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# Lightweight Inexpensive Ozone Lidar Telescope Using a Plastic Fresnel Lens

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## Abstract

An inexpensive lightweight ozone lidar telescope was designed, constructed and operated during an ozone lidar field campaign. This report summarizes the design parameters and performance of the plastic Fresnel lens telescope and shows the ozone lidar performance compared to Zemax calculations.

## I. Introduction

Ground level ozone can harm public health, and even relatively low levels of ozone can cause health effects in people with lung disease, children and older adults. People who are active outdoors may be particularly sensitive to ozone. Ozone is likely to reach unhealthy levels on hot sunny days in urban environments [1]. Ozone contributes to what we typically experience as "smog" or haze, which still occurs most frequently in the summertime, but can occur throughout the year in some southern and mountain regions. Tropospheric, or ground level ozone, is not emitted directly into the air, but is created by chemical reactions between oxides of nitrogen (NO<sub>x</sub>) and volatile organic compounds (VOC). Once formed ozone can also be transported long distances by wind. Thus it is important to measure not only ozone at the ground but also ozone above the ground that can influence the ground level ozone concentration.

The Environmental Protection Agency (EPA) has published National Ambient Air Quality Standards (40 CFR part 50) for pollutants considered harmful to public health and the environment. The standard for ozone requires knowing the ozone concentration over an 8-hour period to be less than 75 ppbv (parts per billion by volume) [2]. Many ground stations, especially in urban areas, constantly measure ozone, but the ozone concentration above ground is not measured. The tropospheric ozone concentration can be measured using the differential absorption lidar (DIAL) technique [3]. These lidars have the ability to determine sources of ozone that transport from other urban areas, stratospheric intrusions and local ozone production separating out ozone sources.

Most lidar systems concentrate on obtaining ozone data in the far field or high altitudes, but at low altitudes (<1000-m) no ozone return is possible because the laser beam and the field of view of the telescope are not fully overlapped at 1000-m and below. The ozone concentration below about 1000-m is very valuable as it links the concentration at the ground with the far field ozone concentration. A separate near field telescope could retrieve this near field concentration.

This paper will describe construction and operation of a lightweight inexpensive telescope capable of detecting ultra-violet (UV) atmospheric backscattered photons emitted by the pulsed laser transmitter in the very near field from approximately 100 to 500-m altitude. Such a telescope may help reduce the cost and complexity of future ozone lidar systems, making them commercially available and thus stationed at many ground in-situ ozone monitoring sites.

## II. Ozone lidar system

The ozone lidar system consists of a Nd:YLF 527nm pulsed laser operation at 1-kHz pumping a

CLBO crystal generating 262nm. This beam is split into two beams that then pump a Ce:LiCAF crystal which generates tunable UV emission at two separate lines between 280 and 295nm with a total transmitted energy of 100 microJ [4]. These pulses are then transmitted into the atmosphere and subsequently backscattered into the receiver telescopes. Figure 1 shows a schematic diagram of the ozone lidar system and the very near field telescope described in this paper. The data retrieved by the telescope is recorded by a National Instruments Inc. data system and displayed real time on a computer monitor. This telescope is designed to retrieve atmospheric ozone profiles very near to the surface from 100 to 500m while the main telescope retrieves returns from 600m to 7 km.

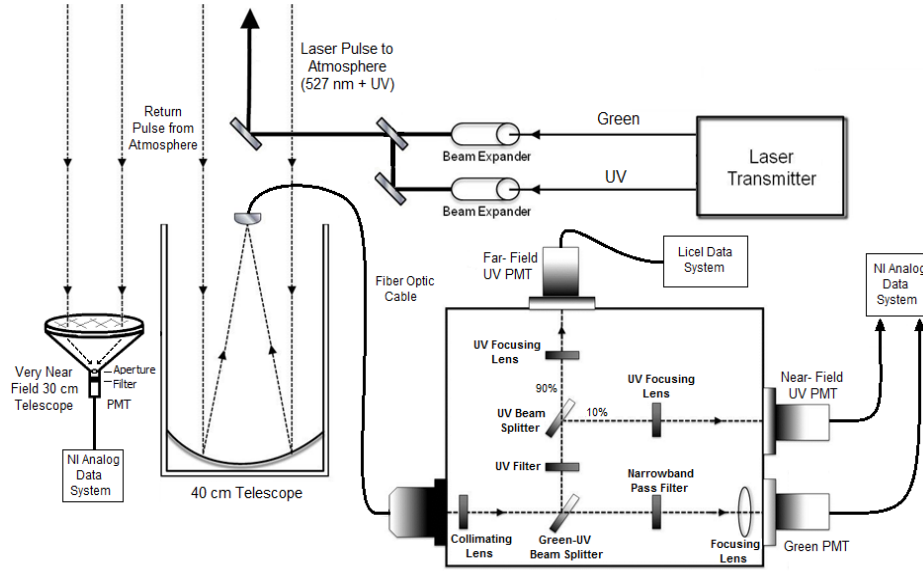


Figure 1. Schematic of the ozone DIAL lidar system with the very near field 30-cm telescope to the left of the far field 40-cm telescope.

### III. Construction and operation of the very near field telescope

The telescope was constructed using a printing process called fused deposition modeling at Langley Research Center in January 2014. The polycarbonate material was printed over a period of 25 hours to form a ridged cone to support the plastic Fresnel lens and the photomultiplier (PMT), filter and iris as shown in Figure 2. The wall thickness was 1.6-mm and the mass without the PMT, filter and iris was 0.91 kg. A photo of the telescope is shown in Figure 3. The telescope tube was painted flat black to reduce stray light reflections. The plastic Fresnel lens was screwed to the cone top edge with four machine screws. The aluminum ring was then placed in a X-Y mirror mount that was attached to the far field telescope frame. This allowed the Fresnel telescope to be manually adjusted in and out of the transmitted laser beam as well as transverse to the beam allowing the telescope field of view to intersect the transmitted beam at variable altitudes.

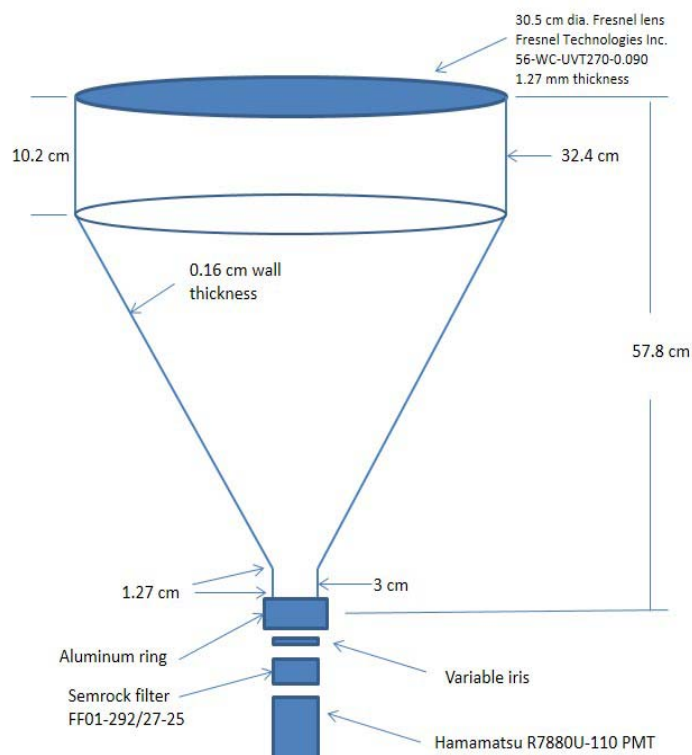


Figure 2. Schematic of the polycarbonate telescope with dimensions.



Figure 3. Photo of the polycarbonate telescope tube with plastic Fresnel lens, filter, iris and PMT.

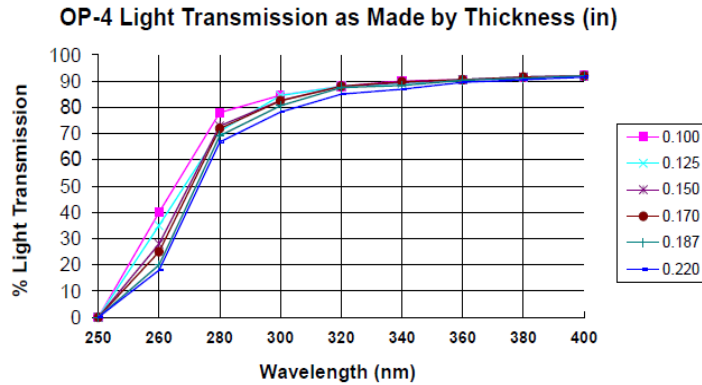


Fig. 4 Light transmission as a function of Fresnel lens thickness (in.) for UV grade acrylic. Used with permission Darrell Sparks, Evonik Cryo LLC.

At the focal length of the Fresnel lens a variable iris was mounted that could aperture the incident light from 1-10-mm diameter. A band pass filter (Semrock FF01-292/27-25, 70% 278-305nm) was used to limit the solar background light entering the detector. A Hamamatsu photomultiplier detector (R9880U-110) was used to detect both the on and off line atmospheric returns. The return signals were digitized by a National Instruments NI 5751, 50 MS/s, 16 channel digitizer module for NI FlexRIO combined with a Field Programmable Gated Array (FPGA) NI PXIe-7966R NI FlexRIO FPGA Module.

The Fresnel lens was manufactured by Fresnel Technologies Inc. and is stock number 56-WC-UVT 270-0.090, ~\$200. The focal length is 610-mm and the thickness is 2.3-mm (0.090 inch) and is made of UV transmitting acrylic (UVT) with refractive index of 1.49. Figure 4 shows a graph of UV grade acrylic (Darrell Sparks, Evonik Cryo LLC) transmission as a function of Fresnel lens thickness (inch). At 0.1 inch thickness the optical transmission is between 80 and 85 percent in the filter region of 278-305-nm which is the region where the on and off line laser wavelengths reside.

A Zemax ray tracing program was written to understand the expected field of view of the telescope shown in figure 2. The results are shown in figure 5. The first curve (open squares) shows the transmission through a 4-mm aperture placed at the focal plane of the 30.5-cm (12") diameter, 61-cm (24") focal length Fresnel lens resulting in a 6.6-mrad field of view. The transmission was calculated by tracing 100000 rays in Zemax and counting the fraction that passed through the 4-mm aperture without vignetting. The source plane in the ray-trace was assumed to be illuminated by a 200  $\mu$ rad laser arranged bi-axially with the transmitter placed at 30.5-cm (12") from the center of the receiver aperture as shown in figure 1. The telescope is assumed to be aimed so that the telescope optical axis intersects the laser beam optical axis at 200-m altitude range, but the laser beam and the field of view of the telescope are fully overlapped at 100-m as shown by the flat curve portion of figure 5.

The R-squared normalized transmission (solid squares) is calculated by multiplying the transmission curve by the square of the return altitude range. This step is necessary to find the expected relative lidar signal return because the ray-trace is setup with the aperture stop at the Fresnel lens which forces all the source rays to pass through the aperture; the R-squared normalization corrects for the diffuse character of scattering. The location of the source of each point on the graph was varied from 50 to 500 m in order to simulate the relative intensity that would be measured by the lidar from those altitude ranges, assuming a constant backscatter ratio over the entire range.



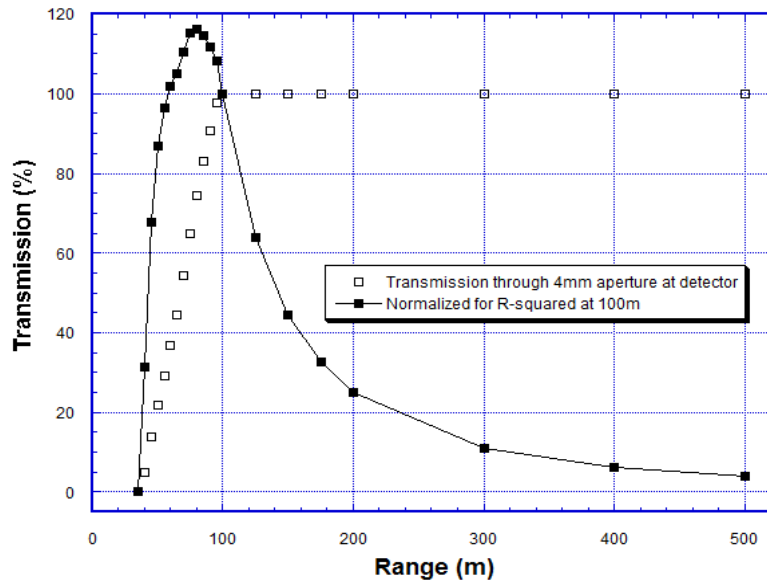


Figure 5 Transmission through a 4-mm aperture and the corresponding range squared normalized lidar return with laser beam and telescope separation of 30.5-cm.

An optical setup was constructed to measure the performance of the Fresnel lens and is shown in Figure 6. Here a large parabolic mirror was illuminated by a xenon arc lamp with the spectrometer. The spectrometer transmitted 532-nm light into a 1-mm diameter fiber which then filled the parabolic mirror. This produced a parallel beam of 1.3-mrad divergence which was captured by the Fresnel lens. A Photon Inc. BeamPro 2320 camera was placed at the focal length of the Fresnel lens and allowed observation of the focal spot size.

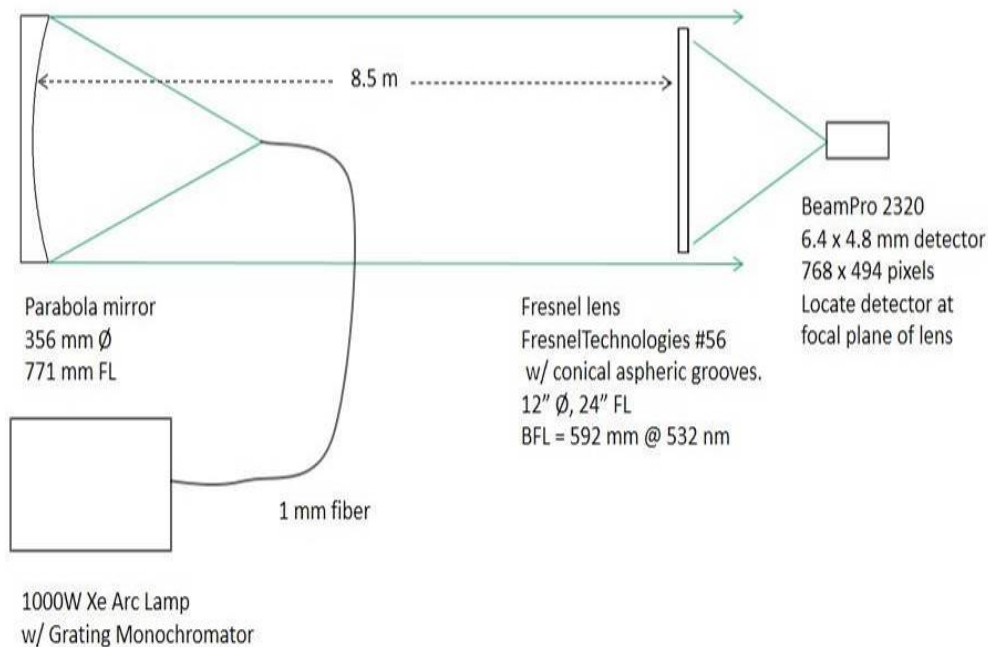


Figure 6. Experimental setup for the measurement of the Fresnel lens focal spot size.

The readout of the Beam Pro camera is shown in Figure 7. Here the focal point beam size is shown and the x and y  $1/e^2$  full width is 2.6 by 2.6-mm. The beam is round with no hot spots but with a long non-Gaussian tail. The diffraction limited spot size was calculated (1.3-mrad divergent input beam) for the 532-nm beam and found to have a  $1/e^2$  full width of 0.77-mm. The Fresnel lens full width was 2.6-mm thus the lens was 3.4 time diffraction limited. This shows the limitation of using a plastic lens, but using a 8-mm photomultiplier detector still captures the focal length spot size.

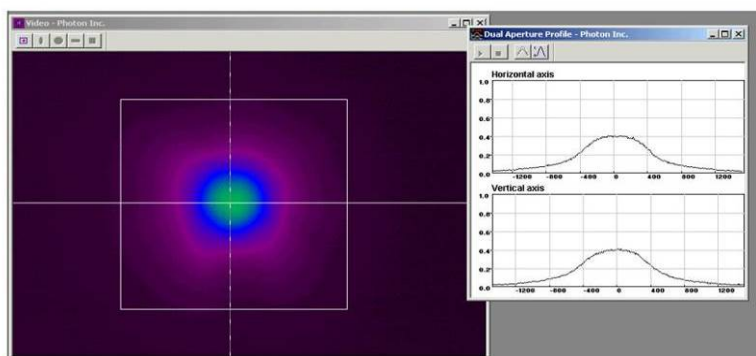


Figure 7. The Fresnel lens focal spot as recorded by the BeamPro camera and x and y full width spot size of 2.6 by 2.6-mm.

Figure 8 shows an example of the usefulness of this field ozone data. This atmospheric ozone data was obtained from the DISCOVER-AQ campaign on July 29, 2014 in Golden, CO. The curtain plot shows the vertical distribution of ozone (color scale from 0 to 100 ppbv) from 15 to 19:30 UTC (9 AM to 1:30 PM local time). The in-situ monitor shows the ozone at 5.5-m above the ground. A collocated ceilometer provided data on the boundary layer height and is shown by the blue line. The far field return (above 900-m) shows an ozone residual layer at 1000-m in the morning that later mixes with the afternoon growing convective boundary layer after 18 UTC. The very near field telescope shows that the morning ozone is indeed a layer above ground but later the boundary layer has higher ozone as indicated by the in-situ ground measurements. This would not be evident without the very near field telescope data. The gap between 400 and 900-m is due to the less than full overlap between the far field telescope and the laser beam. Note that the very near field altitude coverage is close to the predicted results of figure 5.

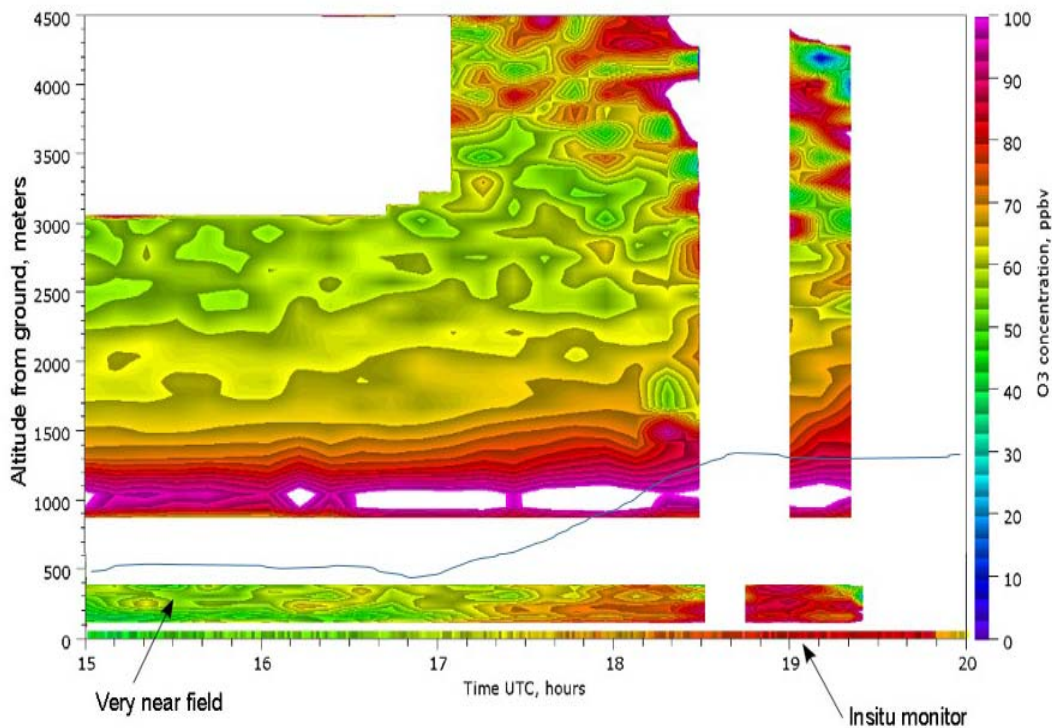


Figure 8. Ozone curtain plot from the DISCOVER\_AQ campaign July 29, 2014 in Golden, CO. The very near field telescope is shown along with the larger far field telescope return. The far field resolution is 90-m (with 5 point smoothing) and the very near field is 36-m resolution. Both are 10 min. time resolution. White space indicate clouds or rain.

#### IV. Conclusions

A very light and inexpensive UV ozone lidar telescope was designed, constructed and operated giving very near field ozone distributions from 100 to approximately 500-m. The use of a UV plastic Fresnel lens (30.5-cm diameter) was the key feature that allowed the telescope to have the characteristics of low mass and cost. While the lens is 3.4 times diffraction limit at 532-nm, it still has sufficient focusing power to allow lidar ozone profile measurements. Actual ozone lidar results confirm the calculated field of view

of the telescope. Such telescopes could find widespread use in networks of ozone lidars for air quality measurements.

#### Acknowledgement

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