Imaging GEOs with a Ground-Based Sparse Aperture Telescope Array

Michael Werth, David Gerwe, Steve Griffin, Brandoch Calef, Paul Idell
The Boeing Company

ABSTRACT

Ground-based imaging of GEO satellites is a major area of technical interest in the field of Space Situational Awareness. To date, proposed GEO imaging systems have estimated costs of a hundred million dollars or more and often require some form of active illumination, a large number of large apertures, or a space-based asset. We propose a novel imaging array configuration of small telescopes with a number of key technical innovations for a relatively low-cost amplitude interferometry approach to the passive GEO imaging problem.

1. INTRODUCTION

Active monitoring of satellites in Geosynchronous Earth Orbit (GEO) using passive ground-based telescopes is a key area of interest for the field of Space Situational Awareness (SSA). However, such monitoring rarely ever includes high-resolution imaging. The achievable resolution attainable by conventional imaging techniques using a single large circular aperture is limited by the Rayleigh Criterion:

$$sin\theta = 1.22\frac{\lambda}{D} \tag{1}$$

where λ is the imaging wavelength and D is the diameter of the collection aperture. The largest telescopes on Earth have a diameter of about 10 meters, which are able to achieve no more than 61 nrad of resolution when using an imaging wavelength of 500 nm. At a range of 36,000 km, this means being unable to resolve details on a GEO satellite smaller than 2.2 meters. Persistent imaging of half-meter details in the GEO belt would require building several telescopes around the world with aperture diameters on the scale of 40 meters, an impractically large primary mirror size to fabricate and support. Atmospheric turbulence further complicates the achievable resolution of such systems, driving down the feasibility of persistent imaging of GEOs using single large (> 10m) ground-based apertures.

A far more promising prospect for ground-based optical imaging of GEO satellites entails constructing an array of small (< 1m) telescopes that use interferometric methods to achieve resolution comparable to a large Rayleigh-limited aperture [1,2]. Such a system combines light from pairs of spatially-separated apertures in order partially sample the complex visibility of a target. The sampling of the frequency plane is determined by the observing geometry of the multiple telescopes, and the coverage can be improved by increasing the number of telescopes or by moving the telescopes and performing multiple measurements. The rotation of the Earth provides a natural means of extending the frequency coverage for imaging of astronomical targets, but for GEO targets we propose a system that consists of one or more centrally-supported telescope-hosting trusses. Each truss rotates between multiple azimuthal positions in order to maximize complex visibility coverage with a relatively small number of telescopes.

2. APERTURE ARRAY WITH SINGLE ROTATING TRUSS

A Large Modular Interferometric Telescope (LMIT) [1] incorporates a rotating truss into an otherwise-static array of small telescopes in order to improve the sampling of the complex visibility (u-v) plane. The systems described herein take inspiration from the Space Infrared Interferometric Telescope (SPIRIT) [3], which rotates a pair of telescopes connected by a rigid beam in order to produce sufficient u-v sampling to create high-resolution images. The truss in a LMIT may hold multiple telescopes, any of which may be translatable along the truss' radial axis. Rotating the truss between multiple azimuthal positions and moving the truss telescopes radially along the truss provides a greater amount of u-v coverage at the cost of additional overall collection time. Light transmission lines can be located separately from the truss, permitting mechanical isolation if necessary. Longer baselines can be achieved by adding ever-larger rings of static telescopes. Fig. 1 shows an example of a LMIT truss with two small siderostat telescopes.

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[1] Patent pending, application number 16/031298

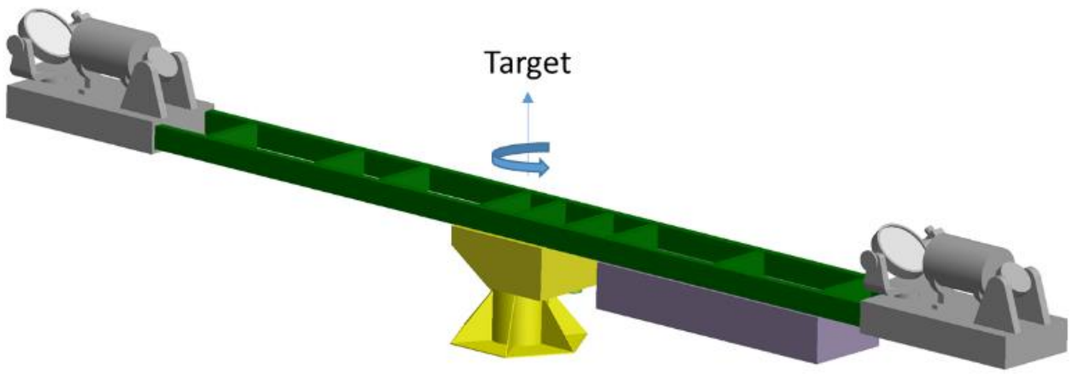


Fig. 1. Example of a LMIT truss with two siderostat telescopes and a beam combiner unit

Fig. 2 shows a pristine image target that is used to compare the potential image quality of the different single-truss LMIT systems described in this section. Fig. 3 shows a minimal configuration implementing three 0.5-meter telescopes, one of which is on an 8-meter truss. Fig. 4 shows the u-v coverage of this configuration when observing over the 500-900 nm waveband, including labels describing how the geometry corresponds to the u-v coverage, as well as the image obtained from taking the inverse Fourier transform of the u-v map. Fig. 5 and 6 similarly show the geometric configuration, u-v coverage, and image reconstruction for a single 8-meter truss holding two telescopes, one of which can move radially along the truss, and a ring of five additional telescopes at static positions. Fig. 7 and 8 show these results for the same kind of truss with an inner ring of four static telescopes and an outer ring of eight static telescopes. Note that sufficient u-v coverage is achieved without requires that light beams from all telescopes be combined with light beams from all other telescopes; for instance, in Fig. 7 and 8 light beams from the outer and inner ring telescopes are only combined with light beams from the truss telescopes.

Fig. 2. Pristine target image

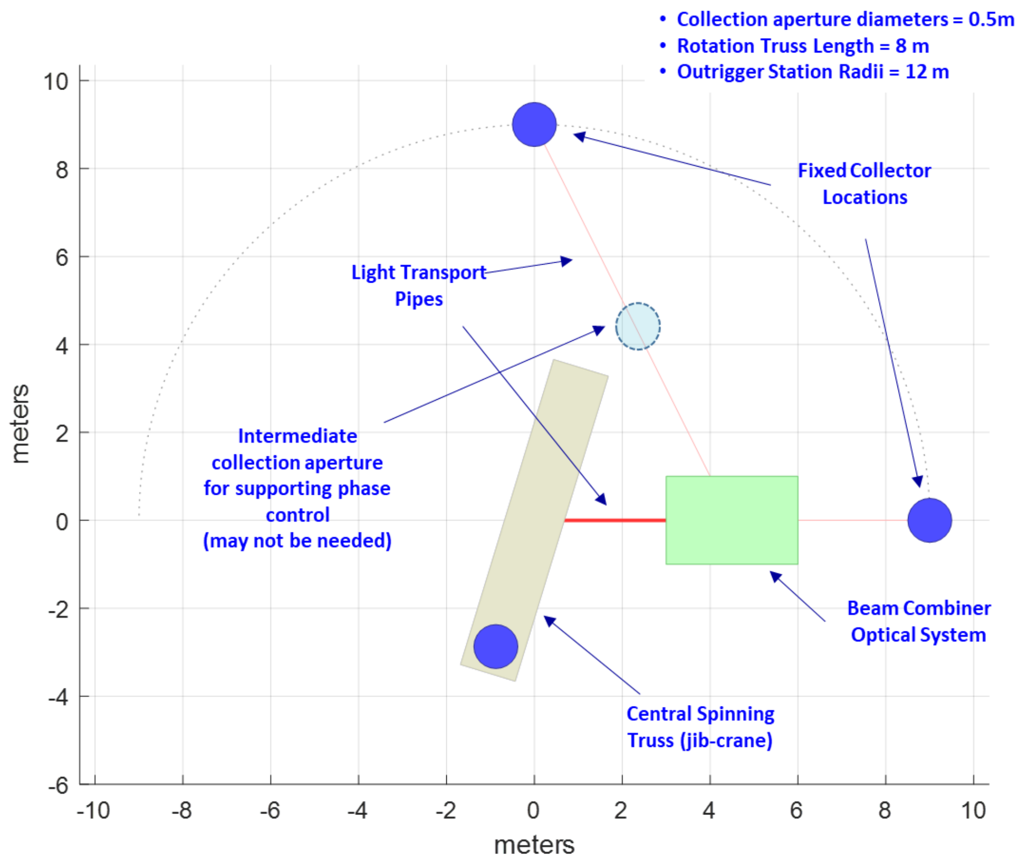
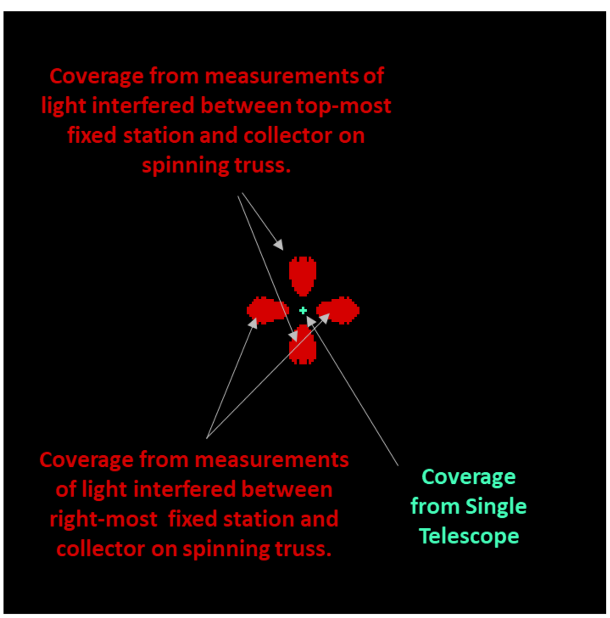


Fig. 3. Minimal-sized LMIT configuration: a rotating truss with one aperture and two static apertures



(a)

(b)

Fig. 4. (a) Frequency (u-v) coverage for smallest LMIT configuration, containing a single one-aperture truss and two static apertures, and (b) the resulting reconstructed image

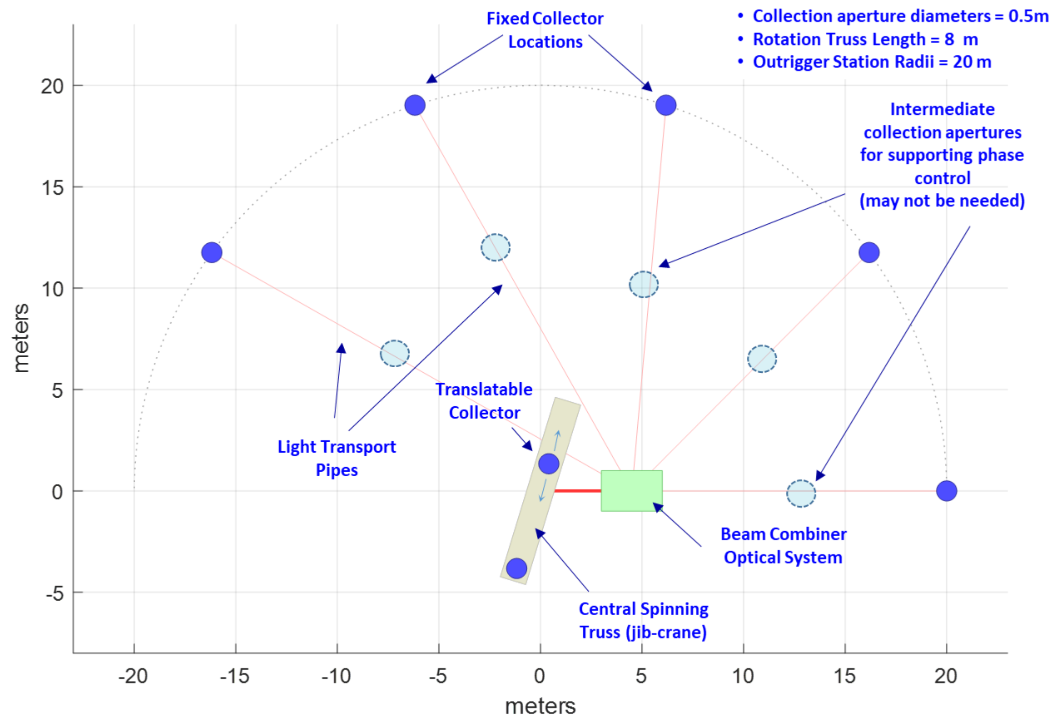
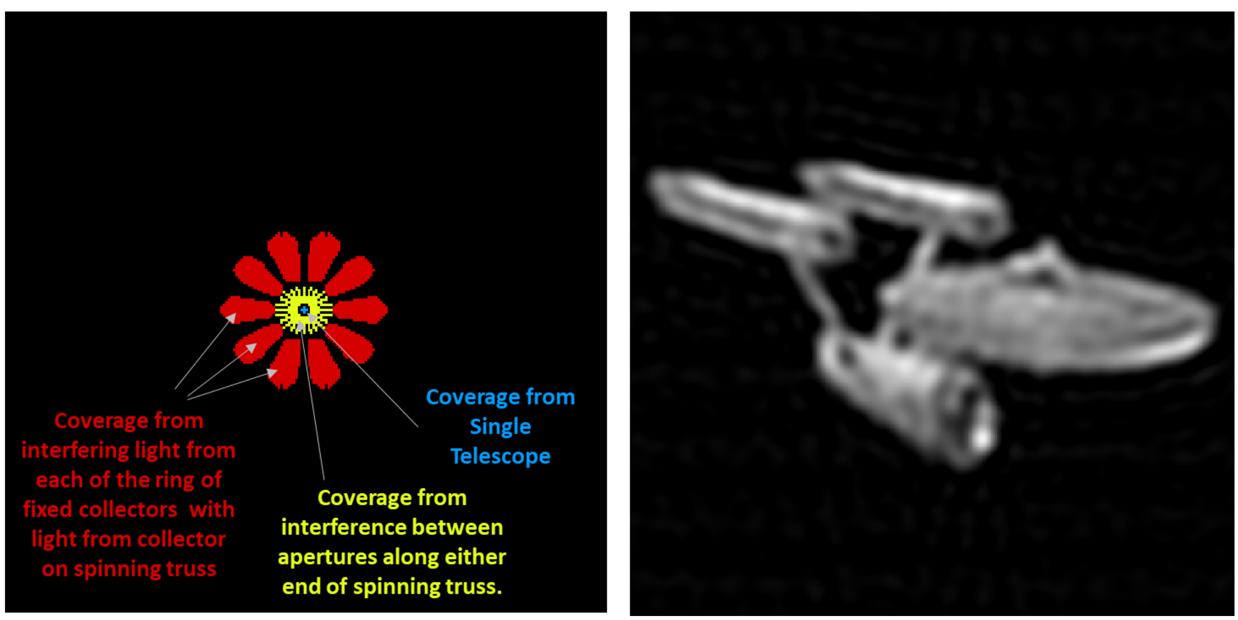


Fig. 5. Medium-sized LMIT configuration: five static apertures and a rotating truss containing two apertures, one of which can be translated along the truss



(a) (b)

Fig. 6. (a) Frequency (u-v) coverage for medium-sized LMIT configuration, consisting of a two-aperture truss with a single ring of five static apertures, and (b) the resulting reconstructed image

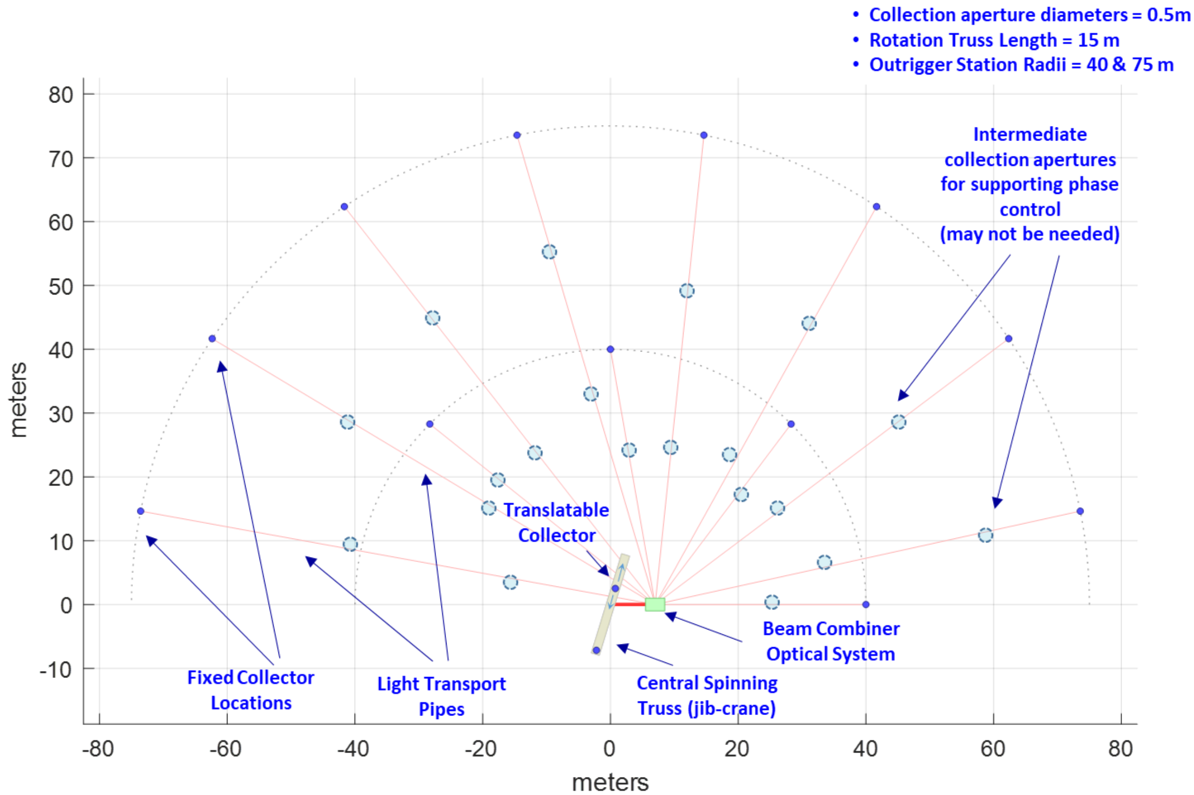
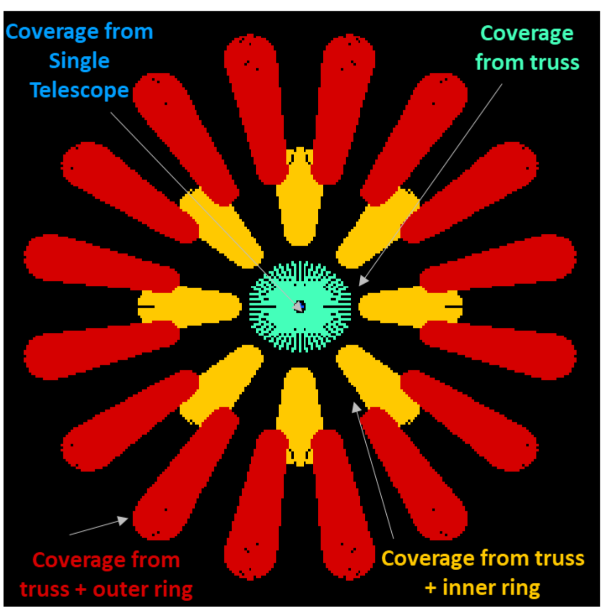
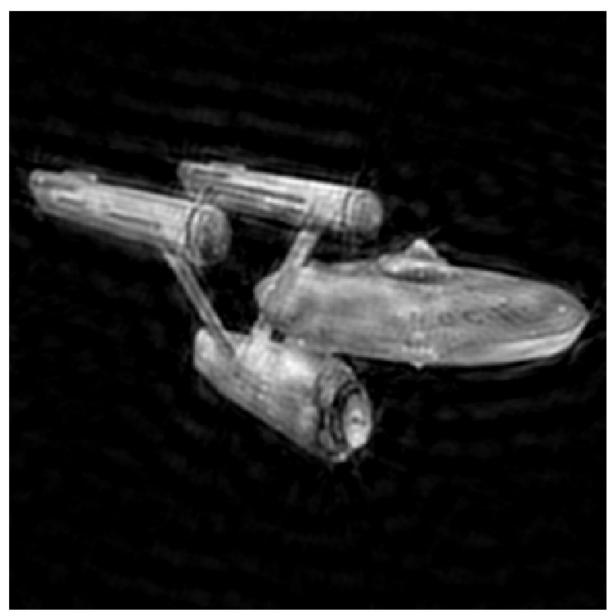


Fig. 7. Large-sized LMIT configuration: four inner-ring static apertures, eight outer-ring static apertures, and a rotating truss containing two apertures, one of which can be translated along the truss



(a)



(b)

Fig. 8. (a) Frequency (u-v) coverage for large-sized LMIT configuration, consisting of a two-aperture truss with an inner ring of four static apertures and an outer ring of eight static apertures, and (b) the resulting reconstructed image

3. APERTURE ARRAY WITH MULTIPLE TRUSS ASSEMBLIES

One could also achieve a large degree of u-v sampling with even fewer telescopes by configuring a LMIT with multiple truss assemblies. Fig. 9 shows a configuration with three 16-m truss assemblies and one 6-m truss assembly, each assembly holding two 0.5-meter siderostat telescopes. The larger assemblies (Assemblies A, B, and C) form a 120-degree ring around the smaller assembly (Assembly D), the center of each large assembly being 22 meters from the center of Assembly D. Figure 10 shows the u-v sampling provided by various apertures in the multi-truss LMIT over the 500-900 nm waveband. Figure 11 shows a spoke reference target and Figure 12 shows the resolved image produced by the multi-truss LMIT as well as the diffraction-limited image of a Rayleigh-limited filled aperture with diameter equal to the maximum baseline of the multi-truss LMIT (33 meters), demonstrating the comparable level of resolvable detail despite the LMIT system only sampling a subset of the u-v plane.

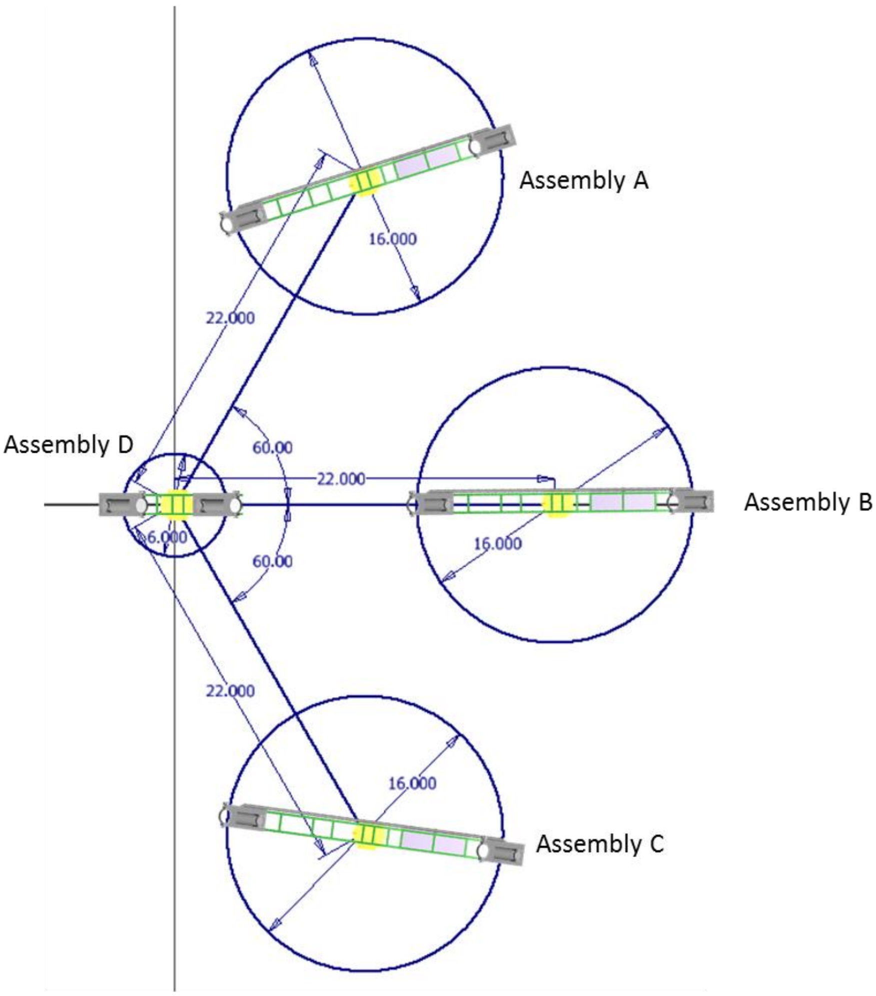


Fig. 9. LMIT configuration with multiple truss assemblies, labeled A-D, each truss hosting two telescopes that do not translate radially along the truss. The longest possible baseline in this configuration is 33 meters.

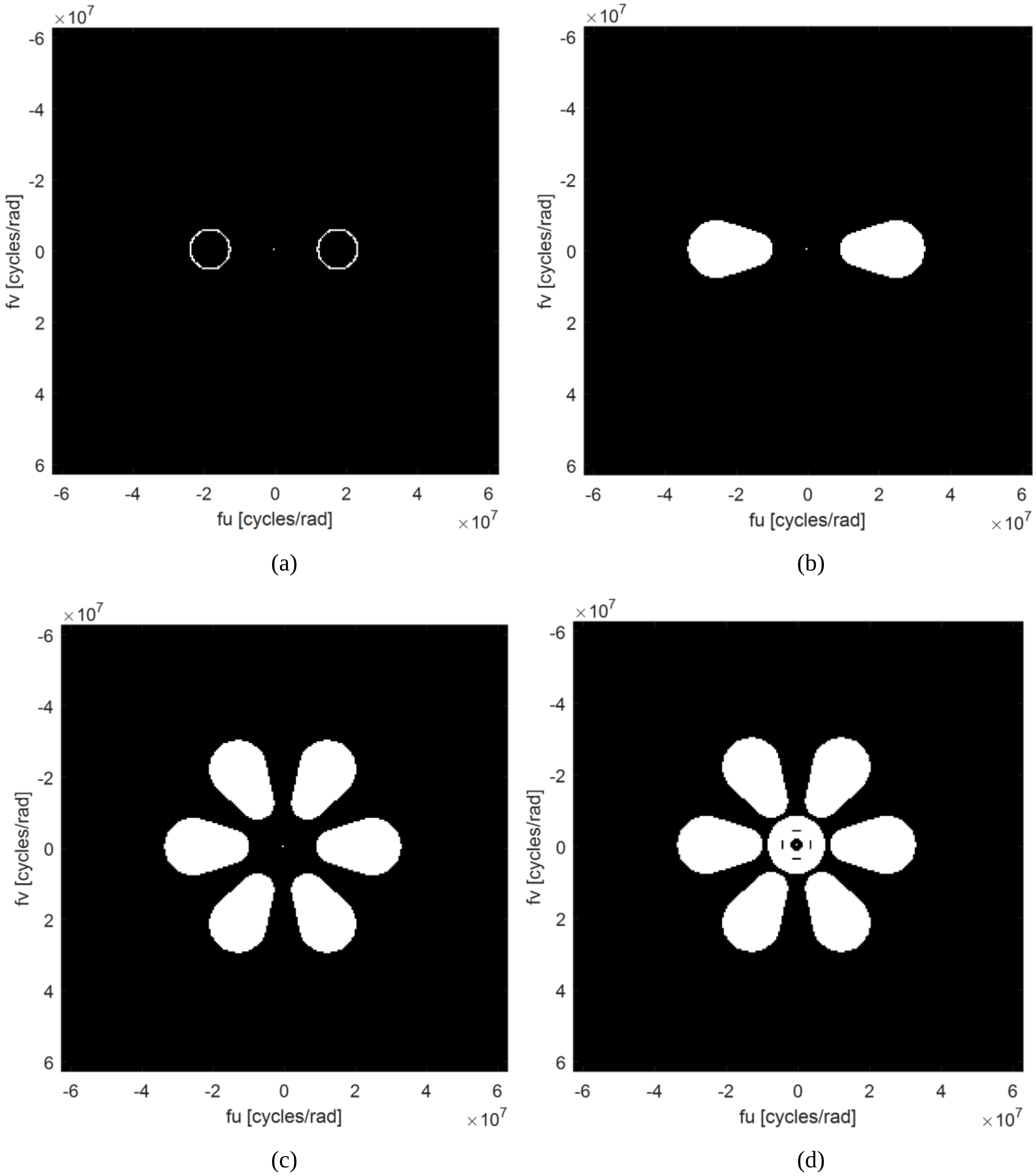


Fig. 10. Fill in u-v plane for (a) assembly B rotation relative to one telescope on Assembly D at 700 nm wavelength, (b) assembly B rotation relative to one telescope on Assembly D over wavelength range from 500-900 nm, (c) assemblies A, B, and C rotation relative to one telescope on Assembly D over wavelength range from 500-900 nm, and (d) all assembly rotations from 500-900 nm

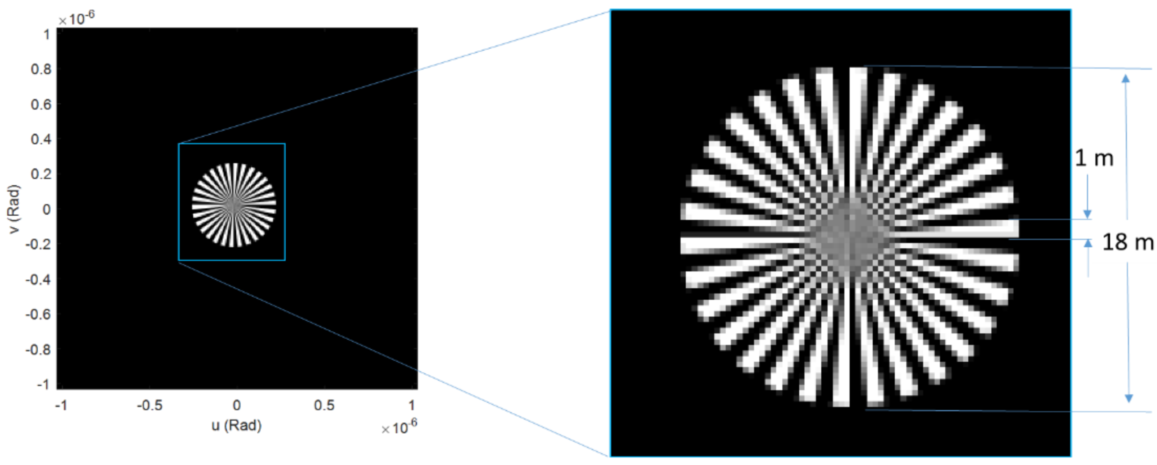
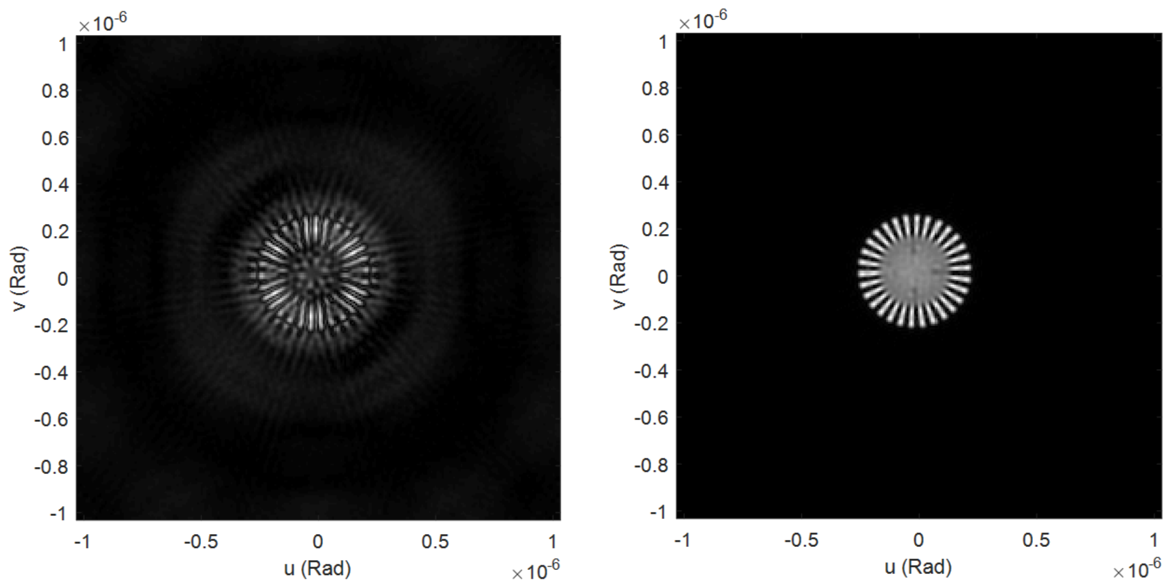


Fig. 11. Reference image for multiple truss configuration



(a)   (b)

Fig. 12. Comparison of reconstructed image from (a) multiple-truss LMIT and (b) an equivalent baseline (33-m) filled-aperture telescope

4. ONE-DIMENSIONAL RESOLUTION ENHANCEMENT

LMIT systems can also be configured to sample different parts of the u-v plane so as to gain greater resolution on specific target components. For instance, if the configuration is modified such that assemblies A and C are 70 (instead of 60) degrees offset, and the telescope on Assembly D counter-rotates as each of the assemblies A, B and C rotate, then the u-v fill shown in Fig. 13 is obtained. Figure 14 shows the image resulting from this new LMIT configuration as well as the image corresponding to a 33-meter filled aperture for comparison. The denser sampling of the u-v plane at the top and bottom of Figure 13 results in superior resolution on the left-hand and right-hand sides of the LMIT target image in Figure 14a.

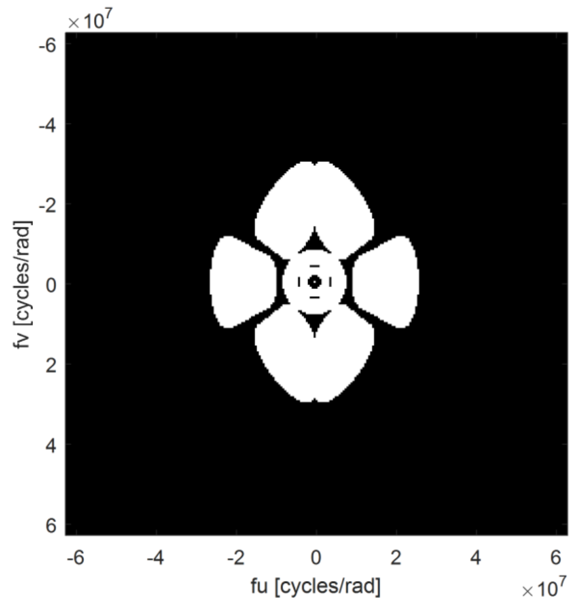


Fig. 13. Fill in u-v plane for a slightly modified LMIT that focuses on gaining additional resolution in one direction

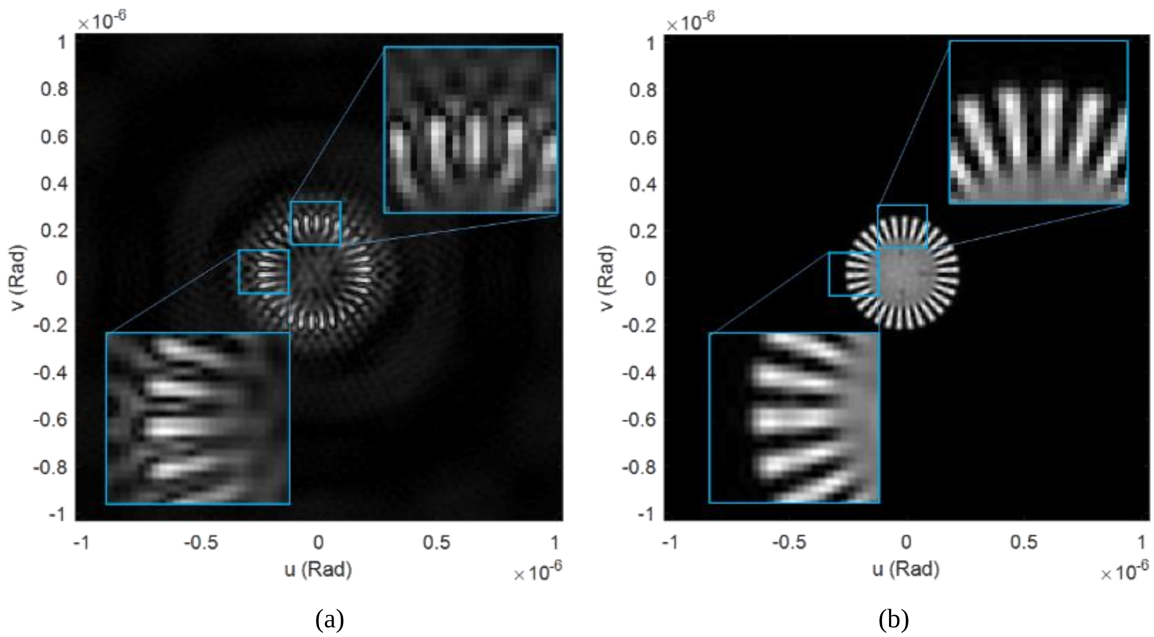


Fig. 14. Comparison of image recoverable from (a) modified LMIT and (b) 33-meter filled aperture

5. CONCLUSIONS

This paper demonstrates that ground-based imaging of GEO targets can be performed with relatively few small-aperture (< 1-m) telescopes in a LMIT configuration. Being able to rotate just two of the telescopes in a seven-aperture array between multiple static azimuthal positions allows for significant complex visibility coverage and can result in an acceptable-quality image of a GEO target. Such a system trades number of telescopes against collection time, and despite implementing a rotating structure may actually be less complex overall than a similar interferometric system implementing a far greater number of small apertures for similar u-v coverage. This kind of system can also be configured such that greater resolution is achievable along a particular axis of the target.

This study has focused on exploring configurations that efficiently provide visibility coverage. However, another challenge is accurately matching the path lengths from the object to detector between paths through each aperture. Otherwise, interference strength will be strongly reduced. Phase errors must also be addressed in order to obtain u-v sample phase information needed for image reconstruction. This may be done directly by exquisite path measurement metrology, use of reference sources, or fringe tracking. Processing techniques that are insensitive to phase errors have also been explored such as phase-closure and image reconstruction by phase retrieval. These considerations may motivate further modifications to the LMIT configurations considered in this paper.

6. REFERENCES

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