PROJECT DESCRIPTION

1 Introduction

The scientific advances made possible through radio astronomy depend on the development of high sensitivity receivers. There are two approaches to improving the sensitivity of radio telescopes, and both must be pursued. First, the amplifiers must be pushed to low noise temperature and maximum bandwidth, and second, focal plane arrays of receivers – multipixel radio cameras – need to be developed and deployed. At low frequencies, technology based on HEMT amplifiers is approaching the fundamental limits set by quantum mechanics, but at 100 GHz and higher frequencies performance is still well above the quantum limit. Amplifier development has built on a large investment made for commercial applications, but there is little commercial interest in cryogenic applications where the devices give their best performance, so progress has been slow.

The work proposed will advance key technologies in two areas: (i) development of improved Monolithic Millimeter-wave Integrated Circuit (MMIC) modules for building larger and more cost-effective focal-plane arrays; and (ii) advancing the state-of-the-art of millimeter-wave amplifiers with an aggressive performance metric of 15 K noise at frequencies $\nu = 85$–115 GHz, i.e., only ~ 3 times the quantum limit $q = h\nu/k \approx \nu/(20\,\mathrm{GHz})$ K. The proposal targets in particular the development of improved polarimeter array modules capable of meeting the goals of the Q/U Imaging ExperimenT (QUIET). The products will be: (i) a small quantity of improved QUIET modules, sufficient to demonstrate the technological readiness of QUIET Phase II — the knowledge gained will also enable us to build low-noise modules for a wide variety of other astrophysical applications; and (ii) a sufficient quantity of InP MMIC amplifiers with noise close to the quantum limit for Phase II of QUIET and for the general radio astronomy community. The improved modules and new amplifiers will facilitate a proposal to measure the B-mode polarization of the Cosmic Microwave Background (CMB) in QUIET Phase II.

2 Science goals

In the last two decades, increasingly precise measurements of CMB temperature anisotropies have provided a wealth of physical information, and have been one of the greatest success stories in cosmology. High-sensitivity measurements of CMB polarization can add qualitatively new information, but they are instrumentally challenging because sensitivities of 10^{-6} K to 10^{-8} K, or better, are needed. After the first detection of polarization in 2002 (Kovac et al., 2002), measurements have steadily improved and are now beginning to produce interesting constraints on cosmological parameters (e.g., Leitch et al., 2005; Readhead et al., 2004; Montroy et al., 2006; Sievers et al., 2007; Bischoff et al., 2008; Pryke et al., 2009; Castro et al., 2009; Brown et al., 2009; Chiang et al., 2010). The polarization of the CMB is uniquely sensitive to primordial gravity waves, which create characteristic degree-scale divergence-free polarization patterns on the sky known as B-modes. Primordial gravity waves are generically predicted by inflationary models, and a measurement of their amplitude would constrain the energy scale of inflation and provide information about the physics of inflation. However, the B-modes have yet to be detected.

2.1 The QUIET experiment and current status

QUIET is an experimental program to measure the polarization of the CMB from the ground using MMIC arrays at two frequencies, 44 GHz (Q-band) and 95 GHz (W-band) (Buder, 2010; Dumoulin, 2010; Monsalve, 2010). QUIET aims to measure or place strong limits on the B-mode polarization. In order to achieve the required sensitivity, the experiment exploits a breakthrough in packaging and miniaturization, which enables the cost-effective mass-production of MMIC-based polarimeter modules (Cleary, 2010) to make large arrays of detectors.

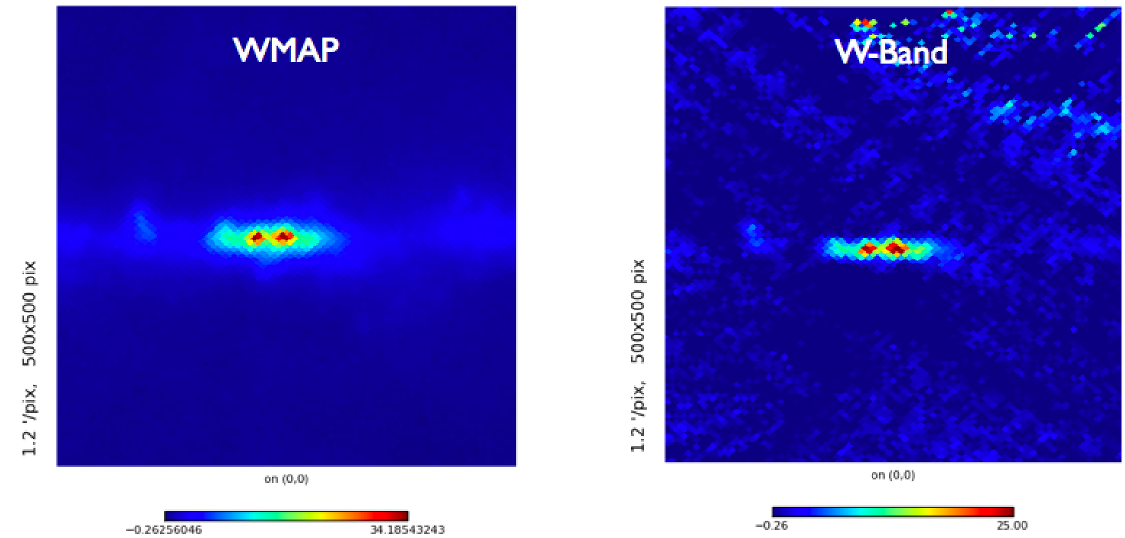

Figure 1: The Galactic center region observed in temperature (total intensity) by WMAP for 7 years *(left)* and the same patch observed by QUIET W-band for 5.5 h *(right)*. Note that just $\sim$ 10% of W-band modules are used to measure total intensity, the remainder being devoted to polarization.

QUIET is nearing completion of its Phase I on the 5080-m Chajnantor Plateau in Chile. The high elevation and the aridity make this an excellent site for microwave astronomy. QUIET has made observations with a 19-element Q-Band array from 2008 October to 2009 June, and with a 90-element W-Band array since 2009 August. During the Q-Band season we achieved 66% observation efficiency, taking 3650 h of astronomical observation data. By 2010 November, the W-Band season has accumulated $\sim$ 5400 h of observation, and an additional $\sim$ 2000 h are expected by the end of 2010. About 10% of the observing time is devoted to calibration on astronomical sources. The Q-band observations have achieved sensitivity in line with the forecasts of the original proposal, and papers on the first results are in preparation. Preliminary W-band results are also excellent (Fig. 1).

2.2 The need for detector improvements

Measuring the faint CMB polarization, and B-modes in particular, requires low instrumental noise and immunity from systematic effects that can create spurious polarization. QUIET Phase I makes precise measurements of the CMB polarization at angular multipoles $25 \lesssim \ell \lesssim 1000$, with the lowest systematic errors of any deployed CMB polarization experiment; however, it will not have the sensitivity necessary to detect B-modes. The number of detectors must be increased to achieve the required sensitivity, and this is planned for Phase II.

However, as discussed in § 3, the noise performance of the polarimeter modules can be improved significantly. Without the technology development proposed here, the detection of B-mode polarization using the Phase I detector design would would require $\sim$ 1500 polarimeter modules at W-band, deployed on 3 separate telescopes, and would be prohibitively expensive. With the developments proposed, the same W-band sensitivity could be reached with just $\sim$ 400 modules on a single telescope mount.

2.3 Science goals of QUIET Phase II

Three central areas define the most important science goals for QUIET:

1. CMB polarization is the ultimate probe of primordial gravity waves, via the B-mode (or odd parity) signal on degree angular scales. A measurement of the primordial tensor-to-scalar ratio r at the 10^{-2} level or better would open a powerful new window on the unknown physics of the early universe. In inflationary

Table 1: QUIET sensitivity versus W-band module noise

Number of W-band polarization modules	W-band T_{RX} (K)	T_{sys}[1] (K)	Bandwidth (GHz)	Module Sensitivity[2] ($\mu K\sqrt{s}$)	Array Sensitivity ($\mu K\sqrt{s}$)	$\sigma(r)$
81	89[3]	97	10	514	57	0.03
400	40	48	15	207	10	0.0079
400	25	33	15	142	7	0.0037
400	20	28	15	121	6	0.0027

[1]System temperatures assuming 5.5 K sky temperatures (ATM model for 1 mm PWV at Chajnantor, 5000 m altitude and 273 K)
[2]Calculated using $T_{sys}/(2\sqrt{\beta\tau})$ and 10% loss from blanking interval
[3]Calculated using noise in actual W-band observations of Chilean sky

models, fine-tuning arguments combined with WMAP data suggest that r is generically $\gtrsim$0.02 (Boyle et al., 2005; Bird et al., 2008; Hotchkiss et al., 2008). Smaller values of r would point to inflationary models associated with new physics below the energy scale of grand unification, or for a non-inflationary origin of our universe (e.g., Khoury et al., 2001). Conversely, detection of nonzero r would rule out most non-inflationary models, and represent indirect observation of a fundamentally new phenomenon in nature, gravity waves on cosmological scales, generated by physics near the grand unification scale. With the developments we propose here, the forecast uncertainty on r in QUIET Phase II is $\sigma(r) = 0.0079$ if we achieve 25 K noise on the modules, and $\sigma(r) = 0.0027$ if we achieve 20 K noise – a factor of ~ 40 or ~ 120 improvement over polarization experiments to date (Table 1).

2. B-mode polarization is generated by gravitational lensing, and measurements of the B-modes can be used to reconstruct the gravitational lenses with high signal-to-noise ratio (Zaldarriaga and Seljak, 1999; Hu and Okamoto, 2002). This will enable the CMB to be a probe of weak lensing, on par with other probes such as galaxy ellipticities, and is an exciting upcoming frontier for the field. Although CMB lensing has not yet been detected in polarization, QUIET Phase II can obtain a few hundred σ detection. This measurement can be used to constrain new parameters, such as the neutrino mass.

3. The E-mode (even parity) component of CMB polarization can be used to complement existing temperature data when making inferences about the early universe. As examples, polarization eliminates degeneracies in the primordial power spectrum (Hu and Okamoto, 2004), removes blind spots when reconstructing the initial potential (Yadav and Wandelt, 2005), and can test whether observed CMB temperature anomalies are primordial in origin (Dvorkin et al., 2008). In QUIET Phase II, we will fully characterize the E-mode power spectrum, by measuring it over the range $40 \lesssim \ell \lesssim 1800$ with percent-level precision.

In Figure 2, we show forecast E-mode and B-mode power spectrum uncertainties for QUIET Phase II, assuming 400 W-band modules with 15 GHz bandwidth and 25 K noise.

Table 1 shows the sensitivity achieved at W-band in Phase I of QUIET with 81 W-band polarization modules and the incremental improvement at each of the proposed milestones in W-band module noise. The improvement is dramatic and shows that the upcoming generation of experiments, including QUIET Phase II, will represent a pivotal moment in the long theoretical and experimental program aimed at using CMB polarization as a probe of fundamental physics. Perhaps the most tantalizing prospect is settling a long-standing question in theoretical cosmology: does our universe contain detectable primordial gravity waves, as generically predicted by inflationary models associated with grand unification; or not, suggesting new physics below the GUT scale or a non-inflationary origin?

2.4 Other applications of improved receivers

The deployment of new front-end amplifiers with high sensitivity and high bandwidth will greatly enhance the power of both existing and future radio telescopes. The major advances will come from focal-plane arrays, which require sensitive, compact, and easily constructed amplifiers. Here we can mention only a few examples.

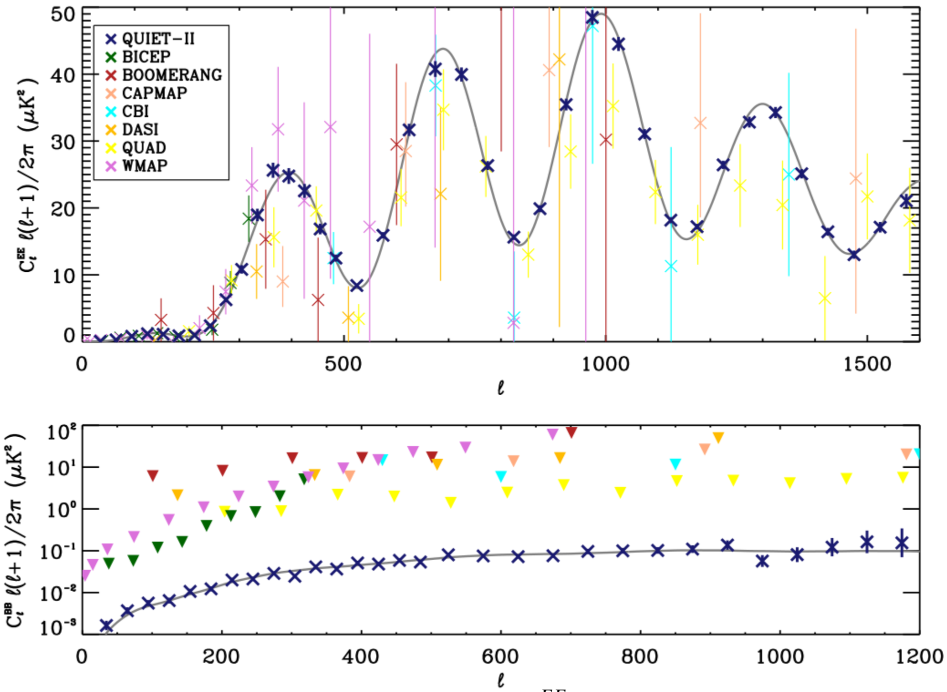

Figure 2: Forecast error bars on the E-mode power spectrum C_ℓ^{EE} (top) and B-mode power spectrum C_ℓ^{BB} (left) for QUIET Phase II (light blue), with results from recent experiments (Brown et al., 2009; Chiang et al., 2010; Leitch et al., 2005; Montroy et al., 2006; Bischoff et al., 2008; Sievers et al., 2007; Nolta et al., 2009) shown for comparison. The B-mode results from recent experiments are shown as 95% confidence upper limits. With 400 W-band modules at 25 K noise, QUIET Phase II would dramatically improve existing results, by making percent-level measurements of the E-mode power spectrum, constraining the gravity wave B-mode to $\sigma(r) = 0.0079$, and measuring the B-mode due to gravitational lensing at 43σ. The ultimate target for this proposal is 15 K W-band module noise which would give $\sigma(r) = 0.0018$.

1. For studies of the interstellar medium and star and planet formation, focal-plane arrays have enormous potential. For example, the technology developed here would enable a dual-polarization, 1024-pixel 85–115 GHz focal-plane array with $T_{\rm rx} \sim 20$ K. The array could be deployed, for example, on the NRAO Green Bank Telescope, the Large Millimeter Telescope (LMT), the new Sardinia Radio Telescope, or the IRAM 30-m Millimeter Telescope, and could be used to make complete maps of nearby star-forming regions or nearby galaxies with resolution of a few arcseconds in 20 or more molecular lines tracing the physical conditions and magnetic fields.

2. For studying high-redshift galaxies, a multi-object spectrograph with ~ 20 feeds positionable in a large ($20'$) focal plane is preferred; such an instrument could be used on the GBT or, with higher-frequency MMICs, on the Cornell-Caltech Atacama Telescope.

3. For high-resolution studies ($\sim 1''$), interferometer arrays are essential; but current interferometers have small fields of view and cannot map large areas of sky with high sensitivity. However, wide-field surveys would be made possible by the installation of focal-plane arrays of, say, 9 elements, on interferometers such as the Combined Array for Research in Millimeter-wave Astronomy (CARMA).

3 Technical Requirements

The technical goal of this proposal is to fabricate the MMIC amplifiers and modules necessary to field the next generation of QUIET receivers in order to pursue the science described in § 2.

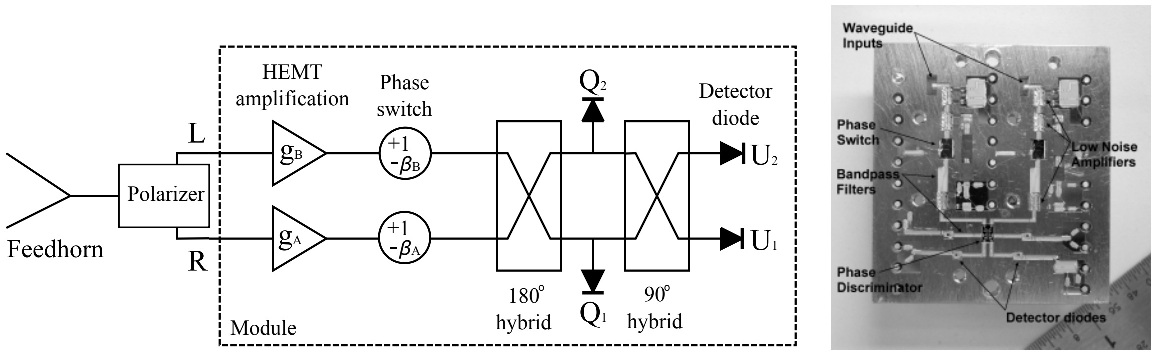

Figure 3: A schematic of the QUIET W-band polarimeter is shown *(left)* and the Phase I module itself is shown with the lid removed *(right)*.

3.1 The QUIET Polarimeter Module

The QUIET polarimeter module (Cleary, 2010) is a pseudocorrelation receiver fed by a left-right circular polarization orthomode transducer (OMT) (Fig. 3). Signals coming from the polarizer enter the module via waveguide. Signals are passed to microstrip transmission lines via a probe in the waveguide. The signals are amplified using indium phosphide (InP) low noise amplifiers with interchip matching provided by 3 dB attenuators. These amplifiers offer the lowest noise available for amplifiers operating above 30 GHz (Weinreb et al., 1999). The MMIC amplifier used at the input of the QUIET module is well documented and has been used in numerous astrophysics instruments including SEQUOIA (Erickson et al., 1999) and CAPMAP (Barkats et al., 2005). *The performance of the QUIET polarimeter is fundamentally limited only by the performance of this amplifier*. The amplifier has an average noise temperature between 30 K and 65 K, depending upon the wafer. The signals are then 0 & 180° phase switched at 4 kHz. A broadband filter reduces out of band gain to limit non-linearities. The resulting signals from both the left and right chains are then combined in a sum-difference, in phase/quadrature phase hybrid. The four outputs then carry E_x, E_y as well as $\pm E_x^* E_y$ signals, allowing simultaneous measurement of Stokes Q and U. Final band definition is provided by 4 separate coupled line bandpass filters and the signals are detected using gallium arsenide (GaAs) Schottky diodes, with floating outputs. Upon detection the signals pass from the cryostat, are amplified at video frequencies, offset-removed and further amplified prior to digitization.

3.2 Performance Limiting Factors in Phase I QUIET Modules

Although the 90 GHz array did not meet its overall performance goal, many of the modules did approach this performance. Furthermore, observations during Phase I revealed that the module design is extremely robust against systematic errors. That said, it is important to understand what the performance limiting factors were in order to improve the module performance for Phase II.

The most significant performance limiting factor in the modules was the input amplifier noise performance. The 100 nm InP HEMT process has inherent noise variability. The origin of this variability is uncertain as the device physics is quite complicated and there are many steps in the MMIC process. From a wafer with good devices, roughly 1/3 of devices perform within 10 K of the best chips. While many amplifiers on other projects have been built using the same chips, their approach provided for the selection of front-end amplifiers after testing, with poor performers relegated to the back stages. This is not possible with integrated design of the QUIET modules.

The screening process for QUIET chips involved room temperature wafer probe measurements, with selection made for gain, pinchoff properties and bias voltage matching within a chain. The problem is exacerbated by the fact that a large number of chips are required for QUIET. No dedicated wafer run was performed for QUIET so the project simply selected from the best chips available from previous runs. Additional cuts had to be made for device leakage which limited supply of "good" performers. This meant the project was forced into performance compromises on the chips, with insufficient data as to the cryogenic performance.

It was clear from the laboratory testing that modules produced with chips from better performing wafers (as measured independently with single amplifier packaged cryogenic tests) had better noise temperature. From this we can infer that reducing the noise figure of the amplifiers will continue to improve the noise performance.

Gain While the QUIET modules have ample gain in each chain (> 60 dB in active elements) this was still a limiting factor in the array performance. In order to obtain sufficient signal to overcome the post-detection noise, the diodes need to detect RF signals at a level > 2 mV. Higher signals led to saturation in the receiver and there was significant effect on the noise from increased RF gain in the second and third MMIC amplifiers in each polarization leg. While the cause of this is uncertain, it is likely due to feedback via the chip cavities from the output to the input. This hypothesis is supported by the observation that continued increase in gain would usually result in module oscillation.

Several steps will be taken to provide design margin to ensure that the modules have a larger gain window in which nominal operation is achieved.

Bandwidth The performance of QUIET is sensitive to the square root of bandwidth. While design bandwidth for the module was 18 GHz, the actual performance achieved is closer to 10 GHz. Several factors limit this performance. The single biggest factor in this bandwidth reduction was the impedance sensitivity of the amplifier bandpass. In particular, the input of the first LNA is very sensitive to impedance variations at 100 GHz, leading to gain and noise peaking at this frequency. No attempt was made to deal with this in the Phase I design. Ripple is introduced in the intermediate stages due to bond wire inductance. Interstage attenuation was employed to reduce this effect, but no attempt was made to tune it out. The net impact was probably 1 GHz of bandwidth. Finally, the hybrid itself was a limiting factor, creating a 1 GHz asymmetry between the outputs.

4 Technical Plan

The technical plan focuses on two key technology areas: (1) Improvements in the module design for impedance and stability; (2) Noise performance improvement of the amplifiers.

4.1 Module improvements

Aim: (i) to ensure that chip noise can be achieved in a multi-chip module; (ii) to increase the bandwidth from 10 GHz to 15 GHz; (iii) to produce 10 improved modules

QUIET module redesign: Caltech has been leading an effort to pinpoint the problems with the QUIET Phase I design. A new test version of the QUIET module has been designed (Fig. 4) in which the module is split into three sections: an amplifier section, a waveguide hybrid, and a detector diode section. In this way, the amplifier section can be fully characterized since it will have RF inputs and outputs. The effect of the hybrid on bandwidth can be separated from that of the amplifiers and the impact on noise of mechanical cavity design, input probe design and bias decoupling can be investigated. We will take the lessons learned from this test block and use them to redesign the module. The aim is to ensure that the QUIET module exhibits the same noise temperature as that measured on the individual input amplifiers and to increase the bandwidth from 10 GHz to 15 GHz. This proposal has milestones in amplifier noise at

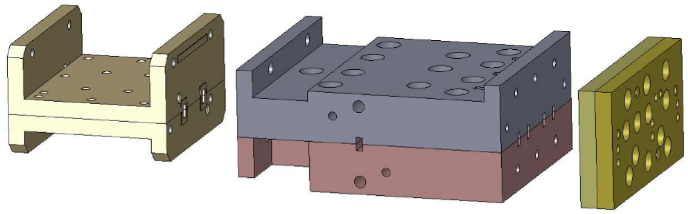

Figure 4: A test version of the QUIET Phase I module, which splits the Phase I module into three parts: the amplifier section *(left)*, waveguide hybrid *(center)* and detector diode section *(right)*. As part of a KISS-funded effort, this test assembly is being used to pinpoint the source(s) of excess noise in the Phase I design.

30 K, 20 K and 15 K. We will place these amplifiers in redesigned QUIET modules and with the goal of demonstrating modules with 40 K, 25 K and 20 K noise, respectively.

Module fabrication: After the 20 K module has been demonstrated, this module (and any waveguide adaptors) will be fabricated resulting in 10 modules exhibiting the improved noise and bandwidth. This will demonstrate that the technical problems have been solved and that such modules can be produced in quantity.

Module testing: The redesigned modules will be tested in the laboratory using total power measurements and polarized loads, as well as on the sky, in order to verify their performance.

The existing W-band cryostat will be brought back from Chile to the UChicago lab and several of the 10 new modules will be installed for testing, both in the lab and on the sky. Many of the first generation modules will be left in the cryostat; in this way we will be able to do a direct comparison of the Phase II modules with the Phase I modules, which are extremely well understood after more than a year of data taking. This work will be done in conjunction with the Fermi and KEK national labs.

4.2 Low Noise Amplifier Technology Development

Aim: To produce MMIC amplifiers with mean noise of 15 K over 85–116 GHz.

Reduction in noise temperature is still the single largest factor available for improving noise at 90 GHz. The most straightforward path to near quantum-limited devices is through 35 nm HEMT technology with high In content InGaAs channels. These devices, which have been pioneered by Northrop Grumman Corporation (NGC), Fraunhofer Institute for Applied Solid State Physics (IAF), and Teledyne Technologies Inc., have obtained the lowest measured noise at frequencies above 90 GHz (see Fig. 5). While the room temperature performance requirements are driven by defense needs at THz frequencies, the technology will clearly benefit the radioastronomy community upon cooling to cryogenic temperatures.

NASA has recognized this and funded a project under the Astronomy and Physics Research and Analysis (APRA) program to develop cryogenic amplifiers in the 40–200 GHz range using the NGC 35 nm InP process. The project has a goal of reaching noise of $3q$ ($3 \times$ the quantum limit) at 90 GHz and $5q$ at 180 GHz. As part of the APRA program, a three-stage MMIC amplifier for the 180 GHz band has been designed and measured at room temperature (Kangaslahti et al., 2008). Its noise performance has also been characterized as a function of physical temperature (Fig. 6). At room temperature, the noise temperature at 160 GHz is less than 400 K, a factor of two smaller than the previous state of the art, with gain of 16 dB. At 30 K physical temperature, the noise temperature is < 100 K up to 170 GHz, the lowest cryogenic LNA noise temperature ever reported at these frequencies. These improved cryogenic results were obtained even though the amplifier showed a clear "kink effect" in its cryogenic DC I–V curves that precluded proper biasing, increasing its noise.

The new processes (InP on InGaAs substrate at NGC, and GaAs on InGaAs at IAF) are clearly producing transistors with performance greatly exceeding that of previous transistors at room temperature

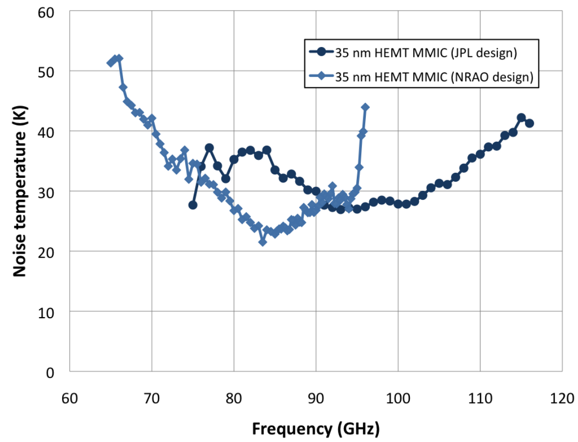

Figure 5: Noise measurements on 35 nm 90 GHz InP HEMT MMIC amplifiers from NRAO (Bryerton et al., 2009) and from JPL (a design by L. Samoska measured at Caltech).

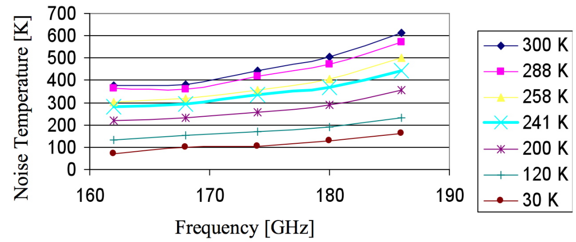

Figure 6: Measurements of a 35 nm 180 GHz amplifier as a function of temperature down to 30 K from Kangaslahti et al. (2008). Noise is a factor of two lower than the best previous results at both room and cryogenic temperatures.

and frequencies < 300 GHz. How does this translate to performance that can be realized at cryogenic temperatures over the frequency range 85–116 GHz, which is the focus of this proposal?

A noise model fitting the performance of the NGC 35 nm InP HEMT device was generated based on the work of Pospieszalski (1989). This empirical model uses two noise sources, represented as resistance at an effective temperature, $T_{\rm physical}$ for the input elements and $T_{\rm drain}$ representing the output drain–source resistance, $R_{\rm ds}$. $T_{\rm drain}$ is known to be proportional to drain current, but must be derived from actual noise data. $T_{\rm drain}$ varies with temperature and bias (as the intrinsic device transconductance increases with decreasing temperature) with a value typically 15–20 times the physical temperature of the device, depending on the technology. The device model, pinned to measured results, predicts a noise figure of 3.3 dB for a single device at 270 GHz. If cascaded in a three stage amplifier with 11.5 dB of gain (assuming 1.5 dB losses in passives in each stage), this translates to a room temperature noise figure of 6.7 dB for the LNA, in good agreement with the measured value of 7.5 dB.

Using this noise model, preliminary design simulations using the 35 nm InP transistor at 20 K show impressive cryogenic results compared to the best previous MMIC LNAs. The simulated noise temperature is 7.9 K ($4q$) at 40 GHz and 11.5 K ($2.6q$) at 90 GHz. Both designs had more than 20 dB of gain, so these numbers would be very close to the final noise temperature of the actual receiver. We emphasize that these design simulations are preliminary, and not optimized. The first W-band devices fabricated on the 35 nm NGC process (Fig. 5) did not achieve the simulated 12 K noise since this first run was to establish the baseline performance of the process and the circuits will be optimized for the NGC process in future APRA wafer runs.

While the APRA project will yield greatly improved devices for astronomy, there are limitations imposed by research with a commercial foundry such as NGC. The DoD has invested significant resources to establish processes which are repeatable enough for THz MMIC development. Cryogenic performance is not their concern; as such, the commercial foundries are rightfully resistant to substantial process changes. A research foundry with a carefully controlled process is better suited to achieving performance near fundamental limits at cryogenic temperatures. We therefore propose to partner with the IAF in Freiburg, Germany, to develop amplifiers from 85 to 116 GHz with 15 K noise. IAF has demonstrated that they can produce repeatable devices with performance similar to those of NGC. They and others have further demonstrated that they can achieve this performance using GaAs substrates and buffer layer technology to fabricate devices with InGaAs channels with an In content exceeding 53%, i.e., they fabricate InP devices

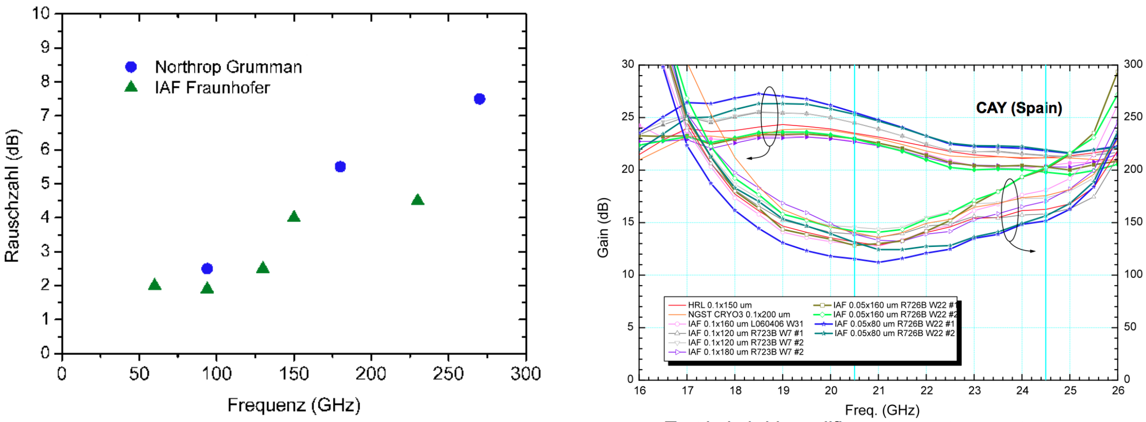

Figure 7: A comparison of room temperature noise figure measurements of HEMT devices from IAF and NGC, at different frequencies (left). When placed in amplifiers, the IAF devices exhibit identical room temperature noise to the NGC devices (right).

on a GaAs substrate.

To date, IAF has demonstrated that these devices are indistinguishable from devices on InP substrates. Fig. 7 (left) shows room temperature noise figure data over a range of frequencies with performance nearly identical to NGC devices. Furthermore, transistors from this process were integrated into amplifiers at Centro Astronomica de Yebes, and shown to have identical room temperature noise performance to NGC InP devices (Fig. 7, right) . The advantages of processing on GaAs instead of InP include better substrate uniformity, larger wafer size, and selective gate etching.

We will perform the detailed design work needed to transfer the APRA designs to the IAF metamorphic process. With only modest process improvements and repeatable wafer runs afforded by the GaAs process, there is an excellent prospect of achieving noise levels of 15 K across W-band.

Although the proposed amplifier technological development runs in parallel to the APRA program, both are complementary. For the APRA program: there is no funding for module development; the NGC fabrication process cannot be significantly changed to optimize cryogenic amplifier performance due to commercial pressures; only a small number of amplifiers will be produced; and there is no funding for cryogenic wafer probing. For the proposed developments, however:

1. A significant effort is made to solve the noise degradation associated with highly integrated millimetric receiver modules. The specific application addressed here is measurement of CMB polarization, but solving these issues will also benefit parallel efforts to develop such modules for spectroscopic arrays.
2. We take advantage of external funding from IAF to open a new source of cryogenic amplifiers.
3. The IAF is committed to optimizing the cryogenic performance of HEMT amplifiers and as a research foundry the IAF is free to alter their fabrication process in pursuit of this goal.
4. The IAF will fund the experimental wafer runs to achieve cryogenic optimization
5. as well as improved modules, the other product of this proposal will be a large quantity of amplifiers with 10 K noise over 80–116 GHz. This quantity will be sufficient for the second phase of QUIET and will also provide a supply for the general radioastronomy community.
6. The proposed use of the cryogenic probe station (developed through separate funding) to perform on-wafer characterization will complement both the APRA and IAF wafer runs, facilitating both optimization efforts.

Multi-site testing: At the outset, the devices which exist prior to the start of this project will be tested at each of the labs involved, including Caltech, UChicago, FNAL, KEK and IAF. This testing will be performed on individually packaged amplifiers. This will (i) firmly establish the state of the art and (ii) ensure that all the test facilities can reliably reproduce each other's measurements. The amplifiers to be tested will include those resulting from JPL's NASA APRA wafer runs and those already produced by IAF for purposes other than radio astronomy.

Amplifier design: The first part of our program with IAF will be to establish baseline performance with initial 90 GHz designs. We will initially use device models provided by IAF to design amplifiers with two and three stages. JPL has extensive experience in designing state-of-the-art low noise cryogenic MMIC amplifiers. The design activities will be led by L. Samoska and P. Kangaslahti, both of whom have designed similar amplifiers on NGC's process. IAF has an extensive MMIC design capability and they will contribute designs by A. Tessmann. NRAO also has significant experience with MMIC amplifier design and they will provide designs by E. Bryerton and M. Morgan.

Experimental wafer runs at IAF: Once a baseline is established, controlled experiments will be carried out, guided by physical device models. With process controls in place each experiment can test the effects of a single variable. Such experiments are facilitated by large size wafer lots with lot splits and even sub-wafer splits. With the latter, a single wafer can be sub-divided at a given fabrication step and processed separately thereafter. This allows many variations in a single process step to be investigated at once.

A total of three experimental runs will be performed over two years. The goal of 15 K will be reached through incremental improvement with milestones at 30 K, 20 K and 15K̇ (see Fig. 8). The first two wafer runs will focus on variations of trap sensitive process steps, to be investigated in wafer splits using IAF's 50 nm gate length technology, since this process is very stable. We aim to get to 20 K amplifiers by the end of the two runs. For the ambitious goal of 15 K it is very likely that we will need the 35 nm technology, so the results of the 50 nm optimization will be transferred to the 35 nm process in the final wafer run.

At IAF each mHEMT process run is started with four 4-inch wafers, although only two are guaranteed for delivery. Typically, a process run takes four months: three months for frontside and one month for backside processing. Each wafer holds 45 reticles with a size of 144 mm^2 each. About 20 mm^2 are used up by test structures for process monitoring, so roughly 120 mm^2 remain for MMICs. The process yield is defined with respect to the performance of the transistors and other test structures. For MMICs it is typically 70% for the 100 nm process and decreases with gate length. Taking yield into account, a single wafer on the 100 nm process would yield $\sim$ 2000 chips.

Amplifier testing at Caltech: The process of evaluating new device technologies has historically been tedious. Devices were modeled, installed in packages and tested at room and cryogenic temperatures. Based on this performance, the models are updated and additional amplifiers can be designed around the device. The slowest part of this process is the cryogenic testing of devices, particularly where device uniformity is important (e.g., in array applications such as QUIET) and statistics must be established.

JPL and MPIfR have both recently demonstrated that it is possible to perform precise cryogenic noise measurements with wafer probes. This is a major technological breakthrough which will increase the evaluation throughput and readily measure large numbers of devices in a statistically significant sample. Using seed funds from the Keck Institute for Space Science (KISS), Caltech has developed a cryogenic probe station capable of measuring entire 4-inch wafers for S-parameters and noise temperature (in two separate cooldowns). The probe station consists of a 24-inch $\times$ 24-inch $\times$ 12-inch Dewar incorporating a Sumitomo 4 K cryocooler which can cool a 4-inch wafer to 15–20 K. Motorized x, y stages allow any chip on the wafer to be brought to the RF probe tips. Separate motorized x, y, z stages allow the probe tips to be moved over small distances, for example when moving from a calibration standard to a chip. An infrared filter on the shield and a quartz window on the Dewar lid allow the use of an external motorized zoom microscope to inspect the probe and chip positions. All motorized movements are initiated using a Labview computer control system. The station is currently configured for 75–116 GHz S-parameter measurements, using specially modified vector network analyzer frequency extenders which operate up to 116 GHz, and the first cold calibration tests are being performed. Using funds from the KISS, Neal Erikson at the University of Massachusetts is building an active noise source which will be used to make on-wafer noise measurements over 75–116 GHz. Since the system can be entirely computer controlled, it is envisaged that, in future, automated mapping of on-wafer noise will be performed to screen wafers for experiments which require large numbers of unpackaged amplifiers, such as QUIET.

The Caltech probe station will be used to characterize: (i) short gate length ≤ 50 nm wafers from experimental IAF runs, (ii) 35 nm APRA runs on the NGC process, (iii) historical samples of 100 nm NGC wafers and (iv) final wafers from production runs. By wafer mapping the cryogenic bias characteristics, noise temperature and S-parameters of IAF and NASA/NGC devices, we will provide rapid feedback for both cryogenic optimization efforts and a direct comparison of the technologies.

Amplifier production: By the end of the second year of the project, we will have optimized the MMIC designs and the IAF fabrication process for cryogenic performance. From the NASA APRA work, we will also have iterated the MMIC designs on the NGC fabrication process. In the third year of the project, we will take the devices which meet our specification (mean 15 K noise from 85–116 GHz) and fabricate two runs of these amplifiers. This will be enough to fully supply QUIET Phase II with all required low noise amplifiers and supply significant numbers for CARMA, GBT and other array projects.

5 Management plan

The work will be carried out primarily at Caltech, the Jet Propulsion Laboratory, and the University of Chicago, who will be supported under this proposal. In addition we will collaborate with the following "external" collaborators, who will be covering their own costs (except that any wafer production runs will be paid for under this proposal): Fermi National Accelerator Laboratory (FNAL); the National Radio Astronomy Observatory (NRAO); the Institute of Nuclear and Particle Studies High Energy Accelerator Research Organization, Japan (KEK); and the Fraunhofer Institute for Applied Solid State Physics in Freiburg, Germany (IAF).

The Project Manager will be Dr Kieran Cleary. He will have overall management responsibility for the whole project. He will track the progress of work at Caltech, JPL, and the University of Chicago, and be the key liaison with the external collaborators. Cleary will spend 70% of his time managing this project and he will work closely with the PI to ensure that milestones and specifications are met. Cleary produced the 90 W-band modules used in QUIET Phase I, and he has been responsible for setting up and managing the Cahill Radio Astronomy Laboratory at Caltech since its inception two years ago and he is also managing the module development effort that was started at Caltech in the spring of 2010. He has much "hands-on" experience of producing low noise W-band modules and of working with MMICs in general.

We have already established two weekly telecons convened by Cleary, one to discuss module improvements and a second to discuss amplifier improvements. We plan to continue these telecons under this project. In addition we plan three visits a year of personnel from Caltech/JPL to both Chicago and the IAF. Likewise, Chicago and IAF will plan reciprocal visits to Caltech/JPL. IAF will cover their own travel costs. Gaier will be directing and overseeing the work at JPL and Winstein will be supervising the Chicago measurements.

5.1 Resources

This collaboration is the best suited in the world to do the work for a number of reasons: (i) The JPL group led by Gaier has been the world leader in this field for the last 15 years; (ii) the collaboration with the QUIET partners here represented, which includes Chicago, Caltech, JPL, KEK, and FNAL, is pioneering this field and well ahead of the competition on both devices and modules; (iii) the NRAO is strongly committed to developing low-noise receivers for a wide variety of applications in radio astronomy; and (iv) the IAF is deeply committed to improving the cryoperformance of MMICs and eager to work closely with the university community in the pursuit of this aim.

Caltech: The Keck Institute for Space Studies (KISS) provided a grant of $1 M to establish the Cahill Radio Astronomy Laboratory (CRAL) at Caltech. The CRAL personnel include PI Readhead, CoI Gaier, and Dr Sander Weinreb, who provide the overall leadership; Cleary, who directs and manages the lab; postdocs O. King and R. Reeves, who have a lot of experience with MMICs and MMIC modules; and half a technician. In addition we plan to hire one more engineer and another half of a technician. The CRAL has been outfitted with the necessary test equipment to study the performance of MMICs and MMIC modules, including the cryoprobe test station described in § 4. The generous KISS funding was sufficient to launch this ambitious program, but the funds will run out early in 2011. In this proposal we hope to be able to continue this effort, until we have achieved the goal of producing low noise modules made up of near quantum-limited MMICs in the quantity required both for QUIET Phase II and to provide a source of such chips to the wider astronomical community for applications in a variety of astronomical instruments, such as CARMA, the GBT, and ALMA. Caltech will be responsible for: (1) oversight and management of the project, (2) testing the performance of both existing MMICs and experimental MMICs, (3) organising the production of the MMIC wafer runs at IAF, (4) redesigning QUIET module (with JPL), (5) fabricating modules and adapter (with JPL and FNAL), and (6) testing new modules (with Chicago, FNAL and KEK).

JPL: JPL has built up a world-class amplifier laboratory under the direction of Gaier over the last 15 years. This lab, working with Northop Grumman, holds most of the records in HEMT and MMIC performance over this period. Their highly successful "CHOP" program produced the "cryo-3" wafer that supplied most of the world's low noise amplifier chips over a period of a decade. We aim to repeat this service to the community with these MMICs, as well as to produce the MMICs required by QUIET Phase II. The laboratory is well outfitted for MMIC and MMIC-module development. The QUIET Phase I Q-band and W-band modules were fabricated here. In addition to Gaier there are two very experienced engineers, P. Kangaslahti and L. Samoska, and several experienced technicians working in this lab. JPL will be responsible for: (1) designing new MMICs (with NRAO and IAF), (2) redesigning QUIET modules (with Caltech), and (3) fabricating modules and adapter (with Caltech and FNAL).

Chicago: Chicago has excellent laboratory facilities in which they assembled the QUIET Phase I W-band cryostat and receiver and built all the backend electronics, and they will also have the QUIET Phase I W-band cryostat. They are therefore in the best position to test the W-band modules in the cryostat. This project will be directed at Chicago by Winstein, the QUIET PI; and there will be one post-doctoral fellow working with Winstein. Chicago will be responsible for: (1) refurbishing the QUIET Phase I receiver and cryostat, (2) testing new modules in cryostat (with Caltech, FNAL and KEK), and (3) testing new modules in the QUIET receiver and cryostat.

FNAL, NRAO, KEK and IAF: The external collaborators all have world-class laboratories that are well-known for making state-of-the-art instrumentation. They have the resources to play the roles that are needed, and their commitments to these roles are given in the attached letters.The FNAL effort will be led by H. Nguyen, the KEK effort will be led by M. Hazumi, the National Radio Astronomy Observatory effort will be carried out by Bryerton and Morgan, and the IAF effort will be led by M. Seelmann-Eggebert. **FNAL** will be responsible for: (1) machining module housings and adapters (with Caltech and JPL), (2) testing assembled modules (with Caltech, Chicago and KEK), (3) investigating the possibility of reducing the weight of the modules. **NRAO** will design new MMICs (with JPL and IAF) . **KEK** will test new modules in cryostat (with Chicago, Caltech and FNAL). **IAF** will design new MMICs (with JPL and NRAO), and fabricate wafers (both experimental runs and final production runs if these are better than competing NGC MMICs).

5.2 Tasks, Labor, and Milestones

The project tasks and responsibilities for this proposal are outlined below; each of these tasks is described in more detail in the technical plan (§4). The tasks can be summarized as (1) QUIET module improvements, and (2) amplifier improvements. The milestones for this proposal are based on an incremental improvement in the amplifier noise and the demonstration of this noise in a redesigned QUIET module with minimal degradation. These milestones are also listed below and shown in Fig. 8. This figure also shows miletsones from the complementary KISS and NASA-APRA programs described described in § 4.

1. **QUIET Module improvements**. Aim: (i) Demonstrate that chip noise level can be achieved in a multi-chip module; (ii) Increase the bandwidth from 10 GHz to 15 GHz; (iii) Produce 10 improved modules.

   (a) Redesign of the QUIET module to achieve the above aims (JPL, Caltech). For each milestone in amplifier noise (30K, 20K, 15K), a QUIET module redesign will be needed to demonstrate modules with improved noise (40K, 25K and 20 K noise respectively). Includes simulations, CAD for module housing, CAD for thin-film substrates, building small quantity, testing small quantity, iterations. Labor: 1.8 FTE/year for 2.5 years.
   Milestones: 40 K QUIET Module (Mar 2012), 25 K QUIET Module (Mar 2013), 15 K QUIET module (Aug 2013)

   (b) Module and adapter fabrication (JPL, Caltech). Once a 15 K QUIET module has been demonstrated, 10 of these modules will be fabricated to prove that the technical issues surrounding production have been solved. The task includes module housing procurement, substrate procurement, preparing cryostat and test equipment, making measurements, analyzing measurements and feedback into module design, operating the probe station, analyzing and reporting results to IAF. Labor: 0.8, 0.6, and 0.4 FTE in years 1, 2, and 3.

   (c) Refurbishment of the QUIET W-band cryostat for module testing (Chicago). The W-band cryostat will be returned to Chicago after the QUIET Phase I observing period. The cryostat will be made to operate in the lab in preparation for testing the redesigned QUIET modules. Labor: 0.5 FTE year 1.

   (d) Module Testing in test cryostat (Caltech), and in the QUIET Phase I W-band cryostat to cross-compare with existing QUIET modules (Chicago). The redesigned QUIET modules will be tested in the lab and on the sky to verify their performance. Some Phase I modules in the Phase I cryostat will be replaced with the redesigned modules and tested. Labor: 0.85, 1.75, and 0.25 FTE in years 1, 2, and 3.
   Milestones: Production of ten 15 K QUIET modules to demonstrate that these modules are ready for large-scale production (Feb 2014)

2. **Amplifier Improvements**. Aim: Design and Fabricate MMIC amplifiers with mean noise of 15 K over 85–116 GHz.

   (a) Design (Caltech, JPL, IAF). The APRA designs will be transferred to the IAF process. Labor 0.5 FTE in years 1 and 2.

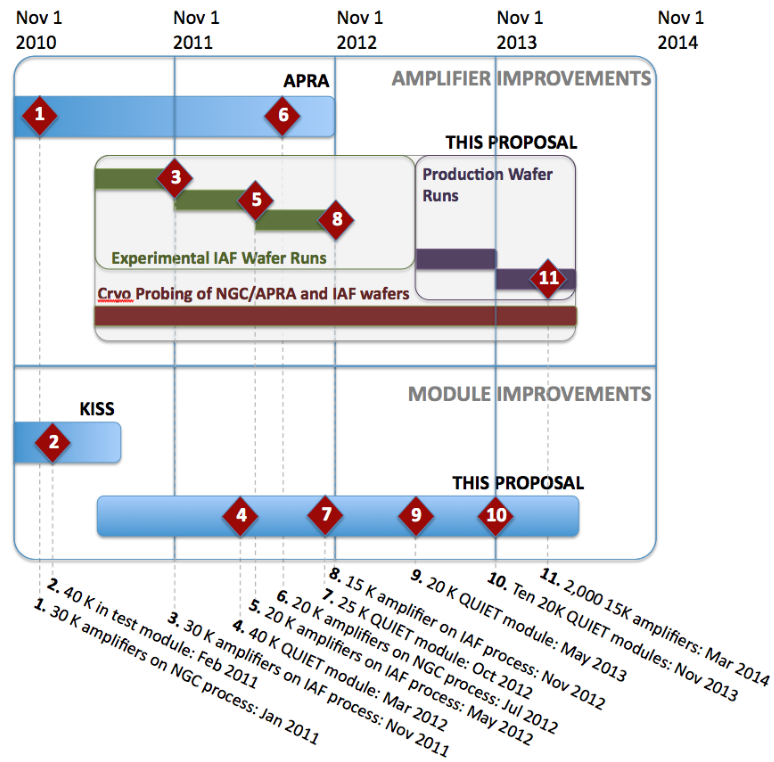

Figure 8: A timeline showing the major project milestones, and their relationship to the APRA and KISS programs.

(b) Sample-testing of existing chips (Caltech). Existing chips will be tested to establish a performance baseline for the IAF process. Labor: 0.2 FTE in year 1.

(c) Experimental wafer runs (IAF). The cryogenic noise of the amplifiers will be optimized over four wafer runs at IAF.
Milestones: 30 K amplifier on IAF process (Nov 2011), 20 K amplifier on IAF process (May 2012), 10 K amplifier on IAF process (Mar 2013)

(d) Testing (Caltech). The NGC/APRA and experimental IAF wafers will be characterized on a cryogenic probe station at Caltech to provide feedback for the cryogenic optimization; Labor:1.8 FTE/yr for 3 years — 1 full-time techician running the station and carrying out the measurements and 0.8 FTE scientist analyzing the results and liasing with IAF and NGC.

(e) Production (Caltech). Once a 10 K amplifier has been demonstrated, two wafer runs will be performed at IAF to produce a large quantity of these devices for QUIET Phase II and the radioastronomy community.
Milestones: Production of 2,000 10 K amplifiers for QUIET Phase II and the radioastronomy community at large (Mar 2014)

6 Broader Impact of the Proposed Work

Contributions to Radio Astronomy Instrumentation The broader impact of this project is primarily the development of devices, both MMIC amplifiers and modules, of a sensitivity that would constitute a major breakthrough in astronomical instrumentation. This would revolutionize radio astronomy by making possible large-format arrays of hundreds to thousand of detectors – effectively the first "radio cameras." Such radio cameras would be used by the astronomy community not only in CMB studies, but also in spectroscopy, and in interferometry on many of our forefront instruments, such as the GBT, CARMA, ALMA and many other telescopes. For surveying, such radio cameras would increase the efficiency of telescopes such as the GBT by factors of hundreds to thousands, thereby opening up completely new fields of study such as wide field spectroscopy of the galaxy at velocity resolution of 0.1 km/s. These devices would also be used in remote sensing observations of the atmosphere and oceans and in observations of planetary atmospheres.

Education and Diversity The training of students and postdocs is a very high priority on this proposal. The PI has a record of heavy involvement of graduate students and postdocs in all of his past projects, in which the students learn about instrumentation at a fundamental level, the same is true of the PI on the Chicago sub-award. In the present case, the CRAL will also be advised by Gaier and Weinreb, two of the world's most experienced radio astronomy instrumentalists, and there is no doubt that the young scientists working in the CRAL and in Chicago will learn the skills needed by the next generation of instrument designers and builders in radio astronomy. There will be three postdocs and one graduate student working on this project. In addition it is anticipated that several Caltech undergraduates will work on this project, supported by Caltech Summer Undergraduate Research Fellowships (SURFs). A Caltech undergraduate has had a summer project in the CRAL for the last two summers and he is now doing a senior thesis in the CRAL. Over the 3-year span of this project we hope involve four or five Caltech undergraduates. The graduate student and postdoc training in this forefront detector technology would be a very important component for the future of radio astronomical instrumentation.

7 Results of Prior NSF Support

Award number AST-0506648, "The QUIET Project: Phase 1," PI Bruce Winstein, $4,456,801, 07/01/06 – 06/30/11

QUIET Phase I has been operating in the Atacama desert in Chile since October, 2008. A 9 month run with the 44 GHz (Q-band) receiver was completed and a run with the 95 GHz (W-band) receiver commenced in August 2009 and is proceeding well. This run will be completed by the end of 2010. This is the largest W-band array ever fielded and we have more information on characteristics and performance than any other group. The polarization sensitivity of the two arrays has been measured and each exceeds those fielded by any other experiment at any frequency. The analysis of the Q-band results has been completed and an ApJ paper will be submitted before the end of the calendar year. We are not yet releasing these results, but we can say that our forecasts just for Phase I yield polarization results that surpass the best that have so far been obtained for multipoles less than 600. QUIET is the only experiment using MMIC-based coherent polarization modules, a technology developed at JPL. It allows fast (4 kHz) electronic modulation of the polarization signal and simultaneous detection of the Q and U Stokes parameters. The per-feed sensitivity at 95 GHz, the frequency for the bulk of the QUIET detectors, is at least as good as for bolometric detectors, and parallel efforts on improving amplifier performance show the promise of significantly enhanced sensitivity for QUIET Phase II. Phase I data has been studied sufficiently well that all QUIET technologies have been verified – the stated goal of Phase I. Areas with room for improvement are understood with a clear upgrade path.

Publications resulting from the NSF award include Buder (2010); Cleary (2010); Dumoulin (2010); Monsalve (2010).