Deployable Asymmetric Space Telescope

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Abstract

We vary the shapes of the sub-apertures both in aperture masking and for segmented space telescopes achieving diffraction limited resolution and uniform spatial frequency coverage (MTF). Instead of circular and hexagonal segments, it is possible to use other shapes such as ellipses or ovoids. Compared to polygons, ellipses reduce diffraction spikes in the point spread function (PSF). The ratios of the major and minor axes, and different rotation angles between each segment, are selected for optimum imaging. In addition all alignment and phasing are performed using only the focal plane images, and without auxiliary sensors and feedback gauges. This procedure allows identification in the focal plane for tip-tilt measurement. In the pupil auto-correlation (*u*-*v*) plane it also allows the unique separation of sub-aperture pairs for piston measurements. Optimisation of orientations lead to approximate values of 67º, 84º, 113º and 96º between segments, over a wide range of ellipticity values. Experimental demonstration by our lab model also verified our procedures.

Introduction

- Ground and space telescope are constrained in volume and mass.
- A solution in both cases are telescopes made up from thinner mirror segments which combine to form a large aperture primary.
- Segmented telescopes keep their sectors very close to each other, avoiding background radiation from behind the gaps while maximizing the collection area.
- On the other extreme, interferometers gain in resolution by increasing the size of the aperture and by making it sparse, at the price of signal lost between the elements.
- The sparse segments cannot be measured with an aperture WFS, because of the gaps.
- Instead, we use a principle from stellar interferometry to uniquely identify and distinguish each pair of segments:
  - chosen base-lines (vectorial separations) must be identifiable or non-redundant[1].
  - the focal-plane fringes between every two segments in the aperture must be unique in order to identify them.
- These two segments contribute to two symmetric and distinct lobes (base-line) in the OTF or the, MTF.

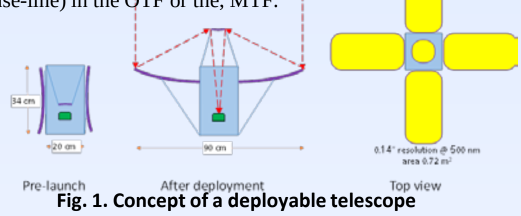
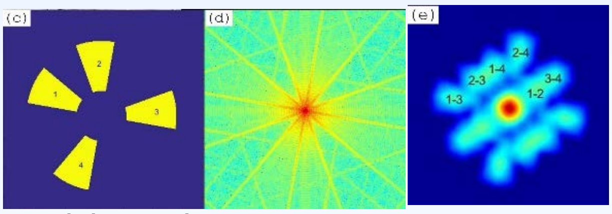


Fig. 1. Concept of a deployable telescope

Shape and Orientation Design

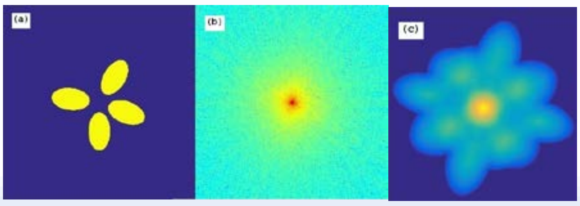
- Current research on sparse aperture imaging deals with identical and symmetrical segments, such as rectangles, circles and hexagons[2].
- **To break segment symmetry**, we devised an optimized search program, to rotate discrete sectors around a central hole, as shown in Fig. 2. Notice that now the base-lines 1-2 and 3-4 are distinct, as opposed to the concept in the Fig. 1.



Segmented telescope pupil Log PSF Log MTF

Fig. 2. Sector-shaped segments have spiky PSF, but pairs are identifiable

- **To minimize diffraction**, we tried different shapes of rounded segments, from circular to elliptical to egg shapes (ovoids)[3]. Ellipses are also advantageous from the manufacturing point of view, even more so if they are identical, and for mechanical and thermal stability of the telescope (Fig. 3). Each ellipse ε_i, of semi-axes *a* and *b*, is radially shifted by *ka*, then rotated about the telescope center by an angle α_i. The pupil function is the sum of ellipses, $P = \Sigma_{i=1,4}\varepsilon_i$, where the ellipses ε_i are pairwise disjoint. The MTF is $Q = P \otimes P$ with a standard deviation, $S = \mathrm{STD}(Q)$.



Elliptical segmented pupil Log PSF Log MTF

Fig. 3. Elliptical segments have smoother PSF; pairs are identifiable

- We optimized two cost functions[4], which yielded very similar results:
  - The first target criterion was the widest MTF (maximal MTF area *A*), namely with the broadest *u*-*v* (Fourier frequencies) coverage.
  - The second target criterion was the smoothest MTF (minimal STD *S*).
- The ellipticity had very little effect on the solutions.

Experiment

- We devised a laboratory experiment as a proof of concept for the theoretical modeling and analysis of the aperture design.
- The lab setup also served to test issues arising from the limits of mechanical actuators and optical quality of the segments.
  - During development of the experiment, we realized that the reflective surfaces near the boundaries the segment edges caused large surface errors, as a result of stress release in the glass during segmentation (Fig. 4, top).
  - To mitigate the boundary edge effects, we placed ovoid masks in front of them. This significantly reduced the spokes in the PSF, as well as created smoother MTF of the aperture (Fig. 4., bottom).

1. The system identified each elongated PSF, even when overlapped with other segments, using the broken rotational symmetry of the ovoid apertures.
2. A control matrix was measured from the influence of every motor on the position of the segment PSF.
3. The segments were moved to overlap all the PSFs at the focal point.
4. Finally, the segments were scanned to obtain white-light fringes between them (Fig. 5).

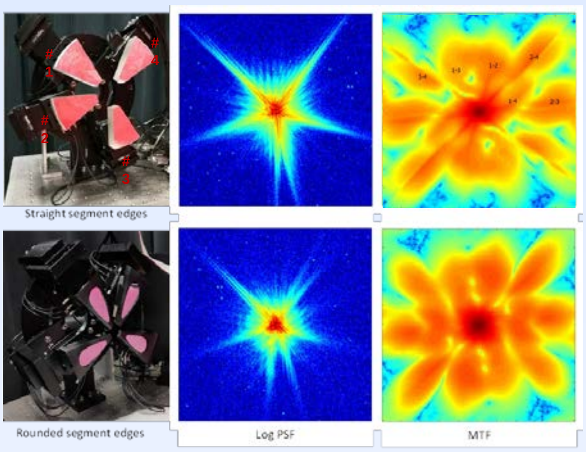
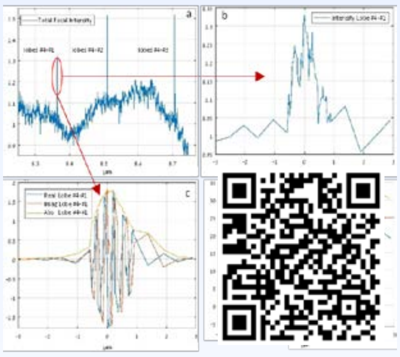


Fig. 4. Full and masked segments. Non-overlapping side-lobes in the MTF



Segment phasing scan movie

Fig. 5. Scanning one segment against the others produced fringes only on equal optical paths; compare with Fig 4.

Conclusions

We have demonstrated a novel method to shape, place and align sparse telescope segments. We have optimized and then used both the non-redundant shape of the aperture segments, and the non-redundant positioning of the segments, to tell them apart, and to identify the segment pairs, based on previous simulation. All of which is demonstrated with a simple laboratory model of a space telescope with no additional feedback hardware, and with minimal assumptions on mechanical or spectral precision.

References

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4. E. N. Ribak and B. M. Levine, Optics Continuum **1**, 1603-12 (2022)