The Iowa State University Direct Sampling L-Band Digital Radiometer

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Abstract—This paper describes a polarimetric-capable L-band radiometer that has been built for Iowa State University (ISU) by The University of Michigan. It is a ‘Direct Sampling Digital Radiometer’ (DSDR), in which most of the operations are performed digitally and mixer stages are eliminated. The system is to be used for soil moisture retrieval studies. It could provide supportive data for future L-band missions and is reconfigurable for radio frequency interference (RFI) mitigation purposes.

I. INTRODUCTION

Recent advances in remote sensing have shown that soil moisture could be measured by various methods including radiometry. Radiometry holds great promise for global measurement of soil moisture since it is possible to make continuous observations over a large area and the primary property that affects the measurements is directly dependent on the liquid water present [1]. Furthermore, at microwave frequencies, signals are not affected by clouds, which makes data collection possible in all-weather conditions. L-band is accepted to be optimum for soil moisture retrieval, however, there has not yet been a dedicated spaceborne mission at this frequency band due to high cost and the need for large antenna apertures. One promising development is the direct RF sampling receiver architecture where the RF signal is sampled and digitized through analog-to-digital converters (ADCs) after the front end amplification and filtering stages so that all subsequent processing is performed digitally [2]. Hence, the gain fluctuations and noise sources due to analog mixers and local oscillators that are used in a conventional receiver are eliminated. A simplified hardware and digital processing allows the integration onto a multi-chip module (or eventually onto a single chip monolithic microwave integrated circuit) and lowers the cost, weight and packaging. In this study, the Direct Sampling Digital Radiometer, which has been built for ISU by the University of Michigan, is introduced. System description as well as antenna performance, RF receiver components, analog to digital converter and digital back end sections are explained. The FPGA firmware and microcontroller operations are emphasized. Thermal control and monitoring mechanism of the system is given.

II. INSTRUMENT DESCRIPTION

The system is an L-band dual-polarization radiometer, with capability for polarimetric operation. It is designed as a total power radiometer. Brightness incident upon the antenna is amplified until it is at a power level that can be detected. Since power is proportional not only to brightness but to bandwidth (P=kTB), filters are employed within the system to carefully define system bandwidth (RF bandwidth).

The radiometer uses a Direct Sampling detection scheme. The radiometric signal, after appropriate amplification and filtering, is digitized for further processing. This further processing occurs in a Field Programmable Gate Array (FPGA) for both receivers (H-pol and V-pol). In addition to quantifying the power in each channel, it is possible to cross-correlate the signals between the channels for polarimetric operation. Also, FPGA processing allows for limited RFI mitigation (in both time and frequency domains) and for special operations such as spectrometry (within the limited bandwidth of the system).

The radiometer is designed to be autonomous. That is, the radiometer is equipped with a microcontroller that has responsibility for taking measurements, monitoring the thermal environment, and storing data until the user requests a download. The user can configure the radiometer to maintain a particular thermal set point, and make periodic measurements of the brightness at both polarizations and the reference load on its own. The master computer, which provides the user interface, does not need to be in continuous communication with the radiometer for the radiometer to be operating as intended. The master computer running the user interface communicates with the radiometer through a Radiometer Control Language, or RadiCL. The data collected by the radiometer is not calibrated within the instrument, since calibration errors could corrupt an otherwise useful dataset. Calibration, using measurements of the sky and an absorber at a measured temperature, should be done in post-processing.

The instrument uses a thermoelectric cooler (TEC) for thermal control of the RF stages. This system uses a state-of-the-art thermal controller, with 0.01°C resolution. The controller is bipolar (it can drive the TEC in reverse, for heating as well as cooling) and uses a PID (proportional-integral-derivative) control algorithm. The aluminum plate to
which all the RF components are attached is chosen to have sufficient thermal mass to eliminate short term thermal drifts. All components attached to this thermal plate, including the TEC, use thermal paste to minimize thermal gradients across junctions.

In order to distribute the mass and heat generation of the system, the electronics are enclosed in two environmental enclosures. To maintain environmental integrity, the aluminum cases used are penetrated with only a minimum of needed holes. These penetrations of the case are, on the receiver module, the bulkheads for RF signal input, DC power input, data connection and heat sinks for exhausting internally generated heat. On the power supply module, the penetrations consist of the AC power input socket and DC power leads to the RF module.

The radiometer and its block diagram are shown in Figure 1 and Figure 2, respectively.

![Figure 1. ISU radiometer. Receiver and power supplies are contained in two separate boxes mounted on the sides of antenna orthomode](image1)

![Figure 2. System block diagram. Contents of the receiver and power supply boxes are outlined in gray](image2)

III. SUBSYSTEMS

A. Antenna

The ISU L-band antenna for the ISU L-band radiometer is a dual polarized square Potter horn employing a custom designed Potter horn, a commercial off-the-shelf (COTS) orthomode transducer, and a pair of COTS waveguide to coax transitions. The RF terminals are N-type female coaxial connectors. The antenna system is tuned for operation in the radio astronomy hydrogen line band of 1400-1427MHz. The aperture is 730mm square (3.44λ at 1413.5MHz). The overall size of the antenna itself is 82cm x 82cm x 137cm tall. The mass of the antenna is 37 kg. All of the components in the system are made from aluminum and all parts have been alodined (gold chromate finished) to prevent corrosion. No radome has been installed on the antenna since prior experience indicates that this tends to trap moisture inside the antenna, possibly adversely affecting the radiometer sensitivity to the microwave brightness of the scene. However, the aperture is equipped with a flange to allow for a future installation of a radome if desired. The antenna is shown in Figure 3.

![Figure 3. L-band Potter antenna. Photo taken during the antenna pattern measurements in anechoic chamber](image3)

Antenna pattern measurements have been performed in the anechoic chamber of the Radiation Laboratory in The University of Michigan. The ISU antenna was fed with a signal generator and the radiated power was received by a small L-band horn antenna connected to a spectrum analyzer. The operational frequency was 1413.5 MHz, which is the center frequency of the available band. Data was electronically recorded. The antenna was rotated from −90° to +90° in azimuth (with respect to boresight) under different transmitter/receiver orientations and orthomode port excitations. Figure 4 shows two of the antenna patterns, for which the orientations of the ISU antenna and the receive antenna are horizontal and vertical, respectively. For the H-port excitation, it represents a copolarization while it is a cross-polarization for the E-port excitation. Note that no distinct sidelobes exist.
The measured 3dB beamwidths for horizontal and vertical polarizations were 20.3° (elevation) x 17.9° (azimuth) and 18.4° (elevation) x 20.4° (azimuth), respectively. The highest sidelobe level was measured to be 26.8 dB down from boresight, which occurred at 41° from boresight in H-pol azimuth.

Largest return loss (RL) was measured as -17 dB at 1427 MHz. The estimated radiation efficiency and polarization coherency were 95% and 98%, respectively. The polarization coherency ($\rho$) was calculated through the following equation:

$$\rho = \frac{\int \int |E_h| E_v^* d\Omega}{\int \int |E_h| |E_v| d\Omega}$$

which is the normalized cross-correlation between the horizontal and vertical components of the electric field ($E_h$ and $E_v$) over the antenna pattern. The polarization coherency can be considered the degree of correlation between signals at the two antenna output ports when the antenna is illuminated by an isotropic (say) left circularly polarized noise. It is also an indirect measure of the separation between the phase centers of the two polarizations.

![Figure 4. Antenna patterns: Copolarization (top curve) and cross-polarization (bottom curve)](image)

**B. RF Chain**

The signal received by the antenna needs to be amplified and filtered before it is digitized. The RF chain block diagram is given in Figure 5.

The majority of the gain in the system is provided by a gain and filtering block consisting of connectorized components. The main advantage of the choice of connectorized components is the fact that very little crosstalk is expected between even physically close components, an important feature when a system has nearly 100dB of gain at a single frequency. This gain block is designed for a radiometer working at the radio astronomy window of 1400 to 1427 MHz. In order to minimize the receiver noise figure, an L-band low-noise amplifier (LNA) is used prior to the majority of filtering and gain. At the very front end of the receiver, before the LNA, the part count and part insertion losses are critical, because the sum of all insertion losses of these parts contribute directly to the receiver noise figure. In particular, the front end parts include:

1. a microwave switch for reference load comparisons,
2. an isolator for stabilizing the subsequent components’ overall gain, which can otherwise vary due to different amounts and phase of reflection when looking from the receiver thru the switch at the different loads (reference or antenna),
3. a directional coupler, for in-field injection of correlated noise into both receivers for calibration purposes,
4. a very low insertion loss ceramic filter (0.7dB) for performing the majority of interference rejection prior to the LNA.

These components contribute to the H-pol and V-pol receiver temperatures of 167.2K and 153.9K, respectively. Calculations indicate that this noise performance will satisfy the instrument requirement of an NEAT of 0.3K over a 10 second integration period.

The remaining components in the receiver function to:

1. amplify the signal to a level that can be detected by ADC (about –35dBm),
2. filter out-of-band interference
3. provide matches between amplifiers and filters to keep the amplifiers stable, and prevent distortion of the filter passbands.

![Figure 5. RF chain block diagram](image)

One important consideration is the receiver linearity. Linearity is important because calibration is achieved at only a...
few points, with the brightnesses between determined by assuming a linear receiver response. The generation of non-linearity is the same mechanism that eventually results in saturation when interference gets through the filters. Figure 6 shows the result of an experiment in which a load immersed in liquid nitrogen and the reference load are used as a cold load and a warm load, respectively. Three attenuators, at values of 1dB, 2dB and 3dB are connected to the output of the cold load in order to generate different brightness temperatures. This setup was also used to determine NEDT and the brightness of the noise diode, which is 130K. The RF chain output power varies linearly with the input brightness temperature, which confirms the receiver linearity.

The amplification in the receiver is large (100 dB) and a small change in gain of the system will incorrectly appear at the output as a change of the brightness. The amplifiers are the devices that cause most of the change in gain of the system, and this is due to their sensitivity to their supply voltage and their ambient temperature. The supply voltage is stabilized by using regulators near the amplifiers and by using other standard electrical noise reduction techniques such as using twisted pair supply and return lines. The amplifiers were thermally stabilized by cycling the operating temperature between the maximum and minimum specified operating temperatures 10 times and then soaking at 45°C for 24 hours, all while powered. The resulting change in the gain vs. operating temperature curve is shown in Figure 7.

Figure 6. RF chain output power versus input brightness temperature for the V-pol receiver. These measurements were used to determine the receiver noise and the noise diode contribution as well as confirming the receiver linearity.

C. Digitizer

The choice of Analog to Digital Converter (ADC) is important. Few ADCs are commercially available which can directly digitize signals at 1.4GHz. The Atmel 8388 family of ADCs is chosen for the system, as it has a number of over other ADCs available. While several ADCs have an input bandwidth covering the radiometer operational frequency of 1.4GHz, no ADC is commercially available that is capable of digitizing at the full Nyquist rate (2.8GSa/s). Fortunately, the Nyquist criterion is strictly applicable only to the bandwidth of the signal to be digitized. As such, the digitizer performs the downconversion operation instead of a mixer and LO. The system has two digitizers (ADCs) for H-pol and V-pol signal digitization. The two digitizers are identical and the sampling rate is 102.8MSa/s. The input bandwidth is 1.8GHz while the RF power level is -20 dBm. Figure 8 shows the ADC (right) and the current source (left) circuits for one polarization. The current source is used to monitor the ADC temperature through the measurement of a voltage drop across a diode in the ADC die which is converted into temperature readings by the microcontroller.

Figure 7. Gain variations with operating temperature before and after thermal stabilization of one amplifier

Figure 8. Analog-to-digital converter (right) and current source (left). 8-bit low voltage differential signal (LVDS) outputs are attached on the right side of the ADC. ADC is surrounded by insulation and is a part of the thermally controlled environment to minimize its gain fluctuations.
Digital back end consists of the correlator and the microcontroller. The correlator generates a clock signal of 102.8MHz for the ADCs and the FPGA. The FPGA is a critical portion of the correlator where several complex mathematical operations such as gray-to-binary conversion, 8-bit to-3-bit mapping, filtering, in-phase and quadrature demodulation, decimation, autocorrelation, crosscorrelation and histogram generation are performed on the digitized signals from H-pol and V-pol receivers. The microcontroller is the ‘brain’ of the radiometer whose responsibilities include temperature monitoring and control, analog to digital conversion control, data logging and storage, serial communication and management of the noise diode and RF switches. Xilinx VirtexE and Z-world LP3500 families are chosen for the FPGA and the microcontroller, respectively. A correlator-centric view of the radiometer system is given in Figure 9.

The FPGA is programmed in VHDL using Xilinx Foundation development software. The firmware design is for basic operation of the radiometer with polarimetric capability, which is reconfigurable even after the radiometer is complete. All eight bits of the digitized signal from both ADCs are piped into the FPGA, where the first operation is a Gray code to binary conversion since the ADC outputs the data in Gray code to minimize the number of bit transistions. Then, a mapping from 8 bits to 3 bits is performed using a look-up table. The next stage is a Finite Impulse Response (FIR) digital filter that supplements the filters in the RF gain chain. A major advantage of the onboard filtering is the fact that it is digital, and therefore can be used to define the noise bandwidth with significantly reduced sensitivity to the temperature of the RF electronics. The filter uses an architecture that is very compact. The I/Q demodulation involves demultiplexing the data stream into an I and Q channel and a delay on I channel to keep the data aligned between the I and Q channels. At this point, the data may be decimated by a factor of two without loss of information. The final stage of the data processing stream is the correlator. In the correlator, each of the four channels is summed in an accumulator, to find any DC bias in the digitized data. The data in each of the four channels is also squared (via a look-up table) and summed in an accumulator for autocorrelation. This data is proportional to the product of the integration time and the system temperature on each channel. Measurements proportional solely to the system temperatures are accomplished by dividing the accumulated values by the number of clock cycles used. This division is performed in the microcontroller. Finally, the correlator also calculates the cross correlations (products) between channels and accumulates the results. The cross correlations between I and Q of a single polarization are not collected, since they are expected to be zero from theory. The firmware description is shown in Figure 10.

The remaining portions of the correlator deal with communication with the outside world. From the point of view of the microcontroller, the operations needed are the ability to read and write registers in the FPGA. Examples of registers for reading are the accumulators in the correlator, and registers in the totalizer, which calculate histograms of the data at different stages in the processing scheme. All of these registers can be written to for the purpose of initializing. Other registers include the clock delays for the ADCs to synchronize the data between them and the FPGA.

Figure 10. Firmware. In addition to the two data processing streams described in the text, two histogram generators are on top, a state machine on the right and a serial interface on the bottom left.

The microcontroller performs several tasks in order for the radiometer to operate properly. The tasks fall into four main categories: Serial communication, temperature control, data logging and FPGA control. The overall efficiency of the system can be improved if the microcontroller can perform these tasks in a parallel manner. Although in reality a microprocessor can only execute one task at a time, it can appear to execute several of them in parallel by utilizing the inherent delays within each task. That is the processor can
carry out the work for one task while others wait for an event. The microprocessor cycles through the tasks completing parts of each task. In this way the tasks can execute almost in parallel. The microcontroller manufacturer provides a software development environment to enable this operation.

The microcontroller communicates serially with the FPGA, the two thermoelectric cooler controllers and the user’s PC. This last link uses RadiCL, which is is an ASCII based communication protocol developed for microwave radiometry. The devices that utilize the RS-232 standard are the FPGA and the two thermoelectric cooler controllers. RS-485 is for the communication with the PC.

IV. THERMAL CONTROL

The temperature inside the radiometer needs to be carefully monitored and controlled at all times during operation. The thermal control of the RF electronics is critical since a temperature instability may result in gain fluctuations within the analog parts. Two ThermoElectric Coolers (TECs), which operate at 24VDC and 6A maximum, are used for fine thermal control of the H-pol and V-pol RF sections. The TEC is bidirectional. That is, while a positive voltage applied to the TEC terminals results in heat flow from the TEC cold plate to exhaust side (physically located in the lower chamber), a negative voltage applied to the TEC terminals moves heat from the lower chamber to the cold plate. The efficiencies of these two modes are asymmetric, however. Resistive heating within the TEC is the same regardless of the sign of the current flowing through the TEC. As a result, using the TEC as a heater (negative voltage applied) requires about 50% of the effort as it does for cooling. For illustration, while the TEC is capable of 24VDC @ 6A = 144W of power consumption (either full power heating or full power cooling), only about 96W is available for heat pumping. The other 48W is dissipated as heat in both heating and cooling modes. Thus, a given number of watts of heating require less effort than the same number of watts of cooling. This is a fundamental limitation of TEC materials. The physical arrangement of the thermal control within the receiver box (side view) is shown in Figure 11. The external fan keeps the lower chamber sufficiently cool to keep the TEC operating near the crossover between heating and cooling, where the thermal control is most precise because the TEC resistive heating is minimized.

The TEC is controlled by a commercially available thermal controller manufactured by Oven Industries, Inc. and marketed as the “McShane” thermal controller. The McShane controller can handle up to 24VDC and 10A, and provides bidirectional control of a TEC via a MOSFET H-bridge circuit. It requires its own thermistor for control feedback. The McShane thermal resolution is 0.01C, and can achieve nearly this level of control if the control algorithm is properly tuned. There are two McShanes in the system, located in the lower chamber and isolated from the RF loads by the interior plate, because they switch large currents as a means of controlling the TEC.

There are a total of eight locations within the radiometer where temperature data is collected. These locations include the antenna, case, H-pol and V-pol reference loads, H-pol and V-pol RF plates and H-pol and V-pol ADCs. Two McShane thermistors are used to control H-pol and V-pol RF plate temperatures while two other thermistors are used for temperature monitoring. Hence, a total of ten temperature measurements are performed continuously. All locations, except for the ADCs, have been populated by precision YSI 44032 thermistors. The voltage across each thermistor, except those connected to the McShanes is fed into the ADC inputs on the microcontroller where it is sampled several times, averaged and converted to a temperature in degrees Kelvin. The ADCs, on the other hand, have a built in temperature diode whose junction voltage varies in direct proportion to the temperature inside the ADC chip. This voltage is also fed to the ADC on the microcontroller and converted to temperature in degrees Kelvin. The temperatures measured by the McShane thermistors are retrieved via the RS-232 serial links.

V. CONCLUSION

The ISU direct sampling L-band digital radiometer is introduced. Components of the system such as the Potter antenna, RF stage, analog to digital converter, digital back end are described. Furthermore, the thermal control, which is especially important for the RF section, is highlighted. The radiometer is capable of performing autocorrelation and crosscorrelation operations, which enables the polarimetric applications.

REFERENCES

