FY99 ANNUAL REPORT for NASA Grant NAG5-7638

INTERFEROMETRIC TECHNIQUES FOR GRAVITATIONAL WAVE DETECTION IN SPACE

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1. Introduction

The Laser Interferometer Space Antenna (LISA) mission will detect gravitational waves from galactic and extragalactic sources, most importantly those involving supermassive black holes. Gravitational waves are detected by laser interferometry between spacecraft 5×10^6 km apart. LISA has recently been added to the OSS Strategic Plan, and it is currently a Cornerstone mission in the ESA Science Programme. A Phase A study has just been completed in Europe.

The primary goal of this project is to investigate stability and robustness issues associated with LISA interferometry. This project is a supplement to another, entitled *Development of Laser Interferometry Techniques for Accurate Measurements of Distance Changes between Widely Separated Spacecraft* (Grant #NAG5-6880), wherein we have constructed a test bed interferometer to demonstrate the fringe timing required for the LISA interferometer. This project is intended to study sources of distance errors analytically and to take advantage of the test bed to develop a differential wavefront sensor and experimentally investigate other systematic effects.

We specifically proposed to study systematic errors arising from: optical misalignments, optical surface errors, thermal effects and pointing tolerances. We also proposed to develop a differential wavefront sensing system based on quadrant photodiodes to test noise models of alignment and figure errors.

The test bed consists of a Mach-Zehnder interferometer to make LISA-like fringes and a fringe timing system. Timing of the LISA fringe signal is complicated by several factors: an underlying frequency ranging from less than 1 MHz to about 15 MHz caused by orbital doppler shifts between spacecraft, the interference of a local laser beam and a laser beam from a distant spacecraft six orders of magnitude different in power, laser phase noise, and a science signal which appears as a phase modulation between 0.1 mHz and 1 Hz. LISA requires timing to 2×10^{-5} wavelength/$\sqrt{\mathrm{Hz}}$ from 1 mHz to 1 Hz under these conditions. Progress on the construction of this test bed and demonstration of LISA fringe timing under our other grant is ahead of schedule, and has allowed us to reorder activities under this grant.

2. FY99 Progress Report

This report covers the first fiscal year of the grant, from January 1st to December 31st 1999. Since this grant supports only a quarter time postdoctoral researcher, progress in this first year has been accomplished through sharing the time of Oliver Jennrich, the postdoc hired for our main grant. Nonetheless, work on the grant has gotten underway and produced a couple of preliminary results. We have made a quantitative study of the effects of misalignment and positioning errors in optical components in two interferometer configurations using optical modeling software developed for the interferometers used in ground-based gravitational wave detection. And, we analyzed the effects of thermo-elastic noise on the LISA optical pathlength. Each of these results will now be discussed in more detail.

We have employed an optical modeling tool to evaluate the effect of misplaced and misaligned optical components. OptoCAD was developed by Roland Schilling of the Max Planck Institut für Quantenoptik in Garching for designing interferometers used in ground-based gravitational wave detection. The program calculates fringe characteristics given the parameters and geometric layout of interferometer components.

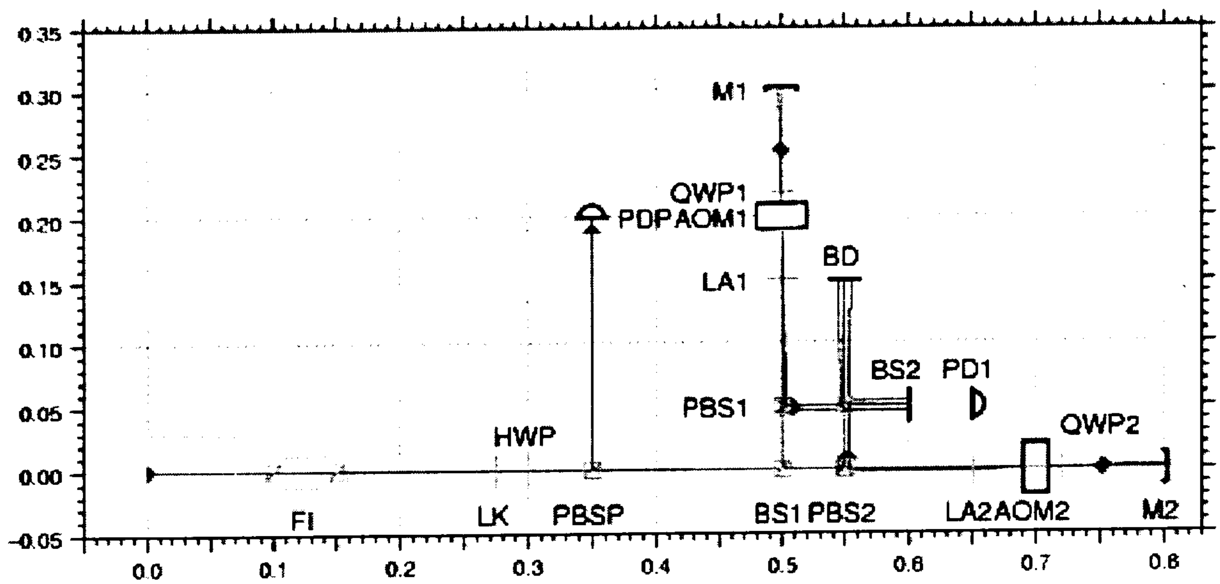

Figure 1. Layout schematic from OptoCAD. See text for configuration description and explanation of codes for elements. Coordinates are in meters.

Figure 1 shows the OptoCAD drawing of our Mach-Zehnder test bed interferometer. The 1.06 μ Nd:YAG laser, located at the origin of the coordinate system, is directed through a Faraday isolator (F1) into the main beamsplitter (BS1) where it is split into the two arms. In each arm, a polarizing beamsplitter (PBS) first passes the beam through an acousto-optic modulator (AOM) and quarter-wave plate (QWP) to a curved mirror (M) that reflects the beam back through the AOM to the PBS. The beams are interfered at a final beamsplitter (BS2) and detected by a photodiode (PD1). The two AOMs are powered with different frequencies f1 and f2, whose difference appears in the fringe signal. The main photodetector output is divided by two and compared against the difference frequency to produce an error signal for adjusting the position of M2. A portion of the original laser beam is deflected by a polarizing beamsplitter (PBSP) to a photodiode (PDP) for intensity stabilization. Element codes beginning with L indicate lenses. BD is a beam dump.

Preliminary results seem to indicate that positional tolerances of 1 μ and angular tolerances of 0.6 mrad produce no significant effect on the achievable contrast of the interference pattern. We have also evaluated the interferometer configuration proposed for the Disturbance Reduction System option on the New Millennium Program's ST5 mission with similar results. That interferometer is one candidate for the metrology on the LISA Test Package, a flight demonstration of the LISA disturbance reduction system.

Thermo-elastic noise has recently received renewed attention in the design of ground-based gravitational wave interferometers, typically operating in the 10 - 2000 Hz region. This noise manifests itself as motion of optical surfaces owing to the thermal fluctuations in the underlying bulk material acting through the coefficient of thermal expansion and the thermo-elastic coefficient (i.e., temperature derivative of the elasticity modulus), and hence as an optical path length change. The spectral behavior of thermo-elastic noise goes as $1/f^2$, in contrast to the frequency-independent behavior for viscous damping and a $1/f$ dependence for structural damping. Consequently, it is of special interest for low frequency measurements like LISA.

In collaboration with Jim Hough and Harry Ward (University of Glasgow), we were able to confirm that this noise, though present, will have no effect on the LISA sensitivity. Its contributions (approximately 10^{-16} m/$\sqrt{\text{Hz}}$) are much smaller than the expected LISA sensitivity level.

3. FY00 Research Plans

Research in FY00 will be affected by three personnel changes. Oliver Jennrich, the postdoc who has performed much of the research under this grant and NAG5-6880, will come to the end of his U.S. visa in August. He is leaving to join our collaborators in the University of Glasgow gravitational wave group. We have hired Scott Pollack, an excellent incoming graduate student from Berkeley, to finish out the work on NAG5-6880 and to carry on the work in this grant. He will start work in June. And, finally, Patricia Neal, an unusual undergraduate from the University of Colorado at Denver, will work on this grant with support from the NSF's Research Experience for Undergraduates (REU) Program for 10 weeks during the summer of 2000. Pat has advanced training in analog electronics from a career in the Navy, and will be going on to graduate school in electronic engineering and neurobiology at Caltech.

Since the work under NAG5-6880 has gone more rapidly than projected, our test bed interferometer is operational, and can be used for measurements of effects that cause beam motion. Hence, we will design, build and characterize a sensor for measuring beam motion, and then install it in the test bed interferometer to quantitatively investigate sources of beam motion. Although we had planned to spend the first and second years concentrating on analytical studies, the rapid progress on the test bed interferometer allows us to make an early assessment of sources of beam motion within the interferometer. For example, we can evaluate beam motion caused by changes in beam pointing and displacement within the laser itself. Similarly, we can investigate beam motion caused by the modulators, air density gradients, microphonics and other effects that would not be characteristic of a LISA interferometer, but might occur in our test bed and mask effects that we wish to study because of their relevance to a LISA interferometer, such as thermally induced misalignment of optical components.

We are planning a differential wavefront sensor based on a quadrant photodiode as a first generation sensor. We have considered a range of designs for beam motion sensors with a range of sensitivities, but given the uncertainties in the size of beam disturbances, a simpler design with a modest sensitivity seems a good target for an initial investigation. We expect that Scott will spend the better part of the summer becoming familiar with the test bed interferometer and the fringe timing electronics. Pat will work on the detailed design, construction and characterization of the quad sensor. Later in the year, after initial measurements with the quad sensor, we will re-evaluate our plans and schedule for laboratory measurements and analytic studies. As stated in our original proposal, some effects, like off-axis propagation through the LISA transmit/receive telescope can only be studied analytically.