Final Report for the design study of HEAT:
A High Elevation Antarctic (Terahertz) Telescope
ANT-0538665

1 Executive Summary

1.1 Instrument Description

The High Elevation Antarctic Telescope (HEAT) is an automated, 0.5-meter Terahertz (THz) observatory proposed for remote operation at the summit of Dome A, the highest point on the Antarctic plateau. The unparalleled stability, exceptional dryness, low wind and extreme cold make Dome A a ground-based site without equal for astronomy at infrared and submillimeter wavelengths. Optimized for operation at Dome A, HEAT will forge entirely new capabilities for ground based infrared and submillimeter astronomy. Indeed, Dome A is likely the only site on Earth where the crucial 1.9 THz window becomes accessible for any length of time. HEAT will routinely access one of the least explored regions of the electromagnetic spectrum and provide new, fundamental knowledge about the distribution and state of matter in the Galaxy. Through large-scale Galactic surveys, the measurement and impact of the Galactic environment on the life cycles of interstellar clouds and their relation to star formation will finally be realized.

HEAT and its accompanying Australian Plateau Observatory (PLATO) represent a new generation of polar instrumentation which permits the excellent conditions available from remote sites like Dome A to be harnessed without the costs and hazards associated with manned operations. The receiver system itself serves as a flexible testbed for heterodyne Terahertz components. Future upgrades of mixer, local oscillator, low-noise amplifier, cryogenic, and digital signal processing technologies are planned and will play essential roles in future Terahertz observatories. This pioneering mission will pave the way for future astronomical investigations from Dome A.

HEAT is an IPY Joint Committee approved, multi-national project, with contributions from the University of New South Wales (UNSW), the Space Research Organization of the Netherlands (SRON), the University of Cologne, as well as NASA and several US universities.

1.2 Scope and Summary of Design Study

To succeed, HEAT must be robust and capable of remote, low-power operation for a year at a time. In many ways HEAT is more like a space-based observatory than a ground-based one. The principal goal of this one-year study was to arrive at a detailed design, cost analysis, and working logistical plan for the entire project. Based on the results of this design study, the revised HEAT design has been proposed to NSF-OPP in June 2007 (ANT-0739777) and is currently under consideration.

The three major accomplishments of this design study are:

- **Achieved a dramatic reduction in risk and cost:** At the outset of the study, the proposed design included a 2-axis (tracking) motorized telescope with a state-of-the-art 4K cryocooler and arrays of Hot Electron Bolometer (HEB) mixers. The high level of risk, particularly for a newly-developed site with no human presence or infrastructure, led us to evaluate new approaches. The new baseline design features a non-tracking one-axis telescope, a low-power "off-the-shelf" 70K cryocooler that does not compromise the mission should it fail, and robust Schottky mixers that can operate satisfactorily at ambient temperature. These, among other alterations, improve the likelihood of success and reduce the mission costs from $4.8M to $2.2M! A full cost breakdown is provided in our June 2007 HEAT OPP proposal.
- **Defined a working Logistical Plan:** A 3-year Memorandum of Understanding has been signed between the University of New South Wales (UNSW) and the Polar Research Institute of China (PRIC) regarding the Australian PLATO site-testing observatory and its attendant instruments, including `HEAT`. At the time of writing a direct MoU is being drafted between PRIC and the University of Arizona. These negotiations have led to the Chinese program agreeing to deliver a UNSW PLATO module to Dome A in Austral summer 2007-8. With the heavy lifting to be performed this year by PRIC under the IPY PANDA program, only personnel transport via Twin Otter air support will be requested from USAP. With extensive operation in the East Antarctic plateau starting in 2008 for AGAP and other endeavors, our air support requests are comparatively modest. A full development plan will be undertaken once `HEAT` is a fully funded NSF project.
- **Defined, proposed and are delivering a prototype mission:** With an Australian PLATO observatory to be delivered to Dome A in Austral Summer 2007-8, the opportunity arose to develop a submillimeter instrument for it. Named `Pre-HEAT`, this 20 cm telescope will soon measure the quality of the 450 μm submillimeter sky above Dome A in advance of HEAT, and will also perform its very own Galactic Plane survey in the J=6-5 line of ^{13}CO at 0.66 THz. This submillimeter survey is the first of its kind and foreshadows the Terahertz surveys that `HEAT` will perform. Furthermore, every part of `Pre-HEAT` is a prototype for the full `HEAT` mission.

2 Description of Major Study Issues

2.1 The Dome A Environment

With operation of an Australian Automated Weather Station (AWS) at Dome A, it is now possible to estimate the submillimeter sky opacity based upon the ground-level temperature, dew point, and atmospheric pressure. A plot of the weather at Dome A is shown in Figure 1 and is restricted to the first half of 2005 for readability. These data demonstrate conclusively the following important points for implementing a submillimeter telescope at Dome A:

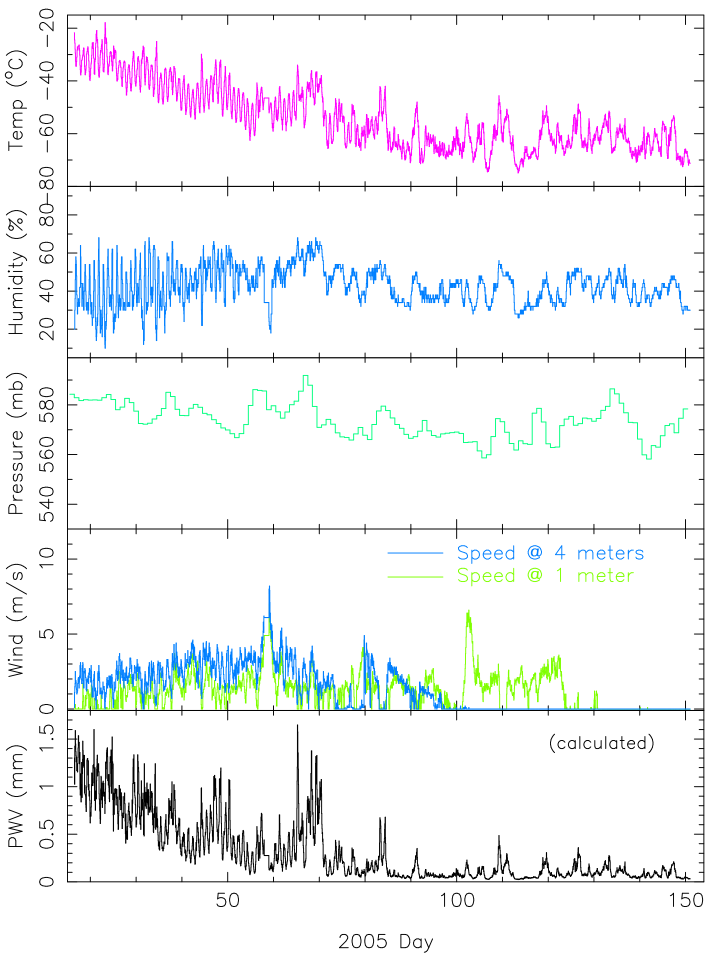

Figure 1: The joint Australian/Chinese deployment of an AWS to Dome A in 2005 demonstrates that Dome A is uniquely colder, drier, with lower atmospheric pressure, and calmer than any other known site on the Antarctic Plateau. These measurements allow estimates of the precipitable water vapor (bottom plot), and hence submillimeter sky opacity, to be made. From these estimates, it is clear that Dome A is the preeminent site on the planet for ground-based Terahertz-wave astronomy; by comparison, the ALMA site in Chile has a best quartile PWV of 0.4mm!

1. Dome A is colder than other continental sites like Dome C and the South Pole. Monthly temperatures in 2005 were consistently 5-7^{o}C colder than at South Pole, falling to -100^{o}F in early April!
2. Hygrometer measurements suggest that the airmass is unsaturated, with a winter RH of 40%, lower than Dome C and South Pole. This lends credence to the suggestion that the virgin "stratospheric" airmass extends essentially all the way to the ground.
3. Although the physical altitude of Dome A is comparable to Mauna Kea in Hawaii (4.1 km), the thinner atmosphere over the Poles reduces the atmospheric pressure significantly. A typical winter reading of 560 mbar is comparable to a pressure altitude of 15,600 ft, or 4.8 km, comparable to the Chilean sites in the high Atacama desert, but much colder.
4. The winds are very low. Although mechanical operation of the AWS anemometer is not reliable below -60^{o}C, the measured winds at Dome A average about 2 m/s; much lower than South Pole (6 m/s) and incrementally lower than Dome C (3 m/s).
5. The resulting calculation of the precipitable water vapor, critical to estimating the

submillimeter and Terahertz sky opacity, indicates that periods where the PWV drops below 0.1 mm are commonplace in winter. This makes Dome A the driest, calmest site for Terahertz astronomy on the planet.

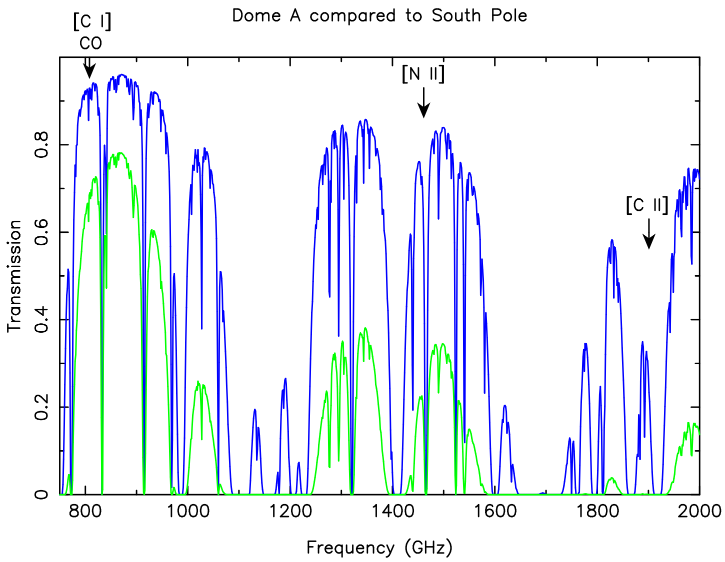

Figure 2: Terahertz atmospheric transmission for good (∼25th percentile) winter conditions for South Pole (bottom) and Dome A (top), derived from precipitable water vapor (PWV) measurements at Pole and actual Automatic Weather Station (AWS) data collected during 2005 from Dome A by our Chinese and Australian colleagues. Arrows indicate the wavelengths of the [N II], [C II], and CO/[C I] lines.

2.2 *Instrument Concept*

HEAT will be a fully automated, state-of-the-art THz observatory designed to operate autonomously from Dome A in Antarctica. The combination of high altitude (4,100 m), low precipitation, and extreme cold make the far-IR atmospheric transmission exceptionally good from this site. In Figure 2 we present a plot of the expected atmospheric transmission above Dome A as a function of wavelength, indicating that winter weather at Dome A approaches (to order of magnitude) the quality of that achieved by SOFIA. The wavelengths of several important astrophysical lines are indicated with arrows. HEAT is designed to take advantage of these unique atmospheric conditions and observe simultaneously in [C II](158 μm), [N II](205 μm), and CO J=7→6 & [C I] (370 μm).

A conceptual drawing of HEAT is shown in Figure 3. For robustness and efficiency, the telescope and instrument are integrated into a common optical support structure (OSS). HEAT will be mounted on top of a University of New South Wales Plateau Observatory (PLATO), a successor to the AASTINO (Automated Astrophysical Site-Testing InterNational Observatory) deployed to Dome C in 2003. PLATO provides power and communications for the HEAT telescope and instrument. The total power budget for HEAT (including cryogenics, telescope drive system, and instrument control system is maximally 600 W, which is readily provided by efficient, high reliability solar panels in the summer and diesel generators in the winter. Data transfer and control of HEAT will be done via satellite and is described in more detail in Section 2.4.7. UNSW will provide a PLATO module for HEAT and participate in the design, integration, deployment, and operation.

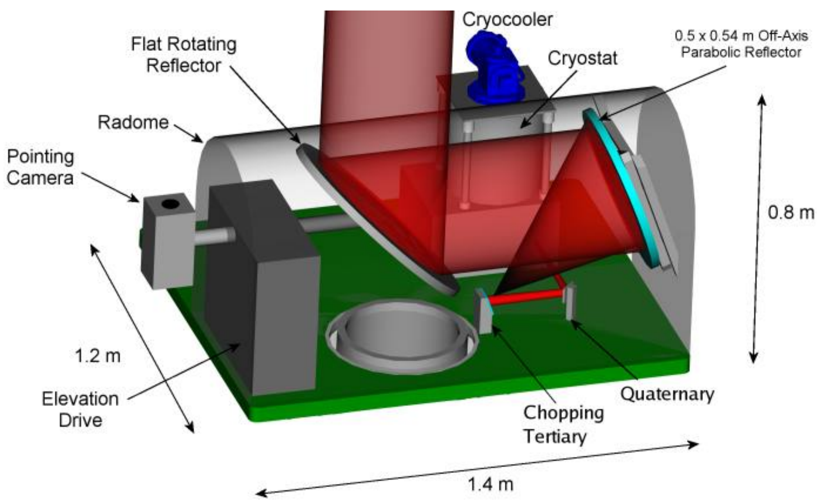

Figure 3: HEAT concept: The telescope has an effective collecting area of 0.5m. Elevation tracking is accomplished by rotating the $45°$ flat reflector. The entire telescope structure is warmed by waste heat conducted from the PLATO instrument module below. The Schottky mixers used in the instrument package are efficiently cooled to ∼70 K using a reliable off-the-shelf closed-cycle cryocooler.

2.3 Telescope

The telescope is designed to have maximum efficiency and the minimum number of optical components. Its design is similar to that of Kraus (1966) and utilizes an off-axis, Gregorian configuration. Incoming light is reflected horizontally off a 45°, 0.5×0.7 m flat reflector to an f/2.2 off-axis parabolic mirror. The converging beam is intercepted by a hyperbolic tertiary mirror that directs it to a flat quaternary and into the receiver. The tertiary mirror can chop the incoming beam between source and reference positions ($\Delta \mathrm{az} \sim 10'$) at a rate of 0 to 4 Hz. The mirrors are fabricated from aluminum on a numerical milling machine and have a surface roughness $\leq 3\,\mu$m rms. Elevation axis motion is achieved by rotating the first flat reflector. Mapping will be typically performed in drift-scanning ("on-the-fly") mode while tracking only in elevation. In fact, some of the Galactic Plane can be mapped purely with zero-motion sidereal-rate scanning! The absolute pointing accuracy will be 15″, 1/5 of the smallest diffraction-limited beam. The maximum slew speed will be 5°/sec. The University of Arizona has a long history of building state-of-the-art telescopes and, with oversight from members of the Instrument Team, has the expertise required to optimize the telescope for operation in a Polar environment.

To prevent ice accumulation, the telescope is enclosed and warmed to -20°C by conduction through the access port from the warmer PLATO module below. A small radome made of a low-loss dielectric (e.g. Goretex or polyethylene) encircles the first flat reflector. This optical configuration provides an unobstructed view of the sky. A near-IR camera (provided by UNSW) is mounted just outside the radome on an extension of the elevation axis. The camera will provide pointing and site testing data.

2.4 Receiver

2.4.1 Design Approach

Heterodyne receivers are needed to achieve the sensitive, high spectral resolution ($R = \lambda/\Delta\lambda > 10^6$) observations of [N II], [C II], and CO/[C I] required for the proposed Galactic plane survey. The key components of a submillimeter-wave heterodyne receiver are the mixer and local oscillator (LO). There are 3 types of mixers in common use; the Schottky diode mixer, the SIS mixer, and, more recently, the Hot Electron Bolometer (HEB) mixer. The Schottky diode mixer is somewhat less sensitive than either SIS or HEB mixers and requires more LO power, but is exceptionally stable in operation and **can operate at ambient temperature**. In contrast, SIS and HEB receivers require cooling to LHe temperatures (4K). HEAT's aggressive development schedule combined with the critical need for robust technologies that will work at low power and in a harsh environment leads us to select Schottky mixer systems for the initial deployment of HEAT. Virginia Diodes, Inc. has a long history of delivering submm-wave Schottky mixer systems and has demonstrated sub-harmonically pumped Schottky mixers using lower frequency LO sources. Virginia Diodes will deliver one such mixer at 1.9 THz and another at 1.46 THz. Two sub-harmonically pumped 810 GHz mixers (one for each polarization) will be provided to increase sensitivity and redundancy. Though the system will function well at ambient temperatures, we plan to improve HEAT's sensitivity to within a factor of $\sim$3 of demonstrated THz HEB systems by cooling the mixer blocks to $\sim$70K using economical, low power, commercial Stirling-cycle cryocoolers such as those sold by Qdrive and Sunpower, Inc. In this manner we will achieve a solid blend of good sensitivity and experimental robustness. A future 4K cryocooled SIS and HEB receiver system for HEAT is now in development at the Space Research Organization of the Netherlands (SRON), with an initial 600K Euros of institutional support.

2.4.2 Receiver Optics and Cryostat

A close-up of the receiver optics is shown in Figure 4. The incoming beam from the quartenary encounters two bandpass filters, the first centered on the [N II] (1.459 THz) line and the second on the [C II] (1.9 THz) line. The three emerging beams are collimated and directed into the instrument cryostat.

Sub-harmonic LO pumping of the Schottky mixers eliminates the quasi-optical injection of the LO signal and simplifies the optical layout of the cryostat. Wire grids direct the horizontal and vertical polarization components of the incoming light into the two 0.8 THz mixers.

The fabrication and integration of the vacuum vessel (10″ in diameter and 5″ tall) with the cryocooler will be performed by Universal Cryogenics of Tucson, Arizona, who has done similar work for the PI's Supercam instrument, as well as for other Steward Observatory projects.

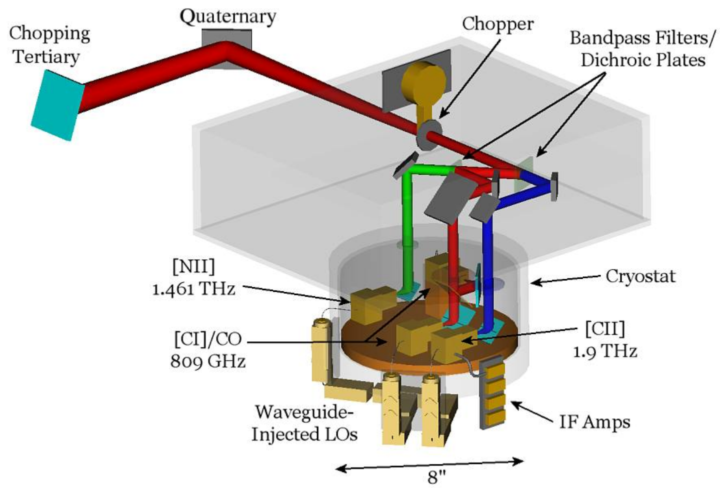

Figure 4: Optical subsystem for HEAT's Schottky mixers consists of bandpass filters and wire grids. Outside of their nominal passband, the filters are highly reflective. Therefore, when the incoming beam encounters the first filter, all but a narrow range of frequencies around the [C II] line are reflected to the [N II] filter. The light reflected off the [N II] filter contains the CO J=7→6 and [C I] lines.

2.4.3 *Mixer Performance*

Virginia Diodes will provide subharmonically-pumped, Schottky mixers with integrated, synthesizer-driven LO chains for HEAT. These mixers provide competitive receiver noise performance even at ambient temperatures. With 5 watts of thermal load, the instrument cryocooler (either from Qdrive or Sunpower Inc.) will cool the mixers to 70 K, sufficient to increase their sensitivity by a factor of 2. We anticipate delivered cooled DSB receiver noise temperatures in the vicinity of 2000K at 0.8 THz, 4000K at 1.4 THz and 6000K at 1.9 THz.

2.4.4 *IF Processors*

The entire IF processing and spectrometer system will be leveraged from the successful design being implemented in SuperCam (the PI's 64-pixel, 345 GHz array receiver). Funds will only be needed to fabricate additional amplifiers, IF processor modules, and spectrometer boards for HEAT. The 5 GHz-centered IF output of the THz mixers is first amplified by a low-noise MMIC amplifier designed by Sander Weinreb's group at Caltech for the Supercam project. In order to simultaneously detect the CO J=7→6 and [C I] lines in separate sidebands, the 0.8 THz mixer will have an IF center frequency of 1.5 GHz and then be upconverted to 5 GHz to match the other channels for subsequent IF processing. Low-noise, cryogenic, 1.5 GHz IF amplifiers are readily available.

The IF processor board provides each channel with an initial 48 dB of gain, a variable digital attenuator, a 1 GHz bandpass filter, a mixer conversion to baseband, a low pass filter, and 50 dB of baseband gain. An additional circuit provides total-power measurements of the IF power for telescope pointing and continuum measurements. A picture of the 8-channel IF processor module and a sample 512 MHz bandpass is shown in Figure 5. Only four of these channels will be utilized by the HEAT instrument.

2.4.5 *FFT-in-FPGA Spectrometer*

The HEAT Galactic Plane surveys require both fine kinematic resolution (1 MHz) to disentangle cloud components and wide instantaneous bandwidth ($\geq$ 1 GHz) to span the ve-

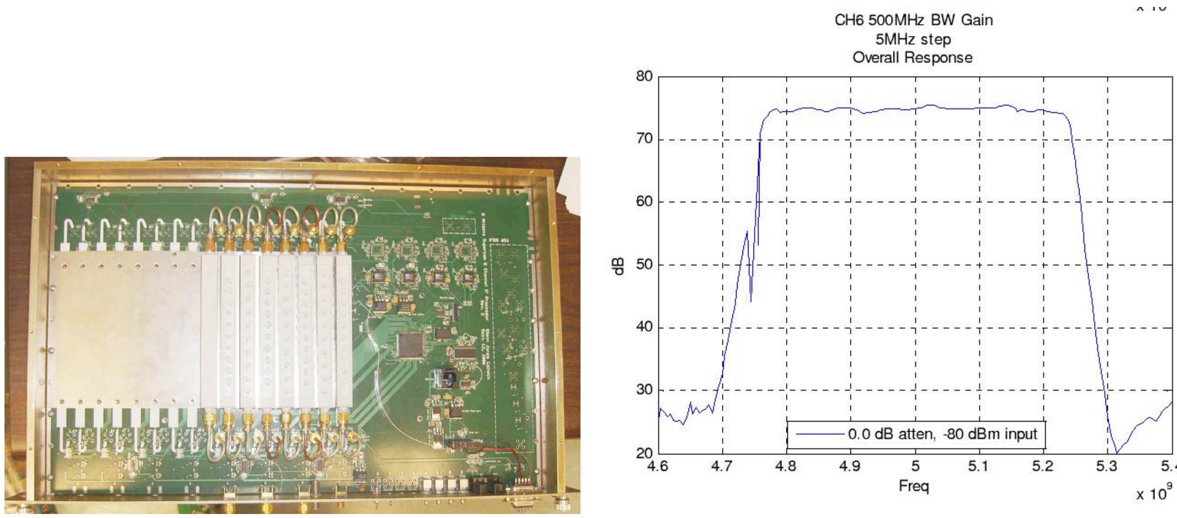

Figure 5: 8-channel IF processor module and sample bandpass

locity dispersion of the Galaxy. Recent gains in high-speed ADCs and FPGAs have made such a wide bandwidth, direct-digitization spectrometer economically feasible. The baseband output of the IF processors is fed into two direct digitization spectrometer boards, each board with 2-IF inputs. For each IF input the spectrometer board provides 1 GHz of instantaneous bandwidth at 1 MHz resolution. The resulting velocity coverage (up to 370 km/s at a resolution ≤ 0.4 km/s) enables all three lines to be resolved and observed throughout the Milky Way. Omnisys Inc. has already designed and delivered 8 of these boards for the PI's Supercam array project. The delivered system is depicted in Figure 6 and performs admirably. The measured Allan variance (stability) time is 650 seconds when using a 5 GHz noise source that has been downconverted through the Caltech IF processor board (Figure 7).

Figure 6: The assembled 8-board, 16 GHz FFT spectrometer from the PI's Supercam project is no larger than a rack-mounted PC and requires only 200 watts of input power! One-fourth of this spectrometer system will be purchased for HEAT.

2.4.6 Calibration

HEAT will be able to calibrate observations through several means. 1) A vane with an ambient temperature absorbing load will be located at the cryostat entrance window, allowing standard chopper wheel calibration to be performed. 2) HEAT will routinely perform sky-dips to compute the atmospheric optical depth in each of its three wavelength bands. 3) HEAT will regularly observe a standard list of calibration sources. 4)

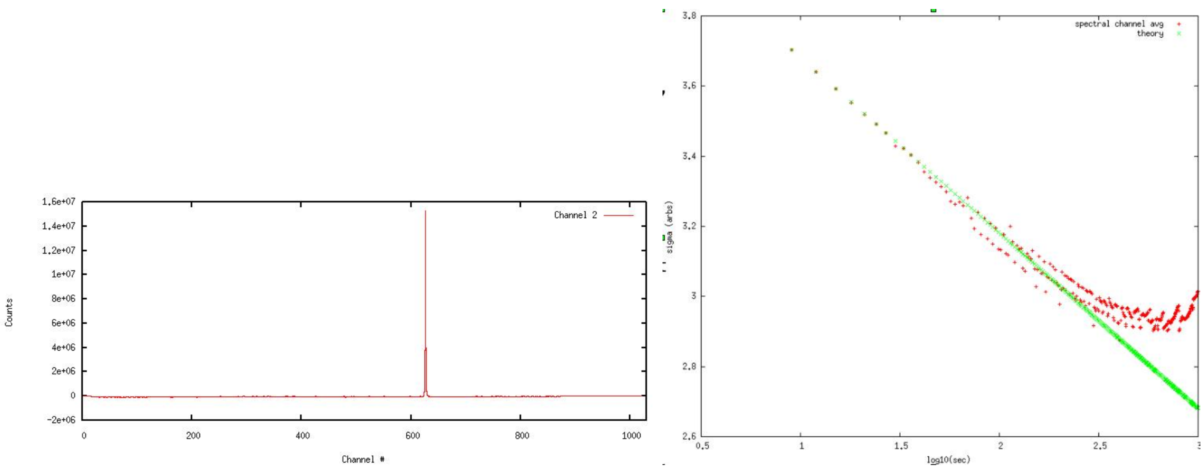

Figure 7: Sample results from the end-to-end test of SuperCam components to be used for HEAT (August 2006): (TOP) First spectral light of an injected line at 346 GHz as detected by the Omnisys FFT spectrometer. (BOTTOM) Allan-variance of the combined Caltech IF processor and Omnisys FFT spectrometer. Classical spectroscopic Allan time is 650 seconds.

The PLATO will host `Pre-HEAT`, a 450 μm tipper that will measure atmospheric transmission. Its measurements will be coordinated with HEAT spectral line observations to provide cross calibration.

2.4.7 *Control System and Communication*

The HEAT control system consists of several subsystems; the telescope drive system, receiver frontend (*e.g.* mixers, LOs, and cryostat) computer, and backend (spectrometer) computer. The subsystems communicate via Ethernet. The subsystems are based on Technologic Systems TS-ARM embedded computers that draw less than 2 watts of power, run Linux or NetBSD, and have been field-tested to survive the cold. These systems provide digital I/O, analog-to-digital conversion, serial I/O, and CAN, SPI and I2C bus interfaces for control of the various electronic subsystems in HEAT. These single-board computers are slave to a UNSW-designed "supervisor" power control board in PLATO that contains a watchdog circuit that will reset the system in case of a software or hardware malfunction and cycle tasks to the next available embedded computer. HEAT will be designed to work autonomously for up to a week at a time, performing pre-programmed observational programs and storing astronomical and housekeeping data on non-volatile memory. Preprocessed sample data will be uploaded to control centers at the Universities of Arizona and New South Wales via dedicated Iridium satellite channels located on each "supervisor" board. Raw data will be recovered from HEAT each year during maintenance and processed into the released data products. We aim to also integrate a portable field antenna for NASA's TDRSS-1 satellite for routine downlink of raw data well in advance of annual maintenance.

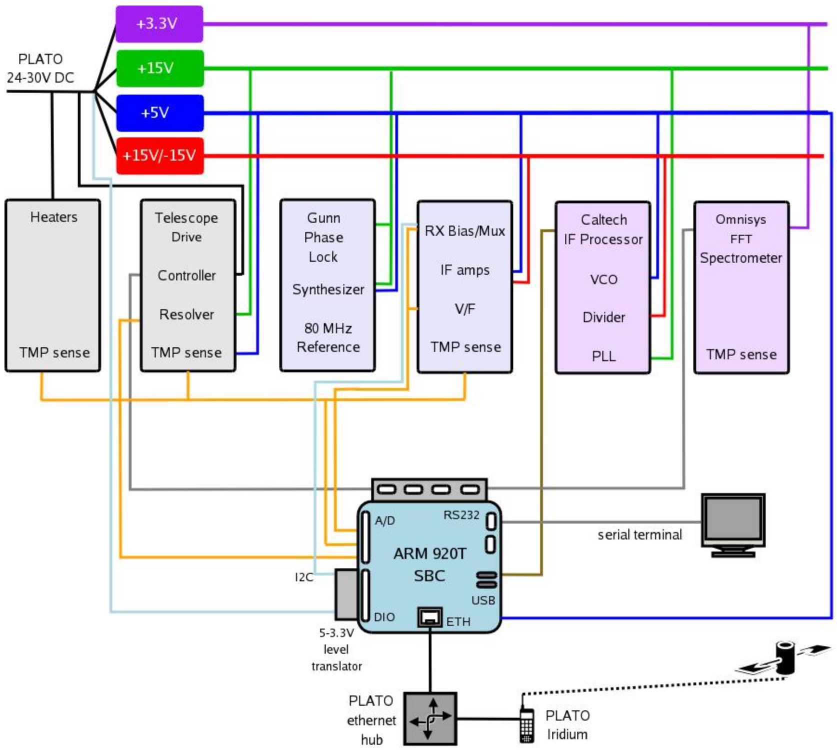

Figure 8: A sample power and control distribution diagram showing schematically the integration of the HEAT subsystems into a single observatory.

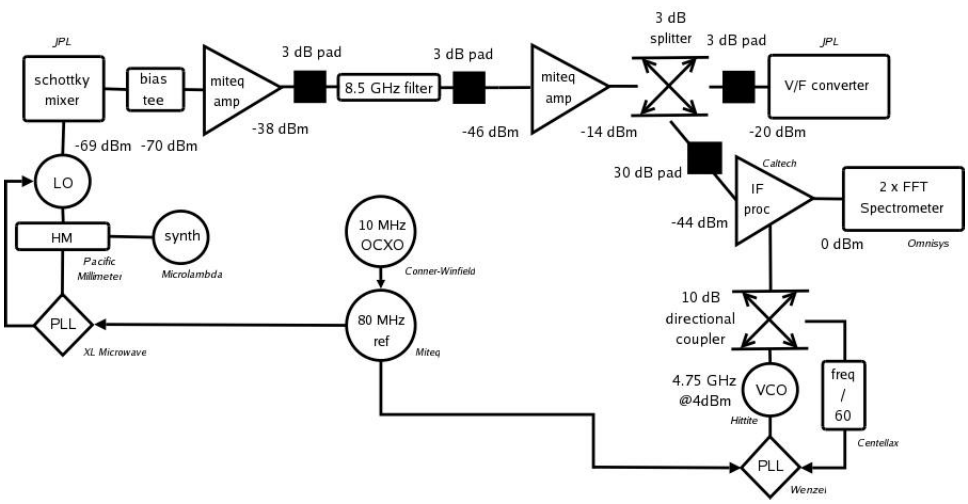

Figure 9: An RF integration diagram showing the (inter)relation of all receiver-level IF components.

2.5 *Integration and Testing*

The use of developed or commercial subsystems in HEAT allows system integration and testing to be performed in a timely manner. Sample system-wide diagrams of power and IF distribution in HEAT are shown in Figures 8-9.

1. **Cold component testing** will be used to determine limiting temperatures for reliable operation of constituent components in each subsystem. These component tests will define a process by which the telescope can be nominally operated in a range of highest reliability, or safely resurrected from an idle state in which all components have been cold-soaked.
2. **Subsystem testing** will demonstrate the proper functionality of large components of the HEAT system, such as the assembled telescope drive system or the Schottky instrument package and control electronics, or the spectrometer and data system.
3. **Integrated system testing** involves the interplay of subsystems in the actual collection of data, such as performing on-the-fly mapping observations with active receivers, spectrometers, data system, while monitored over a Iridium satellite connection; i.e. normal astronomical operation at Dome A.
4. **Failure Mode testing** involves the intentional disabling of a component to observe the fault handling and interplay of the hardware and software systems. A Failure Mode Effects Criticality Analysis (FMECA) will be generated to determine system robustness to component failure. System reliability will then be enhanced through application of redundancy, increased reliability rated components, and improved operational design where indicated.

The combination of Schottky diode receivers, interchangable (and in some cases, dual string) computer control subsystems, Iridium communication links on robust watchdog circuits, diesel power generation with solar panel backup, and adopting a largely fixed, stable, simple optical system, all contribute to a highly **reliable and robust system**.

2.6 Logistics: Deployment to Dome A

Antarctic science has reached a level of maturity where several options exist for fielding instruments on remote sites. For Dome A, these include:

1. **(Chinese) Traverse from Zhongshan to Dome A**: UNSW has recently signed a Memorandum of Understanding (provided in the Supplementary Documentation) with the Polar Research Institute of China and the National Astronomical Observatories of China for Chinese deployment of a UNSW PLATO to Dome A in 2007-8. Our baseline plan is to simply install HEAT atop this PLATO module over two of the remaining spare "roof" ports. It could be installed as part of a 2009 Chinese traverse, combined with supplemental transport options described below.
2. **Twin Otter Air Support**: If a Chinese traverse brings PLATO (in 2007) and HEAT to Dome A (in 2009), USAP Twin Otter air support would allow personnel to be flown in from South Pole or the forthcoming AGAP field camps (such as AGO3) to facilitate the HEAT installation.
3. **CASA 212** (Australian Antarctic Division): J. Storey of UNSW will be requesting one CASA 212 cargo flight directly from e.g. South Pole to Dome A for transport of

the HEAT experiment, with subsequent flights to support fuel and/or personnel for the HEAT installation.

The HEAT team will continue to work closely with the NSF, USAP, Raytheon Polar Services, and the International Community to implement an optimal plan for deployment to Dome A.

2.7 Pre-HEAT: A Forerunner to HEAT

An exciting and timely opportunity has arisen that allows us to perform pioneering research *immediately* at Dome A. Our Chinese and Australian partners will be installing the first base Plateau Observatory (PLATO) on Dome A this coming Austral summer (2007-8) and have given us the opportunity to field a submillimeter radiometer as part of this expedition. This instrument, `Pre-HEAT`, is a 450 μm (660 GHz) tipping radiometer coupled with a digital FFT spectrometer. The goals of `Pre-HEAT` are to (1) Measure the submillimeter sky opacity as a quantitative demonstration of the exceptional conditions of Dome A, (2) Perform strip maps of the Galactic Plane in the ^{13}CO J=6-5 line at 661 GHz, constituting the first astrophysical measurements from Dome A, and (3) Field-test many of the key technologies for `HEAT` as possible. `Pre-HEAT` will pioneer new capabilities for ground-based astronomy and is an opportunity for the US to play a major role in a landmark International Polar Year (IPY) project.

Pre-HEAT is being funded by NSF under the auspices of the Small Grants for Exploratory Research (SGER) program (ANT-0735854). Generous contributions from our domestic and international partners have made this instrument feasible with minimal financial outlay. Pre-HEAT is currently being constructed and will be shipped to UNSW for integration with PLATO in late September 2007! An assembly cutaway of the Pre-HEAT tipper telescope is shown in Figure 10.

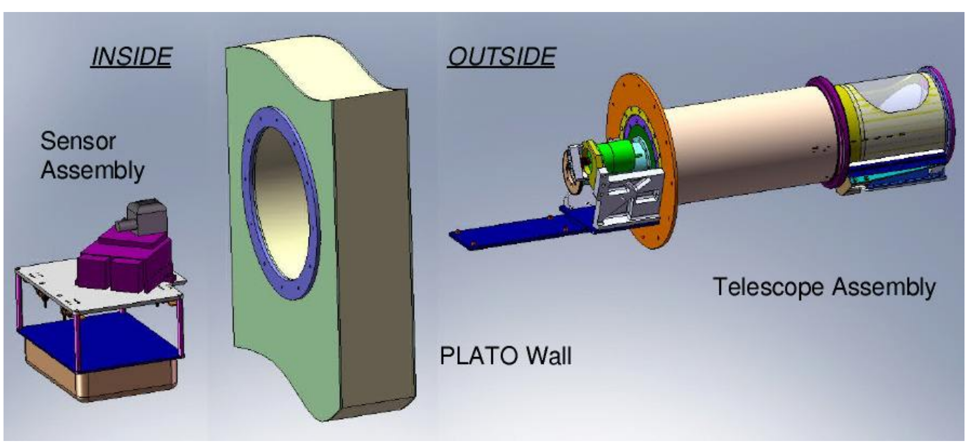

Figure 10: An exploded view of the Pre-HEAT telescope and its installation onto the UNSW PLATO module. Pre-HEAT will test all key technologies for HEAT and conduct its own submillimeter Galactic Plane survey from Dome A in 2008!