Development of the primary mirror for CAS500-1 (Compact Advanced Satellite 500-1)

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Abstract

CAS500-1 (Compact Advanced Satellite 500-1) launched in Mar. 2021 is the first Korean ground observation satellite localizing the entire mirror development, especially the primary mirror M1. M1 is a lightweight concave mirror with a diameter of 0.6 m, and it has 3 square bosses at the rim for flexure mounting. We present the whole development procedure of the flight model M1, including the optomechanical design, fabrication, environmental tests, and a coordinate mapping method for alignment and integration.

Keywords Satellite telescope · Optical mirror · Optomechanics · Space optics

1 Introduction

The front-end optical components of most satellite telescopes are made of mirrors, because multispectral channels can be configured and the beam path can be folded easily for a compact optical system. Also, the mirrors can be lightweighted by making pockets in the backside to reduce the payloads. Nowadays, as the primary mirror (M1) gets larger for better light collecting capability, its substrate design and mounting methods become more important for optical testing and alignment on the ground [1–4]. Silicon carbide (SiC) or beryllium (Be) is used as a mirror substrate material for cryogenic space applications like James Webb Space Telescope (JWST) [5, 6]. But most earth-observation satellites use the low expansion glass such as Schott Zerodur® or Corning ULE®, because their optical performance is proved to be stable under the temperature variation in a low earth orbit [7].

Since the first launch of the KOMPSAT (Korea Multi-Purpose Satellite, Arirang) series in 1999, the diameter of

M1 has reached 0.8 m in KOMPSAT-3A(K3A) which is the largest Korean optical telescope in orbit as of 2021 [8]. K3A uses a Korsch-type front-end optics having 4 aspheric mirrors and a folding mirror [9], and it also has an infra-red back-end optics (IROA). IROA was the first optical system proven for space heritage as being developed from the ground up, i.e., starting with the optomechanical design [10, 11]. Since then, we developed 0.8 [12] and 1.0 m primary mirrors [13–15] as qualification models and verified them with space environmental tests [16]. We have built the whole in-house workflow spanning from the optomechanical design to the lightweighting and acid-etching of mirror substrates, aspheric polishing and testing, durable reflective coating, adhesive bonding with flexure mounts, and finally thermal vacuum tests [17, 18]. We applied the above space-proven technologies to CAS500-1 (Compact Advanced Satellite 500-1) successfully and developed the first Korean satellite localizing the whole mirror development, especially the primary mirror M1.

CAS500-1 launched in Mar. 2021 has an 0.6 m primary mirror and captures the earth images with a spatial resolution of 0.5 m at an altitude of 500 km [19]. The imaging optics are made of 4 reflective mirrors configured as a Korsch-type telescope. Aperture stop is located at the primary mirror, such that the physical aperture of M1 is fully utilized as a clear aperture and its size is optimized to reduce the mass [20]. M1 has a concave aspheric surface with a central hole of 150 mm in diameter. The mirror substrate is lightweighted with hexagonal semi-open pockets, and their

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dimensions are optimized to satisfy the requirements. Mirror surface distortion due to gravity should be low enough for diffraction-limited optical performance when tested on the ground. Also, the mirror and its mounting structure should survive the launch loads and maintain its performance in orbit. Wavefront error and surface quality of M1 is more critical to the system performance than the other mirrors. Therefore, it is important to allocate M1's error budgets based on the performance degradation from all possible sources, including alignment errors. M1 is used as a reference frame when aligning subsequent optical components, and we propose to use a computer-generated hologram (CGH) as a coordinate reference to map the optical axis of M1.

In this paper, we present each step of the development procedure for CAS500-1 M1. Section II describes M1's optomechanical requirements, design, fabrication, assembly, and optical testing methods. Section III presents the environmental test results of vibration, thermal cycling and thermal vacuum. Section IV explains M1's coordinate mapping method for alignment and integration. Section V concludes this paper.

2 Design and fabrication of M1

CAS500-1 features a 500 kg-class standard platform for a multiple earth-observation series [21]. This is less than a half the weight of K3A (about 1100 kg) having a similar optical performance. The size and weight of CAS500-1 mirror components are strictly limited by system requirements, and their dimensional margins for the clear aperture are also tighter than the previous KOMPSAT mirrors. This restriction entails a difficulty in the optomechanical design and fabrication of the primary mirror. Lowering the areal density of the substrate to reduce the weight makes the mirror more susceptible to the print-through effect when polished and the gravitational distortion when tested on the ground. Decreasing the mirror height for a compact system envelope needs shorter flexure supports, and it makes the mirror structure stiffer and vulnerable to external shocks.

Table 1 lists some of the optical and optomechanical requirements for the CAS500-1 M1. The surface error is caused by fabrication error, gravitational sag on the ground, thermal distortion in a vacuum chamber, warpage due to surface tension after a reflective coating, and interferometric testing uncertainties. Their contributions are combined in a root sum of squared form in the measurement setup shown in Fig. 1, and it should be less than 12 nm rms. The horizontal setup, where the optical axis is orthogonal with the gravity direction, is adopted for optical testing. Because non-gravity surface figure can be obtained easily by rotating the test mirror about its axis and averaging 0° and 180° measurement results [16]. The

Table 1 Optical and optomechanical requirements for the CAS500-1 primary mirror M1

Specifications	Requirements
Mirror substrate material	Zerodur 0th expansion class
Physical diameter	610 mm
Clear aperture	≥ 600 mm
Radius of curvature	1918 mm ± 1.0 mm
Surface error	< 12 nm rms
Mirror coating	$R_{\text{avg}} \geq 94\%$ in spectral range of 450–900 nm
Mass including flexure mounts	< 15 kg
Acceleration loads	30 g (gravity)
Fundamental frequency F1	> 150 Hz
Thermal vacuum condition for optical performance tests	< 10 ⁻⁵ torr, 20 °C ± 10 °C
Random vibration loads	11.3 g (gravity) rms

lightweight mirror and its support structure should weigh less than 15 kg, and should maintain the optical performance after acceleration loads up to 30 g (gravity). The natural frequency of the first mode should be over 150 Hz in all directions to avoid the resonance. Once in orbit, M1 suffers temperature variations of ± 10 °C during the operational mode, and its WFE (wavefront error) should be maintained within the requirement. Optomechanical design optimizes the dimensional parameters and material properties to satisfy all those requirements.

The mirror is lightweighted with hexagonal semi-open pockets as shown in Fig. 2. It has circular openings smaller than the pockets to enhance the flexural rigidity of the mirror, and their dimensions are optimized to be compatible with the grinding tool head. The radius of the T-shaped grinding head is smaller than that of the pocket openings and the fillet radius of the hexagonal pockets. The shank of the T-tool should be thick enough for rigid chucking, which avoids the resonance and hammering effect. The mirror has 3 square bosses for flexure mounting, and their sizes are also determined after optimizing the balance between the safety against vibration loads and the optical figure errors due to thermal expansion. Large bonding area is preferred for vibration loads, but small discrete bonding is better for opto-thermal performance.

The bipod support is a combination of radial and tangential blade flexures formed as a triangle [12]. We use an analytical formulation for the initial design of the bipod flexure, where compliance and stiffness matrices based on the screw theory are used to explore the design space satisfying the requirements [15]. For example, the fundamental frequency of M1 and each flexure parameter is related by a stiffness matrix. Also, the displacement of the mirror's surface can be calculated with a stiffness matrix without resorting to a finite element analysis (FEA). The bipod angle or the height

Fig. 1 Interferometric measurement setup of CAS500-1 M1 in a vacuum chamber for performance tests. M1 is enclosed in a thermal shroud for temperature variations of ± 10 °C, and the surface figure is measured during the steady-state dwell time periods

Fig. 2 CAS500-1 primary mirror M1 lightweighted with hexagonal pockets and circular openings. A T-shaped diamond grinding tool makes a semi-open back. Three bipod flexures are assembled at the square bosses

of the bipod apex is selected to minimize the surface figure error in the horizontal setup of Fig. 1 [12].

We used a multiobjective genetic algorithm when optimizing the mirror design, and found the best solution satisfying the design requirements. The mirror's mass and gravitational distortions are two major conflicting objectives for the design optimization, but the optical performance is more critical when deciding a design candidate. As a result, the mass of the mirror is 12.7 kg, and the surface error under a gravitational load in the horizontal setup is 3.5 nm rms in both directions as shown in Fig. 3. As the minimum mirror surface thickness is only 4 mm, corrugated surface ripples are salient in the vicinity of flexure mounting bosses.

The mirror was lightweighted with T-shaped grinding tools as shown in Fig. 4a. The speed of the wheel and its feed rate are found with trial and error to grind away the fragile glass material in a safe and efficient manner. The sub-surface damage over the ground surface, which is over 100 μm in depth, is removed by a hydrofluoric acid-etching process. Therefore, the flexural strength or fracture toughness of the mirror substrate increases providing more safety margins against the launch load. Adhesive strength between the etched mirror and the metallic mount was also proved to increase from the in-house coupon test results.

After the lightweighting procedure, the mirror is embedded in a metallic housing for initial surface figuring as shown in Fig. 4b. Compressed air is supplied into the housing to make the mirror float, which prevents the print-through effect when polishing a mirror surface with honeycomb cells underneath [22]. We used a computer-controlled polishing machine for aspheric surface figuring. Final figuring is performed after assembling the mirror with 3 flexure mounts, which enables the separation of the gravity-induced distortions from the figure error by rotating the mirror about its optical axis. We use Eq. (1), which is the 2-clocking method [23], to obtain the gravity-free figure error S , where P_{0° and P_{180° are the 0° and 180° surface errors respectively, and R_{180° is the 180° rotation operator.

$$\text{Gravity - free surface figure error } S = \frac{1}{2} [P_{0^\circ} + R_{180^\circ} (P_{180^\circ})]. \quad (1)$$

Figure 4c shows the mirror fixed in the evaporation chamber for a protected-silver reflective coating. Witness samples are used to measure the coating's optical properties and to evaluate the durability and wear resistance to abrasion, peel-off, moisture, radiation, and thermal stress. We developed a space-proven reflective coating for a visible spectrum down to 450 nm with an average reflectivity over 96%. We also proposed a prediction method for a mirror deformation due to the moisture release of a reflective coating in space environment, and the result is 2.005 μm of focal shift [18]. But this amount is sufficient to be compensated for by using the focus mechanism operation in orbit. After the reflective coating, M1 is assembled with 3 flexure mounts on the bezel structure to test its optical performance. Figure 4d shows the M1 assembly installed on a gimbal stage for an interferometric testing.

We used a CGH and a Twyman-Green interferometer (PhaseCam 5030, 4D Technology) to test the aspheric surface figure of CAS500-1 M1 as shown in Fig. 5a. The surface error was measured less than 11 nm rms in both 0° and 180° horizontal setups, satisfying the requirement of 12 nm rms in Table 1. In Fig. 5b, the CGH has alignment segments around the main hologram, and they are used for positioning the CGH between the interferometer and the test mirror.

Fig. 3 Surface errors of CAS500-1 M1 under 1 g gravity loads in x and y horizontal directions

Four segments make fiducial spots on the mirror vertex to identify its optical axis, which will be explained more in Sect. 4.

3 Environmental tests

Satellite telescopes suffer from the vibration loads when launched and the temperature variation in the low earth orbit (LEO) space environment. Each mirror component composing the optical system should be verified on the ground whether it can survive the mechanical stress from the vehicle, and whether its optical performance is maintained in a thermal vacuum environment. Figure 6 shows the CAS500-1 M1 assembly installed on a shaker (V964, LDS) for the vibration tests, and the specifications. The acceleration spectral density (ASD) is defined over the frequency range of 20–2000 Hz, and the Grms (root-mean-square acceleration) value, which is the square root of the area under the ASD,

is 11.33. But the actual input profiles of x , y , and z random vibrations are modified and different each other, because resonant frequencies are notch-filtered adaptively depending on their contributions in each direction. The fundamental frequency $F1$ was measured as 250 Hz deviating only 0.4% from the analytical estimation of 249 Hz. Mechanical safety was verified by checking the variation of modal frequencies and coordinate displacements after each vibration test, and the optical performance was evaluated with an interferometric measurement after the test. CAS500-1 M1 was proved to withstand the sine sweep and random vibrations successfully.

Thermal cycling test (TCT) and thermal vacuum test (TVT) were conducted to verify M1's optical performance in survival and operational modes. Temperature range of the TCT is from $-15\text{ }^{\circ}\text{C}$ to $55\text{ }^{\circ}\text{C}$ emulating the survival mode, and 5 or 10 cycles are repeated depending on the mirror model. Surface figure errors are measured before and after the TCT as shown in Fig. 7a, and the WFE change between

Fig. 4 Fabrication process of CAS500-1 M1. **a** Lightweighted mirror substrate with hexagonal semi-open pockets, **b** computer-controlled polishing of the aspheric mirror surface, **c** M1 installed in a coating chamber fixture, **d** M1 and flexure mount assembly on a bezel structure

Fig. 5 **a** Optical testing of CAS500-1 M1 with a CGH **b** CGH design and alignment segments

them is used as a test criterion whether the mirror survives the thermal stress. In the TVT test, the temperature range is ± 10 °C and the vacuum level is 10^{-5} torr as shown in

Fig. 7b. The optical performance is measured while the mirror is in the vacuum chamber as diagrammed in Fig. 1 and when the temperature is in every high and low dwell time

Fig. 6 **a** CAS500-1 M1 assembly installed on a shaker for vibration tests, **b** random vibration input profile and its specification

Fig. 7 **a** Experimental setup for thermal cycling and thermal vacuum tests of CAS500-1 M1, **b** specifications of the thermal vacuum test

period. The WFE results were found within the requirement of 24 nm rms after calibrating the thermal expansion of the metallic bezel structure.

4 Coordinate mapping

M1 is used as a reference frame for dimensional coordinates when aligning subsequent optical components after being fixed on the bezel mount. But M1 is usually enclosed by a baffle structure, and it cannot be reached for mechanical coordinate measurements. Instead, cube mirrors are installed outside the baffle envelope, and they are used as delegates for mapping the reference coordinate. M1's vertex point and optical axis should be identified precisely, and its coordinate and direction cosines are then mapped with respect to the cube mirror's crosshairs and face normals. But M1 usually has a central hole in most on-axis type telescopes, and therefore its vertex is virtual in space and cannot be identified mechanically. Moreover, the optical axis of M1 does not coincide with the physical axis centered at the cylindrical aperture of the mirror substrate due to the surface figure errors.

In this paper, we propose to use the CGH as a coordinate reference for mapping the optical axis of CAS500-1 M1 in a satellite telescope. CGH is a null optics for measuring an aspheric surface with a laser interferometer, and it is now regarded as an optical standard for aspheric optics testing. CGH can have fiducial segments for alignment purposes, and some of them make spots converged onto the mirror's surface to indicate the optical vertex and angular orientation of the test optics. Laser spots converged on M1's vertex is captured by an optical fiber and its position is adjusted until the output intensity is maximum at the other end. Then, the virtual vertex can be observed by 2 theodolites, and its coordinate can be measured with respect to the cube mirror. The optical axis of M1 is aligned parallel with the CGH's surface normal and its direction cosines can also be measured with the theodolites. We already finished a feasibility test and published a preliminary result of this method without the primary mirror [24]. In this paper, we apply the idea to map the primary mirror of CAS500-1 as shown in Fig. 8.

M1's optical axis should be mapped with respect to the cube mirrors fixed on the CFRP bezel structure, and the mapping accuracy of its vertex coordinate and axis angle should be less than $\pm 5 \mu m$ and $\pm 0.002^\circ$, respectively. We used two theodolites (TM6100A, Leica) to measure the x , y coordinates of the mirror vertex and its axis angles. For the z coordinate, which is the axial distance of the mirror vertex from the cube mirrors, we used a portable coordinate measuring machine (Edge 7-axis, Faro) instead, because the fiducial spots captured by an optical fiber have relatively long depth of focus in the axial direction. From the measurement

Fig. 8 Configuration of CAS500-1 M1 coordinate measurement using a CGH, 2 theodolites, and an optical fiber

results, the repeatability of the 3-axis coordinate measurement was less than $14\text{ }\mu\text{m}$ for the distance and 0.0001° for the angle.

5 Conclusion

We reviewed the whole development procedure of the primary mirror for CAS500-1 launched in Mar. 2021. Some of the optical and optomechanical requirements were presented, and optomechanical design strategy to satisfy the requirements was explained. Surface figure error is the most important performance criterion to be kept throughout the process, and we successfully managed the error budget of each step to achieve the project goal of CAS500-1 M1. Even with the small peripheral margins for the clear aperture of

the mirror, the coated surface exhibited a uniform wavefront map around the edges. Environmental tests such as the vibration and the thermal vacuum verified the survival and reliable operation of the primary mirror before the actual launch. We also proposed a new coordinate mapping method for M1's optical vertex by using a CGH and an optical fiber.

Rest of the mirror systems M2–M5 composing CAS500-1 also satisfied the requirements and passed the flight model acceptance tests. The alignment and integration of the CAS500-1 optical system was performed at KARI (Korea Aerospace Research Institute), where multiple theodolites and the cube mirrors were used for the initial alignment of the mirror assemblies. Imaging performance of CAS500-1 was verified by measuring the MTF (modulation transfer function) on the ground, and the recently acquired on-orbit images proved the project mission as successful.

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