Remotely operated infrared radiometer for the measurement of atmospheric water vapor

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ABSTRACT

Astronomical arrays operating at (sub)millimeter wavelengths are seriously compromised by rapid variations in atmospheric water vapor that distort the phase coherence of incoming celestial signals. The signal received by each antenna of the array suffers a phase delay that varies rapidly with time and from antenna to antenna. Unless corrected, these distortions limit the coherence time of the array and seriously compromise its sensitivity and image quality. Building on the success of a prototype infrared radiometer for millimeter astronomy (IRMA), which operates in the 20μm region to measure the column abundance of atmospheric water vapor, this paper describes the latest version of the IRMA concept, which has been developed for operation at Llano de Chajnantor, future site of the Atacama Large Millimeter Array (ALMA). Since there is presently limited infrastructure at the Chilean site the design must pay careful attention to all aspects of remote operation.

Keywords: Infrared, radiometer, water vapor, ALMA, phase correction

1. INTRODUCTION

The development of large baseline, (sub)millimeter wavelength interferometers such as the Atacama Large Millimeter Array (ALMA) to be located high (~5000m) in the Chilean Andes will provide imaging capabilities in the 10 milli-arcsecond range when operating at their highest frequencies. The principle of interferometry requires that the time delays between reception of the electromagnetic wavefront at different antennae composing the array be measured accurately. Any local, line-of-sight variation in the optical path due to atmospheric inhomogeneities will distort the wavefront and, if left uncorrected, lead to a misinterpretation of astronomical source structure. The factor which now limits the attainable spatial resolution of large (sub)millimeter arrays is the variation in the line-of-sight water vapor abundance which causes variations in the electromagnetic path length, and hence interferometric phase.

The principal method used to determine the line-of-sight abundance of atmospheric water vapor is the multi-channel radiometric observation of the 183 GHz water vapor emission line[1]. In this method antenna brightness temperature measurements at three frequencies close to the water vapor line transition at 183.31 GHz are fitted to a simple atmospheric emission model, whose inputs are ground level meteorological information, to derive the column abundance of water vapor, expressed in millimeters of precipitable water vapor (pwv). The principal disadvantages of this approach are the relatively low signal levels (due to the small spectral bandwidths of each radiometric channel (~1 GHz) and the inherently low radiant emission of the atmosphere in this spectral region) and the risk of radio frequency interference from the 183 GHz local oscillator located within the receiver cabin of the antenna.

2. IRMA CONCEPT

Measurements of the atmospheric transmission above Mauna Kea in the 20 μm atmospheric window, using a high resolution infrared Fourier transform spectrometer, have shown that over a large part of this region the atmospheric absorption, and hence emission, is dominated by pure rotational transitions of water vapor[2]. Detailed modeling shows that it is possible to select a continuous region containing several hundred water vapor lines, the vast majority of which are unsaturated for column abundances of ≤1 mm pwv above Mauna Kea, Hawaii. At lower altitude sites the lines in this spectral region become broader and saturated and thus the technique becomes less sensitive or unusable.

An infrared approach to water vapor measurement is attractive for several reasons: Firstly, since the wavelength of 20 μm lies near to the peak of the Planck curve for typical atmospheric temperatures, the spectral radiance from

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atmospheric water vapor at infrared wavelengths is ~3 orders of magnitude greater than at radio frequencies. Secondly, the infrared radiometer uses a spectral bandwidth ~3 orders of magnitude greater than the radio frequency technique. The resulting increase in flux can be traded in terms of more sensitive measurements, faster operation, smaller instrument size, or some combination thereof. Thirdly, infrared photoconductive detectors offer high operating speeds, stability, and simple electronics. Finally, being a passive device, an infrared radiometer can be placed in close proximity to sensitive radio frequency instrumentation without risk of interference.

A prototype infrared radiometer for the measurement of atmospheric water vapor (IRMA I) was developed and tested at the James Clerk Maxwell Telescope (JCMT) in December 1999. The results of these tests[3,4] showed that the infrared technique holds much promise for the challenging requirements of phase correction of the next generation of (sub)millimeter interferometers. Key elements of the prototype radiometer were subsequently improved and the unit modified to allow for remote operation. Analysis of data obtained with IRMA II operating at the JCMT between January and July 2001 shows strong correlations with other measures of water vapor available on the summit of Mauna Kea[5] (e.g. Mauna Kea Weather Center; http://hokukea.soest.hawaii.edu/current) including: the JCMT SCUBA bolometer camera[6], the California Institute of Technology (CSO) opacity monitors[7], the JCMT 183 GHz water vapor radiometer[8] and Hilo-launched radiosonde data (http://hokukea.soest.hawaii.edu/current/raob/ito/text). Our goal now is to evaluate the performance of IRMA at Chajnantor, the future site of ALMA. Since there is presently limited infrastructure at the Chilean site, the design must pay careful attention to all aspects of remote operation.

3. IRMA III DESIGN

The radiometer is conceptually simple, consisting of a primary mirror, optical chopper, filter, detector, calibration source, electronics, embedded microcontrollers and associated software. There are three principal problems associated with remote operation at the ALMA site: there is no surplus electrical power so we must provide our own power through a solar panel array and storage battery system; there are no cryogens and so the detector, which operates at 77 K, is cooled using a Stirling cooler; finally, the site presents an exposed and hostile environment.

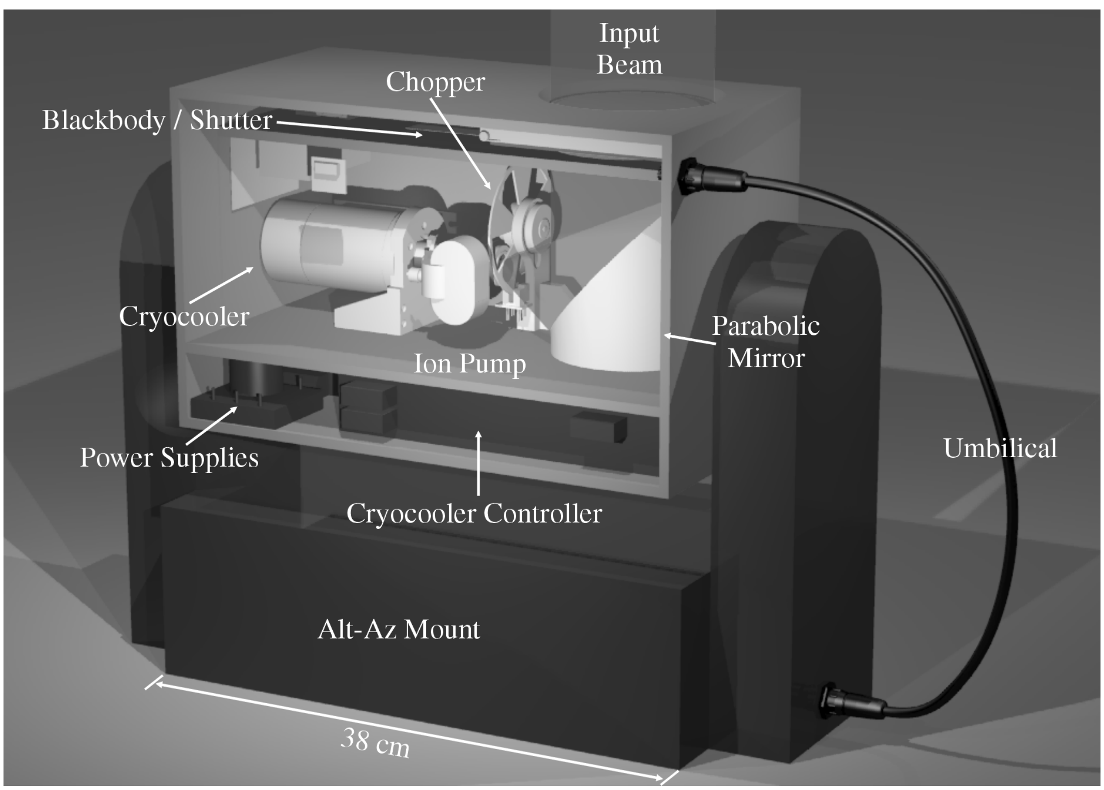

Figure 1. Cut away view of IRMA III in its alt-az mount.

3.1 Mechanical

Figure 1 shows a model of IRMA III mounted between the forks of the alt-az assembly, which allows access to any part of the sky and provides for sky dips; two such units will provide a direct means of monitoring the height of the turbulent layer of atmospheric water vapor by correlating their outputs as a function of zenith angle. The mount is driven by two, low-noise, 50W, brushless DC planetary gearhead motors (Maxon EC167129; http://www.maxonmotor.com), one for each axis, via a timing belt giving a 1024:1 reduction ratio. Optical encoders (US Digital E6M 2048 lines per revolution; 8192 counts per revolution in quadrature; http://www.usdigital.com) provide angular feedback, which, through a PID loop, allows positional accuracy of ~0.1 degrees. The alt-az microcontroller mounted in the alt-az unit performs all pointing tasks and communicates positional information to the IRMA III microcontroller.

IRMA III is a robust, self-contained, sealed mechanical design able to withstand the harsh environmental conditions at the test site. The unit features: all stainless steel and aluminum construction, nitrogen filled sealed optics chamber, sealed electronics and a low-noise brushless DC motor chopper drive. A calibration source can be positioned in front of the primary mirror and entrance window, and acts as a shutter for moisture/dust resistance under inclement weather. This shutter also closes automatically when pointing within 5 degrees of the sun to prevent damage to the detector. Lack of liquid cryogens at the site requires the use of a closed-cycle cooler. A Stirling cycle cooler (Hymatic NAX025-001; http://www.hymatic.co.uk), interfaced to the IRMA III microcontroller, provides 250 mW cooling power at 77K, sufficient to cool both the detector and filter. A stainless steel vacuum vessel with metal compression seals provides UHV outgassing rates necessary to maintain the vacuum at $\leq 10^{-4}$ Torr, which is required for cooler operation, while allowing disassembly if required for detector or filter replacement. A 1mm thick ZnSe entrance window epoxied to this vessel provides an adequate vacuum seal. We are exploring the use of an ion pump and/or getter to extend the lifetime between pump downs.

3.2 Optical

The design goal is to measure the column abundance of water vapor above the ALMA site to an accuracy of ~1 µm pwv, for a column abundance of 0.5–1 mm pwv, in an integration time of ~1 s. Atmospheric model calculations show that the integrated spectral radiance over a wavelength range $\Delta\lambda/\lambda \sim 0.1$, centered at $\lambda \sim 20$ µm, due to 1 mm pwv is ~1 $Wm^{-2}sr^{-1}$. A primary, off-axis parabolic mirror of diameter 100 mm was chosen as a reasonable compromise between collecting area, cost and compact design. While the beam from the radiometer is much smaller than that from the (sub)millimeter telescope, the field of view of the radiometer was designed such that it samples a patch of atmosphere of approximately the same diameter as the radio antenna at a range corresponding to the typical scale height of water vapor (i.e. ~10 m diameter patch at a range of ~1 km).

The optical components of the radiometer are shown in Figure 2. Light enters the radiometer through a 13µm thick polypropylene window, which acts as dust/moisture protector yet has negligible absorption at 20µm. The 100mm, f/1, 90° off-axis parabolic mirror brings the beam to a focus, behind a 1mm thick ZnSe optical window, on a 1mm^2 Mercury-Cadmium-Telluride (MCT) photoconductive detector (Kolmar Technologies; http://www.kolmartech.com) designed to have a long wavelength cutoff at ~22 µm and for operation at 77 K. Band defining infrared filters are difficult to fabricate at these wavelengths because of the high refractive index and hygroscopic properties of most substrates. Furthermore, interference coatings can separate following repeated thermal cycling. The filter used is a resonant grid long pass filter with a band edge at ~18 µm, which is also cooled to 77 K and located immediately behind a field-defining aperture. This technology is well established at submillimeter and far-infrared wavelengths but has only recently been extended to shorter wavelengths[9]. The combination of the band edges of the detector and filter provides for a well-defined and efficient bandpass.

The radiometer signal is modulated at a frequency ~200 Hz by a 5-blade reflective chopper wheel made from 1.5mm thick mirrored stainless steel. A notch on the circumference of this blade provides synchronous sampling of the demodulated output and removes uncertainties associated with differences in the blade-to-blade emittance/reflectance. The overall system responsivity is calibrated with a blackbody source that can be moved in front of the entrance window. This source consists of a thin film electrical heating element, which is coated with a thermally conductive epoxy doped with carbon black (2% by weight) and insulated from the ambient support structure. The temperature of this element is monitored with calibrated diode sensors to a precision of 0.1 K. The frame of the calibration source also acts as a shutter protecting IRMA III from viewing the sun and when not in use.

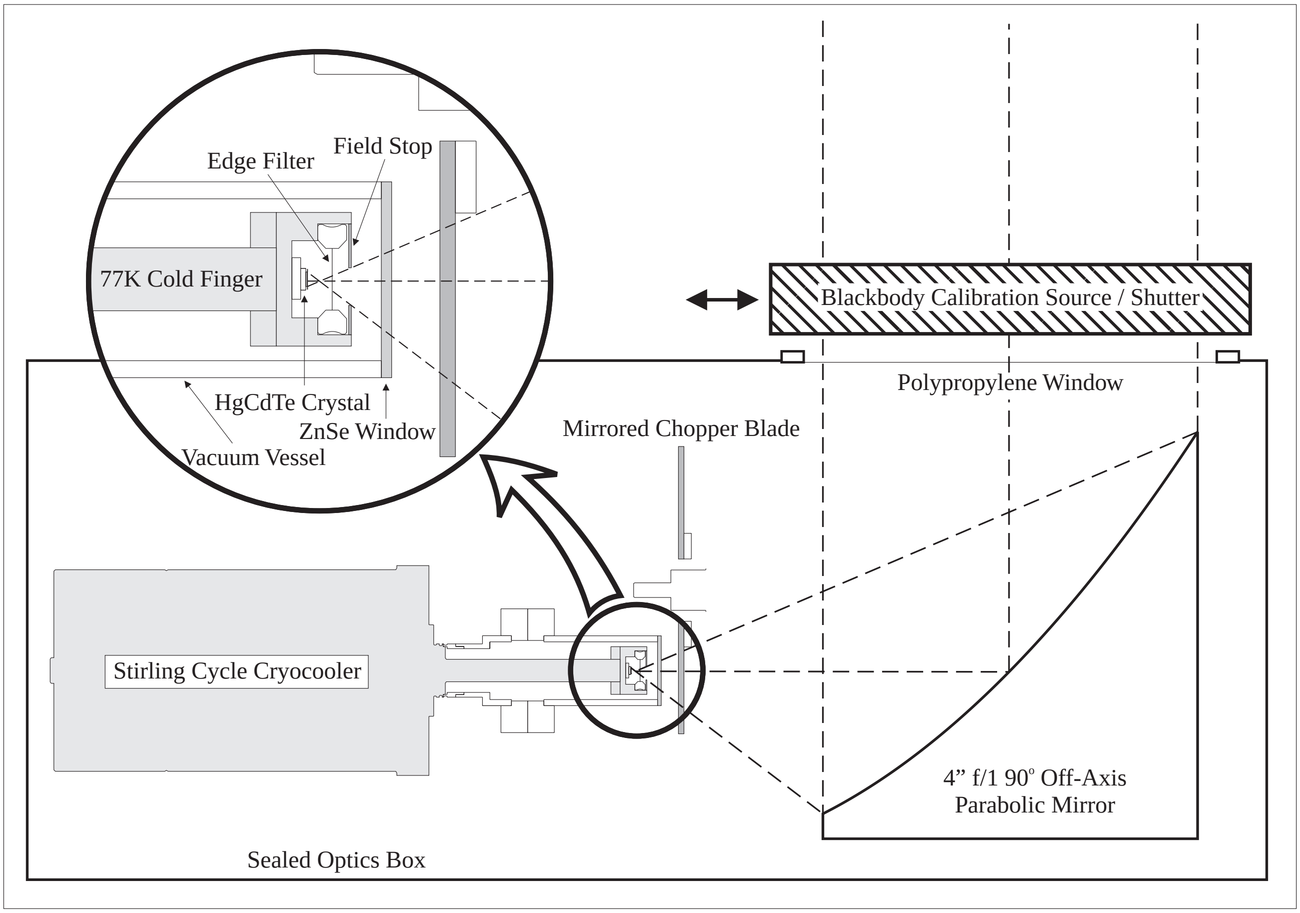

Figure 2. Optical schematic of IRMA III.

3.3 Electronics

The primary concern for the electronics is to minimize the power drain. This requires an efficient Stirling cooler, low power motors and electronics. Table 1 gives the average and peak power load of various electrical components. Where possible standby modes of operation are exploited. A modest size custom solar voltaic system with ~1.5 kWh/day generation and ~3.8kWhr storage capacity is sufficient to supply the average operating power of 46W. The system consists of 3 BP585U (BP Solar; http://www.bpsolar.com) high efficiency solar panels, a charge controller, and a high efficiency, low noise, 120VAC inverter. Power drain and reserve capacity are monitored by an ethernet-linked microcontroller.

System	Average power (W)	Peak power (W)
Net hub/transceiver	7	7
120 V inverter	7	7
Blackbody	1	10
Stirling cooler	16	20
Electronics	5	10
Motors	10	100
TOTAL	46	154

Table 1. System power requirements

The electronics, shown schematically in figure 3, is a modular system comprised of three functional units, IRMA III, the alt-az mount, and the solar power monitor, each controlled by 8-bit microcontrollers, and a networked data archive PC. The IRMA III microcontroller receives and executes observation instructions, acquires and archives data, sends pointing commands to the alt-az microcontroller and monitors the solar power system.

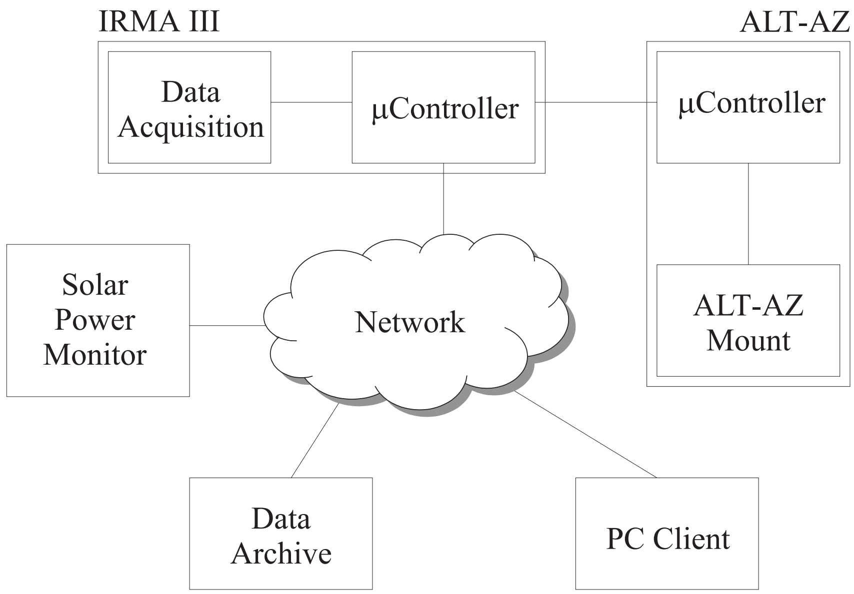

Figure 3. Electronics overview

3.3.1 IRMA III

The IRMA III electronics is shown schematically in figure 4. The IRMA III microcontroller is a RCM 2100 module (Rabbit Semiconductor; http://www.rabbitsemiconductor.com) featuring a 22.1 MHz 8-bit microprocessor, ethernet controller, 1MB total memory, and 40 digital I/O lines of which 8 lines serve as 4 serial communication channels. This embedded microcontroller was chosen for its compact size, low power requirements and its support for a compact real-time multitasking kernel. A GPS unit (GlobalSat Tech Corp. http://www.globalsat.com.tw) provides date/time stamps, latitude, longitude and altitude data. A serial driven LCD/keypad unit allows the user to view status/diagnostic messages and input simple commands. A low-noise preamplifier circuit, featuring a temperature-compensated constant bias current, selectable 60 and 120 Hz notch filters and a 10KHz low pass 8 pole Bessel filter, provides a rail-to-rail gain of 1000 with a noise of 0.5nV/√Hz at 1kHz. This amplified, chopper-modulated detector signal is synchronously detected with a lock-in amplifier employing chopper-stabilized amplifiers and the dc output fed to one of the four analog inputs of a 24-bit ΔΣ analog-to-digital converter (ADC) (CS5534, Cirrus Logic Inc.; http://www.cirrus.com). The other inputs of the ΔΣ ADC monitor meteorological and housekeeping parameters (e.g., pressure, temperature(s), humidity).

The ΔΣ ADC is driven by the RCM 2100 via a 4-wire digital I/O interface. A notch on the reflecting chopper provides a trigger pulse, which generates an external interrupt to the IRMA III microcontroller, which, in turn, initiates a conversion sequence. At the end of conversion the ΔΣ electronics uses the same external interrupt line to notify the IRMA III microcontroller that data are ready. The resolution of the ΔΣ ADC depends on the sampling speed; in practice the sampling rate is set at 10Hz and provides 22-bit resolution. A single 5V supply powers the digital logic; low-noise linear sub-regulators provide power for the analog circuitry. Other tasks assigned to the IRMA III microcontroller include communicating with the cryocooler controller, positioning and temperature control of the blackbody calibration source/shutter, monitoring the status of the solar power generator, sending and receiving pointing information to and from the alt-az mount microcontroller, and handling all network traffic.

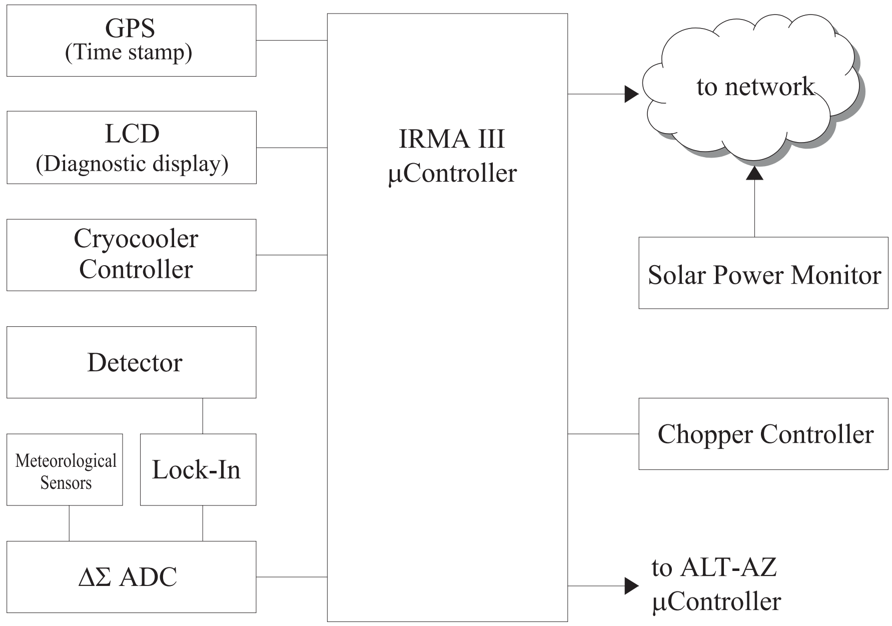

Figure 4. IRMA III electronics overview.

3.3.2 Alt-az mount

The alt-az mount electronics is shown schematically in figure 5. The alt-az mount microcontroller is a RCM 2010 module (Rabbit Semiconductor; http://www.rabbitsemiconductor.com) featuring a 25.8 MHz 8-bit microprocessor, with 256K flash, 128K ram and 40 digital I/O lines again with 8 lines serving as 4 serial communication channels. The main task of the alt-az microcontroller is to point the alt-az mount and return its current position to the IRMA III microcontroller. The 2048 lines per revolution rotary encoders mounted on each axis are interfaced to a 24-bit dual axis quadrature counter (US Digital LS7266; http://www.usdigital.com) to provide positional information. The alt-az mount employs a motion control velocity profile and PID algorithm to control the motor speed with a dual-channel 8 bit serial DAC (Maxim MAX5223; http://www.maxim-ic.com) which drive two brushless motor controllers (Maxon 109982; http://www.maxonmotor.com), one for each axis.

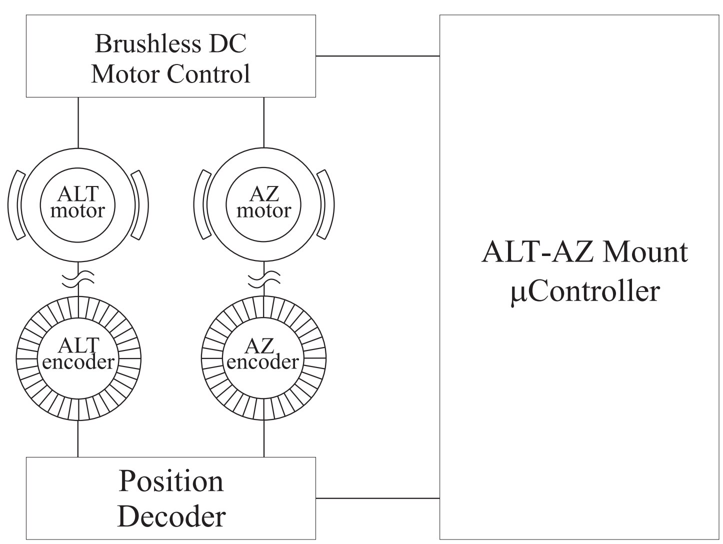

Figure 5. Alt-az mount electronics overview.

3.4 Software

The radiometer, including its alt-az mount must operate remotely and is designed to be network-centric: all communication to and from the system is done via an ethernet network. The system must be able to operate autonomously with commands in the form of *jobs* being stored in non-volatile memory, which can be executed repeatedly according to a prescribed schedule. Data collected by IRMA III are stored locally on a data archive server and downloaded when required. Since multiple tasks must be run concurrently on both the IRMA III and alt-az microcontrollers, a real-time, pre-emptive, multitasking kernel is used (µC/OS-II; Micriµm, Inc. http://www.ucos-ii.com).

3.4.1 IRMA III software modules

The IRMA III microcontroller software, which governs the operation of the IRMA III event loop, is shown schematically in figure 6 and consists of several modules briefly described below:

Network Communication (Netcom):

- receives instructions over the network
- parses instructions into an observation *job*
- passes the job to the Scheduler module

Scheduler

- takes jobs from the Netcom module and inserts them into a schedule table
- periodically (usually once per minute) checks to see if any jobs are pending
- if a job needs to be executed (and no current job is running), pass the job to the Executor module
- receives instructions from the Netcom module to delete jobs from the schedule table

Executor

- receives jobs from the Scheduler module and executes the sequence of instructions embedded in t he job
- sends and receives pointing information to and from the alt-az mount microcontroller
- controls all hardware devices including: the chopper drive, the cryocooler, the ΔΣ converter and the GPS. These devices are connected to the IRMA III microcontroller via serial and digital I/O line interfaces
- establishes a network connection with the local data archive server, and periodically sends buffered data to it

Solar Power Monitor

- establishes a network connection with the power management microcontroller of the solar panel array, and periodically queries it for the current condition of the power system

Real time clock

- periodically (usually once per hour) retrieve the local time from the GPS receiver to synchronize the time stamping of archived data

LCD Panel

- update and display the current system status
- accept user input via the LCD panel's keypad during diagnostic trouble shooting

Interrupt Service Routine (can interrupt any of the above tasks)

- when interrupted, and the source is the chopper notch, initiate a ΔΣ ADC conversion (BOC)
- when interrupted and the source is the ΔΣ ADC end-of-conversion (EOC), retrieve the 24-bit data sample, place it into a buffer, then perform a low-resolution ΔΣ ADC conversion of one of the meteorological or housekeeping sensors

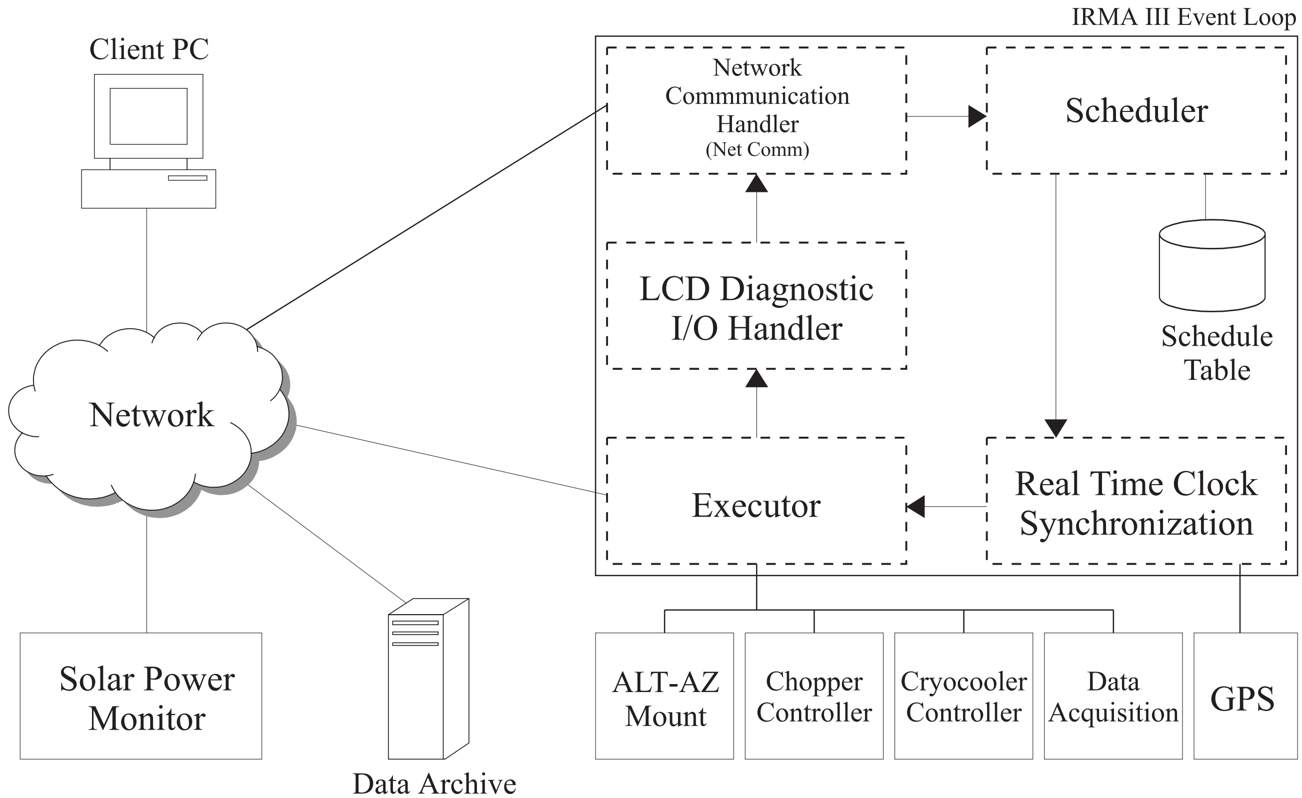

Figure 6. Overview of the IRMA III microcontroller software

Since the interrupt service routine (ISR) is a critical component of the software it is described here in more detail with reference to the flow chart of figure 7. The analog-to-digital data conversion cycle in IRMA III consists of a high-resolution (22-bits) sample of the demodulated infrared detector signal, followed by a low-resolution sample (usually 13-bits) of one of the meteorological or housekeeping sensors. The interrupt driven sampling cycle takes ~72 ms, of which ~70 ms is consumed during the high-resolution signal conversion; this allows IRMA III to sample the infrared signal at ~10Hz. Due to this high overhead, the ISR is divided into two parts: beginning of conversion (BOC), which is triggered by the notch on the reflecting chopper, and end of conversion (EOC), which is triggered by the ΔΣ signaling that th e requested conversion is complete. A BOC interrupt sends an instruction to the ΔΣ ADC to commence the high-resolution sample of the detector signal; this is followed by a request to retrieve the current time and current alt/az positions. Later, after receipt of an EOC, the ΔΣ electronics signals the IRMA III microcontroller to retrieve the digitized data. The IRMA III microcontroller then performs a high speed (~2ms), low-resolution (13-bits) conversion of one of the meteorological or housekeeping sensors, remaining in the ISR, since the ΔΣ ADC conversion time is significantly shorter.

A typical sample job might include the following steps: switch on the cryocooler and wait until it has reached its target temperature; switch on the chopper drive circuitry; send a pointing command to the alt-az microcontroller to position the alt-az mount; verify that the correct position has been attained; open the blackbody shutter; enable the external interrupt; sample the detector signal for a given period of time; close the blackbody shutter; switch the blackbody heater on; take calibration measurements; switch off the heater, chopper drive and cryocooler, and park the alt-az mount.

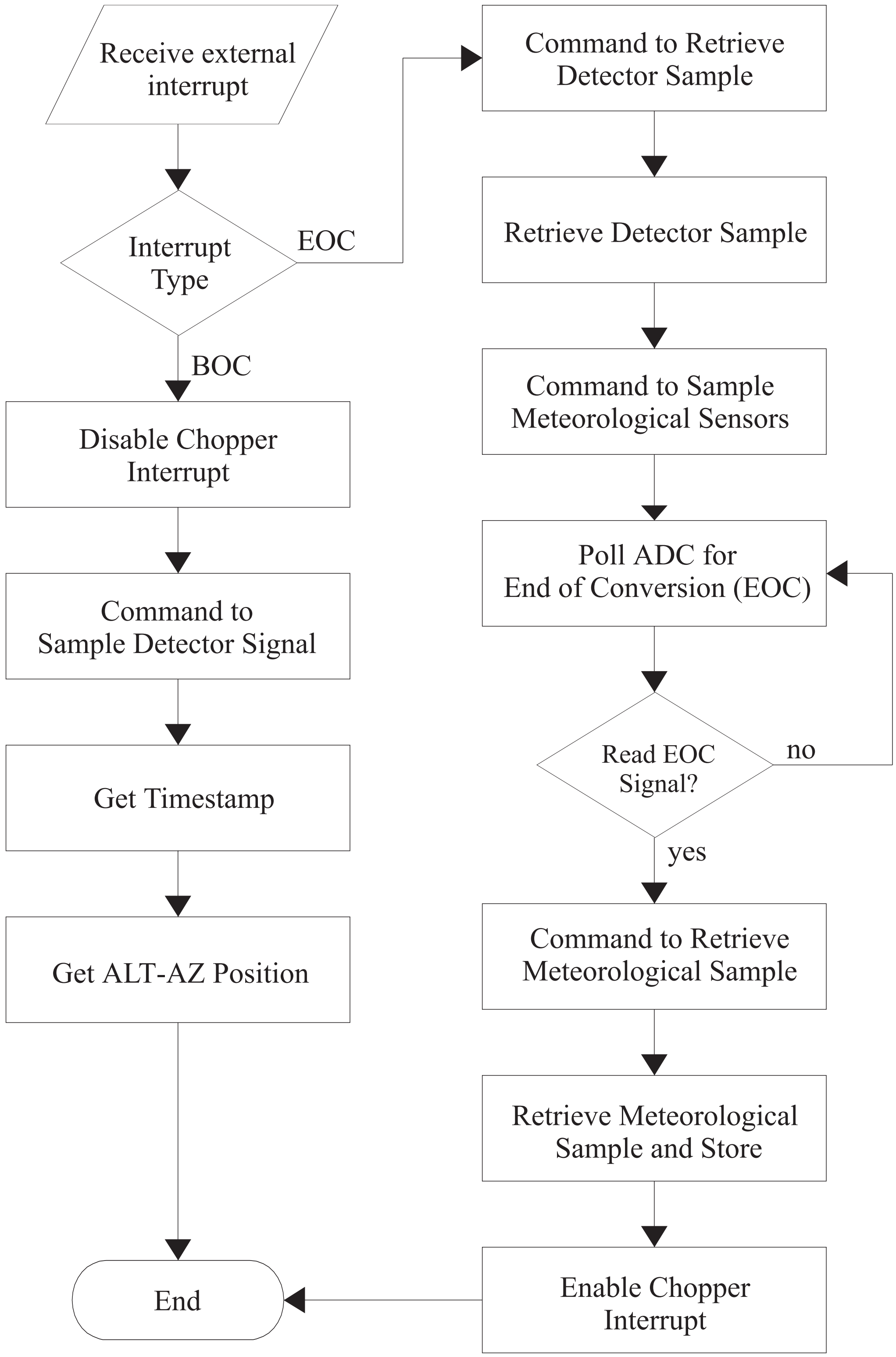

Figure 7. Flow chart of IRMA III externally triggered interrupt service routine.

3.4.2 Alt-az mount software modules

The alt-az microcontroller software, which governs the operation of the alt-az mount event loop, is shown schematically in figure 7 and consists of the following modules:

IRMA III - Alt-az mount Communication Handler

- receives commands from the IRMA III microcontroller
- if the request is to get the current alt-az positions, read and return the current values
- if the request is to repoint the alt-az mount, put request into a *job* and dispatch the job
- convert right ascension/declination coordinates into alt/az coordinates for celestial observations

Alt-az Position Hander

- periodically read the current alt/az coordinates and place the values into a globally accessible variable

Current Job Handler

- take the job passed by IRMA III - alt-az Communication Handler and execute it

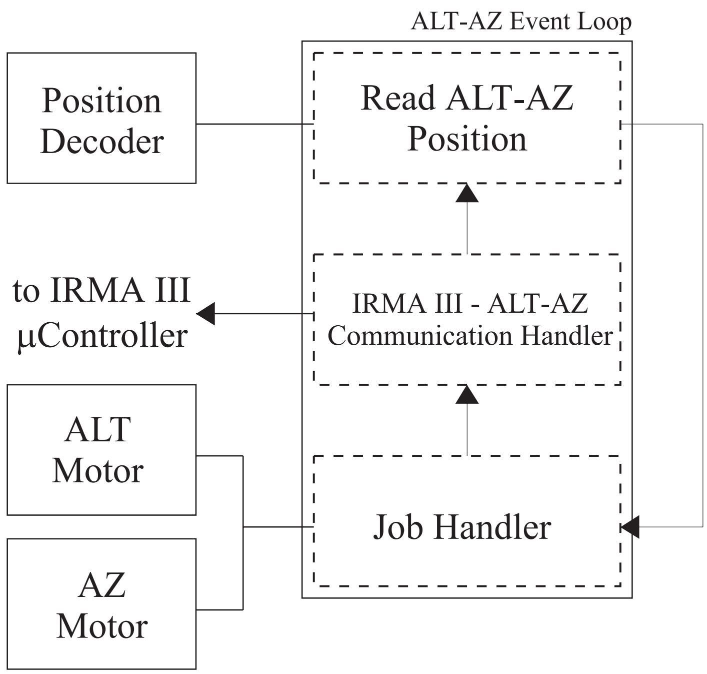

Figure 8. Overview of the alt-az mount microcontroller software.

4. SUMMARY

Building on the success of a prototype infrared radiometer (IRMA) for the measurement of atmospheric water vapor from high altitude mountain sites, this paper describes the the latest version of the IRMA concept, which has been developed for operation at Llano de Chajnantor, Chile, future site of the Atacama Large Millimeter Array (ALMA). Since there is presently limited infrastructure at the Chilean site, the design must pay careful attention to all aspects of remote operation. Key features include: a Stirling cycle cooler, resonant grid infrared filter, photoconductive detector, calibration source, ΔΣ ADC data acquisition system, embedded microcontrollers and associated software, and an alt -az mount to allow IRMA III to point in any direction. Electrical power is provided by a modest size custom solar voltaic system. We are planning to deployed IRMA III in Chile in the fall of 2002.

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