Telescope Co-Alignment Design and Its Performance On-Orbit of Solar Observational Satellite “Hinode”

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The three telescopes on Hinode, a highly sophisticated solar observational satellite, must be able to simultaneously observe the same point on the sun in order to ascertain data on the physical mechanisms for activity and heating in the solar atmosphere. To fulfill this mission requirement, the telescopes must remain co-aligned to within 2.0 arcsec under the temperature fluctuations the satellite experiences while orbiting the earth. Hinode consists of two modules and a connecting structure. Most of the structural elements are made of CFRP in order to suppress thermal deformations. In particular, the laminate configuration of the CFRP in the module holding the telescopes was carefully designed in terms of not only its stiffness and strength but also its coefficient of thermal expansion and thermal conductivity. A thermal deformation analysis was performed to estimate the co-alignment drift on-orbit and a thermal deformation test was conducted to verify the estimation. The results showed that the structural design would sufficiently suppress the drift on-orbit. Measurements on-orbit were conducted using the image of the sun, and the measured drift was in good agreement with the estimation.

Key Words: Co-Alignment, Thermal Deformation, Structural Design, Dimensional Stability

Abbreviations

CCR: corner cube reflector
EIS: extreme-ultraviolet imaging spectrometer
FPP: focal plane package
OBU: optical bench unit
OTA: optical telescope assembly
SOT: solar optical telescope
UFSS: ultra fine sun sensor
XRT: X-ray telescope

tailoring technique to control the CTE of graphite/epoxy composites.

Thermal deformation analysis is a technique to improve the dimensional stability. It analyzes the distribution and magnitude of the thermal deformation, and its results can be used to enhance the dimensional stability.4,5) Garnich et al.6) proposed an approach called “antidistortion appliqués” for increasing the static dimensional stability of composite space structures. The advantage of this approach is that the adjustment to reduce the instability can be made after the initial fabrication.

Ground tests are needed for verifying the dimensional stability of a structure. Edeson et al.7) reported a procedure and measurement system in a novel series of tests on a breadboard high-stability optical bench structure. The on-orbit alignment measurement technique were reported on Resourcesat-I8) and the upper atmospheric research satellite.9)

The Institute of Space and Astronautical Science in Japan developed a sophisticated observational satellite, named Hinode, equipped with three advanced solar telescopes in the early 2000’s. It was launched on September 22nd, 2006 by a M-V scientific satellite launcher from the Uchinoura Space Center in Japan and was successfully put into sun-synchronous orbit. The three telescopes have started their unique solar observations and have already revealed remarkable solar dynamics that have never been seen before. Many studies based on these observations have been presented in journals such as Science.10) The mission require-
ment is that the three telescopes simultaneously observe the same point on the sun, and this calls for strict co-alignment stability between the three telescopes. Therefore, a careful thermal structural design was undertaken to satisfy this requirement. This paper illustrates the thermal structural design concept, thermal deformation analysis, and test of the main structure’s dimensional stability against temperature fluctuations. It also reports the co-alignment drift measured in orbit and compares it with estimates derived from the analysis and ground test results.

2. Overview of Hinode

Hinode is a highly sophisticated observational satellite with three advanced solar telescopes, the solar optical telescope (SOT), the X-ray telescope (XRT) and the extreme-ultraviolet imaging spectrometer (EIS). Its launch configuration is shown in Fig. 1. Hinode is 3.85 m high and weighs approximately 900 kg. The optical axis of each telescope is aligned precisely to the \( z \)-axis, i.e., the longitudinal axis of Hinode in Fig. 1. The SOT consists of two parts, the optical telescope assembly (OTA) whose main mirror has a 50 cm diameter aperture and the focal plane package (FPP). The sunlight concentrated by the OTA is sent to the FPP, where it is split for both its filter observations. The XRT, EIS, and FPP are attached to the optical bench unit (OBU) with mounting legs. The three telescopes observe the magnetic coupling from the photosphere to the corona, which is an important phenomenon for understanding the physical mechanisms of activity and heating in the solar atmosphere.

The ultra fine sun sensor (UFSS) is a key sensor used to point the telescopes to a target on the sun. It is able to detect the incident angle of sunlight in 0.12 arcsec of spatial resolution, and its zero-degree angle is precisely aligned to the \( z \)-axis, like the telescopes.

In this paper, we focus on the co-alignment stability between the telescopes and the UFSS. Since each telescope plays a different role in the observation, all telescopes must observe the same target at the same time. That means Hinode’s structure must retain strict co-alignment between the telescopes and the UFSS in addition to the pointing accuracy and stability of the attitude control system. Table 1 summarizes the co-alignment stability requirements for one hour of orbiting around the earth.

3. Structural Design

To meet the requirements listed in Table 1, it is necessary to reduce temperature fluctuations and induced thermal deformations by orbiting as much as possible. Hinode has three heat input factors: sunlight, radiation from the earth and internal heat from on-board components. The same surface of Hinode is almost always exposed to the sunlight because its \( z \)-axis points toward the sun during observation in sun synchronous orbit. The temperature distribution induced by the sunlight is almost constant irrespective of the orbital phase. The \( x \)-axis and \( y \)-axis of Hinode are nearly aligned to the north-south and east-west directions of the sun respectively, so that the surfaces exposed to the radiation from the earth change gradually in relation with the orbital phase. Thus, this radiation causes a temperature gradient that fluctuates according to the orbital phase. Internal heat from on-board components may yield a fluctuating temperature gradient.

The following structural design principles are based on the careful investigation of these heat inputs and the co-alignment requirements.

1) All the telescopes should be fixed to the same structural module, and the thermal deformation of this module should be extremely small.

2) The sensors for pointing Hinode toward the sun, such as the UFSS or gyros, should be placed as near to the telescopes as possible in order to reduce the co-alignment drifts between the telescopes and the sensors.

3) Electrical components, i.e., the heat sources, should be mounted together in a module apart from the telescopes, so that the thermal deformation due to their heat has less influence on the co-alignment drift of the telescopes and sensors.

Figure 2 shows the resulting main structure of Hinode, and Fig. 3 shows the main structure without side panels. The main structure consists of two modules, a bus module and a mission module. A truss called the OBU support truss connects the bus and mission modules. The XRT, FPP and EIS are mounted on the OBU in the mission module with mounting legs. The middle part of the OTA is mounted on the top of the OBU, and its lower half is inserted in the OBU.

To meet the severe thermal deformation requirements,
most of the elements of the main structure use CFRP. Two types of CFRP are used in the mission module and the OBU support truss in order to obtain optimal thermal and mechanical characteristics: highly elastic and conductive pitch-based carbon fiber and high-strength PAN-based carbon fiber. The resin is a cyanate ester that has little hygroscopic deformation on-orbit. Table 2 lists the mechanical and thermal properties of these CFRPs. The CFRP with highly elastic and conductive carbon fibers is labeled type-A, and the CFRP with high-strength carbon fibers is labeled type-B.

### 3.1. Bus module
The bus module is box-shaped as shown in Fig. 2. Since Hinode always keeps its z-axis toward the sun, four side panels are designed to work as radiator panels. Almost all of the components are directly mounted on their inside surfaces. One of the key problems of its design was how to isolate the mission module from its thermal deformation, especially, considerable thermal deformation of the side panels due to the application of aluminum alloy to their face sheets. The central cylinder and the face sheets of the panels other than the side panels are made of CFRP for the reduction of the thermal deformation itself. Moreover, the central cylinder is designed to be stiff enough that thermal deformation of the side panels causes less elastic deformation in it. Consequently, the influence of the side panels’ thermal deformation on the elastic deformation of the OBU is mitigated while it is being transmitted to the web panels, the central cylinder, and the OBU support truss.

### 3.2. OBU support truss
A structural element connecting the bus module and the mission module is required to suppress the thermal deformation itself and to reduce the heat going from the bus module to the mission module. As shown in Fig. 2, a truss, named the OBU support truss, was selected because its mechanical and thermal properties could be designed by making its struts of CFRP laminate. Each strut is composed of a CFRP laminate tube and end fittings with pin joints. The laminate configuration of the struts is carefully investigated as to whether it meets the requirements and has the CTE robustness against manufacturing errors in the fiber orientations. The result shows that one-third of the laminate is type-A CFRP and the remaining two-thirds of the laminate is type-B CFRP. All of the fibers of the type-A CFRP’s laminate are oriented along the longitudinal axis to increase the longitudinal stiffness. The fiber orientations of the type-B CFRP’s laminate are designed in order to reduce longitudinal CTE and increase longitudinal strength. The tubes have 188 GPa in longitudinal stiffness and 0.04 × 10⁻⁶/K in the longitudinal CTE. Heat transfer of the struts is reduced by making the end fittings of titanium alloy and the heat resistance of the pin joints.

### 3.3. Mission module
As shown in Figs. 2 and 3, the mission module consists of four parts: the IRU box, UFSS tower, mounting legs and OBU. The IRU Box carries gyros and is attached to the OBU. The UFSS is mounted on top of the UFSS tower. This tower is designed so that the UFSS is as near the sun as possible so that reflected stray sunlight from Hinode’s outside surface does not enter it.

#### 3.3.1. OBU
The OBU is a cylindrical structure, and a key element to meet the co-alignment drift requirements. A part of the OBU surface exposed to radiation from the earth changes gradually with the orbital phase. Therefore, it has a circumferential temperature gradient that also varies with the orbital phase. The result of thermal deformation analysis indicates that the z-axis CTE of the OBU is more sensitive to the co-alignment
drift than the circumferential CTE. Therefore, the OBU needs to have an extremely low CTE in the \( z \)-axis direction and high thermal conductivity in the circumferential direction to reduce the circumferential temperature gradient. The robustness of these properties against manufacturing errors in the fiber orientation angles was also taken into account. Approximate optimization was conducted under the mass budget restriction. Type-A CFRP is used in two-thirds of the laminate thickness of 1.65 mm. Its fiber orientation angles are determined so that the laminate has large thermal conductivity in the circumferential direction. Type-B CFRP is used in the remaining one-third. Its fiber orientation angles are determined so that the laminate has an extremely low CTE in the \( z \)-axis direction and is strong enough to bear the expected load during launch. The CTE of the laminate cylinder in the \( z \)-axis direction is \( 0.03 \times 10^{-6} / \text{K} \) and the thermal conductivity in the circumferential direction is \( 1.4 \times 10^3 \text{ W/m-K} \). This thermal conductivity is almost the same as that of aluminum alloy 5052.

3.3.2. Mounting legs

The co-alignment requirements shaped the required functions of the support structure fixing the telescopes to the OBU as follows.

1) The co-alignment of the telescopes should be easy to adjust with high accuracy during assembly and should have good repeatability in its re-assembly.

2) It should relax the initial deformation of the OBU and the telescopes due to inevitable dimensional errors of their structural elements during assembly.

3) It should mitigate the elastic deformation of the OBU (telescopes) caused by thermal deformation of the telescopes (OBU).

4) The OBU should be thermally isolated from the telescopes.

To satisfy these requirements, it was concluded that each telescope needed to be fixed at three points that are as statically determinate as possible. Then, mounting legs were proposed. Its schematic view is shown in Fig. 4. The legs consist of rods, flexures, interface brackets and OBU brackets. The flexures are put at both ends of each rod in order to decrease its bending stiffness for satisfying the second and the third requirements.

A set of mounting legs for the XRT is shown in Fig. 5. Similar sets are used for the EIS and FPP. Each telescope is supported at three points A0, B0 and C0. Point B0 is able to move in the direction of the \( z \)-axis. Point C0 is able to move perpendicular to the longitudinal axis of the mounting leg. Consequently, the 6 degrees of freedom of the telescope are fixed. For the purpose of the thermal isolation between the OBU and the telescopes, the structural elements, except the longest rod forming point A0, are made of titanium alloy. The longest mounting leg is approximately four times longer than the others, and it is only the leg that is closed to being in the \( z \)-axis direction. Accordingly, the variation of its length has a much larger sensitivity to co-alignment drift. Therefore, its rod is a CFRP laminate tube with the same laminate configuration as used for the OBU support truss in order to achieve low CTE.

4. Thermal Deformation Analysis

To confirm that the design satisfied the co-alignment requirements, thermal deformation analysis was performed on the finite element model. Several thermal cases predicted in orbit and given in thermal deformation tests on the ground were analyzed.

Figure 6 shows an analytical result on the thermal deformation under the condition that only the \( -X \) side panel in the bus module is heated to 4 K. Since each side panel is a honeycomb sandwich panel with aluminum alloy face sheets, the \( -X \) side panel elongates as a result of the temperature increase. Although it causes a large elastic deformation in the bus module, it yields a rigid rotation of the mission module around the \( y \)-axis with less co-alignment drifts between the telescopes and the sensors. Figure 7 shows the co-alignment drifts of the telescopes due to orbiting. The thermal condition of this analysis is that Hinode observes the sun of the strongest light intensity at the end of the mission life. The reference axis of the co-alignment drifts in this figure is the \( z \)-axis of the OBU. The initial temperature in all elements of Hinode is set to be 20°C, the temperature in the assembly room. The shift of the average on-orbit temperature of each element causes offset in each locus of the
co-alignment from the origin. Each locus is drawn due to the temperature fluctuations resulting from orbiting. None of the loci becomes a fine ellipse because the heaters attached in the structures works in a certain period during orbiting to keep temperatures of some components within the allowable range. The thermal deformation analysis shows that the co-alignment drifts of the telescopes and the sensors are smaller than the required ones shown in Table 1.

5. Thermal Deformation Test

A thermal deformation test was conducted in order to verify the co-alignment design of telescopes and sensors and, if necessary, to revise the mathematical model of the thermal deformation analysis.

5.1. Test configuration

A schematic view of test configuration is shown in Fig. 8. Instead of the actual telescopes, a dummy panel corresponding to the OTA is directly attached to the OBU, and dummy panels corresponding to the FPP, EIS and XRT are attached to the OBU using mounting legs. The mechanical interface of each dummy panel is identical to the corresponding telescope. To reduce the measurement error caused by thermal warping of the dummy panels, we use 30 mm-thick aluminum honeycomb sandwich panels with CFRP face sheets with CTEs of $-0.7 \times 10^{-6}$/K. A laser interferometer positioning system is employed to obtain the relative displacement between the dummy panels. Panel A has a laser emitter, beam splitters and interference units. In order to calculate the co-alignment angle from measured displacements, four corner cube reflectors (CCRs) are put on Panel B and C, respectively. The dummy panels for the XRT and FPP corresponds to Panel A. The dummy panel for the OTA corresponds to Panel B. The UFSS tower and the dummy panel for the EIS correspond to Panel C. Figure 9 shows a scene from the thermal deformation test.

5.2. Measurement error evaluation

The ideal resolution of the laser interferometer positioning system is 0.01 µm. However, since the measured data include measurement errors, it was necessary to evaluate it before performing the test in order to obtain a reliable test result. We take three factors into account, i.e. the internal thermal deformation of the interference unit, thermal deformation of CCR and its holder and the test room environment. The errors due to the first two factors are derived from the manual and the calculation. The error in the test room environment is due to fluctuations in the air temperature and base micro-vibrations. An experiment was carried out.
in order to estimate the magnitude of the data fluctuation due to the test room environment. The distance between the interference unit and the CCR is set to approximately the same distance in the thermal deformation test. The measurements are made by repeatedly moving the CCR in the range of 10 μm. The result indicates that averaging of the measured data over approximately 10 s could reduce the data fluctuation. The estimated residual error after averaging is below 0.05 μm. Consequently, the total error in this measurement system is estimated as 0.47 μm where the temperature fluctuation of the interference units and the temperature difference between the CCR and its holder during the measurement is empirically and conservatively set to 3 K. In the thermal deformation test, we make the temperature distribution so that the structure yields much larger displacements at the measuring points than this total error.

We also take into account errors due to warping of the dummy panels induced by temperature differences of its face sheets. Although the face sheets are made of low CTE CFRP, the deformation sensitivity between two CCRs 0.85 m apart in the dummy panel is approximately 17 μm/K. This sensitivity is quite large compared to the error of the measurement system. Thus, we cover the dummy panels with insulators to prevent radiation heating from sources such as film heaters. Additionally, because the laser emitter, which dissipates a lot of heat, is on the dummy panel, we fix the laser emitter to the panel through insulating collars (see Fig. 8). An experiment to access the effectiveness of these adiabatic approaches was conducted before the thermal deformation test. The result shows that the temperature difference between face sheets is below 0.1 K. In the test, the temperature distribution of the dummy panels is measured to determine the influence of warping.

5.3. Test results

Since it was difficult to simulate the on-orbit temperature distribution, we tested more than 10 typical temperature distributions to confirm the accuracy of the mathematical model. Figure 10 shows the test result in the case of heating the upper half of the OBU. Some of the mounting legs attached to the upper part of the OBU are also heated. This figure shows the displacements from the dummy XRT panel. “Up” indicates the displacement at the upper CCR B1 or C1 in Fig. 8. “Down” indicates the displacement at the lower CCR B2 or C2. Each column has three bars. The right bar indicates the measured displacement in the test. The center bar is the displacement calculated by applying the measured temperature distribution to the mathematical model. The left bar is the displacement calculated by applying the measured temperature of only the mounting legs to it. The calculated displacements are in good agreement with the measured ones. Moreover, the thermal deformation of the mounting legs seems to be the dominant factor of the co-alignment drifts of the telescopes and sensors.

Table 3 shows the co-alignment drifts by orbiting in the case of the longest eclipse duration. It is estimated using the correlated mathematical model according to the test results. The results of the thermal deformation test indicate that the structural design works as well as expected and the estimated on-orbit co-alignment drifts are small enough to meet the requirements in Table 1.

6. Co-Alignment Drift by Orbiting

After the successful launch in September 2006, the Hinode team has regularly performed co-alignment measurements between SOT and XRT in order to monitor the pointing drift. These measurements have been executed by limb observations to the north and east of the sun, with a few hours runtime for each of the limbs. Using the limb seen in the CCD frames from each telescope, we could monitor how the co-alignments between the telescopes and the sensor drift over time.

Figure 11 shows representative co-alignment drifts of the XRT and SOT field of views from the UFSS as a function of the argument of latitude of which zero is the ascending node. Since the limb observation ran a few hours, Hinode orbited approximately two times during the observation. Accordingly, the argument of latitude in the figure exceeded 360 deg when Hinode went on its second orbit. This data was measured on 14 February 2007. It is obvious from this figure that both the co-alignment drifts \( \theta x \) and \( \theta y \) of the XRT pointing are quite similar to those of the SOT pointing. The co-alignment drifts are well repeated with the period of the orbiting.

Figure 12 shows the predicted co-alignment drifts of the XRT and SOT from the UFSS on the basis of the thermal deformation analysis using the correlated mathematical model based on the ground test. Comparing Figs. 11 and 12, we see that, although the amplitude of the co-alignment drifts and the shapes of the curves show some differences, the predicted co-alignment drifts approximately agree with the measured ones. As for the amplitude difference, the
measured co-alignment drifts are approximately 1.5 times larger in amplitude than the predicted drifts. It is presumed from the temperature data measured in orbit around the IRU box (see Fig. 3) that the actual temperature fluctuation by orbiting is approximately 1.3–1.7 times larger than predicted. This difference is considered to be the cause of the larger drift on-orbit. As for the shapes of curves, it was predicted that the co-alignment drift curves were deformed from a simple sinusoidal wave because of the heater operation in the IRU box to maintain the temperatures of the gyros in it. Since the measured temperatures on-orbit are higher than predicted, the duty of heaters attached in the IRU box is less than planned. This fact results in the curves of the measured drifts resembling sinusoidal waves rather than the curves of the predicted drifts.

Figure 13 summarizes the co-alignment drifts between the SOT and XRT. The predicted drifts, indicated as “Predicted,” are obtained from the ground tests and analysis. Each predicted drift is composed of two parts. “Main Structure” is the contribution due to the thermal deformation of the main structure. This part is what we have addressed in this paper. The other, indicated as “SOT Internal,” is the contribution due to the positional shifts of the mirrors in the SOT induced by the temperature fluctuations. The measured drifts, indicated as “Measured,” include both parts. These parts could not be distinguished because the measured drifts are calculated using the images of the sun. They are in good agreement with the predicted drifts in both rotations to sub-arcsec accuracy. Slight differences are presumed to be due to a larger temperature fluctuation than predicted. Additionally, the measured drifts are sufficiently smaller than the budget, indicated as “Budget” in the figure. Consequently, the on-orbit measurement proves that the design of Hinode’s main structure satisfies the stringent co-alignment requirement for the SOT and XRT.

7. Long-Term Co-Alignment Drift

Figure 14 shows the long-term co-alignment drifts from the XRT to the SOT. The shaded areas between dashed lines indicate the period that an eclipse occurred in an orbit. Each solid circle indicates the measured co-alignment by the cal-
8. Concluding Remarks

Hinode was designed to meet the strict requirement for its three telescopes to simultaneously observe the same point on the sun to within a few arcsec in co-alignment drifts between them under temperature fluctuations due to orbiting. Most of the structure was made of CFRP to suppress thermal deformations. The laminate configuration of CFRP in the module holding the telescopes was carefully designed in terms of not only its stiffness and strength but also its coefficient of thermal expansion and thermal conductivity. An analysis and a test were performed to verify the design. After the launch of Hinode, measurements of the co-alignment drifts on-orbit were conducted using the image of the sun, and it was confirmed that the measured drifts were within the requirement and in good agreement with the estimation, especially to sub-arcsec accuracy for the drift due to orbiting. Therefore, we concluded that the co-alignment design of Hinode and its verification procedure succeeded in fulfilling the full potential of Hinode’s observational ability.

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