# Prototype Holographic Atmospheric Scanner for Environmental Remote Sensing (PHASERS)

David V. Guerra
Department of Physics, Saint Anselm College, 100 Saint Anselm Drive, Manchester, NH 03102

Geary K. Schwemmer
Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, MD 20771

Albert D. Wooten Jr., Sandipan S. Chaudhuri
Department of Physics, Western Maryland College, 2 College Hill, Westminster, MD 21157

Thomas D. Wilkerson
Utah State University, Center for Atmospheric and Space Sciences, Logan, Ut 84322-4405

ABSTRACT
A ground-based atmospheric lidar system that utilizes a Holographic Optical Telescope and Scanner has been developed and successfully operated to obtain atmospheric backscatter profiles. The Prototype Holographic Atmospheric Scanner for Environmental Remote Sensing is built around a volume phase reflection Holographic Optical Element. This single optical element both directs and collimates the outgoing laser beam as well as collects, focuses, and filters the atmospheric laser backscatter, while offering significant weight savings over existing telescope mirror technology. Conical scanning is accomplished as the HOE rotates on a turntable sweeping the 1.2 mrad field of view around a 42$^{o}$ cone. During this technology demonstration, atmospheric aerosol and cloud return signals have been received in both stationary and scanning modes. The success of this program has led to the further development of this technology for integration into airborne and eventually satellite earth observing scanning lidar telescopes.

## 1. Introduction

The ground-based test facility for the Holographic Optical Telescope and Scanner (HOTS) technology (Schwemmer, 1993) is built around a volume phase reflection Holographic Optical Element (HOE). This Prototype Holographic Atmospheric Scanner for Environmental Remote Sensing (PHASERS) employs the HOE to collimate and direct the outgoing laser beam, as well as to collect, focus, and filter the atmospheric laser backscatter. As the HOE rotates about the optical axis of the system, its 1.2 mrad field of view sweeps out a 42$^{o}$ conical scan. The laser beam is bore-sighted with the Field of View (FOV) of the HOE as determined by the field stop. The field stop, which is located on the HOE rotation axis, then tracks the outgoing laser beam throughout the scan.

In this technology demonstration project, the unique properties of the HOTS have been utilized to perform both unidirectional and conical scans during data acquisition. In both operational modes, the HOTS technology has operated successfully in making measurements of the aerosol backscatter profiles (Guerra, et. al. 1998). The development of this technology will allow larger optical and infrared planetary and earth observing scanning lidar telescopes to be deployed, while offering significant weight savings over existing telescope mirror technology. In this paper, we will give a brief overview of the system and present data taken with the system operating in both stationary and scan modes. Along with the field test of the HOTS technology, we have retested the optical properties of the HOE that has been operated in the PHASERS system for almost five years of field use. This is the first assessment of optical qualities of a HOE after long term use in a lidar system.

## 2. Holographic Optical Element

An HOE is a hologram that exhibits optical power, i.e. the ability to focus and/or direct light (Magariños and

Coleman, 1985). It derives this optical power from a diffraction pattern which is manifest as an index modulation throughout the thickness of a thin film (Kogelnick, 1969). A reflection HOE, as used in PHASERS, is produced by exposing a glass plate coated with a film of dichromated gelatin emulsion to two mutually coherent laser beams. To produce a focusing HOE, the object beam emanates from a pinhole producing spherical wave fronts, while a second, plane wave beam serves as the reference beam, interfering with the object beam in the gelatin. The angle between each beam and the plate determines the diffraction angle during reconstruction. Molecular cross links are formed in the photo-sensitised gelatin with exposure to light, so the interference fringes are registered in the film as variations in hardness and index of refraction (Magariños and Coleman, 1985). The photo-sensitive dye is removed from the gelatin during post-exposure chemical processing, and the resulting hologram is relatively free of absorption. The HOE is then dried and hermetically sealed with a cover glass cemented to the film and sealed around the edges. When the completed HOE is illuminated with a plane wave monochromatic source conjugate to the construction reference wave, a conjugate of the original object beam forms a focus or image of the original point source.

The optical properties of the HOE in PHASERS can be understood as the combination of an on axis interferometric zone plate (Horman and Chau, 1967) and a slanted optical grating (Kogelnik, 1969). To achieve a specific focal length, f, at a given wavelength, l, for a reflection HOE the radii, $s_{i,}$ of the circular apertures of the zone plate must be spaced such that

$$\sigma_i = (2)^{1/2}\, im\lambda \qquad (1)$$

where i is the number of the circular apertures, with i = 0, 1, 2,... counting from the center of the optic out to the radial edge, and m is the diffractive order of the light that is focused (Kamiya, 1963). Assuming an input ray normal to the surface of the HOE, the angle, f, at which the HOE deflects the beam is given by the grating equation

$$\lambda = d[1 + \sin(90^o + \phi)]n \qquad (2)$$

where n is the index of refraction and d is the grating period. The additional $90^o$ is added because the fringe planes of the reflection HOE are oriented parallel, instead of perpendicular, to the surface. Unlike the radii of the circular apertures, which vary across the plane of the HOE, the grating period varies through the depth of the HOE. Together the grating period, d, and the radii, si, define the "bowl shaped" fringe planes that give the HOE its optical power. It is important to reiterate that physically the HOE is flat and that the curvature of the fringe planes is independent of the substrate.

In the lidar application, backscattered laser light acts as the reconstruction beam and is focused by the HOE. The wavelength of reconstruction does not have to match that of the construction light, the HOE can be tailored to achieve maximum efficiency and remove wavelength induced aberrations by a number of techniques described by Rallison and Schicker (1995), Jannson and Jannson (1985) and Assenheimer, et. al. (1988). The HOE can also serve as the scan mirror, by rotating it in its own plane. This will direct the outgoing laser beam such that it will sweep out a cone of light. By placing the field stop on the axis of rotation, the focal plane optics and detector can remain static.

The PHASERS HOE, designed at a wavelength of 532 nm, is a circular volume phase reflection hologram of a point source. Mounted on a flat glass substrate, the HOE has a total active diameter of 40 cm. The HOE was independently tested in 1991 prior to deployment in the PHASERS system and again by the authors in 1998. The tests consisted of measurements of focal length, focal spot size and shape, diffraction angle, and diffraction efficiency. A collimated light source at 532 nm that filled the HOE was used to simulate the lidar backscattered signal for the test measurements. The focal spot size was measured using a beam scan system equipped with a ccd camera and software that produced a real time display along with frame grabbing capability. This provided the ability to adjust the location of the camera to find the point of the smallest spot. The focal length was found by measuring the distance from the HOE to the location of the smallest spot produced by the optic.

Interestingly, these exercises revealed that the focal spot of the HOE did not vary significantly over a variation of nearly $\pm 2^o$ of diffraction angle from the one which produced the minimum spot. The focal spot size subtends 1.2 mrad, therefore limiting the smallest useful FOV and constraining measurements made with our 1.0 mJ laser to night time. The aberrations of the HOE are a combination of spherical, astigmatism, and coma. Also, the spot produced by the HOE had a depth of focus comparable to a mirror with similar optical parameters.

Since the HOE acts as a lens or spherical mirror, images of extended sources other than at infinite object distance are possible and plainly observable. The widest FOV of the HOE is limited by those off axis rays which no longer satisfy the Bragg condition for diffraction. This FOV varies with HOE design and is narrower for thicker films. However, thinner films with wider acceptance angles and bandwidths tend to have lower diffraction efficiency.

In 1991 the measurements of diffraction efficiency were performed using a technique that included sampling the power of the incident radiation across the collimated beam and, with knowledge of the detector head area, the power density of the radiation incident on the HOE was calculated. This power density was averaged across the entire beam, with consideration of the tilt angle of the HOE and the obscuration of the collimator pinhole assembly. The power of the radiation focuses off the HOE was then measured with the same detector. The values of averaged input power and measured output power were divided to get the reflectivity percentage. In 1998, the reflectivity was measured by collecting the radiation from a similar collimated spot with a large Fresnel lens before and after reflection. The measured values of input and output power were divided to find the reflection percentage. Another technique was used to confirm the results from the measurement method employed in 1998. In this technique, we utilized a mask with a vertical and a horizontal line of holes that passed through the center of the circular mask. The thirteen holes in the mask made a cross, which had three holes above, below, to the left, and to the right of the center hole. With this mask placed in the path of the collimated radiation, before the HOE, a power meter was used to measure the incident and reflected power of each point. Care was taken to be certain that we were measuring the same point of light before and after the HOE. Also, it is important to note that the holes in the grid where smaller that the size of the detection surface of the power meter. Although these two techniques are significantly different the results of reflection efficiency varied by $\pm$2% for the HOEs measured. This agreement has given us confidence in our efficiency measurements taken in 1998. A summary of the results from all the optical tests performed on the PHASERS HOE are listed in Table 1.

The technique employed to measure the reflectivity of the HOE in 1991 was repeated in 1998, but the variation in the measurements was extreme, $\pm$ 10%. Thus, we abandoned this method and used the methods explained in the above paragraph. The difference in refletivities measured in 1991 and 1998, were due, in part, to the unavailability of the same equipment and facilities in 1998.

All differences in the optical measurements listed in Table 1 are nearly within one standard deviation. The small shifts in diffraction angle may be due to gradual shrinkage and densification of the holographic film over time, but we believe that most of the differences in the measurements are due to unavoidable differences in the measurement techniques.

Table 1.

| Property | April 91 | January 98 |
|---|---|---|
| focal length | 1.29 $\pm$ 0.01m | 1.29 $\pm$ 0.01 m |
| focal spot ($1/e^2$ diam.) | 1.5 $\pm$ 0.1 mrad (max eff.) | 1.2 $\pm$ 0.1 mrad (max eff.) |
| Diff. Angle | $43.2^o \pm 0.5^o$ | $42^o \pm 0.5^o$ |
| Diffraction Efficiency | 73% $\pm$ 8% | 59% $\pm$ 2% |

Overall, these results demonstrate that the optical characteristics of the HOE remain fairly constant even under the uncontrolled environment of the PHASERS roof top facility.

## 3. Experimental Apparatus

The PHASERS, depicted in figure 1, is a complete ground based lidar system operating with the HOTS technology. The HOE is placed on a computer controlled, motorized rotating table that allows for pc based remote operation for both pointing and scanning. A tripod supports the conical baffles, a spider assembly for the laser steering mirror, and the photon counting detector package located at the top. The FOV of the hologram makes a $42^o$ angle with the normal to the plane of the disk. As can be visualized in figure 1, the FOV sweeps out a conical scan as it spins about a perpendicular line through its center, which is aligned with the optic axis of the system. The hologram is the only moving component of this telescope, allowing a significantly lighter structure for supporting the detector package and baffling, both of which remain fixed. The transmitter laser beam is directed to a turning mirror positioned above the HOE, which directs the beam along the rotation axis to the HOE surface. The beam is then directed off the HOE coaxially with the instantaneous FOV of the telescope. Since the HOE is employed as the final reflection surface of the outgoing beam, a lens is used with the HOE to form a transmitter collimating telescope, which expands the beam. The beam is enclosed by tubes as it propagates through the telescope system to help eliminate scattered light from entering the detector and overloading the PMT, which could corrupt the weak atmospheric backscatter signals.

The frequency-doubled, cw diode-pumped, Q-switched, Nd:YAG laser transmitter for the system is

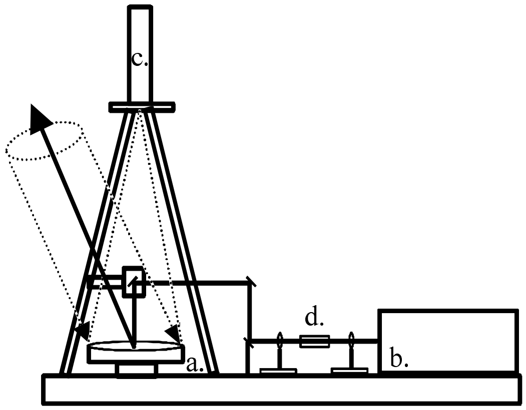


Figure 1. The PHASERS system is comprised of an (a.) HOE, a (b.) laser transmitter, a (c.) PMT detector, and (d.) focusing and collimating optics.

hermetically sealed, which helps reduce complications due to humidity and temperature fluctuations. The output of the laser oscillator is externally frequency doubled to match the wavelength of the HOE. To achieve the maximum doubling efficiency, the fundamental radiation is focused into a 3x3x10 mm Potassium titanyl phosphate (KTP) crystal. The laser is usually operated at a repetition rate of 2 kHz. In this operational mode, the output from the Nd:YAG laser has a pulsewidth of 20 ns and a power of 4.2 W in the fundamental, giving an energy per pulse of 2.1 mJ. The frequency doubled radiation has a slightly shorter average pulsewidth of 19 ns and a power of 1.9 W, which gives an energy per pulse of approximately 1.0 mJ at 532 nm. This repetition rate was chosen because it is the one at which the highest energy per pulse in the green is achieved.

The PHASERS HOE showed no degradation with exposure to the 1.0 mJ, 2 kHz laser, which provides a power density of 0.5 mJ/cm$^2$ at the HOE. In a related experiment, a similar HOE was observed to burn in response to illumination by a 600 mJ, 30 Hz, 532 nm, Q-switched Nd:YAG laser with an approximate power density of 190 mJ/cm$^2$ at the HOE. Although, quantitative optical damage threshold testing has not been done, but it is believed that the epoxy used to cement the cover glass to the HOE film and substate will be the limiting factor.

## 4. Results

PHASERS has been continually operated and upgraded during its approximately five years of operation. In the following section, three data are presented to clearly demonstrate different abilities of the system. The first data set, given in figure 2, is that of a single one minute averaged data file taken at 8:00 PM on October 1996.

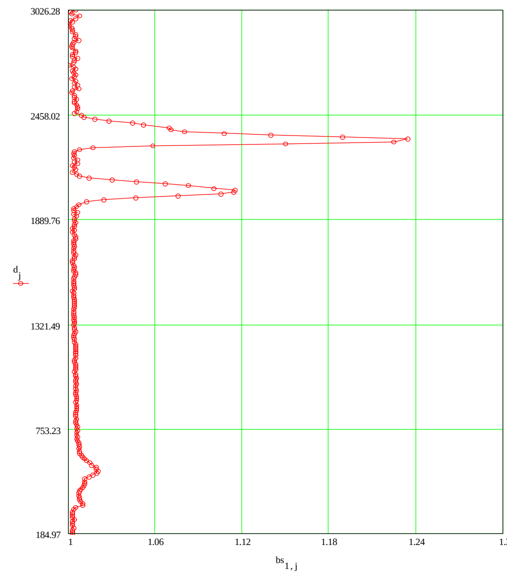


Figure 2. A single 1 minute average data file. The data are plotted as signal strength (photon count) as a function of altitude (m).

The data in this figure are represented as backscattering ratio as a function of altitude in meters. In the earlier version of PHASERS, with which these data were taken, a lower repetition rate laser was operated at 1.0 mJ @ 20 Hz and one minute averaged data files were taken. The data have been background subtracted and r$^2$ corrected. The background subtraction entailed fitting a polynomial to the data such that the base line of the photon count was straight and set to zero at all values of altitude. From these data it is clear that the system can detect returns from multiple layers in the atmosphere.

In its stationary mode of operation, the HOE is oriented to point in one direction and data are taken over a given period of time. The 100 consecutive, one minute averaged, data files presented in the surface plot in figure 3 were taken between 8:00 -9:40 PM on October 1996 with the system pointing north. The lines of maximum contour are at the backscattering ratio value of 1.203 and the additional contour lines are at 0.15 intervals. With this time sequence of data files it is evident that the system can detect the change in multiple aerosol layers as a function of time.

In its scan mode of operation the HOE is rotated at a fixed rate and data are taken continuously and averaged in predetermined intervals. This essentially divides the sky into equal segments of a three dimensional hollow cone. A data set of three continuous conical scans using the 2 kHz laser was taken between 7:00 - 7:30 PM on November 3, 1997.

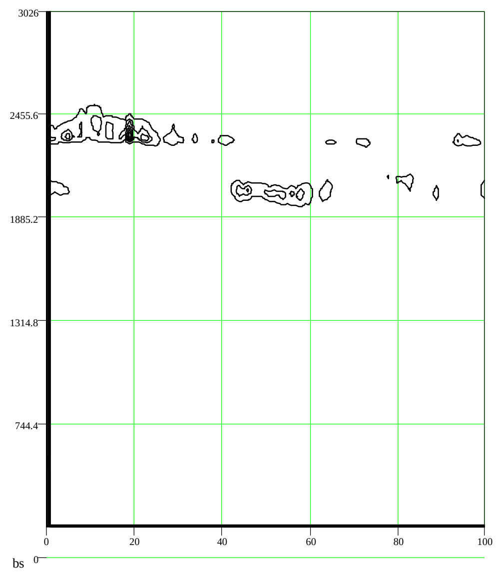


Figure 3. Surface plot of the relative backscatter signal strength as a function of altitude (m) and time (minutes) .

During this data acquisition, the HOE was rotated at a constant rate of one revolution every ten minutes and data files were stored in thirty one-minute averages. Thus, each file represents one tenth of the sky and each scan begins and ends in the north. It is important to recognize that the cones of data produced in this process represent the time evolution of the sky in the FOV swept out by the HOE. By analyzing these data with this in mind, atmospheric structures, such as clouds, can be seen advecting across the sky. A

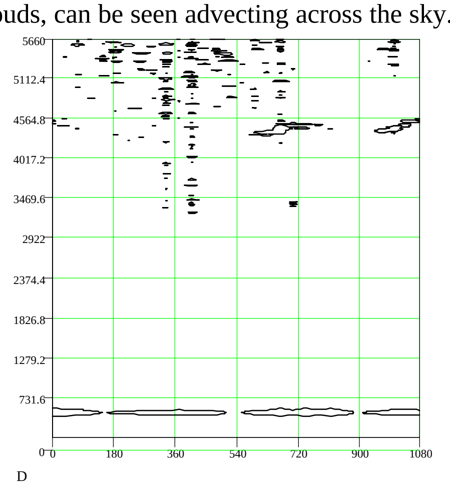


Figure 4. Surface plot of the relative backscatter signal strength as a function of altitude (m) and scan angle (degrees) . The areas of maximum contour have a backscattering ratio of 1.87

composite diagram of these data are presented in a surface plot, in figure 4. The lines of maximum contour are at the backscattering ratio value of 1.870 and the additional contour lines are at 0.15 intervals. The surface plot in figure 4 is the projection of the cones of data, swept out during the scan, onto a flat surface. Thus the data at each altitude on the surface plot can be understood as a series of unraveled circles of data each starting and ending at North. For each scan , the circles have a common axis, with a circumference that increases with altitude. In this format, the structure which first appears distinctly in the second scan at ~600$^o$ shifts further to the southeast in the third scan. This capability of the system will be studied further and a wind measurement technique that utilizes the cross correlation of aerosol densities deviation, as described by Eloranta, King, and Weinman (1975) and Sroga, Eloranta, and Barber (1980) will be explored.

5. Summary

This study represents the first successful use of the HOTS technology to make atmospheric backscattering measurements. The HOE was used in both stationary and scanning modes. Future plans include the addition of a narrow band filter and the necessary optics for day-time measurements, along with additional automation of the system and data handling. Due to the success of this demonstration of the HOTS technology a new class of light weight scanning telescopes for lidar remote sensing from air and space craft platforms are under development and being tested for additional applications (Schwemmer, G. 1998) and (Wilkerson, Hammond, and Wickwar, 1998).

HOEs similar to the one described here are available from a variety of manufactures around the world at costs competitive with conventional reflective optics of similar aperture size. Two U.S. lidar system vendors have licensed the HOTS technology for use in commercial lidar systems. More information is available from the offices of technology transfer and patents at NASA-Goddard Space Flight Center (GSFC).

6. Acknowledgments:

This research was funded by the Laboratory for Atmospheres at NASA - Goddard Space Flight Center. Thanks to Dave Kubalak of Orbital Science Corp. for his help testing the optical properties of the HOE.

References

Assenheimer, M., Amitai, Y., and Friesem, A. A., Recursive design for an efficient HOE with different recording and readout wavelengths, *Appl. Opt.*, **27**, 4747-4752, 1988.

Eloranta, E.W., King, J.M., and Weinman, J.A., The Determination of Wind Speeds in the Boundary Layer by Monostatic Lidar, *J. Applied Meteorology*, 14, 1485-1489, 1975.

Guerra, D. V., Wooten, A. D. Jr., Chaudhuri, S., and Schwemmer G., Operation of the Prototype Holographic Atmospheric Scanner for Environmental Remote Sensing (PHASERS)., , *Proceedings of the 19th International Laser Radar Conference*, NASA conference publication, 879, June 1998.

Horman, M. and Chau, H., Zone Plate Theory Based on Holography, *Appl. Opt.*, **6**(2), 317-322, 1967.

Jannson, T. and Jannson, J., Bragg Holograms and Concentrator Optics, *Proceedings SPIE*, **523**, 219-226, 1985.

Kamiya, K., Theory of Fresnel Zone Plate, *Science of Light*, **12**(2), 35-44, 1963.

Kogelnick, H., Coupled Wave Theory for Thick Hologram Gratings, *Bell Syst. Tech. J.*, **48**, 2909-2947, 1969.

Magariños, J.R., and Coleman, D.J., Holographic Mirrors, *Proceedings, SPIE*, **523**, 203-218, 1985.

Rallison, R.D., Holographic Optical Elements (HOES) in Dichromated Gelatin (DCG):Progress, *Proceedings SPIE*, **523**, 292-295, 1985.

Rallison and Schicker, Wavelength Compensation by Time Reverse Ray Tracing, Proceedings SPIE San Jose, CA, 2404, 217, 1995.

Schwemmer, G., Conically Scanned Holographic Lidar Telescope***, U.S. Patent No. 5,255,065,*** 1993.

Schwemmer, G., Holographic Airborne Rotating Lidar Instrument Experiment (HARLIE), *Proceedings of the 19th International Laser Radar Conference*, NASA conference publication, 623, June 1998.

Sroga, J.T, Eloranta, E.W., and Barber, T., Lidar Measurement of Wind Velocity Profiles in the Boundary Layer, *J. Applied Meteorology*, 19, 598-605, 1980.

Wilkerson, T. D., Hammond, M., and Wickwar V. B., Increased Capabilities for Conventional Lidars Using Holographic Optics., *Proceedings of the 19th International Laser Radar Conference*, NASA conference publication, 923, June 1998.