ATMOSPHERIC LASER COMMUNICATION

NEW CHALLENGES FOR APPLIED METEOROLOGY

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With the help of meteorologists, atmospheric laser communication within cities is becoming more reliable and more widely used.

Communication by modulated optical signals transmitted through the atmosphere using smoke signals, signal lanterns at sea, and the heliograph dates back centuries. In the late nineteenth century, Alexander Graham Bell transmitted his voice through about 183 m of free space (air) using a reflected beam of sunlight. Bell's experimental device, which he named the "photophone," pioneered the principles used in today's optical telecommunication technologies (Killinger 2002). Today, atmospheric laser communication allows users to send high-bandwidth digital data from one point to another using an invisible and eye-safe laser beam in a method similar to fiber optics, but directly through the atmosphere without the fiber. Free-space optics (FSO) and free-space laser (FSL) communication have become the standard nomenclature for atmospheric laser communication. Although these are really misnomers because the laser is not going through space, the terms have become part of the language. FSL is the term that will be used here. Transmission of laser beams through air instead of through fiber offers some obvious advantages but with accompanying disadvantages, most notably high attenuation by fog and clouds.

Determining the feasibility of using laser transmission through the atmosphere requires knowing the frequency distribution of optical thicknesses at the wavelengths of interest over paths of interest at various heights in the atmospheric boundary layer. FSL uses lasers in the near-infrared spectrum, typically at wavelengths at 850 or 1550 nm, to transmit a signal in urban areas at ranges up to around 4 km. Given these wavelengths, fog and low clouds are the primary concerns for links < 1200 m. For longer links, scintillation, heavy rain, and snow frequently become issues.

Applications of broadband telecommunication include high-definition video conferencing, transfer of massive datasets, such as a bank or stock market

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records that require daily backup, or simply large networks having many users. In recent years, much of the need for fast, reliable communication in urban areas has been satisfied by optical fiber networks. These networks are typically deployed in a ring in the urban core with spurs to buildings with customers. For many applications, however, FSL is the best possible solution to reach the locations not connected by fiber (Willebrand and Clark 2001) and the most likely impetus for the future broadband revolution (Acampora 2002). Figure 1 shows an optical network in a city with optical fiber connecting some buildings and with FSL connecting to many others via *fiberless* connections, without digging up streets and sidewalks. The primary advantage of FSL over fiber optic cable is the rapidity with which links can be deployed and the cost, which tends to be considerably less than that of optical fiber connections (Willebrand and Ghuman 2001).

FSL AND LINK MARGIN. The main challenge of FSL is that the atmosphere, due largely to scattering by water droplets in fog and low clouds, can attenuate the signal. Figure 2 depicts an FSL connection with a transmitter that projects carefully aimed light pulses into the air and at the other end of the link a receiver that collects light using lenses and/or mirrors. FSL optical signals are typically transmitted in one of two optical bands centered at a 850- or 1550-nm wavelength, both in atmospheric spectral transmission windows where the absorption of the signal by atmospheric constituents is minimized. The 1550-nm wavelength is used in the fiber optics industry, and some FSL companies favor this wavelength. At this wavelength, background solar radiation is virtually eliminated, and a transmission of laser power higher than at 850 nm can be used while still ensuring eye safety.

Commercial FSL transceivers transmit a few milliwatts up to just over 1000 mW of optical power. The FSL signal is attenuated as the infrared light travels from the transmitter to the receiver so additional optical transmit power is engineered into the system. This extra optical signal is referred to as the link *margin.* FSL designers use the decibel logarithmic scale in the same way that the backscattered signal from meteorological radars is displayed. The ratio of power transmitted and power received is expressed in decibels,

$$\mathrm{dB} = 10 \log (P_T/P_R), \tag{1}$$

where P_T is the transmit power and P_R the received power. Thus, if the transmit power is 10,000 times the power required for satisfactory reception at the receiver under clear atmospheric conditions, the link is said to have a 10 log(10,000) dB, or a 40-dB margin.

Figure 3 shows many of the key factors that can reduce this decibel margin, including fog, low clouds,

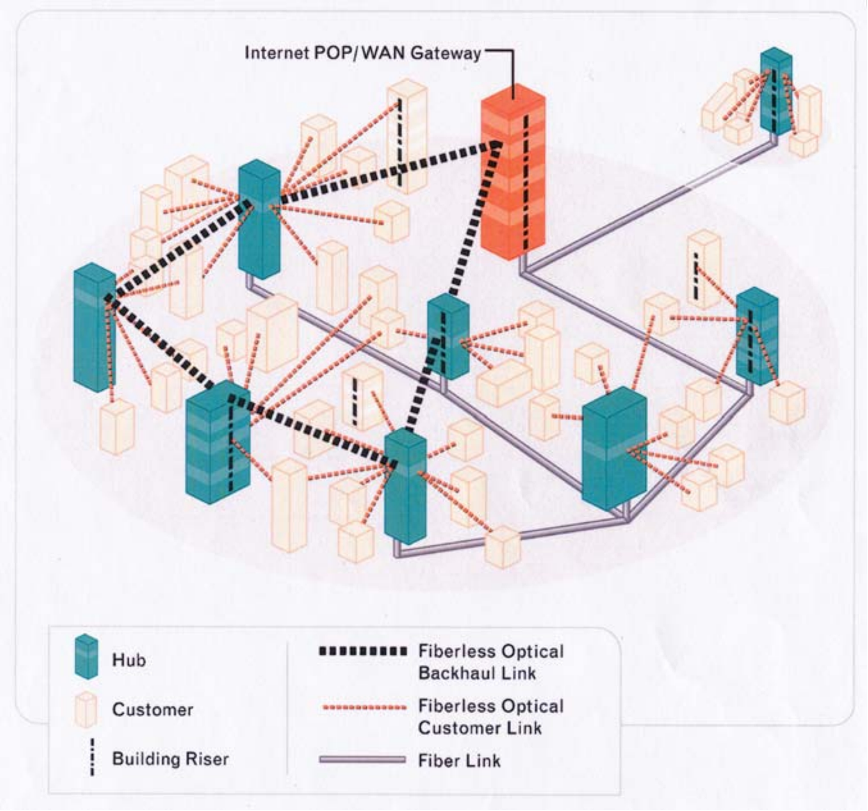

Fig. 1. Urban all-optical network using fiber and *fiberless* connections between buildings. The point of presence (POP)/wide-area network (WAN) is the building in each city where all of the internet optical fiber from across the country and the world come into the city. In FSL telecommunication, *backhaul* is used to refer to a main link connection that carries signals from multiple sites or customers back to a central site such as the POP.

scintillation, and nonatmospheric physical effects such as window attenuation, building motion, construction, and birds. Fortunately, FSL designers have been able to engineer around most of these issues. Depending on the FSL hardware configuration (i.e., laser transmit power and wavelength, beam divergence, receiver aperture, and receiver noise floor) and the physical setup of the link (i.e., distance, geometry, building window attenuation), a link might have a margin of up to 40 dB. The attenuation caused by building windows is generally on the order of 5 dB. This would reduce an initial 40-dB margin to 35 dB, typical for a commercial urban installation.

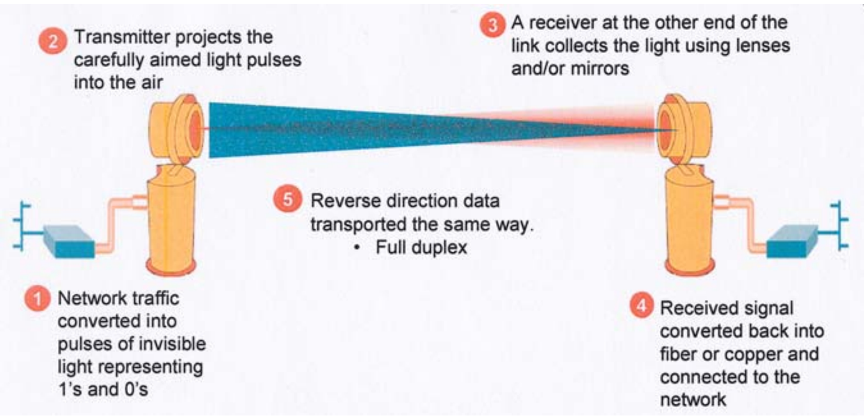

Fig. 2. Description of how FSL connects point to point. A full-duplex FSL system allows data to be transmitted simultaneously in both directions.

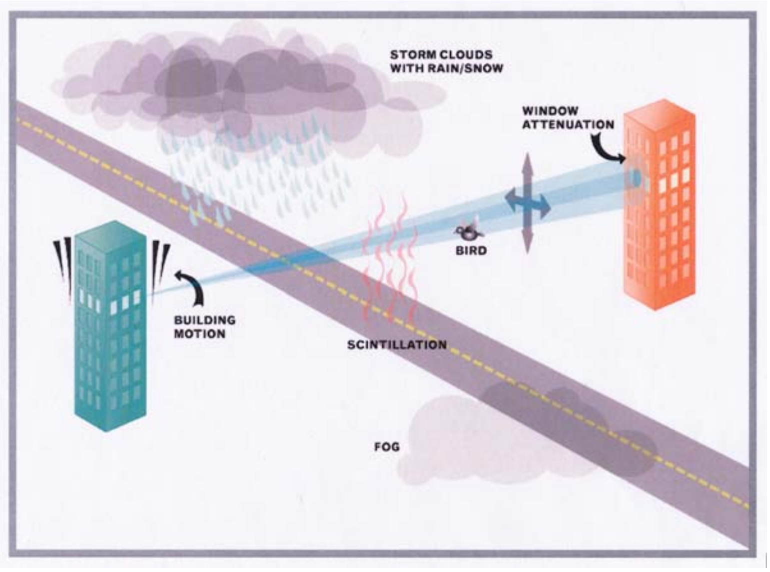

Fig. 3. Several factors can attenuate the transmitted optical signal. However, FSL designers have been able to engineer around most of these.

FOG AND LINK AVAILABILITY.

In telecommunications, customers expect a certain amount of up time or *availability,* when reception is as desired. Table 1 shows the number of minutes or hours in a year that a link will be down for a given availability. With FSL installations, 99.9% or *3 nines* of up time is the typical target availability, this is almost always limited by attenuation due to fog or low clouds. Attenuation is often referred to as extinction at optical wavelengths (Glickman 2000) and can be due to scattering and/or absorption. To calculate the availability of a given link, it is necessary to determine the average number of minutes per year that would produce an optical extinction sufficient to bring down the link under atmospheric conditions that are identical to those at the location of the link. To calculate the number of average threshold extinction minutes in a year, it is necessary to query a database of long-term meteorological observations.

Table 1. Communications industry availability terminology.

Carrier availability terminology	Availability	Outage
5 nines	99.999%	Down <6 min yr^{-1}
4 nines	99.99%	Down ~53 min yr^{-1}
3 nines	99.9%	Down ~8.75 h yr^{-1}
Sub-3 nines	99.7%	Down ~26.25 h yr^{-1} ~1 day yr^{-1}
2 nines	99.0%	Down ~3 days, 15+ h yr^{-1}

Because these wavelengths are in the near-infrared spectrum (850 and 1550 nm), the necessary transmission measurements in clouds and fog have rarely been made, except possibly at a few sites. But visual range, visibility, and/or meteorological range data for a great many sites are readily available, and, with suitable assumptions, visual range can be related to infrared attenuation.[1] These data are primarily collected at airports for aircraft safety, but these same data are equally useful to develop a local climatology for FSL applications.

Table 2. Visual range conditions and attenuation from extremely clear to dense fog (based on the International Visibility Code).

Description	Visual range	Loss (dB km^{-1})
Dense fog	40–70 m	250–143
Thick fog	70–250 m	143–40
Moderate fog	250–500 m	40–20
Light fog	500–1000 m	20–9.3
Thin fog	1–2 km	9.3–4.0
Haze	2–4 km	4.0–1.6
Light haze	4–10 km	1.6–0.5
Clear	10–25 km	0.5–0.1
Very clear	25–50 km	0.1–0.04
Extremely clear	50–150 km	0.04–0.005

Although many will associate visual range with attenuation due to molecules and haze particles in a noncloudy atmosphere, attenuation of an IR laser beam by haze and molecules is insignificant at the ranges at which FSL is typically deployed in urban areas (up to 4 km). Typically, weather that reduces visual range also attenuates the power being emitted by FSL transmitters. Rain, snow, fog, and low clouds are all potentially capable of doing this. However, heavy snow rarely reduces visibilities to the level needed to interrupt a laser link and, except for links longer than 1200 m, is rarely a problem. Adaptation of an International Telecommunication Union model indicates that heavy rain is even less of a problem; a very rare rainfall intensity of 10 in. h^{-1} results in less than 50 dB km^{-1} attenuation at 1550 nm. This has been confirmed by experience gained operating FSL networks, and anyone who has observed rain shafts and snow. Thus, the main weather phenomena of concern are fog and low clouds.

Kruse et al. (1962) developed a semiempirical equation relating visual range to optical extinction at various wavelengths. The Kruse equation is

$$\Gamma(V;\lambda)=\frac{17.0}{V}\left(\frac{550}{\lambda}\right)^{0.585V^{1/3}}\left(\mathrm{dB\,km^{-1}}\right), \qquad (2)$$

where λ is the wavelength in nanometers, V is the visual range in kilometers, and Γ is the resultant attenuation in decibels per kilometer. Measurements, however, show that the apparent advantage that the Kruse equation gives to longer wavelengths vanishes at the low visual ranges that typically cause an FSL link to fail (Rockwell and Mecherle 2001). The Kruse equation for low visual ranges can be reduced to

$$\Gamma(V;\lambda)=\frac{\kappa}{V}\left(\mathrm{dB\,km^{-1}}\right), \qquad (3)$$

where 8.5 dB < κ < 17 dB (Pierce et al. 2001). In using the Kruse equation, the effects of multiple scattering are ignored, which is reasonable when the visual range is >1000 m but may not be negligible when optical thicknesses are large (Bohren 1987). Calculations of attenuation that include multiple scattering will yield attenuation values that are lower than those of calculations that assume only single scattering. Initial measurements in low-visual-range radiation fogs in the Sammamish Valley of Washington indicate κ to have a value close to 10. This result is a slightly lower attenuation than that indicated by the Kruse equation and is consistent with multiple scattering at very low visual ranges. Table 2 shows visual range classes that include both visual range in meters and the corresponding optical loss in decibels per kilometer [e.g., a visual range of 100 m (~1 football field length) yields 130 dB km^{-1}]. Experimental values are used for visual ranges up to 600 m; equation (2) is used thereafter.

Once the decibel margin of a link is established, the visual range and, hence, the attenuation characteristics of a city from long-term records are used to calculate a link's availability or average annual operational time. Visual range records are available from

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[1] Precise definitions of meteorological range, visual range, visibility, and related terms are best expressed in Middleton (1952) and Glickman (2000). All three terms refer qualitatively or quantitatively to how light propagates through the atmosphere and how well an object can be discerned at some distance.

airports worldwide. The period of record available is usually at least 16 yr and for many locations is 30 yr or more. For example, in Seattle, Washington, visual range exceeds 186 m 99.9% of the time at the surface. Using the revised Kruse equation, one would expect attenuation to be less than 54 dB km^{-1} 99.9% of the time over 1 yr in Seattle. For an FSL installation with a 30-dB margin, a link budget for 99.9% availability is calculated by dividing the equipment's margin by the attenuation per kilometer. In this case, a link with a 30-dB margin divided by 93 dB km^{-1} yields a link budget of 0.555 km or 555 m. This allows this FSL equipment to be installed in a link up to 555 m long with confidence that the link will remain operational, on average, 99.9% of the time. Most cities have less fog on average than Seattle, making it possible to install FSL equipment in those cities at much longer distances and still attain a 99.9% availability.

The photograph in Fig. 4 shows the Transamerica Tower in downtown San Francisco, California, partially engulfed in fog up to roughly 180 m above mean sea level. In this case, the fog is fairly thin optically, and many FSL systems can penetrate such a fog. In the case of Phoenix, Arizona, installations of 2000 m or longer will have an availability greater than 99.9%. Obviously, different cities have different fog and visibility climates, and these can strongly impact the performance of the FSL systems operating there. Figure 5 shows a list of major cities worldwide ordered by the 99.9% link margin based on data collected at the primary airport for each city.

LOW CLOUDS. While FSL link budget calculations usually start with long-term surface visual range records from nearby airports, these data are collected typically within a few meters of the ground and are only appropriate for link calculations near the surface (Baars et al. 2002b). Examination of long-term cloud observations, including percent frequency of cloud ceilings occurring at various heights above the ground, shows the importance of including low clouds in the consideration of FSL availability for any situation above about 30 m above ground level. Because FSL links are often sited on top of or within high-rise buildings in downtown urban core areas, links are often sited well above this 30-m height. Observations show that while the surface visual range can be very high, low clouds just a few tens of meters above ground level greatly reduce visibility.

FSL link budgets that are more than 30 m above ground level need to include the effect of low clouds.

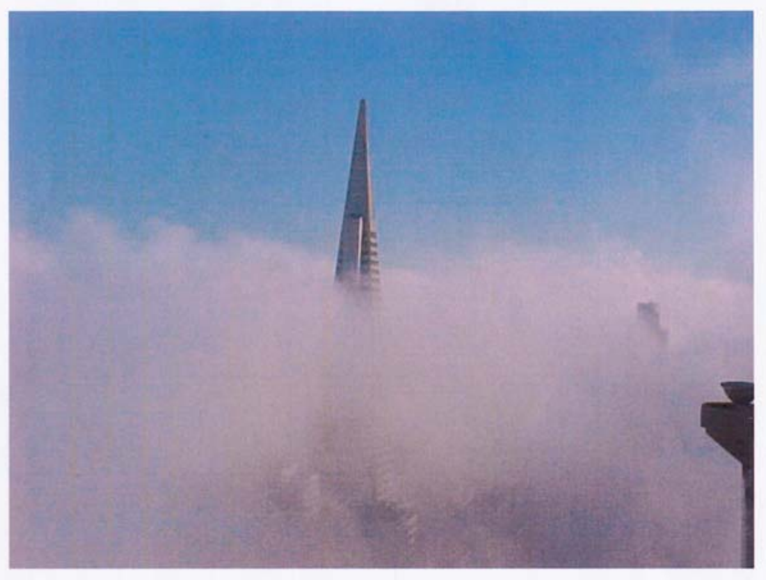

Fig. 4. The Transamerica Tower in the central business district of San Francisco partially engulfed in fog, midmorning, 5 Feb 2002.

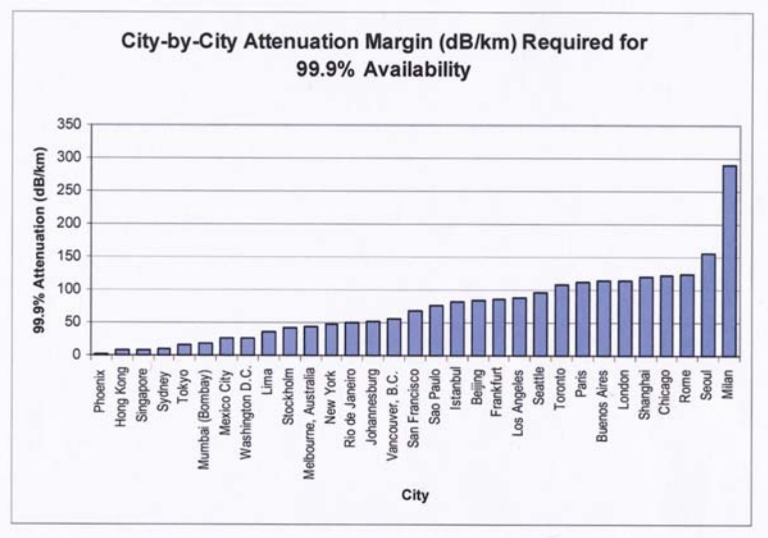

Fig. 5. Cities ordered by attenuation margin (dB km^{-1}) required for 99.9% link availability. Data derived from surface visual range data (altitude effects not included) and application of the unmodified Kruse equation. (Source: Terabeam Weather Group, Jan 2001.)

A technique for evaluating visual range and attenuation in low clouds has been developed (Baars et al. 2002b). Similar to visual range data, cloud data are archived over long periods and can, thus, be used to calculate long-term averages of availability. Even with ceiling cover, cloud type, and sky cover observations, some assumptions must be made in order to estimate average availability of an elevated link. In particular, the optical properties of different cloud types are not well documented. However, attenuation has been observed to increase with height within a cloud (Pinnick et al. 1978; Hobbs and Deepak 1981). Also, the vertical thickness of clouds is not regularly measured and must be estimated. Finally, a ceiling is declared when the sky is more than 50% covered with cloud, so locations that are at or above the ceiling height may at times be cloud free.

For most locations, attenuation due to low clouds is a bigger problems than fog, and as a result, link budgets typically decrease as altitude above ground increases. Figure 6 shows the 99.9th percentile of atmospheric attenuation (dB km^{-1}) as a function of height above ground level during a year in Denver, Colorado (i.e., 0.1% of the time, the atmospheric attenuation exceeded the graphed value at that altitude).

The few exceptions to link budgets' decreasing altitude are mostly cities in developing countries, where additional condensation nuclei from the large amount of pollution increase the optical thickness of surface fog for a given liquid water content (LWC) value (kg m^{-3}). The size distribution of cloud and fog droplets determines the scattering coefficient, and a larger number of smaller droplets yields a higher optical thickness for a given LWC. Once above the polluted surface layer, a smaller number of pollution particles exist, and optical conditions improve. Some progress has been made in measuring the attenuation and vertical depth of low clouds; but, for most locations, assumptions must be made and then tested empirically (Al-Habash et al. 2002).

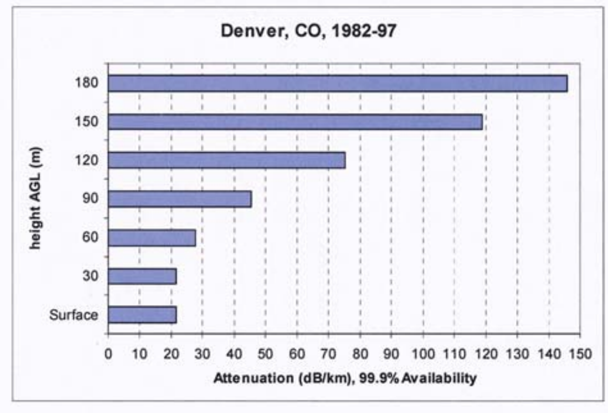

Fig. 6. Percent frequency of clouds with height for Denver International Airport/Denver Stapleton Airport (KDEN), 1982–97. The surface data point is the percent frequency of visibilities less than 400 m.

SCINTILLATION. In the absence of fog or low clouds, scintillation has the most disruptive effect on the signal fidelity of a laser link through the atmosphere. In terms of FSL, scintillation is defined as the fluctuation of laser beam irradiance seen at the receiver due to atmospheric turbulence (Palmer 1993; Stephens 1994). This is due to optical turbulence, minute fluctuations of the refractive index along the path due to random thermal inhomogeneities induced by atmospheric turbulence. The strength of these fluctuations depends on the beam characteristics, the receiving apparatus specifications, and the strength of the turbulence in between.

Due to scintillation, the amount of signal received over a 1000-m link may vary more than 12 dB over a small fraction of a second. In some cases, the strength of the received optical signal might drop below the detector minimum sensitivity, which leads to signal fading. This lack of optical detection will result in an increased bit error rate (BER) or even loss of data transmitted during the fade period. In general, scintillation becomes critically important for FSL systems with receiver apertures 10 cm in diameter or smaller and for FSL links longer than 5 km in a cloudless atmosphere, where scintillation will ultimately limit the link availability. Fortunately, strong scintillation, fog, and low cloud attenuation are associated with mutually exclusive atmospheric states.

OBSERVATIONS AND LIMITATIONS OF DATASETS. The use of airport visual range data when calculating FSL link budgets has certain limitations due to altitude differences, horizontal offsets, microclimates, and urban heat island effects, as well as uncertainty in the application of the Kruse equation for very low visibilities. Visual range at airports is not always representative of the area where an FSL network or FSL links may be deployed, commonly in city centers. For example, in Seattle, the Seattle–Tacoma International Airport is 12 km south of downtown, over 120 m MSL, and is not very representative of downtown Seattle, much of which is well below this altitude. Boeing Field, the other airport station, is closer to downtown and at a lower altitude, but does not reflect some local effects that may affect an FSL network in Seattle's central business district.

Cities have an urban heat island effect due to changes in the surface energy balance and atmospheric composition from that of surrounding areas. This effect keeps the air in the urban boundary layer—and especially below roof level—warmer than that of the surrounding areas (Oke 1982, 1995). This warmth frequently results in surface visual range conditions in a city that are measurably better than those in the suburban or rural areas where the major airport is often located. For example, when comparing data from New York City's Central Park Automated Surface Observation System (ASOS) station, it is clear that long-term visibilities are considerably better than those reported at LaGuardia International Airport. Ronald Reagan Washington National is one of very few major airports sited in the heart of a metropolitan area, and visibilities reported there are considerably higher than elsewhere on the east coast of the United States. Other studies in the United States, Europe, and Asia find reduced fog within cities (Lee 1987; Suckling and Mitchell 1988; Sachweh and Koepke 1997); although, in cities with high aerosol loads, the difference can be reversed.

Another limitation to these datasets is that prior to the mid-1990s, humans made the observations at major reporting locations. For these observations, it was clear what each observation meant. For example, an observation of zero visual range implied the observer could not see the closest visibility marker. If that marker were at 100 m, the individual who was analyzing the data realized that the observation meant the visual range was not actually zero but was less than 100 m. Depending on the distance of an FSL link, having knowledge of the distribution of these very low visuals ranges is important. For example, a 300-m link may require a visual range of 100 m to operate effectively. With the advent of ASOS, the precision of the visual range on the hourly reports has greatly diminished. Visual ranges are now rounded, while previously they were incremented. Also, visual ranges below 400 m are often reported as below ¼ mile, or 400 m (M1/4), with no indication as to the exact visual range. Use of airport visual range data does have these limitations, but it does a reasonable job representing optical extinction for a given urban area and, for many cities, data collected over 30 yr are available, allowing interannual statistics to be calculated.

FUTURE OF FSL AND METEOROLOGY. As we have observed, communication by modulated optical signals transmitted through the atmosphere is centuries old; although, until recently, the source of light has been the sun or lamps. Recently, lasers in the form of FSL have been used as this source. The transmission of laser beams through air instead of through fiber offers some obvious advantages but with accompanying disadvantages, most notably high attenuation by fog and clouds. To harness all of the potential of FSL communication, a full understanding of the effects of meteorology on laser propagation is required.

The bulk of atmospheric research in FSL to date has focused on the climatology of fog and low clouds in major urban areas and the *representativeness* of existing airport long-term data series in the urban core. Improved understanding of optical extinction conditions in urban areas may lead into several areas that have been explored. These include fog typing (Byers 1959; Baars et al. 2002a), fog trends (Witiw et al. 2002), the nature of cloud bases and cloud vertical extent (Al-Habash et al. 2002; Fischer et al. 2003), the effects of scintillation on transmission, and even satellite-derived products to model local elevated fog and low-cloud occurrence (Ellrod 1995; Fischer et al. 2001). Despite this work, much remains to be done.

Deployment of FSL systems at each location must be based upon a combination of the customer's availability requirements and a good understanding of the local climatology. Many meteorological effects can attenuate a laser beam and impact the performance of FSL equipment, including fog, low clouds, snow, rain, scintillation, dust, haze, and air pollution, although fog and clouds are the most critical. For FSL communication, the laser beam can not go above, below, or around the atmosphere. It just has to go through it, which means a complete understanding of optical extinction at these wavelengths in the atmosphere is required.

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