HIGH-PRECISION, LOW-COST OPTICAL READOUT SYSTEM FOR SPACE-BORNE GRAVITATIONAL REFERENCE SENSORS

Interim Report

JPL Task MU1065

Dr. Robert E. Spero, Interferometry Metrology and Optics Section (3834),
Jet Propulsion Laboratory

Professor Robert L. Byer, Dept. of Applied Physics,
Dr. David S. Lauben, Hansen Experimental Physics Laboratory,
Graham S. Allen, Dept. of Applied Physics,
Faruq R. Sabur, Dept. of Aeronautics and Astronautics, Stanford University

A. OBJECTIVES

There are several current and proposed space missions such as LISA, MAXIM and others which will require that freely-floating proof masses act as gravitational reference sensors, with non-gravitational disturbances minimized. One potential source of acceleration noise is the position readout system for the sensor. Such a system should combine high sensitivity with low added stiffness and cross-coupling effects. Capacitive readout techniques are widely used for achieving nanometer position sensitivity. However, the impressed electrostatic field introduces destabilizing negative stiffness and undesired cross-coupling of residual proof mass motion between non-sensitive and sensitive axes. Optical sensing is an alternative which in principal can offer advantages over capacitive sensing: picometer/√Hz resolution at 1 Hz and below, near-zero added stiffness and cross-coupling, insensitivity to electromagnetic interference, and detector thermal dissipation removed from proximity to the proof mass and housing.

The objective of this study is to investigate robust, low-cost, precision optical sensing for space use. The design concept is based on previous work at Stanford on a classic tracking Michelson interferometer with a quadrant-photodiode autocollimator. In his thesis Allen [1] demonstrated several key results, including successful operation with a spherical surface, using a suitable mode-matching lens, good sensitivity using a tiny amount (~ 3 μW) of light, and an interferometer noise floor around 0.1 nm/√ Hz below 100 mHz. The design concept provides up to 6-degree-of-freedom readout adaptable to spherical, cylindrical or faceted proof mass shapes. Our design uses a graded-index (GRIN) lens fiber interferometer/autocollimator and takes advantage of inexpensive off-the-shelf optical components originally developed for fiber communications systems that are adaptable for space. Gray, et al [2] demonstrated that a simple tracking Michelson interferometer could achieve performance better than 10^{-13} m/√Hz at frequencies as low as 6 Hz. Li, et al [3] demonstrated construction of a fiber interferometer using a broadband source while Chen, et al [4] have demonstrated Michelson fiber accelerometers with bandwidths of 5-500 Hz. Our objective is to combine Gray's tracking Michelson interferometer with fiber interferometer technology to create a system capable of 10^{-10} m/√Hz over a range of up to 5 μm, at frequencies below 1 Hz. The system is designed to have the sensor head placed approximately 3 cm from the proof mass. A similarly placed autocollimator will be used to measure surface orientation to better than 10^{-7} rad.

Rather than use free-space optics, which are sensitive to alignment, the majority of the optical path is contained in optical fiber. GRIN lenses are attached to the ends of the fiber to covert the propagating fiber mode into a collimated beam suitable for reflecting off a proof mass and traveling back down the optical fiber. A mirror mounted on a piezo-electric actuator provides the reference surface. This tracking mirror allows the interferometer to operate over a range of up to 5 μm without the need for fringe counting. By using a custom-designed GRIN lens, it is possible to mode-match into an arbitrary surface such as a spherical proof-mass. We chose a commercially available, broadband, erbium-amplified, spontaneous-emission source which combines excellent power and wavelength stability with easy matching to fiber optic components.

Since each interferometer requires less than 1 mW of optical power, it is possible to run several interferometers or auto-collimators off a single source. As shown in Figure 1, the main body of the interferometer is formed from a 3dB (50/50) coupler which takes the place of a beam splitter in a free-space Michelson interferometer. The sensing arm measures the side of a reference test mass. The reference arm is composed of a flat mirror mounted on a piezo-electric actuator. Both arms will use a GRIN lens collimator to generate a collimated beam between the optical fiber and the reference surface. The PZTs are controlled by an analog feedback loop to keep the interferometer locked at the mid-fringe position. The error signal used to drive the PZTs is a measure of the proof-mass position. In order to fully characterize the low-frequency performance of the system, 24-bit ADCs are used. The assembled system is shown in Figure 2.

The precision rotation measurement is made by a basic autocollimator design. A GRIN lens from the ASE source is used to create a beam of collimated light for the system. The light is propagated through a cube beamsplitter that has a 50/50 split at a 90-degree angle. Half of the light is then reflected off of the polished surface of the test mass back to the beamsplitter, which directs the reflected light to a quad diode photodetector. The rotation of the test mass is proportional to the position of the reflected light on the quad photodetector (figure 3). The system uses commercial off-the-shelf parts and a few low-cost, custom-made parts. Due to the fact that the collimated light beam diameter and the viewable surface of the quad detector are on the same order, a focusing lens with a 0.5-inch focal length is used to focus the light on the detector. The readout circuit is placed on a vertical XY stage in order to calibrate the relative normal position of the cube in the center of the quad diode package. The circuit has three outputs: vertical and horizontal positioning, and total power. The readout circuit sums the two photodiodes on top and subtracts them from the sum of the bottom two diodes to determine the vertical position of the reflected light. The horizontal position is determined in a similar fashion. When the output of both horizontal and vertical paths are zero, the light is in the center of the quad diode package. The total power of all four quadrants is used to normalize the results in post processing. Figure 4 shows the actual system with test mass and readout circuit.

B. PROGRESS AND RESULTS

1. Low-Frequency Position-Sensing Results

The position-sensing interferometers, control electronics and data-acquisition software are fully working. All three interferometers are operational and work reliably in tabletop tests. Figure 5 presents initial tabletop test results for position sensing. The noise floor is higher than expected, but this is probably due to the sensitivity of the optical fiber to vibration and thermal stresses. The nature of the coupling of environmental noise is under investigation.

2. Precision Rotational Measurement System Results

Figure 6 presents results from the initial zero-calibration study, in the form of the amplitude spectral density of the vertical- and horizontal-position data normalized against the total power. This experiment measures the long-term stability of the system when the reflected light is centered on the quad detector. The results show the maximum sensitivity to angular movement. The required sensitivity for the ST7 project is 1 μRad/$\sqrt{\text{Hz}}$ at a frequency of 1 mHz. Therefore the desired value for this system is 0.1 μRad/$\sqrt{\text{Hz}}$. The results from this test are at the noise floor for the tests on this day, ~1 μRad/$\sqrt{\text{Hz}}$. Electronic-noise results of ~1 μRad/$\sqrt{\text{Hz}}$ were measured separately and will be improved with better quad diode readout electronics.

C. SIGNIFICANCE OF RESULTS

In the 3-month period of performance, this study demonstrated initial results for both low-frequency position measurement and precision rotation measurement. These results indicate that the expected performance in optical readout is achievable. For the next period, we plan to construct a fiber-optic interferometer made of polarization-maintaining optical fiber to improve the interferometer contrast. Also, alternative techniques for packaging and routing the fibers are under investigation to hopefully reduce the noise floor of the fiber interferometer to a level equivalent to a free-space interferometer, thereby demonstrating the equivalence of the two systems.

Currently the autocollimator is in a two-piece configuration, with the quad detector and readout circuit mounted separately from the rest of the system. This arrangement allows the two parts of the system to drift independently. A custom mechanical housing system is being designed to hold all pieces of the system in one rigid body, making drift common-mode. The readout circuit will be split into two sections. A small pre-amplification circuit will be placed in the housing, while the processing portion of the circuit will be taken away from the measurement area. Improvements in the electronics will also show the true performance of the system. With these improvements, it is believed that the system will go from 1 order of magnitude of desired performance to better than an order of 10 below the desired sensitivity. Finally, we will augment an existing 3-degree-of-freedom capacitive-readout test-stand with these optical systems to provide three axes of translation readout, plus two of rotation. This system will implement a tracking Michelson/autocollimator as shown in Figure 7. The final product will be the instrumented GRS Test-stand, along with test results comparing the capacitive and tracking Michelson/autocollimator sensor measurements.

D. FINANCIAL STATUS

The total funding for this task was $139,700 of which $37,827 has been expended.

E. PERSONNEL

No other personnel were involved.

F. PUBLICATIONS AND PRESENTATIONS

[1] Graham Allen, "Fiber Interferometers for Low Frequency Position Sensing," Presentation to Robert Spero, Stanford University, October 1, 2003, http://lisa.stanford.edu/DRDF/DRDF-ReferenceMetrology-101103.pdf.

[2] Faruq, Sabur, "Precision Rotational Measurement System," Presentation to Robert Spero, Stanford University, October 1, 2003, http://lisa.stanford.edu/DRDF/DRDF-presentation2.pdf.

.

G. REFERENCES

[1] Allen, G., *Precision optical sensor design for drag-free control in the LISA spacecraft*, Stanford University Senior Honors Thesis, Graham.Allen@stanford.edu

[2] Gray, M., et al., A simple high-sensitivity interferometric position sensor for test mass control on an advanced LIGO interferometer, *J. Opt. and Quant. Elect.,31(5),* 571-582, April 1998.

[3] Li, T., et al., White-light scanning fiber Michelson interferometer for absolute position-distance measurement, *Opt. Lett., 20 (7),* 785-787, April 1995.

[4] Chen, B., et al., Nanometer measurement with a dual Fabry-Perot interferometer, *Appl. Opt., 40 (31),* 5632-5637, November 2001.

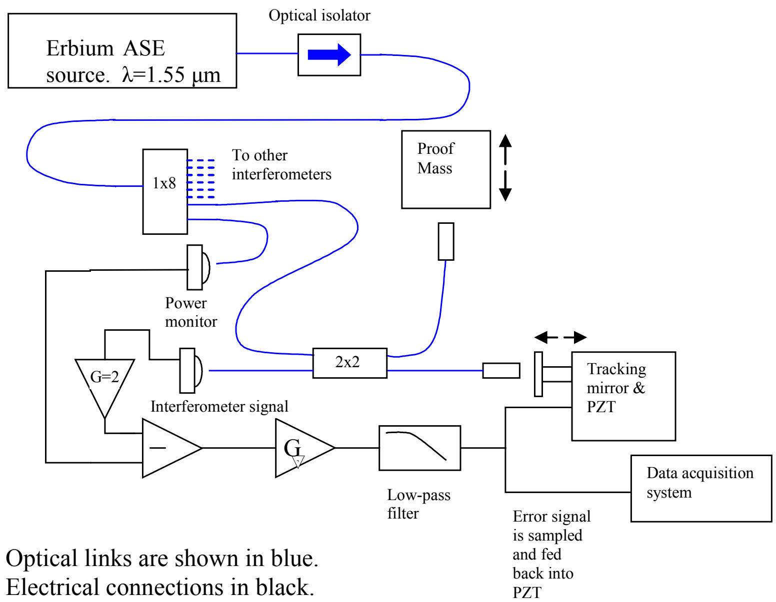

Figure 1: Position-sensing optical system layout. Only one interferometer is shown for clarity.

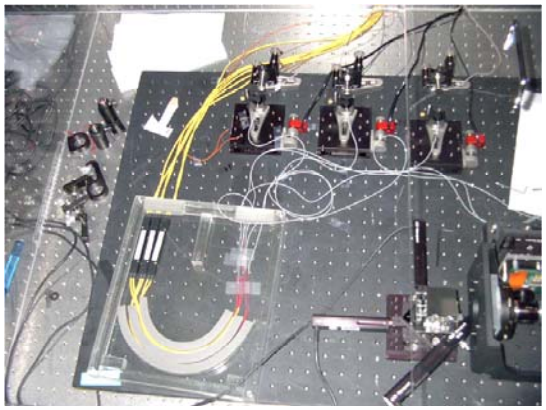

Figure 2: Position-sensing optical system layout.

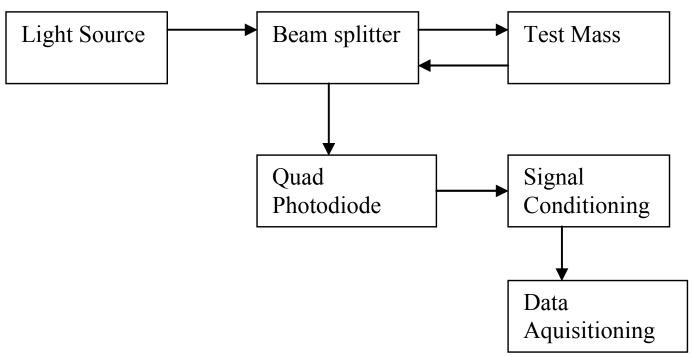

Figure 3: Precision rotation-measurement optical system block diagram.

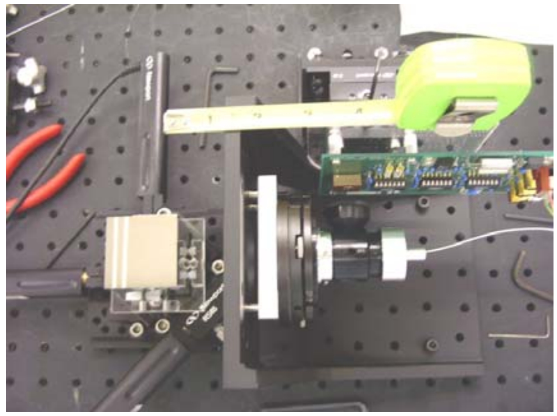

Figure 4: Precision rotation-measurement optical system layout and quad diode readout electronics.

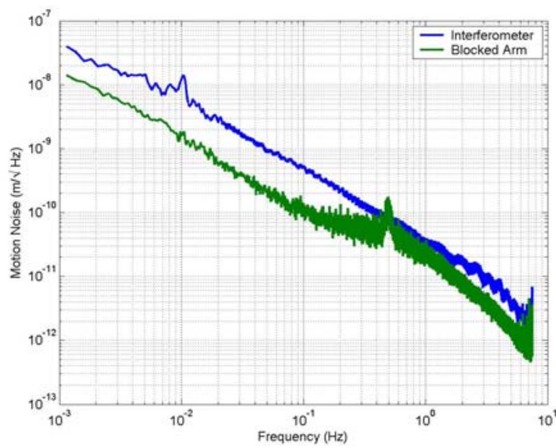

Figure 5: Total position-sensing system noise. The blocked arm signal represents an interferometer with one arm blocked, which removes all interference effects, but still shows the effect of mirror tilt and other possible fiber changes.

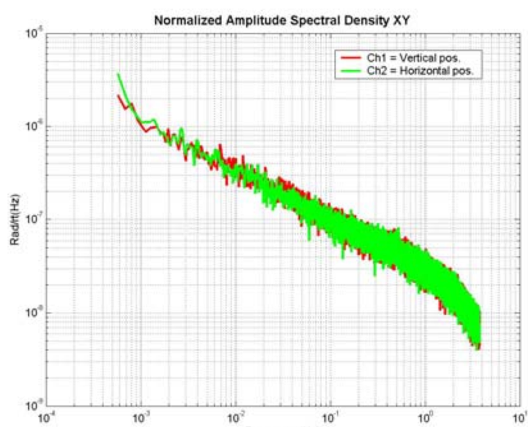

Figure 6: Precision rotation measurement results for zero-calibration run.

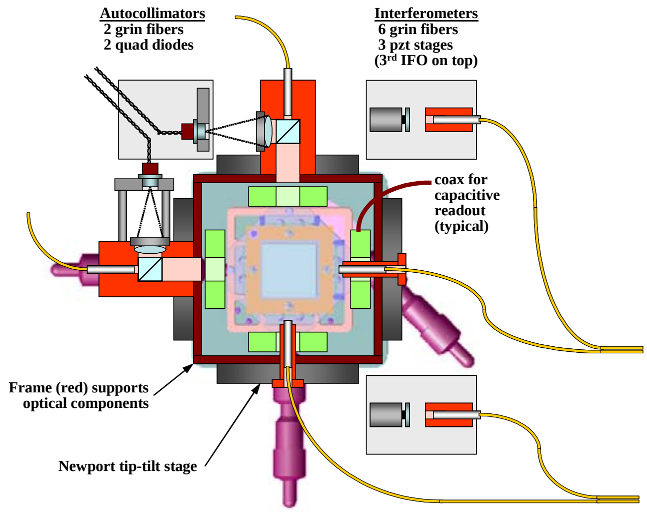

Figure 7: ST7 3-DOF test-stand instrumented for optical readout with two autocollimators and three position-measurement interferometers.