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High-stability temperature control for ST-7/LISA Pathfinder gravitational reference sensor ground verification testing

S. Higuchi, G. Allen, W. Bencze, R. Byer, A. Dang, D. B. DeBra, D. Lauben, S. Dorlybounxou, J. Hanson, L. Ho, G. Huffman, F. Sabur, K. Sun, R. Tavernetti, L. Rolih, R. VanPatten, J. Wallace, S. Williams

Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305-4085, USA

E-mail: sei87@stanford.edu

Abstract. This article demonstrates experimental results of a thermal control system developed for ST-7 gravitational reference sensor (GRS) ground verification testing which provides thermal stability $\delta T < 1\,\mathrm{mK}/\sqrt{\mathrm{Hz}}$ to $f < 0.1\,\mathrm{mHz}$, and which by extension is suitable for in-flight thermal control of the LISA spacecraft to compensate solar irradiate $1/f$ fluctuations. Although for ground testing these specifications can be met fairly readily with sufficient insulation and thermal mass, in contrast, for spacecraft the very limited thermal mass calls for an active control system which can simultaneously meet disturbance rejection and stability requirements in the presence of long time delay; a considerable design challenge. Simple control laws presently provide $\sim 1\,\mathrm{mK}/\sqrt{\mathrm{Hz}}$ for > 24 hours. Continuing development of a model predictive feedforward control algorithm will extend performance to $< 1\,\mathrm{mK}/\sqrt{\mathrm{Hz}}$ at $f < 0.01\,\mathrm{mHz}$ and possibly lower, extending LISA coverage of super massive black hole mergers.

1. Objective

LISA and other precision spaceflight missions require gravitational reference sensors (GRS) for drag-free control [1]. This experiment focuses on achieving thermal stability of the ST-7/GRS sensor model used for simultaneous capacitive and optical sensing cross-calibration and verification [2], [3].

Stabilizing the thermal environment against low frequency disturbance is one of the most important problems for ST-7/GRS performance verification. Lowering the sub-mHz thermal drift caused by diurnal variations is the main objective, with stability requirement $\delta T < 1\,\mathrm{mK}/\sqrt{\mathrm{Hz}}$ at $f = 0.1\,\mathrm{mHz}$ measured at the sensor. Our main concern is the daily ambient temperature variation which causes the thermal drift to the GRS proof-mass support stage and to the optical path lengths. Hence the thermal control system, which is discussed in this article, must be able to reject such thermal disturbance to realize $1\,\mathrm{mK}/\sqrt{\mathrm{Hz}}$ at $1\,\mathrm{mHz}$ for the ST-7 LISA Pathfinder, and ultimately, down to $0.1\,\mathrm{mHz}$ for LISA level verification [4], [5], [6].

2. Experimental system

Figure 1 shows a schematic figure of the experimental system and typical variation in ambient temperature. The various layers of insulation correspond in a rough way to the layers of thermal isolation provided by the LISA spacecraft design [6], although various adaptations were necessary consistent resource availability.

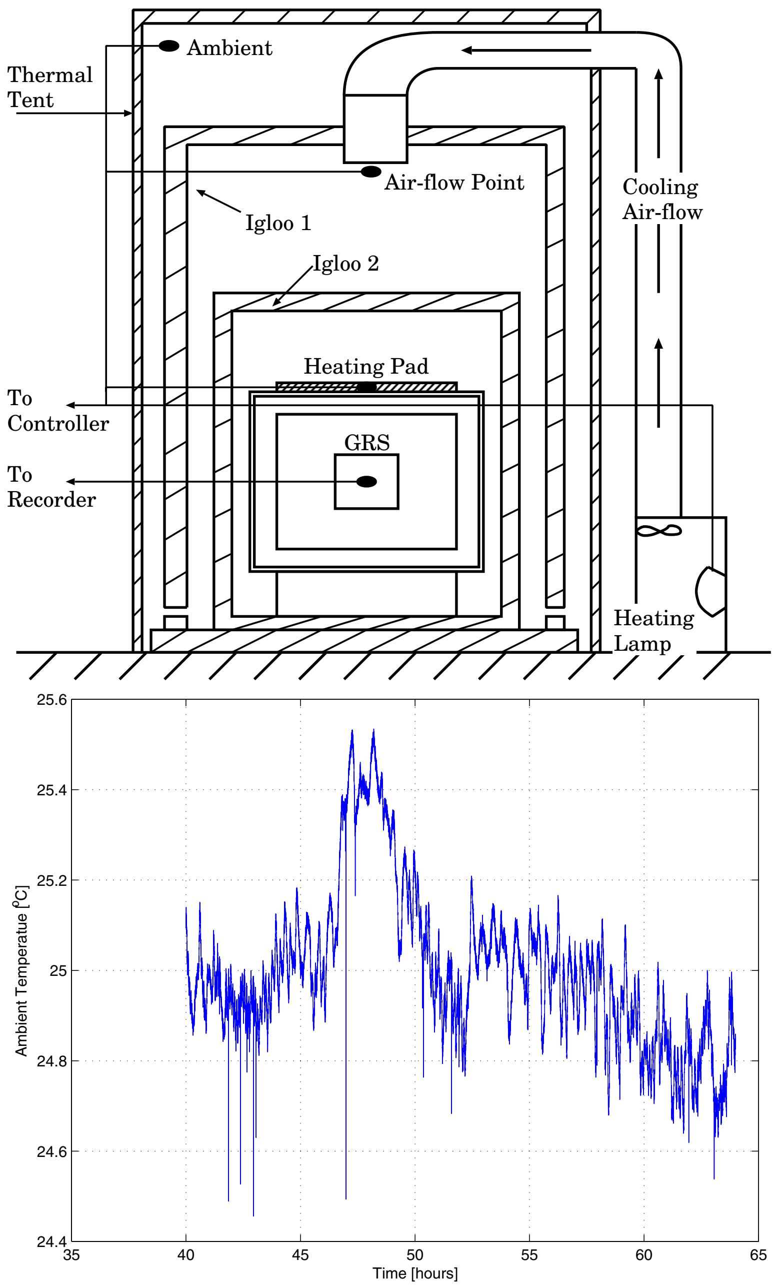

Figure 1. Schematic figure of the experiment (top), the ambient temperature variation (bottom)

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 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/thermistor feedback system. Surrounding the enclosure and heater-pad apparatus is 2" of foil-covered polystyrene foam insulation, labeled igloo2, to create a sealed control volume. Future plans intend to replace igloo2 with a modest vacuum enclosure.

The outer surface of igloo2 is maintained to $< 0.1\,^{o}$C stability by a temperature regulated air-flow system which removes waste heat and provides 1st-order thermal disturbance rejection 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 [6], albeit by analogy only. Finally, the entire system is placed within a clear plastic thermal tent, primarily to cut down on air drafts.

Four temperature sensors are installed to measure the ambient temperature outside igloo1, the air-flow point of igloo2, the heating pad temperature at the copper foil outside double-walled enclosure, and the GRS test-object inside. A typical time history of the ambient temperature is shown at the bottom of Figure 1, which shows $0.5\,^{o}$C bumps during the hot afternoon, despite active laboratory air-conditioning.

Figure 2 represents the control block diagram of the entire system. The air-flow point temperature and the heating pad temperature are controlled by two independent SISO controllers. The GRS temperature measurement is used to set initial control points for the air-flow point and heating pad controllers, and thereafter used only to monitor performance. The air-flow point 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 [7]. The air-flow works only as a large heat sink, simulating for space will be replaced with a cold radiator to deep space. Lastly, the ambient temperature is independently controlled using another system composed of commodity supplies (thermostats and room air conditioners, for example).

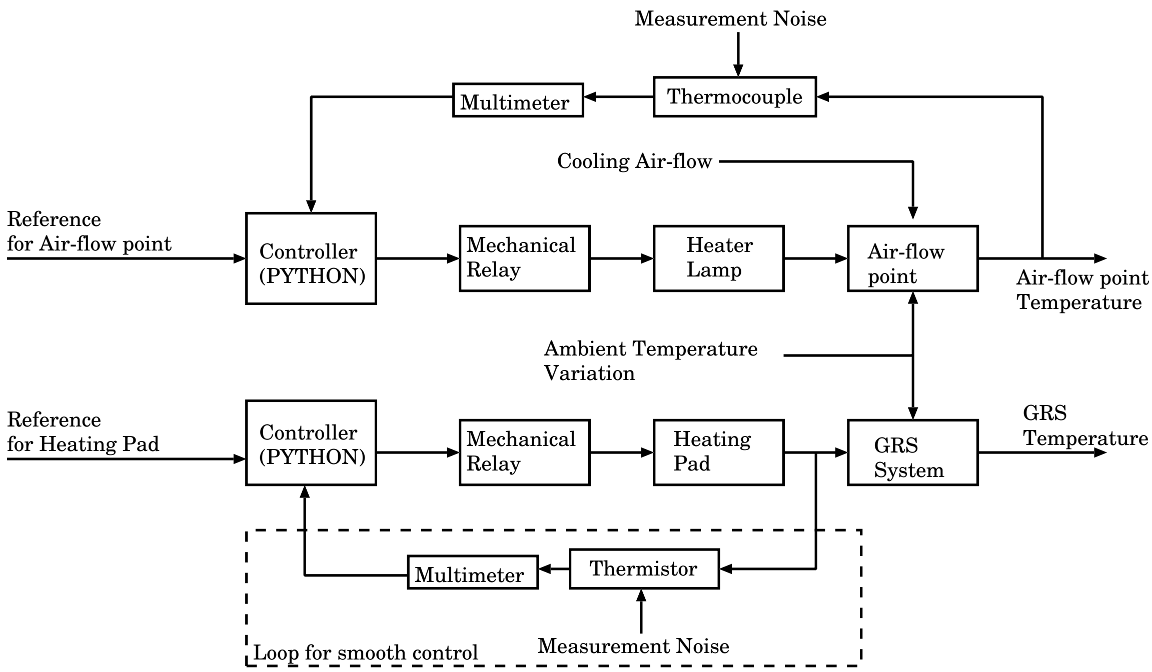

Figure 2. Control block diagram of the entire system

We have to emphasize that the heater temperature is the only quantity to be controlled during experiments at the current development stage. The GRS temperature was being measured out of the control loop. Although the experimental data which is demonstrated in the following section was obtained without taking advantage of feedback from the GRS test-object temperature measurement, the control system performed with satisfactory thermal stability.

The heating pad is driven with an AC power source. Accordingly a variable controllable AC power supply is the most desired equipment. However, due to the limited availability, the experiment is being conducted utilizing 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 the value obtained as the reference of the heating pad. The mechanical relay does the bang-bang control to make the heating pad temperature 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 the smooth control input. The mechanization is represented in the inner feedback loop of Figure 2 and Figure 3.

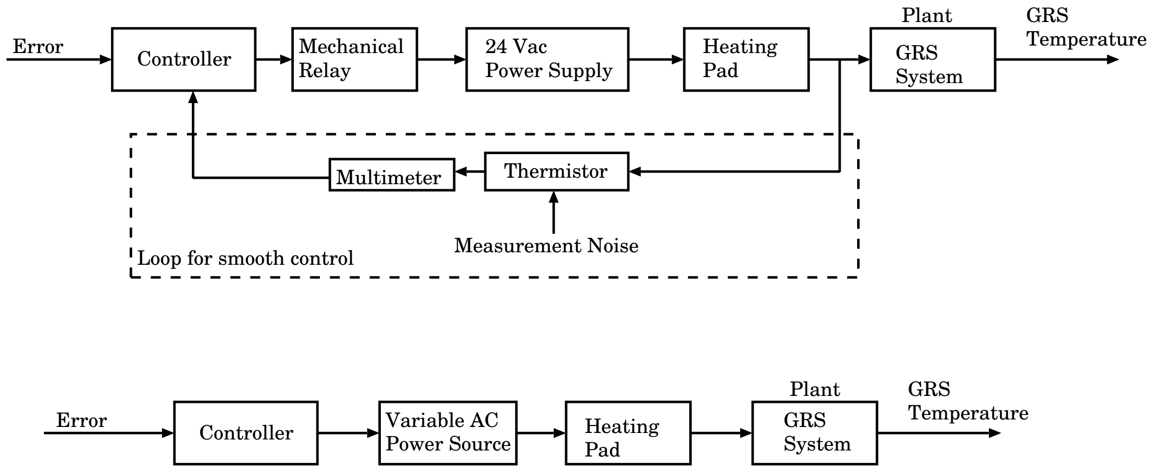

Figure 3. Smooth control using a mechanical relay and constant voltage source (top) and an ideal structure (bottom).

3. Results

Figure 4 demonstrates the 24-hour variation of the GRS (red, middle) together with the air-flow point (blue, bottom) and the heating pad (green, top). The bottom panel of the figure magnifies the GRS temperature variation (noise spikes are due to laboratory EMI which has since been eliminated). The figure shows the best 24-hour portion from over 72-hour operation. The temperature keeps approximately $\pm 2\,\mathrm{mK}$ around $26.114\,^{\circ}\mathrm{C}$ over 24-hour observation. As the daily ambient temperature cycles in 24 hours, the GRS is still largely affected by such a low frequency signal ($\sim 10^{-5}\,\mathrm{Hz}$), which is the major disturbance source.

As was seen in Figure 1, we observed bumps in the ambient temperature. Such sudden temperature changes are attenuated as we look at the temperatures of the inner layers. Thus its impact is not observed at the GRS, which can be clearly seen from the Figure 4.

The power spectrum of temperature variations is presented in Figure 5. The thermal stability of the GRS is approximately $1\,\mathrm{mK}/\sqrt{\mathrm{Hz}}$ below $1\,\mathrm{mHz}$ where the surrounding temperatures are constant as shown in Figure 4. This level of thermal stability, multiplied by typical CTE 10^{-5} /K and $10\,\mathrm{cm}$ scale size of the GRS model, limits the thermally induced displacement noise of the test object to an acceptable level $\sim 1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ [2], [8].

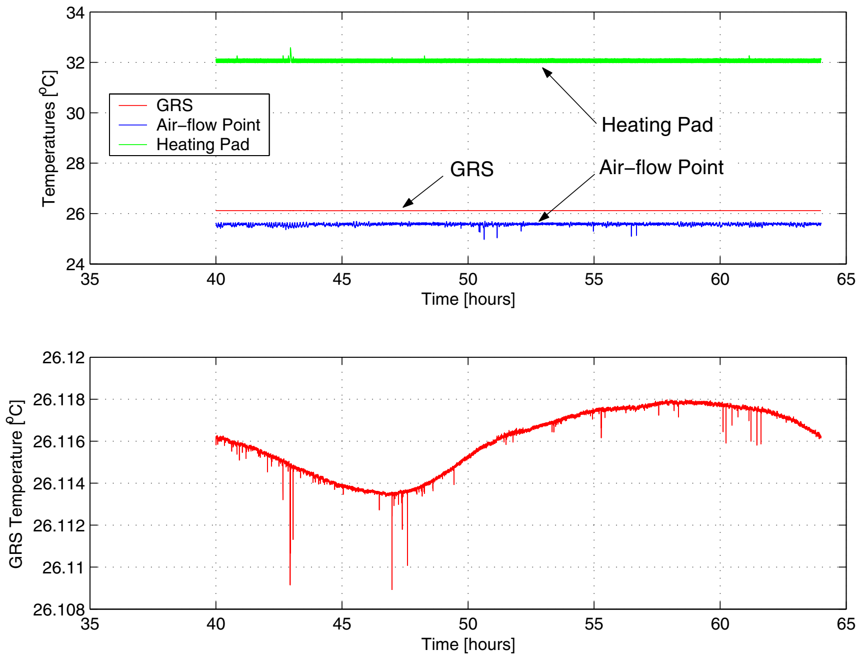

Figure 4. Time history of the GRS temperature: GRS, air-flow point, heating pad temperatures(top), GRS temperature (bottom)

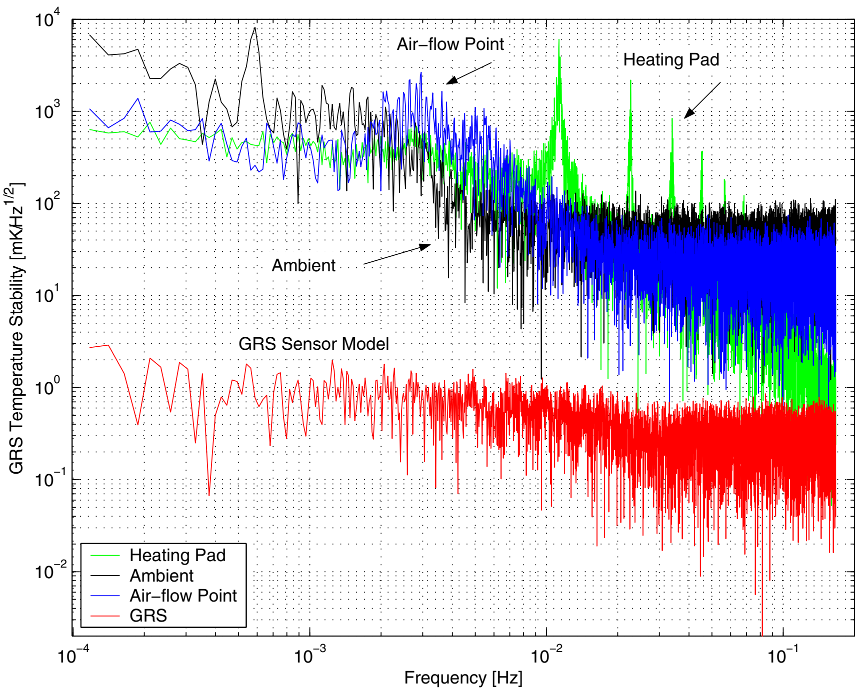

Figure 5. Thermal stability of the GRS system

4. Future Work

Figure 5 shows a slight noise trend $> 1\,\mathrm{mK}/\sqrt{\mathrm{Hz}}$ for $f < 0.3\,\mathrm{mHz}$ due to the trend in ambient diurnal variation at these low frequencies. In order to realize the LISA thermal stability requirement to $f < 0.1\,\mathrm{mHz}$, we need to design an active control law which takes into account the significantly large time delay of > 2 hours. Predictive control and feedforward compensation techniques are the best candidates for our objectives. As the system bandwidth is extremely low due to the very long time delay, a feedback-only method is unable to control by itself. We will fully characterize the system [9] to implement the predictive control. One of the most familiar techniques is Smith's predictor [10] [11] [12] [13]. The preliminary system characterization shows the zero frequency gain is at least $0.01\,\mathrm{K/K}$ and the time delay at least 2 hours. The experimental result indicates that the GRS has $\pm 2\,\mathrm{mK}$ residual errors while the actuator output is kept constant. Based on these preliminary measurements, at least $\pm 200\ mK$ control variation will be necessary at the heater-pad control surface. In addition, for the better precision, less noise and more long-term stability, improved measurement will be required [14].

Some improvements to the experimental system are also warranted. As mentioned, igloo2 should be replaced by a vacuum chamber for better thermal isolation approximating real flight conditions. Furthermore, the simple box-style double-walled thermal enclosure which now surrounds the GRS test object should be redesigned to more closely resemble the LISA Y-tube, including top-plate and bottom-plate, in order to accurately relate the ground verification system to the flight design. Finally, the entire assembly should be fitted above and below with a heat-lamp/cold-plate system, complete with $1/f$ modulation of the heat-lamp intensity, to better replicate the spacecraft ambient environment and $1/f$ solar fluctuations.

5. Conclusion

The thermal experiment and corresponding results are presented. We have suppressed the ambient temperature variations by a factor of $1,000$ down to $1\,\mathrm{mHz}$. We expect to extend the low frequency suppression to $0.1\,\mathrm{mHz}$ and the amplitude to less than $0.1\,\mathrm{mK}/\sqrt{\mathrm{Hz}}$ once our setpoint control law for the GRS temperature is made active.

Acknowledgments

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