Shared Aperture Diffractive Optical Element (ShADOE) Multiplexed Telescope

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Abstract -**The Shared Aperture Diffractive Optical Element (ShADOE) is an Advanced Component Technology program to demonstrate the feasibility of combining several holographic optical elements (HOEs) into a single optic for use as the primary optic of a scanning telescope. The HOEs diffract the beam at a fixed elevation angle, nominally 30 to 55 degrees, but with the azimuthal pointing direction of each individual HOE rotated by 30 or more degrees with respect to the others. Several HOEs are multiplexed into a single ShADOE. This construction is equivalent to having multiple telescope primary lenses all in one optic. This technology allows us to do the equivalent of scanning a large aperture telescope between widely separated fields of view without physically moving or scanning the primary optic. A powered Holographic Corrector Plate is used to collimate the output and correct for wavefront errors induced by the primary HOE, forming an afocal, near diffraction limited holographic telescope. We have observed wavefront errors of only a few times the diffraction limit at 355 nm with a 40-cm diameter SHADOE system.**

I. INTRODUCTION

Lightweight scanning lidar telescope technology will enable the remote sensing of a number of Earth Science parameters from space, particularly atmospheric wind profiles, topographic mapping including land and ice sheet elevations, fresh water resources, land surface vegetation and the 3-D atmospheric radiation environment characterized by clouds and aerosols. Many of these measurements will benefit from cross-track scanning over large angles, as much as +-45 degrees off-nadir. For some applications it is essential; for example, atmospheric wind profiling and 3-D mapping of cloud and aerosol fields. But current technologies are deemed too heavy and costly.

Large Aperture Telescopes are used in atmospheric lidar measurements to increase the signal to noise (S/N), limited due to the small number of backscattered laser photons that make their way from the scattering volume back to the lidar receiver. Increasing the laser output power or the area of the receiver's collecting aperture are the easiest ways to increase the signal. Due to spacecraft limitations of available power for the laser transmitter, larger aperture receivers are more cost effective at increasing S/N than are larger lasers. Many applications also need to scan over wide angles to achieve cross-track coverage or to obtain multiple views into each target volume. For lidar measurements in the daytime, 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 (~ 1m), narrow FOV telescope over large angles requires a large scanning mirror in front of the receiver telescope, or the capability to point the entire telescope. Either of these methods entails the use of large bearings, motors, gearing and their associated electronics. Spaceborne instruments also need reaction wheels to counter the torque applied to the spacecraft by these actions. The Doppler wind lidar application needs a step-and-stare scanning approach that exacerbates the problems of instrument power, momentum compensation, torque, and vibration cancellation.

NASA recently developed lidars using a single rotating Holographic Optical Element (HOE) to produce a conical scanning telescope in a compact package[1,2]. Having a FOV that is ~45° from the normal to the optic, rotating the HOE in its own plane produces a conical scan. In that work, we developed a number of HOEs for use in various lidar applications and wavelengths ranging from 355 nm to 1064 nm [3]. Two of these of were incorporated into operating lidar systems. The 532 nm PHASERS lidar [4] and the 1064 nm HARLIE lidar [5] demonstrated that volume phase holograms can serve as compact conical scanning telescopes for lidar applications. Although smaller than a conventional scanning telescope of the same effective aperture, PHASERS and HARLIE still contain large motors and bearings in order to rotate a large optic.

In order to further reduce the weight and power requirements on spaceborne scanning lidars, we are developing the Shared Aperture Diffractive Optical Element (ShADOE) system of multiplexed telescopes. The ShADOE makes use of several holographic or diffractive optical elements, HOEs or DOEs. Our objective is to eliminate the motion of all the large components in the system. This can be achieved by superimposing multiple copies of an HOE into a single holographic film, each one being the primary optic for an independent telescope, each pointing in a different direction [6]. Referring to Fig. 1, the light from a given FOV is incident on the ShADOE at 40 degrees, and the diffracted light is focused off normal at an angle of 30 degrees. The optical path is then folded back toward the center normal the ShADOE primary with a flat mirror. This light is then diffracted by a second HOE that collimates the light and directs it toward the central axis of the system of telescopes. The light then passes through a Holographic Corrector Plate (HCP) and a pair of Risley prisms to a rotating 45° flat mirror. This mirror rotates on a shaft that lies on the central axis, normal to the surface of the HOE. It directs the light to a lens that focuses it into an optical fiber.

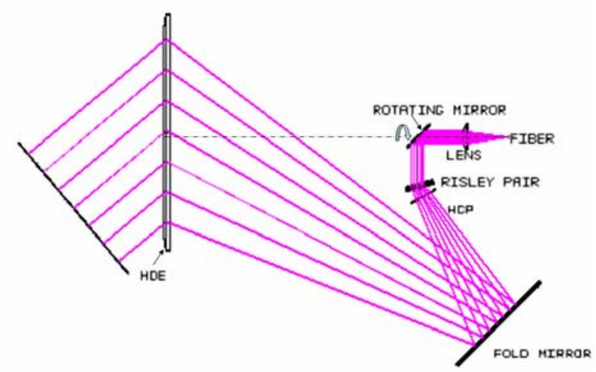

Figure 1. Optical layout for any one of several HOE telescopes within the ShADOE system. The primary optic contains several multiplexed HOEs. The elements along the center normal to the HOE are common elements that all the telescopes share.

Multiple copies of this HOE are exposed into a single film as follows. First, a master HOE of the desired geometry and wavelength is generated. The master is then copied into a fresh holographic film using a contact copy process, analogous to making a photographic proof from a film negative. The master is then rotated with respect to the copy film and another copy exposed. This is repeated until the desired number of HOEs are exposed into the film. Several HOEs can be placed into a single ShADOE without degrading their efficiency and angular resolution. A limit on the number of exposures is determined by several parameters including film thickness, index modulation, and tolerance to cross-talk losses. A practical number for UV lidar applications is currently no more than 6.

A breadboard ShADOE system of four telescopes is being designed. Four sets of optics are arranged radially on the opposite side of the ShADOE from the FOVs, as illustrated in fig. 2. The telescopes can be "addressed" sequentially using the small rotating mirror located on the central axis. This eliminates the need for large ring bearings and motors to scan the primary optic, as well as the associated momentum compensating reaction wheels. It will also enable switching from one FOV to the next in sub-second time intervals. 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.

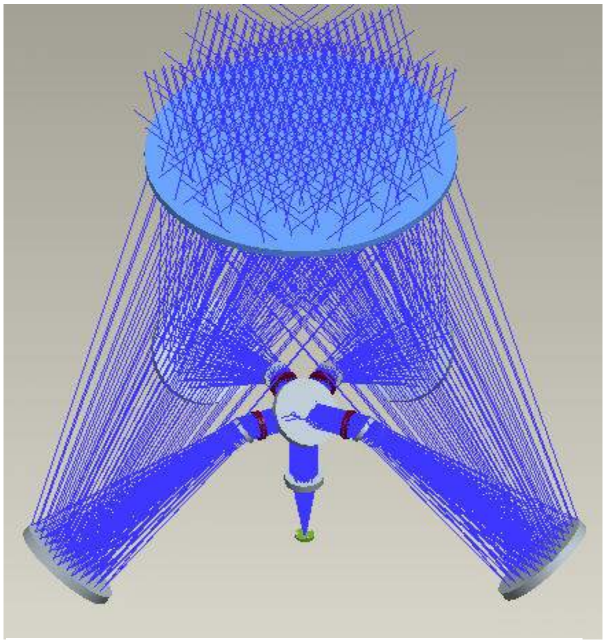

Figure 2. Optical ray tracing for a ShADOE system of 4 telescopes.

2. WAVEFRONT ERROR CORRECTION

In order to do heterodyne detection of 2054 nm radiation, one’s receiver telescope must have a diffraction limited FOV, so that uniformly flat wavefronts are presented to the detector to mix with light from the local laser oscillator. Current HOE technologies do not yield a diffraction limited focal spot. However, a number of groups have been developing techniques to compensate for wavefront phase errors (aberrations) present in low cost optics in general, and these can be applied to the HOEs as well.

One such technique is to use a holographic corrector plate [7, 8]. Made using the aberrated light from the HOE primary optic that it is going to correct, it contains the conjugate of those aberrations and will correct for them when used in the optical system at the location and orientation relative to the primary HOE it was exposed with. This corrector plate also serves to collimate the light and help fold the optical path. An HCP made for use with a 40-cm f/2.5 primary HOE was made and tested. We focused the collimated beam from the HCP onto a CCD camera with a 600 mm focal length lens. The best image of this focal spot is shown in Fig. 3. The camera pixel spacing is 7 microns. The resulting angular resolution of the HOE/HCP telescope

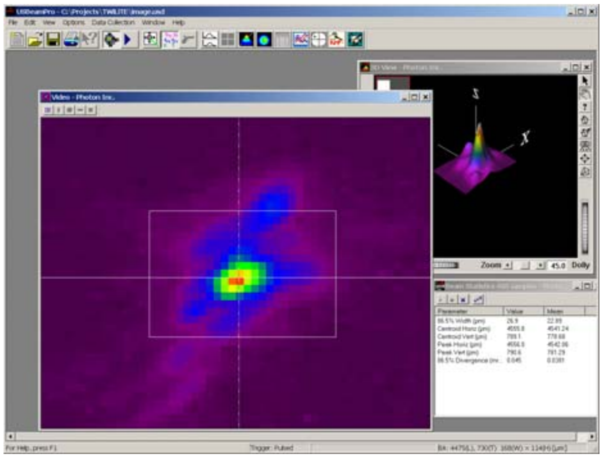

Figure 3. Focal spot from a 600 mm lens illuminated with the collimated output from an HOE/HCP telescope. The camera pixels are spaced on 7-microns centers, and the angular resolution is ~ 40 microradians when the encircled energy is $1/e^2$ of the total.

is ~40 microradians, or ~ 3x the diffraction limit. This is a significant improvement over uncorrected HOE systems, and can be improved further by using polished glass instead of float glass for the HCP substrate and cover. We are also investigating the use of refractive corrections that can be polished into either the HOE or the HCP substrates.

3. OPERATIONAL CONCEPT

In order to retrieve a horizontal wind vector from line-of-sight Doppler measurements, observations must be made along two approximately orthogonal lines-of-sight into the same atmospheric volume. Through modeling and system design studies, a consensus has been reached in the Wind Lidar working group (http://space.hsv.usra.edu/LWG/Index.html) that a step-and-stare approach to scanning is preferred over continuous scanning. One reason for this is to avoid having to perform lag-angle compensation and (for heterodyne lidar) wavefront tilt compensation. These occur because the pointing angle of the telescope changes during the time it takes a laser light pulse to travel from the satellite to Earth and back. The second reason to avoid continuous-motion scanning is to keep consecutive laser shots clustered into a smaller atmospheric volume so as to minimize the measurement variance associated with atmospheric variability over the measurement integration time. Several tracks are desired, spaced more or less equally across a ~70-90 degree swath across the satellite's nadir ground track. The FOV will then be arranged in pairs to provide two perspectives into each of three measurement ground tracks. Fig. 4 illustrates the satellite and measurement ground tracks and the spacecraft location for each of the four sequential line-of-sight measurements of our breadboard design discussed above. The FOV are all oriented 40° off nadir, and the satellite is in a 400 km orbit. This particular operational concept provides 25 second line-of-sight measurements spaced every 800 km along two atmospheric tracks.

4. TECHNOLOGY COMPARISON

A recent technology assessment at NASA's Goddard Space Flight Center (GSFC) estimated that the mass of a 1.25-m diameter silicon carbide (SiC) scanning telescope would be 142 kg. A 1.5-meter rotating HOE having an equivalent collecting area would have 71 kg. Both of these approaches also require large momentum compensation systems that add another 50 kg. A ShADOE telescope system is expected to save about another factor of two in mass over the rotating HOE telescope system. In addition, the average power requirement to rotate a 1.5 m HOE in a step and stare scan pattern is 65 W, with peak powers of 1053 watts during the acceleration and deceleration phases of the scan. This requires a power supply with ~10 kg of mass. The ShADOE would eliminate both this mass and the power required for scanning the large optic.

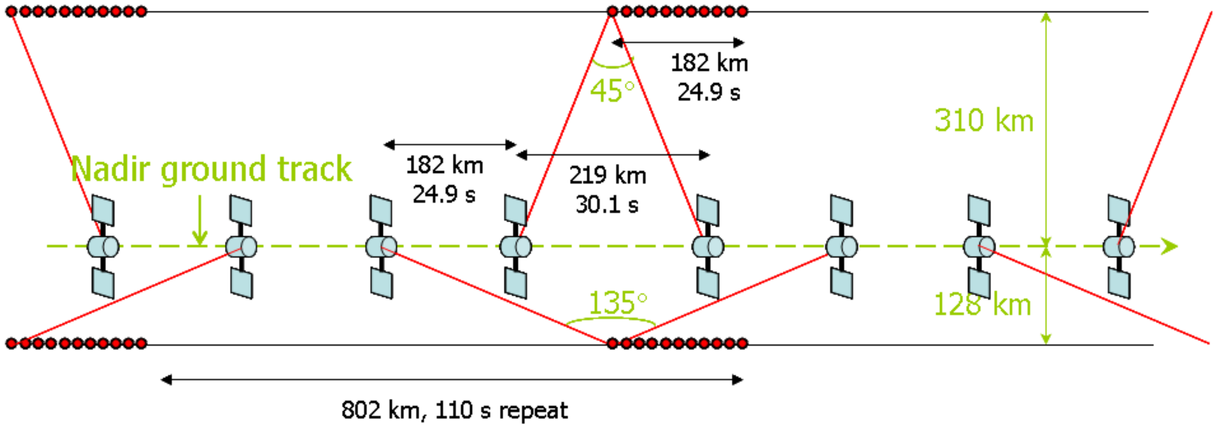

Figure 4. Operational concept for the 4-telescope ShADOE system. The telescopes are used in pairs, with each pair making fore and aft views into a single track in the atmosphere.

Table 1 lists the mass and power estimates for large aperture scanning telescopes, comparing a conventional but state of the art light-weighted SiC telescope on a rotation mount, a rotating HOE telescope and a 6-telescope ShADOE system. All three have the same effective 1.23-m^2 collecting area and comparable throughput. The SiC and rotating HOE estimates were made as part of a Doppler lidar technology assessment at GSFC in 2001. The ShADOE mass estimate and power estimates were calculated using the same scaling laws used in the 2001 assessment.

TABLE 1.
Mass and Power comparisons. (Source - GSFC Doppler Lidar Technology assessment, 2001.)

System	Rotating SiC 1.25 m diam. reflective telescope	Rotating 1.5 m diam. single HOE (note 4)	6-Plex ShADOE (1.5 m diam.)
Optics+structure	42 kg	42 kg	60 kg
Scanning mechanism (note 1)	100 kg	30 kg	0 kg
Scan motor power supply (note 2)	20 kg /130 W	10 kg / 65 W	1 kg / 10 W
Momentum Compensation	100 kg / 130 W	50 kg / 65 W	1 kg / 10 W
Power System mass (note 3)	24 kg	12 kg	2 kg
Radiator mass (note 3)	16 kg	8 kg	1 kg
Total Mass	302 kg	152 kg	65 kg
Total Avg. Power	260 W	130 W	20 W

Notes:
1 – Includes scan motor, bearing, mount.
2 - Does not include solar array or batteries.
3 - Scaled from ISAL rotating HOE analysis: (458 kg * 130 W / 4913 W) total weight of power system times portion of total power attributed to scanner + momentum compensation.
4 - Because the HOE's FOV is 45-degrees off normal, the effective collecting area is reduced by 30%, so a 1.5-m diameter HOE has the same effective collecting area as a 1.25-m diameter telescope.

7. REFERENCES

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