SHARED APERTURE DIFFRACTIVE OPTICAL ELEMENT (SHADOE) TELESCOPE FOR LIDAR

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ABSTRACT

We report on the progress of an experimental research program to demonstrate the feasibility of multiplexing several holographic optical elements (HOEs) in a single film. Named the Shared Aperture Diffractive Optical Element (ShADOE), it is equivalent to multiple telescope primary lenses all contained in one optic, and is used as a scanning telescope without major moving components [1]. Suitable for a broad range of lidar applications and free-space laser optical communications, multiplexed telescope technology will enable a Global Tropospheric Wind Mission by providing scanning for a large aperture over very wide-angles. In addition to multiplexing several HOEs into a single optic, we demonstrate aberration correction using a secondary holographic corrector plate that also collimates the light for an afocal system. We also subject the HOEs to radiation tests as part of a space qualification program.

1. INTRODUCTION

Due to the limited available power for any spaceborne lidar, using a larger aperture receiver will be more cost effective at increasing signal to noise (S/N) ratio than using a larger laser. Many applications need to scan over wide angles to achieve rapid cross-track coverage or to obtain multiple views into a target volume. For lidar measurements in the daytime atmosphere, the instantaneous field-of-view (FOV) must be very small, <100 microradians, in order to keep scattered sunlight from obscuring the weak lidar signals. But scanning a large (up to >~ 1m), narrow FOV telescope over large angles in a short amount of time presents some major engineering challenges. Applications like the Doppler wind lidar prefer step-and-stare scanning which exacerbates the problems of instrument power, momentum compensation, torque, and vibration cancellation. When using conventional geometric optics the requirement for widely separated viewing angles and narrow FOVs forces one to either steer the entire telescope assembly or to scan the entrance aperture using a large flat scanning mirror. Both of these approaches are very expensive in terms of mass, volume and cost when being considered for spaceborne instruments. Another alternative is to use multiple fixed position telescopes which either use multiple lasers and receivers, or are multiplexed to a common receiver and transmitter. The ShADOE is a holographic analog of the multiple telescope arrangement, where each telescope utilizes a holographic primary optic and separate and independent optical systems that may also use separate lasers and receivers or multiplex into common components.

This work builds upon previous scanning lidars utilizing a single HOE that performs the function of the primary optic while allowing the remaining optical and mechanical components of the telescope to remain stationary while the HOE rotates about its center normal axis [2]. The PHASERS lidar [3] uses a 40 cm diameter reflective HOE at a wavelength of 532 nm in a ground-based facility at St. Anselm's College in Manchester, NH. The HARLIE instrument [4] uses a 40 cm diameter transmission HOE at 1064 nm in both airborne and ground-based configurations. The TWiLiTE instrument [5] is a high altitude airborne Doppler lidar using a 40 cm diameter 355 nm HOE telescope.

The main difference between multiplexed conventional telescopes and multiplexed holographic telescopes is that all of the primary optics of the latter are multiplexed into a single optic. In this manner they can make use of the same aperture area while sharing some common volume and weight, thereby making the entire system lighter and more compact. We do this by superimposing multiple copies of an HOE into a single film, each HOE acting as a diffractive lens with a FOV pointing in a unique direction. All of the HOE copies share the same physical aperture. Figure 1 is a ray tracing showing how the optics and ray bundles are arranged in a ShADOE telescope system containing 4 copies of a HOE. To generate the multiple HOE copies, a master HOE made earlier is placed in contact over the ShADOE and scanned with a laser beam to copy the hologram into the ShADOE. The ShADOE is rotated with respect to the master between exposures to fix the desired azimuth angles relative to each other.

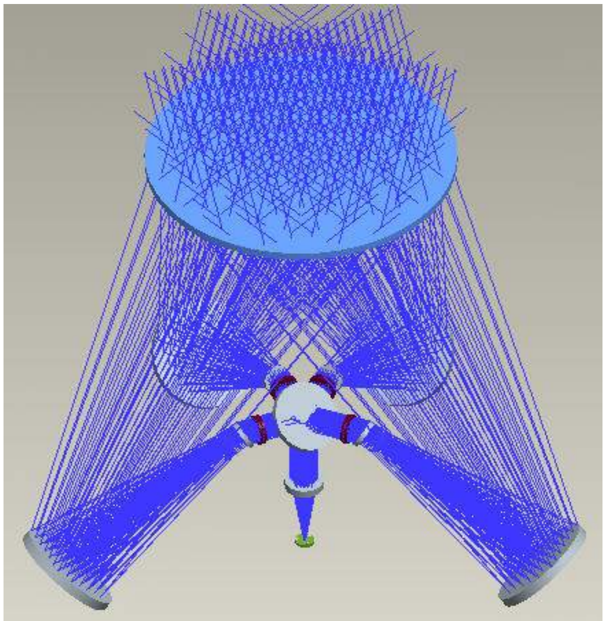

Figure 1. Ray tracing showing the arrangement of the ray bundles and optics in a 4-telescope ShADOE system.

2. OPTICAL DESIGN

Figure 2 is a ray-trace of one of the telescopes in the ShADOE system. The primary is a 1 m focal length HOE that accepts collimated light from 40° off normal and diffracts the principle ray 30° off normal. A flat folding mirror directs the light back toward the central axis of the system. The light is directed through a Holographic Corrector Plate that removes the substantial aberrations from the primary while collimating the ray bundle. A pair of Risley prisms is used for fine alignment of the collimated beam onto the central axis of the system and to align the focus with the field stop. A flat fold mirror mounted on a rotation stage is used to direct the light onto the central axis. The rotation axis of this mirror is coincident with the central axis of the system, allowing each of the telescopes to be selected sequentially. Thus a small rotating mirror replaces the large scanning stages required for conventional approaches to scanning the telescope primary. By eliminating the need to repeatedly rotate and stop a large optic, the ShADOE will also simplify the engineering required to maintain pointing accuracy and stability. Focusing lenses launch the light into a fiber optic or conventional field stop to be relayed to the receiver optical detection system. We have included a cube beamsplitter to allow the use of a bore sight camera or auto-alignment system.

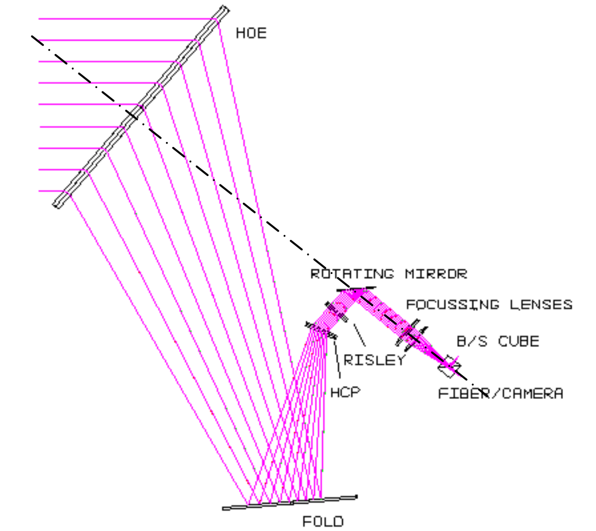

Figure 2. Ray trace of one telescope within the ShADOE system. The primary optic is a 1-m focal length HOE, and the view is in its plane of diffraction. The dot-dash line is the center axis for the system.

3. HOLOGRAPHIC CORRECTOR PLATE

Large volume phase HOEs are difficult to produce without substantial aberrations, and for this reason we use float glass substrates and covers, which also add to the wavefront errors. Our first large 355 nm ShADOE contains six HOEs spaced at various azimuth stations, and they have focal spots that subtend ~300 µrad. We had 5 cm square Holographic Corrector Plates (HCPs) made for two of the six HOEs in our first attempt at using this technology, with the goal of eventually producing ShADOE systems with diffraction limited optical performance. This is a requirement if this technology is to be used in any coherent detection lidar systems. We subjected one of these HCPs to performance testing, measuring the spot size produced in the lab when the ShADOE is illuminated with a 355 nm wavelength, 40 cm diameter collimated light beam.

The HCP is produced by exposing a holographic film plate placed in the converging light from the HOE in the ShADOE that it will be used with. The primary HOE is illuminated with collimated light, a fraction of which is directed to the HCP without going through the primary HOE. This smaller collimated beam is directed to intersect the chief ray of the converging beam at an angle of 60°. The HCP film plate is positioned at the intersection and oriented so that it's normal bisects that angle. In use, the HCP accepts the aberrated converging rays from the primary and diffracts them into an aberration corrected 37.5 mm collimated beam. The HCP must be repositioned to the same location and orientation that was used during its creation in the exposure set-up. The final alignment is performed with the aid of a shear-plate placed in the collimated output beam of the HCP, as well as by observing the focal spot on the CCD camera. Figure 3 is a photo of the ShADOE HCP test set-up, and figure 4 is a time averaged CCD camera image of the focal spot produced with a 1.5 m f. l. objective. An encircled energy analysis of the image shows that 93% of the light falling on the camera is contained in a 50 μrad circle. This is about twice the calculated diffraction limited spot size of 23 μrad.

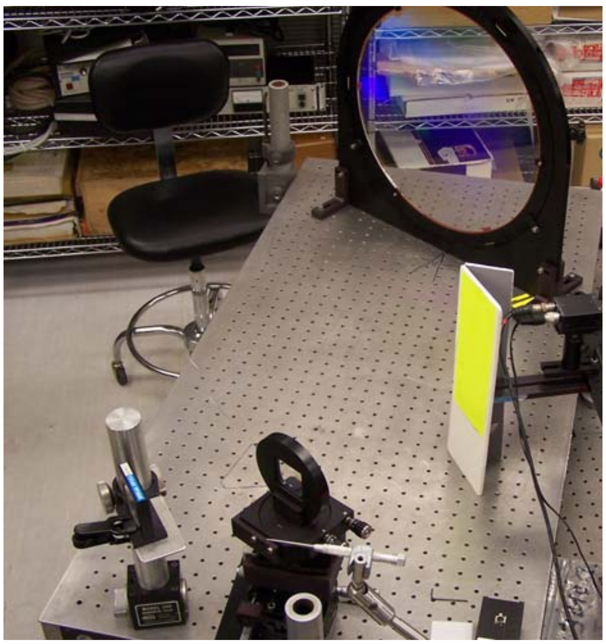

Figure 3. The ShADOE HCP test set-up. The ShADOE placed at the rear of the table focuses light on the pointer in the foreground. The HCP is located 7.5 cm from the focus, and diffracts the light into a nearly aberration-free, 3.75 cm diameter collimated beam. A shear-plate sits in the beam to the left of the HCP.

Alignment sensitivity measurements were made for the HCP, moving it through each of its six degrees of freedom and observing the change in energy encircled by a 50 microradian diameter centered over the center of mass for each image. We assume that any focus X-Y translation errors with respect to a fixed field stop can be removed perfectly using the Risley prisms to adjust the tip and tilt of the collimated beam. The degree of misalignment of the HCP which causes a 10% degradation of the encircled energy was found to be roughly 40 μm for translation error in X and Y, and 120 μm for translation in Z (focus). Rotational errors of ~ 1 mrad about Y and Z caused similar degradation in the focal spot. Rotation about X, which lies in the plane of diffraction, is about half that sensitive.

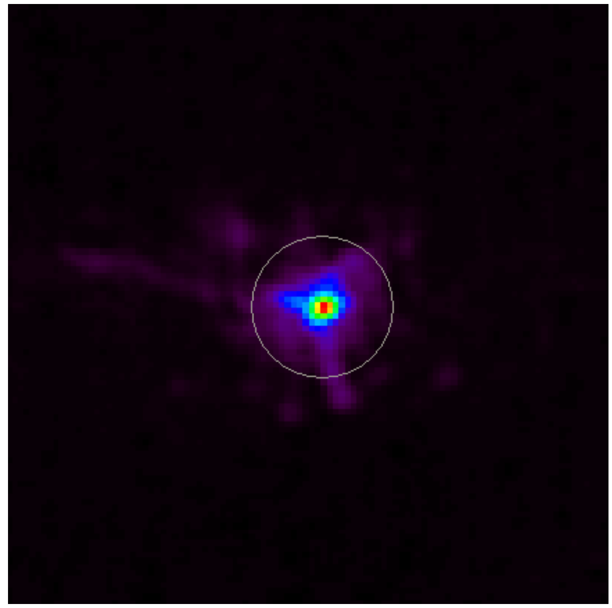

Figure 4. Focal spot produced by the ShADOE and HCP using a 1 m focal length objective lens. The central 50 μrad (white circle) contains 93% of the energy falling on the camera.

Encouraged by these results, a conceptual design for a breadboard version of a complete 4-telescope ShADOE system was undertaken. Figure 5 is a CAD rendering of the breadboard opto-mechanical design. A ray bundle is traced in blue lines for one telescope. The corresponding laser transmit beam path is rendered as a solid orange beam. The laser beam is collimated prior to entering the telescope, and is directed onto the system axis with a fixed flat mirror mounted to a spider. The spider mirror directs the beam down to a second

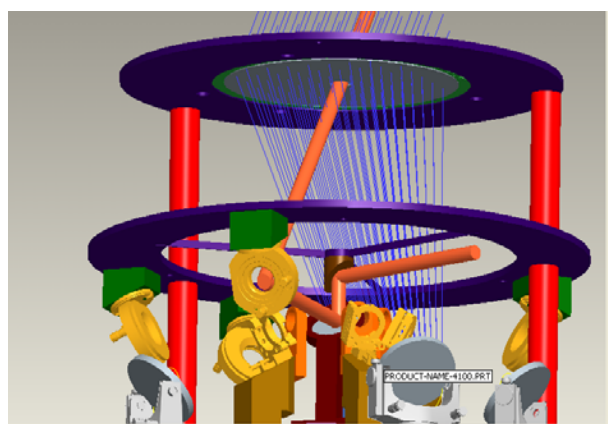

Figure 5. CAD rendering of a breadboard 4-telescope ShADOE system. The ray bundle for one telescope is shown with the corresponding coaxial laser beam path.

flat fold mirror, co-rotating with the telescope selector mirror, to direct the beam to a third flat that transmits the beam through a hole in the center of the ShADOE and coaxially aligned to the telescope FOV. Figure 6 is an aft end view showing how the received rays are directed off of the rotating selector mirror through a hole in the base plate to the aft optics. Production and demonstration of this ShADOE breadboard is planned for this year.

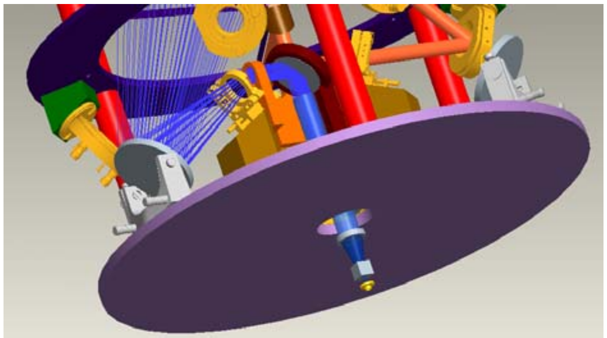

Figure 6. Bottom view of the breadboard system showing the path of the received light rays through the HCP and Risley prisms, off the rotating selector mirror and down through a hole in the base plate to the aft optics.

4. SPACE RADIATION ENVIRONMENTAL TESTS

We put together a test plan based on the expected levels of proton and electron radiation encountered over three and ten year missions in low earth polar orbits. In order to gauge the effects on the various materials that go into a volume phase hologram, we had 2.5 cm holographic transmission gratings (30° in, 30° out) prepared with the same dichromated gelatin (DCG) film recipe as our larger HOEs. Additional, unexposed DCG samples processed in the same manner as the holograms, samples consisting of two pieces of glass epoxied together, and bare glass substrates were also made. We tested three types of glass, a borosilicate float glass, Pilkington Optiwhite used in our UV HOEs, and two types of fused silica, JGS2 and UV grade. Samples of each type were subjected to Cobalt 60 (1.25 MeV) gamma radiation in doses of 30 and 100 KRad. Samples of each type were also subjected to 5 and 20 MeV energy protons, also with total doses of 30 and 100 KRad. In addition, high intensity UV laser radiation tests are underway to look not only for permanent damage effects but also transitory effects such as thermal induced refractive index changes. We measured 355 nm transmission at normal incidence (and 30° incidence for the gratings) of these samples, their diffraction efficiency (grating samples only) at 355 nm, and their Fresnel reflection coefficients. We also measured the spectral transmission from 200 to 2600 nm of many samples before and after radiation exposure. Only those samples that used the UV grade fused silica had negligible darkening from exposure to gamma or proton radiation. From this we conclude that the epoxy and the DCG film are immeasurably affected by particle radiation. This may be due in large part to their thickness of only several microns. We do not expect large doses of shortwave UV radiation in the earth observing configuration for contemplated missions, and what amount is present is readily filtered out with an appropriate long-pass optical coating on the first surface of the ShADOE. The ShADOE master HOE is exposed at 355 nm to form the hologram. Most of the dye is removed during processing, but a residual absorption of about 8-10% in a 6 μm thick film remains after processing. We are evaluating what effect this may have on using the HOE as part of the transmitter optics, and what long term effect there might be from ambient and stray light.

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