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Development of the wide-swath and high-resolution optical imager onboard Advanced Optical Satellite (ALOS-3)

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ABSTRACT

JAXA has developed the Advanced Optical Satellite (ALOS-3) as a successor to the optical mission of the Advanced Land Observing Satellite (ALOS) "Daichi" (2006 - 2011) since FY 2016. The wide-swath and high-resolution optical imager (WISH) is the main instrument of ALOS-3 and equipped with a panchromatic (Pa) band and 6 multispectral (MS) bands. For the optics of WISH, a large off-axis four mirror anastigmat type has been selected to achieve both high-resolution (0.8 m Pa, 3.2 m MS) and wide-swath (70 km). The proto-flight model (PFM) of all mirrors has already in the precision polishing process, and highly accurate measurements of large off-axis aspherical surfaces (primary and tertiary mirror) are carried out both in a contact and a non-contact method. The verification concerning the high precision assembly of the large off-axis optical system was also carried out using the structural model which is manufactured with the same design for the PFM. Manufacture and test of the PFM of WISH would be conducted over the next one year and the PFM would be delivered to the ALOS-3 satellite system within FY 2019. ALOS-3 is scheduled to be launch from Tanegashima Space Center in FY 2020.

Keywords: Earth observation, wide swath and high resolution, optical imager, off-axis four mirror anastigmat, ALOS-3

1. INTRODUCTION

The Advanced Optical Satellite (ALOS-3)[1,2,3] is a successor to the optical mission of the Advanced Land Observing Satellite (ALOS) “Daichi”. ALOS was successfully operated on orbit for more than five years (2006 – 2011) and ALOS’s three sensors acquired about 6.5 million scenes of Earth, which contributed to a variety of fields including cartography, regional observation, and disaster monitoring[4,5].

The primary mission requirements of ALOS-3 with considering the continuation of ALOS are steady acquisition of base map of land for disaster prevention, grasp of detailed damage situation at the time of disaster occurred, and collection of highly accurate geospatial information.

The wide-swath and high-resolution optical imager (WISH) is the main instrument of ALOS-3. Although specifications of WISH are determined from these mission requirements, it was a major task to realize both good enough ground resolution and wide field of view while considering the orbital altitude suitable for periodic observation of all land areas. After feasibility study over several years, we selected the plan to improve the ground resolution by enlarging the optical system of the Panchromatic Remote-Sensing Instrument for Stereo Mapping (PRISM) onboard ALOS[6], while maintaining its wide-swath (70 km). JAXA has started the ALOS-3 project in FY 2016, and the preliminary design review (PDR) of WISH and satellite system has completed in that year. Currently the development of WISH is in the final stage of the critical design phase.

In this paper, we outline the optical system, structure and detector that should be presented at the critical design review. It also shows specific assembly methods and verification methods for optical systems. In the current schedule, WISH's proto-flight model (PFM) manufacturing and following proto-flight tests (PFT) would be conducted over one year from now on. After that, PFM would be delivered to the satellite system by the middle of FY 2019, and the launch of ALOS-3 will be scheduled within FY 2020.

Figure 1 shows on-orbit image of WISH onboard ALOS-3. The operation orbit of ALOS-3 is the sun-synchronous sub-recurrent orbit (local sun time at descending node is 10:30 am) at an altitude 669 km and the revisit time is 35 days (sub-cycle about 3 days).

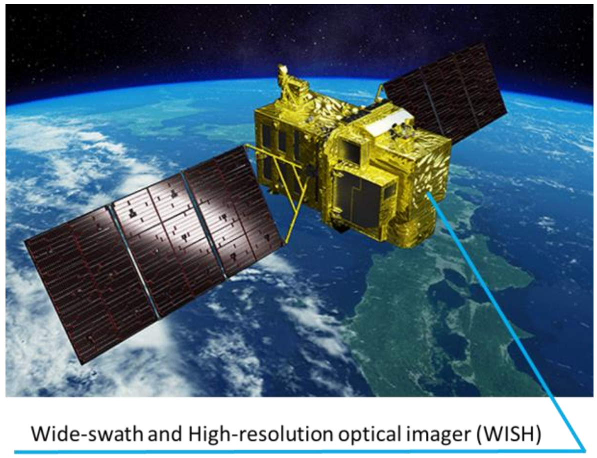

Figure 1. On-orbit image of WISH onboard ALOS-3. The right side of the figure is the direction of the orbital motion of the satellite.

2. WIDE SWATH AND HIGH RESOLUTION OPTICAL IMAGER

2.1 Specifications

WISH onboard ALOS-3 is a push bloom type imager as many remote sensing instruments. In the case of ALOS, it equipped two independent sensors for panchromatic (Pa) band and multispectral (MS) band, whereas WISH has a Pa band and 6 MS bands on a shared focal plane.

The specifications of WISH are shown in Table 1. The main improvement compare to PRISM onboard ALOS is realization of small instantaneous field of view (IFOV) by enlarging the effective aperture diameter and the focal length. The improvement while securing good Signal to Noise ratio (S/N) was realized thanks to the domestic multi-stage TDI-CCD became available (see 2.4). In the table, the "off-axis four mirror anastigmat (FMA)" in the row for "Optics" is basically the same type with off-axis three mirror anastigmat (TMA), but its quaternary mirror has slight curvature. Detail of optics are described in next section.

2.2 Optical design

For the optical system of WISH, a large off-axis "four-mirror" anastigmat (FMA) design is adopted in order to achieve both high-resolution and wide-field of view. This is basically same with well-known off-axis three-mirror anastigmat (TMA) but by making the quaternary mirror have a quite slight curvature, the total length of the entire optics can be 30% smaller than that of conventional TMA. This is a very important issue for the instrument onboard the satellite on the viewpoint of weight saving too. Although off-axis TMA telescopes have a disadvantage that the overall volume is much larger than that of on-axis TMA, it has a good modulation transfer function (MTF) due to the absence of a central obstacle by the secondary mirror, resulting in higher image quality is achieved.

Figure 2 shows optical design of the FMA for WISH. The effective aperture of the WISH primary mirror is about ϕ0.54 m and has about 1 m long in cross-track direction (or Y-axis of the local coordinate system) of the imager. The focal length of the optics is 6.86 m and then system F/# is 12.7. The surface shape of each of the primary (M1), tertiary (M3), and quaternary (M4) mirrors is a sixth-order aspherical whereas the secondary mirror (M2) has a conical surface.

Nominal wavefront error on the ideal design (not including any manufacturing and environmental error) is about 0.026 λ rms (λ = 632.8 nm) for the entire field of view of the optics, and the MTF at Nyquist frequency (62.5 lp/mm for Pa band) is about 0.36.

Table 1. Specifications of WISH.

Item	Specifications
Bands	Panchromatic (Pa): 520 – 760 nm Multispectral (MS): band 1: 400 - 450 nm (Coastal) band 2: 450 - 500 nm (Blue) band 3: 520 - 600 nm (Green) band 4: 610 - 690 nm (Red) band 5: 690 - 740 nm (RedEdge) band 6: 760 - 890 nm (NIR)
IFOV	Panchromatic: < 0.245 arcsec (< 0.8 m at nadir*) Multispectral: < 0.978 arcsec (< 3.2 m at nadir) * Altitude 669 km
Field of view	> 6.0 degree (> 70 km at nadir*) * Altitude 669 km
Optics	off-axis four mirror anastigmat (FMA)
Detectors	Pa: 128 stage TDI (8 μm pitch) 8192-pixel x 12 CCD MS: 32 stage TDI (32 μm pitch) 2048-pixel x 6 band x 12 CCD anti-blooming function is equipped for both CCD
Dynamic Range	11 bit
MTF @ Nyquist Freq.	Pa: > 0.1 MS: > 0.2 *Throughout the FOV, and under the conditions that satisfy S/N (see below)
Signal to Noise Ratio (S/N)	Pa: > 200 MS: > 200 *at northern latitude of 35 degrees, vernal and autumnal equinox, albedo 30%

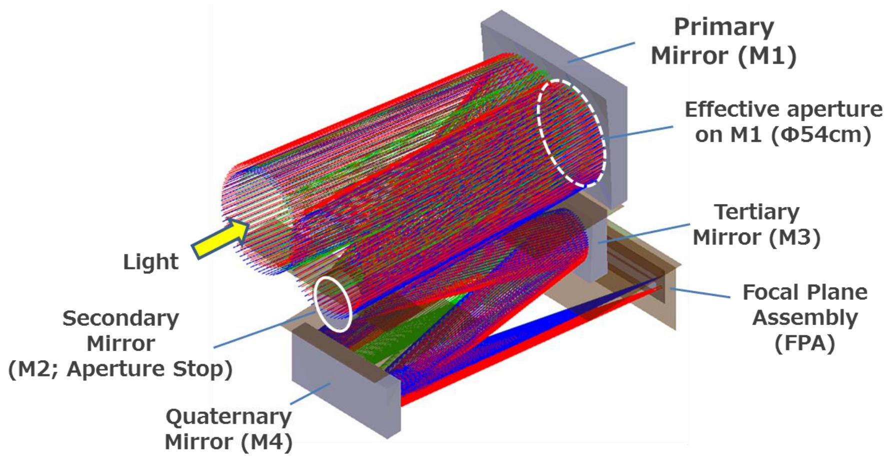

Figure 2. The off-axis four mirror anastigmat (FMA) design for WISH's optics. The diameter of effective aperture on the primary mirror and the aperture stop are shown in the figure as white ring.

2.3 Structural design

The material of all mirrors is Ohara Inc.'s CLEARCERAM®-Z which is a glass-ceramic with an ultra-low thermal expansion coefficient. All the mirrors are lightweighted by Mitsubishi Electric Corp. Subsequent grinding, polishing and coating are carried out by Canon Inc.

The final design of the structure for WISH' optics is shown in Figure 3 (upper). All lightweighted mirrors has an open-back structure as shown in the figure. Three pieces of inversed bi-pod with flexure are adopted for the static support structure for each mirror. Thanks to this support system, any distortion from the telescope structure are suppressed and the mirror surface shape is maintained. The mirrors with support structures are fastened to the metal joint (made of Super Inver) parts on the apex of a triangular CFRP structure. This unitary structure is called as the mirror assembly (e.g., M1 assembly). For the optics structure, a truss type which is consist of the CFRP pipe and the metal joint made of Super Inver is selected. This CFRP pipe is designed such that aluminum is co-cured on the surface at the time of manufacturing to prevent the moisture absorption, and then both thermal deformation and moisture deformation are nominally zero. Thus, the alignment between the mirrors is maintained with high stability in various environment.

The structure of optics is divided into three parts. The M1 & M3 support structure, the M2 & M4 support structure, and the center section. Both of M1 & M3 support and M2 & M4 support are directly connected to the center section, which supports all the loads of optics.

Figure 3 (lower) shows external view of WISH with the outer shield assembly (OSA). The dimensions and the local coordinate system of the base plate (system I/F) are also shown in the figure. Note that the local coordinate system of WISH (optics) is obtained by rotating this coordinate axis counterclockwise around 6.2 deg about the Y axis. Its Z axis coincides with the normal direction of the secondary mirror, that is, the optical axis. Although not shown in the figure, there are several light shielding structures on the OSA or the base plate, and then any stray light (both direct and indirect) from the aperture to the optical component or the detector are blocked.

The total mass of WISH including the components which are attached to the system bus is about 560 kg, among which the mass occupied by the optical system, OSA and the focal plane assembly is about 500 kg in the maximum estimate.

We have already carried out the vibration test (3-axis, sine-sweep, QT level) using the real structural model of WISH. Correlation between the vibration test result and the structural mathematical model was performed, and the analyzed natural frequency agrees well with the test result. The lowest natural frequency in the major mode is 33.5 Hz, which is the rotation mode of the optics around the Y-axis when vibration is applied to the X-axis. It meets the stiffness requirements of the satellite system (> 30 Hz).

The base plate (-X-axis side of WISH) interfaces with the system bus, and between them is thermally insulated by the spacer made of GFRP. The optical system has also an interface structure with the star tracker (STT) on the -Z-axis side (see Figure 3 upper right). STT is a component belonging to the satellite system and is thermally insulated from WISH at this I/F surface.

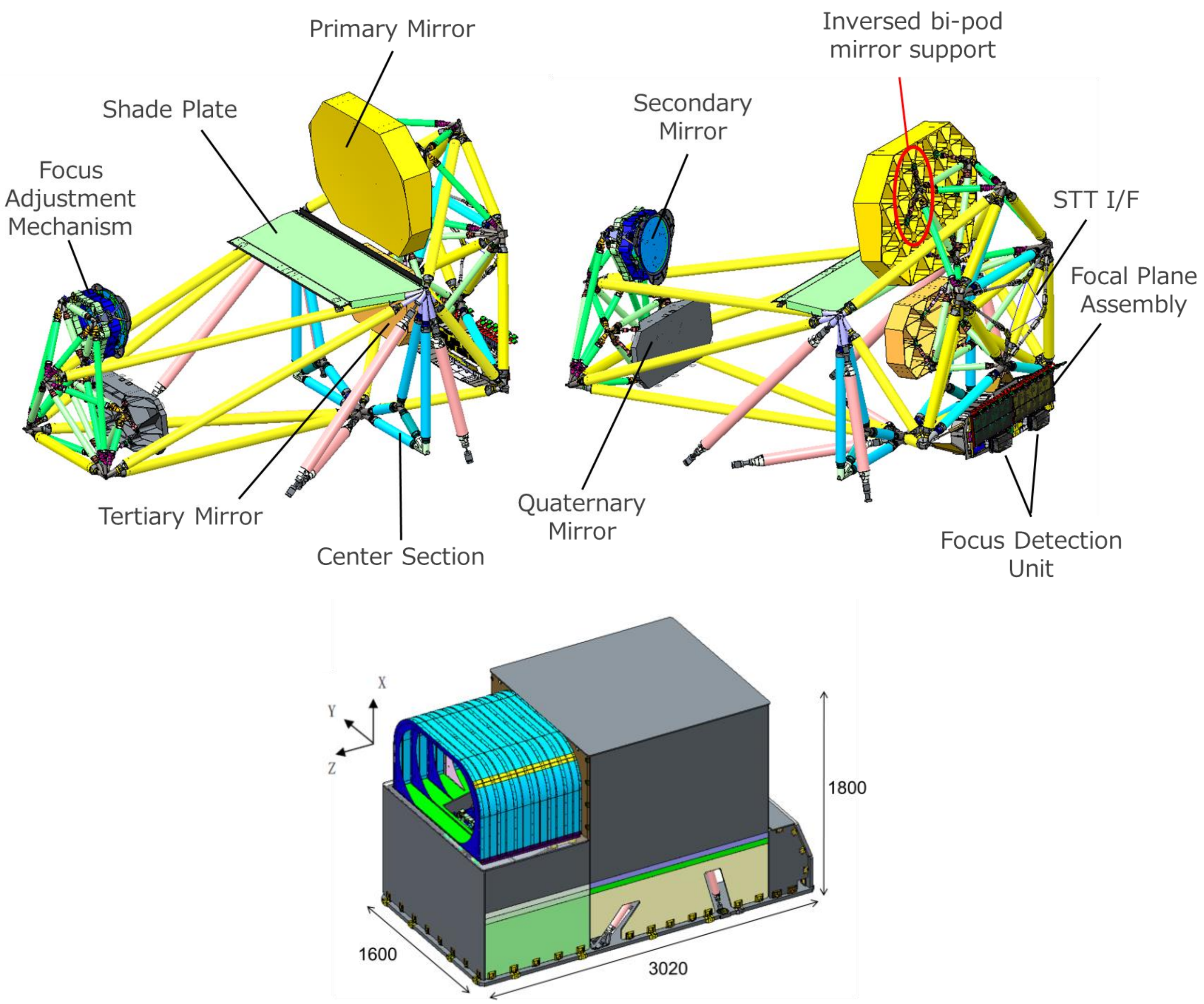

Figure 3. Upper: The final design of the optics structure. Lower: The external view (without MLI) and the dimensions of WISH. The local coordinate system of the base plate is also shown (see text).

2.4 Focal plane assembly

For the panchromatic band (Pa), the 128 stage Time Delay and Integration (TDI) type CCD with 8 μm pitch is used. A TDI-CCD chip has 8192 pixels, and totally 12 CCDs are placed on the focal plane with a staggered configuration to realize a wide swath. Each CCD has 8 readout channels and the drive frequency is 10.89 MHz Minimum integration time is 108.9 μsec. On the other hand, the 32 stage TDI-CCD with 32 μm pitch is used for the multispectral band (MS). A total of six bands (or detector) are formed on one chip. Each band has one readout channel (2048 pixels / channel). Same with Pa band, 12 CCDs are placed on the shared focal plane. For MS band, minimum integration time is 435.6 μsec.

Figure 4 shows the engineering model of CCD for Pa band (left) and MS band (middle). The bandpass filters are already attached on each band. TDI-CCDs for both types are manufactured by Mitsubishi Electric Corp. The photograph of the CCD surface taken by a scanning electron microscope is shown in Figure 4 (right). As shown in the photograph, this CCD performs charge transfer in four phases, thus the degradation of MTF due to charge transfer in the along-track direction is negligible. Although these CCD are based on a front-illuminated type architecture, its surface has aperture electrodes, which makes both high sensitivity and good MTF. Regarding the Pa band, sensitivity improvement is realized by further forming micro-lenses on pixels (of course MTF is getting slightly worse). Furthermore, these CCD has a correlated double sampling circuit and a clock driver on each chip, and although the analog to digital conversion is performed by a signal processing unit mounted on the system bus, sufficient low noise is realized.

As mentioned above, since WISH has a very wide field of view with a large aperture, the size of the focal plane becomes very huge (> 700 mm). A total of 24 CCDs (12 each for Pa and MS) are assembled onto a large focal plane plate, but it is technically challenging to thermally stabilize this huge plate. As a material of a FPA plate which mounts detectors, molybdenum which is a high-strength material is used. Since molybdenum is also characterized by high thermal conductivity and low thermal expansion, it is possible to reduce temperature rise of the detectors and thermal deformation of the detector mounting surface by the suitable thermal design.

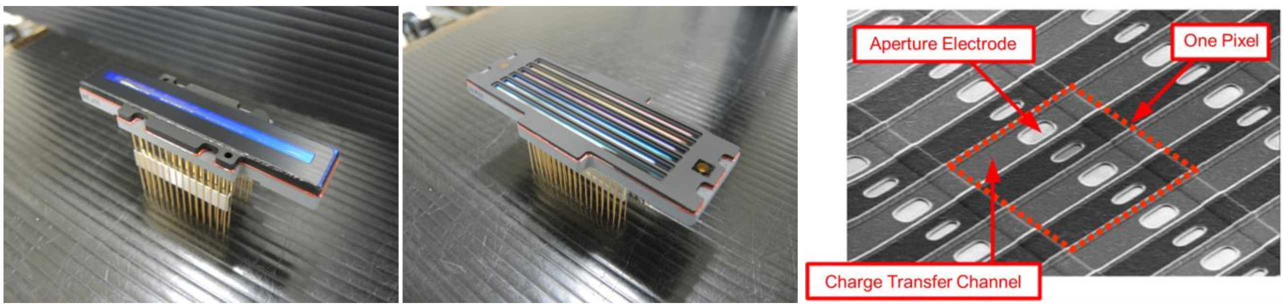

Figure 4. Engineering model of TDI-CCDs. Panchromatic band (left) and Multispectral band (middle) and the photograph of the CCD surface taken by a scanning electron microscope (right).

2.5 Other sub-components

In the case of a large optical system for space, the focus adjustment on orbit is indispensable, so WISH is equipped a focus adjustment mechanism (FAM) on the back side of the secondary mirror. The FAM consists of six linear actuators, and not only adjustment of defocus but also adjustment of tilt and shift are also possible if necessary in orbit. The travel range of focus adjustment corresponds to approximately ± 500 μm at the focal plane position.

Measurement of the focus position on the orbit is performed by a compact device called a focus detection unit. This device is placed on the focal plane near main CCDs. Incident light is converted into parallel light by a relay optics, and then divided into two by a separator lens placed in a position conjugate with the exit pupil. The focal position is determined by measuring the distance between identical images which into two different locations on a detector (same type with Pa band). Since the field of view of WISH is very wide, the focus detection unit is installed in two places of the FPA (see Figure 3 upper-right).

3. OPTICS ASSEMBLY

3.1 Manufacture and assembly of mirrors

Among the mirrors constituting WISH, only a primary mirror assembly with the largest design difficulty is manufactured as the engineering model (EM) of the optical component. The EM of the primary mirror is shown in Figure 5. The outer size of the primary mirror is about 1000 mm on the long side, about 700 mm on the short side and 160 mm in the thickness. The main verification items are: 1) Manufacturability (such as lightweight processing, polishing of the mirror material and high accuracy measuring of the mechanical surface error of the mirror), 2) Mechanical strength of the mirror support (strength of adhesion) and 3) Stability against external distortion input to the mirror support (inversed bi-pod structure). These verification items are completed without major problems, and lessons learned from a series of work are reflected in the manufacture of proto-flight model of all other mirrors.

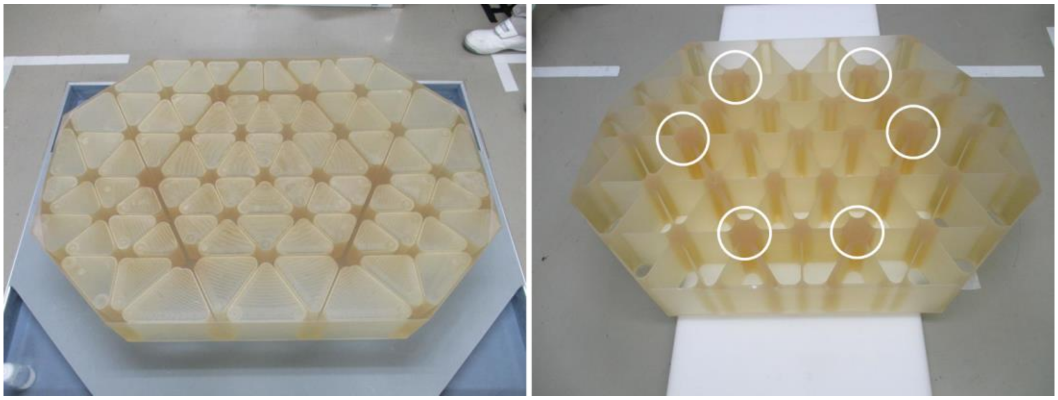

Figure 5. The engineering model of primary mirror after lightweight process. Six positions where the pad part of the inversed bi-pod mirror support structure is adhered are indicated by white ring (right).

Currently, all PFM mirrors have been advanced to the precision polishing process at the factory of Canon Inc. using the Canon Super-Smooth Polisher (CSSP). At this point, polishing of the tertiary mirror (M3) is almost complete, and the surface error on the whole mirror surface is 11.4 nm rms. The surface error of M3 is measured by the high-precision free-form measuring machine called as "A-Ruler" developed by Canon Inc. (see Figure 6) and is the value after gravity correction. The outer dimensions of M3 are 674 mm x 396 mm x 110 mm, of which the diameter of the effective-aperture on the surface is ϕ271 mm. The values of the surface error within the effective-aperture at the eight-different location on M3 surface were all good and its average value was 6.9 nm rms. In addition, the measured surface error is input to the optical model of the optical analysis software, and the influence on the optical performance was evaluated. Polishing and measurement are being carried out sequentially for other mirrors as well, and the surface error levels equivalent to M3 are expected. It should be noted that the precision polishing process of the mirror has been performed after assembled with mirror support and CFRP structure, so that any errors associated with assembly are eliminated (see 2.3 about the mirror assembly).

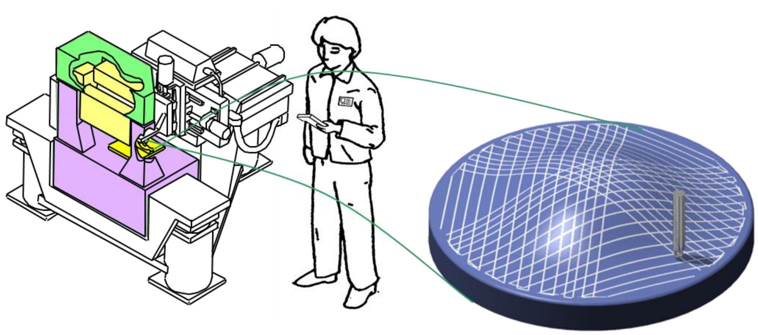

Figure 6. The appearance drawing of the high-precision free-form measuring machine "A-ruler" and its measurement method are shown (the illustration is provided by Canon Inc.).

As shown in the Figure 6, A-Ruler is a contact type measuring device. For the measurement by A-Ruler, the gravity direction is uniquely along to Z-axis and thus the mirror deformation by gravity is obtained from only analysis. Since it is our first experience to evaluate a large, off-axis aspherical and lightweighted mirror for space optics by using such device, we also prepared the surface shape measurement system with a laser interferometer and a computer-generated hologram (CGH) for both M1 and M3. This is positioned as a backup plan to eliminate errors due to uncertainty of gravity correction and strengthen verification.

Figure 7 shows the configurations of measurement system using CGH. Both M1 and M3 are off-axis aspherical mirrors and their curvature of radius are very large (up to about 8 m), so that influence of atmospheric fluctuation cannot be avoided in measuring the surface shape. Although not shown in the photograph, a cavity covering the entire measurement system is prepared, and temperature fluctuation in the cavity is sufficiently suppressed by performing stable air blowing from the upper part. By doing this, very high measurement reproducibility (order of a few nm) could be realized.

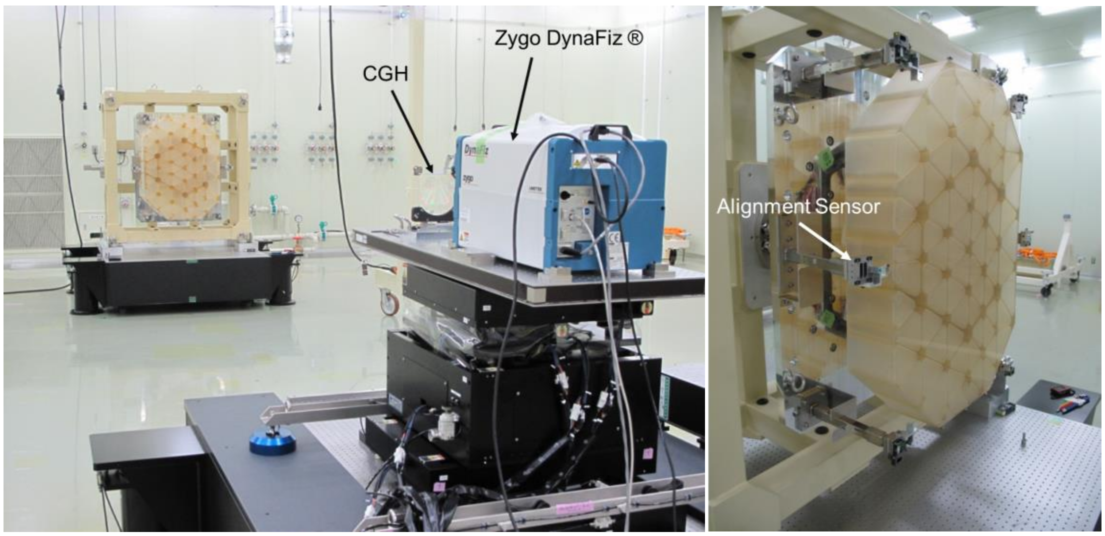

Figure 7. The measuring system for off-axis large aspherical mirror surface using CGH (left). Several sensors are installed around the mirror to measure the alignment status between the mirror and the CGH (right). The specimen shown in the picture is the engineering model of M1.

It is necessary to mention that the direction of the mirror against gravity in the measurement. Although lightweighted mirror cannot avoid large deformation under gravity environment, each mirror of WISH is designed to minimize deformation when gravity is applied in the Y-axis direction. In addition, the mirror stage can change the gravity direction to the mirror by 180 deg and it is possible to obtain the surface shape in the zero-gravity state from the average value of the measurement results of Y $\pm$ 1 G. In the measurement of the surface shape of the aspherical mirror, the alignment accuracy between the mirror and the CGH-interferometer is very critical. The CGH and the interferometer are installed on the high precision 6-axis control stage, and the CGH is designed to be able to project the fiducial mark toward the test mirror. In the configuration of measurement, several alignment sensors are placed around the mirror to be tested, and by these sensors imaging the fiducial marks which are projected from CGH, it is possible to measure the alignment of the system with high accuracy.

Up to now we have polished M1 and M3 by comparing the measured value by A-Ruler and the measured value by CGH, but a slight inconsistency remains. Since a small astigmatism component appears only in the data measured by CGH, the discrepancy is suspected as a problem of system alignment. Currently, we are trying to solve this problem promptly, but even if this aberration is real it has also been confirmed that it is a level that can be canceled by mirror alignment at the time of assembly of the optical system.

3.2 Assembly and alignment of optics

Assembly of optics is done by using 3D coordinate measuring system (CMM). The side of each mirror is attached with several reference balls, and the mirror surface shape and the optical axis of each mirror are linked with the position of these reference balls. By bringing the probes of the CMM into contact with these balls, the relative position between the mirrors is measured correctly, and the alignment adjustment is performed so that each mirror comes to an ideal position.

First, the truss structure of the M1 & M3 side and that of the M2 & M4 side are independently assembled. The measurement of CMM is performed by changing the direction of gravity with respect to the Y-axis of the WISH's coordinate system (see 2.3) by 180 deg using the rotation stage. By using this procedure alignment is iterated so that the position of the mirror becomes the best under zero gravity. Each of the six CFRP rods supporting each mirror assembly has high definition turn-buckles (about 10 μm order resolution in the longitudinal direction) and the position of the mirror can be adjusted in six degrees of freedom, just like a Stewart platform. Once the assembly of M1 & M3 side and M2 & M4 side are completed, they are attached to the center section (see Figure 3 upper left) for the integration of total optics.

The final integration is carried out at the factory of Crystal Optics Inc. which owns an extra-large CMM (Carl Zeiss MMZ-G30/60/20 see Figure 8). The work space of the CMM is very large (3 m x 6 m x 2 m), and the entire optical system of the WISH is completely covered.

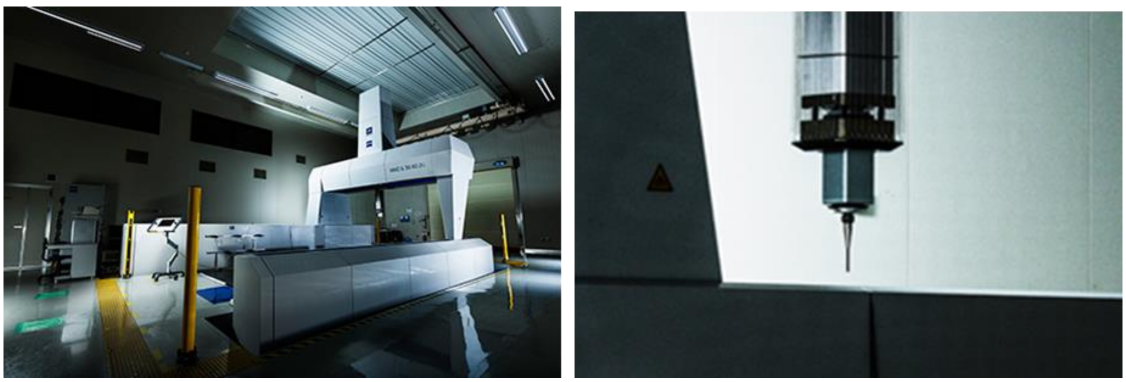

Figure 8. The picture of extra-large 3D coordinate measuring system (CMM) in the factory of Crystal Optics Inc. (left). A probe of the CMM is also shown (right). These pictures are provided by Crystal Optics Inc.

The state of the verification work of alignment adjustment procedure using the WISH structural model (SM) is shown in Figure 9. The optical system is assembled on a large CFRP plate called a base plate which has an interface to the satellite bus, and the whole system is installed on a stage that can rotate around the Z-axis. As described above, the alternately measurement under Y+1G or Y-1G configuration is conducted by using this rotation stage in order to obtain the best alignment on orbit.

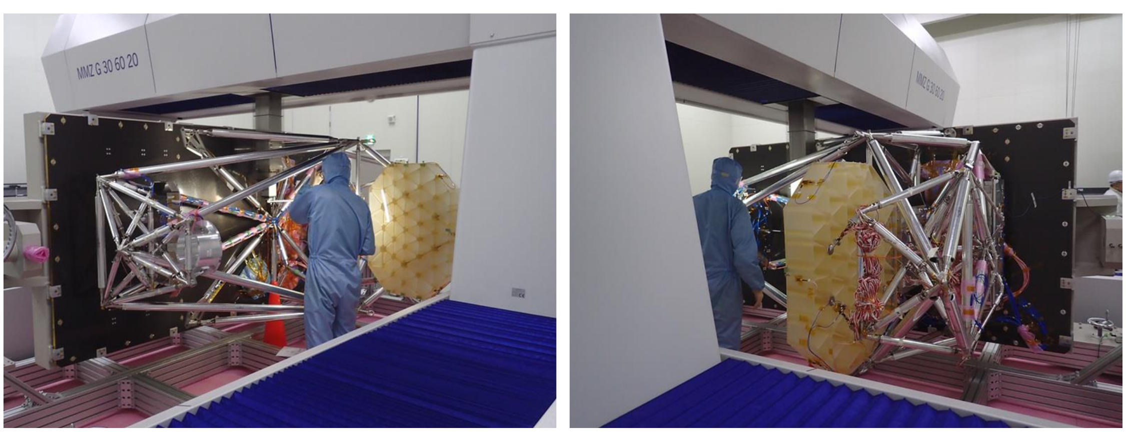

Figure 9. Verification of high precision assembly procedure using CMM.

4. PROTO-FLIGHT TEST AND SCHEDULE

As described above, all PFM mirrors are already advanced to the precision polishing process. After the polishing is completed, the thermal cycle test and the vibration test would be performed individually for each mirror, and then the Ag coating process for all mirror would be done. After that, the overall assembly of the optical system with the procedure described previous section would be started, and the optical performance test would be made during last quarter of this fiscal year.

The optical performance test would be carried out by the optics only, first. The total wavefront error (WFE) of the optical system is measured by the double pass configuration with a high precision flat mirror (ϕ650 mm) and a laser interferometer. To cope with the wide field of view of the optics, the flat mirror is designed to maintain the surface accuracy of 12.6 nm rms in the angular range of ± 5 deg. Furthermore, since the flat mirror can be moved in the X-Y plane, the residual surface error associated with the flat mirror would be separated from the wavefront error of the specimen.

For measurement of WFE under vacuum, a Shack-Hartmann sensor will be used instead of a laser interferometer. This Shack-Hartman sensor system is designed so that it can be used from the -X axis plane side of WISH by a folding mirror inserted into the optical path, therefore, the wavefront error can be measured after mounting the FPA and OSA attached. FPA and other electronic component would be merged to the optics at the timing of completion of the performance test of the optics, the total assembly process of WISH and the subsequent proto-flight test (PFT) of WISH would be executed.

After FPA is installed, the total opto-electrical performance test as one of the PFT is carried out using a collimator. The effective aperture size of the collimator is ϕ625 mm, and the field of view is 0.16 deg. An off-axis optical system with the comparable focal length to WISH, is designed so as to have optical performance equal to or higher than those of specimen. There are various charts used for the MTF measurement on the focal plane of the collimator, MTF in the TDI imaging mode of WISH is measured by moving the chart with a ground speed. In addition to the above, as opto-electrical tests, the total radiometric properties and the effects of stray light from outside the field of view would be measured by using a large integrating sphere. Also, ordinary mechanical environmental test (vibration test, acoustic test) and thermal vacuum test should be conducted. Using the above Shack-Hartmann sensor, confirm that there is no change in optical performance before and after each environmental test.

With the current prospects, PFM manufacturing and subsequent PFT would be completed by the middle of FY 2019. After that, WISH PFM would be delivered to the satellite system for total integration.

5. SUMMARY

This paper described about specifications, final design, its fabrication procedure, and the outline of proto-flight tests of the wide-swath and high-resolution optical imager (WISH) onboard Advanced Optical Satellite (ALOS-3). The development of WISH is now in the final stage of the critical design phase. The development test of the major components using the engineering model has been completed and the final design is confirmed that it satisfies the specification of WISH.

Fabrication of PFM is already advanced with respect to the component whose design is fixed at an early stage or which can utilize past heritage. For the optical system, polishing of all mirrors are in the final stage, and the comprehensive assembling work of the optical system would be started within this fiscal year. Until middle of FY 2019, all proto-flight test of WISH should be completed, and WISH would be delivered to the ALOS-3 satellite system. ALOS-3 would be scheduled to launch from Tanegashima Space Center of Japan in FY 2020.

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