

A Conceptual Study of Formation Defined Optics Based on Small Satellite Formation Flying

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ABSTRACT

The demand for unprecedented performance in space-based Earth and astronomical observation continues to grow, requiring advancements across multiple performance axes, including spatial resolution, field of view, and multi-wavelength capability. Traditionally, meeting these demands has relied on scaling up the physical size of optical systems, leading to the development of massive monolithic or complex segmented primary mirrors. However, these conventional approaches face severe limitations due to escalating costs, structural complexity, and the strict volumetric constraints imposed by launch vehicles.

To overcome these limitations, we previously proposed the concept of the Formation Flying Synthetic Aperture Telescope (FFSAT), which utilizes small satellite formations to synthesize a large aperture. While formation-flying optical concepts have been explored for decades, the stringent requirement for optical precision at a fraction of the observation wavelength has historically hindered their realization. Our team demonstrated the feasibility of FFSAT by integrating high-precision formation flying with advanced adaptive optics, achieving sub-wavelength control accuracy within the limited resources of small satellites.

Building on this foundation, this paper introduces a novel, highly versatile framework called Formation Defined Optics (FDO).

Keywords: Space Telescope, Formation Flying, Active Optics, Adaptive Optics

1. INTRODUCTION

Recent advancements in nano-satellites have allowed satellites to capture detailed images with a spatial resolution of several meters from low Earth orbit. However, many satellites are required to obtain high-frequency observations with high time resolution. As a result, there is increasing interest in maintaining continuous observation from geostationary orbit to achieve high temporal resolution. Various on-orbit demonstrations of small satellites achieving high spatial resolution from low Earth orbit have been conducted in Japan, including HODOYOSHI-1, HODOYOSHI-4, and CE-SAT-I. However, simply bringing a satellite in low earth orbit directly into geostationary orbit degrades the spatial resolution by a factor of nearly 60 due to the increase in distance to the observation target. The spatial resolution depends on the aperture diameter of the optical system, so a large-aperture telescope is required. The optical systems of many satellites in the visible to infrared range are typically built as reflective optical systems. However, manufacturing a large-aperture primary mirror as a single mirror is challenging in terms of both cost and launch size. Segmented mirrors, deployment structures^{1,2}, and tethers are used instead of a single large mirror in constructing large-aperture telescopes for future space missions. This approach is being used for telescopes such as the James Webb Space Telescope (JWST)^{3,4} and LUVUOIR, which have extremely large-aperture primary mirrors. Synthetic aperture technology, utilizing the formation flying of small satellites, has also been proposed^{5,6} to allow for particularly flexible aperture enlargement. However, these methods require precise adjustment of the optical system's position and attitude based on the observed wavelength to achieve optimal optical performance, which poses a significant challenge^{7,8}.

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We therefore focused on formation flying and adaptive optics for nano-satellites. First, recent advances in formation flying technology have made it possible to achieve relative positions and attitudes between satellites with very high accuracy. Regarding adaptive optics, compact deformable mirrors (DMs) have been demonstrated in space⁹, and these are used to correct wavefront aberrations in optical systems. This research aims to achieve optical spatial and temporal resolution by using these techniques to reconstruct a virtual large-aperture telescope in orbit using individual satellites as optical elements.

Building on this foundation, we introduce a novel, highly versatile framework called Formation Defined Optics (FDO). Unlike traditional telescopes constrained by rigid physical structures, FDO leverages the flexibility of structurally unconstrained satellite formations. By dynamically updating the formation configuration and its constituent elements even after deployment, FDO enables in-orbit reconfiguration of the optical system to achieve high performance across multiple axes. This paradigm allows a single formation system to adapt its functionality—for example, transitioning between multi-directional pointing, high-resolution imaging, wide-field observation, and multi-wavelength sensing—depending on mission requirements.

The primary objective of this research is to establish a comprehensive design framework for FDO. This paper describes a method for adjusting the misalignment of multiple mirrors constituting the primary mirror of the Formation Flying Synthetic Aperture Telescope (FFSAT)¹⁰ by optimizing the evaluation function of the observed images and numerical simulation results using this method. The results of numerical simulations using this method are presented. These results and high-precision formation flying technology will lead to FDO, in which optical characteristics tailored to the mission objectives are achieved through the formation configuration.

2. CONCEPT OF THE FORMATION FLYING SYNTHETIC APERTURE TELESCOPE

The proposed synthetic aperture telescope FFSAT aims to achieve an even larger aperture using a synthetic aperture telescope using formation flights of small satellites. The conceptual diagram and main specifications of the FFSAT are shown in Figure 1 and Table 1. Each of the six mirror satellites in the FFSAT is part of the primary mirror by carrying a segmented mirror. The six mirror satellites form a large-aperture primary mirror to achieve a synthetic aperture, and images are acquired by image sensors mounted on the imaging satellites.

The FFSAT has an observation wavelength of 4.0 μm and a ground resolution of 30 m to detect wildfires, which are a social problem in Australia and other countries, as soon as they occur. The peak spectral radiance of blackbody radiation from wildfires occurs at around 4.0 μm , making this wavelength band suitable for observation due to an atmospheric window. It also has the engineering advantage that the accuracy required for the optical system depends on the observation's wavelength, so the adjustment accuracy of the optical system can be relaxed by a factor of 10 compared to visible light. In addition, the sparse aperture of a synthetic aperture telescope makes it challenging to obtain all spatial frequencies, while the observed image contains high spatial frequency information. In other words, the problem of extracting high spatial frequency information from the observed image is essential. In this respect, the problem of detecting the location of a bushfire, rather than obtaining a high-resolution image, also fits the characteristics of synthetic aperture. These conditions determined a focal length of 21.5 m and a synthetic aperture diameter of 5.82 m. The pixel size of the imaging satellite is assumed to be 18 μm . The relative position and attitude accuracy were set to 400 nm and 0.42 μrad , respectively, based on the requirement to achieve alignment with an accuracy of 1/10 of the observation wavelength. The aim is to achieve accuracy using high-precision formation flying and adaptive optics. In adaptive optics, in addition to 6-DOF control of the mirror of the mirror satellite, wavefront correction is performed by the mirror of the mirror satellite itself or by a deformable mirror on board the imaging satellite.

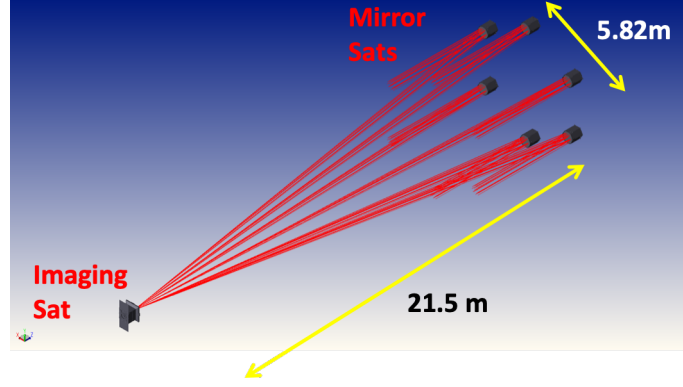


Figure 1. The ZEMAX model of formation-flying synthetic aperture telescope consists of six mirror satellites and an imaging satellite.

Table 1. Specification of FFSAT

Items	Values
Typical observation wavelength [μm]	4.0
Ground sample resolution (GSD) [m]	30
Focal length [m]	21.5
Synthetic aperture diameter [m]	5.82
Pixel size [μm]	18
Relative position accuracy [nm]	400
Relative attitude accuracy [μrad]	0.42

3. THE IMAGE-BASED WAVEFRONT CORRECTION METHOD

The SPGD algorithm corrects the misalignment by optimizing the evaluation function of the observed image. In this algorithm, the control input varies stochastically to search for the optimal solution. First, for all K adjustment degrees of freedom, the control input of the m th step of the k th degree of freedom is denoted by u_n^m . As shown in Eqs. (1) and (2), the control input u_n^m is added to the micro disturbance $\pm r_n^m \delta u$ to give $u_n^{m\pm}$, where r_n^m is assumed to take random values of -1 or 1 and δu is a pre-set micro disturbance.

$$u_n^{m+} = u_n^m + r_n^m \delta u \quad (1)$$

$$u_n^{m-} = u_n^m - r_n^m \delta u \quad (2)$$

For the control input $u_n^{m\pm}$ with micro disturbances added, the evaluation functions J^{m+} and J^{m-} are obtained from the images observed in each sign, and δJ^m is obtained from Eq. (3).

$$\delta J^m = J^{m+} - J^{m-} \quad (3)$$

The control input u_n^{m+1} at the $(m + 1)$ th step is then given by Eq.(4), where γ is the feedback gain.

$$u_n^{m+1} = u_n^m + \gamma \delta J^m r_n^m \delta u \quad (4)$$

The convergence status is determined by evaluating the function J^{m+1} , and the above steps are repeated until convergence is achieved.

In SPGD, optimization is performed for an arbitrary evaluation function J . Here, two evaluation functions, J_1 and J_2 , with different characteristics are defined. J_1 is denoted by Eq. (5) and represents the spatial standard deviation of image i_k . The symbol σ denotes the spatial standard deviation. This evaluation function produces a high value when there is a significant variation in the spatial distribution of a pattern. It is used to assess the deterioration of image quality due to misalignment of the optical system when observing targets such as urban areas and terrain. J_2 , on the other hand, is expressed by Eq. (6) and serves as an evaluation function that represents the image intensity. When assessing the misalignment of the optical system while observing a point light source, this evaluation function considers the widening of the image due to misalignment and the subsequent reduction in center intensity.

$$J_1 = \sigma[i_k] \quad (5)$$

$$J_2 = \sum_{k=1}^K i_k^2 \quad (6)$$

4. NUMERICAL SIMULATION

A sparse synthetic aperture consisting of six sub-apertures arranged at the vertices of a regular hexagon was used to simulate the optical system of the FFSAT. Each mirror was assumed to have misalignments in piston, tip, and tilt, with no other optical aberrations considered. The magnitude of the misalignments for each mirror was determined by the root mean square (RMS) error of the optical wavefront, and the misalignments were generated randomly. Figure 2 illustrates an example of misalignment, where the central wavelength of observation is λ , and the RMS error is 0.3λ .

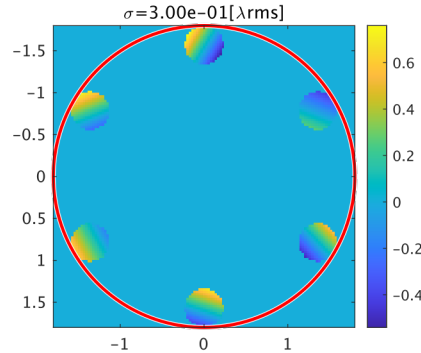


Figure 2. Wavefront aberration due to misalignment of the mirrors comprising the synthetic aperture. The RMS error of the optical wavefront is set to 0.3λ . The solid red circle represents the circumscribed circle of the synthetic aperture.

We conducted numerical experiments for two different observation targets: point light sources and aerial photographs. For point light sources, we used an evaluation function J_2 based on intensity, and for aerial photographs, we used an evaluation function J_1 based on spatial standard deviation.

Figure 3 illustrates the numerical simulation results of phasing a synthetic aperture telescope that consists of six sparse sub-apertures, focusing on both a point source and an aerial photograph. A misalignment of 0.3λ RMS wavefront error was added to the piston and tip/tilt adjustments of each mirror, after which the target was observed. The SPGD algorithm

updated the control inputs across eighteen degrees of freedom based on the observed images. Figure 3(a) displays the target image with wavefront errors caused by misalignment, as depicted in Fig. 3(b). Figure 3(c) presents the modulation transfer function (MTF) map for the wavefront function. The red circle indicates the cutoff spatial frequency of the ideal monolithic primary mirror without wavefront error. Figure 3(d) displays the image of the target after correcting the misalignment and enhancing the wavefront function, as illustrated in Figure 3(e). In this instance, the MTF map has also been enhanced, as illustrated in Fig. 3(f). Additionally, Figure 3(g) depicts the cost function during the SPGD iteration.

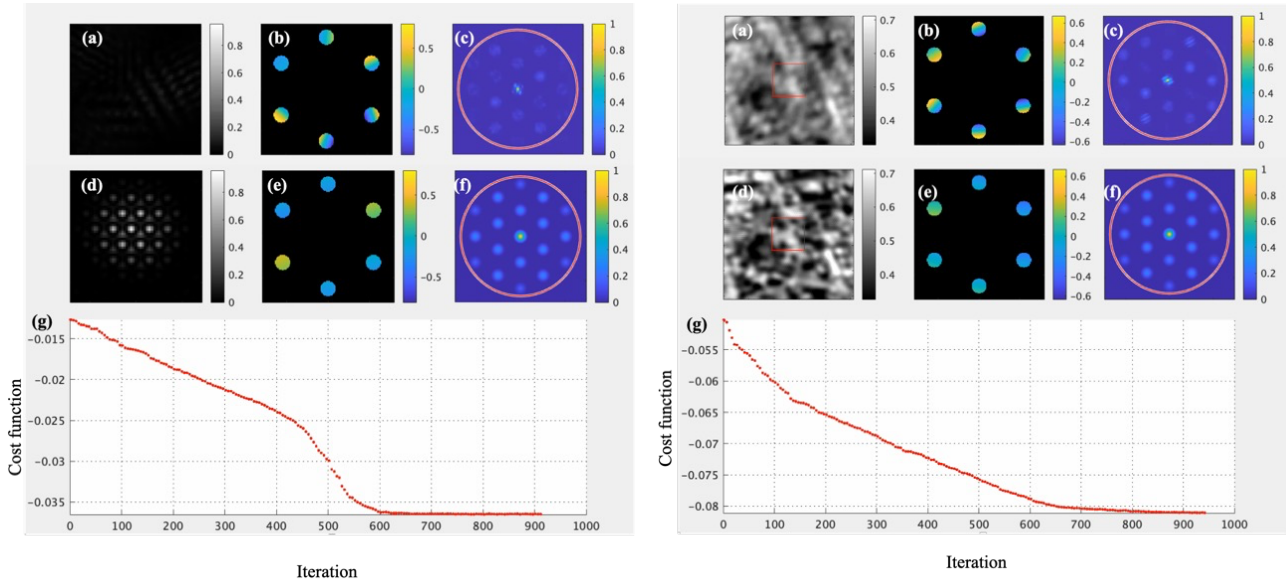


Figure 3. Numerical simulation results of misalignment correction using the SPGD algorithm for a point source with six sub-apertures for a point source and an aerial photo. (a) The initial image, (b) the wavefront error due to misalignment, and (c) the initial modulation transfer function. (d) The final image, (e) the corrected wavefront, and (f) the final modulation transfer function.

5. SUMMARY

Numerical simulations show that the SPGD algorithm can correct the misalignment of mirrors forming each aperture in a synthetic aperture with multiple apertures using an evaluation function computed from observed images. By selecting the appropriate evaluation function for point light sources and aerial photographs, the correction results were comparable to those of ideal images in both cases. These results and high-precision formation flying technology will lead to FDO, in which optical characteristics tailored to the mission objectives are achieved through the formation configuration.

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