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Generating Sub-Millidegree Thermal Stability over Large Volumes for Precision Experiments

– A robust, modular-scalable approach

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Abstract We describe features of an Active Thermal Control System that suppresses long-period (diurnal and semi-diurnal) temperature variations in a region of large volume (~30 m^3) down to amplitudes below 1 millidegree Centigrade. The system possesses attributes of modularity that allow it to be scaled to arbitrary size. It is therefore likely to be of interest to the larger community engaged in Precision Experiments.

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1. Introduction

The Gauribidanur Underground Laboratory is a purpose-built facility for conducting torsion balance experiments at the limits of current sensitivity, to address delicate questions concerning Gravity and Feebler Interactions [1,2]. Located at a remote site on the Deccan Plateau in Southern India, it benefits from low micro-seismic background noise as well as low gravitational-gradient noise. The laboratory already enjoys high thermal stability since it is about 25m underground, owing to which the ambient diurnal (24-hr) and semi-diurnal (12-hr) temperature waves at the lowest zone of the laboratory have amplitudes of $\lesssim$ 50 milli°C. These waves are in fact caused by Sun-synchronous atmospheric pressure oscillations well-known in the belt between the tropics. Temperature variations in the ambient not only couple directly to the motion of the torsion balance but also affect nearly every part of our system (the optics, the electronics, mechanical systems), giving rise to noise, or worse, ***systematic effects*** that seem identical to the signal that we seek. Our Autocollimating Optical Lever with an angular resolution of 3 x 10^{-10} rad/√Hz is also directly affected by these systematic temperature variations. In our Equivalence Principle (EP) Test to a sensitivity of 1 part in 10^{13}, we therefore wish to suppress the residual temperature waves to amplitudes below 1m°C.

Here we describe key aspects of an Active Thermal Control System that provides the necessary thermal stability for our Ultra-High Vacuum Chamber and associated instrumentation at the base of the Underground Laboratory. In the Dicke-Braginsky mode of EP tests (see for example [3,4,5]), with a Sun-synchronous signal of ~ 24 hr period, it is systematic variations of long period that affect us the most. Our Thermal Control System successfully suppresses diurnal and semi-diurnal waves to levels somewhat below the design goal of 1m°C across the very large volume of 30 m^3, while allowing random temperature variations at higher frequencies (“noise”) at slightly higher levels; this is acceptable for us.

In what follows, we describe

a) reliable **temperature measurement** at the millidegree level over periods of months;

b) essential features of an appropriate **Thermal-Mechanical Enclosure** that surrounds the sensitive experimental volume;

c) the **Electronics and Instrumentation**, including the **PID Feedback Control** that we have developed;

d) and finally, the **typical performance** of our system.

We stress that thermal stability is an important requirement across a broad range of experiments: specific examples of millikelvin stability achieved in small volumes (~ <1 m^3) may be cited in optics and standards laboratories [6,7] and in experimental gravitation (e.g., [8]). Our own experimental effort differs from the above in that it stabilizes very large volumes; the approach we describe is fundamentally modular, scaling readily to any realistic size, so it is expected to be of interest to the larger experimental community engaged in Precision Experiments. The overall time duration over which thermal stability can be maintained in our approach is essentially unconstrained.

2. Key aspects of our Thermal Control System

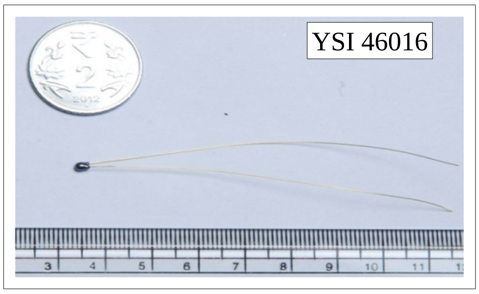
2.1 The Reliable Measurement of Temperature at m°C levels

Thermistors ("YSI #46016 B-mix", 10 kΩ at 25°C) were our preferred choice of temperature sensor, since their large "signal" is easily read off in field conditions. However, before we could begin to use them for our purpose, we had to establish their stability and interchangeability. The particular choice of manufacturer and brand/sub-type of thermistor were driven by hearsay, some "heritage", and relevant dialogue with the manufacturer. One signature study performed at the US National Bureau of Standards [9] in the 1970s indicated adequate stability, but the scale of our effort merited a fresh study with the thermistors readily available to us. Our approach to characterization, described here, differs significantly from [9].

Thermistors have a strongly nonlinear R vs T relationship, and this is best empirically captured by the Steinhart & Hart Equation (S&HE):

$$\frac{1}{T} = a + b \times \ln(R_{ohm}) + c \times \ln(R_{ohm})^3$$

As we discovered, each thermistor turns out to have slightly different values of the coefficient set (*a*,*b*,*c*), and our first task therefore became that of determining the individual coefficient sets (*a*,*b*,*c*) for every thermistor we used. Questions of stability and interchangeability then translated to determining the stabilities of the coefficient sets over time.



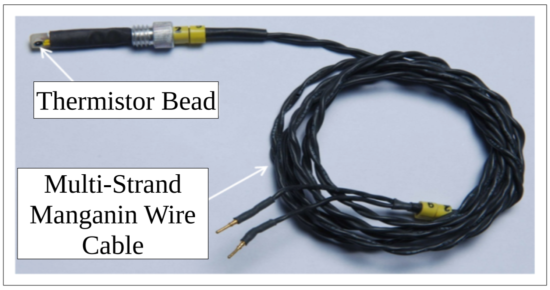


Fig. 1 YSI 46016 Thermistors – bare (left) and terminated (right) in a Manganin Cable – mechanically strong, yet with low-thermal-conductivity, and a very low "tempco" of resistance.

Aspects of our physical preparation of the thermistors, as well as of the calibration-characterization system are captured in figs. 1 and 2. We cross-calibrated our prepared, ready-to-deploy thermistors inside what we call a Multi-Layer Thermal Enclosure (MLTE, fig.2). This unit is specifically designed to reduce thermal gradients between individual thermistors in the ensemble of thermistors being calibrated, while preventing high frequency temperature variations (noise) in the laboratory from reaching the interior, where the thermistors are placed for calibration. The assembly of thermistors includes one designated "Master Thermistor" that is *postulated* to follow the manufacturer's standard R vs T table of values. After an initial raising of temperature in the interior of the MLTE, resistances of thermistors are logged as the interior temperature falls very gradually (and smoothly), in the process yielding {R vs T_{master}} datasets for individual thermistors, where T_{master} is the "temperature" of the Master-Thermistor; these datasets are then regression-fitted to obtain the individual sets (*a*,*b*,*c*). The regression-fit is excellent, with residuals at a given epoch largely remaining below 0.5m°C; indeed, for about

10% of the thermistors, it nowhere exceeds 0.1m°C. This speaks of the quality of fit provided by the entirely empirical S&HE, as well as of the very low thermal gradients inside the MLTE. Calibration studies on the same set of thermistors performed by us roughly every 12 months over a ~ 4 year duration have shown that different thermistors age or drift slightly differently; yet, with a once-determined set of coefficients, they can be used interchangeably to a precision of 1m°C over a 1-year period, while the drifts over a 4-year period are found to be typically less than 3m°C.

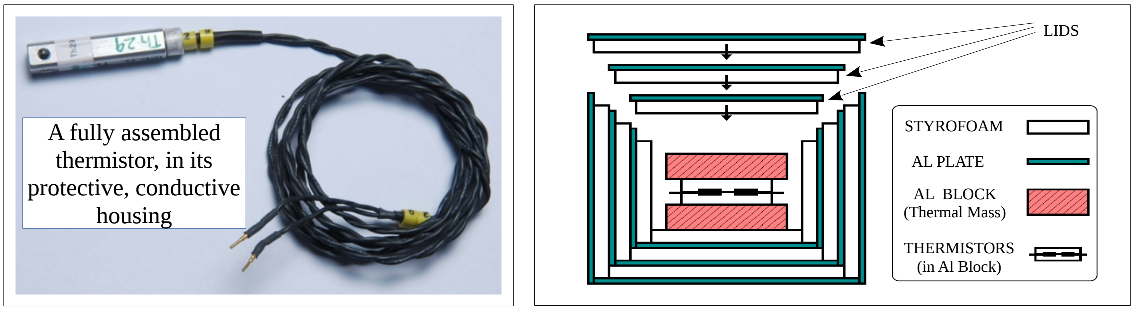


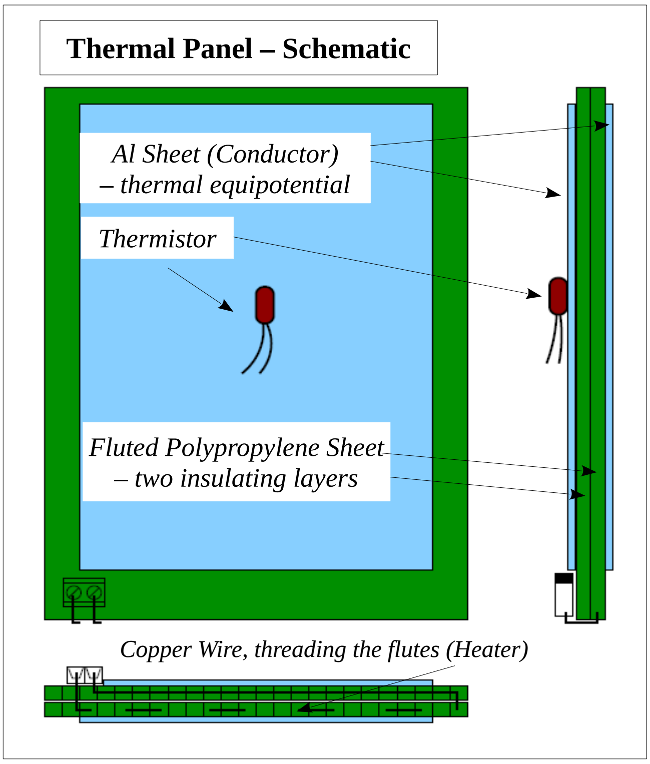
Fig. 2 Fully assembled thermistor (left), and Schematic Illustration (right) of the MLTE. With its nested, alternating layers of conductor and insulator, the MLTE substantially eliminates internal thermal gradients, while also being a thermal low-pass filter in the time-domain.

2.2 The Thermal-Mechanical Enclosure and the Thermal Panels

The experimental region in which we demand Active Thermal Stabilization is large, about 2.2m in diameter x 8m in height, and the most basic requirement is that there be an enshrouding enclosure. We start with a modular scaffolding structure made of hollow, extruded Aluminium profiles; this provides the basic attributes of stiffness without great mass, mechanical modularity, ease of assembly and interchangeability. The structure itself is octagonal in cross-section, and is vertically divided into 3 identical layers, with eight identical thermal heating panels fitted on each layer. Photographs of the scaffold are displayed in fig.3 below, with and without thermal panels fitted on it.

Fig.3 (left) The scaffold for the thermal enclosure, built of extruded Aluminium profiles, and installed in the Underground Laboratory; (right) scaffold, now fitted with thermal panels, looking upwards from the base of the Underground Laboratory.

The schematic illustration in fig.4 shows the design of the thermal panels: the fluted polypropylene sheets provide high stiffness per unit mass; the hollowness of their interior adds to their thermal insulation, while also providing a means to thread current-carrying copper wires through them, thus making them fairly uniform "area-heaters". The aluminium sheets on either side of the sandwich assembly provide an approximation to a thermal equipotential on each surface. This contributes to a reduction of thermal gradients, while also allowing the single thermistor on the outer surface to proxy for the temperature of the entire surface. Overall, the low-mass aspect implies low thermal inertia, and this enables quick response by this *driving* part of the system.



The external dimensions of the thermal panels are precise at the millimetre level, with higher precision for the placement of mounting holes. These aspects are dictated by the demand for interchangeability while fixing the panels onto the underlying modular framework. The necessary precision in the fabrication of these composite panels was gained by the use of suitable jigs.

Fig. 4 A schematic illustration depicting key details of a typical thermal panel. Note that the "threading" of the copper wires is done in the inner layer of fluted polypropylene board, closer to the interior of the volume under thermal control.

2.3 Feedback Control: Electronics and Instrumentation, and implementation of the PID schema

With the conscious choice of correcting only long-period temperature excursions, the loop closure time is chosen to be 10 minutes. This immediately imposes demands on the maximum droop-rate permissible for the Sample-and-hold; the Analog Devices IC AD5533, with 32 channels of "**I**nfinite-droopless **S**ample and **H**old **A**mplifier" capability was found ideal for our requirements (our immediate application uses 24 channels of the 32 available). Accordingly we developed a board around this 74-lead CSPBGA chip, as seen in fig.5 below. Heater power, controlled by the signal-output of the AD5533, is sourced from a simple power amplifier, one for each channel of control. A power-amplifier card with 8 channels is seen in fig.6. Three identical modules serve for the full system (8 panels per layer x 3 layers). Each panel is driven by a constant current through the 10 minutes loop cycle-time before a possible correction (as determined by the controlling algorithm) based on the next temperature measurement.

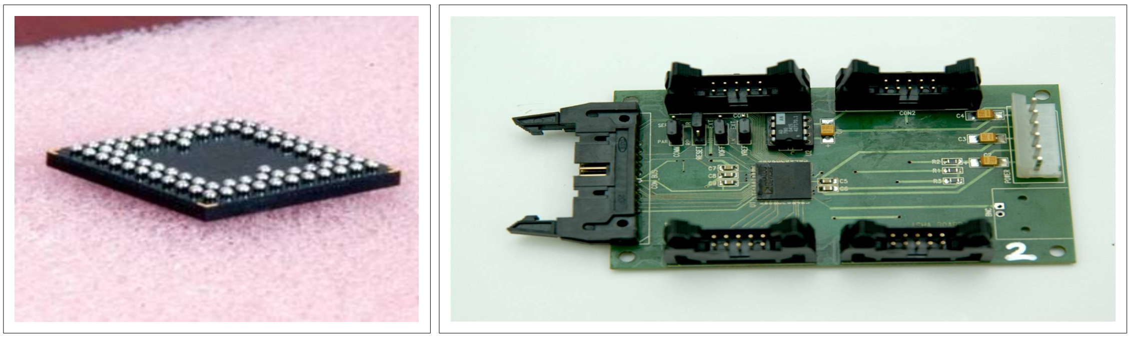


Fig.5 At the heart of the electronics is the AD5533 32-channel ISHA chip (left); the board at right has this chip mounted at centre, together with multiple ports for data and control.

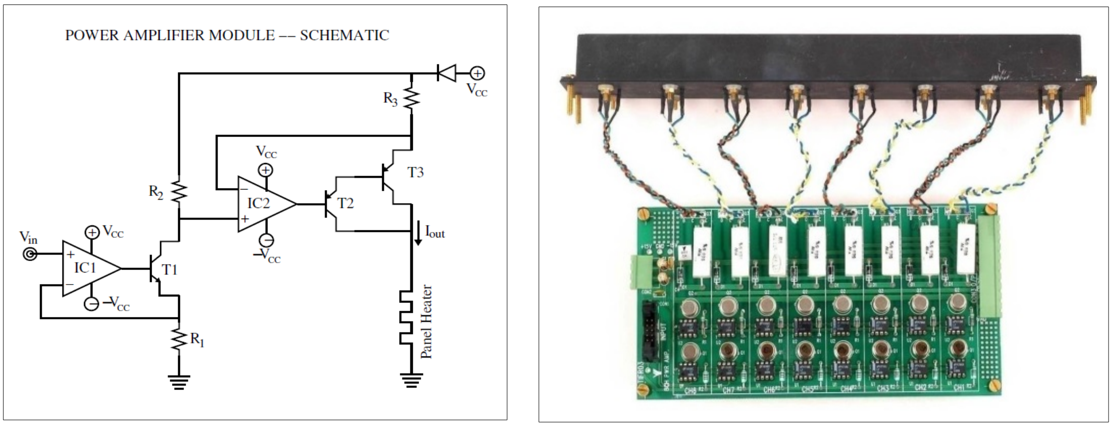


Fig. 6 The circuit-schematic at **left** is that of a basic power amplifier unit, while the module at **right** contains eight such power amplifiers. The designed power output, at less than 5W per channel, is modest, but entirely adequate for sub-millidegree control.

Fig. 7 shows the key elements of the control loop in block-schematic. In our implementation, the Power Amplifiers and the ISHA Board are placed at the top of the underground laboratory, about 25m away from the volume under control, in an instrument rack that houses other parts of the full Control System, notably the controlling computer (PC) and the Data-Logging Multimeter (a 6.5 digit Agilent Model 34970A). The large separation also minimizes injection of “process-heat” from the power electronics into the volume under control. Thermistor resistances are read off by the multimeter, through long multi-core cables traversing the 25m distance. Noise in the reading of resistance is very low despite the long cables, and is further suppressed by use of the “NPLC” mode of the Agilent Multimeter: the standard deviation of resistance for a single reading is typically less than 0.04Ω (≈ 0.1m°C). Thermistor resistances are read off in a pulsed process, once every 10 minutes. The act of taking a single “10 NPLC” reading, that lasts for 200 millisec, induces self-heating of the thermistors, raising their temperatures by $\lesssim$ 3m°C, but this is identical across thermistors and over time. Consequently, the primary effect caused by self-heating is to introduce a small but constant offset error.

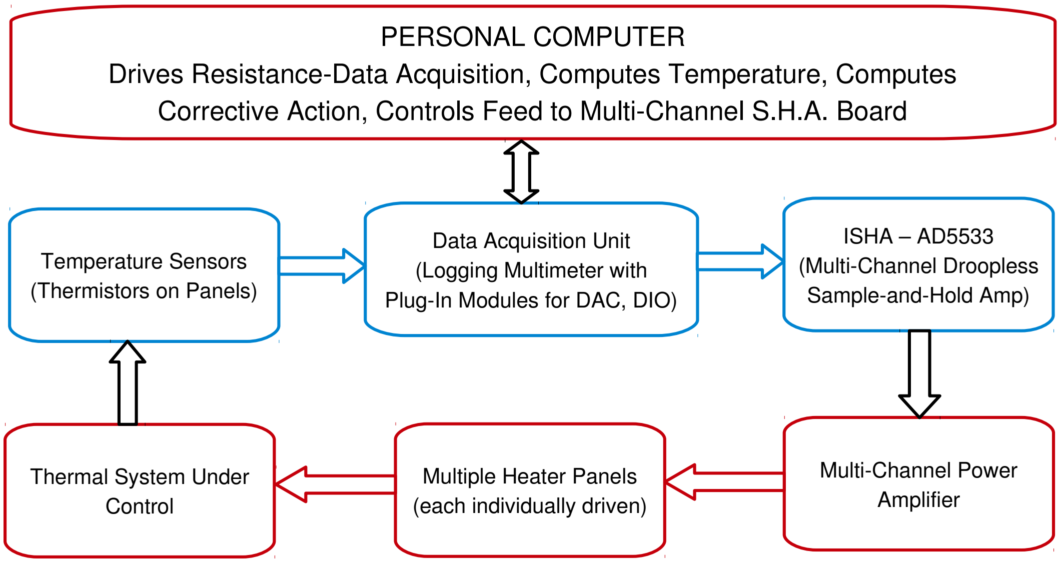


Fig.7 Block Schematic of the logical flow of the Feedback Control System.

We use the Proportional-Integral-Derivative (PID) paradigm for feedback control that is depicted in fig.8. While the basic idea of PID control is well known, the process of "tuning" of the loop (fixing of the feedback coefficients (K_p,K_d,K_i)) is critically important if one wishes to deliver feedback optimally, avoiding both overshoots and oscillations. We found the so-called **Ziegler-Nichols** tuning procedure to be very useful, and obtained a ballpark set of coefficients in the course of ~2 days of experimentation. Fine-tuning was then completed over a further ~3 weeks of trials. This may appear long, but a little reflection over the basic thermal time-scales of the entire underground laboratory (and the fact that we seek evidence of the suppression of a 24-hour wave), will convince one otherwise.

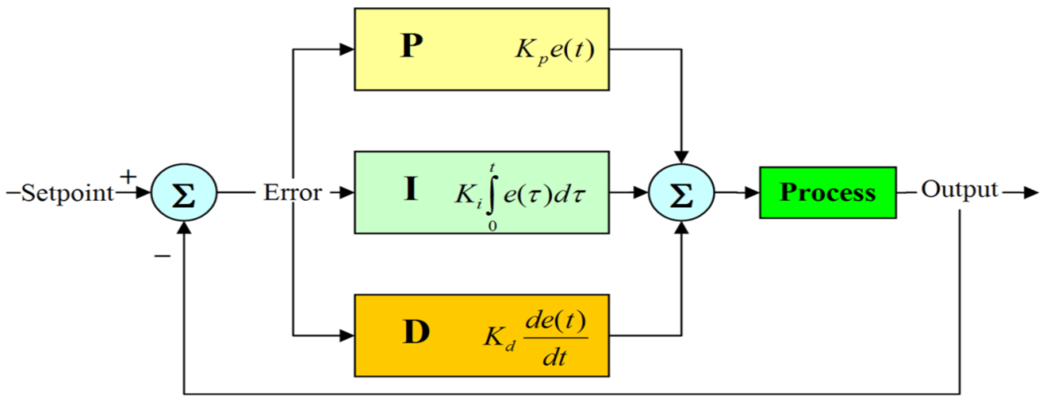


Fig.8 Graphical depiction of the PID control paradigm. (Figure credit: Arturo Urquizo (author) http://commons.wikimedia.org/wiki/File:PID.svg)

3. Typical Performance

As stated earlier, the system performs somewhat better than our original design goal. Thermistor-temperatures logged with and without the control system turned on, are graphed for presentation of performance. In either case, a good summary of performance is gained by looking at the average temperature of the full set of panels on a given layer; these "Layer-Average" temperatures are also regression-fitted to diurnal and semi-diurnal periods for further characterization.

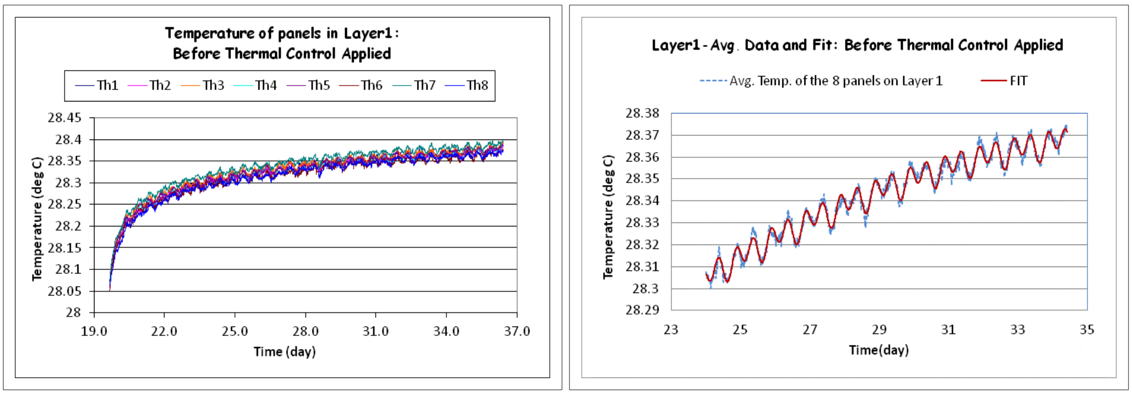


Fig.9 A graphical summary of the Temperature-Time graphs of the 8 panels in "Layer-1", in a phase *before* thermal control is activated. In the graph at **left**, the initial rapid rise in temperature (while the underground laboratory re-equilibrates after being insulated from thermal contact with the cooler upper regions) is followed by a phase of dominantly linear rate of rise of temperature. The graph at **right** focuses on this quasi-linear segment, and fits it with diurnal and semi-diurnal temperature waves, that turn out in this phase to have peak-to-peak variations of ~ 20 m°C. (Graphs here and in Fig.10 can be zoomed for greater detail.)

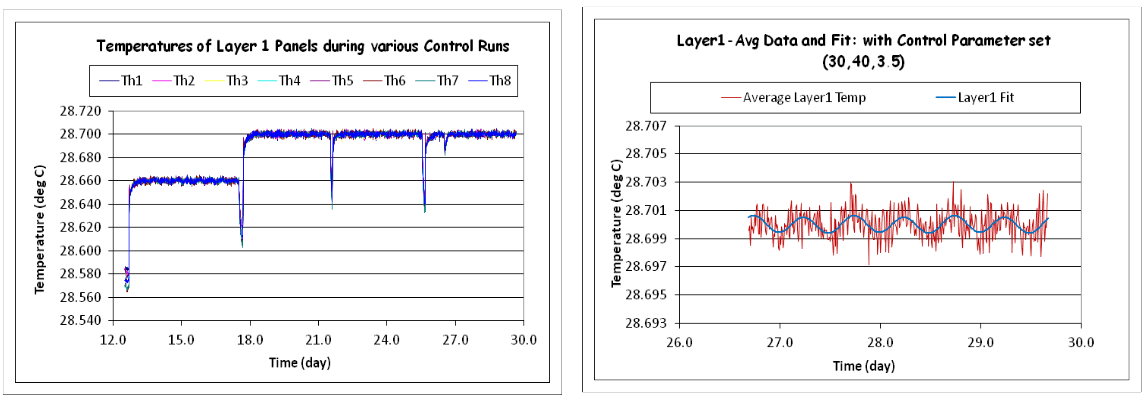


Fig. 10 The graph at **left** shows the results of a series of "tuning" sequences, where different sets of Control Parameters (K_p,K_d,K_i) are tested for performance. The "set point temperature" of the first sequence was chosen to be 28.660°C, different from the common value of 28.700°C in the later sequences. Note especially the "lock" and the absence of drift within the several-day duration of any one sequence. The graph at **right** shows the average temperature for the last and best tuning run from the dataset on the left; also seen is the best fit to this average temperature, where the semi-diurnal and diurnal components have amplitudes of < 0.6m°C, and < 75μ°C respectively. High frequency noise is present, but it too is limited in amplitude.

4. Summary and Conclusions

The successful development of our thermal control system has involved a number of different steps, of which a few are:

- establishing the thermistors' sensitivity, interchangeability and long-term stability
- conceiving of the modular enclosure, with its features of easy assembly and high stiffness-to-mass ratio (and hence low thermal inertia)
- developing and fabricating suitable “area-heaters” that incorporate modularity, mechanical stiffness with low-mass, and low thermal inertia
- developing the ISHA electronics board around the AD5533, and the associated Power Amplifier modules
- developing of a suitable Control Procedure, including also the validation of the Ziegler-Nichols tuning scheme for a system such as ours

We have subsequently made small but steady improvements on the system, such as the “stirring” of the air within the Thermal Enclosure to reduce vertical temperature gradients. The system has more recently been ported to the LabVIEW platform, under which it uses NI hardware to replace the ISHA board.

Systematic effects due to temperature variations in the ambient are often a limiting factor in sensitive precision experiments. Our work shows a constructive way forward to achieving active thermal control at or below millidegree levels; the approach is consciously modular, and can therefore easily be adopted by other experiments in this genre. While our system operates in Gauribidanur in an environment where the ambient variations are already passively reduced to low levels, we first tested our methods on a scaled down system in our Mumbai laboratory, and obtained similar millidegree control against an ambient daily variation of ~ 800mºC.

5. Acknowledgements

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