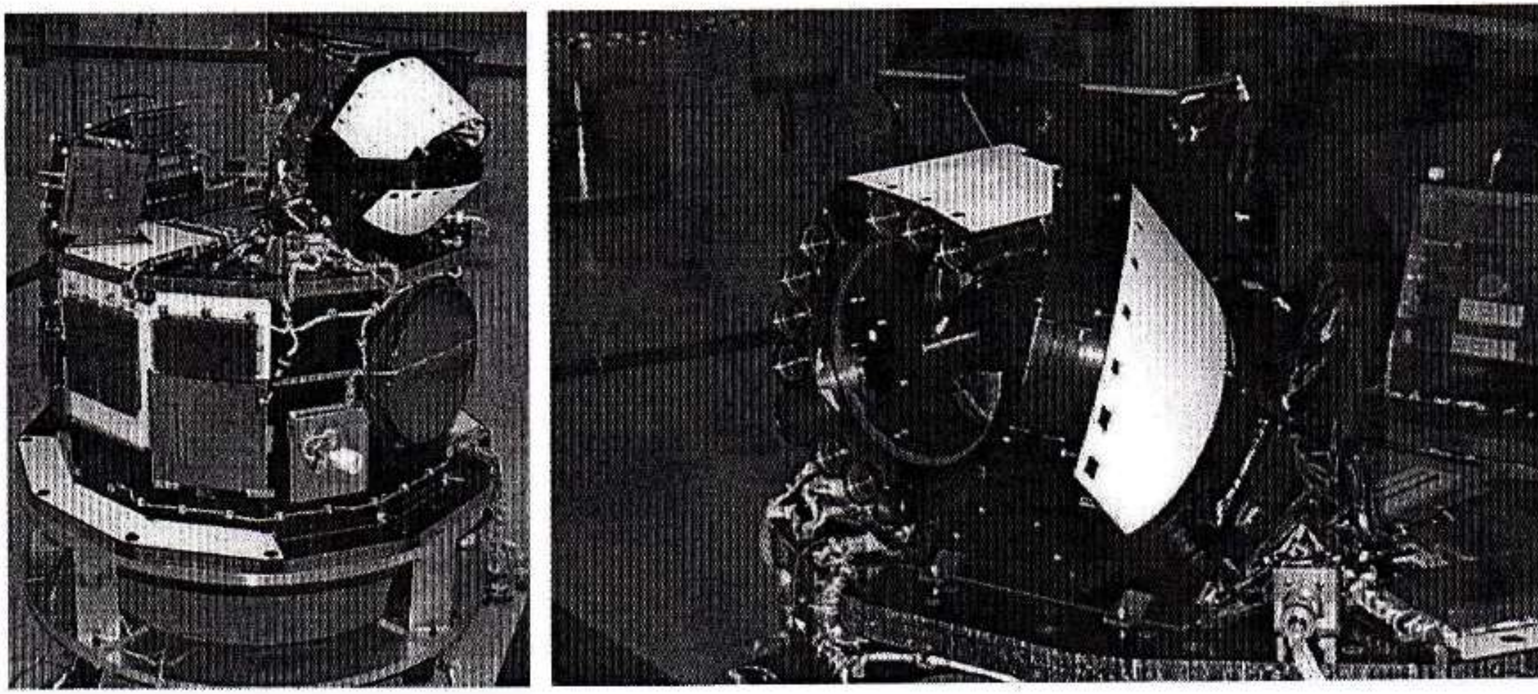


Fig. 3 AstroTerra/BMDO laser communication terminal mounted on the STRV-2 satellite top deck (left) and close-up of the lasercom satellite transceiver (right). It is housed in a two-axis gimbal with a 5.5 in. receive aperture and 8$\times$1 in. transmit and 2$\times$1 in. beacon apertures. The maximum data rate is 1.0 Gbits/s (two channels at 500 Mbits/s) and the LEO to ground range is 600 to 1800 km. The lasercom transceiver is 13.5 in. tall$\times$11 in. wide$\times$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

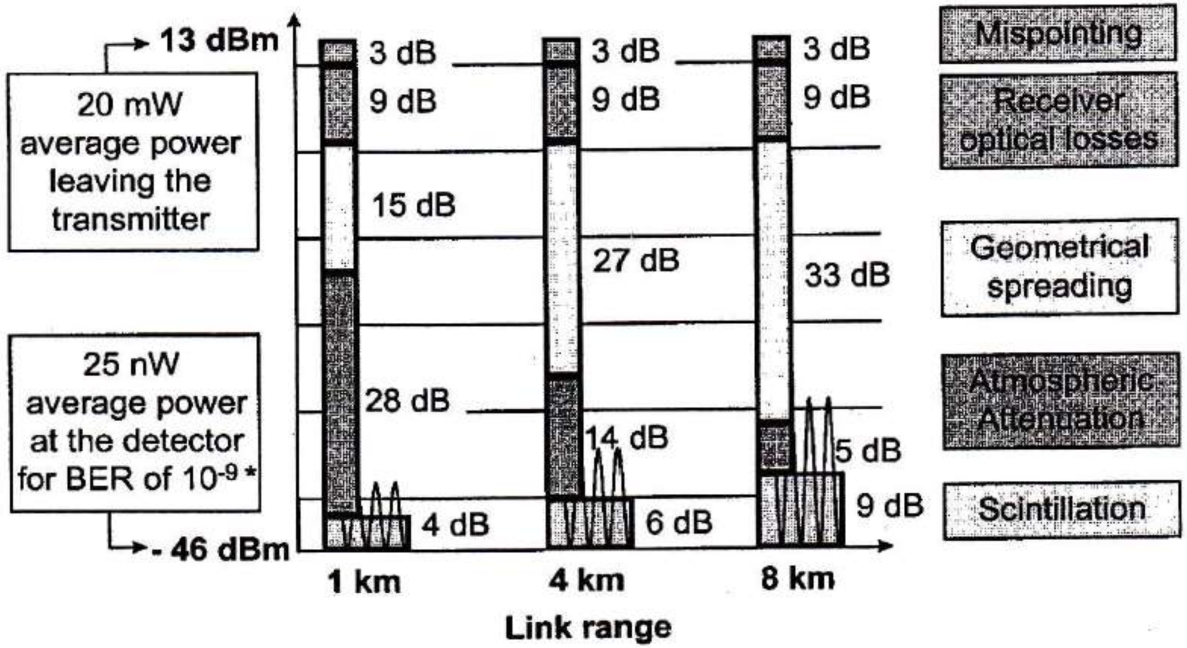
SA_T = surface area of the transmit aperture =0.005 m^2 for the TerraLink 4 and 0.025 m^2 for the TerraLink 8

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



* spec from the manufacturer

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]:

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

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

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 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]

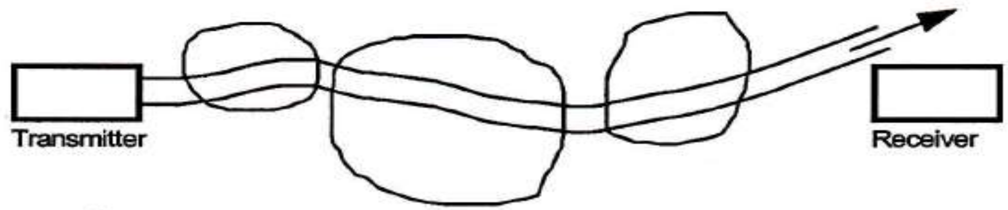


Fig. 5 Laser beam wander due to turbulence cells which are larger than the beam diameter.[7]

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 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.

tering 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.

eral 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-

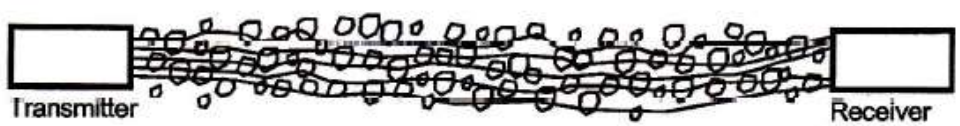


Fig. 6 Scintillation or fluctuations in beam intensity at the receiver due to turbulent cells that are smaller than the beam diameter.[7]

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-

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

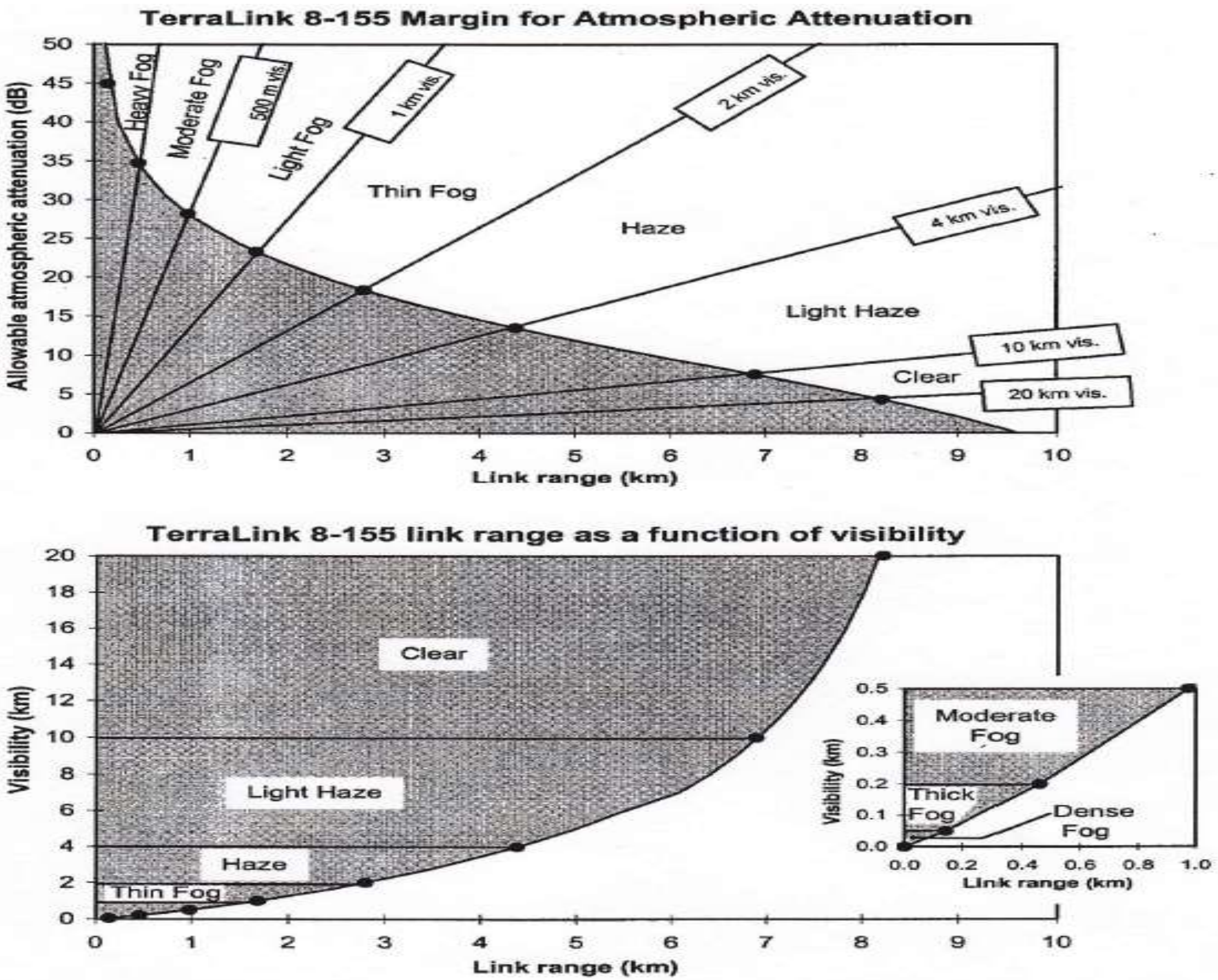


Fig. 7 (top) TerraLink 8-155's allowable margin for atmospheric attenuation as a function of link range (gray area). Straight lines are decibel loss per kilometer in different visibility conditions assuming losses are due to only Mie scattering. The intersection of the straight line with the atmospheric 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.

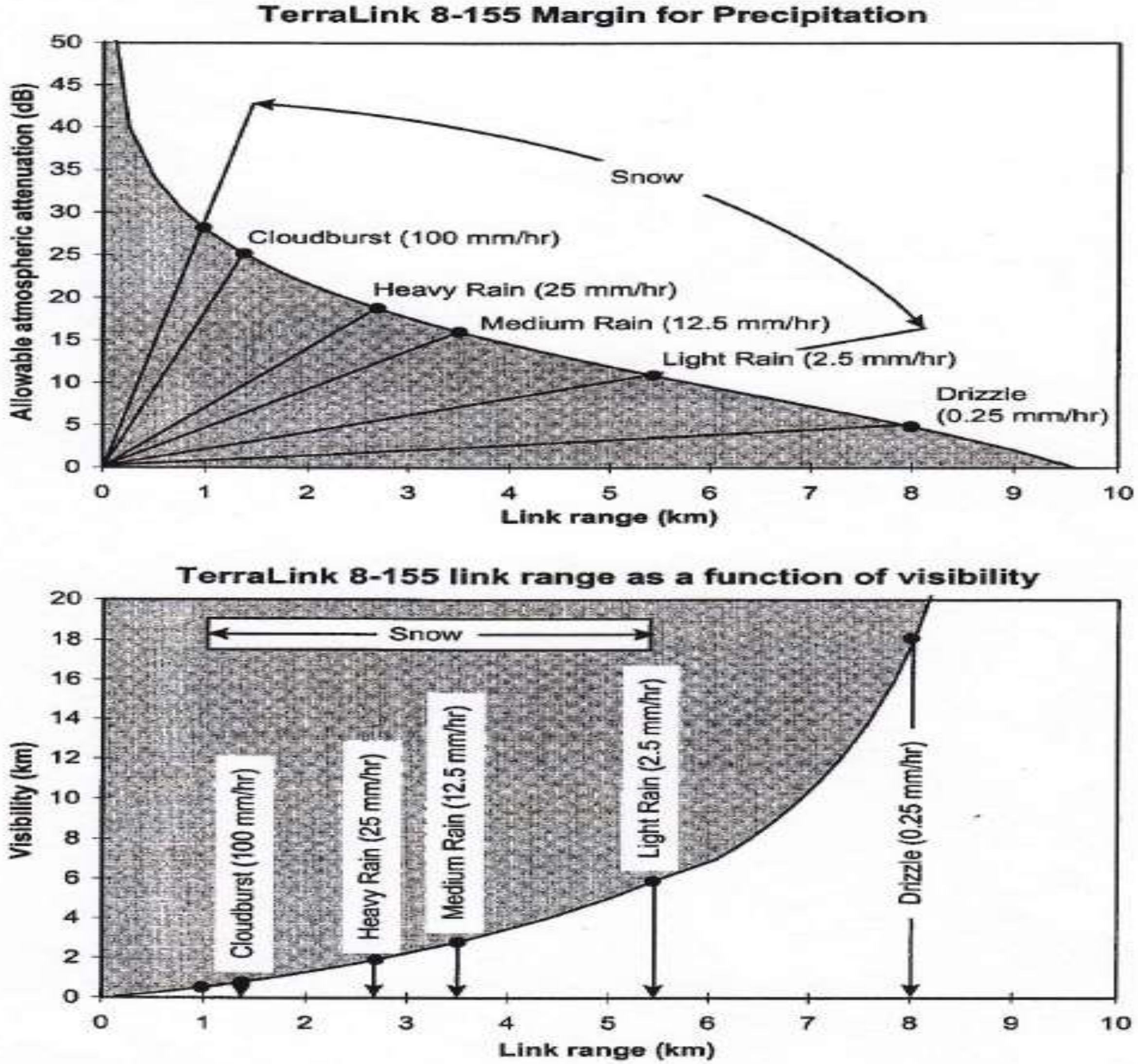


Fig. 8 (top) TerraLink 8-155 margin for precipitation attenuation and (bottom) maximum link range as a function of precipitation.

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
	Snow		1 km	-13.8	1.68 km
Thin fog	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