Dollars versus Decibels:

Long-Range atmospheric optical communications on a tight budget

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Decibels versus dollars: Long range atmospheric optical communications on a tight budget

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ABSTRACT

Three decades of experiment by the authors have shown that the combination of high intensity light emitting diodes, silicon photodiodes, and large aperture moulded Fresnel lens collimators of moderate focal length provide effective and economical long distance atmospheric optical communications. While the use of larger transmitter and receiver lenses increases optical flux at the detector, their greatest advantage is in dramatically reducing the depth of the scintillation or rapid signal fading. This is caused by differential phase distortion, beam steering, focusing/defocusing by air turbulence cells along the transmission path, and the effects of local coherence. It has been observed that scintillation effects diminish rapidly when the transmitter and receiver apertures are larger than the central diffraction peak of the distant aperture, or about 30-cm diameter for red light over a 160-km path.

Keywords: Atmospheric, optical, communications, Fresnel, Luxeon, scintillation, partial coherence, beam expansion, photodiode

1. HISTORICAL BACKGROUND

1.1 Early experiments

The first recorded optical transmission of speech breaking the "100-mile barrier" was made by the Electro-Optical Systems [EOS] Amateur Radio Club of Pasadena, California. They transmitted a Helium-Neon (HeNe) gas laser[E,1] [Fig. 1] beam 190 km across the Mojave Desert using red light (632.8 nm) on the 3rd and 4th of May, 1963.[2,3] This transmission by Jack Pattison (W6POP) was received by a photomultiplier mounted at the focus of a 32-cm diameter reflecting telescope by Robert Legg (W6QYY)[F,4] who, in July, 2007, generously provided the authors with a copy of the log tape and the technical details of the equipment.

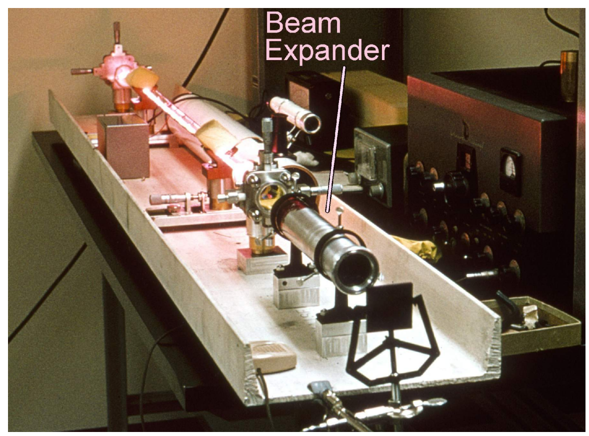

Fig. 1. 125-μW HeNe laser used by the Electro-Optical Systems Amateur Radio Club in May, 1963 to transmit speech over a 190-km tropospheric path. The laser assembly, mounted in a steel channel, was externally excited using amplitude-modulated RF. Note the use of a beam expander.

This may be the oldest sound recording demonstrating

[A] The authors of this paper are, in addition to our respective professional careers, amateur ("ham") radio operators and our self-funded experiments are geared more toward the investigation of propagation and the range limits of atmospheric, free-space optical communications rather than in developing high-reliability, commercially viable or broad bandwidth optical links. The amateur radio callsigns of authors Long, Groth, and Turner are VK3AML, VK7MJ, and KA7OEI, respectively.
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[E] This was only a few months after Bell Labs' first demonstration of visual (632.8-nm) output from a HeNe laser. Prior to this, HeNe lasers had only produced IR output.
[F] Transcribed from the laser-transmitted log tape recorded by Bob Legg W6QYY and members of the EOS team on Panamint Ridge, East of Ballarat and just West of Death Valley, California, 4 May, 1963. The transmission team at Grassy Hollow in the San Gabriel Mountains, North of Los Angeles, was headed by Jack Pattison W6POP. A cassette copy of the tape was sent to Chris Long by Robert Legg in July, 2007. An online account of this event with audio recordings may be found at: http://www.modulatedlight.org/eos

atmospheric scintillation on long distance optical transmissions through the atmosphere, indicating the severity of the problem with a coherent optical beam. The recorded speech has about 15 fade cycles per second, each with a depth of at least 20 dB. This scintillation would have been worse if the EOS team had not used a beam expander on their laser to reduce the diffraction at the laser's exit pupil,[5] but the significance of the transmitter beam diameter was probably not recognised at the time. By straddling adjacent atmospheric turbulence cells in the beam path, the expanded beam provided aperture averaging across the beam profile, which reduced the rate and depth of the fading to the point where the speech modulation became intelligible.

In 1982, a team from the Bell Research Laboratories analysed the transmission of light under real atmospheric conditions over a 37-km optical link, using a chopper-modulated HeNe laser beam expanded through a 30.5-cm diameter telescope, and detected by four photomultipliers at the focus of four large Fresnel lenses.[6,7] This composite receiver aperture had two advantages: First, the spatial diversity provided by the large combined aperture reduced the scintillation effects by averaging over a large number of atmospheric turbulence cells and second, the differential signals from the individual detectors provided a feedback signal which allowed the transmitter to be steered to keep the laser beam centred on the detector array.

Fig. 2. Clinton Turner in October, 2007, at the north end of the 278-km optical path. This lightweight gear used inexpensive Fresnel lenses, a noncoherent light source, and despite rather poor seeing conditions, 2-way communication was established.

1.2 Recent experiments

Using simple, low-cost technology, the authors set a full duplex speech modulated light record range of 168-km in Tasmania in February, 2005.[8] On the 3rd of October, 2007, Clinton Turner [Fig. 2] and associates used similar techniques to set a 278-km optical telephony record between mountain tops in Utah, USA. Neither of these record-setting transmissions employed lasers or high transmission powers.

2. ANALYSIS OF RESULTS

The 1982 Bell Research Labs study demonstrated two important limitations of a laser-based long distance atmospheric optical communications link:

1. The beam diameter at the receiver is *limited primarily by atmospheric turbulence* rather than diffraction from the transmitter exit pupil. The cost and complexity of building a large diameter beam expander with precision optics will not significantly increase the distant beam intensity.
2. A very narrow transmitter beam *needs to be continually steered* to compensate for changes in atmospheric refraction.

The benefits of beam expansion were overlooked by most amateur optical communications experimenters. As higher powered lasers became available, experimenters unfamiliar with atmospheric physics tended to transmit unexpanded pencil-thin laser beams. The severe scintillation and beam steering noise generated by atmospheric turbulence extended into the kilohertz region[G] and masked many attempts at recovering modulation over long ranges. No private experimenter duplicated the EOS team's terrestrial optical telephony range record with readable signals for nearly 30 years.[H] These optical field tests implied that laser light was the most appropriate medium for atmospheric optical communication. Could this impression be incorrect?

[G] Comparisons of LED and diode laser communication beams have been made in the Salt Lake City area on a 24 km path by Clinton Turner during 2007. At times the laser produced scintillation with an average depth of more than 30 dB at a rate so high that it sounded like severe hiss on a direct-detection system. On 3 October, 2007, the distant Luxeon-Fresnel combination could be seen at a distance of 278 km, while co-directed diode lasers could not be sighted at all, even with the aid of a 20-cm diameter astronomical telescope.

3. COHERENCE AND SIGNAL QUALITY

3.1 Effects of distant aperture size on signal quality

The effect of the angular size of the source and the diameter of the receiving aperture on atmospheric scintillation is well known to observers of the night sky. Distant stars often twinkle when viewed by the naked eye, whereas planets with relatively large angular diameters, such as Jupiter or Saturn, do not. This phenomenon was exploited by the optical experimenter A. A. Michelson as far back as 1890,[9,10,11] when he devised his interference method for determining stellar diameters. Briefly, Michelson stated that the light from a distant source would exhibit local coherence if the angular size of the source is significantly smaller than the central diffraction zone of the receiving aperture. For the same reason, stars viewed through a telescope exhibit far less scintillation than when viewed by the naked eye, as the degree of local coherence falls off rapidly with the diameter of the receiving aperture.

As a general rule, the authors have observed that the rate and depth of scintillation of the received signal in an optical communications link decreases rapidly when the diameter of the receiver lens is significantly larger than the local coherence length of the light from the transmitter. Since the coherence length for light from a distant incoherent source is approximately equal to the diameter of the central diffraction zone of the transmitter aperture, the minimum receiver aperture diameter **D_R(min)** is given by:

$$D_R(\text{min}) > \frac{\text{Path length (L)} \cdot \text{Wavelength } (\lambda)}{\text{Transmitter aperture diameter } (D_T)}$$

If similar sized lenses (or mirrors) are used for the transmitter and receiver, then their minimum size is:

$$D(\text{min}) > \sqrt{[\text{Path length (L)} \cdot \text{Wavelength } (\lambda)]}$$

For a 100-km path using red light, this corresponds to minimum transmitter and receiver apertures of 25 to 30 cm, to *avoid* coherence and thereby minimise scintillation through the atmosphere. The apertures necessary to avoid coherence will be smaller at shorter wavelengths and shorter link distances - an argument in favour of the use of visual wavelengths rather than IR.[I]

3.2 Using partially coherent and noncoherent light

In 1972, Kon and Tatarskii[12] suggested the usage of *partially* coherent beams in mitigating atmospheric scintillation on systems using intensity modulation and direct detection. Between 2002 and 2004, Korotkova, Andrews and Phillips[13,14,15,16,17] quantified those effects. It was shown that a thin diffuser placed on the laser output could scramble phase coherence in a controlled way to reduce the likelihood of flux cancellation and signal dropouts without unduly increasing the beam divergence. The authors also indicated that *if* divergence and spectral bandwidth problems could be offset by inexpensive optical systems, non-coherent beams might outperform lasers on atmospheric scintillation.

The key to our success lay in inexpensively *eliminating coherence*, by our choice of a Luxeon LED source and by the use of large, light, inexpensive collimators.

[H] An optical range record using tone-modulated Morse code was set by KY7B/7, WA7CJO and WA7LYI, on 8 June, 1991 between Arizona mountaintops 248 km apart using 15 mW HeCd lasers on 442 nm (violet light). The receiver used a photomultiplier behind a Fresnel lens of about 40 cm by 40 cm aperture. This record, and the 1963 range record of 189 km for one-way *speech*, was finally broken on 3 October, 2007 by Clinton Turner KA7OEI, Ron Jones K7RJ, Gordon Smith K7HFV, and Brett Sutherland N7KG in Utah, operating over a distance of 278 km – a feat that also included two-way Morse communications.

[I] The use of red light preferred as atmospheric transmission losses are lower at the longer, visible wavelengths while the use of visible rather than infrared light understandably simplifies construction and alignment. Additionally, silicon photodiodes have better sensitivity in the red end of the visible spectrum than at the shorter visible wavelengths.

4. OPTICAL GAIN

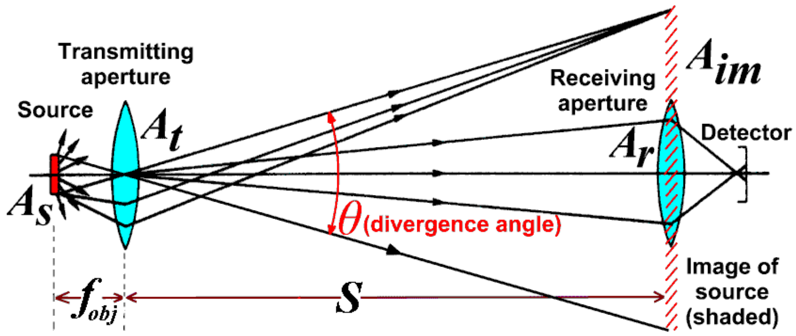

Fig. 3. Representation of a free-space optical system.

Removing all considerations of atmospheric loss and scintillation from the equation, the first approximation formula relating received optical signal strength to terminal optic dimensions on a free-space (unguided) optical system [Fig. 3] with non-coherent sources is:

$$\Phi_R \approx \frac{G_T \cdot A_T \cdot A_R \cdot L}{S^2} \qquad \text{(ref [18])}$$

Where: Φ_R is the received power.
G_T is a geometric correction factor[J,19] for the transmitting collimator, determined by its f/D ratio (see below.)
A_T is the area of the transmitting collimator.
A_R is the area of the receiving collimator.
L is the radiance of the source = total flux emitted/ source area.
S is the distance separating the receiver and transmitter.

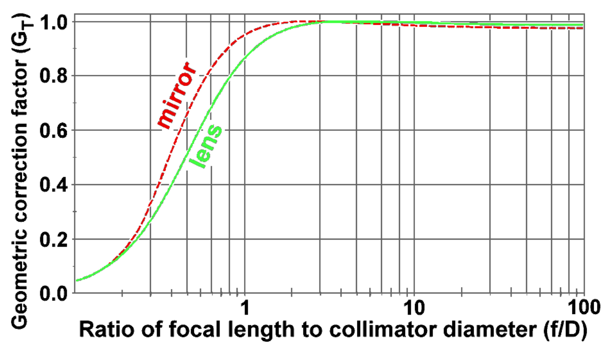

Fig. 4. The geometric correction factor G_T, plotted against collimator f/D ratio, for the radiation pattern of a "Lambertian" Luxeon III LED

4.1 Using collimators with very short focal length

The geometric correction factor G_T, always less than unity, represents a significant loss of efficiency with collimators of very short focal length and low f/D ratio. For a given source, the far-field beam intensity rapidly *decreases* as its collimator f/D ratio is reduced below unity. This is because the transmitter beam divergence (Θ) increases *at a greater rate* than the increase of *total* beam power as the source nears the collimator, with the collimator intercepting a greater solid angle of radiation from it. Note that a parabolic mirror can partially surround a light source, intercepting more of its radiant flux than the flat plane of a lens, so its G_T efficiency loss is less than that of a lens of the same f/D ratio. The geometric correction factor graph [Fig. 4] was calculated for the modified Lambertian[K] polar pattern of a Luxeon III source. An isotropic source, providing greater edge illumination of the collimator, would have *less* geometric efficiency loss at short focal lengths and low f/D ratio.

The geometric correction factor does not directly affect the receiver as all photons falling on it from the distant transmitter are assumed to be collected by the photodetector. However, most photodiodes have a Lambertian spatial response pattern and are relatively insensitive to off-axis light arriving at large incident angles.

[J] The geometric correction factor, G_T, was not included in Gowar's original equation as collimators with f/D<1 are not usually employed in lasercomms. This factor was calculated by Michael Groth for his 1987 article.
[K] The "Lambertian" pattern of the Luxeon devices is not truly Lambertian, but an approximation.

4.2 Practical considerations on the focal length of large collimating lenses

Transmitting and receiving collimators of large aperture are shown to be the prime requirements for long range operation as they give high optical gain as well as reducing scintillation by aperture averaging across cells of atmospheric turbulance. Excessively short collimator focal lengths should be avoided as geometric correction factor loss and uneven transmitting collimator illumination will be detrimental to optical gain. Too long a focal length will unduly increase the size of the optical transceiver unit. The authors have found that collimators with a focal length/diameter ratio between 1.0 and 1.5 provide a good compromise between efficiency and bulk.

5. DECIBELS VERSUS DOLLARS

5.1. Advantages of noncoherent sources

System design involves balancing the benefit of various system components and regimes against their cost of implementation. For many years, diode laser sources were the most efficient method for generating high intensity light beams capable of being modulated into the GHz region. They offered the advantage of a narrow band spectral output (half power width ≤2 nm at 660 nm), which allowed the received signal to be readily extracted from ambient light background via matched optical interference filters. However this narrow spectral bandwidth is a mixed blessing for long distance atmospheric transmission, as the emission wavelength can drift with the emitting chip temperature into a spectral absorption band of one or more atmospheric gases.[20,21,L] A slightly broader spectral source like a "power LED" (with a half-power line width of about 20 nm at 627 nm) may transmit more reliably through the multiple gaps between absorption bands.

Apart from the demonstrated scintillation problems associated with transmitting coherent light through the atmosphere, the use of high powered lasers for long distance atmospheric communications has a number of practical problems.

1. To generate a tightly collimated laser beam requires a beam expander using precision glass optics with at least $\lambda/4$ surface accuracy. For large beam diameters, the optical system will be expensive and heavy, necessitating complex mountings capable of steering the beam to microradian accuracy.
2. The collimation and coherence of a laser beam is degraded by transmission through a turbulent atmosphere, and changes in atmospheric refraction over a long path make it impossible to keep the laser beam aligned on the target without a complex tracking system and feedback via an auxiliary communications channel.
3. The use of intense laser beams projected horizontally through the atmosphere presents a major eye damage hazard to anyone looking down the laser beam.

As amateur experimenters, we require simple, cheap, safe and portable equipment suitable for operating on battery power on mountaintops, which may only be only accessible on foot. The equipment must be easy to align by eye on a portable mount, such as a sturdy tripod or folding table, which sets a practical minimum beamwidth of around 5 millradians or ¼°.

5.2 The Luxeon – A New Modulated Light Source

Amateur optical communications experimenters have been transmitting duplex telephony signals up to 50 km by using ordinary high-intensity light emitting diodes (LEDs) collimated with 19 by 25 cm Fresnel collimators.[M] Unfortunately, the emission geometry of conventional light emitting diodes is not well suited to generating high intensity beams, and their construction does not provide sufficient heat sinking for the source chip to be driven at currents much greater than 20 mA.

[L] The cited graph, covering only a wavelength range of 1nm, indicates about 20 sharp atmospheric absorption bands in that range, some only 0.01 nm wide.

[M] Chris Long (VK3AML) and Peter Wolfenden (then VK3KAU, now VK3RV) achieved a 46-km speech range between the Melbourne (Australia) suburbs of East Hawthorn and Sunbury from April, 1991, into the first months of 1992. 3000-mCd Stanley high-output LEDs were used with 19 cm by 25 cm aperture Fresnel collimators. The LED had its epoxy lens shaved flat and repolished to provide a Lambertian radiation pattern. The collimator was fitted with a secondary lens to match the LED's virtual source size to the Fresnel lens blur circle. 830-nm GaAlAs LEDs were also used on this link, with nearly identical results.

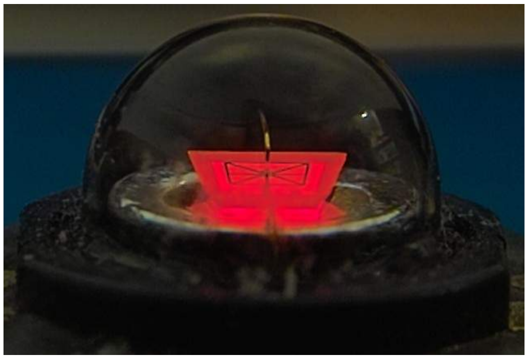

Fig. 5. A close-up view of a Luxeon III LED showing the dome, bond wire, and the TIP (truncated inverted pyramid) structure of the emitting die and its mounting on a reflective metal heat sink.

For most of the 38 years of commercial LED production before the year 2000, plentiful flux was inexpensively available only from devices emitting in the near-IR spectrum, namely the GaAs (930 nm) and GaAlAs (830-850 nm) diodes. Unfortunately, 930 nm corresponds with a severe atmospheric H_2O absorption band so that only the 830-nm LED was useful for long range transmission. There are considerable practical problems in collimating, focusing and aligning an invisible and minimally divergent IR communication beam. In 1991, Chris Long tested 660-nm (red) and 830-nm (IR) beams using identical optical systems over an urban 46-km path[M] and the differences in atmospheric transmission loss and silicon photodiode response over that wavelength range appeared to be insignificant. The more recent advent of the Luxeon power LED has tipped the scales of practicality even further towards the usage of red (630-nm) visible light.

The Philips Lumileds Luxeon, commercially released in 2002,[N] has its source chip mounted on a thick metal heat sink slug surrounded by high temperature silicone encapsulent. The red, red-orange and amber Luxeons use an AlInGaP chip shaped like a truncated inverted pyramid [Fig. 5] with the angled walls throwing light forward via total internal reflection with the aid of the reflective heat sink. A Luxeon's combined efficiency and power capacity are greater than a standard LED's by more than an order of magnitude. They are frequently sold attached to a small star-shaped, metal backed circuit board for heat sink mounting, the so-called Luxeon star.

5.3 Spectrum and modulation of the Luxeon

The red Luxeon emits at 627 nm ±10 nm, a good spectral match for silicon PIN photodiodes and a wavelength relatively free of absorption bands in the atmospheric transmission spectrum. Luxeon optical output is linearly related to current input [Fig. 6], with a specified rise time for the 627 nm model of around 15 nsec,[O] giving it a modulation bandwidth on the order of 10 MHz.[P] Most amateur operators only need sufficient bandwidth for a single channel of speech, so a 3 kHz bandwidth is more than adequate. On the night of 19 February, 2005, the output of a first-generation Luxeon I (1 watt), at the focus of a low quality 19-cm by 25-cm Fresnel lens, produced a beam that appeared relatively bright to the naked eye at a distance of 168 km.

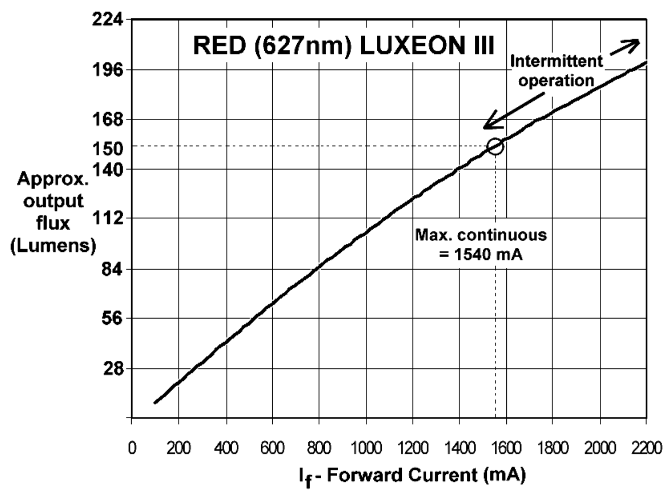

Fig. 6. Luminous output of Luxeon III versus current input for a red AlInGaP chip.

The second generation[22,23] red Luxeon III AlInGaP

[N] Groth and Long had to import the first 1-watt Luxeon I's to Australia from a Canadian supplier, in about July-August, 2002. These were the first to be imported to Australia, to our knowledge.

[O] This information on the rise time of the red Luxeon, previously unpublished, was given by a member of Lumileds' research staff to the "Ronja" optical communication research group on a public Internet newsgroup sometime in 2003. The authors have been unable to retrace the reference, but the ease with which the Luxeon can be modulated with NTSC video suggests that the information on rise time is accurate. A further communication by experimenter J D Bakker to Karel Kulhavy of Ronja on 21 August, 2006 gave a rise time of 30 ns and a fall time of 10 ns for a *red* Luxeon/modulator combination. Lumileds state that the rise time of their *white* phosphor-based Luxeon is 100 ns, much slower than the red Luxeon.

[P] Some experimenters on the Ronja group have reported that short range links using the red Luxeon source can be successfully configured for 10 Mb/sec link speed using Manchester coding, implying a frequency limit of at least 20 MHz.

chip has a stated "wall plug efficiency" of around 40%[Q] and can be driven to current densities on the order of 1.5 Amps (continuous) at 3 volts yielding a luminous output of well over half a watt - an output higher than that of many semiconductor lasers[24] - and it can be pulsed at a low duty cycle to 2.2 Amps. A laser with hundreds of milliwatts of visual output would be prohibitively expensive and would present an eye safety hazard to anyone nearby whereas a Luxeon's output becomes "eye-safe" after beam expansion as this greatly reduces the beam flux density.[R]

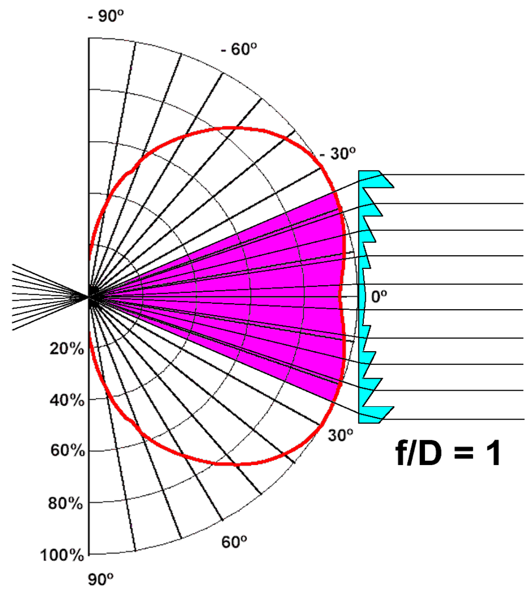

Fig. 7. Luxeon "Lambertian" polar pattern combined with Fresnel ray diagram. Only the portion that is shaded is collimated and over 65% of the LED's output is wasted.

6. LARGE APERTURES AT MINIMUM COST

The intense *non-coherent* Luxeon's source of ≥1 mm diameter eliminates the need for precise, diffraction limited optics and allows the use of cheap, plastic Fresnel collimators at a fraction of the cost.

6.1 Available Fresnel lenses

Fresnel lenses moulded from optical acrylic can provide apertures up to about 1 m^2 with minimal cost, weight and fragility. For example, a 30-cm square Fresnel lens can be purchased from one of several Southeast Asian suppliers for US$8 and it weighs less than 200 grams.[S] These lenses have groove pitches ranging from about 0.125 to 1 mm, the finer pitch producing better image definition, but greater transmission losses.[25,26] The 0.5-mm groove pitch appears to be a good compromise for modulated light collimation.

Modern Fresnel lenses are superior to single-element glass lenses in their freedom from spherical aberration, but moulding inaccuracies on commercial Fresnel lenses result in prime focus blur circles of about 0.1-to 0.5-mm diameter.[T] As long as this is smaller than the emitting area of a high powered Luxeon LED (≥1mm^2), the degree of lens surface accuracy will be acceptable for the task of collimation.

6.2 Considerations pertaining to the use of Fresnel lenses

Red Luxeons have a spatial breadth of radiation exceeding the Lambertian model, causing much of their radiated flux to overshoot the aperture of a Fresnel collimator [Fig. 7], even one with an f/D ratio of 1. A short-focus secondary lens[U] near the Luxeon should be used to recover some of its peripheral emission and to usefully direct it towards the Fresnel collimator. There is another reason for using a compound lens collimating system: A short focal length secondary lens

[Q] Figure quoted for the red "TIP chip" Luxeon in IWN 2002 PowerPoint presentation *"High power LEDs: technology status and market applications,"* by the Lumileds research and development team, July, 2002. The .pdf of this presentation was downloaded from the Lumileds website by the authors on 14 June, 2005, but seems to have been withdrawn since. Wall plug efficiency = optical power output divided by electrical power input.

[R] The amount of transmitter beam flux intercepted by the eye then becomes the area of the eye pupil divided by the area of the transmitter collimator. With a transmitting Fresnel collimator of 30-cm square aperture, even a dark-adapted eye could rarely intercept more that 0.05% of the total beam flux.

[S] These Southeast Asian suppliers include http://www.3dlens.com and http://www.bhlens.com American suppliers include Edmund Scientific of Barrington, New Jersey; Rolyn Optics Company of Covina, California; Fresnel Technologies Inc. of Fort Worth, Texas; and Reflexite Display Optics of Rochester, New York.

[T] Several high-quality moulded Fresnel lenses were evaluated in July, 2007, by Turner using the star Vega as a point-source reference and a CCD imager of known dimensions to determine the approximate size of the prime focus blur circle. For the lenses sampled, the diameter of the blur circle was smaller than $1/1500^{th}$ of the focal length – a ratio largely independent of focal length.

[U] The use of a double-convex secondary lens is not recommended as it cannot capture as much of the peripheral light being emitted by the LED as a plano-convex lens. A positive meniscus lens may be even more efficient as it could partially "wrap around" the LED, intercepting even more energy from the sides.

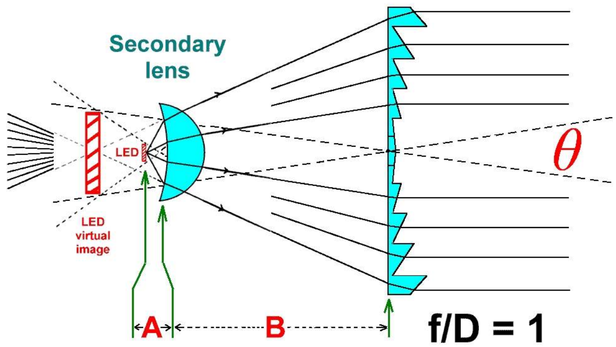

Fig. 8. Through the use of a secondary lens, more of the LED's output is intercepted and made available for collimation.

close to the source allows the virtual source (or photodetector) size to be *optically* adjusted to *match* the diameter of the Fresnel's blur circle, as shown in [Fig. 8]. The lens spacing is adjusted to optimise the far-field intensity of the transmitted beam. With this arrangement, a Luxeon III with a Fresnel lens of 20- to 50-cm aperture and a f/D ratio of 1.0 to 1.5 will produce a beam divergence in the range of 4 to 10 milliradians (0.2° - 0.5°). This relatively broad beam divergence might be considered wasteful of transmitter power, but it allows the optical unit to be mounted on an average photographic tripod and directed manually onto its target with ease. This broad divergence permits faster beam acquisition by the distant station, and more assured maintenance of alignment.

6.3 The practical use of Fresnel lenses

Two Fresnel lenses with a f/D ratio of 1 to 1.5 can be mounted side by side in a rigid pyramidal housing with a central baffle isolating the receiver and transmitter, making a rugged optical transceiver of conveniently small size as shown in [Fig. 9]. For extra portability, the two Fresnels could be hinged to their central separating baffle with a flexible cloth cover on the receiver. The optics could then be folded flat to the dividing baffle for transport. A further potential modification, making use of spatial diversity to mitigate scintillation, would be to arrange *two* transmitter lenses either side of a single central receiver lens. Two transmitter Luxeons could then be electrically connected in series from their modulator, the separation between their collimators increasing the effective transmitter aperture, and decreasing the chance of the composite received beam becoming locally coherent. For two-way communication, the transmitter beamwidth should be slightly wider than the receiver, so that when each transceiver is aligned for the best *received* signal, the units will be optimally aligned.

The transmitter and receiver beams may be co-aligned by pointing a tone-modulated beam at a *distant* target (to minimise parallax) and moving the receiver's photodiode in its focal plane until the reflected tone output is maximized. Adding a sighting telescope allows the unit to be aligned with a distant station. The sighting telescope could be omitted via the cruder expedient of *viewing the back* of the receiver photodiode through a low diopter eyepiece. By making the image of the distant station's red modulated light disappear in front of the photodiode, alignment is assured.

For daytime operation, a honeycomb structure – a series of parallel tubes or open-ended boxes aligned with the incoming collimated beam – would limit the optical unit's field-of-view. This apparatus (called "septa") would reduce the chance of low-angle focused sunlight damaging transceiver components near sunrise or sunset on east-west links.

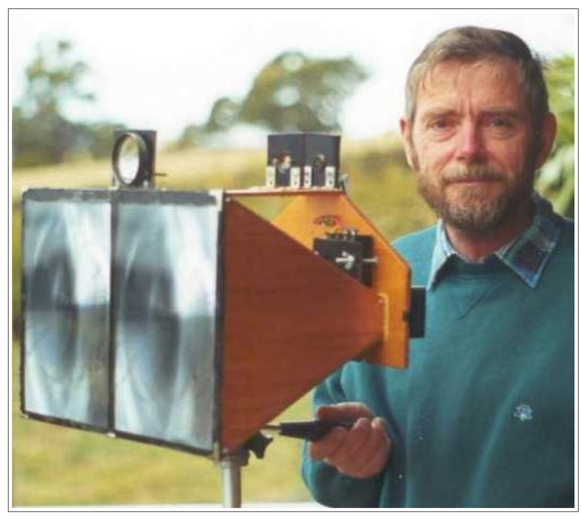

Fig. 9. A compact, truncated-pyramid optical transceiver using a pair of Fresnel lenses. Equipment like this has been used for two-way voice communications over 168-km (and longer) paths.

7. RECEIVER ELECTRONICS

For inexpensive, sensitive and noise-free flux detection at the red end of the visual spectrum, silicon PIN photodiodes are probably the best choice.[27] The dimensions of the photodetector should be carefully chosen to match the focal blur circle of the Fresnel lens used as its collector. If the photodiode is too big, its dark noise and shunt capacitance will be excessive. Too small, and the detector will not collect all available photons from the image's blur circle. The detector should also have an acceptance angle suited to its accompanying collimator's f/D ratio. Some spectral filtering of the detector may improve signal-to-noise ratio in daylight operation with a Luxeon source. A "red 25" Wratten dye filter, and even some spectrally broad interference filters may be of assistance. However, in night operation, any form of filtering will generally introduce excessive loss, with little signal-to-noise gain.

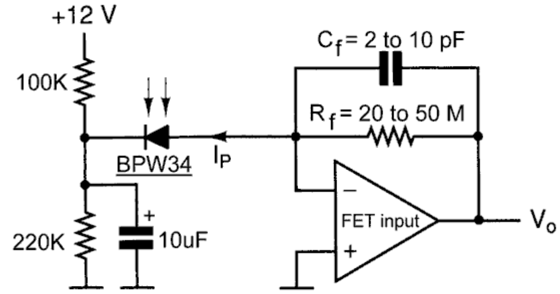

Fig. 10. A typical transimpedance (current-to-voltage) amplifier using a photodiode. The damping effects of the diode's capacitance are reduced as the low-impedance current input minimizes voltage changes.

7.1 Modulation techniques

To set optical speech communication range records, the authors avoided subcarrier systems such as FM, PWM, PPM and high speed digital. Unfortunately, a receiver configured for optimal sensitivity with, for example, a 40-kHz subcarrier would probably be 10 to 20 dB less sensitive than one optimised for the 3-kHz bandwidth of intelligible speech transmitted via baseband brightness modulation.[V] This baseband amplitude modulation of the source places the minimum response speed demands on the photodetector and renders path propagation effects clearly evident, aiding the search for improved *optical* methods of reducing scintillation and system noise. When the link signal-to-noise ratio rises above a threshold value, one could always switch to a more sophisticated, broadband transmission mode.

7.2 Photodiodes and photodiode amplifiers

Silicon PIN photodiodes have a fairly high junction capacitance[W] which can limit their bandwidth unless they work into a low impedance, low noise preamplifier. The standard receiver configuration in most commercial, free space optical links is to use back-bias on the photodiode to spread the depletion region at the p-n junction: This reduces the device's junction capacitance while increasing its response speed. A transimpedance amplifier [Fig. 10] follows the photodiode,[28,29,X] presenting the diode with a very low input impedance by the usage of a negative feedback resistor.[30]

In daytime usage, the photodiode will have a DC offset derived from ambient light. This may potentially bias the amplifier to cutoff, so the DC component should be removed with an extra capacitor [Fig. 11], slightly lowering the signal-to-noise ratio.[Y] The transimpedance amplifier is excellent when *maximum bandwidth* is needed, but for *maximising sensitivity* for the baseband audio that most radio hams need – around 3 to 10 kHz – a different preamplifier topology is necessary.

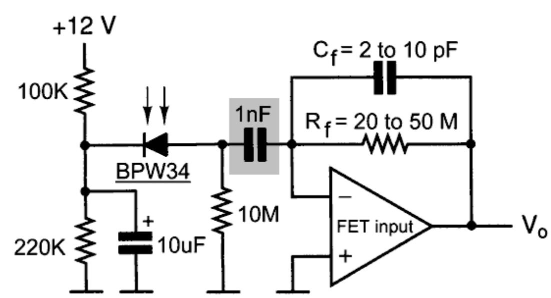

Fig. 11. "Daylight" modification of a transimpedance circuit to avoid DC saturation of the amplifier by photodiode currents.

[V] There is more than the simple relation of noise per ΔHz from the photodiode's shot noise, dark current etc. involved here. A photodiode with a preamplifier configured for broad bandwidth almost always has significant noise contributions from the photodiode load resistor and from the amplifier following it. As one increases the bandwidth of *the preamplifier system* by reducing the (usually noisy) load resistor, a photodiode light detector *system* has *exponentially* increasing noise. A high impedance photodiode preamplifier configured purely for speech frequencies can be made very quiet indeed!

[W] The Siemens (or Vishay) BPW34 photodiode, retailing for around US$1.00, has been used in most of our long range experiments. It has a typical shunt capacitance of 70 pF @ reverse bias=0 volts; 30 pF @ reverse bias=3 volts; 10 pF @ reverse bias=25 volts.

[X] Clinton Turner tried to optimise the Hobbs preamplifier for audio bandwidth in December, 2006. Not unexpectedly, the circuit did not "scale" well and the "open circuit gate FET" arrangement (K3PGP's) outperformed it.

[Y] It should be noted that ambient light is likely to "dilute" the desired signal with thermal noise, further reducing the receiver system's effective sensitivity.

7.3 Optimizing Photodiode-based optical receivers for sensitivity

With sensitivity in mind, during the 1990s John Yurek (K3PGP) devised a high-impedance photodiode amplifier of simple design but complex performance [Fig. 12].[31,32] With ideal components, the photodiode's output would simply charge the junction FET's gate and the amplifier would not function, but if we draw the leakage resistances of *real* components into the circuit diagram, it can be seen that these resistances are cleverly utilised [Fig. 13].

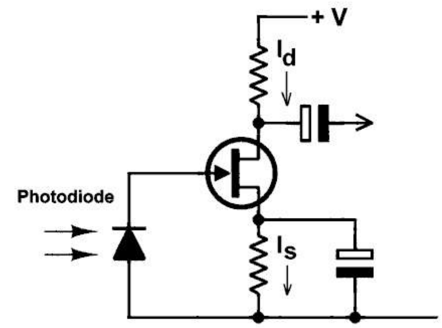

Fig. 12. High-impedance photodiode amplifier – the "K3PGP" circuit.

In Yurek's circuit, current from the photodiode flows only through its own leakage resistance and the gate leakage resistance of the junction FET, which is in the order of hundreds of megohms and this allows the photodiode to establish the highest possible signal voltage at the FET gate. The source bias voltage on the FET causes a very small current to flow through the series combination of the FET's gate-source leakage resistance and the leakage resistance of the photodiode. This current, in turn, causes a small reverse bias to be established across the photodiode, but that bias is signifiant only at the lowest light levels when the photodiode's shunt resistance is at a maximum. The photodiode capacitance, the gate shunt capacitance, and the FET's Miller capacitance appear across the photodiode, limiting the circuit's high frequency response. With a BPW34 photodiode, for example, this results in a 6 dB per octave high frequency rolloff above about 200 Hz.

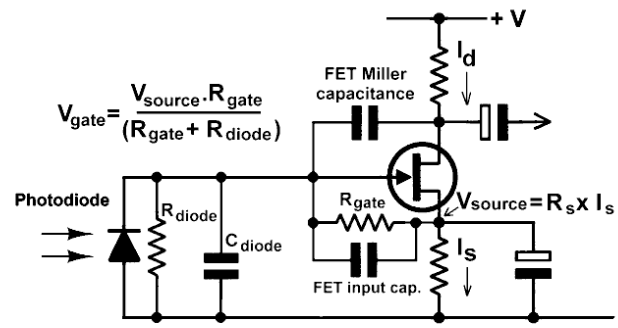

Fig. 13. The circuit of figure 12 with real-world leakage and parasitic components represented.

7.4 Optimizing for speech bandwidth *and* sensitivity

There are ways to electronically raise the rolloff commencement frequency and to compensate for the loss above that frequency, exemplified by some clever improvements devised by Turner [Fig. 14].

Yurek's basic concept of feeding the photodiode into the open-circuit gate of the FET is retained, but Turner adds extra back bias to the photodiode through a voltage divider, reducing the detector's shunt capacitance and improving its frequency response: The fact that a miniscule amount of current flows through the gate-source junction of Q1 doesn't seem to affect sensitivity and the 0.6-volt gate-source voltage drop helps to establish the reverse bias across the BPW34 photodiode. A constant-current source transistor (Q3) applies fairly high standing current[Z] to the FET (Q1) but simultaneously presents the FET drain with a high dynamic impedance. The high standing current maximises the FET's transconductance and increases the circuit's signal-to-noise ratio. A grounded-base amplifier stage (Q2),[AA] which forms the second half of a cascode pair, resists voltage changes on the FET's drain, minimising the effect of the Miller capacitance between the FET drain and the photodiode as well as adding gain to the system. Finally a low-noise, 6-dB-per-octave high-frequency boosting circuit (differentiator U1C) helps to compensate for frequency rolloff due to shunt capacitance across the photodiode,[BB] extending the bandwidth to 10 kHz or more.

Construction of Turner's circuit is quite straightforward, the only unusual requirement being the photodiode's connection to the FET's gate. To minimise stray capacitance and leakage noise, this extremely high impedance connection point *must be suspended be in air,* and *not anchored to a circuit board*, with connecting wires kept as short as possible.

[Z] The optimal current for Q1 is somewhat device-dependent: The value of the 120-ohm resistor at the emitter of Q3 should be adjusted for best noise performance.
[AA] The Q2-circuit operates as grounded-base at AC.
[BB] The optimal "knee" frequency of the differentiator (U1C) will vary with the photodiode's capacitance and amount of reverse bias.

7.5 Evaluation of the speech-optimized receiver

Photodiode receiver circuits optimized for *audio* bandwidth had rarely been comparatively evaluated until conclusive bench measurements were undertaken by Turner in Salt Lake City during 2007. Turner's circuit provides a measured audio bandwidth signal-to-noise ratio improvement of 12 to 20 dB[CC] over the best transimpedance circuit that we've been able to construct. These measurements have been independently confirmed by constructors in Hobart, Tasmania.[DD] Furthermore, this receiver has been used to set what is believed to be the current world distance record for optical communication using speech and noisy slow scan television between Swasey Peak and George Peak in Western Utah, a distance of 278 km through hazy air. It has also been used by Tasmanian experimenters to receive speech-modulated beams reflected from clouds by stations over 50 km away during the latter half of 2007.[EE]

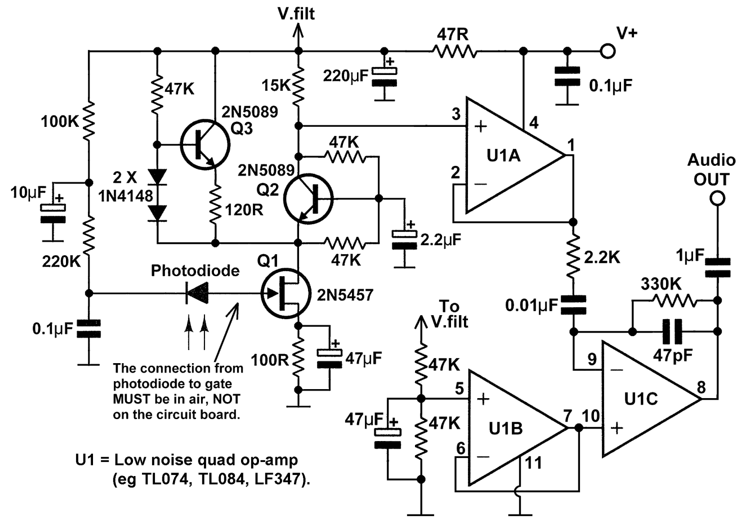

Fig. 14. High-sensitivity speech-bandwidth optical receiver.

8. CONCLUSIONS

We have shown that long range terrestrial optical communication is possible at minimal cost, by *avoiding* the usage of laser (coherent) sources with their concomitant need for expensive, diffraction limited optics. The new Luxeon high power red LEDs, used in association with cheap, large aperture Fresnel lens collimators provide reduced atmospheric scintillation, greater transceiver portability and far less critical alignment requirements for field operation. The system works in full continuous duplex, with digital communication potential for a continuous return error correction path. Bandwidths to 10 MHz are readily supported, though range and bandwidth are inversely related, and speech bandwidth may be most easily conveyed by direct baseband brightness modulation. Receiving circuits with greater sensitivity than the standard transimpedance "front end" have been developed and demonstrated. Most of the necessary optical and electronic components are commonly available worldwide, and the simplicity of this approach has already induced many amateur radio operators to construct similar transceiver units. In many countries, non-coherent modulated light communication systems are legally excluded from the definition of "radio communication" so that licenses are not required for them or for LED-based remote control systems.

It would appear that these *optical* solutions to mitigate atmospheric scintillation are more cost effective, safer and more facile than complex electronic approaches, high power laser usage, or unusual digital coding schemes.

[CC] The relationship between luminous flux and audio recovery is not a linear one. If, for example, one modulates an LED at 1 kHz, takes a signal measurement, and then doubles the luminous flux the audio recovered at the receiver doubles in voltage – but this corresponds to a quadrupling of received audio *power* as the current flowing into the loudspeaker doubles as well. This means that a 3 dB improvement in luminous output or in receiver optical gain will result in a 6 dB improvement in signal/noise ratio, ignoring possible noise contributions from extraneous light sources.

[DD] Tested by Justin Giles-Clark VK7TW and Rex Moncur VK7MO, both of Hobart, Tasmania.

[EE] Rex Moncur, station VK7MO Hobart, pers. corr., 14 December, 2007. The other Tasmanian stations undertaking the "cloudbounce" experiments include Justin Giles-Clark VK7TW (Hobart) and Ken Sulman VK7DY (Orielton). Banks of up to 60 red Luxeon III LEDs, each behind a small collimator, are used for transmitting. Fresnel or parabolic mirror receivers using one or more photodiodes paralleled are used for receiving. Direct speech modulation and robust, narrowband digital modes have been used successfully. For information about some of the highly-robust narrowband digital modes that have been used, see the web site: http://physics.princeton.edu/pulsar/K1JT

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