# Initial Plan for a Precision Temperature Sensor

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# 1 Introduction

Precision microwave radiometry requires accurate internal calibration sources. A microwave terminator is one such internal source, and, under the assumption of a high quality match, produces a noise power directly proportional to the physical temperature of the terminator. Precise measurement of this temperature is required in order to provide a quality calibration standard. It is desirable for this temperature to be monitored and recorded frequently (perhaps every second or few seconds) during operation of the system, so an interface to computer control and recording is of importance. Current research in L-band microwave radiometry is working toward brightness temperature measurement accuracies on the order of 0.1 K, so that even more precise measurements of internal physical temperatures are required. Although a 0.1 K brightness accuracy is not necessarily required for the IIP radiometer, achieving a high accuracy terminator temperature measurement remains a worthwhile goal, and is feasible with moderate effort.

This document provides a review of candidate temperature sensors, and a specific suggested plan for the IIP radiometer. The detailed plan will be described in a future document.

# 2 Temperature sensor technologies

Several sensors are available for measuring temperature, including resistive-temperature detectors (RTDs), thermocouples, semiconductor devices, and thermistors [1]. Among these devices, thermistors typically provide the highest sensitivity measurements at low to moderate temperatures (i.e. $< 100$ C.) Standard thermistors exhibit a decreasing resistance curve versus temperature, and are therefore classified as "negative temperature coefficient" (NTC) devices. The relationship between temperature and resistance for most thermistors is not linear, but is approximately described by the Steinhart and Hart equation:

$$\frac{1}{T} = a + b \ln R + c \left(\ln R\right)^3 \tag{1}$$

where $T$ is the temperature of the thermistor in degrees Celsius and $R$ is the resistance of the thermistor in Ohms. The $a$, $b$, and $c$ coefficients are specified by the manufacturer. Tables of thermistor resistance versus temperature are also typically available.

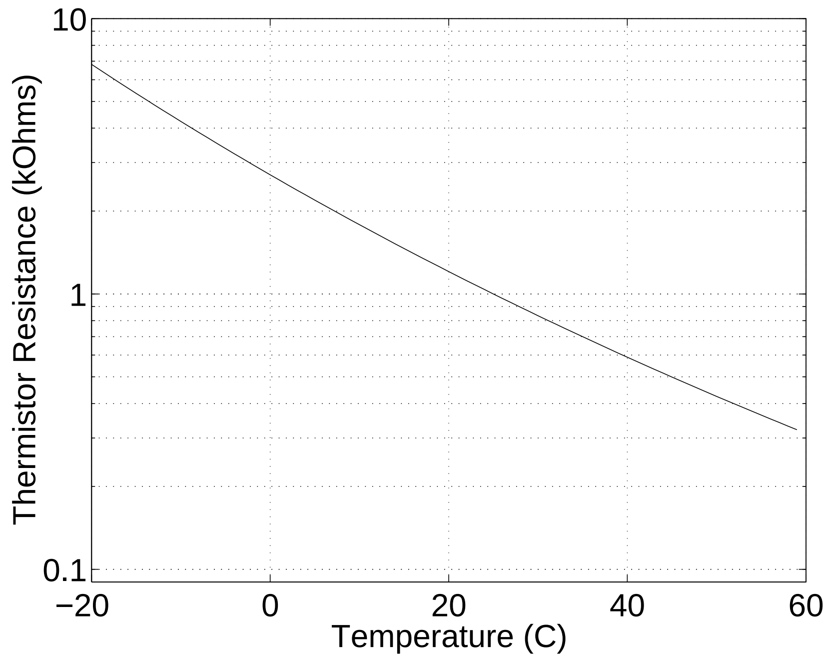


Figure 1: Resistance versus temperature for YSI 44035; note vertical log scale.

As with any manufactured part, the tolerance of any individual part within its specifications is crucial. Resistances of the YSI 44000 series of thermistors are specified with a manufactured tolerance of $\pm 0.1$ C upon inversion [2]. A second issue involves "self-heating" errors introduced due to electrical power dissipation in the thermistor when a resistance measurement is performed. This effect is specified through a "dissipation constant" of the thermistor that describes the amount of electrical power dissipation required to increase the thermistor temperature one degree C. A typical value is 1 milliwatt per degree C for thermistors in air. Electrical power dissipation in thermistors should be kept significantly below this constant to avoid temperature errors, unless a self heating compensation is included in the measurement [2]. Thermistor elements are typically encased in a thermal epoxy material, with wire leads for connection that can be trimmed or soldered as needed. Thermal epoxy is recommended for mounting thermistor elements to the object to be measured, so that stresses due to expansion and contraction effects are minimized. The material "Eccobond 45" is recommended by YSI, Inc. for this purpose [2].

For the IIP temperature sensor, use of the YSI 44035 thermistor (cost $9 each) is recommended. This part has a recommended temperature range of $-80$ to 120 C, a dissipation constant of 1 mW/C in air, and a manufactured tolerance of 0.1 C. The resistance of this thermistor is illustrated in Figure 1, and is specified by the value of 1 kOhm at 25 C.

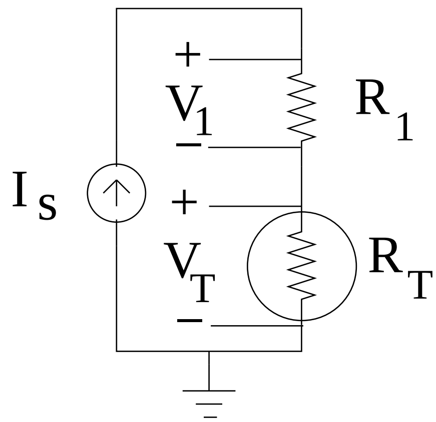


Figure 2: Circuit for measuring thermistor resistance.

## 3 Measurement circuit

Following [3], the simple circuit shown in Figure 2 is recommended for determination of the thermistor resistance. Measurement of both the voltages $V_1$ and $V_T$ allows the ratio $V_T/V_1 = R_T/R_1$ to be determined, independent of any instabilities in the source current $I_s$. Knowledge of $R_1$ (easily measured) then provides $R_T$. $R_1$ should be selected as a resistor that is very insensitive to temperature to avoid additional errors. Note also the use of both "drive" and "sense" (leading to the $V_1$ and $V_T$ measurements) connections in the circuit. For sense wires leading to a high impedance device input, no current will flow in these connections. The voltages measured will be completely related to $R_1$ and $R_T$ and not to the additional resistance of the drive wires. This will allow the resistors $R_1$ and $R_T$ to be located in physically separate locations (with the associated interconnecting "drive" wire) without introducing error into the measurement. To minimize power dissipation and self-heating errors, the current source should be made as small as is practical. At present, the resistances $R_1$ and $R_T$ are not constrained, although the maximum power output of the current source will limit the range of possible choices.

## 4 Basic system design

Although some manufacturers offer single parts specifically designed to convert thermistor measurements to serial data [4], the measurement accuracy available (±0.15 C) is not sufficient for the current application. Design of an analog-to-digital converter system and the associated interface is therefore required. Following [3], the AD7711 from Analog Devices, Inc. [5] is recommended for this purpose (cost $28). The AD7711 provides an effective number of output bits ranging from 10 to 22 depending on internal settings, and includes a programmable front-end amplifier as well as a programmable post-conversion integrating filter. The AD7711 also includes two switchable current source outputs of 200 $\mu$A each (nominal). One differential and one single-ended analog input are supported, selectable by an internal control register. Device output is through a bi-directional serial interface, with data either in 16 or 24 bit format.

For use with the circuit of Figure 2, the "RTD1" current source output of the AD7711 is used for $I_S$, the $V_1$ sense connection is to the AD7711 "REF IN+" and "REF IN-" inputs, and the $V_T$ sense connection is to the AD7711 "AIN1+" and "AIN1-" inputs. The AD7711 inputs "VSS", "AGND", and "DGND" are all tied to a single ground ("VSS" is the negative analog supply voltage for a bi-polar system), while "AVDD" and "DVDD" are tied to a single 5 V DC supply. Finally, the AD7711's internal 2.5 V voltage supply "REF OUT" is connected to the "VBIAS" input for use with a 5 V DC supply.

## 4.1 Choosing $R_1$

A recommended value for the reference voltage REF IN+ - REF IN- is approximately 2.5 V; however, the RTD1 current source is rated for operation only up to a maximum of 3 V. Choosing $R_1$ as 10 kOhms results in a reference voltage of 2 V and allows allows $V_T$ up to 1 V within current source limits. Because the thermistor resistance increases with decreasing temperature, this condition sets a minimum temperature limit of the sensor. Use of a 2 V reference voltage increases the relative importance of A/D internal noise; however, this noise is sufficiently small that performance should still be at least 16 bits (see Table II in [5]).

An additional restriction on $R_1$ and $R_T$ is set by the sampling rate of the A/D inputs: the external $RC$ time constant at both the AIN1 and REF IN+ inputs should be small enough so that additional delays are not introduced. Table IV of [5] specifies an external $RC$ constant of approximately 2.26 $\mu$sec or less as required to avoid errors for an analog gain setting of unity. Using $R_1 = 10$ kOhms results in an external capacitance allowed of 226 pF, while the maximum thermistor resistance of 6.8 kOhm at $-20$ C yields 332 pF. Care should be exercised to avoid external capacitances (i.e. due to sense wires) greater than these values.

Finally, the AD7711 device is susceptible to input noise at integer multiples of the internal sampling frequency 19.5 Khz. A low-pass filter can be added at device inputs to reduce this noise, but the additional filter would contribute to the capacitance limits specified above. Due to the narrow output bandwidth expected for the device, the problematic noise frequencies are extremely narrowband and likely will not be significant.

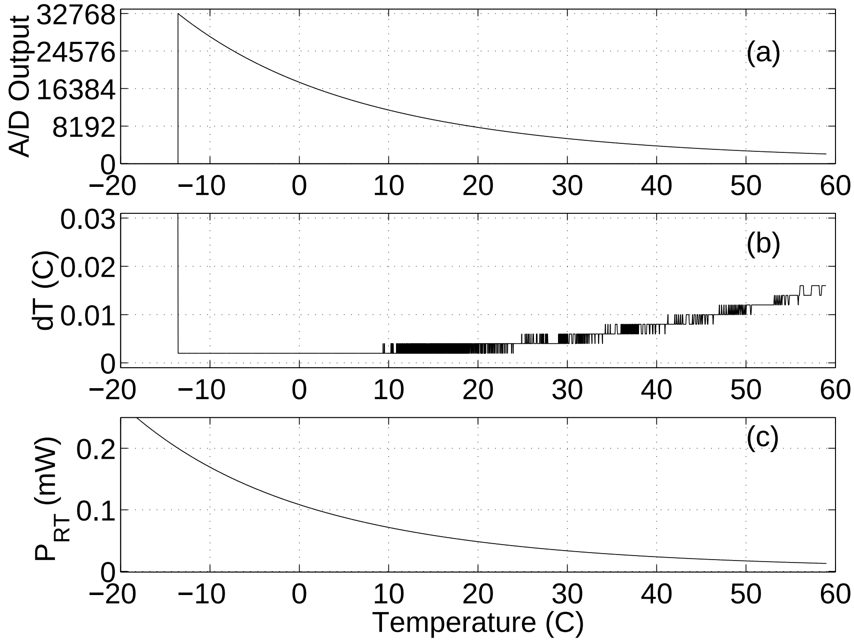


Figure 3: A/D ouputs (a), temperature resolution (b), and thermistor power dissipation (c) for the proposed system versus thermistor temperature

## 4.2 Simulated performance

Figure 3 illustrates predicted A/D output values (16 bit format), the obtained temperature resolution, and power dissipation in the YSI 44035 thermistor in plots (a)-(c), respectively. The simulation was performed with an input AD7711 gain setting of unity, and for temperatures from -20 to 60 C in steps of 0.002 C. A/D output values were set to $-1$ in the simulation when device parameters were violated; in plot (a), this occurs at the lower temperatures due to an excessive voltage across the RTD1 current source. The results show a sensor capable of operating from approximately -15 to 60 C, while providing a resolution of at least 0.02 C up to 60 C. Note the resolution plot is influenced by the discrete nature of the temperatures used in the simulation. Thermistor power dissipation is less than 0.1 mW (producing a self-heating error of 0.1 C or less) for thermistor temperatures greater than 0 C.

# 5 AD7711 Settings

The following settings are recommended for the AD7711:

- Master Clock frequency: 10 MHz is suggested in [5] as the nominal input clock frequency, although clocks down to 0.4 MHz are allowed. Use of 10 MHz is recommended because the majority of the specs in [5] are provided for this clock frequency.

- Calibration: self, system, and background calibration procedures are available to eliminate the effects of thermal or power supply variations on the AD7711. Use of the background calibration mode is recommended so that outputs remain self-calibrated without periodic calibration commands. Use of the background calibration mode results in a 6 fold decrease in the output data rate of the AD7711, although the cutoff frequency of the digital filter is not modified. Note when background calibration is turned on, the first output of the AD7711 is invalid.
- Gain: unity gain setting is sufficient for our application.
- Channel: AIN1
- Word length: 16 bits (24 bits available but should be noisy.)
- RTD excitation currents: on at all times. Switching the RTD currents could potentially reduce self heating errors, but the low data rate of the AD7711 makes this impractical for a resonable sensing data rate.
- Unipolar operation.
- Filter setting: for temperature measurements at least once per second in background calibration mode, the 10 Hz setting is acceptable, and results in a 3 dB filter frequency of 2.62 Hz. Independent data should be available every 0.6 seconds. The "FS" code of the AD7711 has a value of 1953 to obtain this filter setting. Larger filter cutoff frequencies are possible as well if a higher output data rate is desired.

The above settings are achieved by writing 101000000101011110100001 (decimal $10,508,193$) to the 24 bit AD7711 control register.

# 6 AD7711 Digital I/O

Digital input and output to the AD7711 is controlled by 7 pins:

- MODE: a high value indicates a self-clocking SCLK output, while a low value indicates external clocking of SCLK. Use of external clocking is recommended.
- SCLK: the serial interface clock, supplied externally with MODE low. Serial clock frequencies of up to one-fifth the master clock frequency are allowed; a 2 MHz interface clock is recommended. Clocking required only during read/write operations, and intermittent read/write operations are permitted.

- A0: a low value indicates that read and write operations are to the AD7711 control register. A high value indicates that operations are to the data or calibration registers. Read and write operations of the calibration registers occur only in AD7711 calibration steps not considered here. In the current system, A0 should be high except in the initial control register setup phase.

- SDATA: the bi-directional serial data pin. Output data will be in 16 bit format, MSB to LSB. Control register data should be written in 24 bit format, MSB to LSB. Data transitions occur on the falling clock edge and are valid prior to the next rising clock edge.

- $\overline{\text{DRDY}}$: Falling edge generated by the AD7711 indicates that new output data is ready for transmission. Returns high upon completion of output data transmission. Internal data continues to be updated with $\overline{\text{DRDY}}$ low.

- $\overline{\text{RFS}}$: Receive-frame-synchronization. SDATA line becomes active after $\overline{\text{RFS}}$ is brought low (should only occur with $\overline{\text{DRDY}}$ low.) Should be brought high again when $\overline{\text{DRDY}}$ returns high.

- $\overline{\text{TFS}}$: Transmit-frame-synchronization. SDATA line expects input data on falling SCLK edges with $\overline{\text{TFS}}$ low. Should be brought high again upon conclusion of data transmission. Used only in the initial control register write in the current system.

Refer to [5] for more detailed AD7711 I/O timing information.

# 7 Microcontroller

The RCM2200 "Rabbit" microcontroller [6] provides a convenient tool for control of AD7711 operation, and can be programmed to allow communication with an external computer through an ethernet interface. The microcontroller should provide both the 10 MHz master clock (all times) and the 2 MHz serial data clock (intermittent) to the AD7711. Microcontroller functions to be requested by the control computer should include:

- Perform the AD7711 control register write operation. A read operation to verify this write may be desirable as well. Inform the control computer of the status of this operation.

- Read the AD7711 data when the $\overline{\text{DRDY}}$ pin is low. Transmit the resulting data to the control computer.

The microcontroller could potentially implement a look-up table to convert AD7711 outputs directly to temperature, rather than transmitting only the $R_T/R_1$ ratio to the control computer. An FPGA component may be required in the design for generation of the appropriate clock frequencies and for conversion of AD7711 serial data into the parallel format perferable for the microcontroller.

# 8 Implementation

It is recommended that the system be implemented in a single PCB, to include the AD7711, RCM2200, and FPGA if needed. $R_1$ (the 10 kOhm resistor, average power dissipation 0.4 mW) and the appropriate drive and reference sense connections can also be included on the PCB. A four wire connector will be required for the YSI 44035 (located in a distinct location from the PCB, although wire lengths and related capacitances should be kept within the limits described.) The RCM2200 ethernet connection, and appropriate power connections (+5 VDC for the AD7711 system) will also be required. Shunt capacitances of $10\mu F$ and $0.1\mu F$ are recommended in [5] for the AD7711 power supply.

# References


[1] "Temperature sensor technology," *www.transcat.com /inforesource /pdfs /ref /temperaturesensortechnology.pdf*

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[3] Albert O'Grady, "Temperature measurement using a thermistor and the AD7711 sigma delta ADC," Analog Devices Inc. Technical Note, 1998.

[4] *MAX6682: Maxim Thermistor-to-Digital Converter Datasheet,* Maxim Corporation, 2002.

[5] *AD7711 Datasheet,* Analog Devices Inc., 1998.

[6] *RMC2200 RabbitCore,* Rabbit Semiconductor, 2002.

[7] *HY5640: Subminiature Controller for Thermoelectric Coolers Datasheet,* HYTEK Microsystems, 2002.