Holographic Correction and Phasing of Large Sparse-Array Telescopes

(as appears in Appl. Opt. Vol. 44, 1355-1359, March 2005)

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Abstract

We have constructed a 1m-diameter telescope using separate, low-quality spherical primary mirror segments. A single hologram of the mirrors is used to correct the random surface distortions as well as spherical aberration, while simultaneously phasing the individual apertures together. We present experimental results of the removal of thousands of waves error to produce a diffraction-limited instrument operating over a narrow bandwidth. This technique promises to have many benefits in future space-based telescopes for imaging, lidar and optical communications.

OCIS Codes: 110.6770, 090.0090, 110.5100, 350.6090, 090.1000, 350.1260

1. Introduction

Improving the resolution of space telescopes has required ever-increasing effective diameters. Current designs are concentrating on perfect mirror segments which are deployed and phased in space to act as a single large primary. These approaches may be feasible for diameters of up to ~6m, but new techniques will be required for further increases. One of the major problems is fabricating segments with low areal densities; providing rigidity and space worthiness while maintaining diffraction-limited performance. The other challenge is deploying then phasing the segments together to fractions of a wavelength without human intervention. While advances have been made in these areas, orders of magnitude increases in primary diameters can be achieved using low-quality optics and booms which are deployed from compact packages. These telescopes can then be corrected to diffraction-limited performance using small, inexpensive holograms, resulting in a high-resolution instrument operating over a narrow bandwidth. In this paper we will also demonstrate that the hologram can simultaneously provide phasing of segmented or sparsely-distributed apertures which should lead to increased flexibility in telescope design and missions.

2. Holographic Correction

The process of holographic correction is based on a technique introduced by Denisyuk[1-9], as shown in Figure 1. A plane wave of coherent light illuminates an aberrated primary which focuses the beam [Fig. 1(a)]. The light passes through a secondary optic which produces an image of the primary onto some holographic recording medium. A hologram is recorded between this aberrated beam and a diffraction-limited reference beam incident from an angle. On replay [Fig. 1(b)], light from a distant object is collected by the aberrated mirror, and passed through the secondary optic to reconstruct the reference beam. Any intensity modulation originally present is retained in the reconstructed beam, so an aberration-free image of the distant object can be formed.

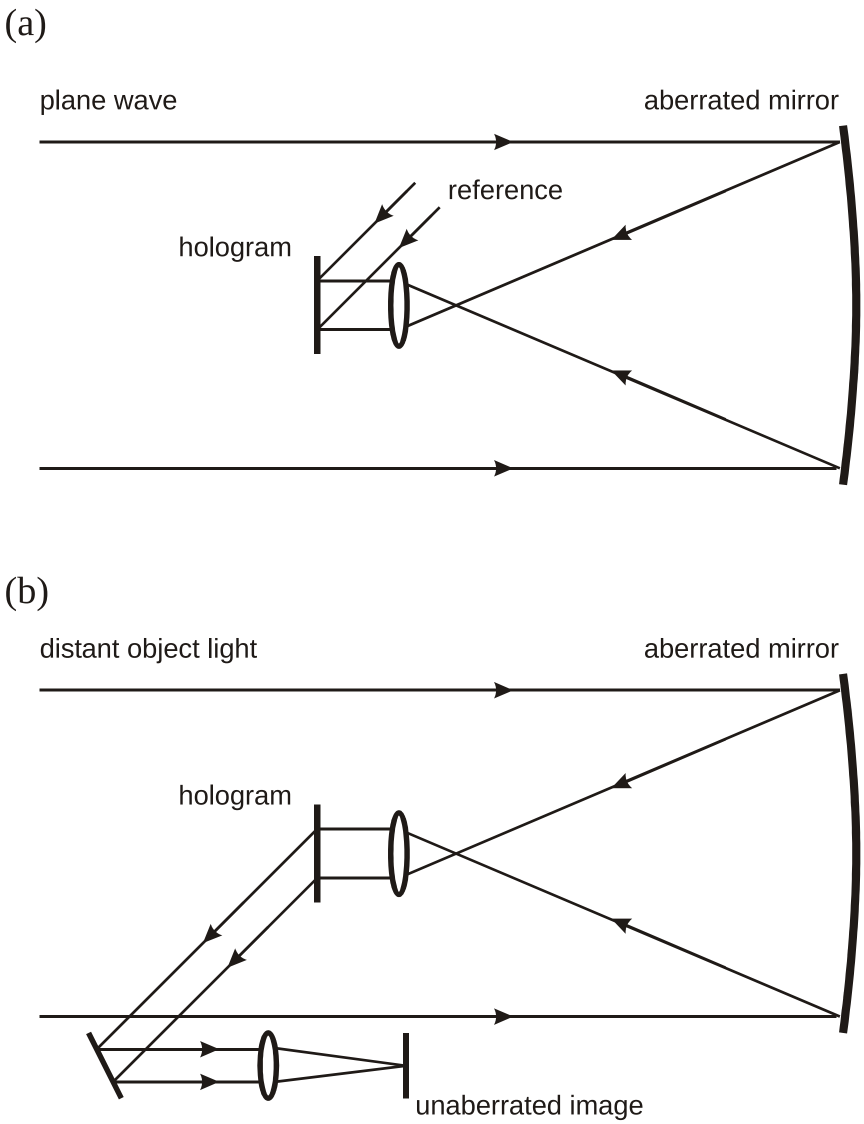


Fig. 1: (a) Recording. A plane wave incident on the aberrated mirror is focused and collected by a secondary. A hologram is recorded between this beam and a plane wave reference beam. (b) Replay. Distant light is focused by the aberrated mirror to reconstruct the reference beam. By focusing this diffraction-limited beam, an unaberrated image of the distant object can be formed.

Any conic may be used since any geometric aberrations are corrected in the same manner as if they were random surface deformations. Furthermore, a variety of individual apertures may be simultaneously corrected by a single hologram which will, in effect, produce a phased array. This approach should lead to improved flexibility and a wider range of applications for the technique. It is important to note that the hologram applies a phase correction to the wavefront, so infinite aberration correction is only possible at the recording wavelength (λ_{rec}). For practical purposes, however, there will be some useable bandwidth ($\Delta\lambda$), depending on the initial and final wavefront aberrations ($\phi_{initial}$ and ϕ_{final} respectively), given by:

$$\Delta\lambda = \lambda_{rec} \frac{\phi_{final}}{\phi_{initial}} \quad (1)$$

3. Experimental results

We constructed a telescope primary consisting of two identical spherical, graphite composite mirrors with square cross-sections (D = 0.6m, R = 2.2m). The mirrors, provided by Composite Mirror Applications (CMA), are produced by a replication process[10-12]. First a convex metal mandrel of the desired radius of curvature is polished to optical quality. A layer of epoxy resin is laid over the mandrel followed by several layers of graphite fiber composite with alternating ply orientations. Once the resin cures, the graphite composite sheet is released from the mandrel, with the front face having a smooth concave surface. A backing structure (such as a graphite composite honeycomb) can then be applied to this sheet for support and structural rigidity. The front surface is given a reflective aluminum coat in a similar manner to conventional glass mirrors. The mirrors had an areal density of just 10kg/m^2, and a surface good to ~50 waves. It is important to note that for our experiments we specifically chose two lower-quality mirrors made very early in the composite-replication developmental process. CMA has since improved their technique and is capable of producing similar mirrors to diffraction-limited performance.

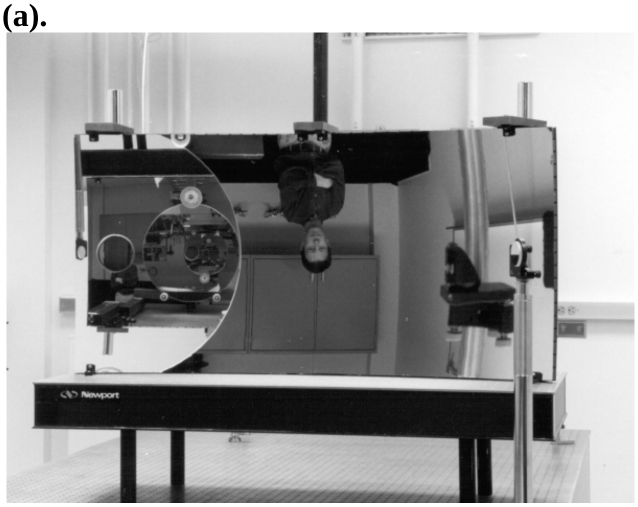
The mirrors were positioned next to each other to form two segments which had to be simultaneously aberration corrected and phased [Fig. 2(a)]. We used a correction set-up similar to that shown in Figure 1, with a plane wave produced by a high quality parabolic collimator (D = 983mm, f = 2.375m, 0.75λ rms). A secondary camera lens (f = 50mm, f/1.2) was used to produce the image hologram shown in Fig. 2(b). Note that the two mirrors were rigidly attached to the table, but no attempt was made to negate the relative piston or tilts. Furthermore, although the mirrors had a separation of just 1mm, this was simply to maximize the aperture tested by our collimator, and could, in principle, be as large as desired, limited only by the speed of the secondary imaging optic. The two aberrated mirrors formed an overall rectangular aperture 1.2m x 0.6m which was too large to be completely illuminated by the collimator. As a result the correction was limited to 0.983m in the horizontal dimension, and produces the distinctive aperture function as shown in Fig. 2(b).

A hologram was recorded between the aberrated beam from the primary and a plane wave reference beam incident on the hologram from an angle. Phase holograms were recorded on bleached Agfa 8E56 silver halide plate film using a frequency-doubled Nd:YAG laser (λ = 532nm). The diffraction efficiencies were typically ~20-50% which are lower than achieved in previous experiments[6,7] due to the abnormally large angle (of 43^o) between the recording beams required to avoid clipping of the reference beam by the secondary optic. Note that the coherence length of the laser must be larger than the size of the aberration for the best correction fidelity. In our case, our laser had a coherence length several orders of magnitude larger than required.

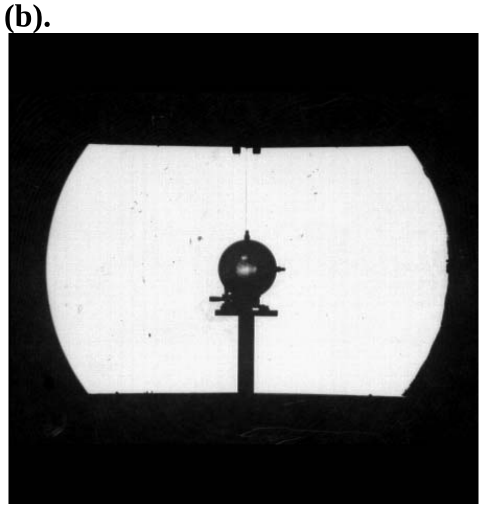
Due to the large amount of spherical aberration, a “before” interferogram could not be presented in the infinite-conjugate arrangement. Fig. 4(c), however, shows the random aberrations present in one of the mirrors in the one-to-one configuration (illumination from the center of curvature). Obviously this error (~50λ) is minor in comparison to the 2770 waves of spherical aberration which is present in the infinite-conjugate configuration, but is corrected nonetheless. On reconstruction, an interference pattern was constructed between the reconstructed beam and a diffraction-limited plane wave [Fig. 4(d)]. The interferogram indicates less than λ/4 residual wavefront error, with the residual being due to air currents present in the large test volume.

The imaging fidelity of the corrected telescope was tested by focusing the reconstructed beam. The uncorrected “focal spot” of the twin mirrors is shown in Fig. 2(e), where the effect of the 2770 waves spherical aberration is clearly evident. On reconstruction the corrected beam was focused with a 500mm focal length achromat to produce the 17.5μm x 17μm focal spot shown magnified in Fig. 2(f). Next, the spatial filter at the focus of the collimator was replaced with a USAF 1951 resolution test target. The illuminating laser beam was passed through a rotating diffuser to disturb the spatial coherence of the beam and remove speckle from the image. The uncorrected image formed at the focus of the two mirrors is shown in Fig. 2(g), with the largest bars on the left (Column 2 in the test target) barely resolvable. The corrected image, shown in Fig. 2(h), is shown to a different scale and should thus be compared to the central portion of Fig. 2(g). It is important to note that much of the blurring towards the edges of this image is actually due to the effect of off-axis aberrations from the limited field of view of the collimator. Magnification of the image shows that the vertical bars are resolved beyond Column 8, Element 6 (456 line pairs per mm) but reach limit of 323 lppmm in the horizontal. The expected limits from diffraction theory are 638 lppmm and 395 lppmm respectively. The slightly lower than expected resolution is believed to be due to the air turbulence and vibrations generated by the rotating diffuser.

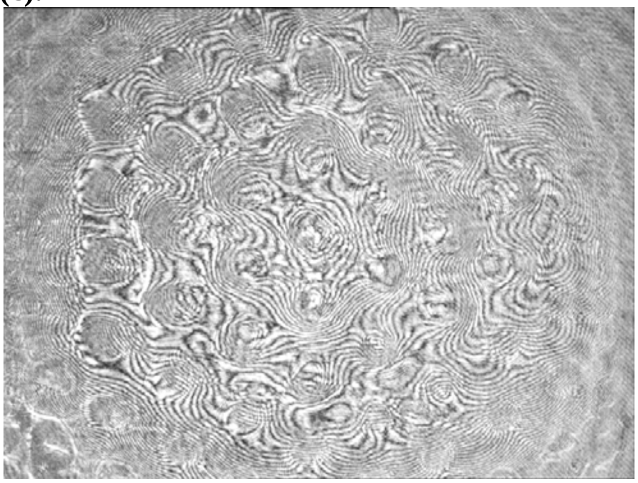
(a).



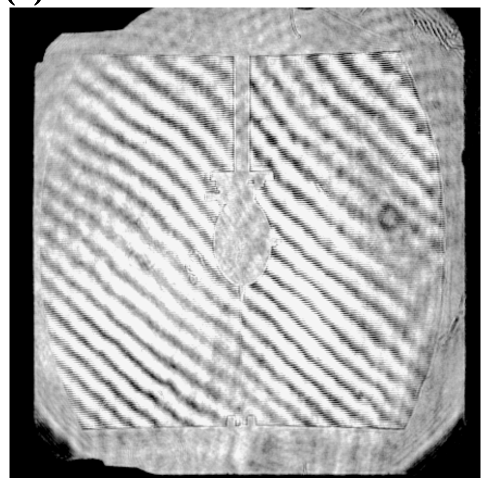
(b).



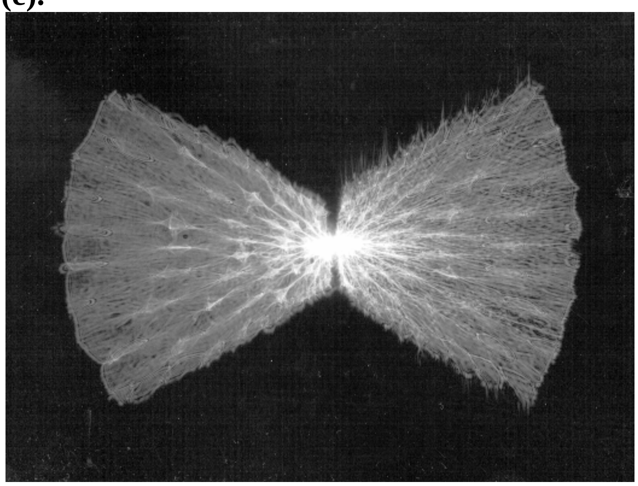
(c).



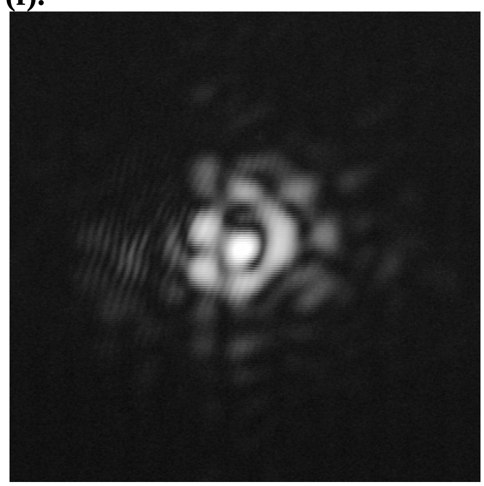
(d).



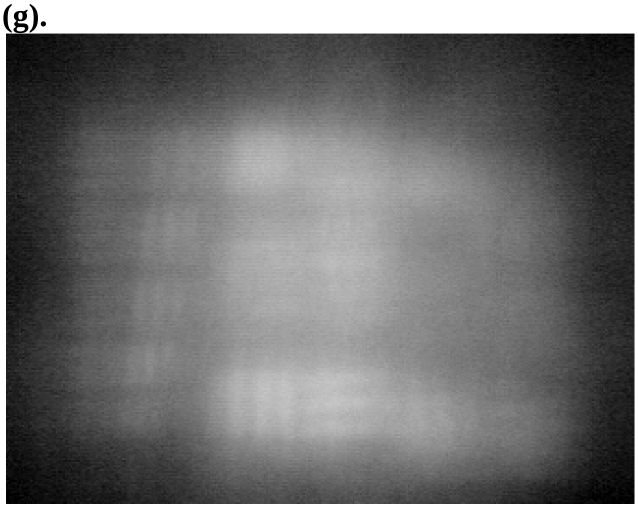
(e).



(f).



(g).



(h).

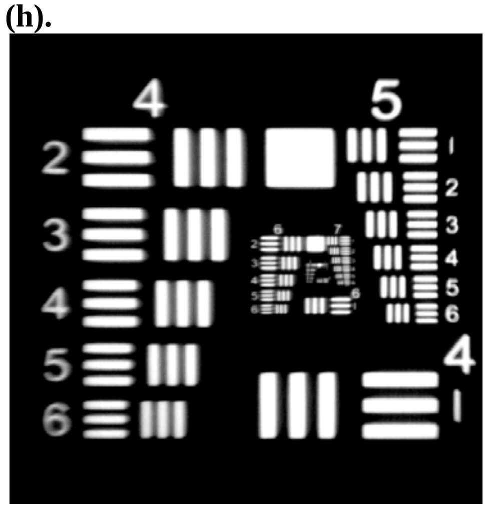


Fig. 2: (a) The twin graphite composite mirrors. Reflected in the mirrors are the collimator (left) and the author. (b) A contact print of the image the illuminated aperture

(0.983m x 0.6m) at the plane of the hologram having dimensions 49mm x 30mm. (c) An interferogram of a single aberrated mirror from the center of curvature. (d) An interferogram of the corrected wavefront. (e) The paraxial focus of the twin mirrors (26.6 x 16.5mm). (f) The corrected focus. (g) An image of a USAF 1951 resolution test target at the focus of the twin mirrors, with the largest bars on the left being those of Column 2. (h) An image of the resolution target after correction. Note the contrast in images (g) and (h) were increased slightly for clarity.

4. Conclusion

A new type of holographically corrected sparse-array telescope has been presented. An experimental demonstration involving two lightweight, carbon composite graphite mirrors was performed. Correction of over 2800 waves spherical aberration and random surface aberration was accomplished, while simultaneously phasing the separated mirror segments. With sparse-array concepts increasingly gaining attention as the next-generation imaging systems in space[13, 14], the process of holographic aberration correction detailed in this paper should lead to the possibility of creating10-20m space telescopes using existing manufacturing methods and launch platforms.

Acknowledgements

We would like to acknowledge the support of this research by the US Air Force Office of Scientific Research. We would also like to thank Robert Romeo of Composite Mirror Applications his help in providing mirrors used in these experiments.

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