Title of Investigation:

An Alignment Cube for Cryogenic, Optomechanical Assemblies

Principal Investigator:

Dr. Raymond G. Ohl (Code 551)

Other In-house Members of the Team:

Carl R. Strojny, John G. Hagopian, and Henry Sampler (Code 551); Joseph McMann (ManTech International Corp.)

Initiation Year:

FY 2004

Aggregate Amount of Funding Authorized in FY 2004 and Earlier Years:

$11,200

FY 2004 Authorized Funding:

$11,200

FY 2004 Authorized Funding:

In-house: $4,200, Contracts: $7,000 (ManTech International Corp.)

Status of Investigation at End of FY 2004:

Transition to other funding: NASA James Webb Space Telescope/Integrated Science Instrument Module

Expected Completion Date:

May 2005

Purpose of Investigation:

Optical instruments for space applications often require that their components be positioned to tight tolerances. Before an instrument flies, mission managers are required to check the instrument's alignment on the ground, but in a space-like environment simulated in a vacuum chamber. One of the tools used to measure alignment is the theodolite, a commercially available surveying instrument used to measure the angular orientation of an object. To measure the alignment, technicians need two theodolites, with differing lines of sight to the object. This is hard to do when the instrument is in a vacuum chamber because vacuum chambers usually have only one window, allowing only one line of sight. Therefore, it is not normally possible to measure the alignment of an object in all three spatial rotations when the theodolite is in a vacuum chamber. The innovation developed as part of this study enables technicians to make alignment measurements in all three degrees of rotational freedom using a commercial theodolite in a vacuum chamber. That is, this innovation allows technicans to obtain all angular alignment information from just one theodolite. The innovation is to replace a reflecting cube inside the vacuum chamber with one that diffracts (like a prism) as well as reflects; the extra information from the diffracted light effectively gives a second line of sight.

Technical Description:

This innovation enhances the measurement of the alignment of cryogenic structures at their operating temperature. Every spacecraft and associated science instrument has a system of fiducials and datum surfaces that define a coordinate system for precision alignment of sensitive components (e.g., gyros and optics). This metrology relies on commercial off-the-shelf (COTS) alignment instruments like theodolites for precision assembly. Many spacecraft and instruments operate at temperatures lower than ambient conditions on Earth. These cryogenic instruments are typically assembled at room temperature with ambient metrology and tested in a vacuum chamber at the operating temperature. The chamber often provides poor line-of-sight to components; so little metrology data is obtained. If science data indicate a problem with alignment at temperature for a complex optical system, it can be difficult to pinpoint the specific errant component(s) without this metrology. Coordinate systems are referenced to a reflective optical alignment cube with known orientation. The cube's orientation in rotations is measured using autocollimating theodolites. For a calibrated cube, at least two orthogonal sides must be visible to establish its orientation in the laboratory — using two theodolites. For cubes on cryogenic assemblies, this requires that the chamber support two windows providing orthogonal lines-of-sight to the cube. It is expensive to retrofit chambers with additional windows. This innovation is a new cube that only requires one line-of-sight to measure its orientation in all three rotational degrees of freedom with one theodolite. The new cube uses a diffractive, grating-like surface on one face. Measurement of both the specular and diffracted orders from this surface provides complete metrology of all three rotational degrees of freedom.

The application of diffractive physics to an alignment cube design (vice reflection only) is the major innovation. The grating is either machined into the surface with a ruling engine or applied via, e.g., replication. Measurement of both the specular and diffracted orders from this surface provides complete metrology of all three rotational degrees of freedom. The theodolite for the measurement is COTS, but its COTS light source may be optionally replaced with a dim, eye-safe laser soruce for greater measurement accuracy.

Potential near-term applications at NASA include the James Webb Space Telescope's (JWST) Integrated Science Instrument Module (ISIM) and ground support equipment for testing the flight hardware. The cube also is useful for measuring non-cryogenic spacecraft and structures during thermal-vacuum testing, and thus has many other government and commercial applications (e.g., reconnisance satellites, infrared cryogenic instruments, ground-based telescopes, aerospace structures).

COTS alignment cubes are usually glass or metal (e.g., aluminum) and have highly orthogonal, optically polished sides (~10 arcsecond orthagonality tolerances), with mechanical dimensions of approximately 25x25x25 mm. The grating material (glass or metal) depends on the application. Reflected light from the orthogonal sides helps mechanical and optical engineers define coordinate systems on spacecraft and align components during installation (using theodolites). Normally, this reflection is purely specular. Our innovation is the placement of a diffractive grating surface on one of the sides of an otherwise COTS cube. The grating surface may be applied with machining or replication, depending on the application (i.e., cube material, etc.). The light from the theodlite striking that surface is diffracted into many orders. However, the diffracted orders of light provide the user alignment data from an extra degree of freedom not normally associated with that cube face for a COTS cube. This retrofitted cube allows the measurement of three rotational degrees of freedom using just one theodolite-cube face measurement.

FY 2004 Accomplishments:

For ambient testing of commercial prototype gratings, we procured several low- and high-resolution commercial gratings and measured higher-order theodolite returns under ambient conditions with the COTS theodolite light source. Qualitatively, we found that the elevation of the diffracted theodolite return was a straightforward measurement. The elevation bar of the image of the diffracted reticle cross-hair was spread out in angular (wavelength) space, but the surface brightness was sufficient for good centroiding using the human eye in a dark room. However, the surface brightness of the azimuth bar of the image of the diffracted reticle cross-hairs was very dim. The bar was spread over >1 arcminute in angular space and was difficult to see and centroid with the human eye under dark conditions. Nevertheless, measurements of the change in clocking (Rz) for small angles were still possible (i.e., arcminutes) to high precision (~5 arcsecond).

For ambient testing of a low-resolution custom grating, we fabricated a low-resolution, custom prototype grating face using a diamond-turning machine as a ruling engine. The grating's frequency was selected such that the +/-1 and +/-2 diffracted orders were easily visible in one theodolite's field of regard (p~8 lines/mm). The grating amplitude was selected such that ~25% of the flux from the specular beam would enter the +/-1 orders (a~120 nm peak-to-valley). These diffracted images were very bright and easy to read under normal lighting conditions. This lower-resolution grating did not cause the azimuthal blurring seen with the higher resolution, commercial gratings. This custom grating was therefore more useful for measuring larger clocking changes (i.e., degrees), but with lower precision (~4 arcminute).

We also made interferometric measurements of the diamond-machined surface for each order to ensure that the theodolite return would be reasonably undistorted. These measurements are tabulated in Table 1. The predominant character of this figure error was cylinder. This magnitude of figure error does not present a significant problem for measuring arcsecond-level position of target cross-hair images.

Table 1. Figure error for diffracted orders from custom grating-cube prototype

Order	RMS figure error (nm)
0 (specular)	86
+1	770
-1	720
+2	960
-2	910

For cryogenic testing of grating-cube substrate material, we measured the figure error on an aluminum mirror during thermal cycling to a cryogenic temperature to demonstrate stability. The aluminum mirror was heat-treated Al 6061 over coated with a high-purity Al plating for decreased scatter properties. The mirror was thermal cycled from ambient to ~80 K three times and the change in figure error was measured. The change was ~60 nm root mean square (RMS), but data reduction is ongoing.

Publications and Conference Presentations:

Under the support of this investigation, we have submitted a NASA technology disclosure and anticipate a NASA Tech Brief publication in 2005:

R. Ohl, H. Sampler, C. Strojny, J. Hagopian and J. McMann, “An alignment cube for cryogenic, optomechanical assemblies,” NASA Tech Briefs, submitted in September 2004, disclosure case number GSC 14954-1.

Planned Future Work:

We are completing the fabrication of a flight-like grating cube prototype (six sides, one for mounting, one with the grating) for calibration and cryogenic testing. This fabrication and testing effort will continue under the direction of the JWST/ISIM project.

Summary:

The novel feature of this innovation is applying the physics of diffraction to a cube made of normal plane mirrors, specially designed for the light from a COTS theodolite. This represents a simple, elegant modification of a COTS alignment cube that greatly enhances its utility for space flight. The benefit to the Goddard Space Flight Center is that this innovation makes it easier and less expensive to measure the orientation of objects that are attached to spacecraft and other precision assemblies while they are being tested in a vacuum chamber. This is especially useful for structures that must be tested at other-than-ambient conditionas, such cryogenics. The main criterion for success of this activity would be a high-precision, highly repeatable series of cryogenic cube calibrations for a flight-like prototype. Material stability and mount-related stress are the biggest risks.