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SUMMARY OF PERSONNEL AND WORK EFFORT

The proposed work is one piece of a larger effort with many components, funded from several sources, as detailed in the proposal. The table below lists the fractional support for investigators requested in this proposal alone, and also the total fraction of time they are devoting to the entire larger effort. Percentages are averages over two years. See budget and text for details.

			Time	
Name	Status	Institution	This prop.	Total
T. Gaier	PI	JPL	22%	72%
C. R. Lawrence	CoI	JPL	5%	15%
M. Seiffert	CoI	JPL	18%	45%
S. Staggs	CoI	Princeton		10%
B. Winstein	CoI	U Chicago		20%
E. Wollack	CoI	GSFC		10%
A. C. S. Readhead	CoIlaborator	Caltech		
T. Pearson	Collaborator	Caltech		10%
M. Shepherd	Collaborator	Caltech		20%
M. Hedman	Postdoc	Chicago	17%	50%
D. Samtleben	Postdoc	Chicato	17%	50%
P. Farese	Postdoc	Princeton		50%
Grad student		Princeton		100%
K. Gorski	Collaborator	JPL		
M. White	Collaborator	Berkeley		

As the table suggests, the proposed program builds on a strong base of support from other funding sources, and will be a major focus of several key personnel.

1 SUMMARY

The polarization of the cosmic microwave background (CMB) offers a unique window into the structure and evolution of the Universe. E-mode polarization can be used to reconstruct the ionization history of the Universe, as recently demonstrated by WMAP (Kogut et al. 2003). B-mode polarization, created on large angular scales by primordial gravitational waves, can in principle reveal the energy scale of inflation. This exciting prospect has led to the inclusion of a "Dark Matter Probe" (sometimes called CMBPol) in the Beyond Einstein program.

At present, we know neither how well we *can* measure B-mode polarization in the presence of astrophysical foregrounds, nor how well we *must* measure B-mode polarization in order to detect a gravitational wave signature whose level is not known to many orders of magnitude. Progress must be made on both issues before we will be in a position to design the Inflation Probe envisioned in the Beyond Einstein program. Fortunately, such progress can be made from the ground with a new generation of powerful CMB experiments.

Individual detectors, whether bolometers or amplifiers, are now near fundamental noise limits set by the photon statistics of the CMB itself. The new generation of CMB experiments requires, therefore, not *better* detectors, but *more* detectors. The key to CMB polarization measurements is massive detector arrays.

We propose here to build an initial 91 element 90 GHz array receiver for CMB polarization measurements. The Q/U Imaging ExperimenT (QUIET) array is enabled by a revolutionary technology advance in millimeter-wave modules, based on an IC-style package with waveguide inputs that can be built and tested in quantity with fully automated equipment. Each module is a fully functional pseudocorrelation polarimeter, capable of detecting the Q and U Stokes parameters simultaneously. The heart of each module is a 90 GHz InP low noise monolithic microwave integrated circuit (MMIC) amplifier. The array is populated on a printed circuit board, providing "motherboard" integration. The motherboard, assembled using commercially available surface mount components, simultaneously provides bias to the individual chips and multiplexes and digitizes the voltage output signals. The PC board also provides the necessary thermal isolation for the 20 K radiometers. **This new array technology is completely scalable, enabling arrays of thousands of elements at a cost of a few hundred dollars per element.**

The 91 element QUIET instrument will achieve a sensitivity on the sky of $50\,\mu\mathrm{K}\,s^{1/2}$ for both Q and U Stokes parameters. This represents an order of magnitude improvement over WMAP and equals the sensitivity of the Planck High Frequency Instrument, but from the ground and four years earlier.

The team we have assembled is uniquely qualified to carry out this task. JPL, working with NGST (formerly TRW), leads the world in the development of millimeter-wave MMIC technology and chip packaging. Leveraging off two different NASA funded technology programs and the development of the Planck-LFI 100 GHz radiometers, the full complement of IC radiometers for QUIET will be developed in less than two years. Princeton University has been a science leader in observations of CMB polarization with the PIQUE and CAPMAP experiments, successfully integrating an array receiver into the Crawford Hill 7-m telescope. The University of Chicago provided both the data acquisition system and radiometer chain integration and optimization for the CAPMAP experiment. Caltech has led the development of CMB interferometers, and has developed a fully operational instrument at an outstanding site in Chile, where CMB polarization has been observed since September 2002. GSFC has demonstrated extraordinary design and performance in orthomode transducers and subsequent systematic impacts, as demonstrated in WMAP. By combining a revolutionary advance in millimeter-wave array technology with existing capabilities and infrastructure, we can have QUIET operational in less than two years.

2 INTRODUCTION, OBJECTIVES, AND SIGNIFICANCE

The temperature structure of the CMB has long been recognized as the most important available repository of information about the contents and geometry of the Universe. Over the last five years, the polarization structure of the CMB has received increased attention (e.g., Hu and White 1997). Polarization of the CMB is an inevitable consequence of almost all current models of cosmology; its recent detection by the DASI experiment (Kovac et al. 2002) and WMAP was therefore both expected and important. These initial detections, and the possible signature of reionization in the early Universe seen in the WMAP temperature-E-mode cross power spectrum, highlight the need for much more sensitive polarization measurements.

Although DASI and WMAP *detected* so-called E-mode polarization, which originates from Thompson scattering of quadrupole anisotropies in the surface of last scattering, neither has the sensitivity to measure the E-mode power spectrum with precision. Planck, with over an order of magnitude greater sensitivity than WMAP, will be able to determine the E-mode power spectrum accurately. Even Planck, however, may be unable to measure the so-called B-mode polarization anisotropies, which would arise from primordial gravitational waves and reveal the energy scale of inflation.

The importance of CMB polarization in general, and the exciting possibility that CMB B-mode polarization could reveal fundamental properties of our Universe 10^{-35} s after the Big Bang, have led to the inclusion of a CMB polarization mission in the OSS *Beyond Einstein* program. The goals of the so-called Inflation Probe are to:

- "Map the polarization of the CMB and determine all the sources of this polarization on both large and small scales. This will provide the most precise test yet of the gravitational theory for the origin of galaxies and structure in our Universe."
- "Search the CMB for the signature of gravitational waves from the Big Bang. This will test theories of the very early Universe, such as inflation models. It will also test physics at energies that are currently inaccessible by any other means."

From DASI and WMAP, we know that a measurement of the E-mode polarization power spectrum to the limits set by cosmic variance (i.e., the number of independent statistical samples provided by our Universe on different angular scales) will require about 30 times greater sensitivity than Planck. For B-mode polarization, we know neither the fundamental limits to measurement accuracy that will be set by polarized astrophysical foregrounds, nor the level of the gravitational wave signal. Estimates of the latter range over at least 24 orders of magnitude (!), and there is no guarantee that it can be detected at all.

Given our lack of knowledge of polarized foregrounds, and uncertainty over the ultimate detectability of the gravitational wave B-mode signal, performance requirements on the Inflation Probe can be nothing more than guesses at present. Two points are clear even at present, however. First, both the sensitivity and the freedom from systematic errors on the Inflation Probe must be much better than on Planck. Second, a great deal must be learned about polarized foregrounds, and perhaps B-mode fluctuations, before a sensible design may be determined.

Given that the sensitivity of individual Planck detectors is near fundamental physical limits, the increase in sensitivity required for CMB polarization measurements can be realized only by increasing the number of detectors. Since instrument sensitivity increases only as the square root of the number of detectors, reaching the cosmic variance limit on the E-mode power specrum would require detector arrays with 10^3 times as many elements as Planck has! Such arrays do not yet exist.

We propose here to take advantage of a breakthrough in amplifier array construction to build an initial array of 91 elements at 90 GHz. This array will be the first big step in a program of instrumental development that within a few years could have arrays of thousands of elements at multiple frequencies measuring the polarization power spectrum on all angular scales with high sensitivity. This would be a major step toward detector arrays that could reach the cosmic variance limit for E-mode polarization in space. Moreover, use of the array on a ground-based platform would provide an essential test of systematic error performance, valuable information on foregrounds, and CMB science results.

The breakthrough lies in the application of mass production techniques to millimeterwave circuits, and in the development of an architecture for cryogenic amplifier arrays to take advantage of those production techniques. The result is an expected reduction in the cost per radiometer (including testing!) of over an order of magnitude, along with scalability to almost arbitrarily large arrays.

The foundation for this breakthrough is the extremely small chip-to-chip variation in monolithic microwave integrated circuit (MMICs) that we have achieved in previous NASA-funded work. Interchangeable parts are the key to mass production in millimeterwave circuits no less than in automobiles.

Here we propose to build on this foundation, develop and apply mass production techniques to millimeterwave circuits, and fabricate a 91-element polarimeter array, QUIET. QUIET will be built within 2 years, and will then be used for observations at intermediate angular scales using the Cosmic Background Imager (CBI, Padin et al. 2002) platform in Chile. The observations themselves, and the existing operational infrastructure that will support them, will be (or have been) funded from other sources, and are not part of this proposal. The instrument can also be used, with modified optics, on a 5-10 m telescope for observations at small angles, where gravitational lensing of the CMB is expected to dominate both the B-mode signal.

Real observations are essential to the successful development of such an array, which must be free of systematic errors to an exquisite degree. Laboratory testing is not enough. Only observations of the sky itself can provide the conditions necessary to assess systematic errors to the requisite degree.

The QUIET receiver will have a sensitivity of $50\,\mu\mathrm{K\,s}^{1/2}$ when operated at the Atacama site. One year of observations from Atacama would give noise of $\lesssim 1\,\mu\mathrm{K\,deg}^{-2}$ over 10,000 degree^2 or $0.3\,\mu\mathrm{K\,deg}^{-2}$ over 1,000 degree^2. On a 7-m telescope, the array could achieve a sensitivity of $0.5\,\mu$K per $4\,\mathrm{arcm}^2$ pixel on a $2^\circ \times 2^\circ$ field near the North or South Celestial Pole. QUIET will achieve the same sensitivity as the Planck High Frequency Instrument in space, but years earlier and from the ground.

The choice of intermediate angular scales for the initial observations with QUIET and the use of the CBI platform are based on several considerations:

- *Intermediate angular scales are important*—If the B-mode signature of primordial gravitational waves can be detected at all, the most sensitive way to search for it is on moderate angular scales (Lewis, Challinor, & Turok 2001). Polarized foregrounds must be characterised on these scales. Such measurements are essential antecedents to the Inflation Probe mission.
- If systematic errors from ground and atmospheric emission can be controlled at very low ℓ, QUIET would measure the "reionization bump" very well.
- *Superb observing conditions*—The CBI/ALMA site, at an elevation of 5080 m in the Chilean Andes, is excellent for mm-wavelength observations. Three years' experience with the CBI operating in the 26–36 GHz band shows that atmospheric conditions are generally superb except during January and February. At other times, the atmosphere has been detected only rarely during snowstorms or periods of heavy cloud cover, on only the shorter CBI baselines. The angular power spectrum is consistent with a Kolomogorov spectrum, with noise rising sharply on large angular scales. However, no contamination has been seen on cross-polarized baselines, showing that the atmospheric noise in polarized emission is at least an order of magnitude lower than in total intensity, as expected. The complete absence of detectable atmospheric noise fluctuations in total intensity during most of the year on scales up to one

degree gives confidence that the atmospheric conditions are good enough for much of the year to permit system-noise-limited observations at 90 GHz on scales up to ∼10° and very possibly beyond that.

- *Infrastructure and operational experience*—The CBI has been in operation for several years. Utilities, trained personnel (experienced in operating cryogenic radiometer systems), control software, and facilities already exist. QUIET, mounted on the CBI platform, could be operational very quickly, in late 2004.

Figure 1 shows the expected result of one month of observations with QUIET, using one of several candidate observing strategies. In this case, 1,000 $\deg^2$ of sky are observed deeply. Multipoles from 10 to 100 can be well-determined. The observed patch of sky is too small to allow a good determination of multipoles much less than 10, depending on the amplitude of the reionization peak, but it is clear from the figure that differences between reionization profiles that cannot be differentiated by the 1-year WMAP data could be detected easily by QUIET.

Alternatively, one could observe a large strip of sky near the equator, but less deeply. If systematics from ground and atmospheric emission permit, the entire reionization bump could be determined accurately. With either observation strategy, we will learn important information about the behavior of the atmosphere, astrophysical foregrounds, and the CMB. The optimum strategy will be studied as part of the work proposed.

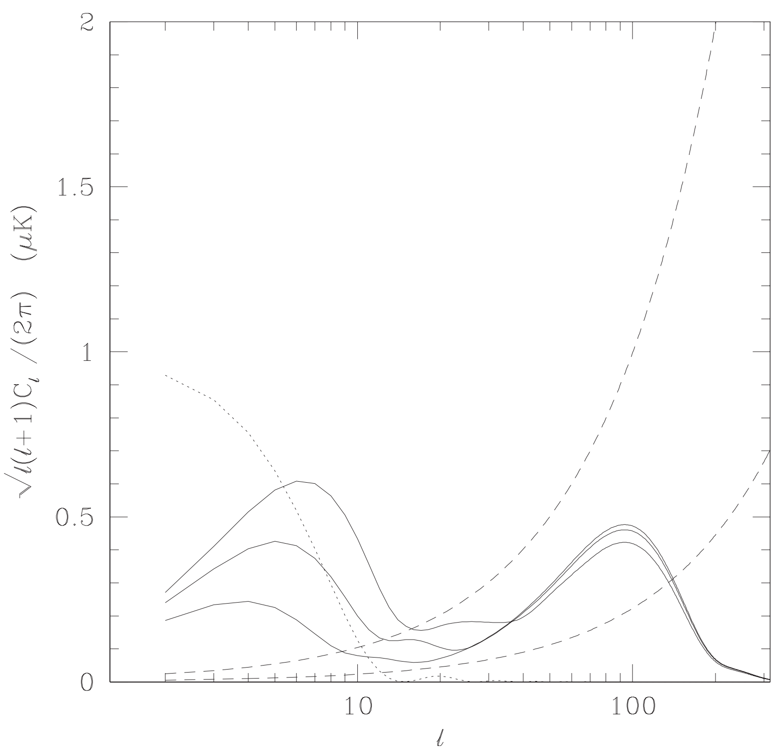

FIG 1.—Anticipated results from one possible observating strategy with QUIET, with only one month of integration time. The solid lines are model E-mode power spectra, all consistent with WMAP data, but having different reionization profiles between $z = 20$ and $z = 10$. The upper dashed curve is the noise expected per individual multipole in one month of QUIET observations over 1,000 $\deg^2$ (corresponding to 1 μK per 1°.5/pixel). The lower dashed curve is the same, but with multipoles combined into $\Delta\ell = 20$ bands. The dotted line is the "sky" window function, i.e., the Fourier transform of a disk of radius 15°. Clearly, QUIET would be a powerful instrument for observing CMB polarization.

Small angular scales are extremely important as well, containing much information about conditions in the early Universe. This information is also necessary for designing the Inflation Probe. Once QUIET demonstrates the viability of the array technology that we are proposing, we will move agressively to implement additional arrays in optical systems providing $\lesssim$0°.5 resolution.

TABLE 1

Relationship to Other Parts of the Program

Aspect	Funding Source
Device development	Code R
Single-element prototype	Code R
91-ELEMENT ARRAY	**THIS PROPOSAL**
Operational infrastructure	CBI/NSF
Other frequencies	Future proposals
~1000 elements	Future proposals

We emphasize that this proposal is aimed at the development of array technology for amplifiers arrays, and the construction of a large array as a proof of concept. That proof requires CMB observations—no laboratory environment can possibly provide the stringent conditions necessary to demonstrate freedom from systematic errors at the level required. Those observations will be funded separately. The work proposed here builds on previous work, and, if successful, will enable a large number of future instruments that are inexpensive to build, straightforward to operate, and which can exploit the scientific potential of CMB polarization at the same time as they prepare the way for the Inflation Probe.

3 TECHNICAL APPROACH

3.1 Introduction

The development over the last 20 years of low-noise transistors for frequencies above 1 GHz has revolutionized coherent (i.e., phase-preserving) receivers for microwave and millimeterwave applications. Developed primarily to meet military and civilian communication requirements at room temperature, high-electron-mobility transistors (HEMTs) offer low noise, low power dissipation, high reliability, inherently wide bandwidths, insensitivity to electromagnetic and charged particle radiation, the ability to handle high signal levels without damage, and operation over a wide temperature range.

The theoretical sensitivity of a "total power" radiometer array of N identical elements (to a signal filling the beam or in surveying the sky) is given by

$$\Delta T_{\rm min} = \frac{T_{\rm sys}}{\sqrt{N\beta\tau}} \qquad (1)$$

where $T_{\rm sys}$ is the system noise temperature, β is the RF bandwidth of the radiometer, τ is the post-detection integration time, and $\Delta T_{\rm min}$ is the minimum detectable signal in that integration time. The sensitivity of other radiometer designs is of the same form, but with additional factors of order unity. Clearly there are three basic ways to make a more sensitive radiometer: 1) reduce the noise $T_{\rm sys}$; 2) increase the bandwidth β; or 3) increase the number of "pixels" N.

There is a lower limit to $T_{\rm sys}$ for coherent receivers set by quantum fluctuations. This "quantum limit" q can be written an as equivalent noise temperature, $q = h\nu/(k \log 2) \approx [\nu_{\rm GHz}/20]$ K. The current state of the art is 3–6$\times q$, depending on frequency. Bandwidth cannot be increased much beyond 30% without introducing spectral confusion problems. Although there are limits on the number of pixels for a given telescope and wavelength (see § 3), that number is large compared to current instruments.

The path to improved sensitivity, therefore, is much the same in the microwave and millimeterwave part of the spectrum as in others: push detector sensitivity to fundamental limits, and make large arrays of detectors. However, the largest (cryogenic) millimeterwave detector arrays now in existence or under construction have only about 50 pixels. It has been a long time since ultraviolet, optical, or near infrared arrays were that small!

Here, we describe a path to a very large array of radiometers optimized for polarimetric measurement of the CMB. There are two key aspects of the strategy. First, use automated semiconductor manufacturing techniques to rapidly assemble "radiometer-on-a-chip" units at high throughput and low per-unit cost. The modular nature will also speed the testing and characterization process. Second, radiometer placement, wiring, analog readout electronics and control are accomplished on a few printed circuit boards minimizing assembly time and enhancing reliability. Below we describe the detailed steps necessary to produce a demonstration array of 91 radiometer elements.

3.2 Radiometer Design and Calibration

The proposed radiometer array will consist of a hexagonally close-packed array of radiometer modules with associated feed horns and polarizers capable of measuring Stokes Q and U simultaneously. A block diagram of the module is presented in Figure 2. The corrugated feed horn directs the sky signal to a waveguide circular polarizer. The left- and right- circular polarization signals enter the radiometer via the top of the module. After low-noise amplification, these signals pass to phase shifters, one of which alternately applies a 0° or 180° phase shift. This produces alternate linear polarization at the diode output.

After synchronous demodulation in the readout electronics, the resulting signal is proportional to Stokes Q. Addition of a second planar coupler and detector diode pair results in detection of Stokes U as well. This radiometer design follows the well known principle that measuring linear polarization with a circular, rather than linear, polarizer minimizes susceptibility to systematics (e.g., Heiles 2001).

For calibration, one amplifier leg of the radiometer can be turned off, which converts the radiometer to total power mode allowing frequent external calibration. A cross check of the calibration in polarimetry mode can be made occasionally with astronomical sources. Instrumental polarization can be measured by occasional observations of bright unpolarized astronomical sources, e.g., planets.

3.3 Radiometer Module — "Radiometer on a Chip"

The development of the Planck LFI receivers has left a legacy of chipsets suitable for low noise CMB polarimeters, namely low noise amplifiers and a broadband phase switches. Thousands of the amplifier chips are currently available and the phase switches can be produced for this program at modest cost.

NASA Code R has funded a program in THz imaging arrays. As part of this program they have provided the initial seed, developing a "unit cell", suitable for development into massive dense arrays of receivers at 90 GHz. Work has been proceeding on this activity with a first deliverable of a demonstration "U" polarization module at 90 GHz by September 2003. Specialized components we have already built and tested include cryogenic detectors and planar "MMIC" magic tee couplers. All other components were already available. The unit cell is being designed to accommodate automated assembly techniques to allow the array size to be scaled to $N = 10^3 - 10^4$ at a unit cost of a *few hundred dollars*. This is being achieved by adapting low cost IC style packages to millimeter wavelengths, rather than the previous specialized "gold brick" approach. The use of the IC style approach allows for the elimination of connectors, instead providing bias and data connections to the radiometers on a simple printed circuit board. RF connections are accomplished through a small waveguide aperture in the lid.

QUIET will utilize the technology developed in the THz Array program. In order to fabricate 10^2 polarimeter elements, we require the fabrication of 2×10^2 phase switches. This will be accommodated easily in a single wafer run on the Northrop Grumman Space Technology (NGST,

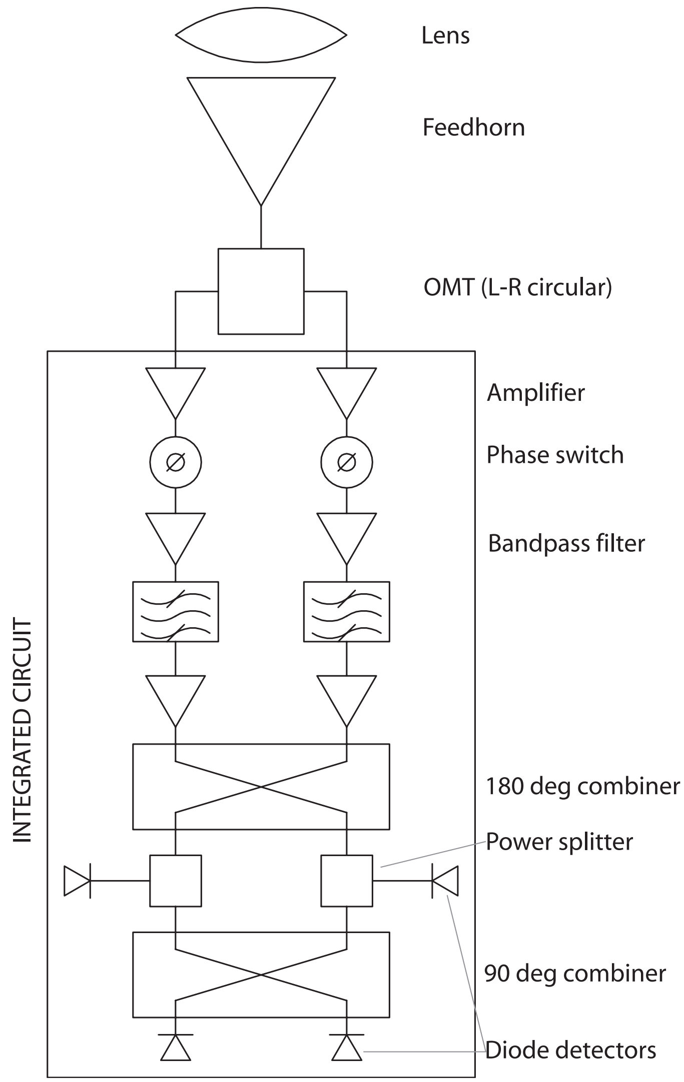

FIG 2.—Block diagram of a polarimeter that detects Stokes Q and U. A full array will be populated with such modules. In about 5% of the array, the OMT will be replaced with a hybrid coupler and a reference load to produce Stokes I.

formerly TRW) InP PIN process. This will be funded by other sources. All of the critical low noise amplifiers for this task exist and have been developed under NASA Code R's Cryogenic HEMT Optimization Program (CHOP).

Mass production of the elements will follow two lines providing a risk reduction and clear path toward even larger arrays in the future. The first few elements will be fabricated manually under the Code R effort. We will then "kit" elements for three lots of 10 modules. Two will be sent out to different vendors for automated assembly, while the third will remain in house for manual assembly. The remaining 70 modules will be fabricated following the evaluation of the automated assembly modules. Two companies have so far indicated an eagerness to demonstrate their capabilities at these frequencies. The quoted part placement and assembly tolerances of 10 μm are more than adequate to the task.

Mass production of these units is enabled by the demonstrated MMIC uniformity exhibited in the Planck radiometers. The LFI modules had a very limited wire harness, forcing us to provide DC distribution circuitry inside the module. We were also forced to separate front and back ends thermally to remain within the 20 K cooler load. In the case of QUIET, the complete RF-DC

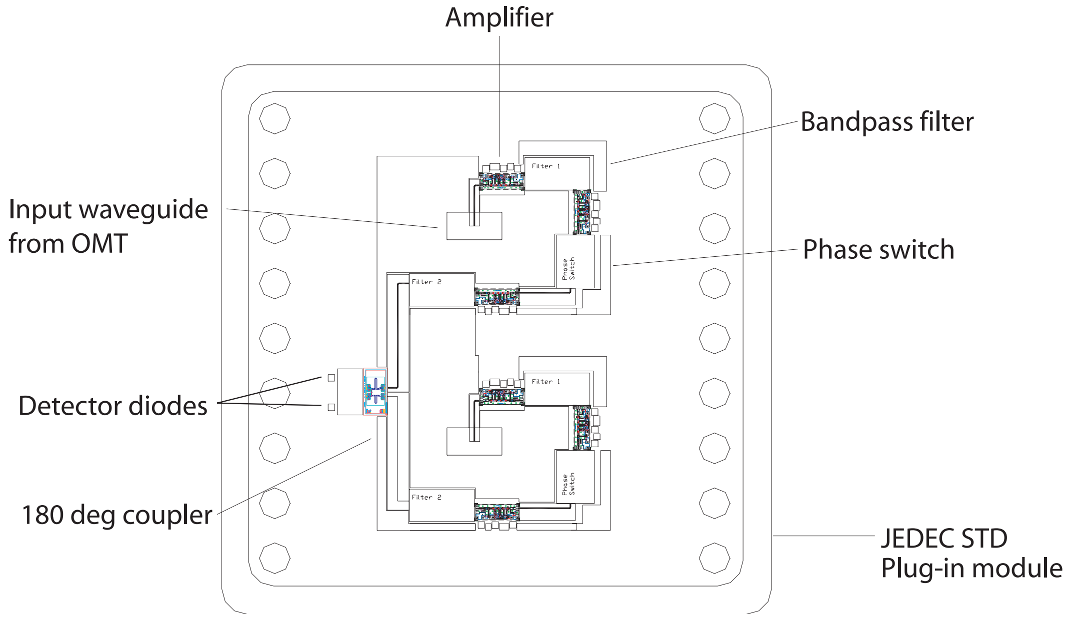

FIG 3.—Layout of polarimeter module in package. Placement of parts will be done by hand for small numbers, by automated equipment for large numbers.

chain is in a single module, cooled to 20 K. Bias controls for each chip in the module are brought out on the module pins. This, and our experience with the LFI radiometer development, will allow automated optimization of each module during the module testing phase, greatly reducing cost. These biases and other signals are routed appropriately on the readiometer ciruit board to an edge connector, eliminating individual cabling or point-to-point wiring anywhere in the entire radiometer assembly as described below.

3.4 Massive Array Integration

A critical aspect of producing massive arrays at low cost is the integration and thermal management of the cryogenic radiometers. The key to our approach is the use of printed circuit board technology. We will design and fabricate a circuit board that can accomodate the 91 radiometers, provide low noise gain for the output signals, and will provide routing for output signals and radiometer bias. The circuit board and the radiometer IC chips mounted on it will run at approximately 20 K. Located near each radiometer chip will be a low-noise gain stage for the radiometer outputs consisting of silicon-based matched transistors which will operate at approximately 90 K. The low-noise gain stage will reside on an isolated island of circuit board connected only by narrow bridges to the rest of the system, thus allowing the necessary thermal isolation between the 20 K radiometers and the 100 K gain stages. The low-noise gain stages will self heat to the required operating temperature once operating bias is applied.

Figure 4 shows a circuit board layout for a test unit. After fabrication, the printed circuit board will be machined to cut out a narrow perimeter between the radiometer and low-noise gain stage, except for the narrow bridges that provide mechanical support and allow for circuit traces. The thermal budget for each radiometer plus gain stage is 50 mW. The active dissipation of the low-noise gain stage along with low thermal conductivity to the 20 K regions of the circuit board are sufficient to allow the gain stage to adequately self heat and not dominate the thermal budget. After construction, test, and optimization of the unit cell circuit board, we will scale the design to a circuit board that can accomodate approximately 100 radiometers.

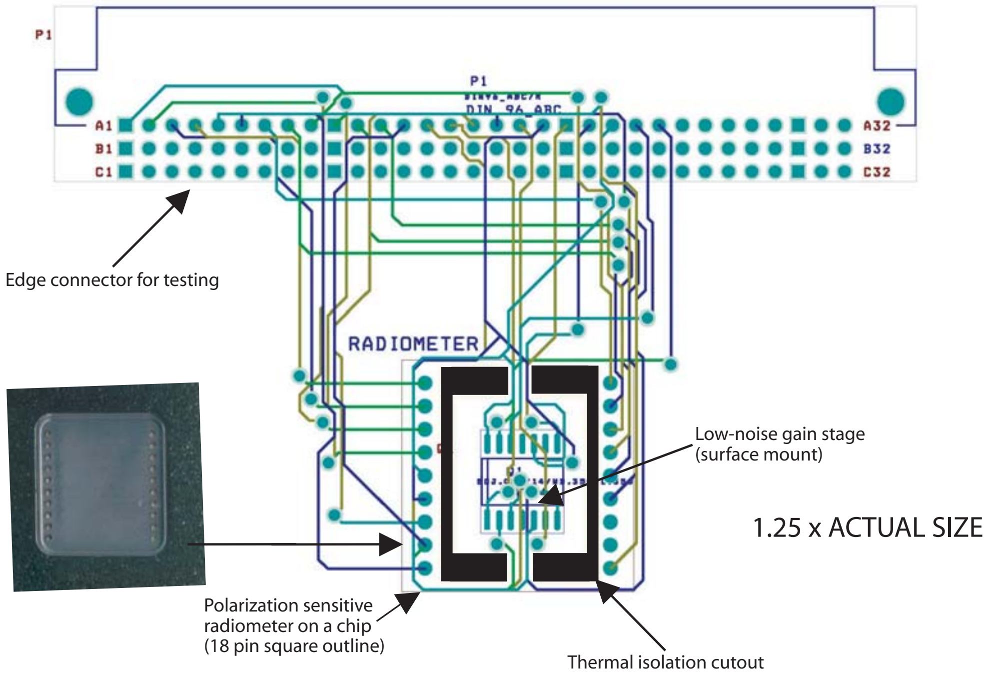

Fig 4.—Printed circuit board layout for test of unit cell radiometer. The thermal isolation cutout in allows the 20 K radiometer to coexist with the 100 K low-noise gain stage on the same circuit board. Generalizing the circuit board to hundreds of radiometers will be straightforward. For QUIET, the central unit shown here will be replicated 91 times. A circuit board will provide distribution of bias and output signals, routed from several large edge connectors that will connect the board to a nearby room temperature board via a kapton film ribbon cable. The room temperature board will contain the rest of the amplification, demodulation, A/D, and bias functions for the 91 elements. Both of these circuit boards will reside in the dewar. The final shielded output will be a serial data stream.

3.5 Optical Design

The optics will be designed to achieve a field of view $16^\circ\!.5$ across with a nominal beamwith (FWHM) of $1^\circ\!.5$. This same constraint is appropriate for several 5–10-m class telescopes we are currently exploring as platforms for the arcminute scale experiment. It is interesting to note that *any* CMB experiment contemplating large focal arrays will have the same optical design constraints, *independent of detector technology*. However, our approach has a degree of freedom that may not be available to other detector technologies, in that it is possible to curve the array surface to match a curved focal surface. Since in general large-field telescopes have curved focal surfaces, this is an important advantage.

Three approaches are currently being explored for the beamforming optics. All three utilize corrugated feed horns to provide a clean symmetric beam with low cross-polarization. Since these experiments are likely to be limited not by instrument noise but by systematics, reduction in the amplitude of systematic signals is paramount. Princeton University will explore the use mass produced stacked ring assemblies to build large numbers of very low cost corrugated feeds.

The first approach is the simplest, and has been used by CAPMAP and DASI. Each feed illuminates a simple dielectric lens. The beamsize is set by the size of the lens, which is larger than the mouth of the feed. Based on the CAPMAP experience, a $1^\circ\!.5$ beam requires a 12 cm lens, leading to a large array. The second approach uses a close-packed array of small feeds illuminating a single thin lens the diameter of the entire array. This has the advantage of small array size, but can introduce polarization offsets and reflections that must be controlled. The third approach uses an offset elliptical tertiary achieve the desired resolution and reduce polarized offsets. Note that with any of these approaches, the array itself is thin in the direction parallel to the optical axis.

3.6 Orthomode Transducers

The performance of QUIET depends upon the performance of the orthomode transducer (OMT). The Q/U design of the modules requires left-right circularly polarized OMTs. Design considerations include polarization isolation, VSWR, and axial ratio (or ellipticity). Excellent performance can be achieved with a linearly polarized OMT and a multi-stage waveplate (Kovac et al. 2002). The standard linearly polarized OMT, as used by WMAP and Planck- LFI, performs well, but is expensive to produce. A design by Co-I Wollack (Wollack 1996) is well suited to low-cost mass production and will be explored. Another option we will explore, is a sloping septum circular polarizer, similar to the ones used by NRAO on the VLA. The polarizers are extremely simple and inexpensive to manufacture, but require additional compensators to provide the required axial ratio of $\lesssim$0.1 dB.

3.7 Data Acquisition and Bias Control Board

One tremendous advantage of coherent detection over bolometer receivers is that the readout electronics are easy to build and easily scaled to very large array sizes. Once the sky signal is amplified at radio frequency, the noise requirements on the following electronics are modest. As a result, the readout electronics can operate at any convenient temperature, and any added heat to the cold end from the readout electronics is a small fraction of the total allowable heat in the focal plane.

The same motherboard which DC-amplifies and digitizes the signals will also provide the bias. A single multilayer PC board with surface mounted components is sufficient for this task. The motherboard also provides automated bias control, utilizing feedback from the detectors under a variety of test inputs, to optimize the array performance, under computer control. The data acquisition and bias board will be designed and fabricated at the University of Chicago CfCP. They are drawing on their combined experience from the data acquisition system and radiometer integration of CAPMAP.

To achieve optimal performance, the bias settings of the MMIC amplifiers must be tuned properly. The first stage amplifiers in each arm must be adjusted to minimize the system temperature, and the other amplifiers must be set so that the two arms of each radiometer have the same effective pathlength. If the biases of hundreds of elements are going to be set, this optimization must be done quickly and automatically.

When all or part of the array is to be tuned, the bias controls and outputs of the array will be managed by a computer program while a series of controlled signals are injected optically into the array. The output voltages will be readout with different bias levels and the optimum settings for the array will be determined quickly in software.

The first signal injected into the array will be a broadband unpolarized noise signal which is switched between two distinct levels. The software will determine the bias settings on the first stage amplifiers which maximize the ratio of the two resulting output voltages; this should minimize the system temperature of the radiometers. Next, a polarized narrow-band swept signal will be injected into the array. This polarized signal will periodically switch between circular and linear states [alternatively, and ideally, a special 90-degree state of the phase switch could be used, if feasible]. The software will then derive the relative phase-shift between the two arms of each module and determine the bias voltages on the subsequent stages to minimize this difference. This optimization procedure can be iterated for rapid convergence.

Once tuned, the array performance can be validated using controlled sources of slightly polarized thermal radiation (employing emissive surfaces and wire grids) to measure the repsonsivity and sensitivity of the array elements. These sources can easily be made to fill the aperture of the array so that the entire array can be characterized at once.

4 BOLOMETERS AND HEMTs: Comparative Assessment

Comparisons between different detector technologies are often made on the basis of raw detector sensitivity. This can be misleading, because many other factors in addition to raw sensitivity contribute to the overall capability of an instrument. In this section we discuss these factors, and show that for CMB polarization measurements at frequencies of 100 GHz and below, HEMT amplifiers offer comparable noise to bolometers, detector for detector, but with significant operational advantages and a great advantage in scalability for large array sytems.

The effective sensitivity of a bolometer receiver in space for CMB observations is limited by the inherent noise of the bolometer, the fraction of incoming photons "lost" before detection (the *optical efficiency*), by the Poisson photon fluctuations in the CMB itself (the "background-limited performance" or BLIP limit), and by other sources of noise (e.g., readout electronics, thermal noise from the telescope). The noise of the best current bolometers is comparable to the CMB Poisson noise. The 100 GHz Planck HFI bolometers in space have an expected temperature sensitivity per detector of approximately $50\,\mu\mathrm{K\,s}^{1/2}$. This corresponds to an effective system noise temperature of about 9 K.

The effective sensitivity of a HEMT amplifier receiver in space is limited by the same factors, but three differences are significant. First, the inherent noise of an amplifier cannot be less than the so-called it quantum limit, given approximately by $h\nu/k = 0.05\,\mathrm{K/GHz}$, a consequence of the fact that amplifiers, unlike bolometers, preserve the phase of the incoming signal. Quantum noise and CMB photon noise are equal at approximately 53 GHz. Second, optical coupling efficiencies can be significantly higher. Third, once the quantum tax is paid in an amplifier, the signal can be replicated and reused with no significant increase in noise. As described in § 3.2, this enables combination of signals from two orthogonal polarizations with two different phases to achieve simultaneous determination of Q and U from a single feed.

For observations from the ground, atmospheric noise is an additional and important factor. Even in outstanding sites such as the South Pole and the CBI/ALMA Atacama site, atmospheric emission is a significant noise source. In addition, bolometers built to handle the higher photon background on the ground are of necessity less sensitive than those built for space.

Table 2 compares the expected sensitivities for single-channel bolometer and HEMT polarimeters in space and on the ground. Each polarimeter channel requires two detectors. Some improvements over Planck are assumed in the optical efficiency and noise of bolometers. A factor of two reduction in amplifier noise (to 3× quantum limit) is assumed for HEMTs in space circa 2010, as may be anticipated for the antimonide-based devices that should be available in a few years. The factor of $\sqrt{2}$ for HEMTs reflects the ability of the coherent system to measure Q and U simultaneously.

The effect of these factors is readily illustrated. The ACBAR experiment recently reported an instantaneous sensitivity of $350\,\mu\mathrm{K\,s}^{1/2}$ at the South Pole. Bolometer noise alone was considerably lower than this, at $200\,\mu\mathrm{K\,s}^{1/2}$. Atmospheric emission and instrumental loading nearly doubled the overall noise (J. Bock, private communication). To convert this instantaneous sensitivity T_x to an equivalent Stokes-parameter sensitivity $(T_x - T_y)/2$, we divide by $\sqrt{2}$, giving $250\,\mu\mathrm{K\,s}^{1/2}$.

A 45 K HEMT pseudocorrelation receiver at 90 GHz, with a 20,GHz bandwidth, has an instantaneous noise of $230\,\mu\mathrm{K\,s}^{1/2}$ per Stokes parameter. If the receiver is configured to detect both Q and U Stokes parameters, the instantaneous sensitivity per module is $\sqrt{2}$ better, or $165\,\mu\mathrm{K\,s}^{1/2}$. Adding 12 K for atmospheric emission and CMB photon background, the overall system sensitivity is $203\,\mu\mathrm{K\,s}^{1/2}$, compared to $250\,\mu\mathrm{K\,s}^{1/2}$for the bolometer system from the ground.

At lower frequencies, HEMT noise is lower, while bolometer noise is roughly flat (Table 2). **For ground-based CMB polarization measurements, HEMT receivers offer better noise than bolometer receivers at frequencies up to 100 GHz.**

Important as it is, noise per detector is not the only consideration for an instrument. Array

TABLE 2

Bolometer & HEMT Sensitivities

Frequency [GHz]	From Space (∼2010) Bolometer [μK s$^{1/2}$]	From Space (∼2010) HEMT/$\sqrt{2}$ [μK s$^{1/2}$]	From Ground (2004) Bolometer [μK s$^{1/2}$]	From Ground (2004) HEMT/$\sqrt{2}$ [μK s$^{1/2}$]
20	82	56		
30	69	56	250	120
45	58	52	250	110
70	50	68	250	180
100	46	84	250	204
150	50	129	250	450
220	70	261		
330	189	966		
500	1442	9633		

[a] Bolometer values from A. Lange (space) and J. Bock (ground), private communications.
[b] The $\sqrt{2}$ in the HEMT values comes from the fact that Q and U can be measured simultaneously behind one feed. Real estate in the focal surface is a critical resource for massive arrays, therefore the reduction in number of feeds by a factor of two should be reflected in the effective sensitivity values. The convention for polarization sensitivity used here is $(T_x - T_y)/2$.

size and operational issues are important as well, and HEMT receivers offer several advantages summarized in Table 3: easy scalability to thousands of elements with commercially available semiconductor packaging processes; operation at 20 K, vs. $\leq$ 300 mK for bolometers; room temperature readout multiplexers that can be implemented easily and cheaply with standard printed circuit board technology, vs. complicated cryogenic readout multiplexers for bolometers; and, most importantly, the ability to modulate the polarized signal after amplification, minimizing the input offset and reducing systematic errors, vs. lossy mechnically rotating waveplates or magnetic Faraday modulators for bolometers, both of which tend to introduce polarimetric offsets. Moreover, the ability of a HEMT system to measure Q and U simultaneously with one feed reduces by a factor of two the number of feeds required in the focal surface for a given sensitivity. Real estate in the focal surface is a precious commodity. (As a rule of thumb, the number of resolution elements in the focal surface of a telescope of diameter $N\lambda$ is roughly $[N/10]^2$.) The Inflation Probe may require many thousands of detectors, and a factor of two reduction in number of feeds is an important advantage.

TABLE 3

Operational Advantages of HEMT Arrays

Aspect	Bolometer	HEMT
Array size	Current limit several hundred	Straightforward for thousands
Physical temperature	150–300 mK	20 K
Readout circuits	Complicated cryogenic multiplexers	Room temperature circuit boards
Polarization modulation	Rotating waveplates; Faraday rotators	Electronic, after amplification
Focal surface real estate	One pixel = Q **or** U	One pixel = Q **and** U

For a future space mission, the linear increase of quantum noise in coherent detectors will limit the use of HEMTs to frequencies of roughly 100 GHz and below. Above that frequency, bolometers will be required. But from the ground, where most CMB polarization science will be obtained for the next decade (with Planck the notable exception), and where atmospheric noise increases rapidly with frequency, HEMT amplifiers are the logical choice for a receiver. Even with the current noise performance of amplifiers (6–8× quantum limit), the straightforward scalability of the receiver technology described in this proposal to arrays of thousands of elements, plus the other operational advantages of amplifiers, guarantee that amplifier arrays will be at the forefront.

Moreover, HEMT technology is also progressing with new materials now being developed, and the 3× quantum limited noise found today at 8 GHz is likely to be available at 100 GHz within a couple of years. Such a receiver will observe the CMB from space with $84\,\mu\mathrm{K\,s}^{1/2}$ sensitivity per polarimeter, less than a factor of two worse than the best bolometer, but it can do it without 100 mK cooling and with better systematics. The instrument proposed here would be not only a powerful instrument for observing CMB polarization from the ground, but also an important step toward the ultimate goal of a space CMB polarization mission.

5 IMPACT ON THE FIELD & RELATIONSHIP TO PREVIOUS AWARD

5.1 Impact on the Field

Measurement of the CMB polarization signal of the gravitational wave background predicted by Grand Unified Theories and inflation would provide the unmistakable signature of inflation, determine the new physics responsible for inflation, and provide a window on the Universe 10^{-36} s after the Big Bang. For this reason, it is one of the key elements in the Beyond Einstein program. The instrument proposed here marks an important step toward such a measurement.

5.2 Results of Previous Work

The proposed work is a natural successor to work funded by the ROSS-96 detector program†, which we proposed as *Ultra-Low-Noise Cryogenic Amplifiers.* That work had two primary goals: 1) amplifier noise less than 5×quantum limit at frequencies up to 110 GHz, across fractional bandwidths of at least 20%; and 2) amplifier gain fluctuations less than 7×10^{-6} at frequencies up to 110 GHz. A secondary goal was to achieve performance with MMICs (monolithis microwave integrated circuits) as good as that of MICs (microwave integrated circuits). The work, linked to CHOP in the same way as we propose here, had the potential to significantly benefit Planck (then called COBRAS/SAMBA), Herschel (then called FIRST), SOFIA, and MMA/ALMA. Here's what we achieved:

- Noise $< 4q$ across 50% bandwidth at 6 GHz; noise $6q$ across $> 30\%$ bandwidth at 100 GHz and $5.5q$ at 106 GHz, with MMIC performance above 50 GHz significantly better than any achieved with MIC amplifiers. Virtually all amplifier noise performance records are held by products or relatives of CHOP and our R&A program.
- Packaging for MMICs that allowed not only record performance, but also assembly times for 100 GHz amplifiers of approximately 2 hours, compared to 2 weeks for the MIC amplifiers built for MAP.
- The radiometers of the Planck Low Frequency Instrument are direct descendants of the amplifiers developed in the R&A program.
- The IF amplifiers of the Herschel HIFI instrument and the SOFIA CASIMIR instrument are direct descendants of the CHOP program.
- As an offshoot of the amplifier packaging work in the R&A program, and the relationship with NGST/TRW, W-band power amplifiers were developed that have revolutionized local oscillator chains for high frequency heterodyne systems. Herschel/HIFI, SOFIA/CASIMIR, APEX, and ALMA will use LO chains consisting of a K-band tunable oscillator, multipliers to W-band, power amplifiers, and multipliers to the sky frequency. CAPMAP now uses these amplifiers for LO distribution.

† Work was funded nominally for three years starting July 1997, but most R&A accounts at JPL were frozen for some time in 1999 and 2000 because of a change in the NASA policy on unobligated carryover funds. As a result, the end date for our R&A funding was 6/01

- New low-noise amplifiers in an increasing number of ground-based telescopes, including the 100-m Effelsberg telescope and the U Massachussetts Sequoia array, plus other CMB experiments (CAPMAP, BEAST, AMIBA, COMPOSAR [a 2.6-m telescope on White Mountain]), and the DSN DSS-13 antenna.
- Earth-observing missions (e.g., CLOUDSAT, MATHS, GeoSTAR).
- We have made state-of-the-art discrete HEMTs and MMICs, plus our knowledge of how to package and use them, freely available to other groups/missions/instruments.

6 RELEVANCE TO NASA STRATEGIC PLAN

The work we propose here is enabling for the Dark Matter Probe in the Beyond Einstein Program, whose origins were the CMB Polarization mission in the SEU Roadmap (*Cosmic Journeys: To the Edge of Gravity, Space, and Time*, SEU Roadmap 2003-2023, p. 38) and the OSS Strategic Plan (*NASA Space Science Strategic Plan*, November 2000, p. 54. The SEU Roadmap states:

> "Current uncertainties in foregrounds and in relevant details of structure-formation models require that we wait for results at least from MAP and possibly from Planck to determine the precise specifications for a polarization satellite. However, it it likely that the satellite will require an angular resolution of order $0\overset{\circ}{.}1$ and a detector sensitivity possibly two orders of magnitude better than Planck. Observations in a wide range of frequencies will be required to subtract foregrounds and full-sky coverage will likely be needed. Although such a program presents serious technical challenges, it is likely achievable (at least in part) in the next decade with a focussed technology development program."

Development of massive detectors arrays up to 100 GHz is an essential part of that program. In addition, measurements of one quarter of the sky to microkelvin noise levels with $1\overset{\circ}{.}5$ resolution would be a major advance in our understanding of CMB polarization.

7 WORK PLAN

7.1 Overview

This effort is intended as part of the NASA program to map the polarization of the CMB. The basic technology which enables the massive arrays is paid for by NASA Code R, funding InP MMIC development at NGST (formerly TRW), under the CHOP program, and a new effort aimed at developing dense array technologies for THz imaging. This proposal takes the output of those two efforts and creates a functional prototype array of 91 elements, capable of delivering essential knowledge of limits to systematic errors in HEMT arrays and astrophysical foregrounds, as well as state-of-the-art science within two years.

Funding is requested for two years only. By moving agressively and efficiently, and by taking full advantage of the results of previous work, we expect to have the array in hand, ready for deployment, within two years.

The array will be fielded on the CBI platform at Atacama with funds from other sources now being sought, to study degree and larger angular scale polarization. It or a similar array will then be mounted on a 5–10 m dish (possibly the ACT telescope) for a very deep study of arcminute scale CMB polarization.

The next step in the array development beyond this QUIET demonstration is a 1000 element array which will be completed two years after this effort. As the cost of developing the arrays approaches $300-500/element (including feed optics), several experiments are likely to be supported by the effort.

7.2 Roles of Investigators

In this larger collaboration, the array elements will be fabricated by JPL. The elements will be integrated onto motherboards, tested and automatically performance tuned by the University of Chicago, CfCP. CfCP is currently exploring providing funding for this part of the effort as well as supporting two post-doctoral researchers to work on this for the first year of this effort. This proposal will help support a post-doctoral researcher at CfCP to assist in integrating the QUIET instrument in the second year.

Feed horns, lenses, OMTs and the cryostat will be provided by Princeton University, funded by this proposal. Array integration is expected to be relatively simple after the effort at CfCP. The OMTs will be designed at GSFC with contractor support for drafting.

Funding for operations in Chile will be sought from other sources. We are currently in discussions with the ACT team about the use of the ACT telescope for the arcminute scale measurement.

7.3 Management Structure

The PI, Gaier, will provide overall direction and coordination for the program. The efforts at the Co-I institutes will be managed by the Co-I's, guaranteeing the closest communication between science and technical aspects. This collaboration has used this model successfully on the CAPMAP experiment.

7.4 Technical Challenges

The are several technical challenges in this effort. First and foremost is the design of modules, horns, and OMTs for low cost manufacturing. Low cost is critical for the realization of larger arrays. QUIET represents a decisive step in this direction.

Automated testing and optimization of the array elements must be demonstrated, and is a key goal of this proposal. The cost of testing the Planck-LFI prototypes was an order of magnitude greater than the recurring cost of assembly. Since the cost of testing now dominates the cost of building HEMT radiometers, the biggest cost savings must come from testing. Automation is the key.

Finally, this and all other CMB polarimeter imaging arrays (whether HEMT or bolometer based) face a challenge of optical design to fit the maximum number of elements into a small focal assembly, without compromising polarization performance. We have described in § 3.5 the approaches that will be studies.

7.5 Milestones

10/01/03	First U module delivered by Code R program
12/15/03	First iteration OMT, feed horn prototype
01/15/04	Q/U prototype module delivered by Code R, prototype motherboard for testing, optical design complete; U module tested on CAPMAP; full team design review
04/15/04	Mass production test run-10 QU modules; test run feed horns and OMTs
06/15/04	10 QU modules, horns, OMTs delivered to CfCP
08/01/04	Critical design review
09/15/04	Production run 90 QU modules; cryostat fabricated, motherboard fabricated
12/01/04	QUIET integrated on motherboard, Feed horns, OMTs completed
03/15/04	QUIET integrated with feed/OMT array
06/01/04	QUIET tuned/tested
09/01/04	QUIET tested on sky

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