QUIET Phase II

The Search for B-Mode Polarization in the Cosmic Microwave Background Using Coherent HEMT Detectors

A Proposed New Initiative for Fermilab

Fritz Dejongh, Scott Dodelson, David McGinnis, Hogan Nguyen, and Albert Stebbins

October 19th, 2009
1 Executive Summary

The Fermilab scientific team consisting of Fritz Dejongh, Scott Dodelson, Dave McGinnis, Hogan Nguyen, and Albert Stebbins are proposing to join the QUIET CMB polarization experiment at the Phase-II level. QUIET is currently funded at the Phase-I level, and has successfully completed operation of a 19-element Q-band telescope in Chile. It is currently operating a 91-element W-band telescope. QUIET Phase-II is factor of 15 increase in array size. The proposal calls for 2 years of construction and 3 years of operation, following Phase-I completion. It is currently under review by the NSF.

The science explores the nature of inflation and HEP physics at the GUT scale. Not only is the science in line with the mission of the FCPA, we also wish to convey our enthusiasm at the prospects of engaging the Lab and ourselves intellectually in this profound science at a very deep level.

This document describes our major proposed contributions to the QUIET Phase-II project. They represent discussions with the QUIET collaboration over a 2-year period. The major contributions would be:

- Production assembly of approximately 1500 W-band modules and spares (section 2).
- Production testing of W-band modules (section 3).
- Receiver Integration of one W-band cryostat at Fermilab, in collaboration with the University of Chicago (section 4).

Section 5 gives an estimate of total cost and effort. In analyzing our proposed contributions, we have carefully considered the lab’s available facilities, the expertise of the technical, engineering, and scientific staff, and the competitiveness and strength of the QUIET collaboration. We feel our proposal is a great fit for Fermilab. It presents a healthy and vibrant collaborative effort between Fermilab, the University community, and other national labs within the US, Japan, and Germany.

We thank the FCPA management, PPD management, and the Associate Director of Research for providing support for us to develop this proposal thus far. We look forward to further discussions and receiving guidance from the Directorate.
2 W-band Module Assembly Plan at Fermilab

2.1 Introduction

The QUIET Phase-II proposal calls for deploying approximately 1500 W-band modules. Caltech, Fermilab, and JPL will be the lead institutions responsible for producing and delivering the modules to the 3 integration sites, for a 2-year production cycle. This document describes the proposed role for each institution, and describes the work at Fermilab in detail.

Caltech and JPL will be responsible for delivering fully cold-tested Monolithic Microwave Integrated Circuits (MMIC) components to Fermilab. These MMIC components utilize High Electron Mobility Transistors (HEMTs), which have the required speed to operate in the W-band (90 GHz). Caltech and JPL are responsible for the overall circuit design, and establishing the component specifications.

Fermilab receives these components, as well as other passive components from vendors, and is responsible for assembling them into modules. Due to the large number of modules, totaling approximately 150,000 components, the technique of choice is automated assembly.

The plan described here is based on the JPL experience with delivering 91 W-band modules in Phase 1. Before describing the assembly work in section 2.4, we provide some technical background material in sections 2.2 and 2.3 to describe how the modules work.

2.2 Functional Description of the W-band Modules

This section provides background material for how the W-band modules work. This material is not important for understanding the W-band production assembly plan. It is included here for completeness, and is more relevant for understanding the production testing plan, which is provided in a separate document.

Each module is attached to the two waveguide outputs of an orthomode transducers (OMT), which uses an internal septum polarizer, shown in figure 2.1. An OMT receives linearly polarized
microwaves from a particular 0.15° diameter circular patch in the sky. It decomposes the fields into $E_x$ and $E_y$, where $x$ and $y$ are orthogonal axes defined by the septum polarizer.

Figure 2.1: Description of Orthomode Transducer used by QUIET
Figure 2.2: Functional diagram of W-band module (left) and the 1.25” x 1.14” module with top clamshell removed (right). Microwaves with amplitudes $E_x + iE_y$ (R) and $E_x - iE_y$ (L) enter from the top. Phase switches in each arm (indicated by ±1) are operated one at a time and provide the Dicke-switching which separates the polarized signal from the total power, as described in the text. The signals pass through low noise amplifiers (LNA), and then enter a series of hybrid couplers, detailed in the text. PS indicates power splitters. The demodulated outputs of detector diodes 1 and 2 are proportional to the Stokes parameter $Q$ while diodes 3 and 4 encode $U$ after demodulation. Filters have been omitted for clarity.

It rotates one polarization direction into the other, recombines them so that only one polarization state is propagated, and then forms two linear combinations with amplitudes $E_x + iE_y$ (R) and $E_x - iE_y$ (L) respectively. These two linear combinations are sent to the two waveguide inputs of the module. The module amplifies these fields, manipulates them, and returns the time-averaged electric field double correlations $<E_x^2>$, $<E_y^2>$, and $<E_xE_y>$ that are needed to calculate the Stokes $Q$ and $U$ polarization observables.

The functional diagram of a module is given in figure 2.2. There are two amplifier chains, one for each waveguide input. The two amplifier chain outputs are combined in a (0°, 180°) hybrid coupler, whose two outputs are sampled by 2 “detector diodes”. These are simply RF rectifier diodes, converting the RF signal into a DC voltage. The two outputs of the (0°, 180°) circuit are combined
again in a (90°, 270°) hybrid coupler, and subsequently sampled by 2 more detector diodes. Therefore, the detector diodes sample linear combinations of $E_x$ and $E_y$, with complex coefficients. And it can be shown that the 4 detector diode output voltages encode the correlations above. The detector diodes voltages are sampled by 800 kHz FADC’s.

An important feature is the high speed switching circuitry internal to the modules. Each of the two amplifier chains contains an active phase switch (PS) that can either maintain (+1) or invert (-1) the signal, for a total of 4 possible phase states: (+1,+1), (+1,-1), (-1,+1), and (-1,-1). By sampling all 4 phase states, the 4 detector diodes sample additional linear complex combinations of the amplified signals. This allows the relative gains of the two amplifier chains to be calibrated away. For Phase-I operation, the two PS’s switched at 4 kHz and 50 Hz respectively. This allowed for canceling the time variations of the gains over a large frequency range and resolving other important systematics.

For Phase-I, when the Stokes Parameters Q and U have been calculated using information from all 4 phase states, in an operation called “Double Demodulation”, the 1/f noise component is essentially absent at frequencies higher than 0.1 Hz.

2.3 Component Description of the W-band Modules

A QUIET W-band module consists of 106 miniature components attached to a 1.25” x 1.14” brass clamshell via high temperature-cure silver epoxy. Figure 2.2 shows a picture of the module, with the top clamshell removed. The components are listed in table 2.1. There are passive RF components such as waveguide antenna couplers, microstrips and waveguide bends, band passes filters, and hybrid couplers. There are active RF components such as the low noise amplifiers (LNA), phase switches (PS), and detector diodes. The active components are DC-biased and utilize capacitors for power filtration. The electrical connections are made via wire bonding or ribbon bonding. The component sizes range from as large as 2 mm x 3 mm, to as small as 230 μm x 230 μm. The RF and non-RF components have a 12.5 μm and 50 μm placement accuracy requirement, respectively.
Table 2.1: Components in the W-band Module

<table>
<thead>
<tr>
<th>Component</th>
<th>Responsible institution</th>
<th>Fermilab Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Noise Amplifiers</td>
<td>Caltech/JPL</td>
<td>Deliver to Fermilab</td>
</tr>
<tr>
<td>Detector Diodes</td>
<td>Caltech/JPL</td>
<td>Deliver to Fermilab</td>
</tr>
<tr>
<td>(0,180) and (90, 270) hybrid couplers</td>
<td>Caltech/JPL</td>
<td>Deliver to Fermilab</td>
</tr>
<tr>
<td>Phase Switches</td>
<td>Caltech/JPL</td>
<td>Deliver to Fermilab</td>
</tr>
<tr>
<td>Brass Chassis</td>
<td>Specified by Caltech/JPL and</td>
<td>Fermilab to oversee</td>
</tr>
<tr>
<td></td>
<td>machined by an outside vendor</td>
<td>procurement process, vendor qualification and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>organize delivery schedule</td>
</tr>
<tr>
<td>Other Passive Components:</td>
<td>Specified by Caltech/JPL and</td>
<td>Fermilab to oversee</td>
</tr>
<tr>
<td>waveguide couplers,</td>
<td>purchase from Applied Thin Film</td>
<td>procurement process and</td>
</tr>
<tr>
<td>microstrips, microwave bends,</td>
<td>Products, Freemont, CA</td>
<td>organize delivery schedule</td>
</tr>
<tr>
<td>capacitors, band pass filters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miniature microwave absorbers for</td>
<td>Purchase from Emerson &amp; Cuming</td>
<td>Fermilab to oversee</td>
</tr>
<tr>
<td>internal module isolation</td>
<td></td>
<td>procurement</td>
</tr>
<tr>
<td>RF gaskets and silver epoxy</td>
<td>Purchase from Epotek</td>
<td>Fermilab to oversee</td>
</tr>
<tr>
<td></td>
<td></td>
<td>procurement</td>
</tr>
</tbody>
</table>
2.4 Overview of Fermilab Work

The assembly work per module consists mainly of attaching 106 miniature components onto a brass chassis, performing the wirebonding, and performing the production testing. The step of production testing is covered in another document. This represents an attachment of approximately 150,000 components. Due to the large volume of parts, automated assembly techniques will be used.

The assembly work is similar in many ways to a silicon detector assembly project for an HEP collider experiment. For this reason, we would utilize the experience of the Sidet staff\(^1\) and the Sidet Lab D 2350 ft\(^2\) class 10,000 clean room. The placement accuracy and ESD requirements are similar to HEP silicon detector needs. The important exceptions are:

- there are far fewer wire bonds than a typical HEP silicon detector
- the components are smaller, requiring smaller vacuum pickup and epoxy dispensing tools to be used
- due to the large temperature difference between the assembly process (300K) and operation (20K), care is needed to minimize thermal stresses. Components with similar CTE to metals will be used.
- the heat load of approximately 40 mW per module (dominated by the LNAs) is far less than a typical HEP silicon detector, which typically performs highspeed digitization at the front end.
- the majority of the components is relatively inexpensive and does not need special handling. The only components requiring special handling are the LNAs. In contrast, nearly every component in an HEP silicon detector requires special handling and represents a huge investment of time and money.

The tooling at Sidet will need to be modified for this work. New vacuum pickup and epoxy dispensing tools will need to be fabricated. This is a relatively straight forward process.

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\(^1\) the Sidet staff has extensive experience with silicon projects for CDF, D0, CMS Tracker Outer Barrel, and CMS Forward Silicon Pixels. Currently it is engaged in CCD assembly for DECAM, and silicon assembly for the PHENIX project at BNL.
The single most important upgrade is to retrofit 4 motorized Zeiss 500 coordinate measuring machines (CMMs) to perform automated assembly (figure 2.3). The tools would be mounted on the CMM optical head, and computer-controlled to perform the die attachment step:

- dispense silver epoxy into desired location on chassis
- pickup component from tray with the correct orientation (rotation)
- place component into desired location on chassis

The Zeiss machines have a large work space and a positioning accuracy exceeding the needs of QUIET. A single pick-and-place operation has been measured to require 15 seconds, which is adequate for QUIET needs. However, the Zeiss machines are currently interfaced to very old Hewlett Packard computers running proprietary Zeiss software, with limited I/O and interrupt handling capability.

A critical upgrade is to replace the HP machines with modern PC’s running Labview and Vision software. The Vision System software provides automated pattern recognition and parts measurements. It is needed for automatic determination of the parts location and orientation. The Labview software is now a widely-accepted multi-purpose graphical programming tool that is easy to use by non-experts and can programmed without extensive computing expertise².

We believe this upgrade will turn the Zeiss 500’s into very powerful general purpose machines. The upgrade will benefit not only QUIET Phase-II, but also the future silicon assembly projects at Sidet.

² The Sidet staff recently programmed the Vision and Labview software to automatically measure the size of plastic extrusions for the NOVA experiment.
Figure 2.3: Zeiss 500 machine, as being utilized for epoxy deposition for the CDF Run-IIb R&D project.
2.5 Production Rate

We estimate the production rate based on the availability and the intrinsic speed of the Zeiss machines. We plan on using 4 machines, out of an available number of 8. These machines are in good working condition but are considered obsolete. However, Sidet has sufficient spare parts, and the staff is trained to perform machine maintenance and calibration. We measured an intrinsic pick-and-place speed of 15 seconds per component.

Additional labor assumptions are:
- 4 mechanical technicians (Class II) for operating the Zeiss machines.
- 1 mechanical technician (Senior Tech) for wirebonding.
- 1 mechanical technician (Technical Supervisor) for inspection and supervision.
- 5 work hours per 8-hour work day, and 260 work days per year.

Assuming that personnel is allowed to be dedicated to this project, we estimate 0.1 years for Zeiss machine operation, 0.9 years for wire bonding, and 1.3 years for inspection and supervision. This is in agreement with experience with the CMS Tracker Outer Barrel Silicon Project, where automatic assembly was also utilized. The actual automatic assembly machine operation is relatively brief. The dominant labor is in the inspection, wirebonding, and supervision. Table 2.2 summarizes the production rate estimates for 1600 W-band modules (100 spares).

For QUIET Phase-II, we need to meet a production rate of delivering modules in 2 calendar years. Assuming that existing light-duty mechanical technicians are allowed to be dedicated to this project, we can meet this production rate.
Table 2.2: Labor and Time Estimate for Production

Time Estimate assuming 100% Efficiency

<table>
<thead>
<tr>
<th>Parts Placement utilizing 4 Tech-II Full time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Place One Part (minutes)</td>
</tr>
<tr>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>0.75</td>
</tr>
</tbody>
</table>

Inspection time, setup, organization (Tech Supervisor)

<table>
<thead>
<tr>
<th>Time per module (hours)</th>
<th>Number of Modules</th>
<th>Total Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1600</td>
<td>1600</td>
</tr>
</tbody>
</table>

Wirebonding Time (Sr. Tech)

<table>
<thead>
<tr>
<th>Time Per Module (hours)</th>
<th>Number of modules</th>
<th>Total Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>1600</td>
<td>1200</td>
</tr>
</tbody>
</table>

Actual Calendar Time Estimate

<table>
<thead>
<tr>
<th>Total assembly time (hours)</th>
<th>Total inspection/org time (hours)</th>
<th>Total Wirebonding Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1600</td>
<td>1200</td>
</tr>
</tbody>
</table>

Number of days (5-hour work day)

<table>
<thead>
<tr>
<th>Number of days</th>
<th>Total time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>320</td>
</tr>
</tbody>
</table>

Number of Personnel

<table>
<thead>
<tr>
<th>Number of Personnel</th>
<th>Total Wirebonding Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>240</td>
</tr>
</tbody>
</table>

Number of days (260 work days/year)

<table>
<thead>
<tr>
<th>Number of days</th>
<th>Total Wirebonding Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>240</td>
</tr>
</tbody>
</table>

Number of years

<table>
<thead>
<tr>
<th>Number of years</th>
<th>Total Wirebonding Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.096153846</td>
<td>0.923076923</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of years</th>
<th>Total Wirebonding Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1230769231</td>
<td>0.923076923</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of years</th>
<th>Total Wirebonding Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1230769231</td>
<td>0.923076923</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of years</th>
<th>Total Wirebonding Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1230769231</td>
<td>0.923076923</td>
</tr>
</tbody>
</table>
2.6 Experience from Phase-I Production Assembly

JPL was responsible for delivering 91 W-band modules to the Chicago integration site. The first half of the modules was manually assembled at JPL. The remaining modules were assembly jointly by NxGen and JPL. NxGen performed the automated die attachment procedure, while JPL completed the remaining steps of wire/ribbon bonding, RF-gasket attachment, and attaching the Eccosorb isolators\(^3\). The modules were then sent to Chicago for integration into the receiver.

However, there was significant rework requiring some fraction of the modules to be sent back to JPL for repair. If a module does not work satisfactorily, a process of troubleshooting is carried out to identify the location of the problem(s). Due to time constraints, the lack of certainty about the origin of the problem and the desire to minimize the number of times a module is opened, rework may involve many changes at once.

For example, a loose bond may be re-bonded, an apparently loose substrate is replaced, and epoxy is cleaned from various areas. Then the module is tested again. If the module works, it is often not obvious which of the various ‘fixes’ resulted in the improvement. Therefore it is not always possible to associate a given problem with its solution. In the example given, it is not clear if a bond had failed or a substrate was loose. This makes it difficult to compile bond or die-attachment failure rates in general.

A common problem with the modules was a low signal on one or both legs of the amplifier chain. It was usually difficult to identify which MMIC in the chain was responsible, and so the MMICs were replaced in a process of elimination. Thus, some MMICs were inevitably replaced even though they were functioning correctly. Also, if a MMIC chip was replaced on one chain, it was not always possible to ensure that it was from the same wafer as the corresponding chip on the other chain. If the new chip was from a different wafer, then the corresponding chip on the other chain would also be replaced. Therefore, not every case of MMIC replacement was due to a faulty chip which might result from a die-attachment fault.

\(^3\) Small Eccosorb microwave absorbers and gaskets are used to isolate the circuit components from each other. They prevent unwanted RF leakage.
Taking the above into consideration, for 5/48 modules, loose substrates were recorded which were replaced. For 12/48 modules, the replacement of amplifier, phase-switch, or hybrid chips was recorded.

The following table 2.3 summarizes the repairs performed on modules built by NxGen/JPL and other important lessons during the assembly procedure.

<table>
<thead>
<tr>
<th>Assembly Step</th>
<th>Issues Encountered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die Attachment at NxGen</td>
<td>Initial die attachment used insufficient amount of epoxy. The die components flexed during wirebonding, which compromised the wire and ribbon bond strength.</td>
</tr>
<tr>
<td>Die Handling at NxGen</td>
<td>Handling of very small parts (230 μm x 230 μm capacitors) was difficult. NxGen used up more parts than required. There is evidence that some parts were also manually assembled.</td>
</tr>
<tr>
<td>MMIC Handling</td>
<td>MMIC chips from failed modules were analyzed and were visibly damaged. It is unclear where the damage occurred. It occurred either during the MMIC preparation process, or during the die attachment process at NxGen.</td>
</tr>
<tr>
<td>Wirebonding failure</td>
<td>24/48 modules had at least 1 wirebonding problem. There were 31 wirebonding problems in total. These fall into two categories: bonding errors (11/31, e.g. missing or misplaced bonds) and bond quality (20/31, e.g. bonds too low or high and therefore shorting to the brass chassis). However, considering that a typical module will have over 200 bonds, the failure rate per bond is 0.3%.</td>
</tr>
<tr>
<td>Miscellaneous failures</td>
<td>Damaged phase switches and hybrids due to handling Eccosorb and Indium(^4) crushing bond Insufficient epoxy and epoxy shorting components</td>
</tr>
</tbody>
</table>

\(^4\) For Phase I, the LNAs were attached by Indium, not silver epoxy. For Phase II, we plan to use entirely silver epoxy.
2.7 R&D Plan and Milestones Before Production

Considerable R&D has been performed, in the context of upgrading the tooling at Sidet. We summarize the important ones here:

- Tooling to handle small parts and for dispensing epoxy have already been fabricated. They are awaiting trial run in late October 2009. See figure 2.4.

- The upgrade of the Zeiss machine has been analyzed. The digital communications protocol necessary to control the Zeiss motors and position readback have been established. They have been determined to be relatively straight-forward. A digital I/O board is being designed. Prototype boards will be delivered in late 2009.

These milestones assure us that we have the right assembly tools (to allow initial manual assembly), and that retrofitting the Zeiss machines for automated assembly will be straight-forward. The following are important R&D tasks, yet to be done, relating to mechanical and thermal properties of the module:

- thermal and vacuum mechanical stress analysis of the module.
- studies of the wirebond and epoxy adhesion strength as a function of thermal cycling.

We have access to a ready-to-use 5 Watt 20 Kelvin cryocooler, vacuum vessel and dry pumps at Fermilab for performing thermal cycling studies. These studies were not fully done for Phase-I, and we believe they will help improve the yield for Phase-II. Table 2.4 summarizes the milestones to be met before we can declare production readiness.

5 The group performing the tooling and Zeiss machine upgrade have extensive experience with fabricating automated precision tooling. Some of the relevant experience include the Fermi-Glast satellite cosmic veto shield, the CMS magnetic field mapper, the COUPP pressure vessel control, and the critical mechanical assemblies for the SDSS fiber spectroscopy.
Figure 2.4: Glue dispensing tool to guarantee uniform glue thickness (bottom of picture), and vacuum pickup tools riding on an air bearing (top of picture). These are being commissioned in late October 2009.
Table 2.4: Key R&D milestones before production, assuming a technically-limited schedule.

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commissioning of tooling to handle small parts and epoxy dispenser</td>
<td>October 2009</td>
</tr>
<tr>
<td>Assembly of a dummy representative module via manual control of the Zeiss 500 machine.</td>
<td>December 2009</td>
</tr>
<tr>
<td>Commissioning of Zeiss 500 with a modern PC and new I/O board.</td>
<td>December 2009</td>
</tr>
<tr>
<td>Completion of the Thermal and vacuum mechanical stress analysis of the module.</td>
<td>December 2009</td>
</tr>
<tr>
<td>Completion of wirebond and epoxy adhesion strength studies.</td>
<td>February 2010</td>
</tr>
<tr>
<td>Commissioning of Vision Software to perform automatic determination of part location and orientation.</td>
<td>April 2010</td>
</tr>
<tr>
<td>Commissioning of Labview Software for overall assembly control.</td>
<td>May 2010</td>
</tr>
<tr>
<td>First pre-production module assembled by automated techniques</td>
<td>May 2010</td>
</tr>
<tr>
<td>Completion of layout of Lab D for QUIET production run.</td>
<td>July 2010</td>
</tr>
</tbody>
</table>
2.8 Summary of Fermilab Cost and Effort for Production Assembly

This section summarizes our estimate of the cost and effort for all aspects related to assembly. We include the tooling development costs. We use 30% contingency for directly purchasable items. We use 50% contingency for software and precision tooling development, even though our analysis indicates that the tooling fabrication and software development will be straightforward.

Table 2.5

<table>
<thead>
<tr>
<th>Material Costs</th>
<th>Cost Per Item</th>
<th>Items</th>
<th>Extended Cost</th>
<th>Contingency</th>
<th>Contingency ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary Stage</td>
<td>1411</td>
<td>4</td>
<td>5644</td>
<td>30%</td>
<td>1693.2</td>
</tr>
<tr>
<td>Linear Stage</td>
<td>1471</td>
<td>8</td>
<td>11768</td>
<td>30%</td>
<td>3530.4</td>
</tr>
<tr>
<td>Motor Controller</td>
<td>800</td>
<td>12</td>
<td>9600</td>
<td>30%</td>
<td>2880</td>
</tr>
<tr>
<td>Vacuum Pickup Tools</td>
<td>100</td>
<td>23</td>
<td>2300</td>
<td>30%</td>
<td>690</td>
</tr>
<tr>
<td>Carriage Trays</td>
<td>100</td>
<td>10</td>
<td>1000</td>
<td>30%</td>
<td>300</td>
</tr>
<tr>
<td>Miscellaneous Tooling</td>
<td>10000</td>
<td>1</td>
<td>10000</td>
<td>30%</td>
<td>3000</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td>40312</td>
<td></td>
<td>12093.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Labor Cost for Developing Tooling</th>
<th>Number of Weeks</th>
<th>Personnel</th>
<th>Extended Cost</th>
<th>Hr Rate</th>
<th>Contingency</th>
<th>Contingency (dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labview Programming Zeiss</td>
<td>20</td>
<td>Computing Professional</td>
<td>62,624</td>
<td>78.28</td>
<td>50%</td>
<td>31312</td>
</tr>
<tr>
<td>Programming</td>
<td>4</td>
<td>Senior Technician</td>
<td>9448</td>
<td>59.05</td>
<td>50%</td>
<td>4724</td>
</tr>
<tr>
<td>Labor to build tooling Sum</td>
<td>10</td>
<td>Senior Technician</td>
<td>23,620</td>
<td>59.05</td>
<td>50%</td>
<td>11,810</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td>85,854</td>
<td></td>
<td></td>
<td>85,854</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Labor Cost for W-band Assembly</th>
<th>Labor Type</th>
<th>Number of Hours</th>
<th>Extended Cost</th>
<th>Hr Rate</th>
<th>Contingency</th>
<th>Contingency (dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wirebonding Assembly</td>
<td>Sr. Tech</td>
<td>1200</td>
<td>70860</td>
<td>59.05</td>
<td>30%</td>
<td>21258</td>
</tr>
<tr>
<td></td>
<td>Technician-II</td>
<td>500</td>
<td>23375</td>
<td>46.75</td>
<td>50%</td>
<td>11687.5</td>
</tr>
<tr>
<td>Inspection and Organization</td>
<td>Technical</td>
<td>1600</td>
<td>130880</td>
<td>81.8</td>
<td>50%</td>
<td>65440</td>
</tr>
<tr>
<td>Sum</td>
<td>Supervisor</td>
<td></td>
<td>228115</td>
<td></td>
<td></td>
<td>98385.5</td>
</tr>
</tbody>
</table>
3 QUIET Phase-II W-band Module Testing Plan

3.1 Introduction

The QUIET Phase-I W-band receiver uses 91 modules, each of which was manually tested and thoroughly studied and optimized. The Fermilab group has made three trips to JPL and held several discussions to understand the Phase-I testing process and testing requirements for Phase-II. Since Phase-II will consist of three receivers with 499 modules each, it is necessary to automate and streamline the testing process relative to Phase-I. This should be aided by an R&D effort at Caltech and JPL to improve the performance and uniformity of the modules. This document describes our plan, based on Phase-I experience, for testing W-band modules prior to their installation in the focal plane.

3.2 Overview of Module Operation

Fig. 3.1 shows a functional diagram of a W-band module. A module contains two legs, one for each polarization component of the input. Each leg includes three low-noise amplifier (LNA) stages, each of which contains four High Electron Mobility Transistor (HEMT) stages. There is both on-chip (Fig. 3.2) and off-chip sharing of the HEMT gate and drain biasing. Since the first stage amplifier has the greatest influence on noise, independent control of its gate and drain is provided. The second and third stages have independent gate control but share drain biasing.

Each leg also includes a phase switch, which delays the signal either 0 or 180 degrees. Each module contains four diode rectifiers, from which the total power in the Q and U polarization components is extracted.

The low-voltage biases needed to operate the module are:

- 3 independent gate voltages per leg for the LNAs.
- 2 independent drain voltages per leg for the LNAs.
- 2 voltages per phase switch, one for each phase state. If both voltages are on or both are off, any signal is attenuated.
- 4 biases per module for the diode detectors.

There are a total of 18 biases needed per module.
The modules can be operated and tested warm, but are eventually cooled to 20K for the best noise performance. The needed bias voltages change with temperature so warm settings do not apply to cooled modules.

Figure 3.1: Sketch of a W-band module.

Figure 3.2: Photo and block diagram of one MMIC LNA.
3.3 Summary of Phase-I Testing Process

The first step in the testing process is a basic power-on test. This tests that the components are functional and connections are in place. The procedure is simply to turn on bias voltages and read back the currents to check if they’re in a reasonable range. This test is first done warm, and any problems are fixed. The module can then be rechecked cold.

The next step was to test the amplifiers and bandwidth using a frequency-swept signal, with the setup illustrated in Fig. 3.3. A magic tee is used for the input to the module, and provides equal inputs to the two legs. While this test can be done warm, it was performed cold for all modules in Phase-I.

This test also provides an approximate set of optimized low-voltage bias settings. The maximum signal-to-noise occurs when the gains and phases of the two legs of the module are matched. With this matching, and equal inputs to the two legs, half of the diodes have a null output for one state of the phase switches, and the other half of the diodes have a null output for the opposite state of the phase switches. Observing the diode outputs and adjusting biases by hand would find settings that achieve the desired matching.

These settings were then used as starting points for the final optimization of the biases after the modules were installed on the receiver. While on the receiver, the signal-to-noise of a small polarization signal can be optimized, but there is no direct way to verify the gain and phase matching of the two legs, so these starting points were felt to be helpful.

![Figure 3.3: Setup for the frequency sweep test.](image-url)
Finally, the noise temperature of the module was measured by measuring the diode output for inputs at various equivalent black-body temperatures, and extrapolating to zero input.

The overall experience from Phase-I is that manual testing of cold modules is very time consuming, given the time needed to cool the module and do the hand tweaking of the many biases. However, every module could be made to work, and bias settings known to be gain-matched provided confidence in the final module optimization.

3.4 Proposed Phase-II Testing Process

Our plan is to develop a warm test stand that automates the power-on test and RF frequency-sweep tests. We will also have a test stand to thermally-cycle modules down to 20 K and then back up to room temperature. Thermal cycling will expose weak bonds and die attachment issues. We have a ready-to-use vacuum vessel and cryocooler with a rating of 5W @ 20K. We’ve determined, via actual measurements, that we can cool down 350 grams of brass (equivalent to 7 modules) in about 2 hours: one hour for pump down, and one hour for cool down. The thermal cycling test is not a time intensive activity. We plan to perform these tests on all modules.

We will do especially intensive studies of the first ~20 modules to come off the assembly line. This will include bringing them to existing test stands at JPL or Caltech where we can perform cold tests and measure noise temperatures. Cold test stands are also available at collaborating institutions in MPI and KEK. After that, a small fraction of modules will be sent out for cold tests to monitor performance trends throughout production.

Therefore most modules will be operated cold for the first time after they are installed on the receiver, and will not have the starting points for the bias optimization that were provided for Phase-I. However, we feel this is necessary in order to keep the testing effort to a reasonable level, and for the following reasons believe it is adequate for optimizing the modules:

- From Phase-I experience, it is believed that the optimization procedure can work without the starting point, there is just less confidence that the best optimum can be found.
There were various tests developed in Phase-I to check the noise temperature and bandwidth of modules on the receiver. If these checks can be done at the integration stage, and a module checks out well for both signal-to-noise and bandwidth, it is very likely that the legs are well gain-matched.

Improvements in module uniformity from the R&D program being conducted at Caltech and JPL should help define better average starting bias settings.

We will study whether it is possible to predict cold bias settings from warm bias settings. If so, warm settings derived from our test stand can provide good starting points for all modules.

3.5 Summary of Fermilab Cost and Effort for Production Testing

Table 3.1 below captures cost estimates related to developing, constructing, operating, and analyzing the test stand data, for the duration of the production run.

<table>
<thead>
<tr>
<th>Material Costs</th>
<th>Cost Per Item</th>
<th>Number Of Items</th>
<th>Extended Cost</th>
<th>Contingency</th>
<th>Contingency ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module Testing Hardware: Computers, NI Modules, electronics, Cryocooler, RF equipment, vac chamber.</td>
<td>100000</td>
<td>1</td>
<td>100000</td>
<td>30%</td>
<td>30000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other Labor</th>
<th>Labor Type</th>
<th>Number of FTE-years</th>
<th>Extended Cost</th>
<th>Hr Rate</th>
<th>Contingency</th>
<th>Contingency (dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Testing</td>
<td>EF-II or Electrical Engineer Equivalent (Testing Engineer)</td>
<td>2</td>
<td>339,582</td>
<td>81.63</td>
<td>30%</td>
<td>101,875</td>
</tr>
<tr>
<td>Teststand Assembly Technician</td>
<td>Mechanical Sr. Technician</td>
<td>0.5</td>
<td>61,417</td>
<td>59.05</td>
<td>30%</td>
<td>18,425</td>
</tr>
<tr>
<td>Computing support for teststand and cryostat assembly</td>
<td>Computing Professional Engineer II (average EE and ME)</td>
<td>0.5</td>
<td>81,408</td>
<td>78.28</td>
<td>30%</td>
<td>24,422</td>
</tr>
<tr>
<td>Electrical and Mechanical Engineering required for Test Stand Design and</td>
<td>0.5</td>
<td>91,343</td>
<td>87.83</td>
<td>30%</td>
<td>27,403</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1
4 QUIET Phase-II Receiver Integration Plan at Fermilab

4.1 Introduction

The QUIET Phase-II proposal calls for the deployment of 3 W-band receivers, each containing 499 W-band modules. There is planned to be 3 sites for receiver “integration”, with one proposed site being at Fermilab.

The integration work would be primarily a partnership between QUIET collaboration members from the University of Chicago and Fermilab. This document describes the work involved, and outlines a suitable role for each institution. The plan is guided by experience with integrating the Phase-I receiver at the University of Chicago in 2008-2009. A man-power and cost estimate is given for the Fermilab effort.

4.2 Overview of Work

The receiver is defined to consist of the following components:

1. The vacuum vessel and everything contained therein
2. The 20 Kelvin cryocooler system, including the compressors
3. The vacuum pumping system
4. The electronics and the data acquisition computer

Figure 4.1 shows two views of the QUIET Phase-I 91-element W-band 22” diameter cryostat, which is about 5 times smaller than the proposed 42” diameter 499-element Phase-II cryostat. The integration work is defined to include:

1. Receiving all necessary components from the QUIET institutions, and assembling them.
2. Performing tests as necessary to guarantee that the receiver is science-capable.
3. Preparation for shipping the receiver to Atacama, Chile.

The following sections describe the steps in more detail, apart from shipping.
4.3 Location for Integration Work

The integration work would take place in Lab A, part of the Sidet complex at Fermilab. Currently Lab A is being used for assembling the Dark Energy Camera (DECam). The DECam assembly work is expected to complete in advance of the work described here.

The Lab A infrastructure (figure 4.2) includes a 20T crane, a 6’ wide x 9’ high entrance door for easy transportation of large items by a fork-lift truck, readily available single phase and three phase AC208/240, a building height exceeding 45 feet, and approximately 2000 square feet of usable lab space. Lab A has backup UPS units, and a natural gas backup electrical generator.

The QUIET cryocooler system will use air-cooled compressors, therefore chilled water will not be needed. The cooling system will expel 38 kWatts of heat, which is 2/3 of the Lab A cooling capacity. There will be office space available to house visiting QUIET collaborators. Therefore Lab A would allow the integration work to proceed safely, smoothly, and without requiring large changes to the building infrastructure.
4.4 Receiving and Assembling Components

Table 4.1 shows the detailed list of items that will be received at Lab A.

<table>
<thead>
<tr>
<th>Item</th>
<th>Institution Responsible for Delivery to Fermilab</th>
<th>Institution Responsible for Final Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-band Modules</td>
<td>Fermilab</td>
<td>Fermilab</td>
</tr>
<tr>
<td>Electronics, cabling, and DAQ and computer</td>
<td>Chicago and KEK</td>
<td>Chicago</td>
</tr>
<tr>
<td>Software for DAQ and Optimization</td>
<td>Chicago and KEK</td>
<td>Chicago</td>
</tr>
<tr>
<td>Cryocooler System</td>
<td>Columbia University</td>
<td>Fermilab</td>
</tr>
<tr>
<td>Vacuum Pump</td>
<td>Columbia University</td>
<td>Fermilab</td>
</tr>
<tr>
<td>Vacuum Tank and</td>
<td>Columbia University</td>
<td>Fermilab</td>
</tr>
</tbody>
</table>
There are three major subsystems: the vacuum vessel and window, the cryocooler system, and the detector array, which is housed inside the vacuum vessel and cooled to 20 K.

The detector array is 7 subarrays arranged in a flower pattern: 6 subarrays of 68 modules surrounding a center subarray of 91 modules (see figure 4.3). Each subarray (figure 4.4) consists of the platelet feed horn system, the OMTs, the W-band modules, and the Module Assembly Boards (MABs), which provide power, protection, and signal connections to the W-band modules. The cooling of the detector array will be achieved by copper-braid attachment from the coldheads to the interface plate of the platelet horn system. It is envisioned that the 91-module center subarray be reused from Phase-I.

We expect the assembly task to occur coincidentally with production. In other words, the assembly task will commence before completed delivery of all items, as the items will have a finite production delivery schedule.

The assembly task will also occur in between the testing steps (described below). This guarantees that problems are caught and fixed before proceeding to the next assembly step. Fermilab would be responsible for mechanical assembly (ie. Vacuum tank, cryocooler, pump), and would provide mechanical technicians for these tasks using existing tools in Lab A. Fermilab would provide a stand to hold the vessel in a manner for safe and easy work access. This will likely require modest mechanical engineering to perform the stress calculations.

Instructions for vacuum vessel, cryocooler, and platelet assembly would be provided by Columbia, Princeton, and Miami. No specialty equipment or tasks, such as welding or machining is expected. Fermilab technicians will handle crane and fork-lift truck operations, equipment storage, and cleanup.
Fermilab staff will perform “Job Hazard Analysis” if deemed necessary. The University of Chicago would provide personnel to assemble electronics and cabling, DAQ, and computing. Fermilab QUIET scientist will handle interfacing the computers to the lab’s network.

Figure 4.3: Horn Platelet Array for 499 elements (left) and the center 91 element (right). The width is approximately 40”.
Figure 4.4: Detector detail. The Module Array Boards are not shown, but would attach directly to the module (right hand side of figure).

Figure 4.5 shows the assembly and testing steps. Assembly steps are shown in rectangles. Testing steps are shown in ovals. The assembly revolves around installing 7 subarrays (either 68-element or 91-element), one after the other in a sequential fashion. This minimizes the number of mechanical operations performed on the (very delicate) modules, MAB, and cables.
4.5 Performing Tests to Guarantee a Science-Capable Receiver

Fermilab "Operational Readiness Clearance" will be needed prior to operation. This will require a safety review of the window, the vacuum vessel, and the cryogenics. A QUIET Fermilab scientist will be responsible for obtaining lab approval. The FEA and long term studies of the window material, made of ultrahigh molecular weight polyethylene, is already under way at the lab.

The first step is to test the assembled vacuum vessel and cryocooler system, in the absence of RF components and electronics. Fermilab mechanical technicians will test the vessel for vacuum leaks. This is a non-trivial step, as the vessel has many vacuum penetrations that need to be checked. Following this, the cryocooler system will be tested using heaters to verify the required cooling capacity.
After installation of a subarray, another vacuum pumping and cool down cycle would be performed. Fermilab technicians will repair leaks as they arise using readily available leak checking equipment at Sidet.

A critical test is to “optimize” the modules while at 20 Kelvin operation. At this stage, the modules have already been verified to have good electrical connections during the production testing task (see production testing plan). The test will:

- verify the end-to-end electrical connection from the modules, through the vacuum interfaces, to electronics external to the cryostat.
- verify that the LV power consumption of the modules meet specifications.
- verify that the modules, operated with nominal LV settings, can detect a signal from a cold load whose polarized signal is modulated in time.
- determine the LV settings that optimize the modules’ polarized signal sensitivity.
- verify that the resultant optimized modules meet specifications in signal sensitivity, white and 1/f noise frequency profiles, and noise temperature.
- using an RF signal generator, verify that the optimized modules have the required input bandwidth sensitivity in the W-band.

The cold load used for the optimization will be the one Fermilab built for QUIET Phase 1. Fermilab would provide the rotatable wiregrid used to polarize the load and modulate electric fields. The items are shown in figure 4.6.

The University of Chicago would be responsible for the optimization testing, which includes assembly of the FE and DAQ hardware, and providing software and analysis tools. Assuming that polarized signals are seen by the modules, the software automatically adjusts the LV settings to optimize the performance. All data and LV settings will be recorded. In Phase I, the LV settings were found within about 8 hours of running. Figure 4.7 shows the output of such an optimization run.
Figure 4.6: The black body load and 24" diameter grid built for QUIET Phase-I. The black body load would be housed in a vacuum vessel and cryostat, also built for Phase-I.

Figure 4.7: An optimization run of the Phase-I 91-element array. The array views a 77K black body load, seen through the grid shown in figure 4.6. The grid imposes approximately 2K of temperature polarization. The grid rotates at constant angular frequency of about 0.15 Hz.

We determine all the module performance features and then at the end, we decide which ones need further work. This strategy minimizes the mechanical operations done to the receiver.
An important outcome of this test is the overall array sensitivity. This together with the band passes for each detector found with the sweeper will give us all the important characteristics to predict performance on the sky.

4.6 A Collaborative Effort

This document has outlined suitable roles for the University of Chicago and Fermilab. However, we emphasize that this is a collaborative effort. The collaborators would naturally be expected to become experts in all aspects of the assembly and testing.

Additional collaborators from outside of Chicago and Fermilab may also choose to participate in the integration effort at Fermilab. The integration work is important training ground for the collaboration. Experience in Phase I has shown the importance of building a strong technical base within the collaboration, in order to provide good expertise coverage at the Chile site.

4.7 Summary of Fermilab Manpower Requirements and Costs for Receiver Integration

For the Phase-I integration work, the cost of material and services purchases was at the $50K level. The integration work included constructing the mechanical assembly for cable penetration through the vacuum vessel, purchasing additional cables and connectors, and cable plant organization. This was at the $10K level.

The integration work also included the cost of thermal regulation electronics (silicon diode thermometers) and miscellaneous vacuum equipment (pressure and humidity gauges). There were small additional costs for purchasing more spare consumable parts for the vacuum vessel (O-rings, Indium) and platelet array system (specialty screws).

The QUIET Phase I array optimizer cost exceeded $10K. This includes Eccosorb foam for use in making cryogenic loads, Styrofoam and Zotefoam insulation, and motorized rotatable mechanical plates. The cost of the rotatable wiregrid assembly built by Fermilab using US/Japan funding, was about $5K. Finally, the cost of dry air, LN2, LAr, and helium was about $300/week.
For Phase-II, we can expect some of these costs to be moved to the subsystems costs, rather than integration. However, we will include comparable costs for thermometry, cabling, and miscellaneous hardware.

There is additional relief by reusing components from Phase-I. In particular, we will use the existing 20 Kelvin load already at Fermilab. This is driven by a cryocooler, and so there is no significant cost for LN2, LAr, and dry air needed to prevent window frosting. It also simplifies the lab-required safety analysis, since there is no significant ODH (oxygen deficiency hazard) concerns with using cryocoolers.

Finally, we expect only incidental use of dry air, N2, LN2, and LAr. These costs as well as electrical power are typically provided by internal building infrastructure funding, and not charged to projects.

Table 4.2 summarizes the major items required from Fermilab for Phase II. The material and services costs appear comparable. However, the services work (light duty tech-shop machining) that was performed and paid explicitly for Phase I, now appear under general mechanical technician labor to be provided by the lab.
Table 4.3: Request to Fermilab for Phase II Receiver Integration

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of Lab A Infrastructure and office space for QUIET collaborators.</td>
<td></td>
</tr>
<tr>
<td>Occupancy of Lab A is expected to last 2 years.</td>
<td></td>
</tr>
<tr>
<td>Existing equipment include dry vacuum roughing and turbo molecular pumps,</td>
<td></td>
</tr>
<tr>
<td>dry leak checker, miscellaneous vacuum hardware from previous projects,</td>
<td></td>
</tr>
<tr>
<td>UPS units, and a natural gas backup generator.</td>
<td></td>
</tr>
<tr>
<td>Incidental usage of LN2, N2, He, and electrical usage are typically not</td>
<td></td>
</tr>
<tr>
<td>charged to the project. These costs are not included here.</td>
<td></td>
</tr>
<tr>
<td>Cold Black Body Load miscellaneous work.</td>
<td>$5K</td>
</tr>
<tr>
<td>42” rotatable wiregrid assembly</td>
<td>$5K</td>
</tr>
<tr>
<td>Cryostat Support Stand Engineering Design</td>
<td>1 month FTE (needed mainly for stress calculations)</td>
</tr>
<tr>
<td>Cryostat Support Stand Fabrication</td>
<td>$5K</td>
</tr>
<tr>
<td>Technician for Mechanical Assembly</td>
<td>6 months FTE</td>
</tr>
<tr>
<td>Operational Readiness Clearance by Lab Mechanical Engineering</td>
<td>5 months FTE</td>
</tr>
<tr>
<td>Thermometry</td>
<td>$10K</td>
</tr>
<tr>
<td>Cabling</td>
<td>$10K</td>
</tr>
<tr>
<td>Miscellaneous Hardware</td>
<td>$10K</td>
</tr>
</tbody>
</table>
5 Summary of Total Costs

In this section, we present again the costs presented in sections 2, 3, and 4. We also include travel to the site for shifts and collaboration meetings. Finally, we add the requested contribution to site construction (2 years) and operations (3 years). The site costs are distributed amongst the collaborating institutions. The proposed site cost is $50K annually per non-NSF supported institution.

Our estimate is a project cost of $1.35M and $0.42M contingency. Our operations cost estimate is $198K, over a 3 year running period. The costs do not include salaries of Fermilab scientists or postdocs.

Table 5.1a Cost Estimate Summary.

<table>
<thead>
<tr>
<th>Material Costs</th>
<th>Cost Per Item</th>
<th>Number Of Items</th>
<th>Extended Cost</th>
<th>Contingency</th>
<th>Contingency ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary Stage</td>
<td>1411</td>
<td>4</td>
<td>5644</td>
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</tr>
<tr>
<td>Linear Stage</td>
<td>1471</td>
<td>8</td>
<td>11768</td>
<td>30%</td>
<td>3530.4</td>
</tr>
<tr>
<td>Motor Controller</td>
<td>800</td>
<td>12</td>
<td>9600</td>
<td>30%</td>
<td>2880</td>
</tr>
<tr>
<td>Vacuum Pickup Tools</td>
<td>100</td>
<td>23</td>
<td>2300</td>
<td>30%</td>
<td>690</td>
</tr>
<tr>
<td>Custom Carriage Trays</td>
<td>100</td>
<td>10</td>
<td>1000</td>
<td>30%</td>
<td>300</td>
</tr>
<tr>
<td>Miscellaneous Tooling</td>
<td>10000</td>
<td>1</td>
<td>10000</td>
<td>30%</td>
<td>3000</td>
</tr>
<tr>
<td>Module Testing Hardware: Computers, NI Modules, electronics, Cryocooler, RF equipment, vac chamber.</td>
<td>100000</td>
<td>1</td>
<td>100000</td>
<td>30%</td>
<td>300000</td>
</tr>
<tr>
<td>Receiver Integration Costs: thermometry, black body load, wiregrid, miscellaneous mechanical assemblies</td>
<td>45000</td>
<td>1</td>
<td>45000</td>
<td>30%</td>
<td>13500</td>
</tr>
</tbody>
</table>

Sum | 185312 | 55593.6 |

<table>
<thead>
<tr>
<th>Labor Cost for Developing Tooling</th>
<th>Number of Weeks</th>
<th>Personnel</th>
<th>Extended Cost</th>
<th>Hr Rate</th>
<th>Contingency</th>
<th>Contingency (dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labview Programming</td>
<td>20</td>
<td>Computing Professional</td>
<td>62,624</td>
<td>78.28</td>
<td>50%</td>
<td>31312</td>
</tr>
<tr>
<td>Zeiss Programming</td>
<td>4</td>
<td>Senior Technician</td>
<td>9448</td>
<td>59.05</td>
<td>50%</td>
<td>4724</td>
</tr>
<tr>
<td>Labor to build tooling</td>
<td>10</td>
<td>Senior Technician</td>
<td>23,620</td>
<td>59.05</td>
<td>50%</td>
<td>11,810</td>
</tr>
</tbody>
</table>

Sum | 95,692 | 47846 |

<table>
<thead>
<tr>
<th>Labor Cost for W-band Assembly</th>
<th>Labor Type</th>
<th>Number of Hours</th>
<th>Extended Cost</th>
<th>Hr Rate</th>
<th>Contingency</th>
<th>Contingency (dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wirebonding</td>
<td>Sr. Tech</td>
<td>1200</td>
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<td>59.05</td>
<td>30%</td>
<td>21258</td>
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<tr>
<td>Assembly</td>
<td>Technician-II</td>
<td>500</td>
<td>23375</td>
<td>46.75</td>
<td>50%</td>
<td>11687.5</td>
</tr>
<tr>
<td>Inspection and Organization</td>
<td>Technical Supervisor</td>
<td>1600</td>
<td>130880</td>
<td>81.8</td>
<td>50%</td>
<td>65440</td>
</tr>
</tbody>
</table>

Sum | 225115 | 98385.5 |
Table 5.1b Cost Estimate Summary, Continued.

<table>
<thead>
<tr>
<th>Other non-scientist Labor</th>
<th>Labor Type</th>
<th>Number of FTE-years</th>
<th>Extended Cost</th>
<th>HR Rate</th>
<th>Contingency</th>
<th>Contingency (dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Testing</td>
<td>EP-11 or Electrical Engineer Equivalent (Testing Engineer)</td>
<td>2</td>
<td>339,582</td>
<td>81.63</td>
<td>30%</td>
<td>101,875</td>
</tr>
<tr>
<td>Teststand Assembly Technician</td>
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Summary of All Project Costs

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1 Introduction and Goals of this Proposal

This Proposal is for the realization of Phase II of QUIET. We begin with a brief review of the physics that can be studied with CMB polarization and the science goals for Phase II. In the following section we present accomplishments from Phase I which has been operating in Chile now for most of a year.

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. Since the early 1990s, it has been appreciated that high-sensitivity measurements of CMB polarization can add qualitatively new information, but are instrumentally challenging due to the smallness of the signal. After the first detection of polarization in 2002 [1], measurements have steadily and are now beginning to produce interesting constraints on cosmological parameters [2, 3, 4, 5, 6, 7, 8, 9].

In anticipation of high-sensitivity polarization datasets, the study of possible applications of CMB polarization and its implications for fundamental physics has become an important subfield of theoretical cosmology, with three central areas that define the most important science goals for QUIET:

1. CMB polarization is the ultimate probe of primordial gravity waves, via the B-mode (or parity-odd) 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 models, fine-tuning arguments combined with WMAP data suggest that $r$ is generically $\gtrsim 0.02$ [10, 11, 12]. 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. [13]). 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. The forecasted uncertainty on $r$ in QUIET Phase II is $\sigma(r) = 0.0079$, a factor $\sim 40$ improvement over polarization experiments to date.

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 [14, 15]. 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 $40\sigma$ detection. This measurement can be used to constrain new parameters. For example the neutrino mass can be constrained to $\sim 0.3$ eV, close to the level of the guaranteed signal from neutrino oscillation experiments [16].

3. The E-mode (or parity-even) 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 [17], removes blind spots when reconstructing the initial potential [18], and can test whether observed CMB temperature anomalies are primordial in origin [19]. 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 1, we have shown forecasted E-mode and B-mode power spectrum uncertainties for QUIET Phase II, with results from recent experiments shown for comparison. 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)?

Furthermore, in QUIET Phase II, we will achieve this dramatic improvement in sensitivity using proven technology, with well-understood noise properties and systematics, as successfully demonstrated in QUIET Phase I.

QUIET Phase I has been operating at Chajnantor Test Facility in the Atacama desert since October of 2008. To reach the sensitivity goal as shown in Figure 1, we propose to construct 3 telescopes and 4 new receivers: 3 in W-band (95 GHz) with a total of 1497 detectors and 1 a mixture of Q (44 GHz) and Ka (32 GHz) bands, with a total of 79 detectors. Table 1 gives the characteristics of the modules, the beam sizes on the sky, and the sensitivity in the polarization maps obtained from scanning the same 4 very clean patches we are currently observing in Phase I. Currently in Phase I we have 90 detectors operating, the largest number of deployed polarization-sensitive CMB detectors in any experiment.

We point out that we have been conservative in our sensitivity estimates: we are using a mean receiver temperature of 75K (based on the best 20% of Phase I modules) whereas improvements and recent developments described in Section 3.3 point to figures below 50K. Nevertheless, our final maps will have a sensitivity that exceeds Planck by a factor of 100.
After describing our accomplishments to date, we will describe the instrumentation for Phase II.

<table>
<thead>
<tr>
<th>Module</th>
<th>Bandwidth (GHz)</th>
<th>$T_x$ (K)</th>
<th>$T_{sys}$ (K)</th>
<th>Module Sensitivity ($\mu K/\sqrt{s}$)</th>
<th>Number of Modules (P/T)</th>
<th>Beam Size (arc-min)</th>
<th>Map Sensitivity ($\mu K/deg^2$)</th>
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<tbody>
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<td>32 (Ka)</td>
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<td>20</td>
<td>28</td>
<td>165</td>
<td>16/2</td>
<td>28</td>
<td>0.51</td>
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<tr>
<td>44 (Q)</td>
<td>9</td>
<td>22</td>
<td>32</td>
<td>178</td>
<td>55/6</td>
<td>20</td>
<td>0.30</td>
</tr>
<tr>
<td>95 (W)</td>
<td>13</td>
<td>75</td>
<td>83</td>
<td>364</td>
<td>1389/108</td>
<td>8.5</td>
<td>0.095</td>
</tr>
</tbody>
</table>

Table 1: Module numbers, for both polarization and temperature, and sensitivities for QUIET-II baseline configuration. Bandwidths and receiver temperatures are based on the best 20% of Phase I modules. Module sensitivities are calculated from the “Radiometer Equation”, taking into account the 10% loss from blanking phase switch changes. The map sensitivities are based on the total number of detector-hours of data with all 4 receivers as shown in our schedule (with a duty cycle consistent with what we have in Phase I), and 2500 square degrees. The W-band modules are contained in 3 “CMB Receivers”. The Ka and Q-band modules are contained in 1 “Foreground Receiver”. All 4 receivers illuminate 2m telescopes.

---

2 Accomplishments from QUIET Phase I

In our original proposal some 4 years ago we wrote “A key element of this proposal is the transition from Phase I to Phase II. In order to proceed with Phase II, we need to show that the technology can produce scientific results at the level of 100 detectors.” We first list our accomplishments (and the few areas that need improvement) and then show some preliminary results, demonstrating that we have proven all the technologies and concepts (described fully in Section 3), putting us ready to embark on Phase II.

We have proven the technology underlying the QUIET detector arrays: We have produced, tested, and optimized the performance of more than 100 polarization modules. We have designed and produced septum polarizers with performance that meets the goals of Phase II. We have successfully implemented platelet arrays, a lower cost option to using electroformed corrugated horns as beam forming elements. Our analog electronics, both cold and warm, has worked to specifications. Our realization of cross-Dragone optics [23, 24], the first use in a CMB experiment, has worked very well (and this design is being used by several new experiments).

We have a proven observing strategy that makes the best use of observing time and reduces systematic errors: We invented and implemented a scheme of “double demodulation” that reduces systematic uncertainty (see Section 3.3). Our scanning strategy, which takes advantage of sky rotation coupled with rotation around the boresight of the telescope (deck rotations), has resulted in highly cross-linked maps, reducing systematic uncertainty. We have achieved a level of high operation efficiency: often a week will contain >130 hours of CMB scanning. We have not been limited by the atmosphere at the Chilean site.

We have in place an excellent system for data management: getting timely feedback and getting the data to the U.S. and abroad promptly. Two independent analysis pipelines are now functional. Some results from each are presented below.

For completeness, we mention here a few areas where we are planning to make changes: The polarization modules did not reach the expected level of performance and took longer to assemble than anticipated; plans for improvements are presented in Section 3.3. Our ADC system introduced (small and correctible) glitches in the data due to a firmware bug which we will fix. The electronics temperature regulation was insufficient, which led to more gain variation than desired. Telescope mirror manufacturing errors were larger than specified, resulting in ~10dB more side lobe power. The full ground screen did not get constructed in time to use, but we plan to install it before we complete data taking. For budgetary reasons, we were not able to support a project manager after the first year of funding; we will not be able
to operate that way in Phase II. And we lost about 6 weeks of data from failures in old components: one of the W-band cold heads and the CBI mount.

**Phase I data** We commenced data taking with our Q-band receiver in October of 2008. Our award ran out in June of 2009 and only at that time was the W-band receiver ready. Thanks to a supplementary award, we have begun data taking with the W-band receiver. We estimate that we have sufficient Q-band data to provide competitive measurements of the first two peaks in the EE power spectrum and limits in the BB spectrum, and that we will collect enough W-band data in Phase I to do the same.

Figure 2: Histogram of Phase I W-Band module sensitivities. The average sensitivity of a single module is 0.5 mK/√s. The 81 polarization modules making up the array have a combined sensitivity of 57 μK/√s. The sensitivity is calculated from the noise in actual observations of the Chilean sky.

**Detector Performance** Figure 2 shows the sensitivity of the W-band modules on the Chilean sky. From this and similar data for Q-band, we derive the sensitivities of the 2 receivers. We calibrate by observing Taurus A, using WMAP3 measurements of its polarization. We find that our Q-band receiver has an array sensitivity of (64 ± 8)μK/√s; the corresponding figure for W-band is (57 ± 14)μK/√s (where the errors come from WMAP uncertainties). These are the best performance figures at a single frequency for any polarization sensitive array that has been fielded to date.

We next show some early results, mostly from the full season of Q-band data.

**Temperature Anisotropies** Figure 3 shows a temperature map of one of our CMB patches: QUIET Q-band data along with that from WMAP. This was obtained with just 2 of the 19 Q-band modules that are devoted to temperature; the other 17 are purely for polarization. Also shown is the TT power spectrum in comparison to the concordance model. While not one of our primary goals (the TT modules are there primarily for the identification of foregrounds) this is an excellent cross check and proves our total power sensitivity to a level well below that of the CMB fluctuations.

**Galactic Polarization** It is a priority to observe our 4 CMB patches, but for a few hours each day, this is not possible. During such periods, we observe two galactic patches. Figure 4 shows polarization maps of each in comparison with those of WMAP.

The much greater sensitivity of the QUIET maps allows us to compute reliable effective foreground spectral indices for the two galactic patches, using only the WMAP K-band (23 GHz) channel and the QUIET Q-band channel. In the two cases, we find a spectral index of \( \beta = -3.1 ± 0.2 \) and \( \beta = -3.2 ± 0.2 \), in good agreement with the high-latitude result obtained by the WMAP team of \( \beta = -3.03 ± 0.04 \).

**CMB Polarization Maps** We show in Figure 5 a polarization map of one of our CMB patches. The source Cen-A, which we can use for calibration, is clearly visible. This map is significantly deeper than the corresponding one from WMAP.
Figure 3: **Top:** Preliminary temperature map of Patch 2a (see Figure 13) derived from Q-band data (left), WMAP (middle), and the difference between the two (right). The large scale structures from both QUIET and WMAP maps have been removed. The difference map shows that the QUIET and WMAP maps are sufficiently consistent: With the exception of one bright and possibly variable point source, the main residuals are on large scales not reliably observed by QUIET. **Bottom:** TT power spectrum with statistical errors derived from the Q-band observations, for about 12.5% of the data. A small contribution from unresolved point sources, corresponding to the current best-fit WMAP point source model, has been subtracted.

**Polarization Power Spectra** Our policy is not to look at polarization power spectra until selection criteria are defined and the data pass a variety of predefined null tests, each of which is designed to validate our understanding of particular possible systematic effects. A suite of 31 such tests has been defined for the Q-band full season and applied to Patch 2a data. In each test, the data are split into two subsets: CMB maps \( m_1 \) and \( m_2 \) are made from each half, and we compute the power spectrum of the difference map \( m_{\text{diff}} = [m_1 - m_2]/2 \), to check consistency with zero signal. One example is to split the data based upon detectors that have high vs. low \( I \rightarrow Q \) leakage: the degree to which the CMB temperature fluctuation can fake a polarization due to instrumental effects (these leakages are well measured, being at the level of \( \sim 1\% \), but not corrected in the analysis here). The result is shown in the left panel of Figure 6, where the power spectra are consistent with zero signal as expected. The error bars of the null-power spectra provide a good measure of those we would obtain in the non-null CMB power spectra. The figure shows that we will achieve a significant detection of E-mode power even from just one of the four CMB patches. Each division has 16 tests, 8 bins in EE and BB power, making a total of 496 points that should, as an ensemble, be consistent with zero. The right panel of Figure 6 shows the distribution of the \( \chi^2 \) values for each of these points. There are two "outliers"; excluding these, the average \( \chi^2 \) is statistically consistent with unity and the distribution matches well. We will investigate the origin of the two outliers and study the statistical impact of possible correlations among the null tests before evaluating non-null power spectra.
Figure 4: Polarization maps of two galactic regions: “Patch gc” at the galactic center (A) and “Patch gb” (B). Each shows Phase I Q-band, (QUIET filtered) WMAP, and difference maps, with Stokes Q on the top and U on the bottom. The maps are minimally filtered and come from two distinct pipelines. The QUIET maps, observing just 1 or 2 hours per day, are less noisy than those of WMAP; on small scales, the difference maps are consistent with noise, validating our calibration and analyses. The locations of these regions are shown in Figure 13.

Figure 5: Left: Preliminary Stokes Q polarization map of Patch 2a from about 600 hours of Phase I Q-band data. Right: Stokes Q from WMAP data. Cen-A is the source at the edge of our field. The scale is in μK.

Figure 6: Example null test. Left: EE and BB power spectra for the Patch 2a difference map, obtained by dividing full-season Q-band data into detectors with high and low I → Q leakage. The errors indicate already that we should have multi-sigma detections of the first and second polarization peaks from just this one patch. Right: the distribution of χ² from all 31 null tests, where each entry in the histogram corresponds to one data point of one of the null power spectra. The red line shows the expected χ² distribution.
3 Phase 2 Instrumentation

Observing the polarized CMB demands exquisite sensitivity and freedom from systematic errors. QUIET is an integrated approach to characterizing the CMB polarization power spectra using large arrays of 32, 44 and 95 GHz polarimeters (Ka, Q and W-band, respectively) which satisfy these requirements. In all, the QUIET project will deploy 1460 polarimeters, each of which is expected to have sensitivity better than 400 μK√s, comparable to the state of the art for ground-based CMB polarimeters of any type. For studies of point sources and other systematics, 10% of the radiometers are configured to measure total power anisotropy, as described in Section 3.3. Table 1 provides sensitivity details for each array.

We describe our methods for realizing each array as a self-contained unit incorporating feed optics, polarizing elements, lock-in modulation, tunable detector biasing, and analog to digital conversion. We conclude with discussion of the cryostat and the 2m optics.

3.1 Overview of QUIET Detector Arrays

The key to the large focal plane arrays described in this proposal is the successful miniaturization of the correlation polarimeter. Phase I took advantage of the breakthrough in millimeter-wave circuit technology and packaging at JPL [25] that enabled that miniaturization. Each array element is based on a QUIET module: a compact IC-style package with waveguide inputs which can be built and tested in quantity with fully automated techniques adapted from the semiconductor industry. The module is a pseudo-correlation receiver comprising low noise amplifiers (LNA)\(^1\), phase shifters, detector diodes, and passive components described below and shown in Figure 7. The polarization properties of an electromagnetic signal are fully characterized by the four Stokes parameters, I, Q, U and V. The total intensity is I, and the circular polarization V is predicted to be 0 for the CMB. Both linear polarization parameters, Q and U, are measured simultaneously by each QUIET module when its inputs are coupled through a septum polarizer, described in Section 3.2. This dual measurement is a distinct advantage not shared by bolometer-based receivers to date.

Correlation polarimeters measure polarized signals by multiplying two linear polarization modes to find the correlated component. Aside from providing both Q and U, this well-established technique offers the advantages of insensitivity to gain fluctuations and unpolarized signals, and post-amplification gain modulation [26, 27, 28]. Detailed analyses of systematic effects associated with pseudo-correlation receivers are given in [29] and [30], and with correlation polarimeters in [31, 32, 33], for example. We summarize critical effects in Section 7.1.

Figure 7 includes photographs of modules and a diagram of their function. The inputs are two circularly polarized modes \((L, R) = (E_x \pm iE_y)/\sqrt{2}\), where \(E_x\) and \(E_y\) are orthogonal components of the incident field. The signals are amplified and combined in a 180° hybrid coupler with outputs proportional to the sum and difference of the inputs. These outputs are amplified versions of \(E_x\) and \(iE_y\), with the phase switch reversing their roles, and so the subsequent diode detectors (1 and 2) detect \(T_x \propto E_x^2\) or \(T_y \propto E_y^2\). Modulation of the phase state results in \(T_x \leftrightarrow T_y\) so that the demodulated outputs of diodes 1 and 2 each measure Q. Similarly, diodes 3 and 4 in Figure 7 each measure U. Gain fluctuations \((1/f)\) due to the amplifiers are common to both diodes and are strongly suppressed upon demodulation [34, 35]. Phase modulation occurs at 4 kHz, faster than the \(1/f\) knee of the atmosphere, amplifiers, and detectors.

In addition to the 4 kHz phase modulation occurring in one arm, the second arm is also modulated at lower frequency (50 Hz). This double demodulation cancels out spurious instrumental polarization that can arise if there are transmission differences between the two phase states in either of the two switches.

\(^1\)The low noise amplifiers are InP monolithic microwave integrated circuit (MMIC) high electron mobility transistor (HEMT) amplifiers.
Double demodulation has been tested and established in Phase I, and confirmed to achieve the expected improvement without any loss of sensitivity.

The integration of the QUIET arrays is simple: the modules are populated on sets of printed circuit boards which operate at 20 K, as seen in Figure 8. The septum polarizers and feedhorns are bolted to
the modules. The horns are constructed as platelet arrays (see Section 3.2). Additional room temperature electronics simultaneously provide bias to the individual chips and demodulate, multiplex, and digitize the output signals. A set of flexible printed circuit (FPC) cables provides thermal isolation. Over a period of a few hours, all elements of a receiver see a modulated polarized source during which time the bias voltages for all detectors are iteratively adjusted simultaneously, converging on the best performance for each.

3.2 Feed Horns and Septum Polarizers

The septum polarizers split the incoming radiation into L and R. QUIET uses waveguide septum polarizers [36] realized in two aluminum split-block assemblies. Good performance of the correlation polarimeters requires that the septum polarizers have 20% bandwidth, low loss, good amplitude balance and flat phase response. Finally we require high isolation on the output ports to reduce sensitivity to the common mode total power signal. Repercussions of such sensitivity are described in Section 7.1, which finds that the achieved performance of the Phase I W-band polarimeters is sufficient. The Q-band modules and septum polarizers were not optimally band-matched for Phase I; we will correct that for Phase II and expect to achieve similar or better performance than seen in W-band. The first prototype septum polarizer we built and tested for QUIET was for Ka-band; we will tweak the design bandpass for use in Phase II.

A 19 element Q-band platelet array of corrugated feedhorns and a 91 element W-band array, shown in Figure 9, have been designed, fabricated, tested, and field deployed as part of QUIET Phase I [38]. The design of the arrays implemented several novel features including thick, corrugated plates and lightweighting holes throughout the bulk of the array that simultaneously acted as access holes for attachment screws. The combined fabrication costs of both the machining and diffusion bonding were at least an order of magnitude less expensive than the costs associated with fabricating electroformed equivalents of these horns. Detailed beam pattern and return loss measurements demonstrated that these horns performed well in comparison to both their electroformed equivalents and theoretical predictions.

For QUIET Phase II we will add onto the existing 91 element W-band array by fabricating six 68 element 'petals' that will surround the 91 element array as shown in Figure 9. Each petal will be tilted inwards by 5° in order to match the curvature of the focal plane. The combination will yield 499 elements in a given W-band cryostat. For the foreground cryostat, the existing 19-element Q-band array will be surrounded by six petals, each consisting of seven Q-band horns and three Ka-band horns. The Ka-band horns will implement a profiled flare in order to make them the same length as the Q-band horns.

Figure 9: The existing 91 element W-band platelet array is shown on the right. This array will be surrounded by six 68 element platelet arrays to form a 499 element array shown on the left.
3.3 The QUIET Polarimetry Modules

In QUIET Phase I, we have built and fielded the largest HEMT-based focal plane arrays ever deployed. For Phase II, we propose to build arrays roughly five times larger. Here we give the path to that goal.

**Module Improvements** For Phase I, most Q-band modules had noise 22-32 K, and most W-band had 60-100K, where both used amplifiers with 0.1 μm gates. For Phase II, in addition to 0.1 μm, we will make new amplifiers, using 35nm InP technology, which have demonstrated noise temperatures as low as 30 K at W-band (Figure 10).

Although the few 35 nm chips we have measured are always better than the 0.1 μm devices, we have insufficient statistics to determine the intra-wafer variation. We therefore conservatively base our sensitivity estimates for Phase II on the performance of the 0.1 μm devices used in Phase I.

In Phase I, the amplifiers were selected on the basis of their bias characteristics at room temperature. This allowed damaged devices to be identified and rejected. However at this stage, the noise performance of the individual amplifiers was not known. For Phase II, the cryogenic noise performance of each input amplifier will be measured and the best will be selected for use in the modules. We are therefore confident that for W-band we can obtain a mean receiver noise temperature of at most 75K, the mean over the best 20% of the modules in Phase I.

In Phase I the bandwidth was practically limited in W-band to ≈13 GHz by the back-end hybrid and amplifiers available. In Phase II, the hybrid circuit will be redesigned using scaled versions of the proven Q-band designs to give improved bandwidth. Conservatively, we are not taking into account this improvement in bandwidth. Finally in Phase I the detector diodes were GaAs Schottky devices requiring bias when cooled. While this worked well, the additional bias circuitry added cost and complexity as well as limiting the module linearity. Therefore we will use cryogenic zero-bias diodes which are now available.

The new 32 GHz modules will be built using identical techniques to the 44 GHz receivers, incorporating proven amplifier and phase-switch designs; this makes the development very low risk.

**Module Mass Production.** Phase I led to practical prescriptions for the mass production of modules using robotic techniques, ranging from device prescreening to testing techniques as well as automated assembly procedures and protocols to minimize manufacturing errors. The mass produced modules needed far fewer repairs and performed with an even better statistical distribution than the manually assembled ones. The successful development of Phase I enables us to predict the mass production cost with reasonable accuracy.

![Figure 10: A 35 nm low-noise amplifier (from NRAO) demonstrates cryogenic receiver temperatures of around 30 K at W-band. The best 0.1 μm LNAs used in Phase I modules had receiver temperatures around 50-60 K.](image)
confidence. Assembly will be performed using these same robotic techniques at FNAL (W band) and SLAC (Ka/Q-band) as were used by NxGen (the company assembling many of the Phase I modules).

**Module Optimization.** In Phase I, we found that an elaborate optimization of the LNA biases is necessary to maximize the module performance. In our optimization procedure, we exploit all the degrees of freedom of the biasing and optimize the signal to noise ratio using a rotating sparse wiregrid as a source of polarized signal. This method has been established in a scalable way and we are able to optimize the 90-element Phase I W-band array in less than 24 hours. Since we optimize many modules in the array simultaneously, the Phase II array optimization will not require a significant increase in time to achieve.

**Total Power Sensitivity** Although measuring the total power (temperature) of the sky is not a primary science goal of QUIET, it is crucial for systematic investigations, foreground identification, and crosschecks with other experiments. The averages of the QUIET diode signals before demodulation trace the total power, but with $1/f$ knee frequencies as high as 1 kHz, due to the lack of modulation. Instead, for Phase I we modified ~10% of the receivers for temperature sensitivity using a scheme similar to WMAP in which the temperature difference between two neighbouring horns is measured. For this configuration the septum polarizers were replaced by orthomode transducers (OMTs) and the output of neighbouring OMTs were routed via magic tees to the modules, now called TT modules.

So far in Phase I, the TT modules have been used to determine the pointing model from observations of planets and bright patches of the galaxy, as well as for the results in Figure 3. When 10% of the modules are TT, the TT array sensitivity is only ~8 times worse than the array polarization sensitivity. (We found slightly worse sensitivity for the Phase I Q-band which we attribute to losses in multiple waveguide interfaces of the assembly which we will eliminate for Phase II.) Thus any foreground with a polarization fraction of 5% will have ~2.5 times higher signal to noise in the TT modules. Similarly, unpolarized sources coupling via 1% I-leakage can be identified in the TT receivers with ~12 times higher signal to noise.

### 3.4 Electronics

The electronics needed for QUIET consist of an analog and a digital component. The analog component provides bias voltages and currents to the LNAs, phase switch modulation signals at 4kHz and 50Hz, and preamplification of the detector diode signals. It also monitors the detector DC voltages, HEMT drain currents, module operating temperatures, cryostat pressure, outside temperature, and other important items. This analog component will be built into circuit boards whose circuits have been designed and tested in Phase I. All will be mass-produced using conventional printed circuit board techniques.

Two types of analog circuit boards are needed: **Module Assembly Boards (MABs)** provide the electrical connection to the modules and protection circuitry for them. The MABs use FPCs to provide high-density, thermally isolated connections to the warm electronics. Each MAB is thus connected to one **Analog Electronics Board (AEB)** which sends the module bias and modulation currents and receives the detector voltages. Each bias is controlled by a 12-bit DAC, which were found to provide sufficient range and precision for optimization in Phase I. The output of each bias circuit is monitored by the AEB. The AEB provides ~100 gain in its preamplification stage before sending the amplified signals to the ADC for digitization.

For monitoring temperatures, pressures, power supply voltages, etc. a 1Hz rate is sufficient. Commercially available readout boards exist for this purpose so custom circuitry will not be required here.

The digital component (**ADC boards**) will sample the detector signals at 800kHz with 18 bit resolution and synchronously demodulate and integrate them down to 100Hz. In Phase I, this digital component consisted of 32-channel ADC boards. Based on the Phase I ADC design, we have produced a 64-channel prototype that will reduce the number of required digital component boards by a factor of 2.
3.5 Cryostats

Each QUIET cryostat must mechanically support, cryogenically cool, and optically mount an array. In addition, they house the associated warm electronics, provide a large microwave transparent high vacuum window, and shield the horn array from infrared radiation.

Figure 8 shows an annotated photograph of the currently deployed Phase I W-band cryostat. This figure also indicates the primary elements of our cryostat design for Phase II: the larger cryostats will be essentially a scaled up version of this design. The array is mounted on a G-10 ring providing support and thermal isolation maintaining the array at \( \approx 20\)\(\text{K} \), cooled by two CTI Gifford-McMahon refrigerators. A Phase II W-band cryostat will require a factor of 4 more cooling power so we will baseline four Sumitomo RDK 408S coolers for each cryostat. We will investigate options for decreasing the heat load as well as other available cooling options when funding becomes available so it is possible that we may be able to operate with fewer coolers. The Phase II window will be considerably larger than that for Phase I - roughly 42" in diameter. Finite element analysis\(^2\) and optical loss calculations, of the type demonstrated to agree with measurements of the Phase I windows, show that a 0.5" thick HDPE window will suffice. For the Phase I windows, an anti-reflection coating of expanded Teflon was hot-pressed onto the UHMWPE at Columbia using a technique developed under a NASA grant for mm-wave filter fabrication. This technique can be extended to work for the larger windows with minimal engineering overhead. With this simple anti-reflection coating efficiency loss through this window will be <1.5% across the 95 GHz band, and <2% across the combined 32 and 44 GHz bands. Work done for Phase I indicates that bowing at the level that we expect for the 42" HDPE windows will not produce unacceptable instrumental polarization or cross-polarization.

Engineering work will take place in the first year to ensure adequate support of the larger arrays and to finalize the design for the 42" window. Although the baseline window design described above is sufficient, we will also investigate a lower-loss design comprising a mesh-backed zotefoam window.

3.6 The QUIET Telescopes

The three Phase II telescopes will be 2m crossed-Dragone reflectors, each on its own 3-axis mount and in an absorber-lined co-moving ground shield. We will scale the well-tested Phase I optical design by \( \sim 1.4 \) which will allow us to reuse the Phase I feedhorn design. The success of Phase I amply demonstrates the advantages of the crossed-Dragone telescope design \([39, 40]\). A number of other CMB polarization experiments, including Clover, ABS and the CMBPol mission have realized these same advantages and adopted this optical design. For Phase I, the telescope optical properties have been calculated with a full physical optics program \([41, 42]\) using the calculated corrugated feedhorn field distribution to excite the optics. These have been confirmed by beam maps run at the JPL test range (Figure 11 and \([43]\)). For Phase II, the beam sizes will be 8.5, 20, and 28 arcminutes (FWHM) for W, Q, and Ka-band, respectively. The field diameters will be 13° across, and the entire field of view is diffraction-limited. The telescope mechanical design will follow the Phase I scheme, with a welded steel tube structure and single-piece aluminum mirrors supported on adjustable hexapods (Figure 12).

A new 3-axis (boresight, elevation, azimuth) mount will be required for each of the three Phase II telescopes. A custom version is shown in Figure 12B. A potentially viable commercial option, shown in Figure 12C,D, incorporates accurate (\( \pm 0.003° \)) encoders and zero backlash worm gears for precision positioning. A controller for all three axes would be provided by the vendor and a QUIET postdoc and/or engineer would be tasked to program the controller. Unlike the original CBI mount, both mount concepts will allow pointing down to the horizon. This increases the number of available observation targets, enables

\(^2\)The finite element analysis work, done at FNAL, was an example of some of the technical overlap between a high-energy lab and a CMB experiment.
Figure 11: Beam profiles of the Phase I telescope at 90 GHz. Left: a 90 degree cut through the beam. Orange is the calculated beam based on the original design, blue is the calculated beam based on the measured surface errors of the manufactured mirrors, and purple is the profile measured at the JPL test range. Right: a similar plot for an off-axis feed, without the calculated original design. The close agreement between calculated and measured beam profiles means that we can closely tailor our mirror specifications to meet our optical goals.

in situ beam mapping, and allows for easier cryostat and electronics maintenance and mounting.

We chose absorber-lined co-moving groundscreens over reflective groundscreens. The chief advantage of the former is that they do not convert the spillover past the edges of the mirrors into extended, polarized sidelobes on the sky. The thermal emission we have in exchange will not vary in any scan-synchronous manner, only slowly varying with drifts in groundscreens temperature. The groundscreens will also have an extended entrance aperture to catch a known low-level sidelobe seen by some edge feeds and generally reduce ground radiation from entering the enclosure.

Figure 12: A: Views of QUIET Phase I, underside of primary mirror and during early observations (without the upper baffle of the groundscreens). B-D: Three-axis mount concepts. B: Sketch of optimal mount design with fixed center of gravity, providing minimum torque requirements and bearing loads. The co-moving groundscreens are shown only as an outline. The black cylinders represent the cable-wrap drums to handle the cables and helium lines for the cryocoolers. C: Alternate mount concept using commercial positioners. Not shown are the co-moving groundscreens or provision to handle the cables and helium lines. D: A commercial positioner from MI Technologies (formerly Scientific Atlanta) suitable for our needs.

We next discuss the site, its infrastructure and characteristics of the atmosphere.
4 The Site

In Phase II, QUIET will continue observations from the Chajnantor Test Facility (CTF). Located at 5080 m altitude on the Chajnantor plateau near the village of San Pedro de Atacama in northern Chile, the CTF was established by Caltech in 1998 for CBI [44]. This area has been recognized as one of the premier locations in the world for millimeter and submillimeter astronomy, leading to the installation of several telescopes in recent years, including the international ALMA project\(^3\) now under construction. By virtue of an agreement with the University of Chile, Caltech enjoys several legal privileges that facilitate the operation of an observatory in Chile.

QUIET will continue observing from the CTF for several reasons:

- **Observing Experience:** During Phase I, the overall observing efficiency from 2008 October to 2009 June, was close to 70% and for several weeks in autumn (March – May) the sustained efficiency was >90%.

- **Scan Strategy:** The cross linked scan strategy adopted for QUIET to minimize systematic errors is possible from this tropical site without elevation changes or rotation about the optical axis (see Section 5.1).

- **Sky Coverage:** Because the CTF is located at 23°S, a substantial fraction of the sky is visible in the northern, as well as the southern, hemisphere. This facilitates observations of calibration sources and comparisons with other experiments. Overlapping coverage with bolometer arrays operating at higher frequencies will help in separating foreground contaminants and will provide a check on systematic errors, which are quite different for bolometric and coherent polarimeters.

4.1 Observing Conditions

Extensive measurements have demonstrated Chajnantor enjoys exceptional conditions for millimeter and submillimeter astronomy because of its high altitude and low water vapor [45, 46, 47]. Under median conditions, the zenith sky brightness at 90 GHz is 5–6 K. For CMB observations, atmospheric fluctuations are of greater concern than overall sky brightness because fluctuations would appear in the data as additional noise that is not always stationary. Moreover for QUIET, polarization, rather than intensity, fluctuations are the greatest concern. Water vapor inhomogeneities are the principal cause of atmospheric intensity fluctuations. Fortunately atmospheric water vapor is not strongly polarized. At Chajnantor, neither the entire CBI polarization data nor preliminary QUIET Phase I data show evidence of atmospheric polarization fluctuations. Hence we are optimistic observing conditions will not limit Phase II.

At Chajnantor, the weather is less stable and more humid during the summer (January–March) than the rest of the year. When possible, therefore, we will schedule instrument installations and upgrades during this period.

4.2 Infrastructure and Logistics

QUIET will benefit from the extensive existing infrastructure at the CTF. Insulated and heated buildings contain a control room, a laboratory, and two bedrooms. To alleviate the adverse physiological effects of high altitude hypoxia, the oxygen concentration in these spaces is enriched so the effective altitude is about 3000 m [48, 49, 50]. Outdoors, portable supplemental oxygen is used. The laboratory is fully equipped for instrument repair. A second, unheated laboratory provides a setup space for large receivers. An infrared link to a nearby ALMA building connects to the internet through the ALMA network, allowing remote monitoring of observations. Diesel generators provide electrical power. In December 2008, we installed a new generator with 125 kVA (derated) capacity, which is sufficient for operation of the facility and the first new telescope. Fuel consumption is \( \approx 15 \text{ m}^3 \) per month. A small local staff maintains the telescope

\(^3\)http://www.almaobservatory.org
and facility systems, including the generators, arranges and supervises external contractors, does upgrade work, and assists with telescope and receiver deployment and observations.

Some upgrades will be necessary for Phase II: a satellite link will be installed to provide backup internet communications, the electrical distribution system will be rebuilt, and new foundations will be installed to support the new telescopes. In full operation with three telescopes and receivers, the electrical load will be about 213 kW. New, larger generators will be installed to meet the power demand as the new telescopes are deployed, with proportionally greater fuel consumption.

By way of a public highway and private gravel road constructed by ALMA, observers and staff commute to the telescope daily from San Pedro, where a small residence shared with the ACT, ASTE, and NANTEN groups provides comfortable lodging at modest expense. About 100 km away is Calama, a major mining support city, where the airport has several commercial flights every day for passengers and cargo.

5 Collecting and Processing the Data

We present our observing strategy and plans for acquiring, calibrating and analyzing the data.

5.1 CMB Observing Strategies

We intend to use precisely the same strategy as we did in Phase I: a periodical scan in azimuth (~6°/second, where we had negligible residual effects from detector 1/f noise) at elevations ≥45° (minimizing ground and atmospheric contributions), fixing the elevation and rotation angle about the optical axis (bore-sight axis). To make the necessary deep observations, we periodically re-pointed and changed elevation, to track regions of the sky, every ≈90 min: environmental properties are sufficiently stable on this time scale.

Even though QUIET radiometers measure both Q and U simultaneously, in order to best separate Q and U, and control spurious polarization due to instrumental systematic effects, it is desirable to re-measure each pixel multiple times where the detector Q/U components see different combinations of the sky Q/U components, i.e. at different parallactic angles.

We used two means to achieve the parallactic angle coverage: the sky rotation owing to the diurnal sky motion and the telescope rotation around the bore-sight axis. The scan trajectory we adopted in Phase I typically provides 110 degrees of parallactic angle coverage near the central region of the patch without bore-sight rotations (this is something that cannot be said for polar locations). The rotation along the bore-sight axis was performed weekly, giving nearly perfect parallactic angle coverage at every pixel.

5.2 CMB Observation Plan

The telescopes will scan the four patches listed in Table 2 (shown in Figure 13 and further described in Section 7.2) with roughly 90° difference in RA, covering a total of ≈2500 square degrees. The choice of patches allows us to dedicate more than 20 hours per day for CMB observation. As we mention later, both PolarBear and ABS will observe the same patches at different frequencies, providing important - likely even critical - comparisons of results. The scan will be performed with an amplitude of about 12.5°, and re-pointing when the sky has drifted 25°. Sky rotation and weekly changes in deck angle yield highly cross-linked maps with excellent parallactic angle coverage. By observing the same regions with all the Ka, Q- and W-band detectors, we are able to measure and remove possible foreground contamination in the observed regions. Table 1 lists our sensitivities over the regions for each frequency band.
QUIET Observing Patches

Figure 13: The locations of the four clean QUIET CMB observing patches (2a, 4a, 6a, 7b) and two galactic observing patches (gb, gc). The CMB patches were chosen to minimize foreground contamination. Together the CMB patches cover 2500 square degrees on the sky. The galactic patches were chosen to have a strong signal which could be used for calibration. Detail maps of these patches using Phase I QUIET data are in Figures 3, 4, and 5. The background in this figure is the WMAP Q-band temperature map. The map is projected in equatorial coordinates (RA/DEC), with the central meridian at RA=180°.

<table>
<thead>
<tr>
<th>Patch</th>
<th>RA</th>
<th>DEC</th>
<th>l</th>
<th>b</th>
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<tbody>
<tr>
<td>6a</td>
<td>0h 48m</td>
<td>-48</td>
<td>305</td>
<td>69</td>
</tr>
<tr>
<td>4a</td>
<td>5h 12m</td>
<td>-39</td>
<td>243</td>
<td>-35</td>
</tr>
<tr>
<td>2a</td>
<td>12h 4m</td>
<td>-39</td>
<td>293</td>
<td>23</td>
</tr>
<tr>
<td>7b</td>
<td>22h 44m</td>
<td>-36</td>
<td>7</td>
<td>-61</td>
</tr>
<tr>
<td>gb</td>
<td>16h 0m</td>
<td>-53</td>
<td>329</td>
<td>0</td>
</tr>
<tr>
<td>gc</td>
<td>17h 46m</td>
<td>-29</td>
<td>360</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2: The coordinates of the currently observed CMB patches (6a, 4a, 2a, 7b) and galactic patches are given in equatorial and galactic coordinates.

5.3 Calibration Strategy

Good calibration is essential for reducing systematic biases. The most critical are those that can create fake B-mode signals. Based on the estimates described in Section 7.1, our target accuracy for critical calibration items is: (i) better than 1° polarization angle calibration, (ii) knowledge of the I → Q/U instrumental leakage with accuracy of 0.1%, and (iii) ~5% gain calibration, for Q vs. U detectors within and among the modules. These are achievable; about 10% of the observing time will be used for calibration.

An important part of calibration is characterization of the beams. Our plan is that once the first telescope, mount and ground shield are delivered, we will perform a series of beam pattern measurements to evaluate the shape of the copolar patterns and measure the level of the crosspolar and far sidelobe response. These will be used to verify the beam pattern predictions, assess the effects of imperfect reflector fabrication, as was done in Phase I (see Figure 11), and evaluate the performance of the ground shields. These measurements will likely be performed using an ambient temperature, narrow band, heterodyne detector system mounted on a platelet array in lieu of the full-up QUIET receiver system since the latter does not have the necessary dynamic range.
Polarization Angle Our primary calibrator for the detector angles is a rotating sparse wire grid which partially polarizes the incoming radiation, producing a $\approx 1K$ polarization signal, modulated on the $Q$ and $U$ diodes. The phase of the signal determines the detector angle of each diode. In Phase I we measured the detector angles to $\sim 2^\circ$ precision, which was dominated by systematic uncertainty. The grids will be equipped with an encoder so that we can achieve $< 1^\circ$ total uncertainty. We have found that observations of Taurus A and the Moon provide supplementary measurements of the polarization angles.

$I - Q/U$ Instrumental Leakage Imperfections in the septum polarizers and the optics cause a leakage of the total intensity into the polarization signals, causing CMB intensity anisotropy to leak into the polarization, an effect that must be minimized. Every time we change our elevation, we characterize this effect by scanning the telescope up and down in elevation ("skydip"), modulating the effective temperature by $\sim 1K$. Since the atmosphere is unpolarized, we extract the $I - Q/U$ leakage fraction from comparing the total power modulation to the polarization modulation. In Phase I we were able to measure this leakage to $\approx 0.1\%$, already good enough to render the systematic bias negligible in Phase II.

Gain We use the Moon to calibrate the relative gain among the pixels. The Moon is an extremely bright and polarized radio source, which allows us to resolve its quadrupolar polarization pattern. Given its brightness, we can obtain a high S/N measurement in $< 1$ hour. Uncertainty about its brightness uniformity makes it a poor choice for absolute calibration but it still provides relative gains among the modules and that between $Q$ and $U$ diodes in each module. In Phase I, an accuracy of $\approx 5\%$ has been achieved, satisfying the Phase II requirement. We plan to make this measurement once/week.

The above mentioned rotating sparse wire grid provides the calibration of the relative gain between $Q$ and $U$ measurements in each pixel. In Phase I, we achieved a calibration accuracy of $1\%$, far better than the requirement in Phase II.

We have also used a broad-band polarized noise source to measure the stability of the polarization gain. Because intensities much greater than astronomical polarized sources are achievable, the gain can be measured from only a brief exposure. Therefore we will measure the gain stability hourly with an accuracy $< 5\%$, allowing monitoring and correction for time variation to the accuracy of the Phase II requirement.

The absolute gain is calibrated by observing the supernova remnant Taurus A, one of the brightest polarized sources in the sky, referencing to other experiments such as WMAP or Planck. In Phase I, we measured the absolute gain of a module with precision $< 10\%$ in an hour of observation and $\sim 1\%$ over the season. The accuracy will be dominated by the errors of the experiments we reference to; by the time of Phase II analysis, we expect they should have uncertainties of $10\%$ or less, satisfying the absolute gain calibration requirement for Phase II. (The requirement here is milder than those for the items discussed above since absolute gain mis-calibration does not create a fake B-mode signal.)

A supplemental gain calibration of the total power channels is done using the planets Jupiter and Venus, which act like bright and unpolarized point sources given our beam sizes. In Phase I, we determined the gain with accuracy of $5\%$, observing for $\sim 30$ minutes. Such observations are also useful for determining the total power beam shapes.

5.4 Data Acquisition, Storage and Distribution

In Phase I we collected the data using a RAID array at the site with weekly shipments to the States. For Phase II we will upgrade the RAID array to accommodate the increased data rate (7.2MB/s) and ship the data on 800GB LTO tapes. The total amount of data generated during the experiment will be $\sim 300$TB. This data will be permanently stored at one data center in the U.S., with mirror data centers at our international institutions. The data centers will distribute the data to all other institutions, but due to high transfer cost most data processing will take place at the data centers themselves.
5.5 Data Analysis

Data handling and processing for QUIET will be a serious challenge, but we understand what tools will be needed to overcome it. The final time stream for the polarization analysis amounts, with reasonable assumptions about the duty cycle, a sampling rate of 100 Hz, 4 bytes per sample, and four polarization outputs per detector, to a rate of 141GB/day (52TB/year) when 1500 modules have been deployed. This puts QUIET far beyond any previous ground- or space- based CMB experiment.

We plan three analysis centers in QUIET (Chicago, KEK and Oslo) which take advantage of existing infrastructure and expertise. Several experiments (including QUIET Phase I) have, even at current sensitivity levels, shown the benefits of parallel analyses in uncovering and quantifying systematic effects.

As done in QUIET Phase I, the two pipelines will adopt different approaches. The Chicago pipeline uses pseudo-C\(_\ell\) estimators [51, 52]. These offer the advantage of scaling linearly with data volume, a considerable algorithmic efficiency when dealing with such large data sets. Furthermore computational resources can be cleanly separated into two components: Input/Output (I/O) and CPU-hours. Computation on the data is limited by I/O: each of our data centers is designed to read the entire data set in a few hours. This pipeline also requires large numbers (1000s) of Monte Carlo simulations to characterize the errors. These simulations do not require access to the full collected data and are thus limited only by CPU-hours. Based on timing the existing Phase I pipeline, we estimate we will need 10\(^6\) CPU-hours per month when analyzing the full experiment, a resource available at the NERSC facility. We also propose to build smaller clusters allowing 3 \times 10^5 CPU-hours/month at our analysis centers. These will be used for independent simulations targeted at particular systematics or of partial data sets.

The Oslo pipeline is based on maximum-likelihood map making and power spectrum estimation [53, 54]. While computationally more expensive than the pseudo-C\(_\ell\) approach, it allows exact and optimal propagation of uncertainties, analytically taking into account the effects of most relevant filters (e.g., map-, FFT- and TOD-based projections). Computational complexity is controlled by a combination of massive parallelization and implementational speed-ups, e.g. multi-resolution map making, which adjusts the pixel resolution to the local number of observations. The joint foreground and power spectrum estimation problem is solved by a particular implementation of the CMB Gibbs sampler [54]. Making a single maximum-likelihood map from the 19 Q-band modules in Phase I required \(\sim\)100 CPU hours. Scaling to Phase II implies that a map will require \(\sim\)100,000 CPU hours. This is already well within the capabilities of our current supercomputing facilities, and will not be a major issue in 2012-2015.

6 Forecasts of the Science Reach for QUIET

Figure 14: Forecasted constraints on EE (left panel) and BB (right panel) power spectra from QUIET Phase II. In the right panel, the low-\(\ell\) region has been expanded for clarity, and BB spectra are shown for two inflationary models: \(r = 0\) (solid blue curve) and \(r = 0.05\) (red dashed curve). QUIET Phase II can distinguish these two models at 6.3\(\sigma\) (see Section 6.2).
In Figure 14, we show forecasted statistical errors on EE and BB power spectra from QUIET Phase II. These forecasts include the effects of \((1/f)\) noise and "E-B mixing" from boundary conditions, using a semianalytic fitting formula [55] which agrees with Monte Carlo errorbars from the analysis pipeline currently being used to analyze Phase I data. Foregrounds were treated by assuming that all instrumental sensitivity in W-band, and none of the sensitivity in Ka-band or Q-band, can be used to constrain CMB power spectra. This assumption will be justified quantitatively in Section 7.2, where it is shown that Ka-band and Q-band data, in combination with higher frequency dust measurements from Planck, can be used to remove foregrounds in W-band with marginal loss of sensitivity.

The EE power spectrum will be measured with unprecedented accuracy for \(40 \leq \ell \leq 2000\). In conjunction with future temperature measurements from Planck, such a measurement will be an exceptionally powerful probe of the primordial fluctuations. The polarized instrumental noise per pixel will be \(~100\) times better (in detector-hours) than Planck. This means we will have an extended reach for new physical effects, such as unexpected features of the power spectrum, non-Gaussian signals from inflation, or new sources of foregrounds, effects that experiments with lower sensitivity would not be able to detect.

QUIET Phase II will measure the BB power spectrum over a wide range of angular scales \((40 \leq \ell \leq 1200)\), with sufficient sensitivity to measure the B-mode spectrum from gravitational lensing to \(35\sigma\), and (via the gravity wave B-mode) constrain the tensor-to-scalar ratio from inflation to \(\sigma(\tau) = 0.0079\), a factor \(~40\) better than any polarization experiment to date. We will discuss the B-mode measurements in detail in the next two subsections.

### 6.1 Gravitational Lensing

The gravitational lensing component of the B-mode power spectrum depends on the evolution of potentials after recombination, and is therefore sensitive to parameters which affect distances or growth in the late universe (such as neutrino mass) which the CMB could not otherwise constrain.

In addition to the B-mode power spectrum, there is an alternate statistical technique which gives a more direct handle on gravitational lensing: lens reconstruction. By cross-correlating E-modes and B-modes on small angular scales, the lensing deflection field can be reconstructed mode-by-mode throughout the survey region [14, 15]. Using this technique, a high-resolution CMB dataset can be interpreted as measuring three fields: the E-modes, the B-modes, and the lensing deflection field. Constraints on cosmological parameters obtained from the deflection power spectrum \(C_\ell^{dd}\) are typically slightly stronger, for the same dataset, than those obtained from the lensing B-mode power spectrum \(C_\ell^{BB}\). In addition, measuring the shape of the deflection power spectrum helps break parameter degeneracies that would be obtained using the B-mode power spectrum. Lens reconstruction in real datasets is still in its infancy [56, 57] but is expected to be a powerful source of cosmological information in the near future, on the same footing as other probes of weak lensing such as galaxy ellipticities.

In Figure 15, we show the power spectrum of the deflection field combined with forecasted statistical errors from QUIET Phase II. The deflection power spectrum can be characterized for \(\ell \leq 1000\), and the reconstruction is sample variance limited for \(\ell \leq 100\). This measurement has a wealth of potential applications, such as constraining dark energy (particularly early dark energy [58]), spatial curvature [59], and modified gravity [60]. As one quantitative example, the sum of the neutrino masses (summed over neutrino species) can be measured with 1\(\sigma\) uncertainty \(\sigma(\sum \nu_m) = 0.3\) eV. This is a significant improvement over current upper limits, and approaching the level of the guaranteed signal from neutrino oscillation measurements [16].
6.2 Gravity Waves

It has been appreciated for 15 years that B-mode polarization is uniquely sensitive to primordial gravity waves, and that CMB polarization experiments will ultimately place constraints on $r$ which are orders of magnitude better than any other method [61]. In anticipation of these measurements, much theoretical effort has been invested into understanding the implications of such a measurement for the unknown physics of the early universe. On the experimental side, polarization experiments have made steady improvements in instrumental sensitivity, recently obtaining upper limits on $r$ of $r \lesssim 1$ [9]. Future generations of experiments, including QUIET Phase II, will bring this long theoretical and experimental program to fruition by measuring $r$ at the $10^{-2}$ level and beyond, far better than would be achievable without CMB polarization.

Using the forecasting machinery from Section 6, and marginalizing over an unknown amplitude for the lensing B-mode, we find that the $1\sigma$ uncertainty on $r$ from QUIET Phase II is $\sigma(r) = 0.0079$. This measurement will improve current constraints by a factor $\sim 40$ and will be a fundamentally new constraint on the physics of the early universe. Furthermore this dramatic improvement can be achieved using proven technology, with well-understood noise properties and systematics, as successfully demonstrated in QUIET Phase I.

<table>
<thead>
<tr>
<th>B-mode Physics</th>
<th>B-mode power spectrum</th>
<th>Deflection power spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational lensing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statistical significance of detection</td>
<td>$35\sigma$</td>
<td>$43\sigma$</td>
</tr>
<tr>
<td>Error $\sigma(A)$ on overall amplitude</td>
<td>$0.036$</td>
<td>$0.024$</td>
</tr>
<tr>
<td>Error $\sigma(m_{\nu})$ on neutrino mass</td>
<td>$0.4$ eV</td>
<td>$0.3$ eV</td>
</tr>
<tr>
<td>Primordial gravity waves</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error $\sigma(r)$ on tensor-to-scalar ratio</td>
<td>$0.0079$</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 3: Summary of B-mode forecasts from Sections 6.1 and 6.2. For forecasts involving gravitational lensing, we consider two alternate statistical techniques: constraints can be obtained from the B-mode power spectrum $C_{BB}^E$, or from the deflection power spectrum $C_{\ell}^{dd}$ after reconstructing the deflection field $d$. The deflection power spectrum gives slightly stronger constraints, and we have used it when quoting forecasts throughout this proposal.
7 Systematic Uncertainties

In this section we discuss sources of systematic uncertainty and how QUIET plans to deal with them. This includes those associated with the detection and with the sky (foregrounds). We also contrast our approach with those of other experiments.

7.1 Instrumental Systematics

Here we draw on the formalism developed by Hu, Hedman, and Zaldarriaga [62] to discuss the sensitivity/immunity of QUIET to the most important sources of systematic uncertainty; reference [32] is also very helpful. Reference [62] distinguishes several critical effects which can result in spurious or contaminated polarization signals. These are associated either with the detectors or with the optics.

In this discussion, we need to keep in mind the noise-per-pixel levels for the experiment as given in Table 1. The discussion shows that our scanning strategy coupled with means to reduce and quantify spurious effects leads to residual uncertainties below these levels.

Polarimeter-induced Spurious Polarization  Gain fluctuations can create spurious polarization signals. For directly differencing the power in the two polarization states, as is effectively done with bolometric systems, differences in gain mimic a polarized signal. For a correlation polarimeter, however, these are negligible as the polarization signal is affected by the product (rather than the difference) of the the two gains so that gain fluctuations cannot fake a signal.

Gain fluctuations and miscalibration of the modules can cause "E mode \rightarrow B mode" leakage. Since each module directly measures Q and U, gain mismatch produces this leakage only at second order. Calibration with an accuracy of \(\sim 5\%\) (See Section 5.3) is sufficient to render this effect negligible.

The axis of polarization orientation can be misaligned due to a spurious phase between the two arms of the polarimeter, e.g., rotating Q into the U direction. However, since Q and U are each measured, no information: we know the small displacements in these axes to better than 1° accuracy (see Section 5.3).

Finally, instrumental imperfections can cause the temperature to feed into the polarization, the so-called "I to Q (or U)" leakage term. For correlation polarimeters, this comes about from the finite return loss of the low-noise amplifiers together with the finite isolation of the septum polarizers (so that some of the power input on one of the LNAs reflects back through the septum polarizer and appears in the other arm). For Phase I, this effect was at the level of -22dB, so that an 80 \(\mu\text{K}\) temperature anisotropy could become an approximately 0.6 \(\mu\text{K}\) polarization anisotropy. This effect is further reduced when one observes pixels at varying parallactic angles, and our scanning strategy is chosen, among other reasons, to reduce this effect. Figure 16 shows simulated bias in B-mode power induced by instrumental leakage. The Phase I data points are simulated based on the measured leakage coefficients. For W-band, where the leakage coefficients distribute randomly over the modules, we can expect suppression of the bias as the number of modules increases. We will achieve negligible bias in Phase II by taking advantage of this suppression using the same septum polarizer as Phase I. For Q-band, we will reduce the instrumental leakages by employing better matched septum polarizer+modules; the expected improvement is sufficient to make the bias negligible. Note that the bias estimate here does not assume any correction for the leakage in the analysis. In Phase I, we established a calibration procedure to measure the leakage coefficients to better than 0.1% accuracy using sky-dip (see Section 5.3). With these calibration coefficients used in the data analysis to correct the leakage, the systematic bias will be further reduced by an order of magnitude, making this systematic bias completely irrelevant in Phase II.
Optics-induced Spurious Polarization  If the two polarized beams have differing ellipticities, or equivalently the beam has a quadrupole component of I to Q/U leakages, there is a coupling to the local CMB quadrupole, generating spurious polarization. This form of pickup is particularly difficult in that it behaves just like a polarized signal with respect to how one scans or orients the detection axes. We have performed a semi-analytical calculation to estimate the possible systematic bias due to the beam quadrupole leakage based on the simulated leakage beam-map of the Phase I 1.4 m optics (Figure 16), which shows the expected systematic error is negligibly small: the spurious B-modes arise only from the beam quadrupole leakage component that has the angular dependence of $\alpha \sin 2\phi (\alpha \cos 2\phi)$ in the $I \to Q$ ($I \to U$) beam-map. Here, $\phi$ is the angle that defines the polar coordinate in the beam map. On the other hand, as shown in Figure 16, the simulated leakage beam-maps of the Phase I 1.4 m optics suggests the main quadrupole components are $\alpha \cos 2\phi (\alpha \sin 2\phi)$ in $I \to Q$ ($I \to U$) and thus the spurious B-mode is highly suppressed. This situation holds in Phase II: our optics system is immune to this systematic bias.

Non-linear distortion of the CMB map caused by spatially varying pointing errors can also lead to spurious B-modes [62]. Such pointing errors are most likely to be caused by periods of acceleration such as those at turnaround in the azimuth scans. We have performed full pipeline simulations including these errors. This study shows that even an error as large as 10 arcmin creates a negligible spurious B-mode signal of 0.005 $\mu K^2$ peaking around $\ell \sim 900$. The possible pointing error is well below this level and thus this systematic bias is well controlled.

Ground Pickup  Another potentially important source of systematic uncertainty would be beam side-lobes illuminating the ground, fluctuations in such pickup being most serious. Even in interferometric experiments, this is important: DASI differenced fields, losing sensitivity, and CBI projected out the common mode between their six fields. We have not seen ground pickup in Phase I data - we use absorbing ground screens (see Section 3.6), absorbing the vast majority of stray radiation. In CAPMAP we removed residual ground structure effectively daily, but QUIET's scanning strategy is designed so that we can do this every hour or even more frequently if necessary, with little loss of sensitivity.
7.2 Foreground Contamination

In this section we consider the impact of galactic (synchrotron and dust) and extra-galactic (point sources) foregrounds on the extraction of cosmological information from QUIET observations, and describe our strategy for mitigation. Our simulations show that foregrounds will not be a limiting factor.

Figure 17 shows projected galactic foreground power spectra from the Planck Sky Model (PSM) for EE and BB between $\ell = 80$ and 120 as a function of frequency for various sky coverages. The diffuse components are based on a model by [63]: this is the best available model of the sky at millimeter wavelengths. The QUIET patches are chosen from the cleanest on the sky: the expected foreground levels in the QUIET bands (also displayed in the figure) should be approximated by those of the lowest foreground curves in the figure. There is uncertainty in both the synchrotron (at low frequencies) and dust (at high frequencies) spectra but the latter uncertainty dominates, partly given the excellent WMAP coverage at the lower frequencies.

Our 95 GHz channel should be relatively clean of foregrounds to a level of $r \approx 0.05$; below that, we will have to determine and remove the contamination, with synchrotron expected to dominate. We have chosen to add the 32 GHz channel in Phase II so that we can effectively determine the synchrotron spectral index and extrapolate to 95 GHz with little dilution of our sensitivity.

With the two lower frequencies we retain sensitivity for a third low frequency component, such as spinning dust (which is however polarized at only a very low level).

The dust contamination is expected to be much lower than that from synchrotron radiation at 95 GHz. To determine its effects, we rely on information from other experiments. In particular, we have reached agreements with PolarBeaR and ABS who will both observe the same sky patches as QUIET but at higher frequencies. As well, Planck is on schedule to release high-sensitivity and full sky polarized maps at 143, 217 and 353 GHz in 2013, and these will comprise an outstanding data set for studies of dust emission.

![Figure 17: Estimates of diffuse foreground power (based on the Planck Sky Model v1.6.5) at angular scales $80 \leq \ell \leq 120$ as a function of frequency and sky coverage, compared to the EE power (left) and BB power (right) for $r = 0.1$. The QUIET bands are in gray. The CMB is constant in thermodynamic temperature and thus decreases with frequency in these units. The curves are for different sky coverage: full-sky, $|b| > 10^\circ$, $|b| > 30^\circ$, $|b| > 50^\circ$, and circular patches of radius $10^\circ$ and $7^\circ$ centered on $(l,b) = (240^\circ,-70^\circ)$.]

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Analysis and Algorithms To assess the foreground contaminations, we use a parametric model:

$$d_v(p) = s_{cmb}(p) + \sum_i A_i(p)g(\nu)\left(\frac{\nu}{\nu_{0,i}}\right)^{\beta_i(p)} + n_v(p),$$

where $d$ is the observed signal in pixel $p$ at frequency $\nu$, $s$ is the CMB signal, $n$ is instrumental noise, and the summation index $i$ runs over all relevant foreground components. We fit for $s(p)$, $A_i(p)$ and $\beta_i(p)$ at each pixel; $g(\nu)$ is a smooth modulating function. (The spectral indices may be fitted over larger patches to reduce uncertainties; see below.) Our goal is to determine the degradation in sensitivity after marginalizing over the residual foregrounds. Using modern Markov Chain Monte Carlo methods (e.g. [54]), it is also straightforward to couple this foreground model to the CMB power spectrum $G_{\ell}$, in which case errors due to residual foregrounds are propagated from the raw data through to power spectra and cosmological parameters.

Simulated Error Degradation from Foreground Marginalization We illustrate the technique for one of the four QUIET patches (Patch 6a; Oh 48m RA, -48° dec). On $1^\circ$ scales, the RMS synchrotron amplitude over Patch 6a at 90 GHz is 0.08 $\mu$K, and the corresponding RMS dust amplitude is 0.03 $\mu$K, roughly three times lower in map space or an order of magnitude in power. For reference, the CMB RMS is 1.7 $\mu$K. Over the pixels in the patch, the spectral indices for the foreground components are $\beta_{\text{synch}} = -3.13 \pm 0.02$ and $\beta_{\text{dust}} = +1.36 \pm 0.01$, and the polarization fractions are $f_{\text{synch}} = 0.20 \pm 0.10$ and $f_{\text{dust}} = 0.02 \pm 0.01$. In our further analysis here, we assume a common spectral index for each foreground component over the patch. The synchrotron index is fitted freely, while the dust index is kept fixed at a fiducial value, which we vary to assess systematic uncertainty.

We find the sensitivity degradation factors $f$ to be 1.17 when fitting only our own data for synchrotron and 1.53 when using the expected data from both PolarBear and Planck to constrain the dust component. Further, we find that systematic uncertainties from modeling of the two components add negligibly. Note that the E- and B-mode power spectrum uncertainties are proportional to $f^2$.

Point Sources Figure 18 shows the EE power spectrum (BB is similar) of polarized point sources, based on the PSM which includes a realistic population of both radio and infrared sources. Although subject to some uncertainty, particularly in the polarization at QUIET frequencies, this gives a good indication of the power level. The plot shows 2 frequencies (40GHz and 90GHz) and different flux cut-off levels in total intensity down to 0.1Jy. The E-mode signal is plotted as well as a B-mode signal for a tensor-to-scalar ratio $r = 0.1$. At 40GHz it is clear that trying to measure the faint B-mode signal would be significantly compromised by point sources, even if the bright ones (>0.1Jy) are removed. However at 90GHz, the power from point sources is reduced considerably to levels below $r = 0.01$. From our modules that measure the TT spectrum, we can remove sources below 0.1Jy, to further reduce the contamination.

We will mask all resolved sources, based on both external catalogs and our own CMB temperature measurements. Also, since our parametric component separation method performs all fits pixel-by-pixel, any contribution from unresolved sources with a spectrum similar to either synchrotron or thermal dust will automatically be marginalized out. We then expect only a very low additional contribution to the final power spectrum. Nevertheless, for safety we can marginalize over a point source power spectrum template similar to the WMAP approach. This should allow us to reach well below $r \sim 10^{-2}$.

In summary, for QUIET-II the statistical errors are increased by $\lesssim 20\%$ due to marginalization over the dominant synchrotron emission. Most likely, thermal dust emission may be neglected for our patches and noise levels. If not and in the worst case of full marginalization over the dust spectral parameters, the errors would increase by $\sim 50\%$. We conclude that QUIET will not be foreground limited.
Figure 18: The expected polarized power spectrum from unresolved extragalactic point sources for 40 and 90 GHz and with cutoffs from 0.1 to 1 Jy. The black curves show the CMB EE (top) and BB (bottom) spectra, the latter corresponding to $r = 0.1$.

7.3 Comparisons with Other Experiments

This section describes the features of QUIET that distinguish it from other funded or proposed experiments at the level of hundreds of detectors that are being mounted to measure large-scale B-mode power from gravity waves. These include the balloon experiments EBEX, Spider, and PIPER; and the ground-based experiments ABS, BICEP2, Keck Array, Poincare, PolarBeaR, ACTPOL, and SPTPOL.

QUIET has the sensitivity to reach values of $r$ in the range of 0.01, but we emphasize that raw sensitivity is not the most critical parameter. Like searches for dark matter, immunity from contaminants and systematic effects are critical. This justifies the simultaneous mounting of a variety of experiments with different approaches. A consistent result using different techniques will convincingly establish the existence of something as fundamental as primordial gravity waves.

Sensitivity. Sensitivity is nevertheless important, and we begin with a discussion of QUIET Phase-II sensitivity. At 32 and 44 GHz HEMT sensitivity is superior to bolometers. At 95 GHz with conservative assumptions from Phase I performance, the sensitivity per horn is quite comparable to that demonstrated with bolometers - where our noise figure is about 13 times the quantum limit. With 35 nm gates which will be used in this project it is anticipated that the noise should drop by a factor of 2 or more.

Simultaneous Detection of $Q$ and $U$ in each Feed. QUIET is the only experiment with this feature which makes maximum use of all CMB photons. This not only means that there is no time lag between the $Q$ and $U$ measurements in a pixel but even with the added amplifier noise, the overall polarization sensitivity to the CMB at 95 GHz is quite comparable to that for a bolometric detector.

Modulation. Because of the extreme faintness of the signal, modulation is critical. QUIET is the only experiment using MMIC amplifiers, permitting the signal manipulations allowing 4KHz modulation of the polarization signal. That fast modulation is complemented by the sky rotation which every 6 hours turns a $+Q$ measurement first into a $+U$ measurement and then into a $-Q$ measurement. Finally, by rotating the deck angle of the telescope (done roughly weekly in Phase I), we gain an additional degree of modulation that helps control systematics.

Time Constants and Readout. The diode outputs, even after conditioning, have multi-megahertz bandwidths so there is effectively no "time constant" to the outputs that needs characterization and
associated corrections. We are thus able to do our digitization at 800 KHz; writing out data streams at this rate is impractical, but we save “flashes” every minute or so which permit the identification and study of noise sources well above the nominal readout frequency of 100 Hz (where the signals are digitally demodulated in FPGAs).

**Dynamic Range.** HEMT-based detectors have the desirable feature of large dynamic range, something bolometers generally do not. In the lab, calibrating with cryogenic (LN2) loads, we find only of order 10% compression at room temperature. And at the site, we often calibrate by looking at the Moon with no biasing change necessary.

**Frequencies.** In Phase I, we just used 44 and 95 GHz and we will likely be able to extract cosmological information from each data set. But to go deep enough to see the primordial B modes, it is clear that the 44 GHz channel will be foreground contaminated (see Figure 17) by polarized synchrotron radiation. Dust, the foreground component currently with the highest uncertainty, is much less important for us than for most competing experiments. So to be sure we can reliably clean our 95 GHz maps of synchrotron, we have added channels in Phase II at 32 GHz, allowing precise extrapolation between the two low frequency channels. It is important to point out that QUIET is the only B-mode experiment which will characterize the polarized synchrotron foreground at sensitivities necessary for its removal. Such data will be of great interest to bolometer experiments, particularly (see the following paragraph) to PolarBear and ABS.

**Alliances with Other Experiments.** The patches we have chosen are those expected to be lowest in foregrounds. The PolarBear group has agreed to observe the very same patches, and since they too operate from the Atacama plateau, the two experiments will have excellent (near 100%) overlap. ABS as well has indicated that they are interested in similarly observing these patches. Especially if the dust component turns out to be larger than expected, measurements from these two experiments will help in cleaning the QUIET patches (although synchrotron will likely still dominate), and our synchrotron measurements will help these two experiments make clean maps. We stress again the importance of observing the same patches with this broad frequency sweep: likely each patch (if not each pixel) will need to be separately characterized and we will together have redundancy at 95 GHz with 2 frequencies above and 2 frequencies below.

**Connections to Particle Physics Laboratories.** The joining of the particle physics laboratories KEK and Fermilab has increased the strength of the QUIET collaboration. We mention that QUIET is the first CMB anisotropy experiment in which the country of Japan is participating. These labs bring a wealth of experience and quality control in building large-scale sophisticated instrumentation of the kind we need in QUIET. In addition, their experience in analog and digital electronics and data management is utilized in QUIET as detailed in the next section.

**Upgrade Path.** Finally, we can anticipate with the launching of the Keck Institute’s study of HEMT amplifiers and module components, new generations of components with substantially better performance. Improvements of even an order of magnitude in sensitivity over and above what we have proposed, by only replacing components in the modules, provide a most exciting possibility.

### 8 The QUIET Project Plan and Schedule

We present the plan for realizing the goals of QUIET. We first discuss the costs for the necessary equipment and the institutional responsibilities for delivering that equipment. After then presenting our schedule, we discuss our management plan. The 13 institution collaboration has been functional already for several years; these plans are based upon our past successes and awareness of areas for improvement. Results from prior support to the NSF supported institutions are described in Section 10. We point out that very recently we have been joined by a new CMB group at Michigan University (headed by Assistant Professor J. McMahon), and by a new Assistant Professor at Miami (K. Huffenberger).
Costs  In Table 4 we list the estimated costs to the NSF for the new components of QUIET all of which are discussed in the earlier sections of this proposal; costs for the personnel, travel, etc., are also included. Contributions from non-NSF supported institutions are given later in this section.

The estimated costs for the equipment items of QUIET are based in many cases on costs for the same items in Phase I and in others upon designs and quotations from industry. The assigned contingencies reflect the relative firmness of the estimates. Where we have firm quotations or anticipated price drops (computers), no contingency is shown.

We have requested funding for 8 students (two of whom are already on QUIET) and 6 postdocs (3 of whom are already on QUIET), to support the construction and data taking phases and to produce the science. We expect to have additional students and postdocs on the project, through institutional (e.g., Dicke, Kavli, Miller) and National (e.g., NSF) fellowships. Our science goals are: state-of-the-art limits or detections of primordial gravity waves, precision measurements of the E-mode power spectrum, and studies of the lensing of the CMB from the intervening matter distribution. These are to be carried out over 5 years using 4 receivers having state-of-the-art detectors at 3 frequencies, allowing other studies of galactic foregrounds. The requested manpower is needed for executing the experiment and there should be ample science for the young scientists on the project.

All the experimenters on QUIET will be involved in deployment, operations, and data analysis. Chicago, KEK, and Oslo are responsible for setting up analysis centers with enough processing power and storage to fully perform the analyses. The resources of these analysis centers will be available to the full collaboration. Already in Phase I, these institutions are contributing the vast majority of the storage and CPU cycles used by the collaboration.

<table>
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<tr>
<th>QUIET-II Costs to the NSF</th>
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<td>Component</td>
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<td>Analysis Cluster</td>
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<td>Electronics</td>
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<td>3 Telescopes</td>
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<td>Mounts</td>
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<td>Data Storage and Backup</td>
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<td>Module Housing/Parts</td>
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<td>Ground Screens</td>
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<td>Wafer Runs/Support</td>
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<td>Site Facilities (Generators, Foundations, Vehicles, etc.)</td>
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<td>3 Cryostats</td>
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<td>FPCs</td>
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<td>Septum Polarizers</td>
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<td>Beam Mapping/Reflectometer</td>
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<td>Interface Plates</td>
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<td>W arrays</td>
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<td>Ka/Q arrays</td>
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<td>EQUIPMENT TOTAL</td>
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<td>Faculty Summer Salaries</td>
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<td>6 Postdocs</td>
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<td>8 Graduate Students</td>
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<td>Project Manager</td>
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<td>Other Professionals</td>
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<td>PROJECT TOTAL</td>
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Table 4: NSF cost estimates and contingencies for major parts of the project.
Figure 19: Key milestones for the QUIET project.

Schedule  Figure 19 lists key milestones for the project. The 3 telescopes are staged in their construction and deployment. Sensitivity estimates have been made based on the scheduled number of months that each will operate.

In the sections below, we give the institutional responsibilities and the manpower at each institution devoted to QUIET.

8.1 Institutional Responsibilities: NSF Supported Institutions

Chicago  The Project Manager will reside in Chicago, the managing institution in QUIET. The PI will be 100% devoted to QUIET as will Postdoc Akito Kusaka, graduate student Immanuel Buder and at least one other student. As was the case in Phase I, we can anticipate additional students and Fellows supported through the Kavli Institute for Cosmological Physics, which also supports a budget manager for QUIET. Chicago will be responsible for supporting an Analysis Center and developing one of the two analysis pipelines; and for the integration and optimization/characterization of the first W-band receiver, a responsibility shared with Fermilab. Chicago is also responsible for the production and testing of the two electronics systems for all receivers: the Module Assembly Boards inside the cryostats and the Analog Electronics Boards which are mounted on the cryostats.
Caltech is responsible for the procurement of the InP MMIC wafers from Northrop Grumman, and the evaluation of the wafers and delivery of the resulting chips to the module integrators (FNAL, SLAC and Manchester). Caltech will lead an effort on the redesign and test of 44 and 95 GHz modules for improved performance and ease of assembly. Following this activity Caltech will provide consulting support to the module integrators during assembly and test. A graduate student and (effectively) one postdoc will be full time on QUIET. Caltech is also responsible for upgrade and operation of the Chajnantor Test Facility, logistics in Chile, assistance with equipment deployment, assistance with observations, and development of the telescope control and observing software in conjunction with other institutions. In Chile, the local staff consists of a lead engineer, a junior engineer, a technician, and an administrative assistant. The Pasadena staff are the Facility Director, a senior programmer, and an administrative assistant.

Columbia is responsible for leading the effort to adapt the existing cryostat design for Phase II, and will fabricate and test the first two cryostats. Columbia will be responsible for the integration and optimization of the Q/Ka-band receiver, and will lead the effort to integrate this receiver with the corresponding telescope. Manpower required for this work includes a senior researcher (Limon), support for one full-time postdoctoral researcher and two graduate students. Funding for one of the graduate students will be sought elsewhere. Faculty member Miller will supervise all Columbia effort.

JPL is responsible for the design of the MMIC amplifiers using 35 nm technology and detector circuits using HRL Tunnel Diode technology. JPL personnel will also monitor both the NGC and HRL contracts. In addition, JPL will be working closely with Caltech on module improvements, supporting design and assembly activities. JPL will provide a low level of support for the MMICs and modules after delivery and deployment. JPL will provide design support for the QUIET-II optics, verifying the optical performance of the mechanical designs and comparing with the measured optical performance.

Michigan will lead and oversee the development, manufacture and deployment of the three 2m telescopes for QUIET. This work includes finishing all simulations needed to finalize and characterize the optical design of the crossed-Dragonne system including the ground shield. Concurrently, they will design the mounts and coordinate with a vendor to have them manufactured. Once the first telescope is delivered the group will align and characterize the mirrors using photogrammetry or a laser tracker and then perform near field and far side lobe beam maps. They will also oversee the deployment and commissioning of these telescopes in Chile.

Miami is responsible for the design, fabrication and testing of the W-band, Q-band and Ka-band platelet arrays. Miami will perform the beam pattern measurements and return loss measurements of the arrays at the University of Miami. Two graduate students will be recruited to support these efforts. Once the platelet arrays are delivered, Miami personnel will assist in the beam pattern measurements of the telescopes, the deployment of the receivers in Chile and the subsequent observations. Faculty members Gundersen and Huffenberger will oversee the hardware development and data analysis efforts at Miami.

Princeton is responsible for the design realization, construction, testing and implementation of the Q- and W-band septum polarizers and of the cryomechanical wiring interconnects (FPCs) and associated protection circuitry. Princeton will also be in charge of the integration and test of one of the W-band receivers. Faculty member Staggs, supported with a student and postdoc, will oversee these efforts, as well as Princeton’s field work and analysis work.

The Kavli Institute for Particle Astrophysics and Cosmology (KIPAC) at Stanford is responsible for the manufacture and testing of the Q-band modules, and will design the Ka-band modules, septum polarizers and OMTs, in collaboration with Manchester University. We intend for the Q-band fabrication work to be carried out at the SLAC National Accelerator Laboratory using separate funds (see below) and for the Ka design and prototyping work to be carried out by campus members of KIPAC including Church and a graduate student and postdoc. Research Associate Thompson, who played a leading role in the design and manufacture of the Phase I telescope, will be partially supported to aid the telescope design and manufacture effort in collaboration with the universities of Michigan and Miami.
8.2 Institutional Responsibilities: non-NSF Supported Institutions

Fermilab has modestly contributed to Phase I since June 2007: several calibration wiregrids were built and used in detector optimization, commissioning, and calibration; a 20K black body was fabricated; and FE analysis of vacuum windows was performed. Funding from within Fermilab/DOE is being sought to participate in Phase II. The primary item to be delivered is production tooling, labor, quality assurance, and supervision to assemble approximately 1500 W-band modules, adapting existing tools in the SIDET facility to perform automatic assembly operations. The group also seeks to host and participate in the assembly, integration, and commissioning of one W-band 500-element receiver, perform FE analysis of the larger windows, and fabricate calibration grids. The group currently consists of 5 tenured lab scientists (Dejongh, Dodelson, McGinnis, Nguyen, and Stebbins) and would support a postdoc.

The SLAC group will seek funding from within SLAC/DOE to build the Q-band modules, using existing or modified capabilities at SLAC. The group consists of SLAC faculty member Tantawi, and SLAC scientists/engineers Fox and Van Winkle. If our funding application to SLAC is successful, the deliverables from SLAC will be a set of 70 modules from which the best 61 will be selected for integration into the Q/Ka receiver. An existing Laboratory Directed Research and Development (LDRD) fund is being used to develop light weight feeds and OMTs for mm wavelengths and supports a collaboration with Stanford Physics Dept members and with Caltech/JPL, so the preparatory design work can begin immediately. The production of the Q-band modules, and any participation in observing and data analysis will require extra funds above and beyond the existing LDRD.

The Keck Institute for Space Studies (KISS) is a joint endeavor between Caltech and JPL. The programs operate with grants from the Keck Foundation and matching funds from R&T to support activities and staff from JPL. We anticipate that a KISS program will be funded to improve the performance of low noise amplifiers and QUIET-style modules. Proposed improvements include the development of lower noise 35 nm InP MMICs designed specifically for cryogenic operation and multi-chip module design changes aimed at increased bandwidth and reduced noise. The KISS program will be funded for a period of 2 years and while it cannot be responsible for QUIET-II deliverables, the project will certainly benefit from these technology developments.

KEK is responsible for the integration, optimization/characterization and deployment of a W-band receiver system, for the production and testing of the ADCs for all receivers, and for global design and development of the data acquisition system including the monitoring system, the latter a responsibility shared with Chicago. KEK is responsible for setting up an analysis center and contributing to development of pipeline software for data processing and analyses. The KEK QUIET group consists of the KEK PI (Hazumi) and three assistant professors (Hasegawa, Higuchi, Tajima). Tajima contributed to the Phase I W-band receiver integration and deployment while he visited Chicago for two years. Higuchi has a lot of experience in developing large scale DAQ systems for accelerator-based particle physics experiments. In addition to the members listed above, KEK will hire two postdocs for four years for QUIET Phase II and will have one or two students dedicated to QUIET. KEK has already secured 2.2M$ for QUIET Phase II to fully fund these activities. The grant (Grant-in-Aid for Scientific Research on Innovative Areas from MEXT, Japan) starts in Oct. 2009 and ends Mar. 2014.

The MPIfR Bonn is responsible for the design, construction and characterization of the total power assemblies of 108 W-band, 6 Q-band and 2 Ka-band receivers. The group will also help with the assembly and optimization of the polarimeter subarrays (68 W-band receivers) before their integration into the large cryostats. The lab is already prepared with a multibeam test cryostat as well as RF hardware and electronics for testing purposes which has been set up and used during Phase I. We seek to acquire the required funds for the hardware (estimated 1M$) from the Max Planck Gesellschaft which had also funded the MPIfR effort for Phase I. We aim to fund at least one postdoc, a student and one engineer dedicated to the project.
Oslo will be responsible for setting up and maintaining a data processing center (both hardware and technical support) capable of handling the expected petabyte sized data set, and developing the necessary software for reducing the raw data into high-level data products (component maps, power spectra, cosmological parameters etc.). This work will build on the experience from Phase I. We already have funding for one Ph. D. student, and will apply for additional funding for one postdoctoral fellow and a second Ph. D. fellowship.

Oxford shares responsibility for the design and construction of the telescopes (optics and mounts) with Michigan, Manchester and Stanford. Oxford will seek UK funding for telescope components and can in any case provide design effort and at-cost manufacturing. With Manchester, Oxford will design and build the Ka-band polarimeter modules. Oxford will also contribute to the analysis effort, particularly with mapping software, and will seek funding for a student dedicated to QUIET operations and analysis.

Manchester will lead the design, production, testing and integration of 18 Ka-band modules in collaboration with the other QUIET institutions producing modules. The specific design will be agreed with the QUIET collaborators and will be based on the current Q-band design, although variations containing waveguide components like filters or hybrids will be considered. In the initial R&D phase, we will use existing MMIC amplifiers in Manchester. Subject to ITAR authorization, we will use new NGST MMICs in the final modules. Manchester will also deliver 16 split-block septum polarizers based on their own design on a timescale compatible with the Ka-band module delivery schedule. Three PhD students will be 100% on QUIET. Manchester is seeking STFC funds to participate in the design, construction and testing of one of the QUIET cryostats, in collaboration with Oxford, Stanford and Columbia.

Non-NSF contributions NSF funding for QUIET will be highly leveraged by contributions from international partners and non-NSF funded U.S. institutions, roughly $8M. This estimate includes components, salary support, and contributions to the operations in Chile. Prospects of QUIET obtaining the majority of this funding are good: already nearly half this amount is already in hand.

8.3 Management Plan

The PI is responsible for the allocation of resources to best construct, deploy, and operate the QUIET systems. He will be advised by an executive council of senior QUIET members. Efforts at the collaborating institutions will be managed locally; as in Phase I, written reports on progress and problems will be submitted quarterly.

An external advisory board will be constituted upon approval. It will hear reports from the project at least annually and report to the project management and the NSF. The first major review will be held before deployment of the first W-band array, now scheduled for April 2012.

There are 5 non-faculty professional scientists for whom we are seeking partial support: Imbriale, Limon, Radford, Shepherd, and Thomson. These individuals will have a collaboration-wide role and report directly to the Project Manager. The Project Manager will be charged with seeing to it that requirements are set (and met) for all electrical and mechanical interfaces in the project and for monitoring the schedule.

Non-NSF supported institutions will contribute $50K annually to the expenses at the site, reducing the total site costs (preparations, operations, and overhead) to the NSF over the 5 year life of the project from $6.2M to $3.9M.

The collaboration will continue to have multiple teleconferences every week with an annual face-to-face meeting. At these meetings, reports on progress on all the systems will be presented. The PI and Project Manager will assess progress and if not adequate, will, with the advice of the council, redirect resources. The project will conduct other reviews of systems under construction and will call upon recognized experts in the field where necessary.
9 Summary

QUIET Phase I has been operating in the Atacama desert in Chile since October, 2008. A 9 month run with the 44 GHz receiver was completed and one with the 95 GHz receiver is commencing (August, 2009). The polarization sensitivity of the two arrays has been measured and each exceeds those fielded by any other experiment at any frequency. Accordingly, 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, will be at least as good as for bolometric detectors, and parallel efforts on improving amplifier performance show the promise of significantly enhanced sensitivity.

Phase I data has been studied sufficiently well that all QUIET technologies have been verified - the stated goal of Phase I. The detector and readout technology, feedhorn and telescope format, observing strategy, data handling, and even institutional responsibilities and logistics will be substantially replicated. Areas with room for improvement are understood with a clear upgrade path. Phase II is ready to proceed.

Phase II is conservatively forecast to have an uncertainty on $r$, the tensor to scalar ratio, of less than 0.01. This derives from maps of over 4% of the sky with 100 nK/deg$^2$ polarization sensitivity, 100 times deeper than Planck. These forecasts are based upon operational experience in Chile, including actual duty cycle, cut efficiencies, and 1/f detector noise. In addition to the study of primordial gravity waves, these maps allow the determination of the matter power spectrum and constrain neutrino masses to $\sim 0.3$eV.

At 95 GHz, foregrounds from synchrotron radiation will dominate over those from dust. There is good reason to believe that down to a level of $r \approx 0.05$, no foreground cleaning will be required. To go below this level, QUIET is unique in having detectors at both 32 and 44 GHz: extrapolation of the synchrotron radiation from these two channels provides the necessary cleaning. Most other experiments operate at frequencies above 90 GHz where the foregrounds are dominated by dust, the level of which is less certain.

Scientists from KEK and Fermilab are already participating in QUIET and together with SLAC, these labs are poised to contribute their expertise and experience in complex experiments. Further leverage is provided by QUIET's other international partners in England, Germany, and Norway.

QUIET is building an alliance with both PolarBear and ABS, two other NSF-funded experiments that will also operate from the Atacama desert. Those experiments have agreed to map the very same patches that QUIET is observing. Together, this will provide high sensitivity cross-linked maps at 5 frequencies, spanning the synchrotron region, the foreground minimum, and the dust region - likely a critical combination should $r$ be closer to 0.01 than 0.05.
10 Results from Prior NSF Support

Six Institutions were supported with our Phase I funding through subawards from Chicago ((AST-0506648)); their activities have been described in the body of this proposal (no publications have yet resulted from this work). This section gives the results from other sources of support to the institutions.

A. Readhead (California Institute of Technology). Award: AST-0808050, $553,966, 24-Jun-08 to 24-Jun-11, “Multi-wavelength Observations of Gamma-Ray Blazars - the GLAST Connection” We have monitored 1158 CGRaBS blazars north of declination -20 degrees, twice per week with the Owens Valley Radio Observatory 40 Meter Telescope, since June 2007. We recently released our light curves at http://www.astro.caltech.edu/ovroblazars/ with the username “guest” and the password “40mguest”. We have also developed this website for the distribution of our monitoring data. We have completely re-written the telescope scheduling program to enable us to add more sources more easily, and we are in process of re-writing the telescope control program and upgrading the telescope computers, which were 25 years old. We are now engaged in analyzing our light curves using several analysis methods, including Structure Function, Lomb-Scargle, and wavelet-scalegram methods of analysis. We have also added several other samples to the CGRaBS sample. Development of human resources: the light curves for all 1158 CGRaBS will be made publically available by September 30 2009. These show the two-year light curves for these objects, from June 2007 to June 2009. Publications: Abdo et al. 2009, ApJ, 699, 976: “Fermi/LAT discovery of gamma-ray emission from a relativistic jet in the narrow-line quasar PMN J0948+0022” In press “PKS 1502+106: A new and distant gamma-ray blazar in outburst discovered by the Fermi Large Area Telescope”.

A. Miller (Columbia University) AST-04-48909 CAREER: A Novel Cosmic Microwave Background Polarization Experiment Based on Large Arrays of Coherent Polarimeters $876,382 15-May-05 to 30-April-10.

With this support, the Columbia team built the QUIET Phase I Q-band cryostat and led the integration, testing, and deployment of the the Q-band QUIET Phase I receiver [64]. We also aided in the testing of the Q-band polarization modules, built and tested window materials, electronics, and other components for the experiment, and played a central role in the observations throughout the first season. The first season of observations is now complete and Columbia postdoctoral researcher and two thesis students are engaged in the data analysis. With other support, the Columbia team designed and built the W-band Phase I cryostat, participated in W-band deployment, and is currently actively involved in the W-band observations.

Other relevant publications funded by additional NSF grants, are: [65, 66, 67, 68].

S. Staggs (Princeton University). Award: PHY-0355328, $3,354,773, “Gravitational Physics from the Cosmic Microwave Background.” This is the most relevant of recent grants; it funded several areas of research, including construction of the prototype receiver for the Atacama Cosmology Telescope (ACT) to prove that the novel free-space, multiplexed, 0.3 K TES, fλ/2 array concept worked, extensive work on the ACT detector development effort including process and test of over 3500 detectors, and other ACT-related activities. Three graduate students received their theses under this part of the funding (Lau, Marriage, Switzer) and four in subsequent years (Fisher, Hincks, Niemack, Zhao). Some research results are given in [69, 70, 71, 72, 73, 74, 75, 76, 77]. The most closely related research, however, was CAPMAP, which comprised 12 W-band and 4 Q-band cryogenic phase-switched correlation polarimeters coupled to a 7 m telescope. The instrument is described in detail in [78]. Early work is reported in [79]. In 2008 we published a final paper[5] The E-mode spectrum was detected at 11σ; the BB measurements provided one of the best limits yet on B-mode power at 4.8 μK2 (95%cl). The data are available at the LAMBDA website. Three graduate students received their theses under this part of the funding (Barkats, Hyatt, McMahon).
S. Church (Stanford University) OPP awards 0338138 ($659,914, 4/1/04-3/1/07), 0638615 ($149,315, 4/1/07-3/31/08) and 0739729 ($70,000, 4/1/08-3/31/09) Church is the PI of the QUA D CMB polarization experiment and her group designed and built the 31-element polarization-sensitive QUA D bolometric receiver. QUA D has mapped out multiple acoustic peaks in the E-mode power spectrum and has set the best limits to date on the B-mode power spectrum in the multipole range 200-2500. Former Church group graduate student James Hinderks, now at NASA Goddard, wrote a thesis on the instrument design, fabrication and testing and submitted a paper "QUAD: A High-Resolution Cosmic Microwave Background Polarimeter" that has been accepted for publication in the Astrophysical Journal. Current Church group student Ed Wu will complete a thesis on QUA D data analysis and has submitted a paper "Parity violation constraints using 2006-2007 QUA D CMB polarization spectra" to Physical Review Letters. QUA D has been used to train a number of undergraduate students including Evan Kirby, now at the University of Santa Cruz.

B. Winstein (University of Chicago). Award: PHY 0551142, $14,970,000, Aug 01, 2006 thru July 31, 2011, “The Physics Frontier Center of the Kavli Institute for Cosmological Physics” Funding from this PFC enabled the formation of a new CMB research group at Chicago, supporting Fellows, graduate and undergraduate students to participate in the CAPMAP experiment. Results from the final season of this experiment were recently reported (Bischoff et al. 2008). An 11 standard deviation detection was reported, the best in the business (along with the CBI) for its time. Keith Vanderlinde (now a Fellow at McGill) and Kendrick Smith (co-supervised with Wayne Hu and now a Fellow at Princeton) wrote their PhD theses based in part on CAPMAP data. In addition to the papers below [78, 80, 81, 82, 5, 83], 6 papers from the Fermilab KTeV collaboration were co-authored by the PI since 2006.

J. Gundersen (University of Miami). Award: AST-0206241, $301,164, 1-Aug-02 to 31-Jul-05, “A Survey of High and Low Galactic Latitude Polarization at a Wavelength of Two Centimeters” A low noise polarimeter operating at 12–18 GHz (Ku-band) was built for operations on Lucent Technologies Crawford Hill 7-meter antenna [84]. This Ku-band Polarization Identifier (KUPID) polarimeter began operations after the CAPMAP experiment was decommissioned and operated for 3.5 months at the end of 2005. KUPID mapped the polarized emission in a small region (10 square degrees with an angular resolution of 0.2”) encompassing the North Celestial Pole where previous CMB polarization measurements, including PIQUE [85, 86], COMPASS [87], and CAPMAP [79] have observed. In addition a number of other science targets were measured including the galactic plane and spinning dust target LDN1622, and calibration targets including the Crab nebula and the Moon were observed. Several undergraduates were trained on this project including Santiago Contreras, Yunior Savon, and Luis Bryce; and graduate student Eugenia Stefanescu wrote her thesis on this project [88].
References


