Investigation of the Tower Mounted Radiometer System and Proposed Improvements

EECS Directed Research Report

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Abstract

The Tower Mounted Radiometer System (TMRS) was designed by the Remote Sensing Laboratory to study microwave energy fluxes in the Tundra and Northern Great Plains. The latest Radiobrightness Energy Balance Experiment (REBEX-4) was performed in the northern prairie near Sioux Falls, South Dakota during the 1996 summer growth season. For my directed research, I investigated and modified the system electronics in preparation for this experiment. Also by maintaining the TMRS opeation throughout the summer, I gained an understanding of how I may improve the performance and reliability of the next generation radiometric system.

The TMRS housing is mounted on a ten-meter tower and consists of an infrared sensor and three dual-polarized radiometers operating at 19, 37, and 85 GHz. On the front of the tower housing, a motorized metal door is opened partially to reflect the main beam toward the sky for calibration, or opened completely to track the microwave radiometric response of a 2 m x 4 m swath of land. Inside each radiometer, a PID controller is used to regulate the reference load and receiver physical temperatures to within ±0.1 K. Weather conditions are monitored by a tripod station with various sensors, including anemometers, pyranometers, soil and vegetation temperature sensors, and time-domain reflectometry probes for measuring soil moisture. The instrument signals are multiplexed and then sent via serial interface to a Macintosh II computer with National Instruments data acquisition hardware. Data is stored and presented graphically using the Hypercard visual programming language.

Complete circuit diagrams were created for the tripod chassis, high-speed serial interface, Macintosh watchdog timer, and tower's solid-state relay array. Also, new circuitry was devised to sense and control the housing door angle with greater accuracy. To improve TMRS performance in the hot summer environment, heat sinks were added to the housing surface and the tower circuitry was modified to reduce power dissipation.

During the course of REBEX-4, we encountered several TMRS malfunctions. These problems were related to three hardware design issues: data bus conflicts, semiconductor reliability, and quality of circuit board assembly. A bus protocol is proposed for future radiometer systems which would reduce data conflicts and simplify the serial interface. High and low temperature tests are proposed to detect semiconductor failures early in the design stage. Finally, quality control can be improved by cross-checking each circuit with its schematic and parts list, and by planning a thorough design review of the entire system.

Investigation of the Tower Mounted Radiometer System and Proposed Improvements

(1) Introduction and Objectives

The second Tower Mounted Radiometer System (TMRS II) was designed several years ago by the Remote Sensing Laboratory to study microwave energy fluxes emitted by various types of terrain. The Radiobrightness Energy Balance Experiments (REBEX) are a series of field studies performed with TMRS in the Alaskan Tundra and the North American Great Plains. Because these land-masses are relatively homogeneous over large distances, a one-dimensional Land Surface Process (LSP) model can be applied to correlate surface soil moisture with ground brightness temperature.

The latest experiment, REBEX-4, took place in the northern prairie near Sioux Falls, South Dakota during the 1996 summer growth season. Tower mounted radiometers and a meteorological Tripod station perform remote and in-situ measurements, respectively, of the surface soil and vegetation characteristics. The TMRS operating frequencies match those used in the Special Sensor Microwave / Imager (SSM/I) satellite which was deployed in 1987 by the Department of Defense.

Results from REBEX experiments can be used to validate LSP models and to promote remote sensing of soil moisture from space. However, this report will not address the science issues detailing why we performed the REBEX-4 experiment. Instead this paper emphasizes how the hardware system works and how the electronics were modified in preparation for the summer experiment.

(2) TMRS System Overview

Tower Housing

The TMRS housing is mounted on a ten-meter tower and consists of an infrared (IR) sensor, video camera, and three radiometers operating at 19.35, 37.0, and 85.5 GHz. The 19 and 37 GHz radiometers contain dual-polarized horn antennas while the 85 GHz unit supports only one polarization. On the front of the tower housing, a motorized metal door is opened partially to reflect the main beam toward the sky for calibration, or opened completely to measure the brightness of a two meter by four meter swath of land.

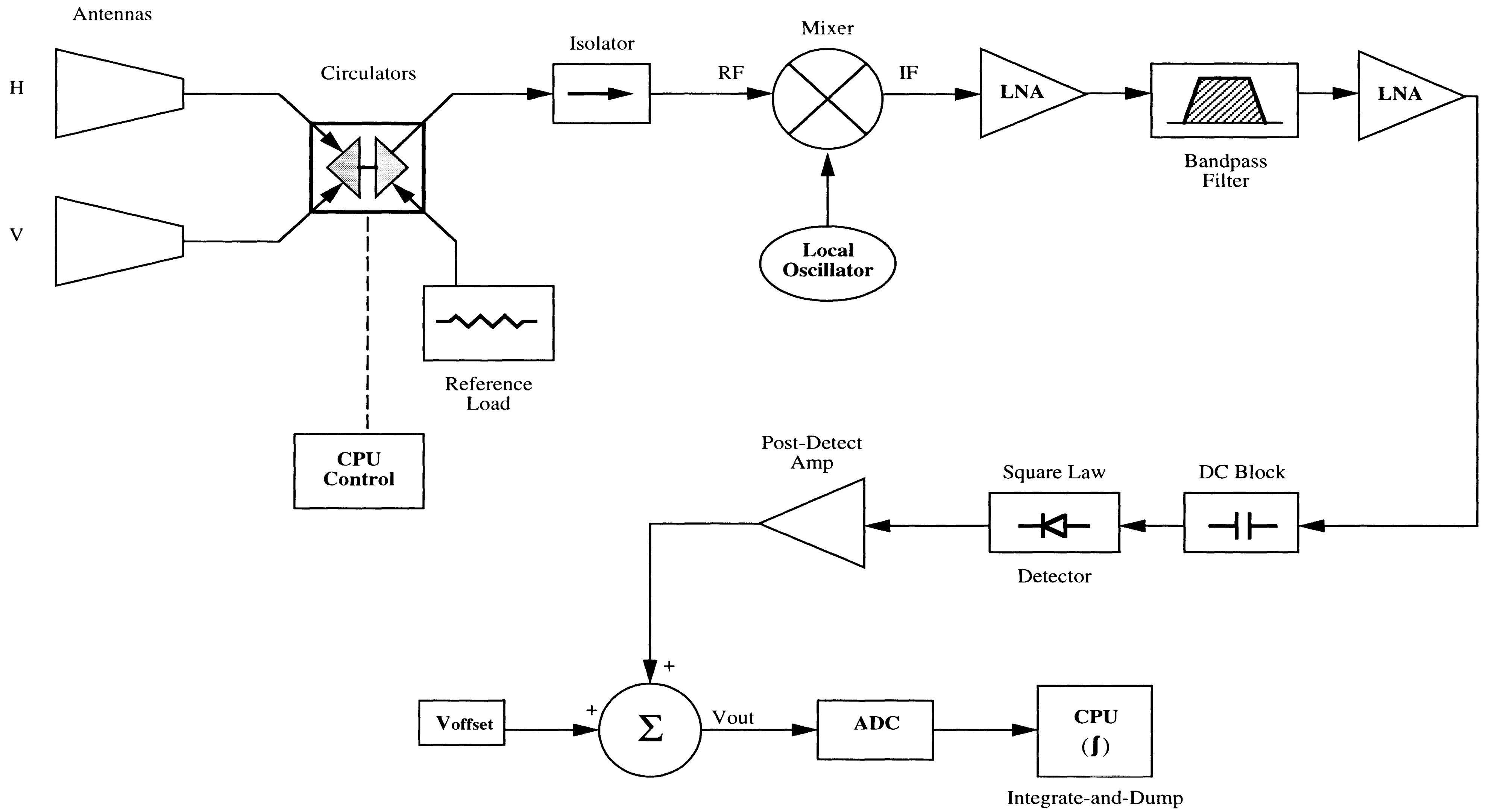

Figure 1. Dicke / Total Power Radiometer Design

All three radiometers are designed to operate in Dicke or Total Power Radiometer modes. (See figure 1.) A circulator network selects the radio frequency signal from either the horizontally or vertically polarized antenna, or from a matched waveguide reference load. The front end signal is sent to a microwave mixer / heterodyne network. The intermediate frequency signal is input to a low noise amplifier with bandpass filter, square-law detector diode, post-detection amplifier with adjustable offset voltage, and 12-bit, 48kHz analog-to-digital converter (ADC). Once the radiometer output data is in digital form, it is sent via a fiber optic *3-line bus* to a Macintosh II CPU with interface hardware. Integration of the data is performed by the CPU software.

Inside each radiometer, a PID controller is used to regulate the physical temperature of the electronics to within 0.1°C. This minimizes system gain fluctuations and controls the thermal noise generated by the reference load. A wheatstone bridge network with thermistors is used to measure the antenna, heat sink, and reference load temperatures. These voltages are sampled by the ADC and multiplexed onto the 3-line bus every 60 seconds. A PID software algorithm determines the appropriate time-averaged power to deliver to the fiberglass heaters mounted inside each radiometer. A National Instruments NB-TIO-10 interface card then generates duty cycle signals which pulse the heaters on and off.

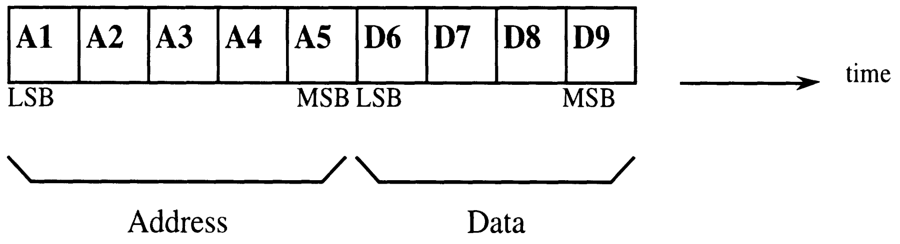

Figure 2. 9-Bit Serial Uplink

Power distribution to the three radiometers, IR sensor, video camera, and door actuator is controlled by the *Center Box.* At the heart of the Center Box is an array of Motorola MC145027 decoder ICs which receive a *9-bit serial uplink* from the Macintosh. The first 5 bits designate the address of a particular decoder IC, and the remaining 4 bits represent data (figure 2). An MC145027 is enabled when the uplink address matches the chip's hardwired address. Data is latched and asserted by 4 parallel output lines. Each data output is buffered by a Darlington inverter and then sent to control one of the Solid-State Relays (SSR's). The Center Box houses over twenty direct current and alternating current

SSR's to individually switch radiometer heaters, actuator solenoids, and ±15V, +5V dc power supplies.

A metal door is hinged to the front of the housing and can be opened or closed with a Thompson Saginaw *Linear Actuator.* In the closed position the door acts as a thermal insulator for the radiometers. During brightness experiments, which occur every thirty minutes, the door can open partially to serve as a reflector plate for sky temperature calibration, or it can open completely for soil and vegetation brightness measurements. Last spring TMRS was retrofitted with a closed-loop system which controls the door angle to within 0.5°. The system includes a Hewlett-Packard HEDS-550 optical encoder which is mechanically coupled to the motor shaft, a digital *up/down counter* circuit, and control software.

To keep the operating temperature low in the summertime South Dakota environment, the IR power supply was modified to reduce dissipation, and heat sinks and a sun shield were mounted on top of the housing for passive cooling.

Tripod Instruments

A meteorological *Tripod Weather Station* is erected near the tower with sensors such as anemometers, solar pyranometers, temperature probes, etc., to retrieve climate data. A weatherproof enclosure mounted to the tripod contains a Bowen Ratio system for water vapor flux measurements and an electronic chassis for data multiplexing.

The weather instrument signals are conditioned inside the Tripod chassis. "Switched signal" instruments, including the anemometer and rain gauge, are conditioned with debounce circuitry to remove spurious rising and falling edges. To detect small changes in sensor output voltage, many of the instruments are fed directly to INA114 instrumentation amplifiers. Then these signals are input to an array of Harris HI-506 analog multiplexers. The Macintosh CPU sends address and data information via the 9-bit serial uplink to enable one of the HI-506 ICs and to select one of the input channels. Five MC145027 chips are used to decode the uplink.

The voltage signal from the selected channel is sent to the differential input of a Keithley M2131 ADC module. The Macintosh communicates with the module via an RS-232 interface. When the CPU sends an ASCII-coded command to sample data, the module performs an A-to-D conversion and returns an ASCII string representing a digital word to the Macintosh serial port. In summary, the Tripod multiplexes dozens of weather sensor signals so that the Macintosh may acquire many kinds of data.

Time Domain Reflectometry

Soil moisture content is directly measured by the Tektronix 1502C Time Domain Reflectometer (TDR). A pair of soil moisture probes are connected to the terminals of a coaxial cable extending from the TDR. By inserting the probes parallel to one another and at a fixed distance in the soil, they effectively serve as a length of twin-lead open-ended transmission line. Changes in water content directly affect the permittivity and phase velocity of the line, which are calculated by generating a pulse at the TDR and measuring the lag time of the reflected signal.

A weatherproof *TDR Multiplexer* box is used to connect up to 15 separate soil moisture probes to the TDR. Channel selection is controlled by six digital output lines from the National Instruments NB-DIO-24 interface card. The TDR houses an SP-232 module which interfaces to the Macintosh II serial port for control and data acquisition. During REBEX-4, the probes measured moisture levels at several depths below the soil surface and in the prairie canopy.

Power Bus

120Vac / 60Hz power is supplied to the Trailer, radiometer housing, and Tripod system. Several outlets in the Trailer are used to power the Macintosh II, *Trailer Box* interface circuitry, TDR, modem, and uninterruptible power supply (UPS). The 120Vac is delivered to the Tower housing and converted to +18V, -24V, and +9V unregulated dc lines by the *Lid Power Supply*. These lines are then stepped down to ±15Vdc and +5Vdc by several three-terminal regulators inside each radiometer. A separate 120Vac line to the tower supplies power to the linear actuator and the heater pads. Two linear power supplies are used in the Tripod system: one inside the Tripod cabinet which supplies ±12V and +5V to the electronic chassis, and one external supply which delivers +12V to the Hygrometer pump inside the Bowen Ratio system.

Data Acquisition System and Software

Several kinds of communication bus links are used by the Macintosh II to control the TMRS II hardware and to acquire data from many instruments: (1) 9-bit serial uplink, (2) 3-line bus downlink, (3) RS-232 serial line, (4) National Instrument I/O interfaces. (See figure 3.) The main tasks of the CPU are to acquire, process, and present the data.

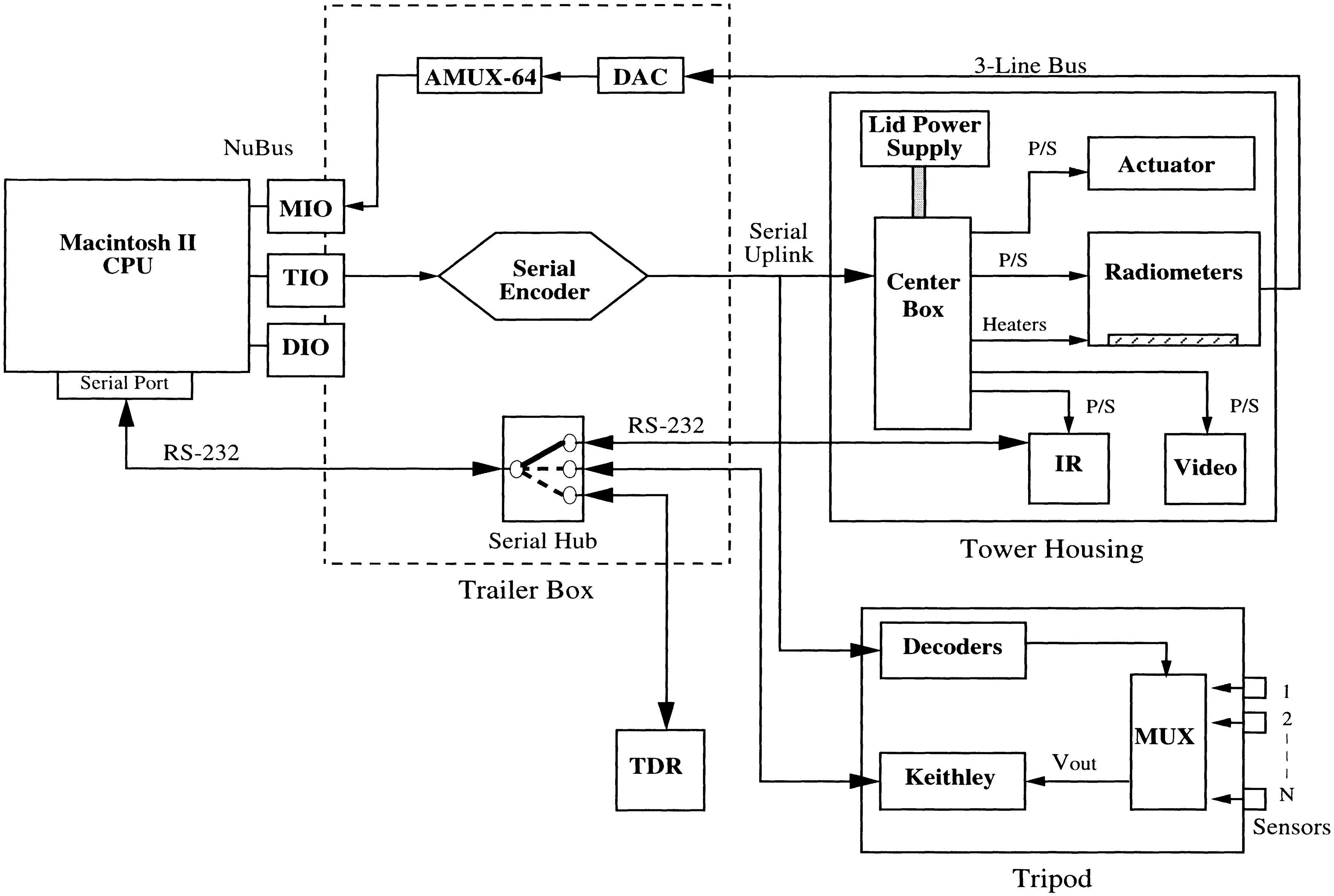

Figure 3. TMRS II Communication Buses

This is accomplished with *FluxMon*, a complete data acquisition software package created several years ago in the Passive Remote Sensing Group. FluxMon is written in the HyperCard visual programming language. External commands (XCMD's) to drive the hardware interface are written in ANSI C. The graphical user interface includes windows for real-time data retrieval, archived data, virtual control panels, and radiometer calibration.

Three National Instrument interface cards are connected to the Macintosh II NuBus expansion slots: (1) NB-DIO-24 for digital input / output ports, (2) NB-TIO-10 for timer or counter applications, and (3) NB-MIO-16 for mixed-signal input / output ports. The National Instrument ports and Macintosh RS-232 serial port interface with the *Trailer Box* circuitry, which serves as a hub for data transferred between the computer and TMRS hardware. The three TMRS devices using the RS-232 protocol are the Keithley module, TDR, and IR sensor. Because the Macintosh serial port can only talk to one slave device at a time, the Trailer Box includes logic to route this port to one of three RS-232 devices. The enabled device is selected by a two-bit address sent by the DIO board to the Trailer Box.

The Trailer Box also generates electrical and optical signals for the 9-bit serial uplink. An eight-bit word is sent from the TIO board to the input gates of a Motorola MC145026 encoder IC. (The ninth bit is not sent because the address's Most Significant Bit is hardwired to zero inside the Trailer Box.) A transmitting fiber optic link converts the encoder's serial output to an optical signal which is then sent to the Tower. Also the serial uplink is electrically sent to the Tripod box.

Brightness and physical temperature data from the Tower is sent down the fiber-optic 3-Line Bus to the Trailer Box. The clock, data, and enable signals are converted into voltages by receiving fiber optic links. An Analog Devices AD7233 12-bit serial DAC converts the data into an analog signal which is then passed through a four-stage active filter. The conditioned signal is output to the National Instruments AMUX-64T (64 channel analog multiplexer) and sampled by the MIO board. Once the CPU has sampled a sequence of digital words, integrating the data over a time interval will reduce the uncertainty of the brightness or temperature measurement.

(3) Calibration Method

A Total Power Radiometer is designed so that the detected output voltage V_{out} is proportional to the antenna power received, $P = kT_AB$. Therefore there is a linear relation between V_{out} and the brightness temperature T_A. The gain (slope) and offset (y-intercept) of the linear transfer function can be calculated by measuring the output voltage when two targets with distinct, known brightness temperatures fill the beam of the horn antenna.

The calibration error becomes small as the temperature difference between "hot" and "cold" targets is made large. This is realized by using one blackbody absorber pad at room temperature (~300K) for the hot load and another pad soaked in liquid nitrogen (~80 K) for the cold load. By definition, a blackbody has a microwave emissivity of unity, therefore the brightness temperature of the absorber is equal to its physical temperature. FluxMon provides a screen that steps through calibration of all five antennas. When prompted by the software, the experimenter places one of the loads directly in front of the enabled antenna so that the target is beam-filling. FluxMon can measure the physical temperature of the hot absorber automatically with a thermistor probe, or the temperature can be measured with a thermometer and entered manually. For the cold load, FluxMon always sets the temperature to 80 K.

After the two-point calibration is performed, FluxMon stores gain and offset variables for each radiometer so that succeeding radiobrightness measurement can be automatically calibrated. To ensure that V_{out} is within the range of the radiometer's 12-bit ADC, the post-detection amplifier offset voltage can be adjusted with an on-board trimpot.

(4) Proposed Improvements

Bus Topography

One design flaw in TMRS II is that the communication buses can occasionally send conflicting signals at the same time. Because the CPU can send commands via serial uplink to enable several MC145027 encoders simultaneously, poor hardware design methods can lead to a situation where two or more active output ports are electrically connected! In fact, during last summer's experiment we had the experience of damaging hardware through an unfortunate sequence of keystrokes at the Macintosh terminal.

The 3-Line Bus output from the three radiometers could be made more robust by centralizing the bus enable circuitry. Currently each radiometer has its own decoder chip with unique address. When the decoder is enabled, the radiometer's serial data is output from a tri-state buffer. All three radiometer's tri-state buffers are electrically connected. Therefore it is possible through software commands to send conflicting voltage levels on the 3-Line bus and cause a catastrophic failure. To eliminate this problem, one central decoder IC can be used to control all three radiometers. The decoded data word can be sent to a demultiplexer IC to produce one of three mutually exclusive outputs. Therefore only one tri-state buffer can be enabled at any time.

A similar design flaw was found in the linear actuator control logic. The solid-state relays that command the actuator to extend or retract can be enabled simultaneously. This causes the main actuator fuse to blow. Digital logic can be improved here also with a demultiplexer so that the SSR outputs are mutually exclusive. The rule of thumb here is that the hardware should always be designed so that it is impossible for the software to cause physical damage.

Bus Unification

The four different communication buses have already been explained in some detail. There are several advantages to designing just one bus protocol to control and acquire data from all TMRS hardware. First, it can simplify the hardware by reducing the variety of interfacing, D-to-A and A-to-D conversion circuitry. Second, servicing is simplified because only one *break-out box* would need to be designed to troubleshoot each separate hardware component. For example, if the radiometers, IR sensor, and Tripod chassis communicated solely through an RS-232 line, then a laptop Personal Computer could be used to troubleshoot each device separately. Finally, serial protocols like the RS-232 and RS-485 are standardized, so asynchronous communications chips (e.g., UART) are readily available from a variety of vendors.

The most widely used serial bus is the RS-232. Most personal computers are now produced with at least two built-in serial ports. However, RS-232 is only single-drop, from one master to one slave device, so a hub circuit similar to the Trailer Box must be designed to communicate with multiple sensors. The RS-485 is multi-drop with faster data transmission than RS-232, and also the electrical signal can travel much greater distances over twisted-pair wires. Unfortunately most computers and measuring instruments do not support RS-485, so the technical advantages are outweighed by the inaccessibility of devices using this protocol.

If a slower serial link such as RS-232 is implemented, then more of the control functions and high speed signal processing must be moved from the CPU to the instruments. For instance, in TMRS II the 12-bit 48KSample/sec radiobrightness data is downlinked through fiber optic lines to the Macintosh, and then the software integrates the data. RS-232 is too slow for this data rate, so the radiometer's integrate-and-dump must be performed by an on-board microcontroller. The controller could also carry out other functions, such as adjusting the radiometer's offset voltage and performing local PID temperature control. By adding "intelligent" hardware to the radiometer, CPU dead-time and the risk of losing data or temperature stability during software crashes can be greatly reduced.

Antenna Beam Forming

All five TMRS antennas are standard gain horns (directivity = 25dB). The dominant TE_{10} mode in each antenna has a field distribution in the E-plane which is nearly uniform. Therefore finite side-lobe levels (SLL), particularly in the E-plane, can cause significant errors in the apparent brightness T_A seen by the antenna. To simulate the SSM/I satellite viewing angle, the TMRS housing is mounted such that the main beam axis is 53° from nadir. The brightness energy captured by side-lobes, especially those aimed at soil, vegetation, and other warm targets, is added to the brightness of the desired target, thus resulting in an error.

For the next generation TMRS, we will experiment with beam-forming antenna arrays to minimize the side-lobe levels. For instance, a binomial array of antenna elements has no side-lobes, according to scalar diffraction theory. Although a side effect is a slight widening of the beamwidth, for LSP modeling we are willing to sacrifice spatial resolution in exchange for less T_A error. This technique is useful also for Synthetic Thinned Array Radiometry, which uses an array of antenna "sticks" to create the real and synthesized apertures. Each stick can consist of several antenna elements forming a one-dimensional array with a tapered amplitude distribution.

Semiconductor Reliability

Several semiconductor failures occurred for high power and microwave components during REBEX-4. However, during the REBEX-3 experiment on the Alaskan North Slope, the same equipment ran untended for one year with no significant semiconductor failures. The difference in ambient temperature between the two sites suggests that the root cause of the malfunctions was overheating of semiconductor junctions.

To assure that the electronics can operate over a wide range of ambient temperatures, mounted boards should be tested environmentally, early in the design stage.

In a high temperature chamber (50°C), the case temperature of critical semiconductors can be measured while the circuit under test is operating. Then once the power dissipation and thermal resistance (θ_{jc}) of the part is determined, the junction temperature T_j can be calculated. A design review of each circuit board confirms whether T_j is less than the absolute maximum rating minus an acceptable safety margin.

It is recommended that a low temperature test (-40°C) be performed to ensure safe power-up and operation of all circuitry. The designers should confirm whether solid-state power switches are within the Area of Safe Operation (ASO) during initial power-up.

Quality Control Recommendations

Many of the hardware glitches encountered last summer fell under the category of *quality control* problems. These included mismounted electrical parts, ambiguous connection schemes, loose interconnections, flimsy circuit board construction, poor routing of wire harnesses in the chassis, and mechanical instability.

For the next generation TMRS, the quality of circuit boards can be improved by using standard wire-wrap boards with printed bus pads for power and ground, and by soldering IC sockets and other components to these pads for mechanical stability. On a single circuit board, the connector scheme should be well labeled and unambiguous to prevent mis-insertion. Also, use connectors with mechanical latches for all outdoor field hardware.

Create up-to-date schematics and parts lists for each mounted circuit board, and cross-check every component on the final mounted board with both documents to find any discrepancies. Before an actual experiment, perform an outdoor *shake-down* test with all hardware components assembled. Since climatological studies require uninterrupted collection of data over diurnal cycles, the entire system should be tested for several days to study performance or reliability problems. Afterwards, conduct a thorough design review to determine each detected symptom, priority level (e.g., critical / safety, major, minor, etc.), root cause, and corrective action.