Continued development of a precision cryogenic dilatometer for the James Webb Space Telescope

Paul B. Karlmann*, Matthew J. Dudik, Peter G. Halverson, Marie Levine,
Martin Marcin, Robert D. Peters, Stuart Shaklan, David Van Buren
NASA Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109-8099

ABSTRACT

As part of the James Webb Space Telescope (JWST) materials working group, a novel cryogenic dilatometer was designed and built at NASA Jet Propulsion Laboratory to help address stringent coefficient of thermal expansion (CTE) knowledge requirements. Previously reported results and error analysis have estimated a CTE measurement accuracy for ULE of 1.7 ppb/K with a 20K thermal load and 0.1 ppb/K with a 280K thermal load.[1] Presented here is a further discussion of the cryogenic dilatometer system and a description of recent work including system modifications and investigations.

Keywords: Coefficient of thermal expansion, dilatometer, thermal strain, fused silica, zerodur

1. INTRODUCTION

NASA's James Webb Space Telescope (JWST) is a 6.5 m diameter orbiting infrared telescope, located in L2 orbit, passively cooled to below 50K, and tentatively scheduled for launch in 2011. With a primary mirror total wave-front error (WFE) requirement of 60 nm and operating temperatures down to 30K, the thermo-mechanical properties of the both the mirror substrate as well as the composite back structure must be known to an extremely high precision. Preliminary estimates indicate that the coefficient of thermal expansion (CTE) for these materials must be known to a precision of at least 10 ppb/K down to 30K. To help satisfy these material property knowledge requirements, the JWST project funded the development of a new cryogenic dilatometer facility at NASA Jet Propulsion Laboratory (JPL) and described by Dudik et al.[1] During the past year, several modifications have been made to the dilatometer system to increase performance, enhance system robustness, and improve ease of testing. Modifications include new photo-detector post-amplifier electronics, a new vibration isolation system for the helium cryocooler, and general design changes to the kinematic mounting of both the sample dewar and test sample. Also during this period, samples of ULE, zerodur, and fused silica were tested for JWST and the Space Interferometry Mission (SIM).

1. APPARATUS

The initial design of the JPL cryogenic dilatometer was previously described by Dudik et al.[1] The primary components of the system are the laser source, interferometer, vacuum chamber, thermal control system, test sample alignment stage, signal processing electronics, and data acquisition and control system. Both the laser source and the interferometer are similar to those described by Zhao et al.[2,3] Shown in Figures 1 and 2 are a photos of the JPL cryogenic dilatometer test facility.

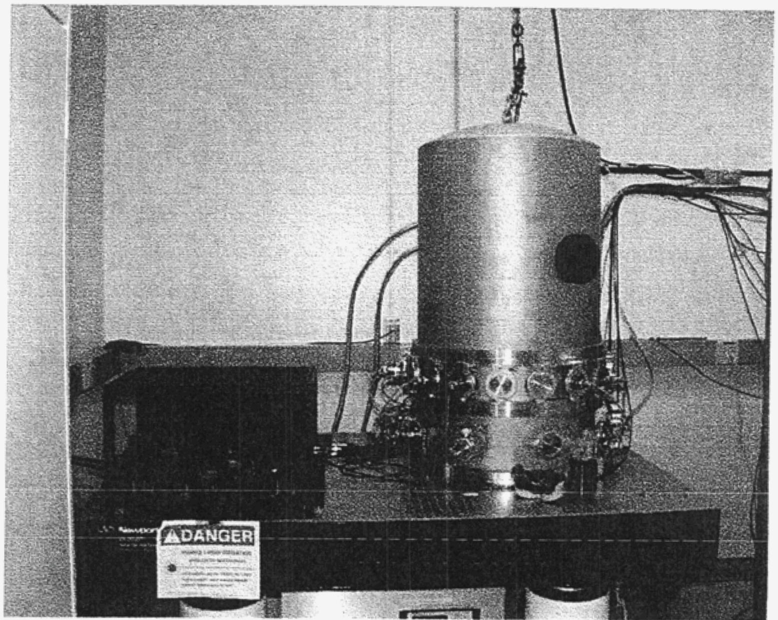

Figure 1. Optical table with dilatometer laser source and thermal vacuum chamber.

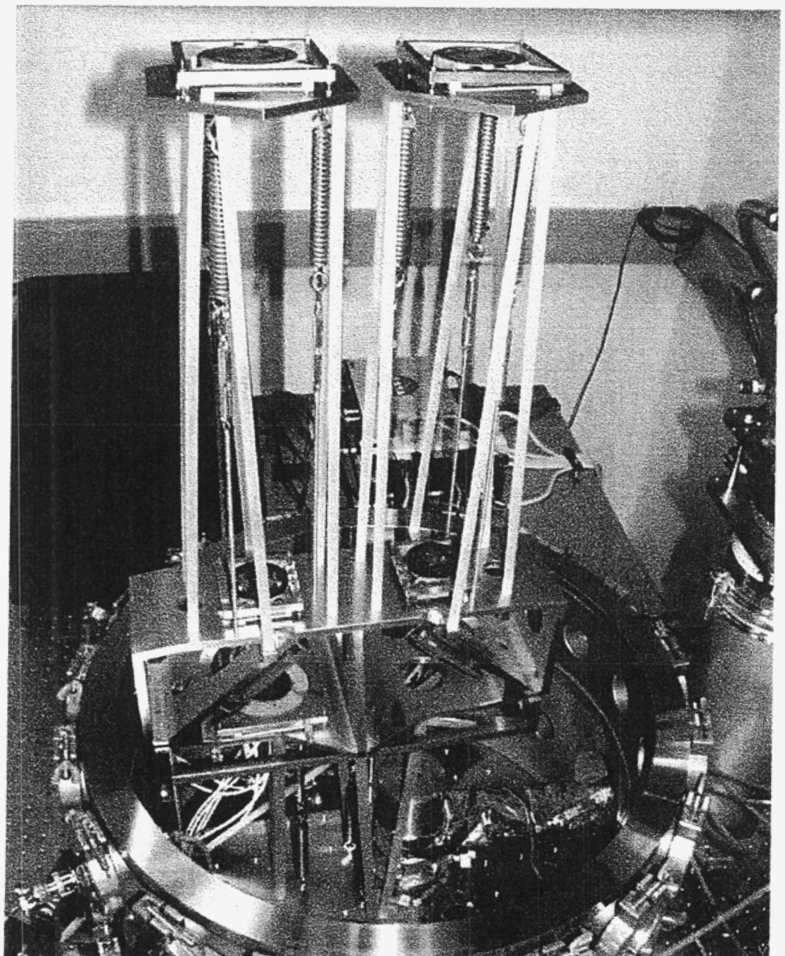

Figure 2. Interior of thermal vacuum chamber.

2.1 Laser source

The laser source is a temperature stabilized doubled YAG laser operating at 532 nm with a power of 100 mW. Output from the laser is split into a measurement beam and a local oscillator beam. Acousto-optic modulators (AOMs) are used to shift the measurement beam by 80.016 Mhz and the local oscillator beam by 80 Mhz. The difference between these two beam frequencies represents the 16 kHz heterodyne frequency utilized by the interferometer. Both beams are then sent via angle-polished optical fibers from the optical table through a feed-through into the vacuum chamber. Future plans involve the possibility of acquiring an off-the-shelf laser source with it's output wavelength locked to an iodine absorption line. This would result in improved frequency stability and therefore improved system precision. Shown in Figure 3 is a photo of the dilatometer laser source with iodine cell.

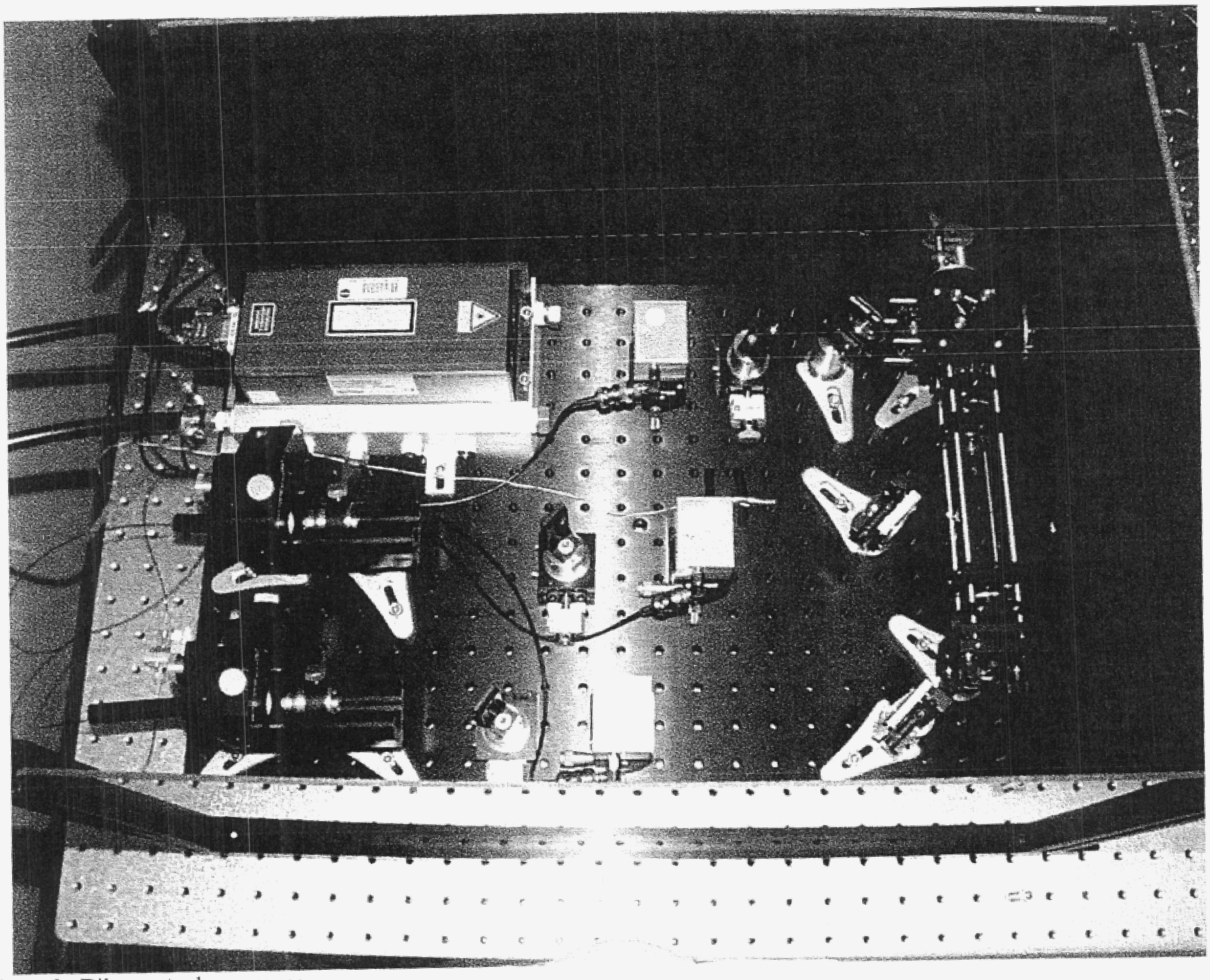

Figure 3. Dilatometer laser source.

2.2 Interferometer

The interferometer assembled for use by the cryogenic dilatometer is shown in Figure 4. The main body is machined from a single piece of invar 36 and is heat treated for dimensional stability. Attached to the main body are invar flexural mounts which hold two beam splitters, two optical fiber couplers, two beam masks, and a photo-detector board. Above the main body are supported two off-axis parabolic mirrors (OAPs) held by invar flexural mounts and kinematically maintained at their 63cm focal lengths by spring-loaded zerodur bipods. The entire structure is supported on the base of the vacuum chamber by spring loaded zerodur bipods.

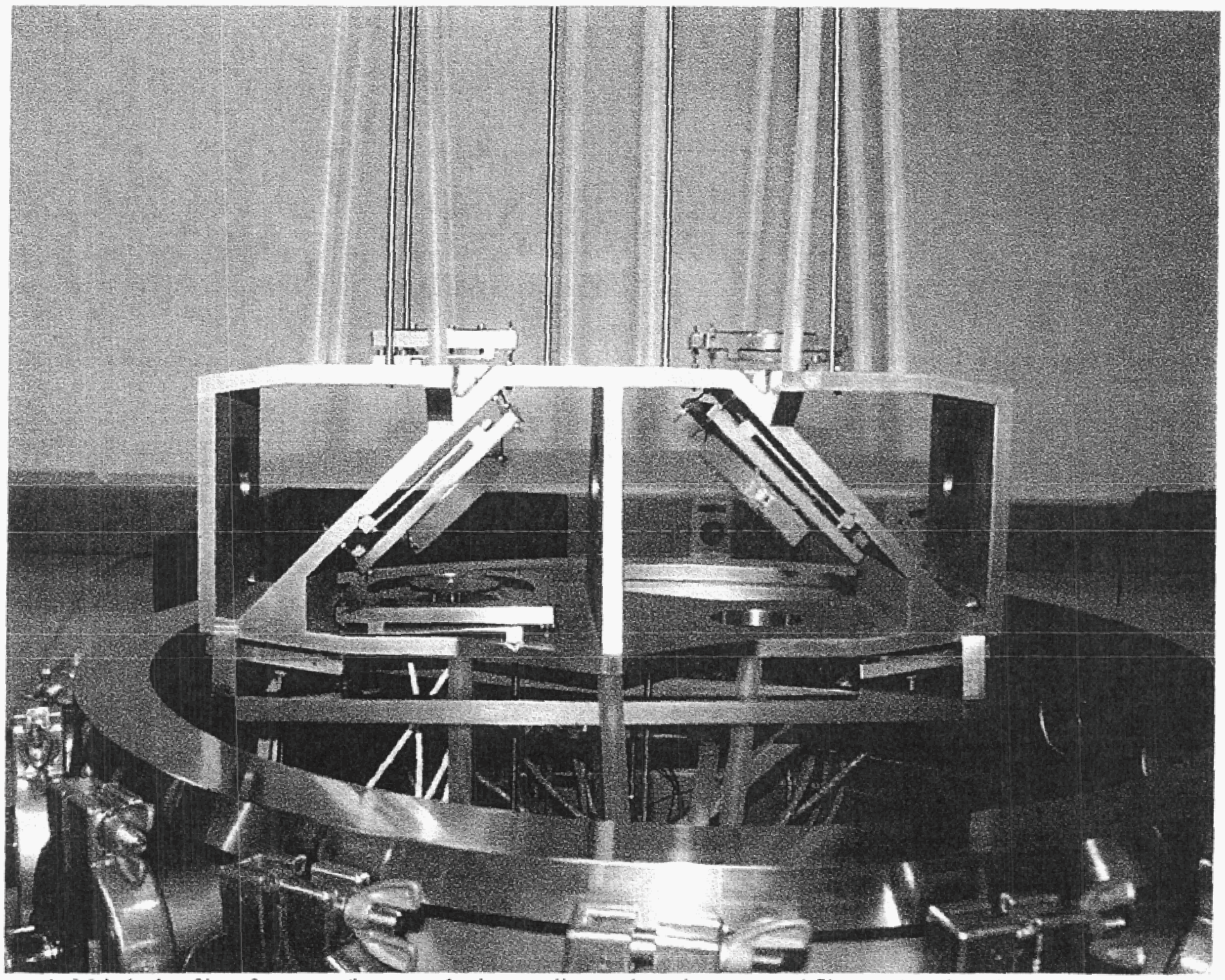

Figure 4. Main body of interferometer (beam masks, beam splitters, photo detectors, and fiber mounts shown).

2.3 Vacuum chamber

The interferometer, sample alignment stage, and part of the thermal control system are all contained within a 36" diameter x 36" tall, stainless steel, vacuum belljar chamber that sits directly on a 6' x 4' optical table. Attached to the base of the chamber via a gate valve is a turbo molecular vacuum pump with a second-stage roughing pump. Electrical signals into and out of the chamber are all via hermetically sealed vacuum feed-throughs and laser light is fed into the chamber via an optical fiber feed-through. Under typical test conditions, chamber pressure is maintained at $< 5\times10^{-5}$ torr as measured by a vacuum ion gauge.

2.4 Thermal control system

A Gifford-McMahon closed-cycle helium cryocooler is directly mounted to the chamber via a helium-filled vibration isolating bellows and conductively cools a heat transfer bar connected to a flexible thermal strap connected to a thermal shroud. All of these thermal components are made from oxygen-free high-conductivity (OFHC) copper to aid in thermal performance at cryogenic temperatures. The flexible thermal strap is fabricated from copper wire braids, provides another layer of vibration isolation from the externally mounted cryocooler, and also helps reduce sample misalignment due to thermally-induced movement of the heat transfer bar. Kapton-film heaters on both the heat transfer bar and base of the thermal shroud are controlled by a Lakeshore 340 Temperature Controller reading calibrated Lakeshore DT-470 silicon diode temperature sensors. Under typical test conditions, the thermal shroud is maintained within +/- .005 K of temperature set points over the temperature range of 300 K to 20 K. During a typical test run, the following temperatures are recorded using Lakeshore DT-470 silicon diode temperature sensors: heat transfer bar, thermal shroud (bottom), thermal shroud (top), sample base (right), sample base (left), sample base (center), sample pillar (top), and sample pillar (bottom). Externally, air temperature, chamber temperature, laser temperature, and post-amp electronics temperature are also measured and recorded.

2.5 Test sample alignment stage

The sample alignment stage provides tip/tilt adjustment to maintain alignment between the test sample reflecting surfaces and the measurement beams of the interferometer. The entire stage is machined from single piece of invar 36 and heat treated for dimensional stability. A set of three invar screws and their associated invar spherical nuts adjust integral flexures to provide course tip/tilt adjustment of the stage of up to 23 milliradians with a resolution of at least 13 microradians. Fine adjustment of the stage is provided by three piezoelectric actuators (pzts) acting against integral flexures to achieve 220 microradians of adjustment with a resolution of better than 0.15 nanoradians. Mounting of the stage to the chamber floor is via three machined balls resting in three V-grooves. Kinematic mounting of the thermal shroud to the alignment stage is via three invar bipods to minimize heat conduction and minimize lateral sample movement. Shown in Figure 5 is a photo of the sample alignment stage.

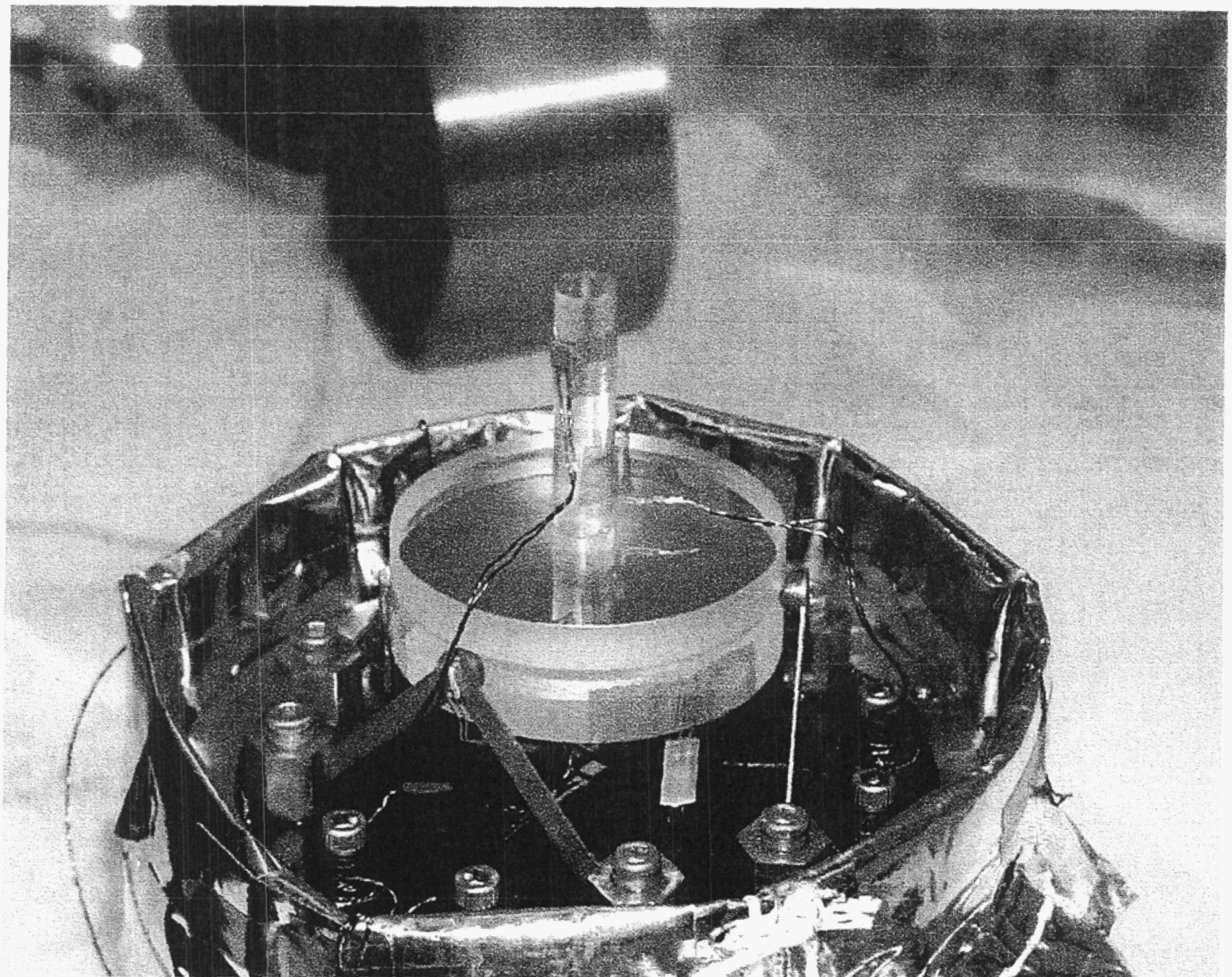

Figure 5. Sample alignment stage.

2.6 Signal processing electronics

Output from the four photo-detectors and pre-amplifiers of the interferometer pass through noise filters and exit the vacuum chamber via hermetically sealed electrical feed-throughs. Each signal is then processed by its own post-amplifier electronics box which generates a cleaned-up, amplified square wave of the proper frequency by means of a zero-crossing detector and phase-locked-loop (PLL). These four square waves are then read and interpreted by a phase meter board to produce measurements of differential movement within the test sample. Shown in Figure 6 is a photo of the dilatometer electronics and data acquisition system.

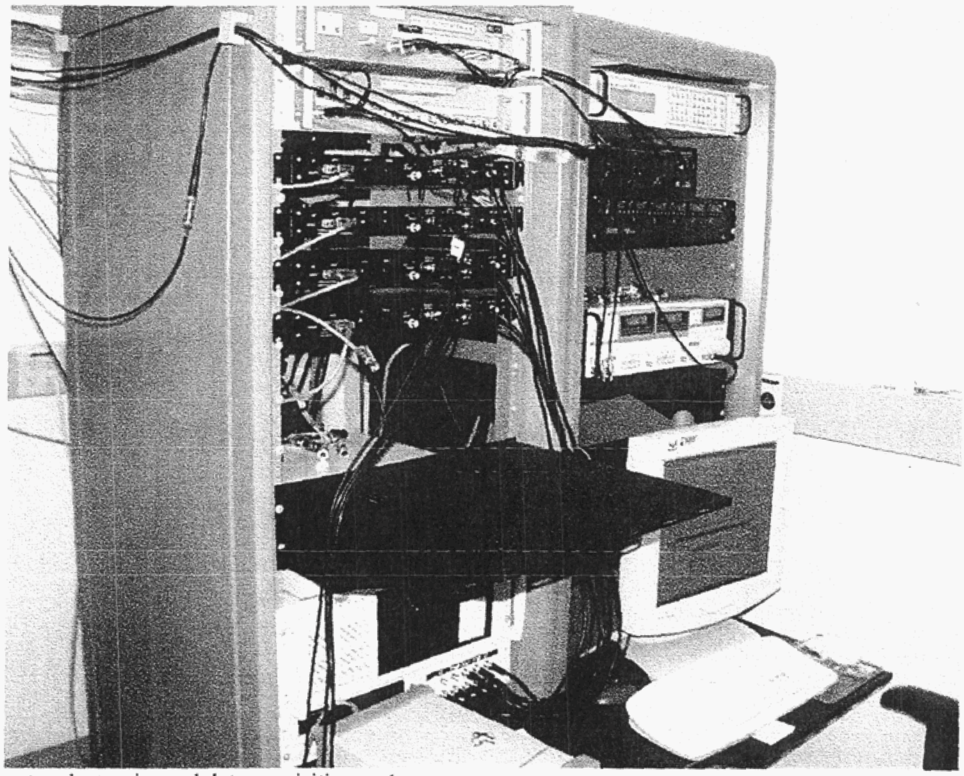

Figure 6. Dilatometer electronics and data acquisition rack.

2.7 Data acquisition and control system

A PC based LabVIEW software system is used for all data acquisition and control of the cryogenic dilatometer. Interferometer data, temperatures, laser output, heater powers, and sample alignment are all graphically displayed in real time and stored to memory. Built-in algorithms are available to process raw data files and generate thermal strain and CTE results with minimal user input.

Temperature measurement and heater control are achieved via GPIB communication with a Lakeshore 340 Temperature Controller. Temperature set points, ramp rates, stability criteria, set point duration, and heater control parameters are all entered within the LabVIEW interface and allow for unattended or remote operation of the dilatometer.

During operation, continual precision tip/tilt control of the sample alignment stage is maintained by the computer. The output to the three piezoelectric actuators is constantly updated to equalize the optical paths of the three outer reference beams as measured by the phasemeter. In this way, the sample pillar and reference base always remain precisely aligned with the rest of the interferometer.

1. RECENT SYSTEM MODIFICATIONS

2.1 Cryocooler vibration isolation

The Gifford-McMahon closed cycle helium cryocooler used by the dilatometer generates significant vibration during operation on the order of 0.5 Hz. Because the cooler must mount directly to the side of the vacuum chamber, this vibration represented a potential source of noise for the interferometer and sample alignment stage since both desire an ultra-stable environment. Early attempts to float the optical table while the cooler was operating resulted in oscillations of the table on the order of few centimeters. Operation of the dilatometer was only possible without floating the optical table. To remedy this problem, a commercially available vibration isolation bellows was installed between the cooler and the vacuum chamber. During normal operation, the cooler is rigidly supported by an external structure while the connection to the chamber is only via a helium pressurized rubber bellows. In this mode, the table can be floated, therefore isolation is improved from both the cryocooler and the surrounding lab environment. Figure 7 shows a photo of the cryocooler vibration isolation bellows.

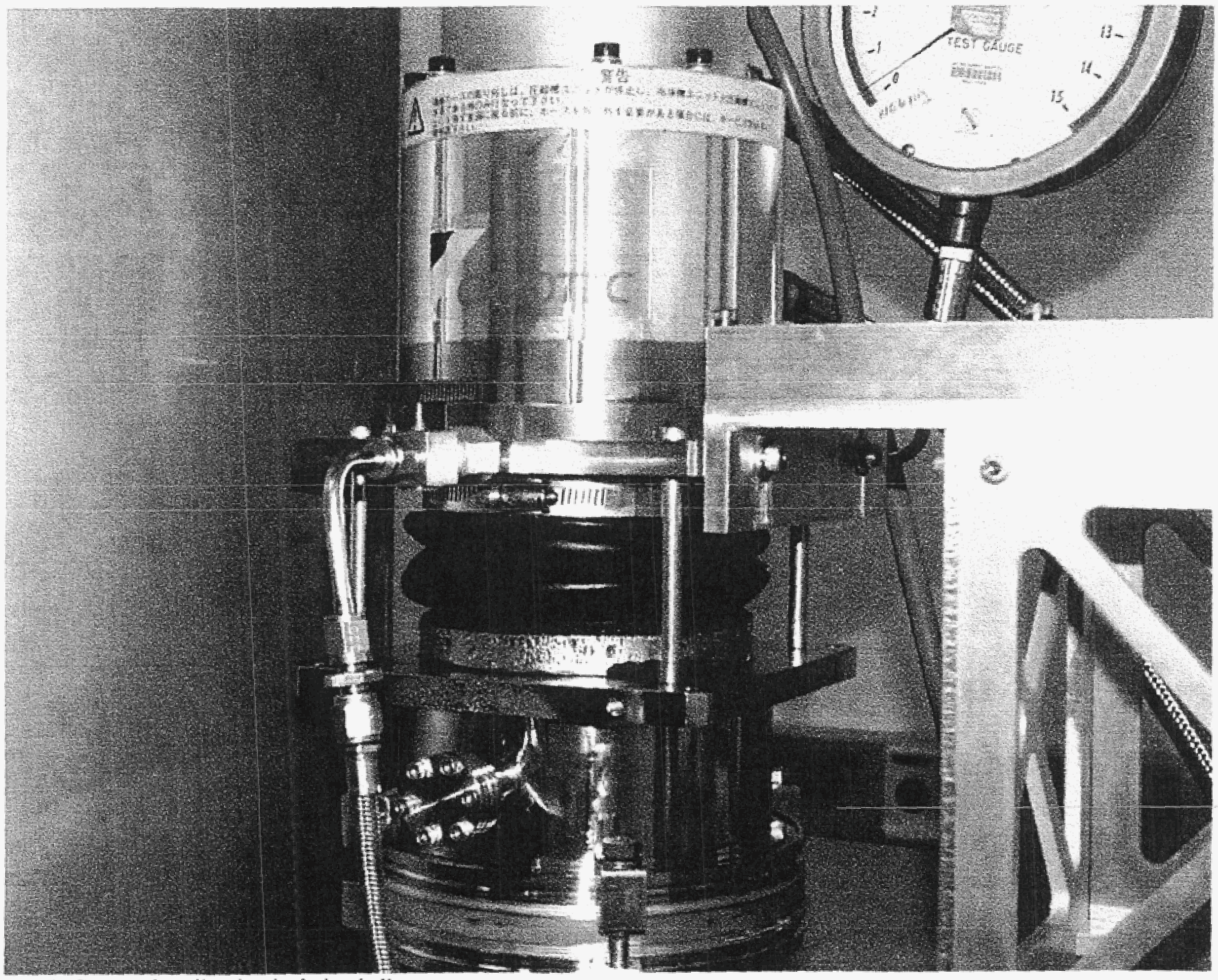

Figure 7. Cryocooler vibration isolation bellows.

2.2 New post-amp electronics

With the goals of improving signal clarity and minimizing long-term signal drift, six new post-amp electronics boxes were designed and built. Within each box is a thermally insulated zone with a small heater and temperature sensor. Active temperature control maintains the enclosed parts at a stable temperature over time and thereby reduces thermal drift of the interferometer signals. By using a phase locked loop, the post amp electronics are able to generate a frequency-matched signal without most of the noise associated with the raw incoming signal. In this way, the system is made more robust and less sensitive to signal noise.

2.3 New thermal shroud and bipods

The initial design of the sample alignment stage relied on three spring-loaded zerodur bipods to kinematically hold the thermal shroud to the room temperature alignment stage. While these bipods offered excellent thermal isolation as well as dimensional stability, the difficulty of a spring-loaded assembly and the center-location of the preload spring lead to a modified design. By switching to bolt-on invar bipods, the ease of assembly was improved, and the bottom center of the thermal shroud was made available as a more desirable thermal strap attachment point to minimize thermal gradients.

In addition to the change in the location of the thermal strap attachment point, the thermal shroud was modified from an all aluminum design to an all copper design. The higher thermal conductivity of OFHC copper, especially at cryogenic temperatures, would reduce thermal gradients and allow greater cooling of the sample. Previously, with the all aluminum design, the sample bipods were machined directly into the thermal shroud. In the event of a broken bipod, the entire base of the thermal shroud would have to be re-machined. For this reason, the new shroud design incorporated bolt-on bipods which could be replaced if necessary.

2.4 Frequency stabilization using iodine locking

Because the frequency stability of the laser source is one of the primary error sources for the dilatometer, efforts were made to investigate the use of an iodine cell to effectively "lock" the laser output to one of the major absorption lines of iodine. So far, schedule constraints and limitations of the existing laser system have prevented this option from being fully incorporated. An alternative to this approach that is currently being considered is the purchase of an off-the-shelf laser system with built-in iodine locking. Incorporation of this system would effectively eliminate frequency stability as a significant source of error for the dilatometer.

2. FUTURE PLANS

The long-term goal of this facility is to provide high-precision CTE and creep measurements of precision materials for future NASA missions such as James Webb Space Telescope (JWST), Space Interferometry Mission (SIM), Terrestrial Planet Finder Coronagraph (TPF-C) and Terrestrial Planet Finder Interferometer (TPF-I). With this goal in mind, efforts have been focused on reducing major sources of error, increasing system robustness, increasing sample through-put, and increasing ease of operation. Additional goals are to reduce the minimum operating temperature and to relax the stringent surface quality and parallelism requirements on test samples.

Round-robin tests of ULE and single crystal silicon samples are currently in work between JPL and GSFC as part of the JWST materials working group. Further testing of zerodur and fused silica samples will also be performed to support the SIM TOM-1C testbed at Lockheed Martin. For TPF Coronagraph, efforts are currently underway to have CTE test samples manufactured from PMN, a "lead ceramic" used in deformable mirrors. Also, there have been some early discussions regarding the testing of some additional materials for both SIM and TPF.

ACKNOWLEDGEMENTS

The authors greatly appreciate the generous support for the development of this facility by NASA's James Webb Space Telescope project. We also would like to thank the additional support provided by the Terrestrial Planet Finder mission as well as the Space Interferometry Mission. Special thanks go to R. Scott Leland and Lillian Shido for their contributions.

REFERENCES

1. M. Dudik, P. Halverson, M. Levine, M. Marcin, R. Peters, S. Shaklan, "Development of a Precision Cryogenic Dilatometer for James Webb Space Telescope Materials Testing," *SPIE Proceedings of Optical Materials and Structures Technologies*, **vol. 5179**, p. 155-164, 2003.

2. F. Zhao, J. Logan, S. Shaklan, M. Shao, *SPIE Proceedings of Optical Engineering for Sensing and Nanotechnology*, **vol. 3740**, p. 642, 1999.

3. F. Zhao, *Proceedings of the ASPE Annual Meeting*, p. 345, 2001.

*paul.b.karlmann@jpl.nasa.gov; phone 818 354-7876; fax 818 393-4206