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 that will demonstrate the feasibility of combining several holographic optical elements (HOEs) in a single device 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. As many as six HOEs can be multiplexed into a single ShADOE. This construction is equivalent to having multiple telescope primary lenses all in one optic. Optically addressing each HOE in sequence is equivalent to scanning a large aperture telescope between widely separated fields of view without moving its components. The ShADOE telescope will therefore reduce the instrument mass by 4.5 and power by 13 when compared to light-weighted conventionally scanned telescopes.

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.

Atmospheric lidar measurements are almost always signal to noise (S/N) limited due to the small number of backscattered laser photons that make their way from the target 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 often more cost effective at increasing S/N than are larger lasers. Many applications need to scan over wide angles to achieve rapid cross-track coverage or multiple views into each 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 (~ 1m), narrow FOV telescope over large angles in a short amount of time presents some major engineering challenges. Some applications like the Doppler wind lidar need step-and-stare scanning which exacerbates the problems of instrument power, momentum compensation, torque, and vibration cancellation.

II. Conventional Scanning Telescopes

A conventional lidar telescope makes up a substantial portion of the instrument's size and weight. Wide angle scanning typically requires a large scanning mirror in front of the receiver telescope, or pointing the entire telescope and aft optics assembly. 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 motions.

In general there are three ways of scanning a telescope with conventional optics. One technique is to mount the telescope and associated transceiver optics on a scanning mount. Such mounts are relatively large and expensive in order to accommodate the mass and inertia of the telescope assembly. Astronomical telescopes and tracking mounts are examples of this type. A second type of scanning telescope utilizes one or more large flat scanning optics in front of the telescope aperture. A somewhat larger flat mirror is required to scan an equivalent aperture size. This configuration is awkward and expensive to incorporate into airborne systems and would be prohibitively large and heavy for spaceborne use. Rotating polygon mirrors are sometimes used for rapid scanning in one axis, but these systems are limited in size to smaller apertures and are usually applied in terrain mapping or other hard-target lidars. Again, for space, this type of system would make inefficient use of available space and power for any spaceborne instrument. A more compact design uses a rotating refractive wedge instead of mirrors to generate a conical scan. However, the refractive wedge required for 45° off axis viewing would also be heavy and expensive to produce.

NASA has previously developed lidars using a single rotating Holographic Optical Element (HOE) to produce a conical scanning telescope in a compact package weighing about one-third that of similarly scanned conventional telescope systems [1,2]. The FOV is ~45° from the normal to the optic, and 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. Two of these of were incorporated into operating lidar systems. The 532 nm PHASERS lidar [3] and the 1064 nm HARLIE lidar [4] 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.

3. SHARED APERTURE DIFFRACTIVE OPTICAL ELEMENT MULTIPLEXED TELESCOPE

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 [5]. The light from each FOV is incident on the ShADOE at 40 degrees, and the diffracted light is focused off normal at an angle of 30 degrees. 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. Fig. 1 illustrates chief and marginal ray tracings for one HOE as an example. 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, similar 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. As many as six HOEs can be placed into a single ShADOE without noticeably degrading their efficiency and angular resolution.

The six foci from the HOEs are arranged radially on the opposite side of the ShADOE from the FOV, as illustrated in fig. 2. The telescopes can be "addressed" sequentially using a small rotating mirror or fiber switching device 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.

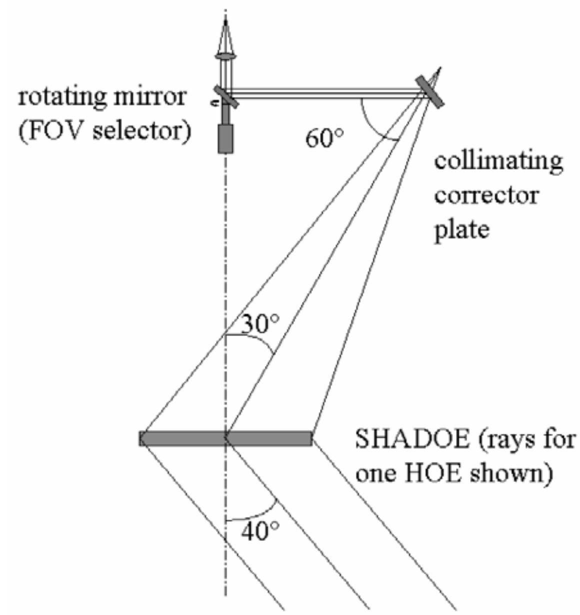

Fig. 1. Optical ray tracing for one HOE telescope within the ShADOE.

4. 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 present on 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 HOEs as well.

One such technique is to use a holographic corrector plate [6,7]. Made using the aberrated light from the HOE 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 may also serve to collimate the light and fold the optical path as shown in fig. 1.

5. 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

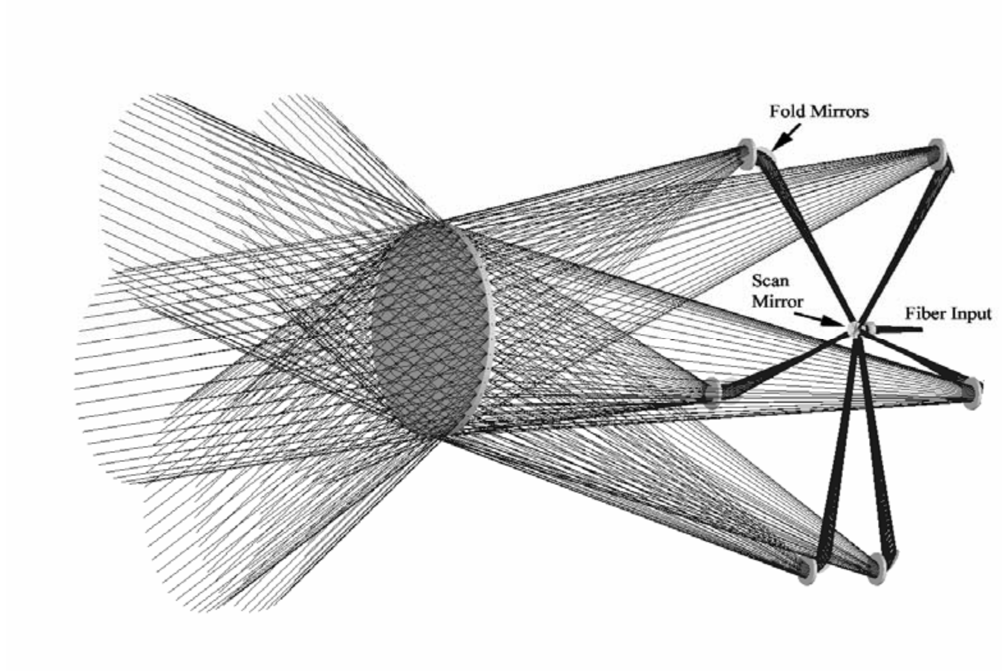

Fig. 2. Ray tracings for a ShADOE with six exposures

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. 3 illustrates the satellite and measurement ground tracks and the spacecraft location for each of the six sequential line-of-sight measurements. The FOV are all oriented 40° off nadir, and the satellite is in a 400 km orbit.

For UV wavelengths where the holographic film has some absorption, the laser beam will be transmitted and scanned via separate means located on one side of the ShADOE. For the 2-micron wavelength, the laser will be transmitted out through the ShADOE in a manner similar to the way it is now transmitted in a conventional transceiver telescope.

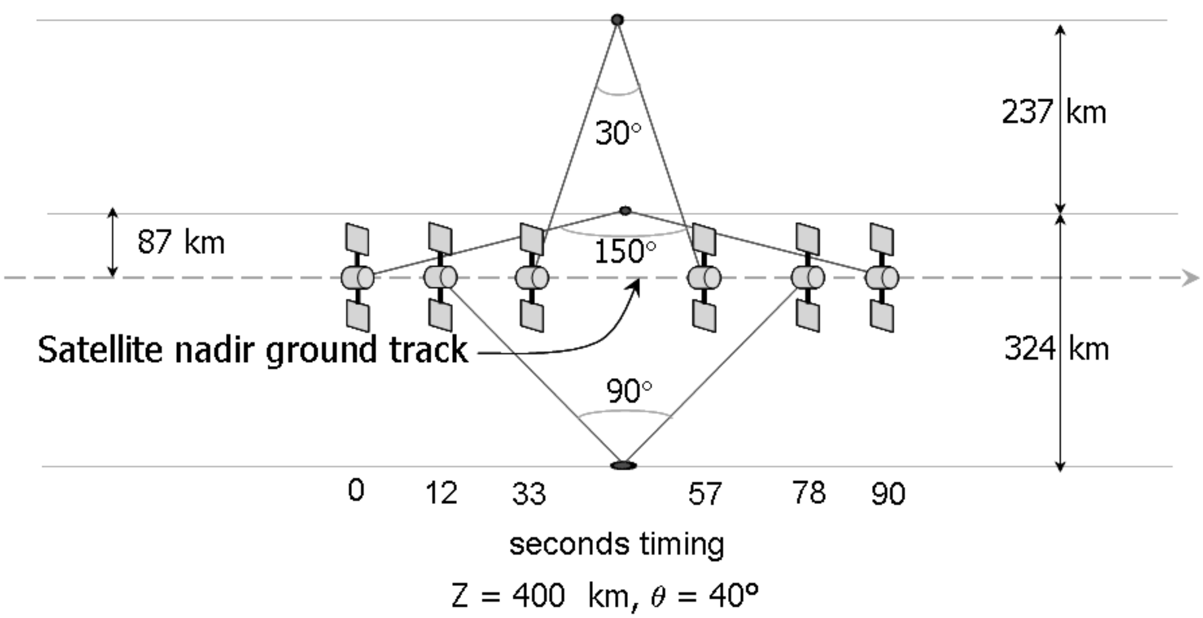

Fig. 3. Satellite and measurement ground tracks for a lidar orbiting at 400 km altitude with 6 lines-of-sight 40-deg off nadir. Each pair of HOEs provide two measurement perspectives into a measurement track, producing 3 tracks.

6. 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.

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

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

[1] Schwemmer, G., 1993: “Conically Scanned Holographic Lidar Telescope,” *United States Patent No. 5,255,065*, issued Oct. 19, 1993.

[2] Schwemmer, G. K. and T. Wilkerson, 1994: “Development of a holographic telescope for optical remote sensing,” in *Spin-Off Technologies from NASA for Commercial Sensors and Scientific Applications*, N. K. Minnifield, ed., Proc. SPIE, **2270,** 40-47.

[3] Guerra, D. V., A. D. Wooten, Jr., S. S. Chaudhuri, G. K. Schwemmer, and T. D. Wilkerson, 1999: "Prototype Holographic Atmospheric Scanner for Environmental Remote Sensing ", *J. Geophysical Research*, Vol. 104, No. D18, 22,287-22,292.

[4] Schwemmer, G. K., 1998: "Holographic Airborne Rotating Lidar Instrument Experiment," *19th International Laser Radar Conference*, NASA/CP-1998-207671/PT2, pp. 623-626, Annapolis, Maryland, 6-10 July 1998.

[5] Schwemmer, G., 2002, “Methods and Systems for Collecting Data from Multiple Fields of View,” *US Patent No. 6,479,808,* issued Nov. 12, 2002.

[6] Anderson, G., J. Munch, and P. Veitch, "Compact, Holographic Correction of Aberrated Telescopes," *Appl. Opt*. **36**, pp. 1427-1432, 1997.

[7] Anderson, G., and R. J. Knize, "Holographically Corrected Telescope for High-Bandwidth Optical Communications," *Appl. Opt.* **38**, pp. 6833-6835, 1999.