# ALIGNMENT OF ASPHERIC OPTICAL SURFACES AT GODDARD SPACE FLIGHT CENTER

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## 1. INTRODUCTION

Aspheric optical surfaces are becoming common in optical design. Fabrication efforts have improved, costs have reduced, and aspheres allow a designer to control more degrees of freedom using fewer surfaces. However, testing and alignment of aspheric surfaces is considerably more difficult than that of spherical surfaces. Testing requires expensive null lenses, and alignment requires numerous datums. Optomechanical alignment of aspheric surfaces began at Goddard Space Flight Center (GSFC) in the early 1980's. Since then, many instrument designs have included aspheric optics, including *COBE/DIRBE*, *HST/COSTAR*, *SIRTF/IRAC*, *Cassini/CIRS*, *HST/WFC3*, and *IRMOS*. We outline the alignment procedure using datums, testing of aspheric surfaces using computer generated holograms, and the independent verification of alignment via interferometry and image testing. Recently, GSFC has been developing the *Infrared Multi-Object Spectrometer* (*IRMOS*). This ground-based, imaging spectrometer is a MEMS-technology demonstrator for the *James Webb Space Telescope*, and is built in collaboration with the Space Telescope Science Institute and Kitt Peak National Observatory. The optical design includes four aspheric surfaces, one of which can be characterized as free-form. We detail the methodology in aligning the datum surfaces of the optics to the instrument bench, and the verification of optical performance.

## 2. HISTORY

Optomechanical alignment of optical surfaces began at the Goddard Space Flight Center (GSFC) in the early 1980's. The area used to assemble instruments and spacecraft was called the optical alignment facility (OAF).[1] The purpose of the OAF was to determine the relative alignment between different components of a spacecraft with respect to a common coordinate frame. To accomplish this, a spacecraft was mounted on a precision rotary table, and theodolites were used in autocollimation to locate mirrors or alignment cubes mounted to the optics. Prior to assembly, the location of each datum was determined with respect to the optical axis of its component. A common azimuth origin was referenced by the theodolites, and a common elevation origin was established using the gravity vector. After all the datums were measured with theodolites, each measurement went through a coordinate transformation to put the measured vector in a base coordinate system, or reference frame. This frame can be arbitrary, but was usually chosen to correspond with a spacecraft-based coordinate system. The data was handled with a computer program called OAFDAP, and is still used today.

The above procedure was used to locate components in rotational degrees of freedom. To locate components in translation, other methods were used. A cathetometer is a telescope on an orthogonal, two-axis translation stage. Cathetometers were used to measure the location of the edges of optics, and also to measure the distance between an optic and a relevant surface of the spacecraft. After a common coordinate system was established (spacecraft based), the optics were aligned by measuring and adjusting their translational offsets. Theodolites were also used to align in translation, using triangulation. First, a stationary length standard is measured with several theodolites, such that the three-dimensional position of the theodolites can be determined. Next, the theodolites view each other in autocollimation. Finally, identical points on the target (spacecraft or optic) are viewed through multiple theodolites (not in autocollimation, but at finite focus). With computer analysis, the translational position of the target can be determined.

Eventually, the datums became integral with the optic. Instead of mounting an alignment cube to the back (or edge) of an optic, flat surfaces are polished or diamond machined on the rear (or side) of an optic. These flat surfaces allow the optic to be located in three rotational degrees of freedom. Instead of viewing the edge of an optic, a fine mechanical scribe (fiducial) is machined onto the rear (or side) of an optic. These fiducials allow the optic to be located in three translational degrees of freedom.

## 3. METROLOGY

In order to use datums to align an optical system, it is necessary to know the location and orientation of the datums with respect to a feature of the optical surface prescription (e.g., the vertex). This is a complicated, expensive, and time-intensive step for aspheric optics. We describe two methods to match a datum to the vertex : interferometry, and contact profilometry with a coordinate measuring machine (CMM).

To measure wavefront quality and the position of a vertex, a matching null wavefront must be generated. Because aspheric optics are usually designed to play a specific role in an instrument, they are not mass produced. Thus, null aspheric wavefront generators are not produced in bulk. They are custom built for each aspheric surface, and called null lenses. The null lens must be aligned using its own fiducial system to the interferometer before its matching asphere is tested, which adds time and complexity to the testing schedule. When the null lens and optic are aligned to the interferometer, the optical vertex may be related to the datums. An example of a null lens is a computer generated hologram (CGH). A CMM may also be used to measure the location of the datums, with respect to the optical surface/vertex. A probe is attached to a digitally controlled arm on the CMM, and senses and maps the optical surface in a grid pattern. The probe then touches the datums and determines their relative positions. Choosing between these metrology methods depends on the necessary level of knowledge of the datum/vertex relationship.

## 4. VERIFICATION

After an instrument has been aligned using the optomechanical techniques described above, it is necessary to verify alignment. There are two methods used for alignment verification : interferometry and image testing (including wavefront sensing). The optical model predicts wavefront errors in the design, and system level testing should match the prediction. The optical model also predicts image size and morphology. An end-to-end image test in agreement with the model proves that the aspheres were characterized and aligned correctly, or provides input for correcting or compensating for misalignment.

In the 1990's, GSFC aligned the *Composite Infrared Spectrometer* (*CIRS*) for the *Cassini* mission to Saturn. After aligning the optics as outlined above, the instrument underwent independent verification of alignment via interferometry.[2] It was determined that the wavefront error and instrument boresight were within tolerance. The second method of alignment verification is image testing. A simulated point source is located at the center and corners of the instrument focal plane, and the image quality is assessed at the detector. The PSF size and morphology through focus agreed with that predicted by the instrument model.

## 5. EXAMPLE : THE INFRARED MULTI-OBJECT SPECTROMETER

Recently, GSFC has been developing the *Infrared Multi-Object Spectrometer* (*IRMOS*). The imaging spectrometer is a MEMS-technology demonstrator for the *James Webb Space Telescope*, and its optical design includes four aspheric surfaces, including a biconic (free-form).[3] We detail the methodology in aligning the datums of the optics to the instrument bench, and the independent verification of optical performance.

### 5.1 Facility

The *IRMOS* optical bench consists of two plates (top and bottom) connected by four longerons (beams). During population, the bench is bolted horizontally to an L-bracket fixture attached to a rotary table. We define an alignment coordinate system (ACS) whose origin is located at a fiducial at the center of the outside of the top plate (Figure 1). There are four fiducials (at the four poles)

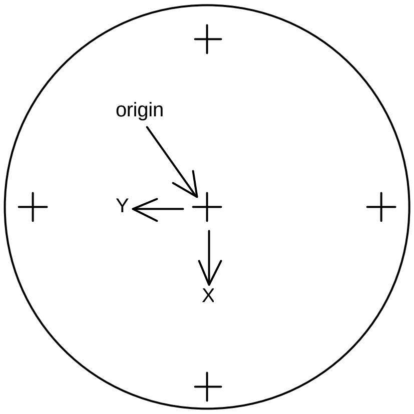

Figure 1. Schematic of the outside of the top plate, with ACS.

near the edge of the top plate, and lines connecting these fiducials through the center fiducial define the x and y axes. The z axis is defined orthogonal to the plane of the top plate, and positive towards the bottom plate.

Several pieces of hardware are included in the population assembly: the L-bracket, a precision rotary table,[*] a flat granite table, and a tip/tilt plate above and below the rotary table for leveling its axis of rotation and the plane of the optical bench (Figure 2). The gravity vector is perpendicular to the horizontal plane of the L-bracket and to the rotation plane of the rotary table to ±2 arcsec. The rotation stage rotates at one degree intervals around a full circle.

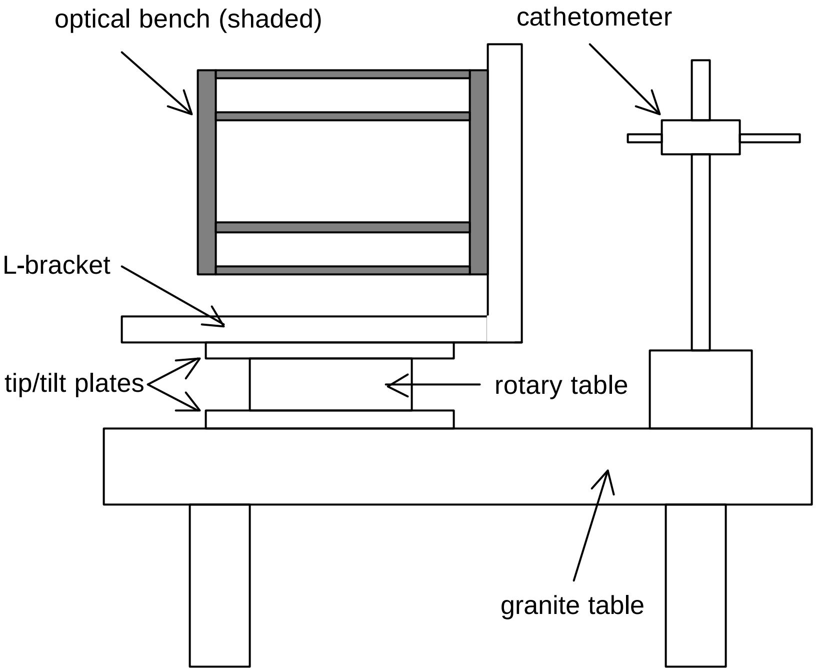

Figure 2. Side view of the bench/L-bracket.

The cathetometer is aligned to the ACS in three rotational degrees of freedom. The telescope on the cathetometer points perpendicular to the plane defined by the axes of the cathetometer, and directly along the z axis. The telescope translates horizontally along the y axis, and translates vertically along the x axis (parallel to the gravity vector). Theodolites are mounted on movable stands, and are positioned around the table as needed.

### 5.2 Datums

The *IRMOS* optical design includes four aspheres and two fold flats. Each mirror is equipped with a set of datums that allow alignment to the ACS in six degrees of freedom. The datums are placed on the optic during fabrication in a manner that can be related to the origin of the parent surface (vertex).[4] There are three sets of datums as follows (Figure 3):

1. The rear surface of the substrate is diamond machined flat to < 0.25 $\lambda$ RMS. A theodolite is used in autocollimation with the rear surface to orient the optics in tip ($R_x$) and tilt ($R_y$).

2. Three thin scribe crosshairs are machined onto the rear surface of the substrate. These fiducials lie along a line that is parallel to a line from the center of the mirror aperture through the vertex. A cathetometer is used to locate these fiducials and align the optics in x, y, and clocking ($R_z$).

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[*] AA Gage, Sterling Heights, Michigan, tel.: (810) 977-9000

3. One crosshair fiducial is inscribed on each side of the rectangular substrates. A cathetometer is used to locate these fiducials from the side to align the optics in z (focus).

Fabrication tolerances for the datums (with respect to the vertex) are as follows: the aperture is located to better than ±0.125 mm. The placement tolerance of the rear fiducials is ±0.125 mm, and the knowledge tolerance of the fiducials is ±0.025 mm. The side fiducials have a best effort placement tolerance and a knowledge tolerance of ±0.125 mm. The angular orientation of the rear surface is ±30 arcsec in placement and ±15 arcsec in knowledge. The vendor achieved significantly better placement and knowledge of the datums. For all mirrors, the placement and knowledge of the fiducials is ±0.011 mm. The rear surface is established at ±10 arcsec and measured to ±1 arcsec. We verify alignment fiducial knowledge during component level acceptance testing at GSFC.[5]

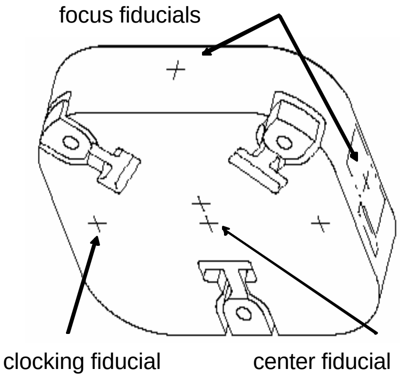

Figure 3. The rear of a typical mirror substrate. The center fiducial is at the center of the mirror aperture as projected parallel to the optical axis.

### 5.3 Alignment

The instrument ray trace model is generated with ZEMAX.[*] For each optic, the model provides the angular and translational offset from the origin. The center fiducial on the top plate is chosen as the translation origin, the plane of the top plate is chosen as the x-y plane, and the vector orthogonal to the x-y plane and into the instrument is chosen as the z axis. A coordinate transformation is used to convert the direction cosines from the ZEMAX model into a laboratory measurable, namely theodolite azimuth and elevation. The translation offsets are easily measured because the rotary table can be rotated such that the cathetometer axes are parallel to the ACS axes.

System level bench population is accomplished in a sequential manner. Each optic must be aligned in six degrees of freedom. The mirrors attach to the bench via a mirror bracket (Figure 4). Between the bracket and mirror is a three point aluminum shim. To align each optic in tip and tilt ($R_x$ and $R_y$), a normal vector from the rear flat surface must match that predicted by the instrument model. The shims are inserted, measured, taken out of the bench, machined to the correct angle, and re-inserted. The thickness of the shim is adjusted to align the despace component (?z). The bench is rotated 90 degrees, and the side focus fiducial is measured and compared to its target location. Shim cuts usually took several iterations before alignment was acceptable : the machining precision was ~0.013 mm (corresponding to ~30 arcsec), the repeatability of installing and removing the shim was between 0.013-0.125 mm, and the alignment tolerance was between 0.025-250 mm. To align an optic in decenter (?x and ?y), the center fiducial on the rear is located with the cathetometer telescope. The designed offset from the origin is set on the cathetometer, and one operator sights through the telescope. A second operator places and nudges the optic until the center fiducial is aligned with the telescope. To align an optic in clocking ($R_z$), the rear fiducials (to the left and right of the center fiducial) must be in their designed orientation. The operators iterate between decenter and clocking. All optics are thus aligned to within their tolerances.[6]

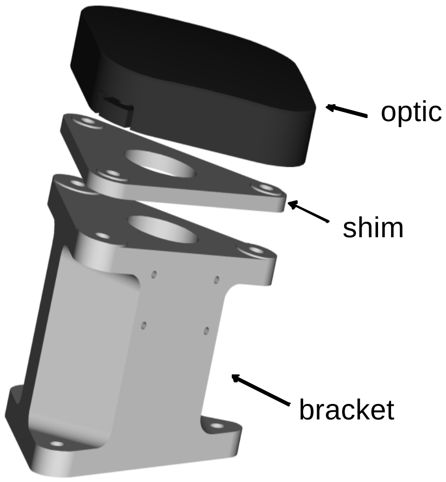

Figure 4. Bracket, shim, and mirror interface.

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[*] Focus Software, Tucson, Arizona, tel. (520) 733-0130

### 5.4 Verification

Interferometric alignment verification proves useful more as a guide than as a proof. During fabrication, the *IRMOS* mirrors developed mid-frequency and micro-roughness errors that were greater than expected. These errors are not well modeled, thus a quantitative comparison of expected vs. actual wavefronts is impossible. Instead, the qualitative features of the wavefronts are compared. A laser unequal path interferometer* (LUPI) is used to measure the *IRMOS* wavefront error. The LUPI is placed such that its optical axis points directly along the chief ray that would enter the instrument from the ground-based telescope. The center of the telescope focal plane is located with a 75 µm pinhole, and aligned in translations using the cathetometer. A spherical lens is attached to the LUPI, and the focus of the lens is translated until coincident with the pinhole. A spherical, reflective tooling ball (TB) is placed at the focus of the instrument such that a double-pass interferogram is obtained (Figure 5). General features of the modeled and measured wavefronts are in agreement.[6]

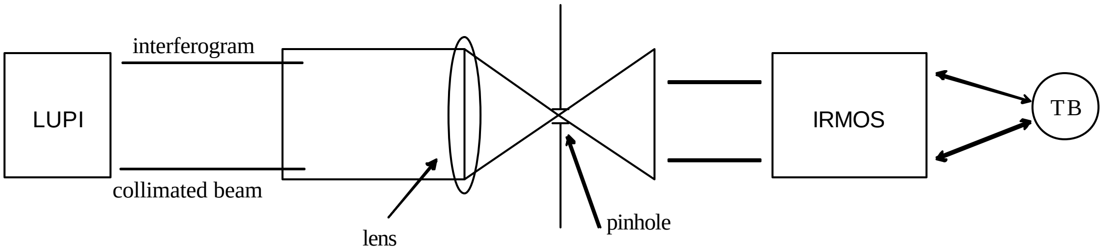

Figure 5. Schematic of the double-pass interferometric setup.

Image testing provides a more robust proof of alignment. Imaging is performed using a 75 µm pinhole backlit with a white light source, with the imaging grating and Z-band filter in the optical path. The center and four corners of the field are tested. A two-dimensional Gaussian function is fit to the resultant images. The full width at half maximum (FWHM) of the Gaussian can then be directly compared to the predicted spot size from the ZEMAX model. The measured FWHM values range from 45-80 µm across the full field, and the predicted RMS diameter values are 35-70 µm. The slightly larger values are acceptable, and are attributed to mirror mid-frequency errors and undiagnosed misalignment. The curvature of the focal plane is measured and in agreement with the model. Finally, the sign and magnitude of the through-focus astigmatism agrees with the model.

## 6. CONCLUSION

As aspheric surfaces become more common in optical design, the alignment techniques become more refined. The optical alignment facility that was established at GSFC decades ago laid out the principles, tools, and mathematical techniques for optomechanical alignment. The datums used to align aspheric surfaces have become integral with the optic, and the metrology efforts of relating the datums to the optical surface are improving. The introduction of independent alignment verification via interferometry and image testing allows end-to-end performance characterization of an optical system. Today, we have instruments like *IRMOS*, whose unique optical design relies solely on aspheres as powered elements. The goals of reducing mass and volume of an instrument have driven the need for compact systems, using aspheric optical components.

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* Buccini Instrument Company, Wilmington, North Carolina, tel.: (910) 350-1968

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