Experimental demonstration of enhanced resolution of a Golay3 sparse-aperture telescope

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In this Letter, we report a Golay3 sparse-aperture telescope newly built in the Key Laboratory of Optical Engineering, Chinese Academy of Sciences and present the experimental results of enhanced resolution. The telescope consisting of 3 collector telescopes of 127 mm diameter can achieve a theoretical resolution corresponding to a monolithic aperture of 245 mm diameter. It is shown by the experimental results that the resolution is improved to 3.33 μrad with respect to the diffraction limit of 6.07 μrad for a single aperture using the Rayleigh criteria at 632 nm. The compact optical configuration and cophasing approach are also described.

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Optical imaging systems are being required to have large apertures to meet the demands of increasing angular resolution[1,2]. For traditional monolith telescopes, the cost and volume undesirably increase with increasing aperture. The concept of sparse aperture imaging, which is aimed at achieving a high-resolution telescope by combining several smaller telescopes, has grown out of the quest for addressing the problem[3,4].

As the simplest sparse-aperture configuration that can improve the resolution along all the directions and serve as a good start for other complex designs, Golay3 telescope systems have captured the interests of many scientists and have been researched a lot. Wu *et al.* analyzed the characteristics[5] and errors[6] of the Golay3 sparse-aperture imaging system and proposed a Golay3 structure with a spherical primary mirror[7]. Besides theoretical investigation, some Golay3 testbeds have also been established for practical research. A phasing experiment performed on a three-telescope testbed called Phaser at the Air Force Weapons Laboratory first demonstrated the availability of feedback control techniques to optically phase a sparse-aperture system[8]. Office National d'Etudes et de Recherche Aérospatiales (ONERA) has designed and built a testbed, called A Banc Reconfigurable d'Imagerie sur Scènes Etendues, to test the performance of cophasing sensors[9]. A simulated spaceborne sparse-aperture telescope testbed, Adaptive Reconnaissance Golay-3 Optical Satellite (ARGOS), has been built at the Massachusetts Institute of Technology for the purpose of dealing with some real-world problems that may occur when the system is operating in space[10,11].

Recently, at the Key Laboratory of Optical Engineering, Chinese Academy of Sciences, we built a compact Golay3 sparse-aperture telescope, a front view of which is shown in Fig. 1. This Letter presents what we believe is the first experimental result of enhanced resolution based upon a practical Golay3 sparse-aperture system to the best of our knowledge. The compact optical design and the cophasing approach are also introduced.

As shown in Fig. 2, our Golay3 system consists of three subsystems, a beam combiner, and an imaging system. Each subsystem has an afocal collector telescope comprised of a 127 mm diameter Maksutov–Cassegrain telescope (Meade, ETX-125) and a collimating lens. The structures of the horizontal two subsystems are the same.

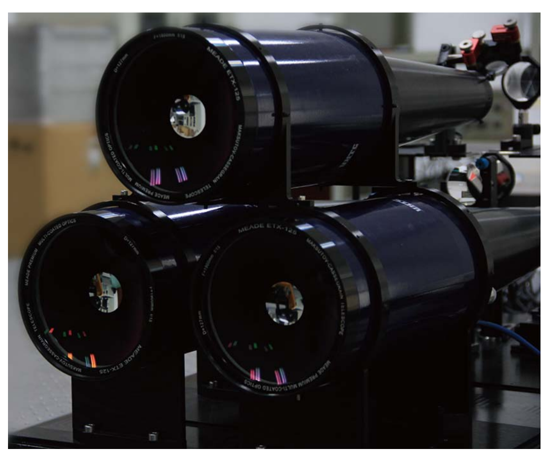

Fig. 1. Front view of the Golay3 sparse-aperture telescope.

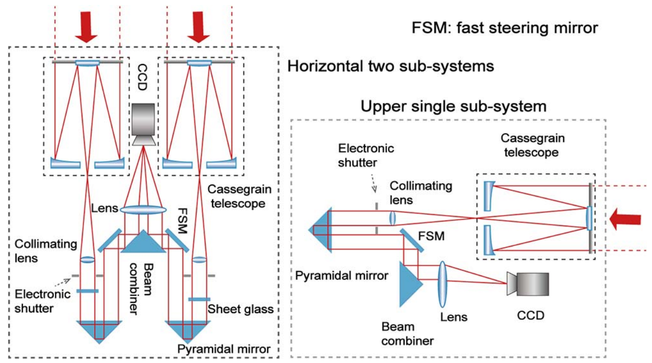

Fig. 2. Optical configuration of the Golay3 sparse-aperture system. Left: top view of the configuration of the horizontal two subsystems; right: side view of the configuration of the upper single subsystem.

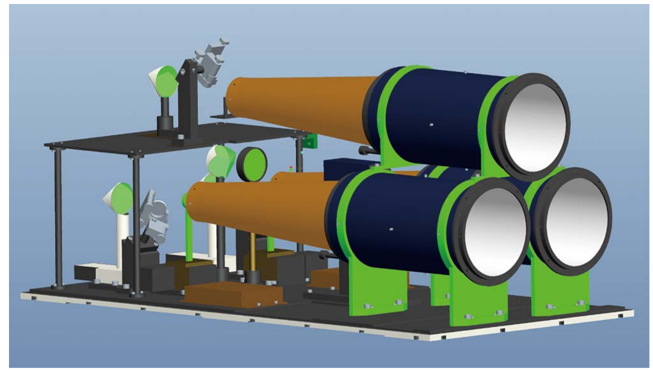

Fig. 3. Three-dimensional schematic of the optical layout of the Golay3 sparse-aperture telescope.

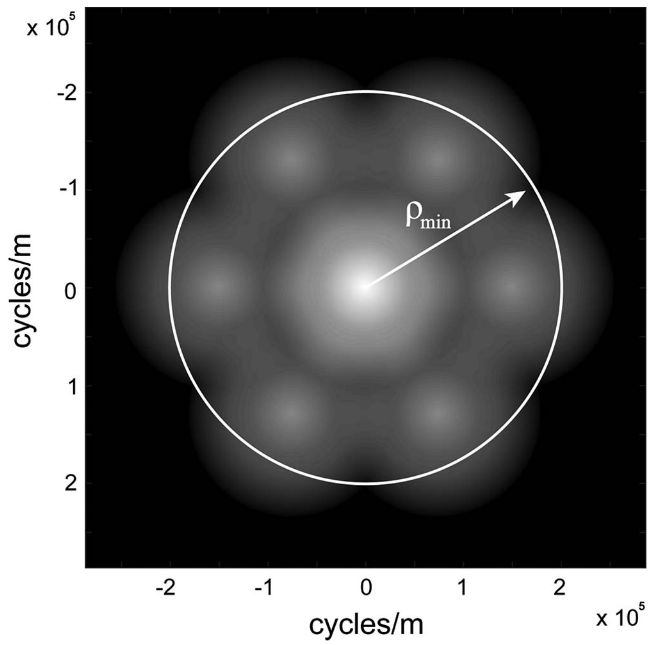

Fig. 4. Theoretic MTF of the Golay3 telescope. The spatial cutoff frequency $\rho_{\min}$, shown by the white circle, is determined by the largest circle inscribed within the contiguous portion of the MTF.

In this subsystem, an electronic shutter is inserted into the optical path to control the beam propagation, a glass sheet is mounted on a high-precision rotation stage to finely adjust the optical path, a pyramidal mirror attached to a motorized translation stage is used to realize a coarse adjustment of the optical path length and reflect beams, and a fast steering mirror is active in tip-tilt alignment. Taken as a reference aperture, the upper subsystem has the same configuration except for the elements for optical path adjustment, such as the glass sheet and motorized translation stage. We note that the pyramidal mirror used here can compact the whole system by making the exit beams propagate back along the coming direction. Such a compact configuration is absolutely different from the optical design of the previous sparse-aperture systems[11,12] and would be preferred for space-based multi-aperture systems.

An outwardly reflective pyramidal mirror is used here as a beam combiner to inject the beams from 3 subsystems into the imaging system consisting of an imaging lens with a focal length of 180 mm and a CCD camera (Daheng-Image, MER-1070-10GM/GC) with a 3840×2748 array of 1.67 μm pixel size. It is designed to be available for the beam combiner to move along the axis vertical to the entrance pupil plane of the Golay3 system. In this way, the positions of the output pupils can be controlled to satisfy the well-known "golden rule" for Fizeau interferometric imaging, which means the output pupils of the testbed should be a scaled replica of its entrance pupils[11,13]. Figure 3 shows a three-dimensional diagram of the configuration of our Golay3 system.

The three collector telescopes are arranged in a Golay configuration with a center-to-center distance of 180 mm between each other. Such an arrangement generates the modulation transfer function (MTF), as shown in Fig. 4 on a gamma scale ($\mathrm{MTF_{disp}} = \mathrm{MTF}^{\gamma}$, $\gamma = 1/2.2$). Based on the MTF, the spatial frequency cutoff can be found numerically. There are many choices of single characteristic MTF cutoff frequency such as $\rho_{\max}$, $\rho_{\min}$, or a mean of $\rho_{\min}$ and $\rho_{\max}$. Considering the inevitable system errors, such as aberrations or magnification error, we select $\rho_{\min}$ as the cutoff frequency, the most conservative measure also chosen for other sparse-aperture system[4,12]. Then the effective diameter D_{eff} can be defined according to[4]

$$D_{\mathrm{eff}} = \rho_{\min}\lambda f, \tag{1}$$

where λ is the imaging wavelength and f is the system focal length. Given a wavelength of 632 nm and an equivalent focal length of 1900 mm, we can easily obtain the diameter of an effective fully filled aperture of 245 mm, corresponding to a minimum resolvable angle of 3.15 μrad using the Rayleigh criteria.

The three subsystems need to be cophased to synthesize a high-resolution image. In the present Golay3 system, a manual mode is used in which some commands need to be sent to the actuators, while a research of an automatic closed-loop mode is also proceeding. The phasing approach operates in a two-system mode like STAR-9[14]. We first close one of the horizontal two subsystems and let the upper one open as a reference. Then the upper subsystem is closed with the other one of the horizontal two subsystems open as variable.

A point object is used to cophase the subsystems with a collimator to simulate an infinite distance. With only two telescopes open, the tip-tilt is first corrected by controlling the active FSM to slightly adjust the two Airy disks to be superimposed upon each other. Then we use the symmetry measurement algorithm[14] to quantifiaby characterize the piston error. More details of the algorithm can be seen in reference [14]. By commanding the modules of coarse and precision optical path adjustment the piston error becomes nearly zero, which means the open two subsystems are cophased. The cophased point spread function of the Golay3 telescope is shown in Fig. 5.

To demonstrate the enhanced resolution of the Golay3 telescope, the object scene is then changed to an A4 resolution test chart uniformly illuminated by a red LED with a diffuser inserted into the illumination path after our cophasing the three subtelescopes. Figure 6 presents the experimental results. The image formed by one single aperture system is shown as a reference in Fig. 6(a). The directly observed image and the processed one with the deconvolution algorithm are shown in Figs. 6(b) and 6(c), respectively. Though showing a performance of enhanced resolution, Fig. 6(b) suffers from blurring and loss of contrast caused by the reduced MTF. The processed one, shown as Fig. 6(c), presents improved quality and contrast. From the comparison between Figs. 6(a) and 6(c), it can be easily seen that the resolution is apparently enhanced by the Golay3 system. Almost every bar group cannot be resolvable in the single aperture image, while most of the bar groups in the Golay3 synthesis can be resolved although suffering from aberrations and

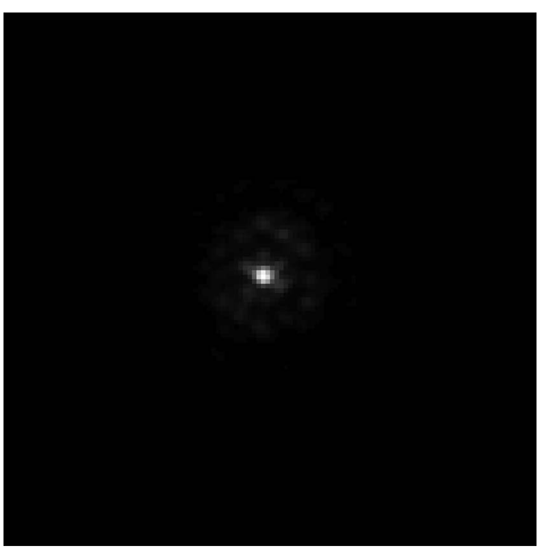

Fig. 5. Cophased point spread function of the Golay3 telescope.

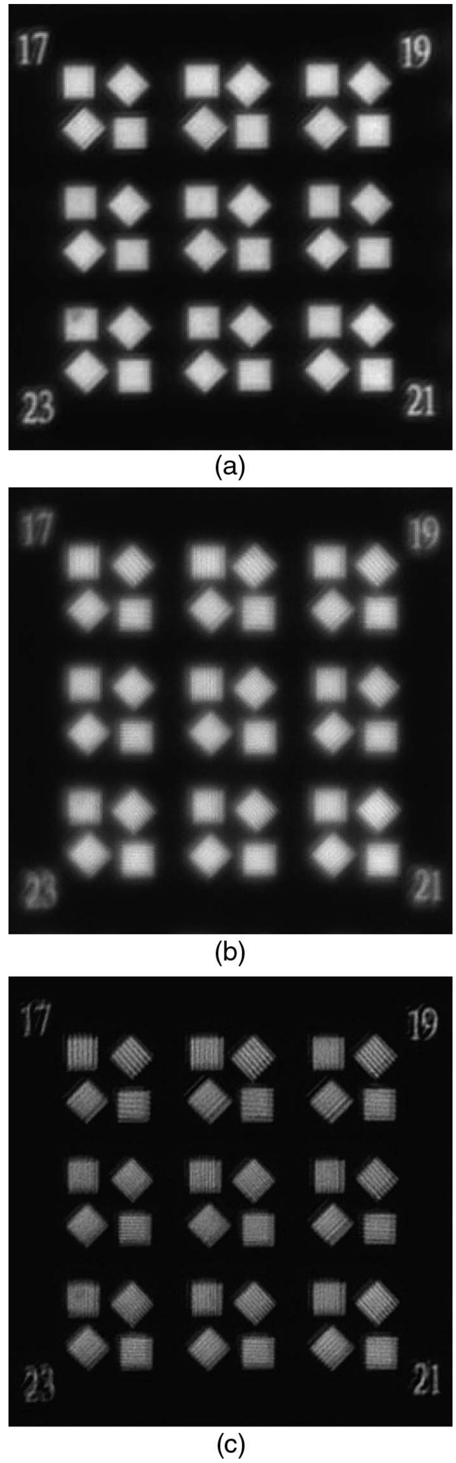

Fig. 6. Experimental results of enhance resolution: (a) the image from one single aperture telescope; (b) the directly observed image from the Golay3 sparse-aperture telescope; (c) the processed image.

misalignment more or less. The limited resolvable angle for a single 127 mm diameter aperture at 632 nm is 6.07 μrad with the Rayleigh criteria. For the Golay3 telescope, given a bar width b of group 25 having the highest spatial frequency of 5 μm and a focal length f' of the scene projector of 3000 mm, it is easy to estimate that the experimental minimum resolvable angle is 3.33 μrad using $2b/f'$, which is very close to 3.15 μrad, the theoretical predicted diffraction limit for the Glay3 telescope.

In conclusion, we describe a newly built compact Golay3 sparse-aperture system and present its performance of enhanced resolution. To the best of our knowledge, it is the first successful experimental demonstration of a practical Golay3 array to enhance resolution. The compact optical layout is described and the cophasing approach is also introduced. In theory, the reported system can achieve a resolution that is consistent with the effective monolith telescope of 245 mm diameter, which is determined by the conservative minimum cutoff frequency. The experimental results using an extended resolution test chart object show clearly that the resolution is enhanced and the theoretical diffraction limit for the Golay3 is almost achieved.

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