

# HIGH-STABILITY TEMPERATURE CONTROL SYSTEM FOR LISA

Sei Higuchi<sup>1</sup>, and Daniel B. DeBra<sup>1</sup>

<sup>1</sup>Department of Aeronautics & Astronautics, Stanford University  
Stanford, CA 94305, USA

## INTRODUCTION

The Laser Interferometer Space Antenna (LISA) and other precision spaceflight missions require gravitational reference sensors (GRS) for drag-free control [1]. LISA uses laser metrology to measure distance between proof masses in three identical spacecrafts. The primary mission goal of LISA is detecting the gravitational waves. The total acceleration disturbance to each proof mass is required to be below  $3 \times 10^{-15} m/s^2 \sqrt{Hz}$ . Optical path length variations on each optical bench must be kept below  $40 pm/\sqrt{Hz}$  over  $1 Hz$  to  $0.1 mHz$ . Thermal variations due to, for example, solar irradiation, or temperature gradients across the proof mass housing are expected to be significant disturbance sources.

This article focuses on a thermal control system developed for LISA gravitational reference sensor (GRS) ground verification testing which provides thermal stability better than  $1 mK/\sqrt{Hz}$  to  $f < 1 mHz$ , and which by extension is suitable for in-flight thermal control for the LISA spacecraft to compensate solar irradiation.

Stabilizing the thermal environment against low frequency disturbance is one of the most important problems for LISA performance verification. Lowering the sub- $mHz$  thermal drift caused by diurnal variations is the main objective, with stability requirement  $\delta T < 30 \mu K/\sqrt{Hz}$  for  $f > 0.01 mHz$  measured at the sensor. Our main concern in the laboratory is the daily ambient temperature variations which causes the thermal drift of the GRS proof-mass support stage and the optical path lengths. Hence the thermal control system, which is discussed in this article, must be able to reject such thermal disturbance in the very low frequency band to realize the LISA level verification

[2], [3].

In a lab environment these specifications can be met with sufficient insulation and thermal mass. For spacecraft, the very limited thermal mass calls for an active control system which can meet disturbance rejection and stability requirements simultaneously in the presence of long time delay.

A simple proportional plus integral control law presently provide approximately  $1 mK/\sqrt{Hz}$  of thermal stability for over 80 hours. Continuing development of a model predictive feedforward algorithm will extend performance to below  $1 mK/\sqrt{Hz}$  at  $f < 1 mHz$  and lower.

## EXPERIMENTAL SYSTEM

Figure 1 shows a schematic of the experimental system. The various layers of insulation correspond roughly to the layers of thermal isolation provided by the LISA spacecraft design [3], constructed from readily available lightweight materials.

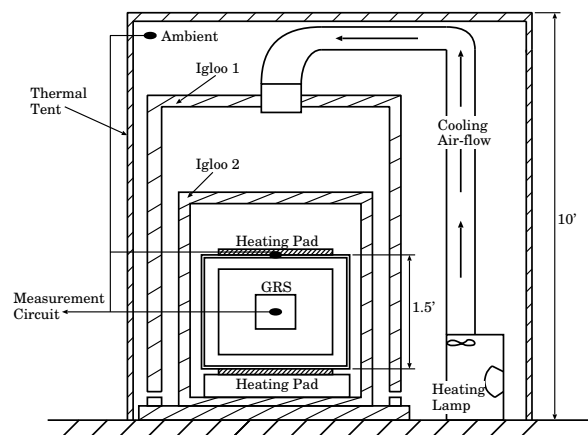


FIGURE 1. Schematic of the experimental system

The GRS sensor test-object is placed in the center of a double walled thin metal thermal enclosure, analogous to the LISA internal shield. A precision thermistor monitors the test-object with ( $< 100 \mu K / \sqrt{Hz}$ ) noise. The enclosure is wrapped in flexible insulation, and wrapped again with copper foil. This copper foil surface corresponds roughly to the LISA Y-tube surface, and here is temperature controlled to high-precision by a heating-pad/thermocouple feedback system. Surrounding the enclosure and heater-pad apparatus is 2'' of foil-covered polystyrene foam insulation, labeled igloo1 and igloo2, to create sealed control volumes. An improved design would use a vacuum enclosure.

The outer surface of igloo2 is maintained by a temperature regulated air-flow system which removes waste heat and provides 1st-order thermal disturbance relaxation of ambient laboratory temperature fluctuations. In this regard, the air-flow system functions to provide approximately the same level of thermal isolation, and stability as should the first layer of thermal isolation provided by the spacecraft structure. The air-flow point temperature is controlled by independent SISO controllers, which is regulated by a bang-bang control law operating a heater lamp and a mechanical relay combined with steady cold air flow from an air-chiller [4]. However, the air-flow works only as a large heat sink, simulating for space will be replaced with a cold radiator to deep space. The ambient temperature can be independently controlled using another system composed of commodity supplies (thermostats and room air-conditioners, for example). Note that our objective is not to reduce the disturbance itself, but instead to generate a compensating input so that net heat flux and thus temperature of the test object is tightly controlled.

Two heating pads, our primary actuators, are driven with an AC power source. They are installed at the top and bottom of the thermal enclosure inside igloo2. Accordingly a continuously variable computer controlled supply is the most desired equipment. However, due to the limited availability, the experiment is being conducted uti-

lizing a 24 Vac power source, the output level of which is fixed. Therefore, the control program first computes the numerical value of the heating pad temperature (control signal) based on the desired final output and then sets as the value obtained as the reference track the reference of the control signal. Since the band width of the heating pad is significantly greater than that of the GRS, this scheme performs very well to emulate a smooth control input. Finally, the entire system is placed within a clear plastic thermal tent, primarily to cut down on air drafts.

Three temperature sensors are installed to measure the ambient temperature inside the thermal tent, the heating-pad temperatures at the copper foil outside double-walled enclosure, and the GRS test-object inside. A typical time history of the ambient and GRS test-object temperature is shown in Figure 2.

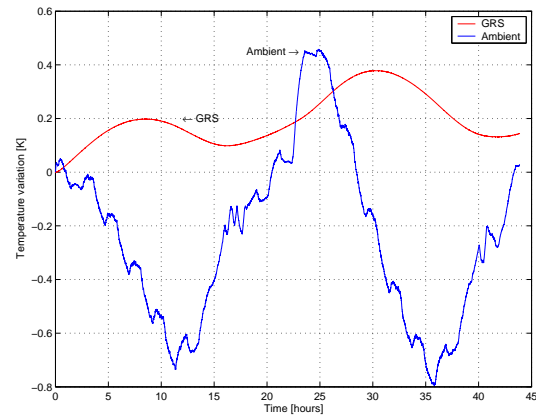


FIGURE 2. Time history of typical daily ambient temperature variation

The data was acquired without control authority and reveals significant coupling between the ambient and the GRS temperatures, which makes it difficult to reduce the fluctuations below the LISA thermal requirement [5] at least with the limited amount of thermal mass. Although the system has multiple layers of thermal insulation, the GRS test-object temperature is still varying roughly  $\pm 0.2 K$ , which is obviously too large fluctuation for the LISA requirement.

In summary, the main objective of the experiment

is to develop robust control system that can suppress the ambient temperature variation as low as possible to the LISA thermal requirement level by using an active control algorithm in a limited thermal mass environment at the low frequency band,  $f \sim 0.01 \text{ mHz}$ . Ultimately, the control techniques being developed through experiments could be adapted to any types of systems that possess large time-delays and their dynamics are heavily dominated by them.

## CONTROL SYSTEM

Figure 3 represents the control block diagram of the entire system corresponding to Figure 1.

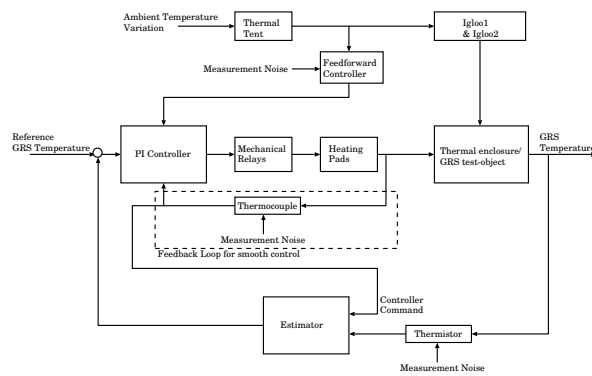


FIGURE 3. Control system block diagram

Feedback and feedforward control loops are formulated. As seen in Figure 2, the time delay between the ambient temperature and the GRS temperature is approximately 0.5 hours. Thus, by measuring the future potential disturbance that affects the GRS temperature beforehand and having the controller compute appropriate commands before the plant responds to the disturbance, the feedforward controller provides effective first-order disturbance reduction.

In addition to feedforward control, the system takes advantage of the feedback loop. In general, feedforward control performance largely depends on how accurately sensing mechanisms are able to predict the behavior of disturbance. The feedback control enhances the performance of rejecting the disturbance effects and adds robustness. The feedback loop takes a measurement at the sensor placed on the GRS. And the measured output and the control command are fed to a Smith

regulator [6] [7] [8] to estimate the state so that a PI controller can compute the command signal. The parameters of the PI controller were determined from a mathematical model and numerical optimization.

The physical plant is modeled as a combination of a second-order system plus a single time-delay element. The model parameters are fitted empirically using least-square technique and MATLAB simulations. Figure 4 demonstrates dynamics of the plant in the frequency domain, which is embedded in the estimator in Figure 3.

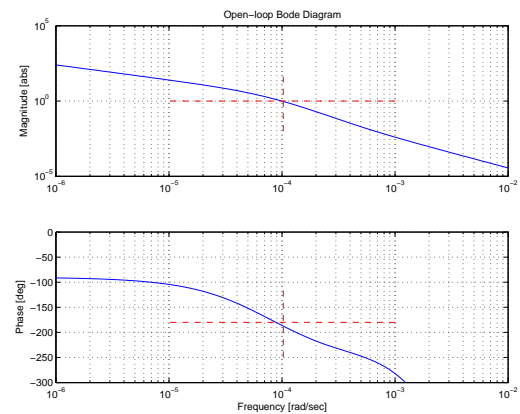


FIGURE 4. Bode plot of the plant

## EXPERIMENTAL RESULTS

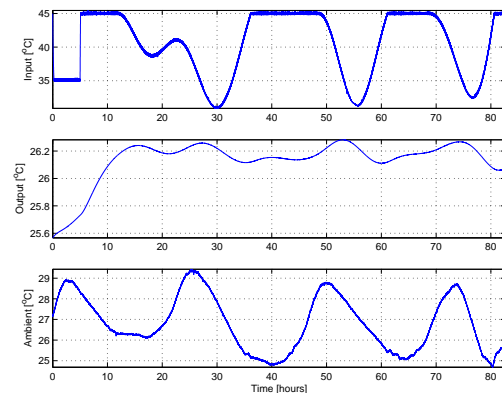


FIGURE 5. Time history of the first experiment: heating pad temperature (control effort, top), GRS temperature (output, middle), ambient temperature (disturbance, bottom)

Figure 5 demonstrates the 80-hour variation of the GRS temperature (output) together with the heating pad (input) and the ambient temperature (disturbance). The temperature is maintained approximately  $\pm 20 \text{ mK}$  around  $26.2 \text{ }^\circ\text{C}$  over 80-hour observation. As the daily ambient temperature cycles in 24 hours, the GRS is still largely affected by such a low frequency signal ( $\sim 10^{-5} \text{ Hz}$ ), which is the major disturbance source.

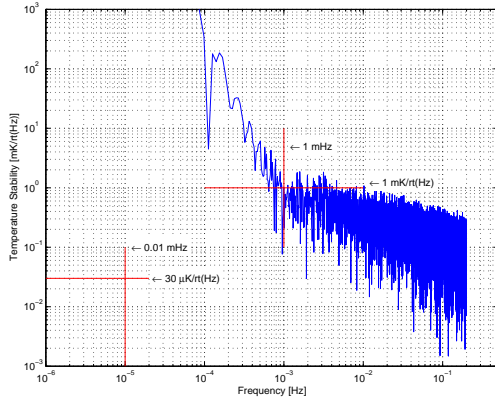


FIGURE 6. Thermal stability of the GRS test-object for 80-hour test

The mean square power spectral density of temperature variations of the GRS test-object is presented in Figure 6. The thermal stability is approximately  $1 \text{ mK}/\sqrt{\text{Hz}}$  above  $1 \text{ mHz}$ .

## CONCLUSION

The thermal experiment and corresponding results are presented. We have suppressed the ambient temperature variations by a factor of 1,000 down to  $1 \text{ mHz}$ . We expect to extend the low frequency suppression to  $0.01 \text{ mHz}$  and the amplitude to less than  $30 \text{ } \mu\text{K}/\sqrt{\text{Hz}}$ .

The LISA thermal requirement is also illustrated at the bottom left corner of the Figure 6. In order to push the spectral density curve to the region, two tasks are needed to be completed. Obviously, in order to suppress temperature variations even lower than the current level, the control algorithm has to be improved. However, the ultimate performance is limited by measurement noise from sensors. Thus, in addition to continuing development of the control system, for the better precision, less noise and more intermediate-term sta-

bility, improved measurement will be required [9] to fully satisfy the LISA thermal requirement.

## REFERENCES

1. Daniel B. DeBra. Drag-free spacecraft as platforms for space missions and fundamental physics. *Classical and Quantum Gravity*, 14:1549–1555, 1997.
2. Bonny L Schumaker. Disturbance reduction requirements for LISA. *Classical and Quantum Gravity*, 20(10):S239–S253, 2003.
3. Hume Peabody and Stephen Merkowitz. Lisa thermal design. *Classical and Quantum Gravity*, 22(10):S403–S411, 2005.
4. K.M.Lawton and S.R.Patterson. A high-stability air temperature control system. *Precision Engineering*, 24(2):174–182, 2000.
5. Alberto Lobo, M. Nofrarias, and J. Sanjuan. Thermal diagnostics for ltp. *Classical and Quantum Gravity*, 22(10):S171–S176, 2005.
6. O.J.M. Smith. Closer control of loops with dead time. *Chemical Engineering Progress*, 53:217–219, 1957.
7. J.E.Normey-Rico and E.F.Camacho. Multivariable generalised predictive controller based on the smith predictor. *IEE Proc.-Control Theory Appl.*, 147(5):538–546, 2000.
8. J.J.Huang. Liquid temperature control for precision machines. *Ph.D. Thesis, Department of Aeronautics and Astronautics, Stanford University*, 1997.
9. K. M. Lawton and S. R. Patterson. Long-term relative stability of thermistors: Part 2. *Precision Engineering*, 26(3), 2002.