Large Diameter Refractive Fresnel Lenses as Low-Cost Optical Communication Ground Receiver Aperture

Hamid Hemmati
Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Dr., Pasadena, CA 91109

ABSTRACT

Feasibility of utilizing large diameter custom designed and fabricated Fresnel lenses as the front optical aperture for Earth-based reception of optical communication signals from remote spacecraft is investigated. This includes preliminary optical designs, investigation of stray-light effects for a particular optical design, effect of temperature variations and mechanical sag on the performance of the photon bucket, and effect of temporal dispersion on the link performance. Experimental results for several commercial off-the-shelf Fresnel lenses with diameters exceeding 1-meter are presented as well as plans for custom diamond turning fabrication of two-meter diameter Fresnel lenses.

Keywords: Fresnel lenses, optical communications, optical receiver, receiver terminal

1.0 INTRODUCTION

Large diameter Earth-based optical receivers are required to facilitate high data-rate downlink for free-space Optical Communication with space probes. For deep space optical communications, there is a need for photon collecting ground-based receivers having apertures of at least 5 meters, and ideally much greater than 10 meters. Since photon collection, rather than imaging, is the function of optical receiver, the required aperture could be less than diffraction-limited quality. Several schemes have been devised and studied to generate optical receivers with effective diameters of 8 to 12 meters. These schemes include a single large monolithic primary mirror, a segmented large primary mirror, and a large array (tens to hundreds) of smaller diameter individual telescopes [1]. Low-cost, large-aperture optics are highly desirable for all above options. Wide use of deep space optical communication may depend in part on the successful design and implementation of low cost Earth-based optical terminals. Application of large diameter refractive Fresnel lenses as one such option for low-cost large aperture telescopes is reported here. Fresnel lenses are nearly flat, thin plastic or glass lenses that could be manufactured in diameters exceeding 5 meters and may be arrayed to provide effective apertures tens of meters in diameter. Fresnel lenses can have small F/numbers on the order of 1 to 5. The resulting ground-terminal optical system sizes are in the practical realm. Fresnel lenses are more suitable to photon-collection for optical communications detection than imaging applications since received light is monochromatic (e.g. 1064 or 1550 nm), and field of view is very narrow (e.g. 50 urad for deep-space links). A leading photon-counting detector for deep-space optical communications has an active diameter of 1-mm. Therefore, this is the upper limit target for the blurred spot size of the optical receiver made of Fresnel lenses. An array of very low noise detectors will enable accommodation of large focal spot sizes (e.g. 3 mm in diameter)

The attractive features of Fresnel lens-based optical receivers over the state-of-the-art include:

- Analysis and preliminary experiments indicate that with a multi-meter in diameter Fresnel lens, it is quite feasible to focus a single wavelength atmospheric-propagated received signal to fit within the 1 mm;
- Inexpensive to develop. Fresnel lens replication costs are on the order of a few thousand dollars since the replication technique has been perfected for consumer applications;
- Very lightweight (density <1 kg/m2 compared with about 10 kg/m^2 for light-weighted telescope mirrors).
- Manufacturable now in large (5-m) diameters with precision diamond turning and scalable to tens of meters in an array.
- Much lower fabrication time (months vs. years).
- Technology is directly applicable use in air or space for airborne or space-borne receivers.

Refractive and Diffractive Fresnel Lenses are formed by generating grooves onto the surface of a plastic plate and appropriately tilting the optical surface within each groove to form a narrow annular lens makes. In conventional refractive Fresnel lenses, there is no phase relation between the annular lens steps so the image is an incoherent sum of contributions from all the annuli. Therefore, all rings incoherently add their collected light at focus. In a diffractive Fresnel lens, phase relationship is maintained between the consecutive rings [2-4]. So all rings coherently add their collected light at the focus. Their image may be nearly as good as that of a solid thick lens, for a narrow spectral band. The focal length of a diffractive Fresnel lens varies inversely with wavelength. These lenses may be fabricated by photolithographic techniques using a large mask that matches the designed pattern.

2. RECEIVER ARCHITECTURE CONCEPTS

Multiple aperture arraying concepts may be implemented to form an effectively large diameter. Figure 1a shows an example of light collected by individual 5-m lenses and directed to a small off-axis parabola (or an array of smaller off-axis paraboloidal mirrors) that focuses the beams onto a single detector. In this case, the distance from each lens to the focal spot size will have to be controlled to sub-nsec accuracy such that phase delays in time are minimized. In another example (Figure 1b), an individual detector or an array of detectors is coupled with each telescope. With proper selection of very low noise photon-counting detectors, the signals may be added electronically with minimal addition of noise from each detector. With the above schemes, acquisition and tracking of a spacecraft can be performed in a manner identical to conventional telescopes. Typically, the ephemeris (orbit predicts) of the spacecraft is fed into a precisely calibrated telescope mount.

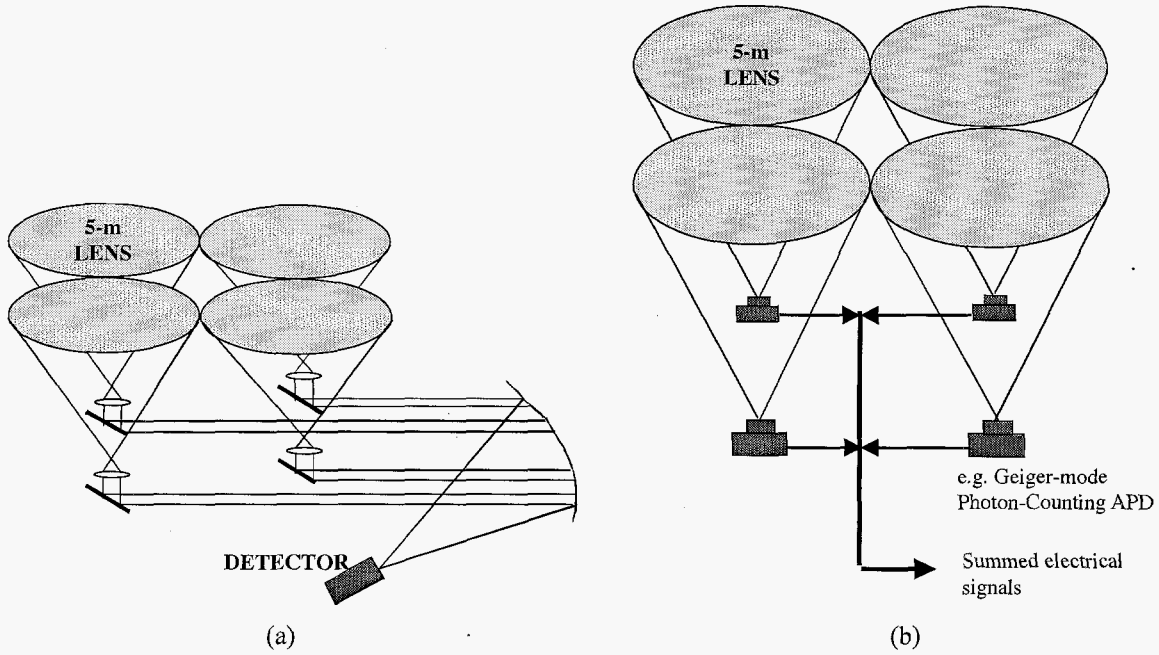

Figure 1a and 1b. Four 5-m lens collector with beam focusing onto a single detector and with individual detectors behind each lens.

Many other implementation options may be envisioned to achieve effective aperture diameters exceeding ten meters.

3. SYSTEMS ENGINEERING ISSUES

Some of the systems engineering issues that are unique to Fresnel lenses, and techniques to mitigate these issues are briefly investigated below.

Effects of Atmosphere On Focal Spot Size

Telescopes based on Fresnel lenses are significantly more aberration limited than diffraction limited. Atmospheric effects including scintillation and turbulence increase the blur size at the focus of the telescope by a factor of D/r_0, where typical values of r_0 are on the range of 5 to 12. For a 5-m lens, an r_0 = 10 cm, gives D/r_0 = 50 (corresponding to an atmospheric seeing of 1-2 arcsec). This gives a seeing blur circle of about 0.1 mm, which is small compared to the expected blur spot from the Fresnel lens. The adaptive optics technology for atmospheric correction would not be either useful or necessary in this case, since the telescope is not limited by the atmospheric seeing.

Stray Light Effects

Because Fresnel lenses are made up of a large number of concentric facet zones with multiple reflections, edges and back cuts, the geometry can cause a number of different undesired stray light effects. The Fresnel lens facet geometry can cause out of field radiation to be directed into the field of view as well as directing wanted infield radiation to outside the field of view. The Fresnel lens geometry can also cause significant ray blocking and light scattering due to the large number of edges and residual manufacturing artifacts and contamination in the Fresnel lens grooves. All these effects either cause unwanted radiation overlapping the communication signal at the detector and/or reduce in the optical communication signal level at the detector.

One of the most troublesome sources of unwanted radiation at the focal plane is caused by the refractive/reflective effect of the Fresnel lens back cuts. Radiation far outside the field of view can be refracted and/or reflected into the field of view. Lamb and Hillman identified how this kind of stray light can be analyzed in a Fresnel lens optical system [5]. Placing a baffle in front of the Fresnel lens can reduce out-of-field scattering. If the Fresnel lens is large in diameter and/or operated close to the sun, the baffle would need to be quite long. The use of a field stop and a Layot stop significantly reduces the possibility of stray radiation getting to the focal plane. Internal structure near the optical path can cause stray light problems. Typically, a relay system is used to provide a location for these two types of stops. Out of field scattering could also be reduced to some extent by placing a filter over the Fresnel lens aperture or the data receive detector. Both locations would reduce the background level at the detector. However, placing the filter in front of the Fresnel lens aperture would have the advantage that it would reduce thermal loads within the Fresnel lens and the internal mounting structure.

Breault Research Organization (BRO) calculated the stray light background produced by reflection and scatter of sunlight from a F/1 two-meter diameter Fresnel lens that designed by Optical research Associates. This design is explained in the section (4) of this paper. A baffle was designed that reduces stray light at large Mars-Sun angles to an acceptable level. However, a bright halo of stray light caused by scatter from the Fresnel lens persists from 3 to 12 *degrees*, and a dimmer halo caused by scatter from a pointing mirror extends well beyond this.

The optical receiver system consists of a detector, Fresnel lens, bandpass filter, pointing mirror, and supporting mechanical structures. The length of the baffle is 5 meters. The ASAP (Advanced Systems Analysis Program) Fresnel lens model includes not only the front surface and facets that focus the light, but also cylindrical surfaces that connect the facets and rounded edges at the boundaries between facets. The BRDF (bi-directional reflectance distribution function) of the mirror was based on an rms roughness of 10 *Angstroms* for a spatial frequency range of 1 to 1000 mm^{-1}. Level 300 contamination (250 *parts per million* (*ppm*)) was assumed. Given that the lens or a reflection mirror in front of the lens is exposed to the outside air, it must be cleaned frequently (probably on a daily basis) to achieve this cleanliness level. Initial stray light calculations assumed Level 500 contamination (2900 *ppm*) on the Fresnel lens and filter. Also a higher BTDF (bi-directional transmittance distribution function) was used, because: (1) light can be scattered by in homogeneities within the material; (2) the diamond turned surface may scatter more light, and (3) multilayer coatings on the filter elements will scatter more light. Figure (2) shows the BTDF model for the lens and filter, including both scatter from the surfaces and scatter from the particulates.

The largest stray light path (nearly 80% contribution) is light that suffers a combination of total internal reflection (TIR) and Fresnel reflections from the surfaces of the Fresnel lens. Figure (3) illustrates one such path. Since the angle of incidence is

far from the angle of incidence of the light that is focused on the detector, unconventional AR coating techniques will have to be employed. The other stray light contributor is scatter from the rounded edges between one facet and another. Refraction through these edges contributes only 6% to the total stray light in the halo. The edges were assigned a radius of 50 μm. The stray light from these edges is proportional to the edge radius, so it can be reduced further if the edges can be made sharper.

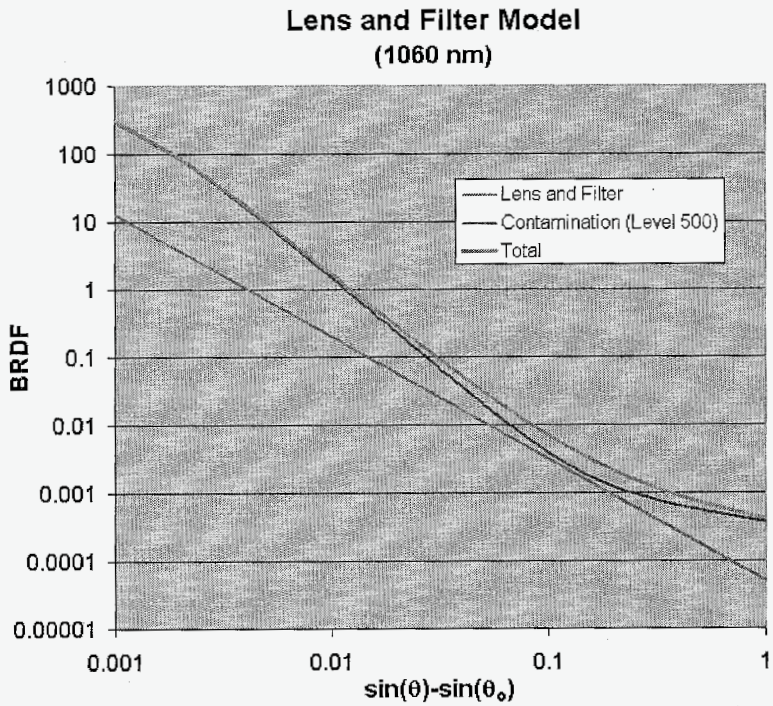

Figure (2): BTDF model for the lens and filter, including both scatter from the surfaces and scatter from the particulates.

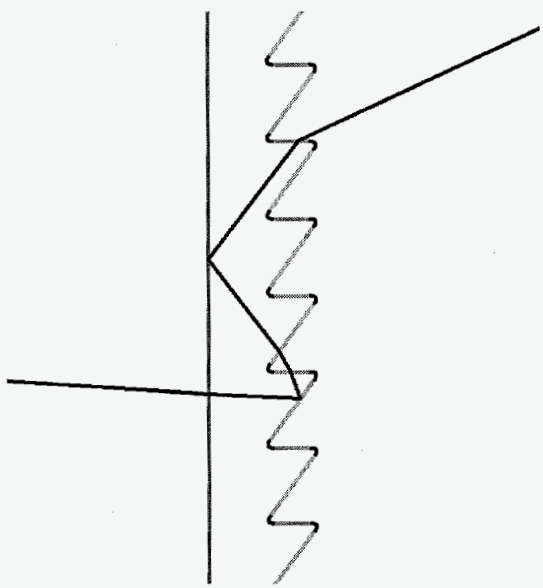

Figure (3): Illustration of total internal reflection and a Fresnel reflection that produce the halo of stray light around the image.

Thermal Effects

The Optical Communication receiving stations need to operate during daytime as well as nighttime. To avoid long communication outages during the mission, the telescope has to operate at small Sun angles, possibly as little as 3°. Therefore, heating effects due to incident Sunlight falling directly into the receiver must be avoided since misalignments and damage to the receiver may result. Analysis indicates that localized thermal gradients are the primary cause of thermal issues. Analysis indicates that significant spherical aberrations can occur with a five degrees change in temperature of a plastic lens. A focal length shift of 0.015% was measured with a 5 °C change in temperature. For a non-diffraction-limited, Sunlight filtered lens system where we seek only to focus the beam on the order of 1-mm, the thermal effects on Fresnel groove spacing, thickness and dimensional change do not have a pronounced effect on performance.

Effect of Excessive Dust Collection on the Surface

Excessive dust will increase light scatter and attenuation. The related sensitivity levels will be analyzed. A sunlight rejection filter at the dome of the telescope would help to keep dust away from the lens. Use of the flat side of the lens towards the incoming signal would help simplify the lens cleaning process that is typically applied to the primary mirror of large telescopes.

Effects of Lens's Temporal Dispersion on the Communication Signal

The photodiode receiver at the focus of the Fresnel lens sees delayed signal arrivals from those in light focused from the outer zones of the lens relative to the light from the central zones. For a 5-m diameter, F/2 refractive Fresnel lens, there is approximately 0.3 m of path length difference (resulting in 1 nsec delay) for signals from the edge relative to the center of the lens. For a 10 Mega-bits-per-sec (Mbps) link with a 256 Pulse Position Modulation (PPM) format, the slot time is (8*100 nsec)/256= 3.1 ns. In this case, a 1 nsec delay is tolerable. For a 100 Mbps link with 64 PPM modulation, the slot time is (6*10ns)/64 = 0.94 ns. Thus for this example, a delay of more than 0.3 ns is excessive and will affect the quality of the communication signals. Several options are available to alleviate this potential problem: use of slower F/#s for the lens; proper selection of the pulse-width relative to slot width at the transmitter terminal of the link, optical correction, electronic correction, or a combination of these options [6].

Manufacturing Errors and Tolerancing

Analysis of a 2-m F/1 lens designed for the single wavelength of 1064nm indicated that a spot size of 40 micron for 80% encircled energy is theoretically possible. Due to manufacturing errors and tolerances, this level of performance may be difficult to achieve in a manufactured Fresnel lens. Two lenses are now being manufactured through diamond turning to determine how close the manufactured lenses can come to the designed versions of the lens. The primary limitation on the Fresnel lens system optical design and analysis will be the ability to analyze the scattered light characteristics and to specify the proper requirements and tolerances for the Fresnel lens manufacturer. For manufacturing tolerances, we specify requirements and tolerances for the aperture size, the focal length, the field of view, and the effective transmittance, in field and out of field scattering limits, and the $1/e^2$ spot size at the wavelength of interest.

4. CUSTOM LENS DESIGN

A 71 zone F/1 Fresnel lens with flat substrate toward infinite conjugate was developed using CODE V software. A wave optics analysis of the lens indicated that this lens generates a spot of 90 μm for 80% encircled energy (Figure 5). Manufacturing tolerances are not to be the same as the design, resulting in lens performance degradation. Because each zone utilizes a different aspheric surface, each zone is described by a different zoom position in the CODE V model. Each Fresnel zone was optimized separately to produce an image spot size of less than 90 μm at the image plane. Each of the Fresnel zones is described by an inner and outer radius, vertex location, and an aspheric surface sag polynomial describe each Fresnel facet surface (Figure 4). The expected diameter image plane spot produced by the Fresnel lens is shown in Figure (5) as a function of encircled energy.

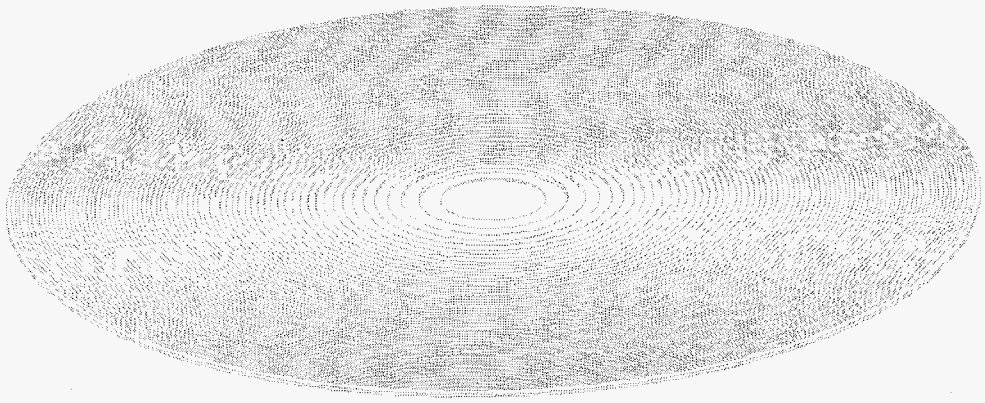

Figure 4. A 2-m F/1 Fresnel lens designed by Optical Research Associates

5. LABORATORY CHARACTERIZATION

Several off-the-shelf Fresnel lens with dimensions greater than 1-meter were characterized experimentally. These lenses are mass-produced primarily for consumer electronics applications. Reflexite Inc manufactures one such lens. The prescription for the Reflexite Fresnel lens is known and was modeled in Code V to determine the theoretical design performance. The raytrace results indicate that the panel is theoretically capable of producing a geometric $1/e^2$ spot size of 0.550mm over the full aperture. Utilizing a 40-cm amateur astronomy telescope as beam expander for 650-nm laser light, a spot size of nearly 0.5 mm was measured. The smallest focal spot size measured utilizing a second large Fresnel lens to illuminate the full aperture of this lens was about 1.2 mm. The fact that this spot size was not achieved in the laboratory testing probably indicates that the panel manufacturing errors, tolerances, and test equipment (beam expander) errors combined to give less performance than is theoretically possible. Figure (6) shows t a focal image of one of the lenses tested. Use of beam compressors and active beam correctors are being examined to further reduce the spot size.

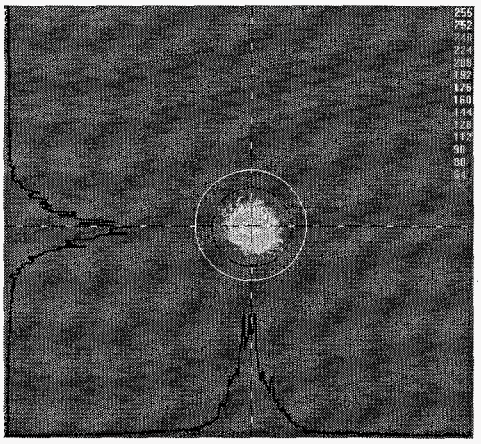

Figure 5. A focal image of one of the off-the-shelf large diameter Fresnel lenses examined experimentally at 650-nm collimated incident

6. REFERENCES

[1]. M. Britcliffe et. al., "A ten meter ground station telescope for deep-space optical communications: a preliminary design," IND Progress Report, 42-147, Nov. 2001, http://lasers.jpl.nasa.gov/PAPERS/GR_DEF/147g.pdf

[2]. R. Hyde, "eyeglass – Very large aperture diffractive telescopes," Appl. Opt. V. 38, 4198-4212 (1999).

[3]. A. B. Meinel and M. P. Meinel, "A comparison of lens and Fresnel null correctors," Appl. Opt. (2001).

[4]. S. Dixit et. al., "Fabrication of a 5-m diameter diffractive Fresnel lens," LLNL, Livermore, CA (2002). www.llnl.gov/nif/lst/LSTpubs/LST_nov2002.pdf

[5]. D. J. Lamb and L. W. Hillman, *Computer Modeling and Analysis of Veiling Glare and Stray Light in Fresnel Lens Optical Systems,* SPIE, Vol. 3779, Conference on Current Developments in Optical Design and Optical Eng. (1999).

[6]. D. Falkis and G. M. Morris, "Broadband imaging with holographic lenses; "Optical Engineering, V.28, 592-598 (1989).

7. ACKNOWLEDGEMENTS

The author is indebted to James McGuire and Les Foo of ORA Inc, and Gary Peterson of BRO Inc, Norman Page and Lawrence Scherr of JPL for analysis, and Xu Wang, Carlos Esproles and Vachik Garkanian of JPL for laboratory measurements, This research described in this paper was carried out at the Jet propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.