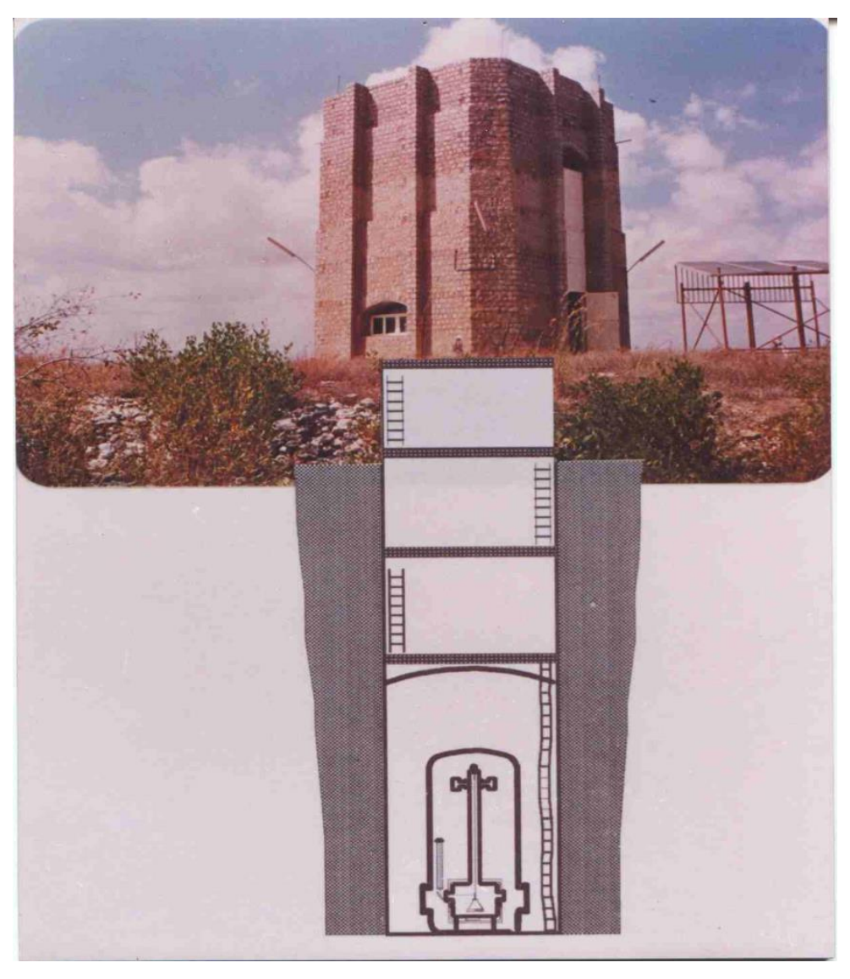
Generating sub-Millidegree Thermal Stability over Large Volumes

- A robust, modular-scalable approach

N. Krishnan, S.M. Pereira, A.Vaidyanathan
Gravitation Group, Tata Institute of Fundamental Research,
Mumbai – 400005, INDIA



Abstract We describe features of an Active Thermal Control System that suppresses long-period (diurnal and semi-diurnal) temperature variations in a volume of 30 m^3 to amplitudes below a 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.

The Background and the Need for m^{0}C thermal control

The **Gauribidanur Underground Laboratory**, purpose-built for **sensitive Torsion Balance Experiments**, already has high thermal stability – the passive shielding gained by going underground, suppresses diurnal (24-hr) and semi-diurnal (12-hr) temperature waves to amplitudes well below 50 milli ^{0}C.

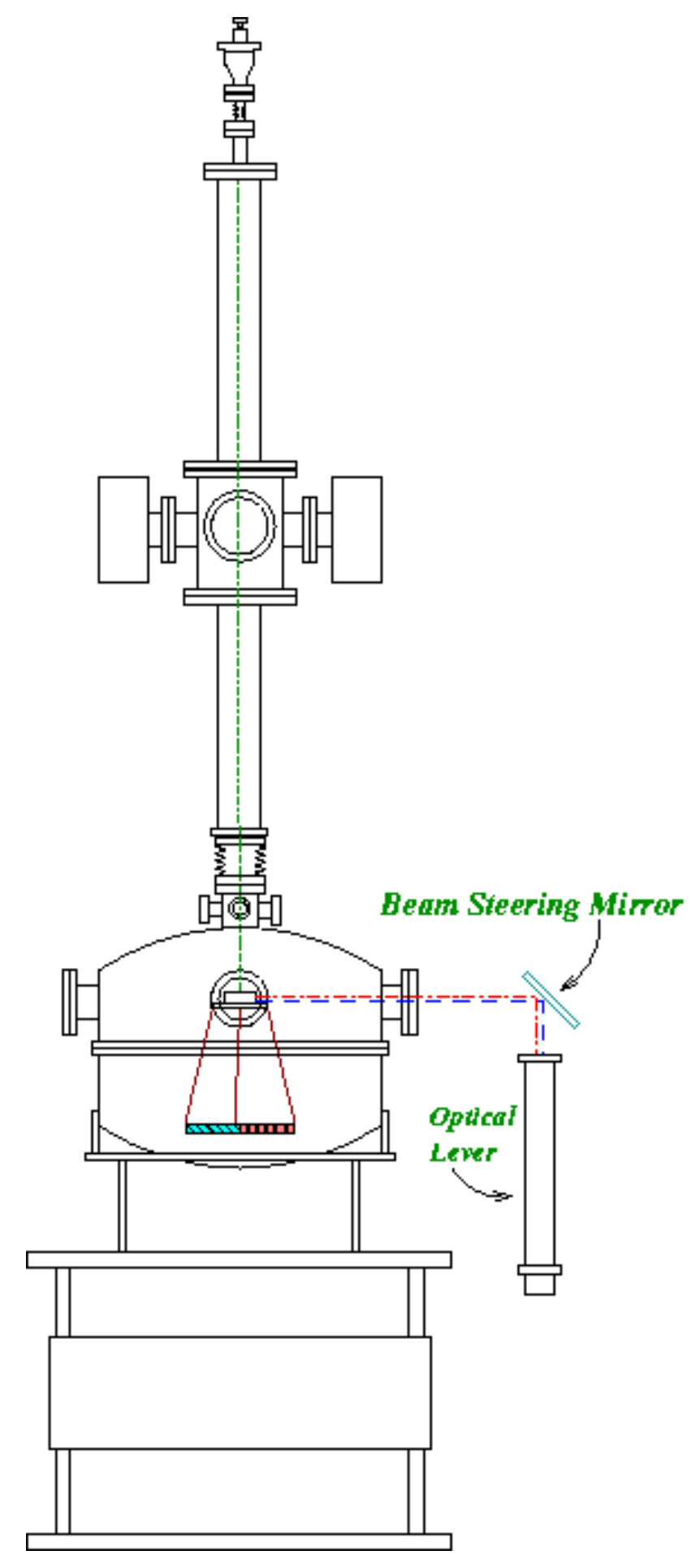
However, variations of the temperature not only couple directly to the motion of the torsion balance but also affect nearly every part of a system (the optics, the electronics, mechanical systems), giving rise to noise, or worse, ***systematic effects*** that seem identical to the signal that we seek. The sensitive Autocollimating Optical Lever with an angular resolution of 3 x 10^{-10} rad is affected by these systematic temperature variations. In the target Equivalence Principle Test to a sensitivity of 1 part in 10^{13}, we therefore need to suppress the residual temperature waves to amplitudes below 1 m^{0}C.

We describe key aspects of a complete Active Thermal Control System that surrounds the Ultra-High-Vacuum Chamber and associated instrumentation at the base of the Underground Laboratory. In the Dicke-Braginsky mode of operation, it is slow, systematic variations that affect us most. While diurnal and semi-diurnal waves have been suppressed to levels even below the design goal, random temperature variation at higher frequencies ("noise") remains at slightly higher levels, but this is acceptable.

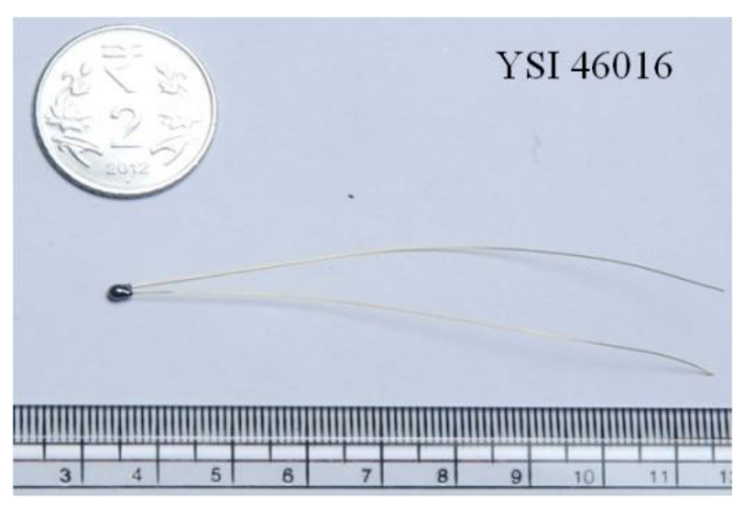
Described here are

a) **RELIABLE TEMPERATURE MEASUREMENT AT THE MILLIDEGREE LEVEL,**
b) **ENGINEERING OF AN APPROPRIATE THERMAL-MECHANICAL ENCLOSURE,**
c) **ELECTRONICS AND INSTRUMENTATION FOR FEEDBACK CONTROL**
d) **OUR PID FEEDBACK CONTROL SYSTEM,**

Finally, OUR RESULTS (actual performance of the full system).



Reliable Temperature Measurement

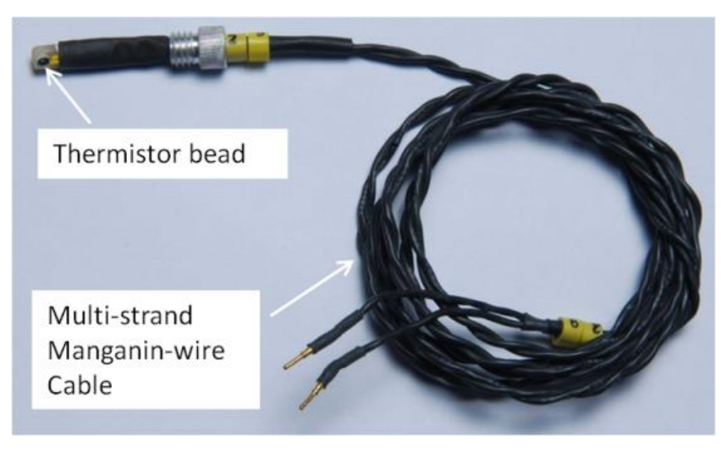


Thermistors ("YSI # 46016 B-mix") are our preferred choice of temperature sensor, since their large "signal" is easily read off in "field" conditions. Much effort went into establishing their stability and interchangeability, key factors in the reliable functioning of a large, distributed control system.

Thermistors have a highly nonlinear R vs T relationship. The best empirical descriptor is the Steinhart-Hart Equation:

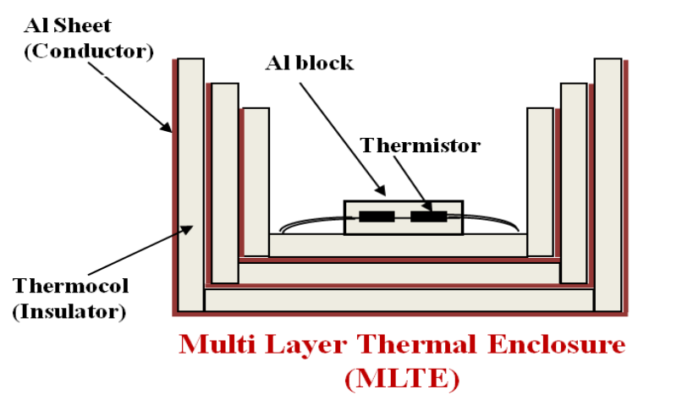
$$\frac{1}{T} = a + b*(\ln(R_\Omega)) + c*(\ln(R_\Omega))^3$$

Each thermistor has slightly different values of the coefficient set *(a,b,c)*. **Our task:** to measure the sets *(a,b,c)* for every thermistor we used. **Questions of stability translate into stability of *(a,b,c)*.**



We **CROSS-CALIBRATED** our thermistors inside what we call a **"Multi-Layer Thermal Enclosure"**, engineered to reduce thermal gradients between individual thermistors in the ensemble of thermistors being calibrated. The assembly of thermistors includes one designated "Master Thermistor" that is postulated to follow the manufacturer's standard R vs T curve.

Individual thermistors are regression-fitted to the Master Thermistor's temperature to far better than **1 m^{0}C.** Calibration studies on the same set of thermistors performed roughly every 12 months over ~ 4 years show that different thermistors age or drift slightly differently. However, over a 1 year period they can be used interchangeably within a precision of about **1 m^{0}C.**



The Thermal-Mechanical Enclosure

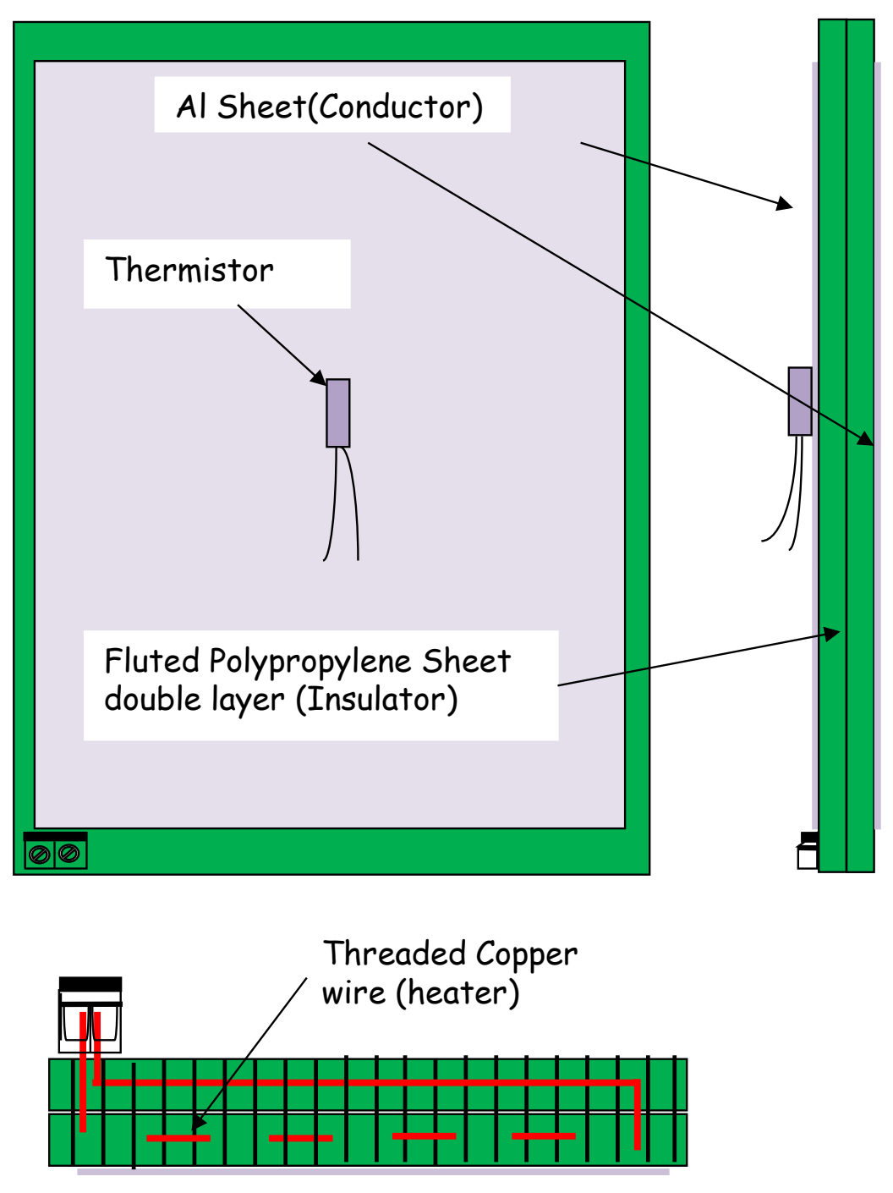
Active Stabilization of Temperature has to be delivered over a **region about 2.2m in diameter x 8m in height.** Central to our system is a sturdy, modular scaffolding structure. On this are fitted 24 identical thermal panels (8 each on the sides of the octagon, and distributed in three layers).

The scaffold, built with extruded Alum. Profiles for ease of fitting and modularity. **As installed** in Underground Laboratory

Above View from inside the scaffold, after panels have been fitted on.;

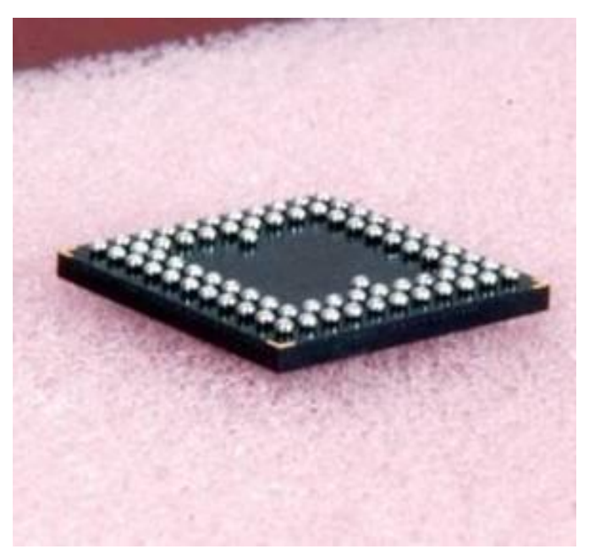
Below View from outside, looking upwards from the base of Undergnd Lab.

A finished Thermal Panel. Note the Alu sheet on the exterior. Both surfaces of panels are **thermal equipotentials**.



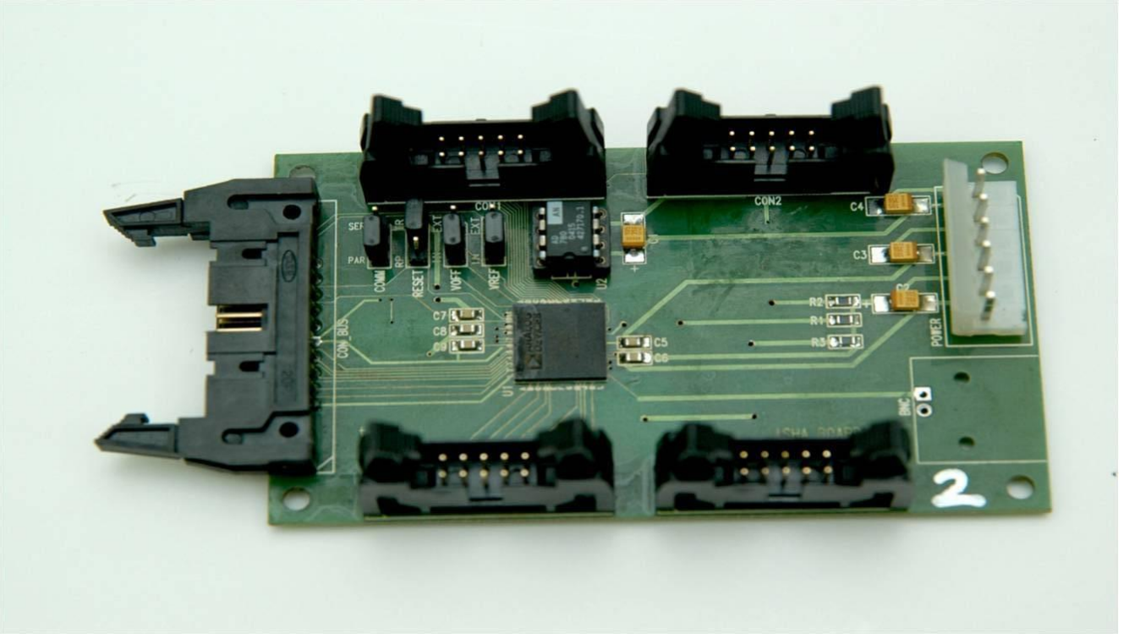
Cross-section and construction details of a thermal panel. The Fluted Polypropylene sheets are stiff, though light-weight. The single thermistor measures (proxies for) the temperature of the entire panel, cf., **"thermal equipotential"**.

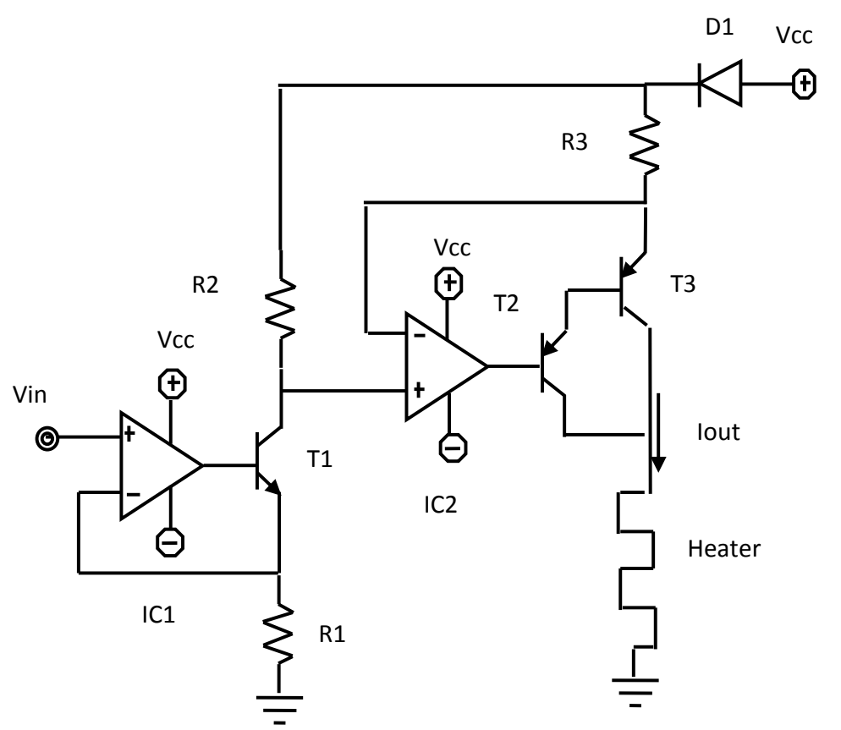
Electronics and Instrumentation for Feedback Control



At the heart of the Electronics is the 32 channel, **I**ntegrated droopless **S**ample and **H**old **A**mplifier chip (or ISHA), the AD5533 at left, from Analog Devices.

At right, a board that has this BGA chip mounted at centre, and multiple ports for data and control.

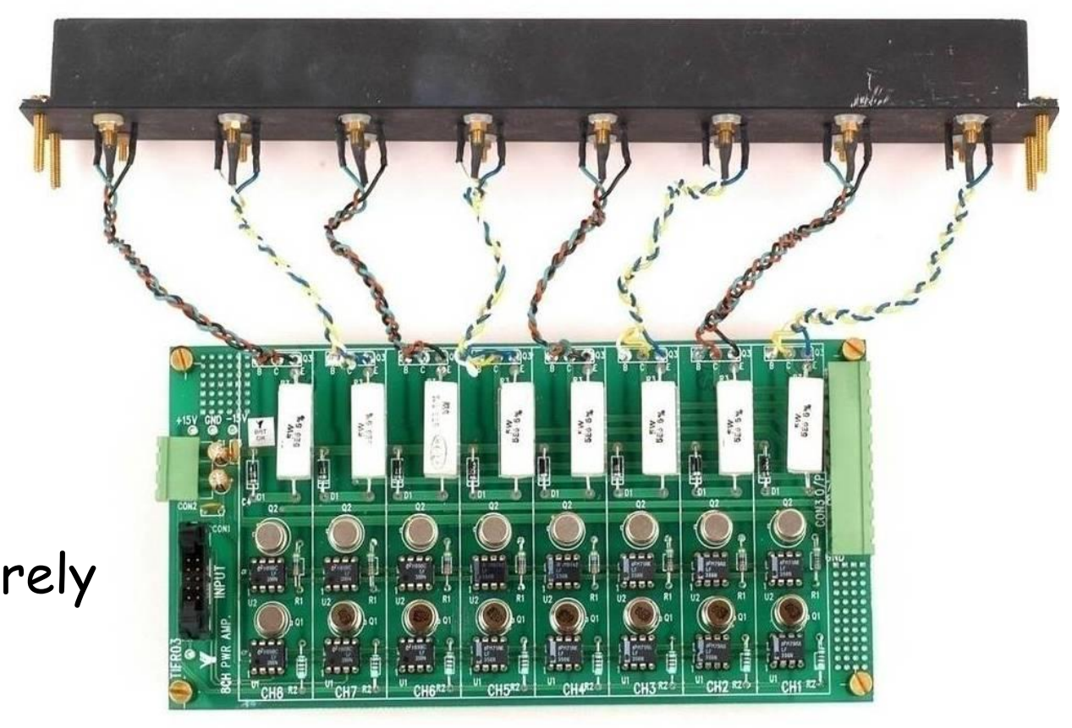




At left, schematic of a basic Power Amplifier Module.

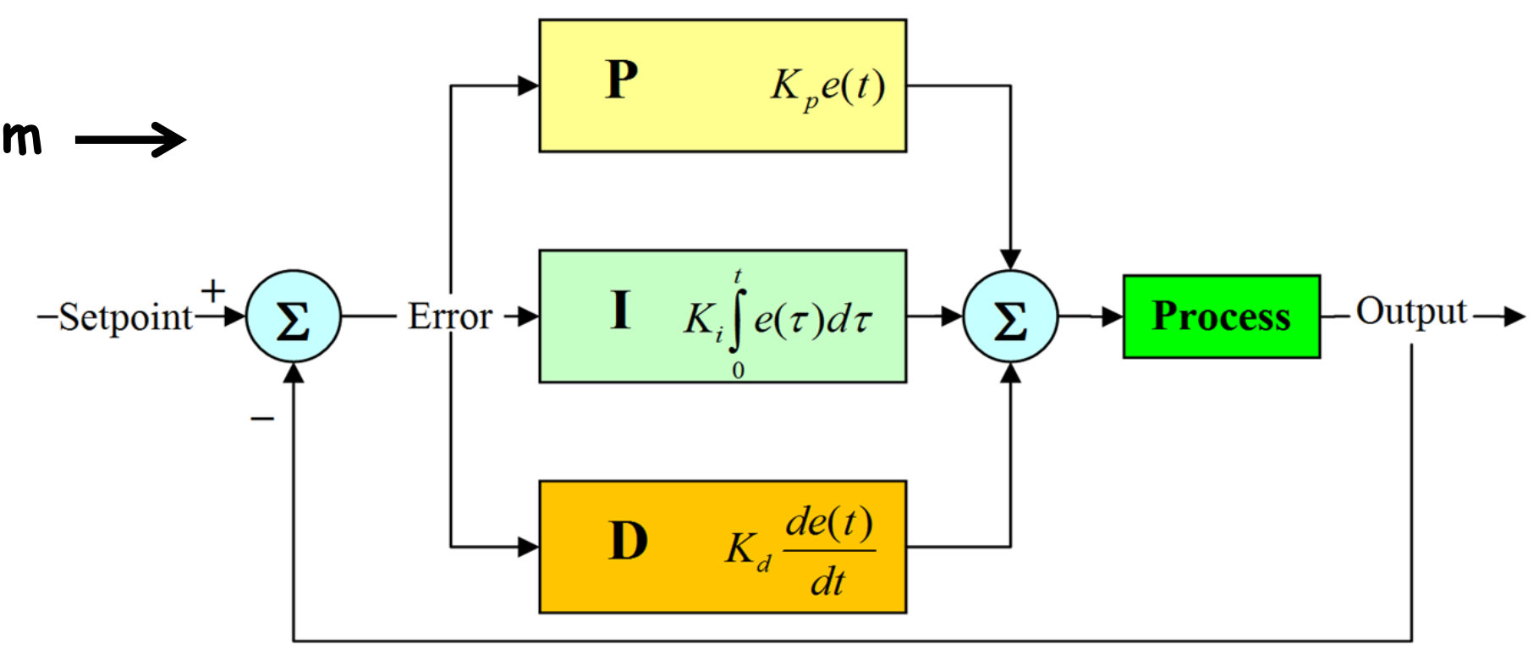
At right, a modular card, with 8 such Power Amplifier modules.

The designed power output is modest, at less than 5W per channel, but entirely adequate for sub-millidegree control.



PID Control

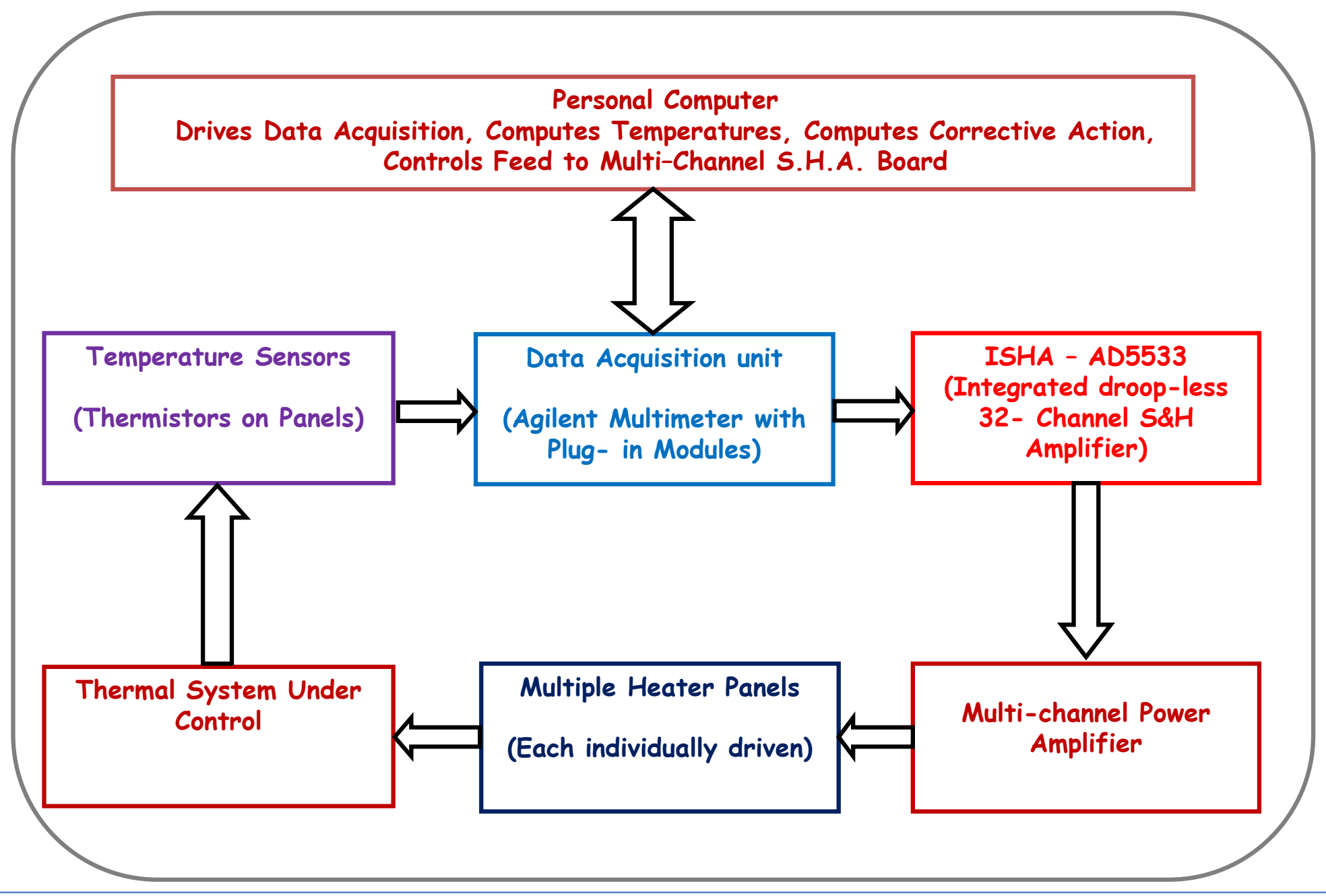
A: The General Paradigm →



Graphic Courtesy Arturo Urquizo (author): http://commons.wikimedia.org/wiki/File:PID.svg

B: Our Particularization

↓



Personal Computer
Drives Data Acquisition, Computes Temperatures, Computes Corrective Action, Controls Feed to Multi-Channel S.H.A. Board

Temperature Sensors
(Thermistors on Panels)

Data Acquisition unit
(Agilent Multimeter with Plug- in Modules)

ISHA - AD5533
(Integrated droop-less 32- Channel S&H Amplifier)

Thermal System Under Control

Multiple Heater Panels
(Each individually driven)

Multi-channel Power Amplifier

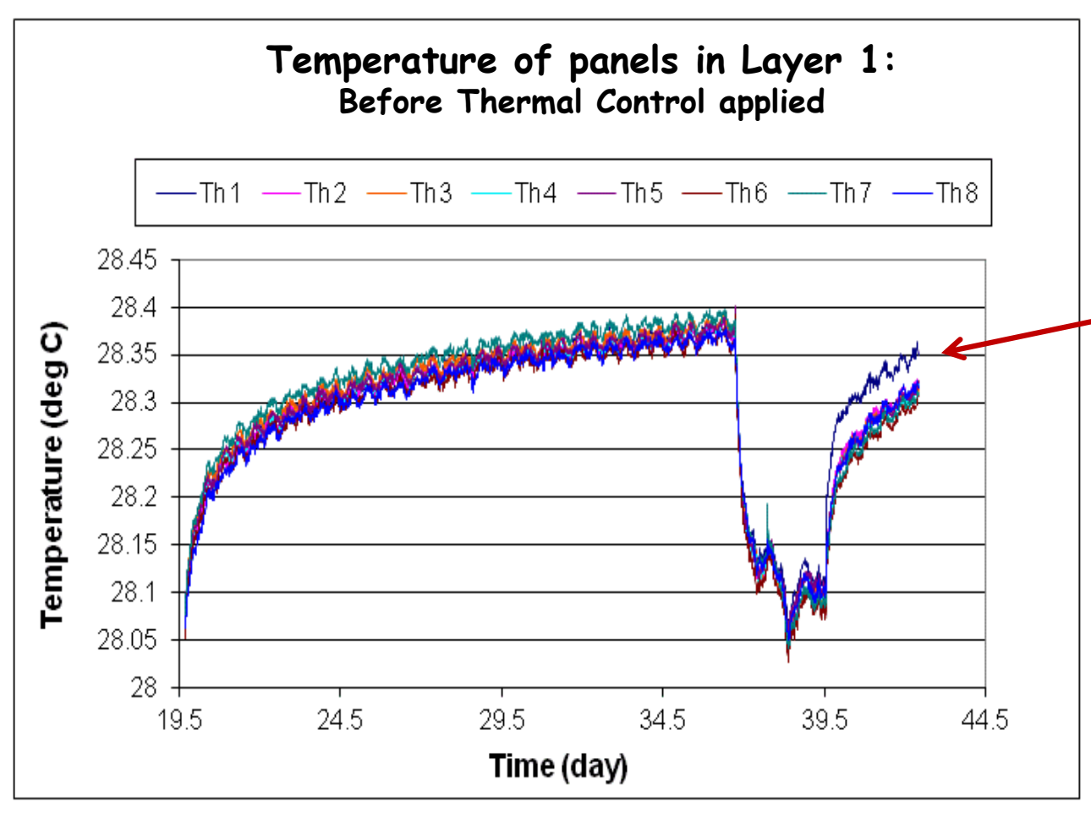
C: Tuning

We followed the "Ziegler-Nichols" tuning procedure, and obtained satisfactory closure in less than 2 weeks of experimenting.

"Closure" ≡ obtaining a set of control parameters (k_p,k_d,k_i) that lead to acceptable rates of convergence to the set-point and negligible oscillation about it.

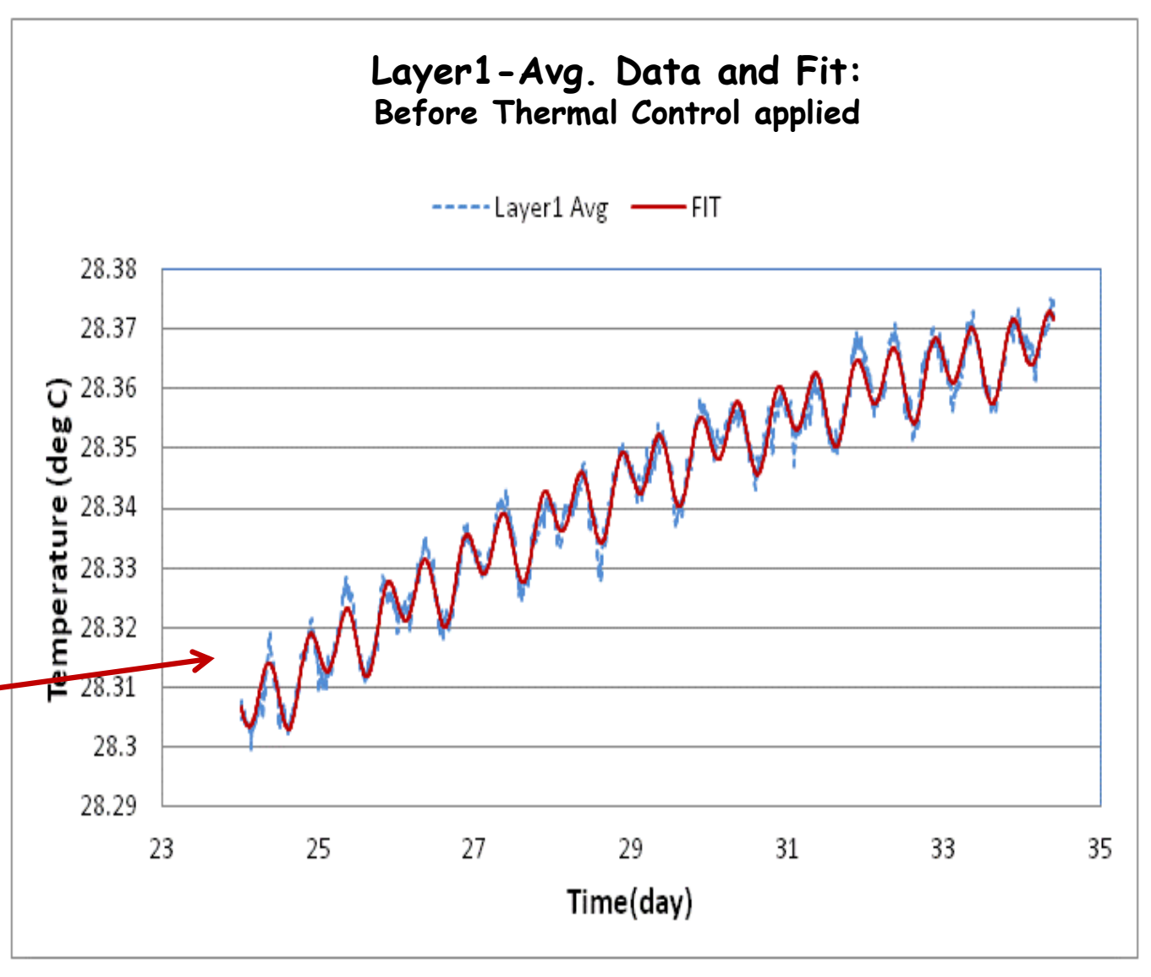
A Report on the RESULTS – 1

Some representative Temperatures Logged BEFORE The Thermal Control System was switched on



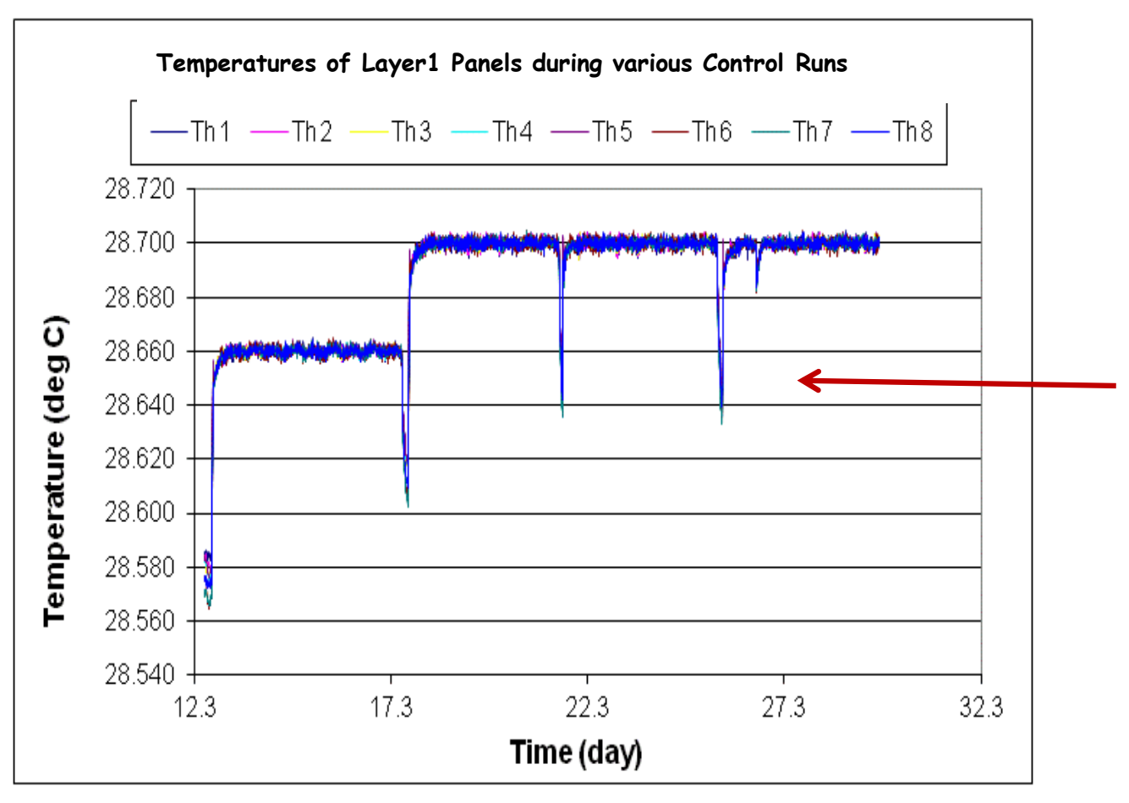
These data immediately after the Underground Lab was Closed Off; NO Control being applied. Note the DRIFT, dominantly linear

<u>Average of Layer-1 Panel temperatures</u>: the <u>Raw Data</u> and a <u>Fit</u> to them – Linear + Quadratic Drift + ½ day and 1day periods



A Report on the RESULTS – 2

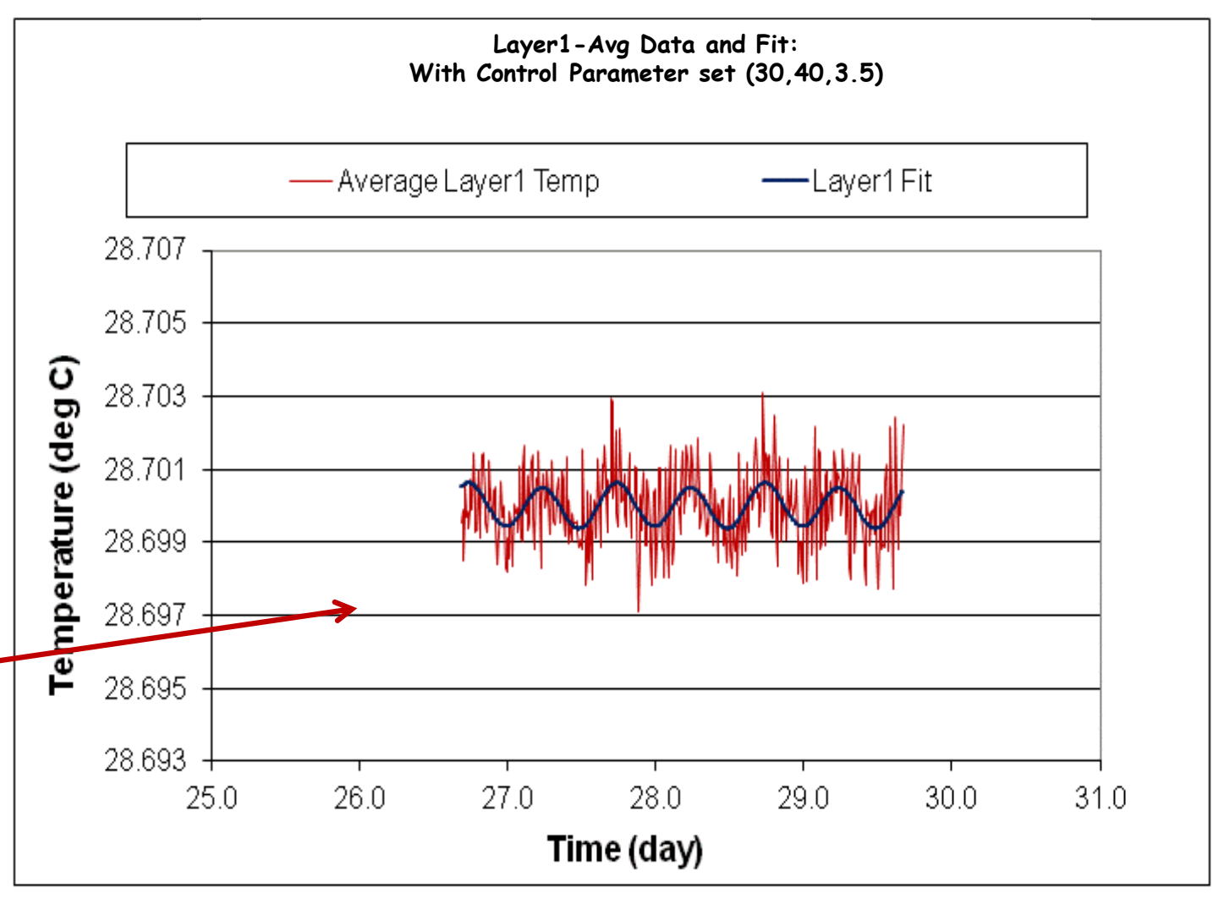
Temperature Logs AFTER The Thermal Control System was switched on



A series of "tuning" runs with different Control Parameters. Note especially the "lock" And the absence of Drift.

	$A_{1/2\ d}$ (deg C)	$A_{1\ d}$ (deg C)
Layer 1	5.8 x 10^{-4}	7.2 x 10^{-5}
Layer 2	7.5 x 10^{-4}	1.0 x 10^{-4}
Layer 3	6.4 x 10^{-4}	7.9 x 10^{-5}

Diurnal and semi-diurnal temperature amplitudes



The last and best tuning run from the dataset above. Fit has amplitude < 0.6 m degC.

In Summary

The development of the thermal control system has involved a number of different steps. Just a few of them are:

- proving the sensors' (i.e.,thermistors') sensitivity, interchangeability and long-term stability;
- inventing suitable "space-heaters" that incorporate
  - ❖modularity
  - ❖mechanical stiffness with low-mass, and low thermal inertia
- development of the ISHA Board around the AD5533, associated electronics, Power Amplifier modules
- development of suitable Control Algorithms

We have subsequently made small but steady improvements on the system, such as the "stirring" of the air inside the Thermal Enclosure to reduce vertical temperature gradients.
More recently the system has been ported to the LabVIEW platform, and uses NI hardware to replace the ISHA board.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the debt we owe to several persons within the Tata Institute of Fundamental Research.

Our CENTRAL WORKSHOP played a key role in helping us at two different stages: a) while building the modular scaffolding structure, and turning out various specialty parts for it; and b) while manufacturing the thermal control panels from the fluted polypropylene board. In the second stage, they helped us turn out near-identical panels using jigs that we designed, helping us maintain dimensional matching to as good as 3 mm over 2.6m. We gratefully acknowledge **Sangam Sinha, R. Chogale, P. Chaudhuri and Ramesh Mistry** in this effort.

P.G. Rodrigues contributed during early stages of the conceptualization of the system, especially with a survey of ICs for SHA. **S.K. Guram** similarly provided machining help in the early stages.

The GREATEST CONTRIBUTIONS are of course from **our Colleagues in the Gravitation Laboratory, both at Mumbai and Gauribidanur**, especially **D.B. Mane, C. Rajanna, K.C. Nallaraju, G. Somaiah.**, and **P.K.S. Murthy.**

Kasey Wagoner participated in early attempts at characterizing the system.