

## Optical Testing of Retroreflectors for Cryogenic Applications

Commercial uses include cryogenic metrology on aerospace structures and optical metrology instrumentation.

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A laser tracker (LT) is an important coordinate metrology tool that uses laser interferometry to determine precise distances to objects, points, or surfaces defined by an optical reference, such as a retroreflector. A retroreflector is a precision optic consisting of three orthogonal faces that returns an incident laser beam nearly exactly parallel to the incident beam. Commercial retroreflectors are designed for operation at room temperature and are specified by the divergence, or beam deviation, of the returning laser beam, usually a few arcseconds or less. When a retroreflector goes to extreme cold ( $\approx 35$  K), however, it could be anticipated that the precision alignment between the three faces and the surface

figure of each face would be compromised, resulting in wavefront errors and beam divergence, degrading the accuracy of the LT position determination.

Controlled tests must be done beforehand to determine survivability and these LT coordinate errors. Since conventional interferometer systems and laser trackers do not operate in vacuum or at cold temperatures, measurements must be done through a vacuum window, and care must be taken to ensure window-induced errors are negligible, or can be subtracted out. Retroreflector holders must be carefully designed to minimize thermally induced stresses. Changes in the path length and refractive index of the retroreflector have to be considered.

Cryogenic vacuum testing was done on commercial solid glass retroreflectors for use on cryogenic metrology tasks. The capabilities to measure wavefront errors, measure beam deviations, and acquire laser tracker coordinate data were demonstrated. Measurable but relatively small increases in beam deviation were shown, and further tests are planned to make an accurate determination of coordinate errors.

*This work was done by Raymond G. Ohl and Bradley J. Frey of Goddard Space Flight Center, Joseph M. Stock of SGT, Inc., Joseph C. McMann of QinetiQ-North America, and Tmitri J. Zukowski of Research Support Instruments. For further information, contact the Goddard Innovative Partnerships Office at (301) 286-5810. GSC-15702-1*

## Measuring Cyclic Error in Laser Heterodyne Interferometers

Amplitude modulation, instead of phase modulation, associated with displacement oscillations is measured.

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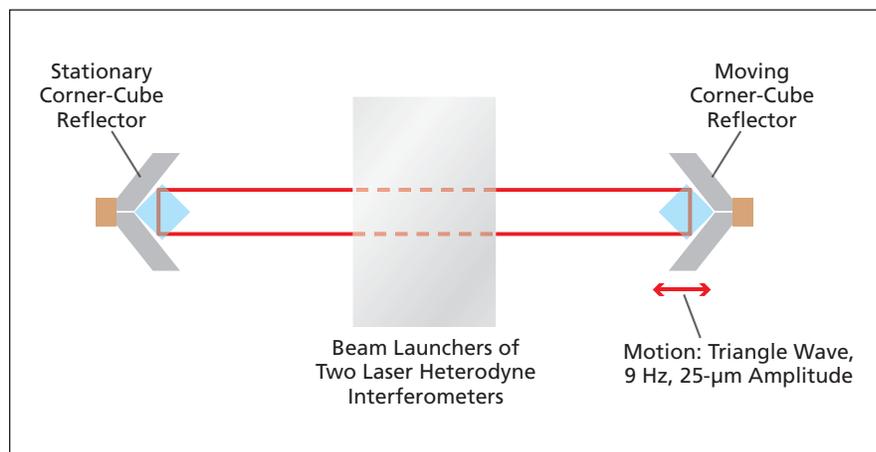
An improved method and apparatus have been devised for measuring cyclic errors in the readouts of laser heterodyne interferometers that are configured and operated as displacement gauges. The cyclic errors arise as a consequence of mixing of spurious optical and electrical signals in beam launchers that are subsystems of such interferometers. The conventional approach to measurement of cyclic error involves phase measurements and yields values precise to within about 10 pm over air optical paths at laser wavelengths in the visible and near infrared. The present approach, which involves amplitude measurements instead of phase measurements, yields values precise to about  $\approx 0.1$  pm — about 100 times the precision of the conventional approach.

In a displacement gauge of the type of interest here, the laser heterodyne interferometer is used to measure any change in distance along an optical axis between two corner-cube retroreflectors. One of the corner-cube retroreflectors is mounted on a piezoelectric transducer (see figure), which is used to

introduce a low-frequency periodic displacement that can be measured by the gauges. The transducer is excited at a frequency of 9 Hz by a triangular waveform to generate a 9-Hz triangular-wave displacement having an amplitude of 25  $\mu\text{m}$ .

The displacement gives rise to both amplitude and phase modulation of the heterodyne signals in the gauges.

The modulation includes cyclic error components, and the magnitude of the cyclic-error component of the phase modulation is what one needs to measure in order to determine the magnitude of the cyclic displacement error. The precision attainable in the conventional (phase measurement) approach to measuring cyclic error is limited because the phase measurements are af-



**Displacement Oscillations** are introduced between two corner-cube retroreflectors that are common to two displacement gauges. The magnitude of an amplitude modulation in the outputs of the gauges is measured.

ected by phase noise contributed mainly by vibrations and air turbulence. However, the amplitude modulation associated with the cyclic phase error is not affected by vibrations and air turbulence.

Therefore, in the present approach, in order to achieve higher precision in measuring cyclic error, one measures

the amplitude modulation instead of the phase modulation. The heterodyne error signal is fed to a relatively simple demodulator circuit, which removes the radio-frequency component of the heterodyne error signal, leaving only the 9-Hz amplitude modulation. The output of the demodulator is fed to a spectrum analyzer or an oscilloscope for measure-

ment of the magnitude of the 9-Hz amplitude modulation.

*This work was done by Daniel Ryan, Alexander Abramovici, Feng Zhao, Frank Dekens, Xin An, Alireza Azizi, Jacob Chap-sky, and Peter Halverson of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-45157*

## Self-Referencing Hartmann Test for Large-Aperture Telescopes

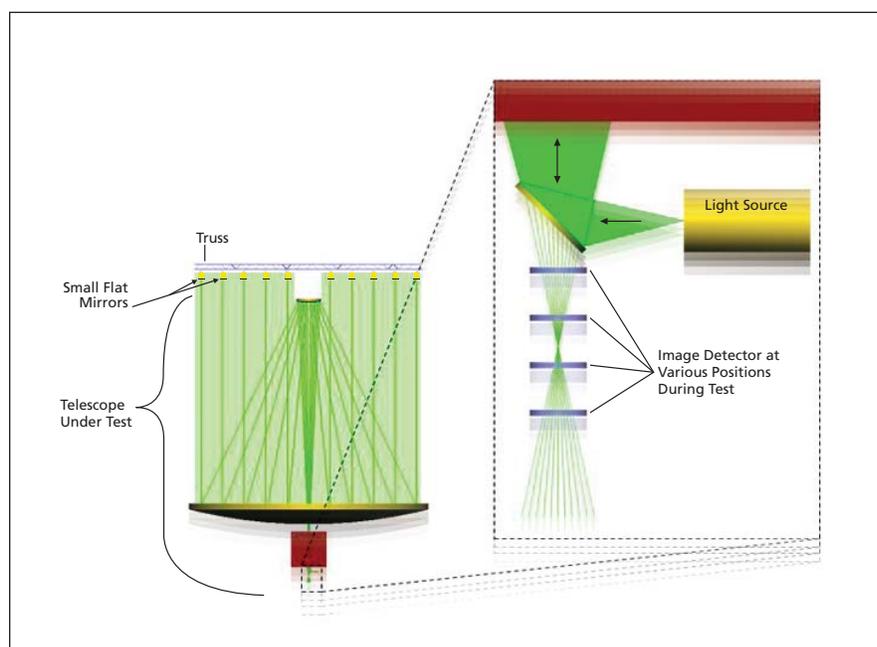
**Full aperture testing of large-aperture telescopes is performed without the need for an equally large-aperture autocollimating flat.**

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A method is proposed for end-to-end, full aperture testing of large-aperture telescopes using an innovative variation of a Hartmann mask. This technique is practical for telescopes with primary mirrors tens of meters in diameter and of any design. Furthermore, it is applicable to the entire optical band (near IR, visible, ultraviolet), relatively insensitive to environmental perturbations, and is suitable for ambient laboratory as well as thermal-vacuum environments. The only restriction is that the telescope optical axis must be parallel to the local gravity vector during testing.

The standard Hartmann test utilizes an array of pencil beams that are cut out of a well-corrected wavefront using a mask. The pencil beam array is expanded to fill the full aperture of the telescope. The detector plane of the telescope is translated back and forth along the optical axis in the vicinity of the nominal focal plane, and the centroid of each pencil beam image is recorded. Standard analytical techniques are then used to reconstruct the telescope wavefront from the centroid data. The expansion of the array of pencil beams is usually accomplished by double passing the beams through the telescope under test. However, this requires a well-corrected, autocollimation flat, the diameter or which is approximately equal to that of the telescope aperture. Thus, the standard Hartmann method does not scale well because of the difficulty and expense of building and mounting a well-corrected, large aperture flat.

The innovation in the testing method proposed here is to replace the large aperture, well-corrected, monolithic autocollimation flat with an array of small-aperture mirrors. In addition to eliminating the need for a large optic, the surface



An Array of Small Flat Mirrors would be used in a self-referencing, double-pass version of the Hartmann test configuration.

figure requirement for the small mirrors is relaxed compared to that required of the large autocollimation flat. The key point that allows this method to work is that the small mirrors need to operate as a monolithic flat only with regard to tip/tilt and not piston because in collimated space piston has no effect on the image centroids. The problem of aligning the small mirrors in tip/tilt requires a two-part solution. First, each mirror is suspended from a two-axis gimbal. The orientation of the gimbal is maintained by gravity. Second, the mirror is aligned such that the mirror normal is parallel to gravity vector. This is accomplished interferometrically in a test fixture. Of course, the test fixture itself needs to be calibrated with respect to gravity.

Another significant advantage of the array of gimballed small mirrors is the tolerance of the apparatus to thermal and mechanical perturbations. The individual mirrors are not affected by thermal distortions of the array structure because their orientation is self-correcting. That is, the pointing is maintained by gravity, not their supporting structure. Likewise, vibrations will cause the mirrors to sway about their equilibrium position. Thus, integrating the pencil beam image centroids over a sufficiently long period of time will make the measurements insensitive to vibration.

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