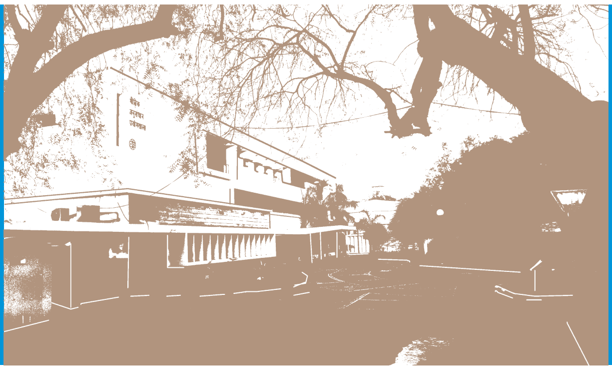
PRL-TN-2013-103

Technical Note



Low Cost, high Precision Temperature Controller

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Varun Dongre, F. M. Pathan, Abhijit Chakraborty and Vaibhav Dixit
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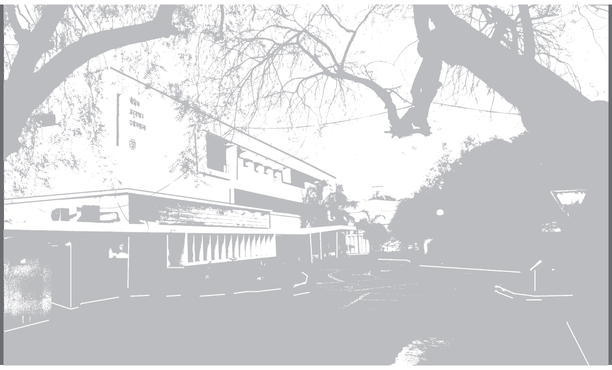

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Published by
The Dean's office, PRL.

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Low Cost, High Precision Temperature Controller

Varun Dongre*,F.M. Pathan*,Abhijit Chakrabarty*,Vaibhav Dixit *

Abstract

The “Low Cost, Precision Temperature Controller”’ is designed for the project PARAS (PRL Advance Radial velocity All sky Search) to achieve a temperature stability of 0.02°C rms throughout the period of observation of thermally insulated chamber where PARAS spectrograph is installed. The scientific aspect of the temperature controlled environment is to bring down the error in radial velocity measurement to $1m/s$. Radial velocity (RV) technique is used to determine various orbital parameters in exo-planet search. It has been found that temperature variation of 1°C at the spectrograph environment can increase the error in radial velocity measurement by few thousands of m/s. Due to temperature and pressure variations, mechanical flexures(in the scale of micrometers) in the optical components can increase the error by a significant percentage. The cost of the project is extremely modest as against the cost of a commercially available temperature controller of similar kind. A typical temperature controller available in the market capable of giving 0.03°C rms stability costs 3-4 lakhs INR. In contrast PRL’s indigenous temperature controller can drive 500W heaters and give 0.03°C rms stability at 25°C at a price of only 50K INR.

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Contents

1. Introduction

The temperature controller has achieved the stability very close to desired aim by means of enclosing the PARAS instrument in a closed concentric volume space consisting of two thermally insulated outer and inner chambers. The outer chamber’s temperature control is achieved at 23°C ± 1°C by conventional heating and cooling algorithm. This is accomplished by commercially available PID temperature controller which has the facility to set the temperature of the outer chamber between 18°C to 28°C. We have set it to 23°C for the outer chamber. After attaining the stability of ±1°C in the outer chamber we have maintained the inner room temperature by PRL made “Low Cost, High Precision electronic temperature controller”’ to 25°C. The inner chamber’s temperature is raised by 2°C by means of 10 heater panels having NICHROME 28SWG wires. Each heater is operated at variable DC (30W max) power and controlled by microcontroller. This system consists of PT100 as temperature sensor for feedback mechanism which is well known for its accuracy and stability. This unit also sends inner chamber’s temperature data serially for data acquisition. The data acquisition software is written in Visual Basic6. By this system we can set the temperature between 21°C to 28°C and can get the stability down to 0.04°C rms. One thing worth noticeable here is that the temperature stability means the temperature should not vary when the observation is going on, it should be very stable near the set point.

2. Design Considerations and Temperature Stability

The preliminary step in the commencement of designing of temperature controller is to perceive the scientific need of stability and accuracy of the instrument despite the variations in ambient temperature. Radial velocity drifts about 1000 m/s by 1°C change in temperature (Pepe et. al. 2002) at a constant pressure. Hence to get the RV measurement down to 1 m/s. we have to maintain the temperature stability down to ±0.01°C and pressure stability of up to $1mbar$ throughout the observation. To achieve temperature stability the instrument is enclosed in two concentric chambers of highly insulated thick puff material and for pressure stability the instrument is kept in thick stainless steel (SS) vessel under vacuum. Outer chamber’s temperature is controlled by commercial PID temperature controller with a stability of 1°C. To achieve further stability inner chamber’s temperature is raised by 2°C above the outer chamber’s temperature by PRL made “Low cost, precision temperature controller”’.

The inner chamber has dimensions of 6m × 5m × 3.5m ($105m^2$) enclosing a hollow stainless steel vessel of 0.7m

× 2.4m × 1m (1.68 m^2) and 1*inch* thickness. The mass of the stainless steel vessel is approximate 20000kg. The Paras spectrograph is installed within this SS vessel. So the total air filled volume in chamber is 105-1.68=103.32 m^2. To calculate amount of heat required to raise the temperature of inner chamber by 2°C above the outer chamber's room temperature let us assume the pressure inside the inner chamber is 1bar and temperature is 23°C then Mass of air in the room is

$$m = \rho \times V$$

Where ρ=1.19Kg/m^3 at 1bar pressure

so $m = 1.19\mathrm{Kg/m^3} \times 103.32\mathrm{m^3} = 122.95\mathrm{Kg}$

Now Heat required

$$Q = mC_p\,\Delta T$$
$$= 122.95\mathrm{Kg} \times 1.00692\mathrm{KJ}\cdot\mathrm{Kg}^{-1}\cdot{}^{\circ}\mathrm{C}^{-1} \times 2^{\circ}\mathrm{C} = 247.06\mathrm{KJ}$$

Where C_p is specific heat of air ($1.00692\mathrm{KJ}\cdot\mathrm{Kg}^{-1}\cdot{}^{\circ}\mathrm{C}^{-1}$)

Heat required for stainless steel vessel

$$Q = mC_p$$
$$= 20000\mathrm{Kg} \times 0.45\mathrm{KJ}\cdot\mathrm{Kg}^{-1}\cdot{}^{\circ}\mathrm{C}^{-1} \times 2^{\circ}\mathrm{C} = 18000\mathrm{KJ}$$

So if we use total 300W power in inner room then time required to obtain this much heat is

$$E_{(KJ)} = \frac{P_{(W)} \times t_{(s)}}{1000}$$

$$t = (247.06 + 18000)\mathrm{KJ} \times (1000)_{\overline{300W}}$$
$$= 60823.53\ \mathrm{sec} \cong 1013.72\ \mathrm{min} = 16.89\ \mathrm{hour}$$

The temperature controller feeds 30W DC power to each of the 10 heaters. The heater panels are installed on the walls of the inner chamber at about 1*m* height from the floor sounding the stainless steel vessel. The 300W (30W × 10) power is sufficient to raise the inner chamber's temperature by 2°C as per the above calculation. The power supplied to the heaters is not constant but proportional to the difference between the set temperature and the actual temperature of the chamber sensed by PT100. We refrain from the use of AC heaters as it will generate more electromagnetic interference in the inner chamber undesirable for PARAS instrument, also it can be a fire hazard. Hence we feed DC power to the heaters by the APLAB's L3220S model regulated DC power source which is externally programmable and controlled by MCU unit. The power supply can give up to 500W of total power to the heaters. Even though the inner chamber is thermally insulated by puff material walls and the outer chamber we found some heat leakage during extreme winter conditions (outside temperature approaching 0°C). To compensate this effect we required give more heat to sustain the stability in extreme winters. For this reason we have given an option to raise the output power. We give 400W power to stabilize the temperature in winter nights. In summer we required to give 300W power because more power will result in increased oscillations in temperature near the set value. Figure 1 shows the block diagram of the system developed.

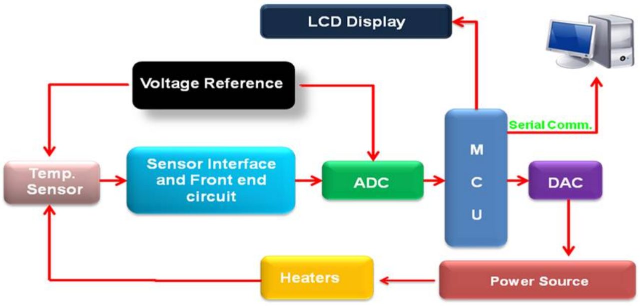


Figure 1. Block diagram of the system developed

2.1 Choice of Sensor and its Error Analysis

To get the stability of 0.01°C the sensor should be able to give a resolution and accuracy of at least 0.01°C or better than that. The most popular temperature sensors used today are the Thermocouple, Resis-tive Temperature Detector (RTD), Thermistor, and the newest technology, the Integrated Silicon Based Sen-sors. There are other sensing technologies, such as Infrared (Pyrometers) and Thermal Pile. Each of these sensor technologies is useful for specific temperature range and environmental conditions. The sensor's temperature range, ruggedness and sensitivity are the characteristics that are used to determine whether or not the device will satisfy the requirements of the application. Table 1 summarizes the main characteristics of these four temperature sensors. This table is used during the first pass of the sensor selection process. In all these temperature sensors RTD is the most suitable sensor for our application. Other temperature sensing devices such as thermocouples doesn't meet the criteria as they are unable to give a linear response over temperature. The linear relation between resistance and temperature of the RTD simplifies the implementa-tion of signal conditioning circuitry. Platinum RTDs are one of the most accurate temperature sensor suited for precision applications. The platinum material is less affected to environmental contamination. The PRTD has nearly linear temperature response, well chemical inertness and is easy to manufacture. Platinum RTD is the reference on which the international definition of temperature is based. Hence PRTD is the most accurate sensor for measuring temperature. The linearization of RTD can be done in different ways. For high end pro-cessors direct fitting to RTD equation is used. This method gives the most accurate temperature reading. Look up table method gives better accuracy in small temperature range measurements.

Following table compares the specifications of various sensors

Table 1. Comparison of different temperature sensors available

	Thermocouple	**RTD**	**Thermistor**	**Integrated Silicon**
Temperature Range	-270 to 180°C	-250 to 900°C	-100 to 450°C	-55 to 150°C
Sensitivity	10-100μV	0.00385Ω/°C	Several Ω/°C	Based on Technology (i.e. $2mV/$°C)
Accuracy	±0.5°C	±0.01°C	±0.1°C	±1°C
Responsiveness	Fast (<1sec)	Moderate (1-10 sec)	Moderate (1-5 sec)	Slow (4-60 sec)
Excitation	Not Required	Current Source	Voltage Source	Typical Voltage Source
Output Form	Voltage	Resistance	Resistance	Voltage/Current/Digital
Linearity	Requires at least 4^{th} order polynomial or lookup table	Requires at least 2^{nd} order polynomial or look up table	Requires at least 3^{rd} order polynomial or look up table	No linearization required

Ref: Temperature Sensing Technologies, Bonnie Baker, microchip technologies

available in the market.
The $3^r d$ method is the analog technique in which temperature is converted to equivalent voltage by amplification assuming the RTD response almost linear. This gives least accuracy in wide range measurement but tolerable in small range measurement.
PRTD is available in two types, wire wound and film type in which wire wound type PRTD is most accurate and linear.

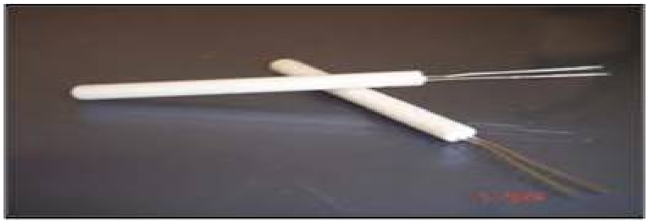


Figure 2. PRTD sensor used in design

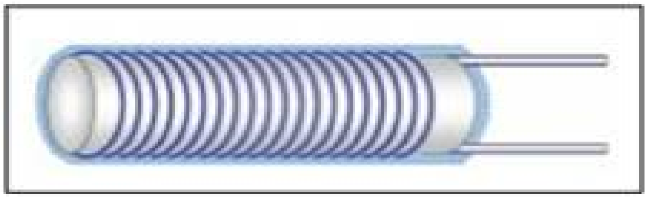


Figure 3. Wire wound PRTD

RTD is the most linear with only two coefficients in the linearization. Equation, for temperature range -250° to 900°

$$R_t = R_0[1+At+Bt^2+C(t-100)^3]$$

Where,

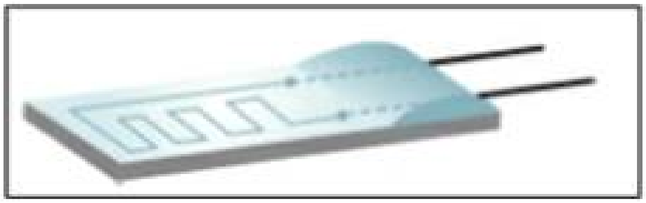


Figure 4. Film type PRTD

R_t is the resistance of the RTD at measurement temperature. t is the temperature being measured, R_0 is the resistance of the RTD at 0°C, A, B and C are calibration coefficients derived from experimentation. C=0 for temperature above 0°C.

By using these equations we can resolve temperature up to ±0.001°C of accuracy. We consider PT100 temperature sensor best suitable for our application which is platinum RTD and has great stability, linearity and accuracy features. Also a typical drift value for Pt100 detector is 0.05°C per annum. High-quality detectors exhibit maximum drift of 0.01°C per annum. If the temperature range is confined to 25–150°C, drift is as low as 0.005°C a year. Following graph shows linearity feature of PT100 sensor (Ref: - Analog linearization of RTD: Bruce Trump). RTD has significant second order nonlinearity of 0.38% per 100°C measurement range as indicated in figure-5 (Ref:- Analog linearization of RTD: Bruce Trump). This nonlinearity is often corrected digitally but there are many applications for analog processing and linearization of RTD. In the analog technique of linearization when the RTD is excited by a current source the resulting RTD voltage is directly proportional to the resistance yielding the same nonlinearity. If the excitation current is gradually increased as the RTD temperature is increased the nonlinearity can be greatly reduced. Figure-6 shows an increasing excitation current derived from the output of the amplified RTD voltage.

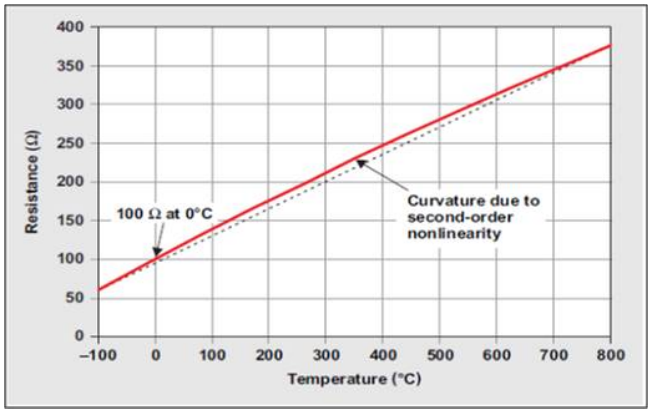


Figure 5. RTD's temperature VS resistance linearity

The RTD voltage at the input of the amplifier is linearized when the output of the amplifier is linearized and vice-versa. The amplifier output is optimized by a positive feedback which results in an S shaped error with equal and opposite values (see figure 6 (Ref: Analog linearization of RTD: Bruce Trump)). This is actually the 3^{rd} order nonlinearity which does not originate from RTD but from the linearization technique. Its magnitude depends on the temperature range selected.

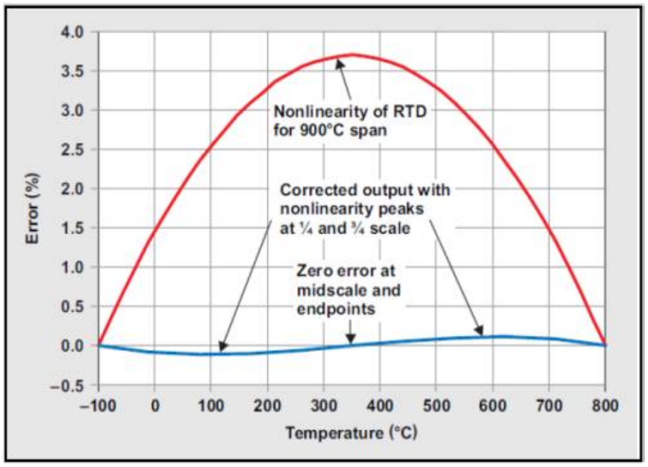


Figure 6. Percentage of RTD error and temperature

To use a PT100 sensor in precision application, one must take care of its connection in the circuit to its excitation source as this greatly affects sensors stability and accuracy. For example if the lead wire is constructed of 5 gages copper leads that are 50 meters long (with a wire resistance of 1.028Ω/km) the contribution of both wires increases the resistance by 0.1028Ω. This translates into a temperature measurement error of 0.26°C for a 100Ω at 0°C RTD. This error contributes to the non-linearity of the overall measurement. Circuits can be configured to effectively use the 3 wire and 4 wire configuration to remove the error contribution of the lead wires completely. We have used 4 wire configuration of the sensor to eliminate the lead wire resistances. Connecting wires are Teflon coated multi core coaxial wire having 75 Ω characteristic impedance that is best suited to reject magnetic or EMI pickups.

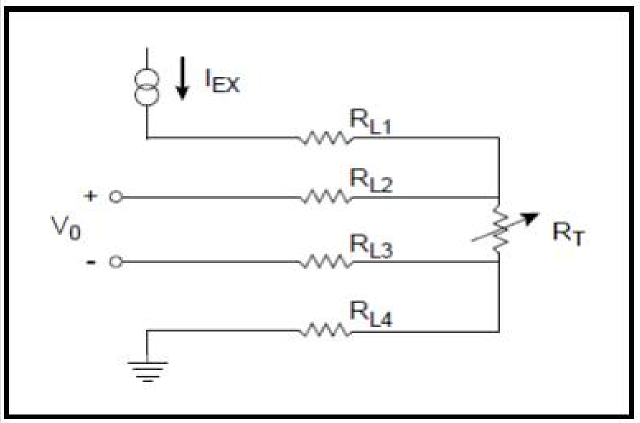


Figure 7. 4 wire RTD Configuration for high accuracy

For best linearity, the RTD sensing element requires a very stable current reference for excitation which we have achieved by using AD588 precision voltage reference IC from ANALOG DEVICES. It provides a very low temperature drift of 1.5ppm/°C. The AD588 offers 12-bit absolute accuracy. Output noise of the AD588 is very low, typically $6\mu V_{pp}$ (ref:datasheet AD588).

The error contribution of the heat generated by the element‘s power dissipation is easily calculated given the package thermal resistance ($\theta_{package}$), the magnitude of the current excitation and the value of the PT100 resistance.

For example, if the package thermal resistance is 50°C/W, the RTD's nominal resistance is 100Ω, and the element is excited with a $5mA$ current source, the artificial increase in temperature (°C) as a result of self heating is

$$\Delta°C = I^2\, R_{PT100} \times \theta_{package}$$
$$\Delta°C = (5mA)^2 \times (100\Omega) \times 50°C/W$$
$$\Delta°C = 0.1250°C$$

This example illustrates the importance of keeping the magnitude of current excitation as low as possible. We have excited the sensor by $1mA$ current, driven by AD588 IC as it generates 0.005°C heat that can be neglected for our application.

2.2 Sensor Interfacing and Front End Circuit

The PT100 element has the resistance of 100Ω at 0°C. If it is used to sense temperature over the range of 0°C to 100°C, the resistance produced by the RTD would be nominally between

100 Ω and 138.51 Ω giving a voltage across the PT100 between 100 *mV* and 138.51 *mV* by a 1 *mA* excitation current.

This signal span is very low to be digitized directly and also very susceptible to noise. Hence signal amplification and filtering is a necessity prior to sending for digitization. We have used OP177 opamp from ANALOG DEVICES for signal amplification. This opamp has outstanding offset voltage drift of maximum 0.1. The OP177 open loop gain of 12 V/μV is maintained over the full ±10V output range. CMRR of 130 dB minimum, PSRR of 120dB minimum and maximum supply current of 2*mA* are just a few examples of the excellent performance of this operational amplifier (ref: datasheet OP177). Opamp is used as a non inverting amplifier with a fixed gain of 7.2V/μV. In addition with amplification we have used OP177 as a unity gain buffer to avoid ADC from loading effect. To create a span for temperature range, offset trim method is used. For that purpose R1, R2 resistors are connected with dual power supply. Hence the gain and span equation of the circuit is shown in figure 8.

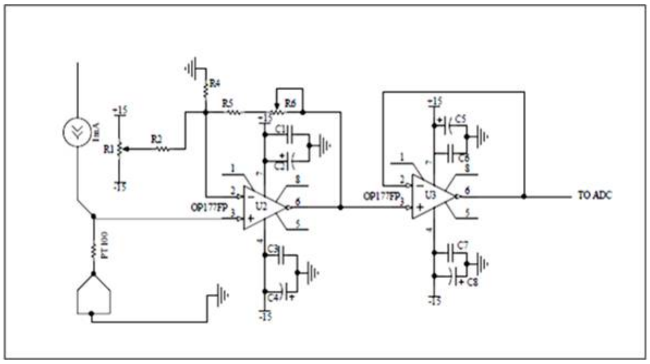


Figure 8. Front end interfacing circuit

$$\mathrm{V}_{out} = [1 + \frac{R5+R6}{R4}]V_{in} \pm [\ \frac{R5+R6}{R2}]V_\gamma$$

where,

V_{in} = Voltage across PT100
$\mathrm{V}_\gamma = fixedlowimpedancereferencevoltagesources, \pm \mathrm{V}_\gamma$

Note that R2>>R4 otherwise gain may be unstable as the offset potentiometer is adjusted.

After amplification this signal is sent to digitization. The analog to digital conversion is carried out by precision ICL7135 ADC which gives $4\frac{1}{2}$ digits BCD coded output. The ICL7135 brings together a unique combination of high accuracy, versatility, and true economy. It features auto-zero to less than 10μV, zero drift of less than 1μV/°C, input bias current of 10pA (Max), and rollover error of less than one count. The ADC guarantees the accuracy of ±1 count over the entire range of ±20000 counts (ref: datasheet Intersil ICL7135). To get the best from ADC and accurate digital output ADC should have a very stable reference voltage which is again given by AD588 IC. Long term stability depends on the temperature drifts of each component in circuit. Hence we have used polycarbonate capacitors which are known for long term stability and ideal for filtering and precision metal film (0.1%) 10 ppm/°C resistors to minimize the temperature drift.

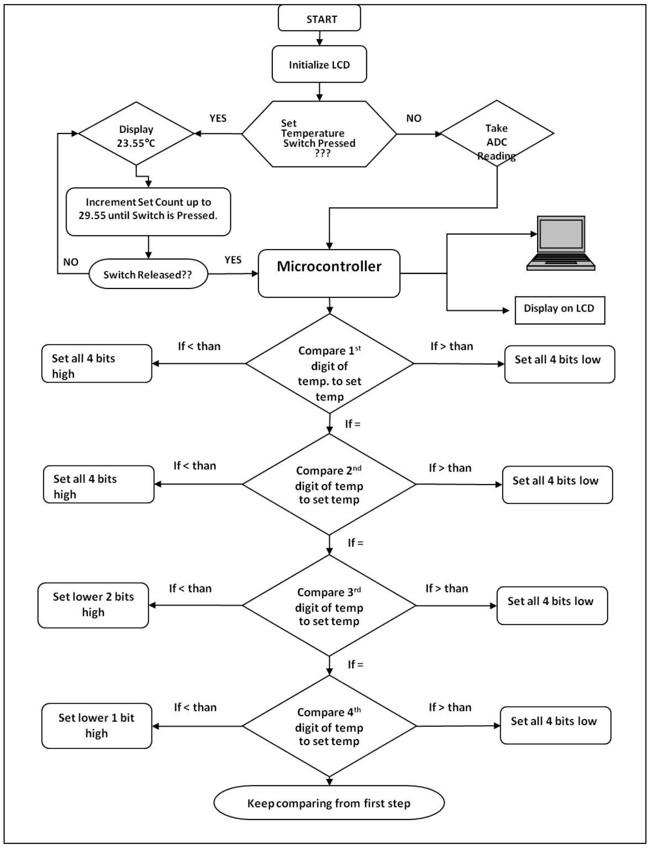
2.3 Microcontroller, DAC and Heater Interface

The brain of the system is ATMEL'S 8 bit 89S51 microcontroller which is a very basic, easy to use and very suitable microcontroller for this application. ATMEL'S 89S51 is known for its 8051 compatibility, 4KB of ISP flash memory, 128 × 8-bit Internal RAM, 32 Programmable I/O Lines, and Two 16-bit Timer/Counters, Six Interrupt Sources, Full Duplex UART Serial Channel(ref: datasheet Atmel89s52). Microcontroller is driven by an 11.0592 MHz crystal oscillator. Digitized signal coming from ADC is converted to equivalent temperature by the programming and calibration with reference to a standard thermometer. A 16×2 LCD module is interfaced with MCU to display and set the desired temperature. We can set the desired temperature through a push button which is interfaced to one of the pin of MCU. We have fixed the set temperature range from 21°C to 28°C as per our need. An 8bit DAC is interfaced with one of the port of MCU to get the digital command and convert it into analog signal and this analog signal is then amplified by OP177 opamp and sent to the power supply followed by heaters. The Aplab L3220S model Regulated DC power supply has a gain of 2 for external programming voltage hence it can give required power to the heaters. The algorithm used in controlling the power supplied to the heaters is changing the MSB bits of DAC according to the difference between the set value and the current value of temperature. If the difference in the set value and the current value is greater than 1°C then all the bits of DAC is high, hence power supplied to the heaters is at their full capacity until the difference comes down to less than 1°C. If the difference is less than 1°C then 2 bits of DAC is set low to give half the power to the heaters. As the difference decreases to 0.5°C 1bit of DAC is set low to give quarter power to the heaters. After an hour the chamber temperature comes close to the set value and as it equals the set value, all the bits of the DAC is set low to shut down the power supply to the heaters. The programming is done in assembly language and the Keil μVision compiler is used. We have also interfaced RS232 com port for serial communication between MCU and desktop to continuously log the data points at the far end of system. Front end of the system is programmed in Visual Basic 6.0. The table summarizes the algorithm used with a reference to set temperature of 25.55°C.

The inner chamber is kept at a temperature of 2°C above that of the outer chamber causing the inner temperature to

Table 2. MCU temperature controlling algorithm

Temperature	**MSB bits of DAC**	**DAC output Voltage**	**Amplified o/p voltage given to Aplab power supply**	Voltage given to each heater
24.00°	1111	4	8	16V/2A
25.00°	0111	2	4	8V/2A
25.50°	0001	1	2	4V/2A
25.55°	0000	0	0	0V/2A
25.50°	0001	1	2	4V/2A
25.00°	0111	2	4	8V/2A



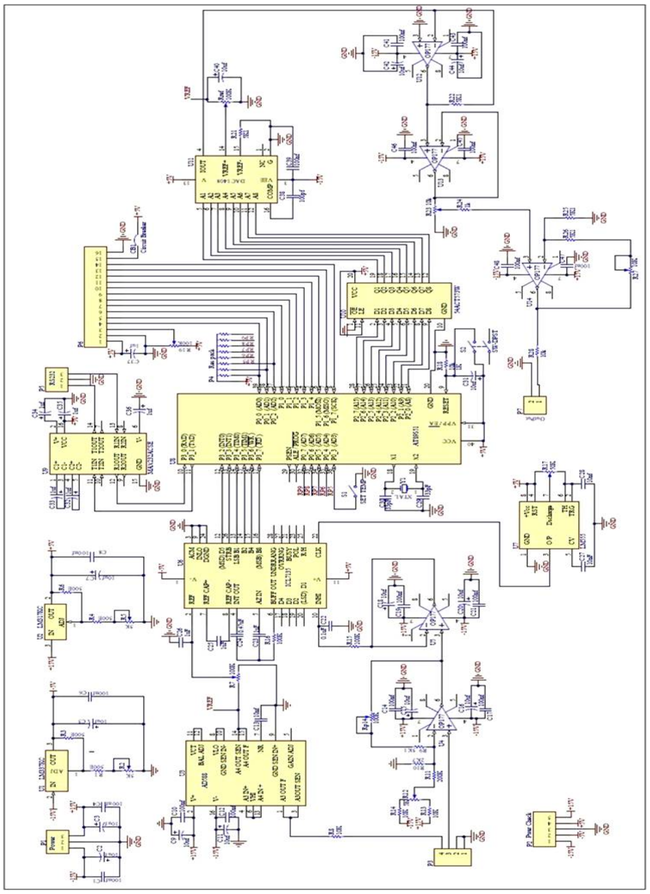


Figure 9. Circuit Diagram of the System

slowly cool down to equilibrate with the outer one. This triggers the controlling action back to play and within a small time inner room's temperature stabilizes to ±0.03°C (rms). The flow chart describes the control algorithm used by the microcontroller unit according to the difference between set temperature and sensed temperature.

2.4 Hardware, Software, and Cost Estimation

The hardware of the project mainly consists of electronics controller box, sensors and heaters. The box is 21" rack compatible made in PRL workshop having an electronics controller installed within. Printing of the PCB is carried out by third party vendors in the market. Mounting of the heaters is made on 50×50cm card-board panels which were brought from third party vendor at a cost of 5k. Nichrome 24SWG wires are used as heaters. Sensor is interfaced with the controller through four 8m long coaxial cables. Another external part is Aplab power source which feeds regulated power to the heaters. It is a commercially available power supply with externally programmable output.

In the software part programming is done in free version (code compilation limit up to 4kb) of Kiel μVision c compiler. Other compilation software like SPJ C compiler and Microsoft Visual Basic 6.0 is used for making front end program. Altium AD10 and Dip trace PCB software is used in PCB designing.

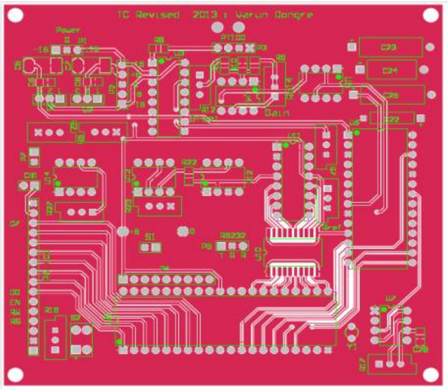


Figure 10. PCB layout: Top Layer

PCB made is a two layer PCB whose layouts are shown below.

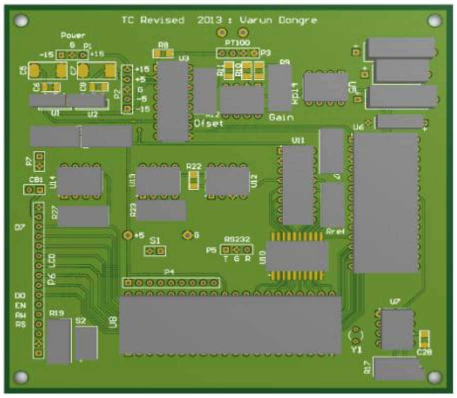


Figure 11. PCB layout: Component placement and 3D view

Cost of the project depends on the electronics components used. The cost of sensor depends on its class and accuracy. We have used class B PT100 which costs 3000 INR per unit. Rest of the components comprises a range of 1000 -1500 INR. The Aplab power supply is somewhat expensive as compared to rest of the instrument which costs 20000 INR. In the software part most of the software used are of free versions. The total cost of the project is around 30K-35K as against 3 to 4 lakhs for commercially available temperature controller in the market.

3. Experiments and Results

We have tested the system continuously in every session of observation for 10-12 days. The system including the SS vessel takes 16-20 hours to stabilize completely. The SS vessel's (where the PARAS optics and spectrograph is installed) Temperature is monitored every 1 minute throughout the night of observation by a separate temperature monitoring system having temperature measuring accuracy of 0.01°C also the data is logged through serial communication between MCU and desktop. The inner room temperature stabilizes at 25.50°C with 0.03°C rms stability. As we have kept the instrument in the thick stainless steel vacuumed vessel and due to its high inertia, the instrument gets the temperature stability of 0.01°C rms. There is a heat difference of 0.5°C inside the SS vessel and the surrounding room temperature. The temperature inside the SS vessel stabilizes at 25.00°C.

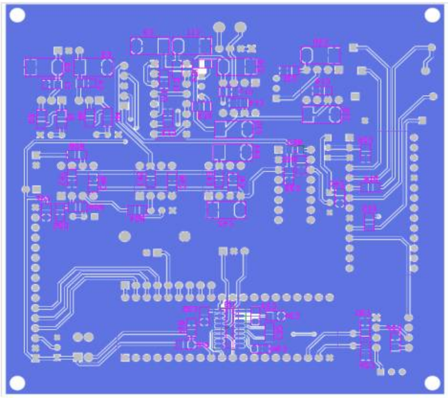


Figure 12. PCB Layout: Bottom Layer

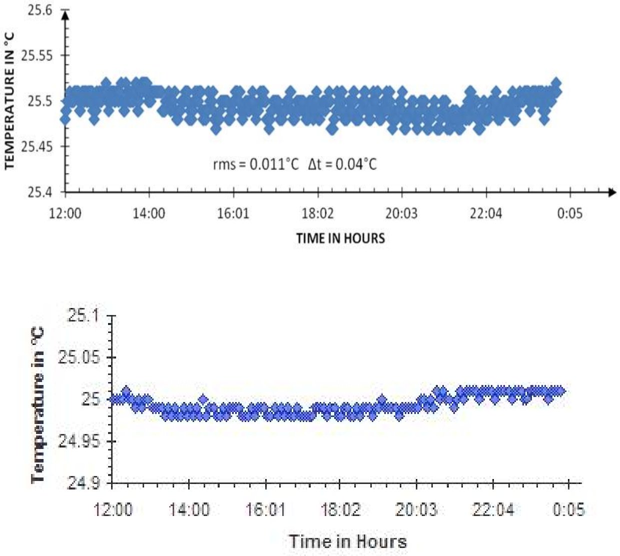


Figure 13. Temperature stability in inner room and stainless steel vessel

The radial velocity measurement is carried out by two fibres giving Thorium-Thorium, Tho-rium-Dark, Dark-Thorium and Tungsten Flat spectra. The following graphs show the temperature stability in the inner chamber and inside the SS chamber on the observing night of JUNE 2012 session. From the graphs below it is observed that temperature stability of 0.03°C gives absolute fiber drift of about 90 to 150m/s and differential fiber drift of 1 to 1.4m/s. If we further increase the temperature stability down to 0.005°C, we can get the absolute fibre drift down to 20m/s and differential fibre drift down to sub meters. The following graphs describe the temperature stability and their corresponding radial velocity measurement of an observing night of 12 hours.

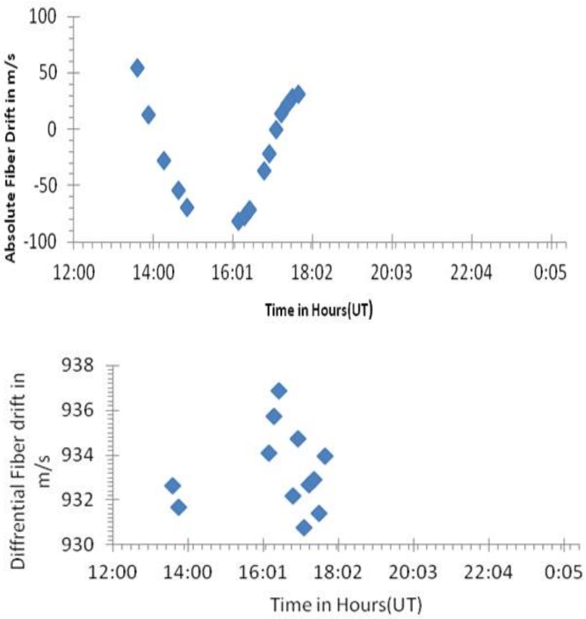


Figure 14. Absolute and Differential Fiber drifts

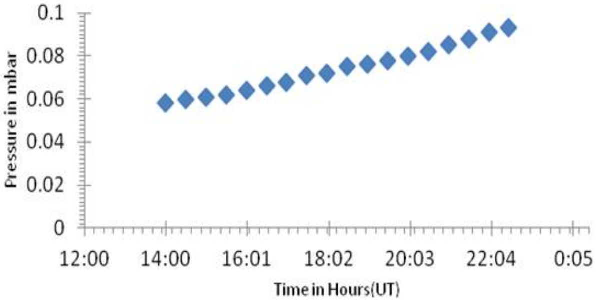


Figure 15. Pressure stability in stainless steel vessel

We chose the stability graph of month of June when the humidity of atmosphere is at its peak, in that conditions the system showed a temperature stability of 0.011°C rms(Δt=0.03°C)with pressure stability of $0.04 mbar$ and the spectrograph showed the differential fiber drift of $1.4 m/s$. The above graphs are drawn with the data of 13 June 2012 which shows negligible effect of humidity on the system's performance.

It is worth noticeable that whenever temperature stability went down to 0.1°C, the spectrograph showed differential fiber drift of 2-3m/s. Following graphs shows the data of 11 June 2012 when temperature stability went down to 0.1°C and hence differential fiber drift increased to the $2.8 m/s$. The pressure stability is $0.03 mbar$ on the same time. This lower stability in temperature is because of the frequent door opening of the inner chamber room primarily because of some maintenance works with the air circulating Fans.

From the above graphs it is clearly visible that temperature stability of spectrograph affects the radial velocity measurements. Thus as precise the stability of temperature we provide at the spectrograph, the radial velocity measurements will get better.

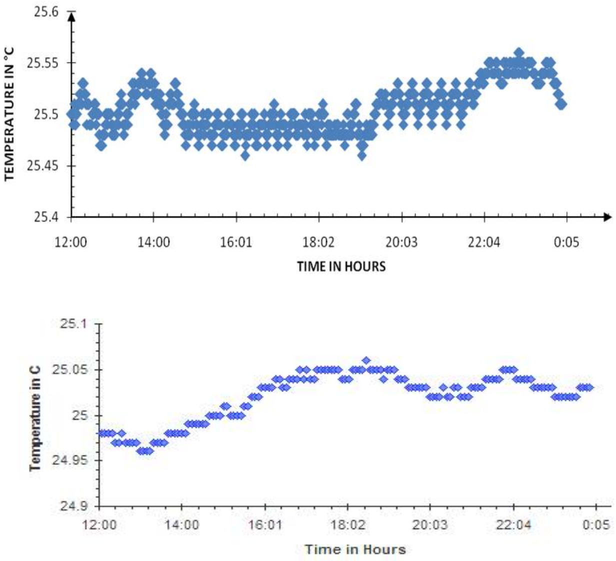


Figure 16. Temperature Stability in inner room and stainless steel vessel

4. Future Developments

For further improvement in the system we have planned to increase the instrument stability up to ±0.005°C and up to 0.01°C accuracy. For that we have to increase its resolution up to 0.001°C. Thus we have moved to ADS1247 ADC which is a latest and fast ADC from Texas instrument. It is a 24 bit ADC and can give 20 bits of noise free resolution. In the present system we have faced the offset voltage shifting problem of the opamp which is greatly affecting the temperature stability. Although it can be eliminated by using ultra low offset voltage, ultra low temperature drift opamp and advanced passive components available. So in order to remove this shifting problem we have chosen OPA2175 Opamp with zero temperature drift and other great features. Implementation of look up table linearization method will be tried to get better accuracy. To make the system more versatile and user friendly we have planned to use differential heating algorithm with multiple sensors installed on different places inside the chamber and power supplied to each heater is according to the error in measurement. The front end visual basic program will be replaced by Labview for better data acquisition. Further improvement in the pre amplification circuit is planned to make the measurement more accurate and precise. Another scope of improvement is that the temperature stability also depends on the rate of change in the ambient temperature of the site which means it falls sharply in winter whereas very slowly in summer. Hence the system should be able to deal with this variation in ambient temperature irrespective of season.

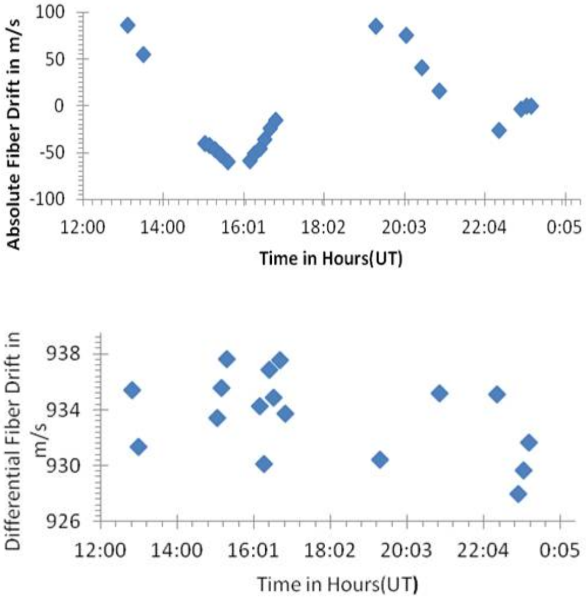


Figure 17. Absolute and differential Fiber drifts

To achieve this we have planned to implement Proportional, differential and integral (PID) control algorithm so that it can withstand the different rate of fall in ambient temperature.

Acknowledgment

This project is funded by Physical Research Laboratory which is a unit of Department Of Space. We are thankful to Mr. Rajesh Shah for his valuable guidelines and support. We show our sincere thanks to Priyanka Chaturvedi and Vishal M. Shah who were always ready for our help in experimenting, testing and also made us understand the scientific need of the project. We are also thankful to Mr. Girish Ubale, Vishnu bhai and other workshop staff for their contribution in designing in the mechanical model of the project. The project is accomplished by sincere suggestions and efforts of other technical staff of PRL and we say thanks to all of them.

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सूर्य
जो निमीलित हैं
चुंबकीय क्षेत्र एवं विकिरण में
अनंत से अनंत तक
जिन्हे प्रकट कर सकती है
मानव की जिज्ञासा एवं विचारशक्ति