Coherent detectors

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Abstract. Coherent systems offer significant advantages in simplicity, testability, control of systematic errors for CMB polarization measurements, due to the fact that the full phase and amplitude information in the incoming signal is available for multiple uses in later signal processing. Operation at 20 K rather than ~ 0.1 K also results in simpler systems.

The cost of preserving the phase of the incoming signal is quantum noise, which is proportional to frequency. We assess the current state of coherent receivers, and discuss the technology developments required to improve performance. There are good reasons to believe that noise within a factor of 2 or 3 of the quantum limit up to 150–200 GHz can be achieved within a few years.

Whether detector noise is a serious and limiting problem for coherent detection of CMB polarization depends on the frequency range required for accurate foreground removal in CMB polarization observations and how close to the quantum limit amplifiers can get. The frequency range required is under consideration by a separate activity of the mission concept study; however, a definitive answer must await the better understanding of polarized foregrounds that will be gained by Planck and suborbital experiments over the next few years. If noise levels of 2–3 × quantum can be achieved, experiments based on amplifiers could reach the noise levels recommended by the TFCR in space. The active cooling requirements at 20 K for such experiments could be met with existing technology in space. If, on the other hand, observations at frequencies much higher than 150 or 200 GHz are required for control of foregrounds, adequate noise levels will be hard to achieve with amplifiers.

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The ultimate control of many systematics is afforded by coherent interferometers. In the past, the power requirements of large correlators made coherent interferometers impossible to contemplate for space. No longer. Rapid development of correlator technology driven by commercial forces has reduced the power required for large digital correlators by orders of magnitude. It is now possible to correlate of hundreds of elements for an amount of power readily available in space. As a result, a serious investigation of the potential for B-mode measurements of coherent interferometers in space should now be undertaken.

The Task Force on Cosmic Microwave Background Research (TFCR 2005) recommended:

- “Technology development leading to receivers that contain a thousand or more polarization sensitive detectors, and adequate support for the facilities that produce these detectors... It is important to keep open a variety of approaches until a clear technological winner has emerged.”
- “A strategy that supports alternative technical approaches to detectors and instruments. Advances in CMB science have been based on a variety of technologies. Though we expect that bolometers will be the clear choice for CMBPOL, it is premature to shut down the development of alternatives. We recommend the continued development of HEMT-based detectors as they might lead to an alternative space mission and will certainly be used in ground-based measurements.”

The noise projected for amplifier systems has changed dramatically even since the TFCR deliberated, when the expectation for amplifier noise at 140 GHz was too high to list in their table. This elevates the importance of the TFCR recommendation to support multiple approaches including HEMT-based detectors. Transistors now exist that far exceed the performance of anything that existed or was projected in 2005 at millimeter-wave frequencies.

A downselect of detector technology should not be made before foregrounds are better measured, or before all new technologies required for either bolometer or amplifier missions have been demonstrated in suborbital experiments and shown to be suitable for CMB work.

2. INTRODUCTION

In this paper we review the status and promise of phase-preserving or coherent detection systems for measurements of CMB polarization, and outline the scope and scale of the development program that would be required to realize the promise of the technologies involved. We consider both large arrays of independent continuum detectors looking at the sky through feeds or telescopes, as well as interferometers, in which signals from different elements are correlated. Low-noise amplifiers are common to both approaches. Interferometers require in addition local oscillators (LOs), mixers, and correlators.

Transistor performance has improved dramatically over the last 20 years, driven primarily by 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. Transistors are not the only possible active element. SIS mixers have extremely low noise, and are still in widespread use for spectroscopy and interferometry at frequencies > 100 GHz or so. However, it is difficult to achieve the 20–30% fractional bandwidths needed for CMB work with SIS mixers. As a result, we will restrict our attention to amplifiers only.

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

\[
\Delta T_{\text{min}} = \frac{T_{\text{sys}}}{\sqrt{N\tau}}
\]
where $T_{\text{sys}}$ is the system noise temperature, $\beta$ is the RF bandwidth of the radiometer, $\tau$ is the post-detection integration time, and $\Delta T_{\text{min}}$ 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 $T_{\text{sys}}$; 2) increase the bandwidth $\beta$; or 3) increase the number of “pixels” $N$.

The path to improved sensitivity, therefore, is 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.

3. ADVANTAGES & DISADVANTAGES OF COHERENT DETECTORS

There are both benefits and costs of preserving the full amplitude and phase information in the incoming signal. The cost is a noise floor set by quantum fluctuations. In terms of system noise equivalent temperature, this “quantum noise” or “quantum limit” $q$ can be written as $q = h\nu/(k\log 2) \approx [\nu_{\text{GHz}}/20] \, \text{K}$.

The most important benefit stems from the availability of gain in the device defining the noise temperature. The “quantum tax” must be paid only once, but multiple copies of the incident signal can be produced at a high level, so that further processing adds essentially no noise. These multiple copies may be used in ways that allow significant control of systematic effects. One could imagine digitizing the raw signal after amplification and performing arbitrary phase and amplitude operations in software with essentially unlimited fidelity. Even without going that far, one one can design a system to be largely free of many important systematics at the outset (e.g., band leveling and band subdivision can reduce bandpass issues; multiplying interferometry solves many calibration issues).

Amplifier-based detector systems have practical advantages as well, including: large dynamic range; operation over a broad temperature range, with lowest noise achieved at a relatively high 20K; insensitivity to cosmic rays and microphonics; and simplified filtering, taking advantage of their inherent bandpass. These advantages provide a significant reduction in overall system complexity, both in construction and testing/validation, with concomitant decrease in cost.

We discuss these factors in more detail in the following sections, starting with noise because it is the factor that has dominated recent discussions about detectors for CMB polarization.

3.1. Noise

The characteristic of bolometers that has lifted them to prominence in the CMB field is the potential for extremely low noise. The linear dependence of quantum noise on frequency in coherent systems guarantees that above some frequency, bolometer systems can achieve lower raw noise than amplifier systems. What is that frequency?

It depends on many factors, both intrinsic to the detectors and as part of the receiver system and its radiation environment. For example, the small dynamic range of bolometers means that the same bolometers cannot be used on the ground as in space; the background radiation level from the atmosphere and ground would saturate space bolometers. Although it should be possible in principle to make bolometers that are close to photon noise limited, whatever the photon environment, manufacturing tolerances, the need for margins, and other practical matters mean that in practice bolometers built for use on the ground are significantly less sensitive than those built for space. Moreover, unlike amplifiers, bolometers must be the final element in the detector chain, so any optical inefficiency through the optical elements leads directly to a loss of sensitivity.

Figures 1 and 2 compare sensitivities and noise levels for amplifiers and bolometers for ground-based observations (Figure 1) and space (Figure 2). See the Appendix for details on the comparison. The sensitivities of a “perfect” quantum-noise-limited amplifier and a “perfect”
Figure 1. Sensitivity of a quantum-limited amplifier compared with the sensitivity of a photon-noise-limited bolometer (i.e., “perfect” amplifier and bolometer, respectively), from the ground at a high dry site. The dramatic effect of the atmospheric loading on bolometer sensitivity even in good atmospheric windows can be seen by comparison with Figure 2. We assume 8 K of thermal noise from the telescope and ground, independent of frequency (surely is an overestimate at low frequencies) and a 25% bandwidth for both detector systems. Amplifier sensitivities are divided by $\sqrt{2}$ because an amplifier polarimeter can measure $Q$ and $U$ simultaneously, while a bolometer measures $Q$ or $U$ at a given time. For a description of the various colored points and lines, see text.

Figure 2. Same as Figure 1, but in space. Below 40 GHz photon noise would dominate quantum noise for the amplifier. We have not added the two together so that their relative strength can be seen. The amplifier sensitivities are divided by $\sqrt{2}$ because an amplifier polarimeter can measure $Q$ and $U$ simultaneously, while a bolometer measures $Q$ or $U$ at a given time. For a description of the various colored points and lines, see text.
photon-noise-limited bolometer are indicated by black solid and dashed curves, respectively. A 25% bandwidth is assumed for both. The amplifier sensitivity includes a factor of $1/\sqrt{2}$ because amplifiers can measure $Q$ and $U$ simultaneously through a single feed, whereas direct detectors can measure only $Q$ or $U$ at one time. The effect of atmospheric loading of the bolometers on sensitivity can be seen by comparing the bolometer curve in the atmospheric windows in Figure 1 with the curve in Figure 2.

In both Figure 1 and 2, sensitivity curves are shown also for amplifiers at 3 and 5 times the quantum limit. Discrete points show measured or projected sensitivity values for various current or planned experiments, as follows:

- BICEP bolometer (from John Kovac), measured
- BICEP2, projected from known bolometer parameters (John Kovac)
- MIC amplifiers, measured in lab
- MMIC amplifier modules for QUIET, measured in lab
- MMIC amplifiers, projected from high frequency, room temperature measurements of 35 nm gate process devices

The horizontal blue and green lines in Figure 1 show the sensitivity required for each of 512 feeds (or planar antennas) at each frequency, to reach 100 nK noise per square degree in the 4% of the sky with the lowest foreground levels, integrating for 1 year (blue) or 4 years (green) from the ground. This is the target noise level recommended by the Task Force on Cosmic Microwave Background Research. Such an array of amplifiers at the noise levels projected for 35-nm gate process HEMTs (see §4.2) could reach this level in less than a year of integration time up to about 160 GHz. An array of projected bolometers could reach this level in four years up to same frequency.

With the performance expected from both technologies in the foreseeable future, both can reach the recommended noise level in a reasonable experimental lifetime. As will be seen in later sections, the work required to bring amplifiers to the projected level of performance will take several years. But if an instrument with $3 \times q$ amplifiers can be deployed in 2012, and if the performance expected of bolometers is realized on the projected schedule, then by 2013, both bolometer and HEMT experiments could reach 100 nK deg$^2$ over the cleanest 4% of the sky. This would result in:

- Possibly a first detection of B-modes
- Certainly a great deal of essential information on foregrounds
- An assessment of systematics for two different detection systems operated in a real and stressful environment.

We believe that we should work towards this situation, and that a down-select between the two technologies should not take place before this comparison can be made.

In Figure 2, discrete points show:

- MMIC amplifiers, projected from high frequency, room temperature measurements of 35 nm gate process devices
- Bolometers, projected (Andrew Lange)

The horizontal green, blue, and magenta lines in Figure 2 show the sensitivity required for each of 512 feeds (or planar antennas) at each frequency, to reach 100 nK noise per square degree over the full sky, integrating for 1 year (green), 2 years (blue), and 4 years (magenta) in space. Projected bolometers could reach this level in 1 year up to about 140 GHz, and in 2 years up to about 220 GHz. Amplifiers could reach this level up to about 140 GHz in 4 years.
3.2. Foregrounds & Frequency range
For CMB polarization, foregrounds are a critical consideration, and may well be the limiting factor in measuring B modes. The June workshop has considered foregrounds at length, and work continues that will be reported in the mission concept study report and other papers. This section is not meant to substitute for that work, but rather to highlight the critical role that foreground separation will play in setting requirements for a CMB polarization mission.

Figure 3 shows foreground levels compared to CMB fluctuations for various sky areas, from full sky to one of the quietest (i.e., lowest foreground fluctuation) hundreds-of-square-degree patches on the sky, as calculated from angular power spectra of the various components based on the Planck Sky Model (see June workshop). Limited regions of the sky have much smaller fluctuations; however, the lowest multipoles, where the reionization bump makes the \( B \)-modes strongest compared to other sky signals, are the prime target for a space CMB polarization mission.

Simulations of component separation by Dickinson et al. (reported at the June workshop) suggest that experiments with SNR independent of frequency will give the best results (i.e., lowest error on the CMB itself for a given focal plane detector area). The signal of relevance is the \( \text{total} \) signal, CMB+foregrounds, not the CMB alone. If this preliminary result holds up, it is clear from Figure 3 that experimental noise can and should be much higher at low and high frequencies than near the foreground minimum. Neither a large number of detectors achieving low noise at high frequencies nor a large number of (large) detectors dominating the focal plane at low frequencies would be necessary or desirable.

If frequencies much higher than 150 or 200 GHz are required, amplifiers will not be the detector of choice because of their raw sensitivity disadvantage compared to bolometers. If frequencies up to this frequency range are enough, however, an amplifier mission will be very attractive.

3.3. Advantages
We can divide advantages of coherent systems into two categories: those that involve the signals and their processing, and therefore may have a direct impact on systematic errors and their control as well as on practical matters of complexity, reliability, risk, testability, and cost of the overall system; and those that are “merely” practical. §3.3.1 discusses the former; §§3.3.2–3.3.7 the latter.

The systematic requirements on CMB polarization experiments are demanding. For both coherent and incoherent systems, satisfactory performance can be demonstrated only with observations of the sky. The importance of a strong suborbital experimental program in providing this testing cannot be overemphasized

3.3.1. Signal processing and design possibilities
As mentioned before, the availability of gain in the device defining the noise temperature allows multiple copies of the full incident signal to be produced and used to measure the properties of the incident radiation without further noise penalty. This ability opens up a variety of signal processing and instrumentation approaches, with significant advantages.

- The “science data channel” can have a null signal. Baselines and offsets can be made small and stable.
- The desired set of measurements (e.g., \( Q/U/I \), \( Q/V/I \), etc.) can be made simultaneously by the receiver topology. Table 1 gives examples of phase switched pseudo-correlation signal detection schemes. (A Jones matrix formalism was used to compute the response of a selection of polarization sensitive receiver topologies [Jones 1941; 1942].) In selecting a receiver configuration for polarimetry, the residuals and baseline (i.e., the portion of the
Figure 3. Level of synchrotron and dust temperature fluctuations in absolute units (left) and relative to the CMB (right), calculated over different regions of the sky (i.e., different Galactic “cuts”, plus a \(~10^\circ\) patch with minimal foregrounds) as indicated in the upper right panel. The lowest multipoles can be observed only from space, and only by observing a large fraction of the sky. The lower curves representing small sky fractions are therefore relevant only for suborbital experiments. The foregrounds are based on the Planck Sky Model (see Theory and Foregrounds workshop for details). Too little is known about polarized foregrounds to support conclusive simulations, but there is no question that at high and low frequencies foreground fluctuations will dominate the measured signal. For example, in TT for a Kp2 sky cut, for which the foregrounds are known moderately well from WMAP up to 94 GHz, at 40 and 130 GHz dust and synchrotron fluctuations are up by a factor of five over their values at the minimum at 70 GHz. At 30 and 180 GHz the foregrounds are up by a factor of 25. By 300 GHz, dust fluctuations are up by three orders of magnitude compared to CMB fluctuations, which drop fast on the Wien side of the spectrum. If the foreground spectra are complicated, a very wide frequency range may be disadvantageous. [Figure from Clive Dickinson.] For EE the foreground data are much more uncertain, especially concerning dust, for which there is suspicion that the Planck Sky Model underestimates polarization fluctuations. The green curve in the EE ratio plot reaches the same values at about 50 and 240 GHz.
signals which ideally would not be present) should be considered in addition to desired lock-in channel sensitivity.

- The desired signal (e.g., polarization state, incident angle, intensity, frequency, phase) can be rapidly and appropriately modulated, strongly suppressing undesired and competing signals that may be present in the instrument’s environment, giving excellent systematic control. The addition of beam waveguide polarization modulators (e.g., half wave plates, variable(?) polarization modulators, etc.), which add complexity and risk to the system, is not needed.

- The signal can be appropriately processed by subsequent circuitry (e.g., polarization diplexers, quadrature hybrids, magic-tees, in-phase power splitters, phase delay/modulators) before power detection. This ability to encode the desired properties of the signal fields and subsequently look for correlations is a powerful tool for obtaining precision control over systematic effects. More importantly, in a single-mode coherent system, each incident mode (i.e., in our case of interest polarization state) can be independently processed. In practice, examples from precision radiometry (Predmore et al. 1985), interferometry (Blum 1959; Faris et al. 1967), and polarimetry (Tinbergen 1996) have demonstrated the power and maturity of this overall approach.

Incoherent systems do not have these options. They typically rely upon synchronous modulation/demodulation of the incident power in front of the detector. In the absence of detector gain, this places stringent constraints upon the allowable loss, emission, temperature and temperature stability, as well as achievable switching speeds. As described in the other papers associated with the Boulder Workshop, a great deal of work is being devoted to the development of pre-detector components for incoherent systems. Success is nearer at hand in some areas than other, and ultimately success can only be demonstrated in on-sky observations.

In addressing thermal drifts, finite beams and sidelobes, differing frequency responses, astrophysical foregrounds, and other forms of radiation, merely encoding/decoding the incident signals is not sufficient. Calibration of the system response requires instrument stability on a time scale long compared to the modulation in order to achieve the ultimate detector sensitivity. The resultant linkages between detector speed/noise, scan, modulation, and calibration rates required to achieve the mission goals can be addressed in principle in either system approach; however, when considering a system’s overall testability, the ability to minimize/retire risk before flight, and simplicity, a coherent system has strong advantages.
Ultimately, the most important advantage of coherent systems is likely to be that the required control of systematics can be achieved at lower complexity, risk, and cost.

We turn now to a number of practical considerations.

3.3.2. Dynamic range Amplifiers can handle a very large range of input signal levels. Non-linearities are much less than seen for bolometers. Even more importantly, the noise temperature depends very little on input signal level up to very high levels. Although in principle bolometers can be built that are photon noise limited at any level, in practice the limited dynamic range of bolometers coupled with the difficulty of knowing in advance the total photon load (CMB + foregrounds + sky + telescope + ... ) at a given site for a given instrument, and the uncertainties in fabrication, mean that bolometers built for the ground are significantly less sensitive than those built for space. This is not the case with amplifiers, whose large dynamic range can easily accommodate the difference in signal between ground and space. This simplifies design and testing.

3.3.3. Operating temperature and testability Physical temperature requirements for minimum noise are modest, at around 20 K. Moreover, amplifiers work over a broad temperature range, from above room temperature to well below 4 K. The system noise properties degrade gracefully as detector physical temperature increases above 20 K. This has broad impact on system design:

- Thermal and cooler systems to achieve 20K are substantially simpler than systems to achieve sub-kelvin temperatures, as well as faster and easier to test.
- An amplifier system designed to operate cryogenically can be checked out and tested very well at higher temperatures. Both for ground testing and for in-orbit checkout this can result in substantial simplifications and savings.

3.3.4. Insensitivity to cosmic rays and microphonics Cosmic rays produce no detectable disturbance in the output signal of amplifiers. Although “spider web” type bolometers have reduced the susceptibility of bolometers to cosmic rays dramatically, detection and removal of cosmic rays spikes is still a first and necessary step in the processing of bolometer data from Planck. Up to a few percent of Planck HFI data will be thrown away because of this.

3.3.5. Filtering As an added benefit, the presence of in-band gain lowers the overall filtering requirements to limit the influence of out-of-band response.

3.3.6. Straightforward arrayability As shown below in §3.2, cost-effective techniques for building large arrays of amplifier detectors have been demonstrated. Signals can be digitized at the cryogenic stage, eliminating the need for complicated cryogenic readout/multiplexer circuits.

3.3.7. Industrial infrastructure Amplifiers are the detector of choice for communications and remote sensing applications in the commercial and military world up to frequencies of several hundred gigahertz, at least. Moreover, while optimization of amplifiers for cryogenic operation may well be different from optimization at room temperature, it is a general rule that the best devices (transistors, MMICs) at room temperature are the best devices at cryogenic temperatures. As a result, the commercial and military development of high performance amplifier systems is of direct benefit to the scientific world. The area of low noise amplifier technology is one that NASA does not have to develop on its own. Significant synergies exist. This substantially decreases the size of the investment in technology required to realize the best cryogenic performance.


Table 2. Operational and systematic comparison of HEMT and bolometer arrays

| Requirement                          | MMIC HEMTs                      | Bolometers                                      |
|--------------------------------------|--------------------------------|-------------------------------------------------|
| Response time                        | Excellent, $\tau \approx 1/\beta$ | Adequate, can be modeled                         |
| Linearity                            | Excellent                       | Adequate, can be modeled                         |
| Dynamic range                        | Large                           | Small. Different devices required for space and ground. |
| Gain stability                       | Excellent with modulation       | Excellent for Planck NTD Ge technology, not yet public for TES |
| Offset stability                      | Excellent with modulation       | Excellent for Planck NTD Ge technology, not yet public for TES |
| Polarization systematics             | Excellent; $Q$ and $U$ from same pixel. Modulation electronic and fast, after amplification. Effect of gain mismatch removed by radiometer design. | Good; $Q$ and $U$ from different pixels, or complicated and relatively slow modulation. Gain mismatch leads to leakage of temperature to polarization. |
| B-field, microphonics, EMI, RFI susceptibility, cosmic rays | Good                            | Adequate (?) B-fields a particular issue for TES. |
| Device uniformity                    | Not established                 | Good for Planck, not yet public for TES          |
|                                    | **PRACTICALITIES FOR SPACE**    |                                                 |
| Cooling requirements                | Passive + active (20 K). Heat lift required is large but achievable. | 0.1 K operation requires multi-stage cooling chain. Heat lift required at 0.1 K depends on parasites. Complicated. |
| System testability & risk reduction before flight | Easier & less expensive         | Harder & more expensive                         |
| Cryogenic readout & multiplexer      | Not needed                      | Complicated                                     |

3.4. Disadvantages

3.4.1. Quantum noise  As described in §2, there is a lower limit to $T_{\text{sys}}$ for coherent receivers set by quantum fluctuations. But as shown in §2.1, even with quantum noise amplifiers can reach the noise levels required for CMB polarizaiton over a broad frequency range.

3.4.2. Power dissipation  Amplifiers dissipate significant power. A W-band (75–110 GHz) module to measure $Q$ and $U$ simultaneously with present technology dissipates about 12 mW, from which predictions at other frequencies can be made: 4 mW at 30 GHz, 7 mW at 40 GHz, 10 mW at 70 GHz, and 15 mW at 150 GHz. Hundreds of detectors would require watts of heat lift at 20 K or so. A cooler with this kind of heat lift would have a major impact on flight system design, but is not a showstopper by any means. For example, the two hydrogen sorption coolers on Planck, combined together into a single cooler with a JT valve optimized for a 45 K radiative precool temperature, would have a heat lift of about 4 W with 1100 W of input power. If a radiative precool temperature of 35 K could be achieved, the heat lift for the same power input would be 10 W. 1100 W is serious but not scary power in space.

3.5. Summary of Operational and Systematic Comparisons

Table 2 summarizes the characteristics and practicalities of amplifier detectors, with comparison to bolometer systems.
4. TECHNOLOGY STATUS AND PROSPECTS

Dramatic improvements in noise and power dissipation of transistors have been achieved over the last 20 years, first with high electron mobility transistors (HEMTs) fabricated on GaAs substrates, then on InP substrates. Developments over the last two years promise noise performance of a few times the quantum limit in the foreseeable future over a large frequency range.

Similarly dramatic advances have been made over the last few years in the packaging of amplifier receivers, making large arrays of receivers possible and achievable for CMB polarization. We discuss the state of both areas below, and identify technology development required to realize the kind of performance required for $B$-mode measurements on the ground or in space.

4.1. Transistor and Amplifier Performance

Figures 4 and 5 show the state of the art for cryogenic performance of transistor amplifiers in 2007, as well as goals for the future. In 2006, Northrop Grumman Corporation (NGC) developed a new ultra-short-gate-length high electron mobility transistor (HEMT) process\(^1\) (Deal et al. 2006), incorporating the following changes:

- gate length reduced from 0.1 $\mu$m to 0.035 $\mu$m $\Rightarrow$ parasitic gate-source capacitance is reduced and cutoff frequency is increased by a factor of 2
- ohmic metal and contact resistance reduced by a factor of 2
- InAs channel enabled through new epitaxy design $\Rightarrow$ improved electron mobility by 25%
- 2-mil thick wafer process $\Rightarrow$ reduction of via hole size and pads by as much as a factor of 4, to support higher frequency designs
- reduction of minimum line size and spacings by 30-40%

Amplifiers using this technology give breakthrough performance up to 340 GHz at room temperature, as reported by Dawson et al. (2005), Deal et al. (2006, 2007), Gaier et al. (2007), Pukala et al. (2008), Samoska et al. (2008), and Kangaslahti et al. (2008). Figure 6 shows a 3-stage amplifier with 15 dB of gain at room temperature, or 5 dB per stage. This design is the highest frequency amplifier reported to date, and shows excellent correspondence between modelled and measured results.

A transistor model based on measurements on-wafer predicts that the 35 nm devices have a maximum stable gain (MaxGain) of 5 dB up to 600 GHz (Fig. 7), with 10–17 dB gain per stage predicted from 30–200 GHz, under ideal circuit matching conditions.

The technology has demonstrated very low noise at these frequencies (Deal et al. 2006; Gaier et al. 2007), with a noise figure\(^2\) of 7.5 dB at room temperature for a 270 GHz LNA (Fig. 8).

4.1.1. Cryogenic Performance

The lowest noise is achieved with amplifiers cooled to cryogenic temperatures. Little change in noise is observed below 20 K physical temperature, so hereafter “cryogenic” will mean $\sim 20$ K unless otherwise specified. Kangaslahti et al. (2008) characterized the noise performance of a three-stage MMIC amplifier for the 180 GHz band as a function of physical temperature (Fig. 9). At room temperature, the noise temperature at 160 GHz is less than 400 K, a factor of two smaller than the previous state of the art, with gain of $\sim 16$ dB. At 30 K physical temperature, the noise temperature is $\lesssim 100$ K up to 170 GHz, the lowest cryogenic LNA noise temperature ever reported at these frequencies. These improved cryogenic results

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\(^1\) Funded in part by the DARPA Submillimeter Wave Imaging Focal-plane Technology (SWIFT) program, whose goal is room-temperature imaging arrays at submillimeter frequencies.

\(^2\) Noise figure in dB is the standard measure of noise in the non-astronomical world. The correspondence between $NF$ and noise temperature $T$, the astronomical standard, is given by $NF = 10 \log\{T/290 + 1\}$, with $T$ in kelvin.
Figure 4. Amplifier noise temperature vs. frequency for the state-of-the-art in cryogenic noise performance in 2007, as well as near-term and 3q goals for the future. Double sideband SIS mixers are shown for comparison. Single sideband SIS mixers would have twice the temperature.

Figure 5. Same as Figure 4, but as a multiple of the quantum limit.

were obtained even though the amplifier showed a clear “kink effect” in its cryogenic DC I-V curves. This precluded proper biasing of the amplifier, increasing its noise.

In general, the noise of previous InP transistors (whether MIC of MMIC) decreased by roughly an order of magnitude from room temperature to 20K. The factor of four measured for the 180 GHz amplifier is clearly less than a factor of 10, even allowing for the small additional
Figure 6. *Left*—Three-stage MMIC amplifier with 15 dB of gain from 285–340 GHz at room temperature. *Right*—Three-stage MMIC amplifier measurements and model of S21 (gain), S11 (input return loss), and S22 (output return loss). In each case, the smoother curve of the pair shows the model. Excellent agreement is seen between the measurements and the model. The black curve shows modelled noise figure (right-hand scale, see §2.2.2). The high frequency is limited by the frequency range of the measurement, not of the amplifier.

Figure 7. Predicted maximum available/maximum stable gain (MaxGain) of the 35 nm gate HEMTs. MaxGain is above 5 dB up to 600 GHz, and is between 10 and 17 dB for frequencies between 30 and 200 GHz.

Figure 8. Measured noise figure and gain for a 270 GHz amplifier at room temperature. $NF = 7.5$ dB at maximum gain of 11.5 dB.
Figure 9. Measurements of 180 GHz amplifier (inset photo) at room temperature (left) and as a function of temperature down to 30 K (right). Noise is a factor of two lower than the best previous results at both room and cryogenic temperatures. The low cryogenic noise was obtained despite the fact that the DC bias performance was not optimum (a clear “kink effect” was seen in the cryogenic I-V curves; see §2.2.3).

reduction that would be expected between 30 K and 20 K physical temperature. One might worry that cryogenic performance is being limited in the 35 nm gate devices by some factor not previously seen in other devices. An even more recent measurement shows that this is not the case.

Figure 10 shows the noise temperature for a W-band amplifier built by Eric Bryerton at NRAO cooled to about 15 K. From 300 K to 15 K the noise decreased by a factor of ten, showing that the 35 nm devices follow the trend of the best previous devices when they are cooled to cryogenic temperatures.

4.1.2. Noise Models and Predictions The key question is how close to the fundamental quantum limit can amplifiers be brought, and what is required to get there? A more immediate question is what is the full cryogenic potential of the 35 nm gate devices now being produced? Their performance significantly exceeds anything seen before, judged by room temperature performance at frequencies up to ~350 GHz and the first cryogenic measurements. Even more specifically, we can ask what gains in performance can be realized at cryogenic temperatures over the range of frequencies important for CMB polarization?

A theoretical answer to the second question can be given by a noise model of the new devices. For nearly two decades, the standard model of low noise transistor noise has been that of Pospieszalski (1989), which uses two noise sources, one on the gate and one at the drain of the device. These noise sources are realized in practice by setting the physical temperatures of the $R_g$ and $R_{ds}$ to values that match our measured results. The correct temperature of the $R_g$ is the physical temperature of the circuit (either 295 K or 20 K, depending on whether we model the room temperature or cryogenic performance of the amplifier). The $r_{ds}$ models the drain noise of the transistor and is typically 15-20 times the physical temperature of the device, depending on the technology. Kangaslahi (private communication) has developed such a model, and with it obtains a noise figure of 3.3 dB for a single device at 270 GHz. If cascaded in a three stage amplifier with 11.5 dB of gain (assuming 1.5 dB losses in passives in each stage), this would translate to a noise figure of 6.7 dB for the amplifier in Figure 8, in good agreement with the measured value of 7.5 dB.

Using this noise model at 20 K gives the results shown in Figure 11, namely 7.9 K (4g) at 40 GHz, 11.5 K (2.6q) at 90 GHz, 19.5 K (2.8q) at 140 GHz, and 24 K (2.9q) at 165 GHz. All designs had more than 20 dB of gain, so these numbers would be very close to the final noise temperature of the actual receiver (i.e., later components in the receiver signal path would have little effect on the system noise). These design simulations are preliminary and not optimized.
And although the predicted performance is still a factor of two better than measured for the amplifier in Figure 10 that was the very first W-band 35 nm amplifier measure cryogenically.

All of this suggests that there is an excellent prospect of achieving noise levels of \( \sim 2.5q \) over a range of frequencies important for CMB polarization, levels which only a year or two ago seemed far off in the future. Figures 1 and 2 show that these levels would enable CMB polarization experiments and missions with the capabilities recommended by the TFCR.

4.2. Arrays and array performance

The experimental sensitivity needed for B-mode observations requires both low noise from individual detectors and many detectors. The detectors used for WMAP and Planck, whether amplifiers or bolometers, could not be scaled up to a level of hundreds of detectors per frequency. Over the last few years, designs for highly scalable coherent radiometers and polarimeters have been demonstrated and implemented in the QUIET experiment, a collaboration of 12 institutions (http://quiet.uchicago.edu). QUIET has deployed in Phase I a Q-band receiver of 19 elements, and is preparing a W-band receiver of 91 elements.

QUIET uses polarization modules built at JPL, shown schematically in Figure 12, which simultaneously measure both Q and U. A single Q-band module is shown on the right side of Figure 13; a 7-element W-band array with an OMT is shown in Figure 14.

Each module has 18 bias voltages that need to be set. An efficient means of optimizing these

Figure 10. W-band MMIC amplifier cooled to \( \sim 15 \) K. The noise is the lowest ever measured for an amplifier at these frequencies, and an order of magnitude lower than at room temperature.
values for the best polarization sensitivity was developed at The University of Chicago and used there for W-band and at Columbia for Q-band. The performance measured in the laboratory and scaled to the Chilean site (see Figure 1) gives array sensitivities for both receivers of order 60–70 μK s^{1/2}. In the case of Q-band, which is currently operating in Chile, this prediction has been confirmed at the site. These array sensitivities for Phase I of QUIET are as good as those for BICEP in its first incarnation, but are not as good as would be expected from the best current 100-nm devices as shown in Figure 11. We will return to this important point below. Phase II will have of order 1000 detectors and will take advantage of the improvements in amplifier performance discussed in this document.

Horn platelet arrays are a cost effective means of coupling the radiation into the modules. For QUIET, these have been developed at the University of Miami. The W-band array is shown on the left side of Figure 13. The arrangement of the receiver in its cryostat (designed and built at Columbia) is shown in Figure 15.

Three key points can be made about large arrays of coherent polarimeters suitable for B-mode instruments:

- The basic packaging technology for large arrays has been demonstrated. No technological breakthroughs are required. Savings in fabrication, assembly, integration, and testing of roughly two orders of magnitude over discrete component techniques used in the past are in hand. These techniques seem appropriate for arrays of the size that can be fit into the undistorted focal plane areas of CMB telescopes.
- Even more highly integrated packaging techniques, using multiple wafers stacked in 3-D, are being developed, and could be used for even larger arrays if there were a need. Set-up costs would be higher, but per unit costs could be much lower for large numbers.
- Although the basic arraying techniques have been well-demonstrated, there is one critical area in which current results are inadequate. In going from MMIC to module, a performance hit of a factor of roughly two is suffered. That is, the noise temperature of the module is
roughly twice the noise temperature of the MMIC itself.

The last point is critical for the work that must be done. A factor of two in noise is simply too much to give up in going from individual amplifiers to array building blocks.

4.3. Development Plan

In the previous sections we have identified two critical areas of development needed to realize the full promise of coherent instruments for CMB polarization in space. These are:

- Improving the performance of individual transistors and MMICs to at least the level predicted to be achievable with 35 nm gate technology (Figure 11), and perhaps even further.
- Integrating high-performing MMICs into the building blocks of large arrays without loss of performance. Currently a factor of two or so in both noise and bandwidth is lost at this step.

We discuss these in §§ 4.3.1 and 4.3.2 below.

4.3.1. Device and MMIC level issues

To achieve noise of \( \leq 3 \times q \) from 30 to 150 or 200 GHz, a range important for CMB polarimetry, we can identify known issues and potential innovations that should be addressed.

Figure 16 shows a preliminary top level research plan. There are three main thrusts.
Figure 13. QUIET W-band 91-element feed array. This is a “platelet” array, in which an array of corrugated feed horns is built from many layers of aluminum with appropriately sized holes machined in them, all vacuum welded together. [Josh Gunderson, Miami] Right—QUIET Q-band module. Larger than the W-band module in Figure 13 because the array spacing for this wavelength is greater, the Q-band module combines some of the discrete components of the W-band module onto miniature circuit boards, making automated assembly even easier.

Figure 14. Test array of seven W-band modules mounted in standard sockets on a circuit board. One left-right circularly polarizing orthomode transducer (OMT) is attached to one module at the top. It is straightforward to build up large hex-packed arrays from these basic components. [Chicago]

- Measure and study existing devices and circuits for cryogenic performance and behavior to improve understanding of device physics, and to guide and focus the future device development.
- Develop new devices, with at least three iterations of experimental runs. At the end of each run, benchmarking and analysis inform the next run. The results from these runs will feed
Figure 15. Sections of the QUIET cryostat, showing how a 91-feed platelet array, OMTs, and modules are arranged. The modules are placed in standard pin sockets on circuit boards. The size envelope for a given polarimeter module is limited by the spacing of the corrugated feeds, whose size is determined by the optical system. [Laura Newburgh, Columbia]

into the third main thrust

- Two amplifier design iterations and fabrication runs to demonstrate amplifiers with improved cryogenic performance. This type of comprehensive study to optimize HEMTs for cryogenic noise performance should enable reaching the ultimate limit for these devices, which may require new devices and materials not currently available.

Performance improvements will require addressing or solving the following issues, which are likely performance limiters.

**Shot noise due to excessive gate leakage**—In pursuit of the highest gain and transconductance InP HEMT devices, excessive leakage current at operating conditions limits the ultimate noise performance, especially at low frequencies where thermal noise is extremely reduced. Current research into alternate gate metals, barrier designs, gate recess chemistries and etch stops may improve both the turn-on voltage and reverse gate leakage for the InP HEMT devices while maintaining the other key dc and rf parameters. Of greatest interest is reduction of gate leakage at cryogenic operation which has not been studied or optimized carefully. NGST and JPL have observed wafer to wafer and lot to lot variation in the gate leakage. Although is less of an issue at higher frequencies, future improvements in device performance at higher frequencies will necessitate gate leakage below $1 \mu A$ to realize the target levels of noise performance.

**High ohmic resistance at cryogenic temperatures**—Recent investigations have shown that current InP HEMT ohmic contacts are not optimal and studies of the ohmic contact resistance to cryogenic temperatures may be important. This will have an impact not only on device gain, but also on the optimal dc bias voltage/current needed to achieve usable gain and its effect on drain temperature. Alternate ohmic contact and epitaxial schemes look promising for $> 2 \times$ improvement, which may translate directly to cryogenic device noise improvements. Limits of epitaxial doping and design have also not been explored, especially for cryogenic operation.

**Anomalous cryogenic HEMT behavior**—Although not consistently observed, known potential issues such as IV kink at cryogenic temperatures (light sensitive), high output conductance, poor device pinchoff, low breakdown devices, high leakage and gain fluctuation need to be understood and avoided. Customized cryogenic tests can be developed to study these occurrences and how to avoid them. In some areas, promising room temperature solutions
have been developed and it will be beneficial to translate these improvements to cryogenic products.

**InP HEMT yield limiters**—Ohmic contact and sheet resistance, gate yield and defects, device breakdown, gate leakage, damaged airbridges, via hole yield, back metal adhesion, TFR damage, probe and metal scratch damage, dicing (splitting die), wafer breakage, and line errors are all factors.

**Cryogenic device and noise models**—Pospiesalski’s cryogenic model is simple and predicts fairly well the noise parameters and overall performance of low noise amplifiers, especially for discrete device amplifiers. Updates to this and other alternately improved cryogenic HEMT noise models are important for future designs to improve ultimate noise performance.

Over the past several years, NGST has developed advanced semiconductor materials, epitaxial designs, ohmic, gate and interconnect metals, device topologies, passivation thickness and interfaces, and backside wafer process improvements for its HEMT devices. The central focus for these advances at NGST continues to be to improve room temperature noise performance of LNAs with low dc power consumption and further system advantages in size and weight that can be derived through higher frequency implementations. These products are primarily aimed towards insertion into NGST’s satellite communication payloads. To spur these innovations,
NGST has invested significant internal R&D funding for device and MMIC research (totaling more than $10 M/year) and has consistently won contract R&D funding mainly from DoD services (also totaling more than $10 M/year) over various semiconductor devices and products. NGST also continues to invest semiconductor equipment capital exceeding $10 M/year especially to develop these novel materials and device processes.

What has not been studied recently is how these advances may spur improvements in the cryogenic operation of these devices. It can be projected that the room temperature improvements especially in noise performance may translate to improvements with cryogenic operation, but a careful engineering study and optimization have not been conducted to date. Listed below are key innovations both near and long term that can improve the state-of-art for cryogenic noise performance.

**Nanometer-scale gate length reduction**—Fabrication of short gate devices (70 nm and 35 nm) has achieved reasonable yield and reproducibility in combination with optimized epitaxial profile designs for each of these nodes. The use of these device technologies has focused mainly on a new generation of amplifiers from 140 GHz to 400 GHz, but extremely high device gain may also provide distinct low noise advantages at any frequency where the device and amplifier noise performance is potentially gain limited.

**Atomic scale material growth and design**—Advanced HEMT materials may offer higher frequency operation and low noise performance. Electron transport in InGaAs channels grown pseudomorphically on InP substrates has been improved with InAs channels (100% Indium) through the design of a composite channel epitaxy design. Extremely high room temperature mobilities of 16,000 \( \text{cm}^2 \text{V}^{-1} \text{s}^{-1} \), which represents a 30–50% increase compared to the baseline 60% InGaAs channels, have been observed. Further study of these devices is necessary with the potential of alloy scattering and impact ionization dominating with cryogenic operation. ABCS (Antimonide-based Compound Semiconductor) devices employing metamorphically grown InAs and potential InAsSb channels represent future material innovations that could push mobilities and electron velocities to even higher values. Limited cryogenic data have not achieved new state-of-art performance as current challenges in material quality, high leakage, and impact ionization still need to be addressed.

**Device parasitics**—Significant improvements have been made recently in ohmic contact and access resistance, in both epitaxial designs and new refractory ohmic metals. Contact resistance improvement by as much as 3× and sheet resistance improvement of 50% have been achieved on the most aggressive devices at room temperature, and should benefit cryogenic operation and low noise performance. Further development and exploration of sheet resistance limits through new epitaxial designs and smaller ohmic-to-gate spacings, including self-aligned gate device schemes, should be part of further work. Reduction of resistance in cryogenic operation is critical for lowering operating drain currents and voltages for high gain, which ultimately reduces drain temperature in the standard cryogenic FET model. Innovations for reduction of capacitance parasitics with both alternate low dielectric constant passivation films and thinner passivation films should be explored. The latter has been employed on recent high frequency devices and should be studied for potential benefits with cryogenic operation.

**HEMT gate innovations**—For HEMT devices, the gate process and metal-semiconductor junction remains the most critical in determining device performance. Barrier height and threshold voltage are crucial in optimizing device transconductance and gain, but breakdown and leakage current must be controlled to enable a useable device. Often these requirements conflict and the trades are even less understood at cryogenic operations where certain leakage currents are suppressed, while others are enhanced. The gate recess process formation is equally critical as it impacts breakdown, leakage, and access resistance. Many of the effects and variations with cryogenic operation have not been carefully studied and optimized. Several innovations are
being explored. New refractory gate metals, especially Mo and TiW, are being explored that may provide lower leakage and superior cryogenic Schottky junctions. Controlled interdiffused junctions that could reduce 1/f noise for cryogenic operation have not yet been explored. Epitaxial growth is still critical, and although not studied to date, heterostructure and doping interface sharpness may be critical to determine limits on gate-to-channel separation, where we face tradeoffs between transconductance and gain vs. excess leakage and degraded Schottky junctions. Combined with new refractory metals, the trade space should be explored for optimal cryogenic performance. Tailoring the gate recess profile through etch stops and multiple recess steps may provide advantages where the designs are aimed towards cryogenic low noise operation. However, current research is aimed more towards higher power, higher device density circuits. Barrier layer epitaxial designs for both etch stop and bandgap engineering should be studied more carefully for cryogenic optimization. As an example, current ABCS HEMT device utilization is limited due to manufacturing issues of the gate barrier layer AlSb and GaSb.

**New devices, materials, ideas**—The advent of new transistors and materials as they come to some level of maturity and utility may be crucial to achieving the noise goal ≤ 3× quantum limit or even beyond. Among the promising technologies being pursued are quantum wire devices, as well as carbon nanotube and graphene transistors. Nanolithography will also push the limits on device scaling and we anticipate research in smaller gate length nodes down to 20 nm or less to achieve amplifiers that could operate as high as 1 THz in the future. Optimizing these types of concepts for cryogenic noise operation may also reveal unexpected and further performance breakthroughs.

4.3.2. **Module level issues** The key is to realize the full performance potential of the transistors and MMICs in a unit cell package that enables massive arrays. This requires cryogenic measurement and characterization of MMICs and other components, isolation of the critical factors in performance, design and fabrication iterations, and exquisite control of fabrication.

An essential point that must be emphasized again is that while there is substantial commercial and military interest in coherent detectors for communications and imaging, there is little interest outside the astronomical world for cryogenic applications. The development for CMB polarimetry of array building blocks with no loss in MMIC performance is inherently cryogenic. The commercial world will not provide this development.

The work will involve both MMIC amplifier design and prototype multichip MMIC module development. A simple mask set with transistor test cells, simple MMIC test amplifiers, and space for new MMIC designs, must be developed. Multiple iterations of design, wafer processing, test and characterization, and module fabrication will be required. Based on recent history, there is no reason to expect that fundamental technological breakthroughs will be required, but careful attention to engineering details will be essential.

We emphasize that the the work requires three types of institutions: national labs, university groups, and industry. Industry provides materials and device design and processing capability. The national labs and universities provide the application-specific and cryogenic design and testing capability, as well as the critical experimental requirements and validation for ultimate performance. Experience shows that the participation of all three types of institutions, including postdocs and students, is essential.

5. **HETERODYNE INTERFEROMETRY**

5.1. **Introduction**

Heterodyne interferometry provides one of the most powerful techniques for making thermal-noise-limited observations of astrophysical and cosmological targets. It is particularly effective in eliminating many sources of systematic error that complicate observations with single antennas. Heterodyne interferometers have a long heritage in ground-based measurements of the CMB,
with DASI making the first detection of polarization and CBI making some of the first measurements of the shape of the E-mode power spectrum. Both DASI and CBI also made detailed measurements of the CMB temperature power spectrum, detecting multiple peaks in the power spectrum prior to the launch of WMAP.

§ 4.4 discusses the advantages and disadvantages of heterodyne interferometry in more detail. For now, they are summed up well in a comment made by Tony Readhead, PI of the OVRO single-dish CMB experiment and the CBI, who said “In our experience over the last three decades with both single-aperture systems and interferometers, we found that it took many months to identify and eliminate a wide variety of sources of systematic error with single antennas, whereas such sources of contamination could be identified and eliminated in a matter of a few days with interferometers.”

The key question to address immediately is this: if heterodyne interferometers are so great, why have they not been seriously studied or proposed for B-mode experiments? The answer is straightforward, and comes in three steps:

- For sensitivity, extremely low sidelobe levels, and frequency coverage to support component separation, a very large number of elements in a filled or nearly-filled array is required, resulting in of order a (very large number)² of baselines that must be correlated, requiring a very big correlator.
- Frequency coverage to realize the most accurate component separation can only be achieved from space.
- Historically, big correlators have been physically large and notorious power hogs (tens or hundreds of kilowatts!), far too demanding of mass and power to contemplate flying in space.

As a result, heterodyne interferometry, potentially the ultimate technique for control of systematic errors for the most demanding B-mode applications, was simply impossible. However, THE SITUATION HAS CHANGED!! Driven by the huge demands and needs of wireless communications, the capability of application specific integrated circuit (ASIC) technology has been increasing at a “Moore’s Law” rate. In the next section we show that it has now reached a level where large interferometers in space are practical. The situation will only improve rapidly with time.

Interferometers with a large number of elements, broad bandwidth, and wide frequency coverage of the sort that would be needed in space to make definitive measurements of B-modes have not been studied seriously. Without enabling low-powered correlators, it made little sense to do so, and without such studies in hand, we cannot and do not claim that a space interferometer is the best way to measure B-modes. However, we strongly believe that the time has come to study heterodyne interferometers seriously for the measurement of B-modes. The rest of this section outlines some basic considerations of interferometers that lead us to that conclusion, starting with the status of low-powered correlators.

5.2. Low-Powered Correlators Enable Space Interferometers
The number of required correlations at a given frequency is:

\[ N_{\text{cor}} = \frac{N_{\text{feed}}(N_{\text{feed}} - 1)}{2} \times 4N_{\text{sub}} \approx 2N_{\text{feed}}^2N_{\text{sub}}, \]

where \( N_{\text{feed}} \) is the number of pixels, \( N_{\text{sub}} \) is the number of IF sub-bands, and the factor of 4 comes from the requirement to correlate \( LL, RR, LR, \) and \( RL \), where \( R \) and \( L \) are the two polarization states. The number of sub-bands will be determined by the need to avoid chromatic
aberration, and by the clock speed of the digitizer. The number of bits that must be correlated will be determined by the dynamic range required.

Recent technology developments with space-based cross-correlators for Fourier synthesis interferometers have been driven by Earth Science remote sensing missions, in particular the Lightweight Rainfall Radiometer (LRR) and the Geosynchronous Earth Orbit Synthetic Thinned Aperture Radiometer (GEOSTAR). In both cases, emphasis has been placed on reducing the power requirements, increasing the clock speed, and improving the radiation tolerance of the digitizers and the multipliers/accumulators through the use of ultra-low power CMOS ASICs based on a 0.5 V logic protocol with resistance by design to radiation-induced single event upsets. This protocol has extensive spaceflight heritage for other high speed digital signal processing applications in space.

The new multiplier/accumulator for the GEOSTAR project is being built using a 90 nm, 0.5 V, CMOS ASIC process. It is projected to be capable of complex cross-correlations of all possible pairs of 196 In-Phase and 196-Quadrature Phase 2-bit input signals, clocked at 1400 MHz, while drawing 1.68 W of DC power.

Scaling from these chips, the power for multiplier/accumulators for a CMB application given current mature technology would scale as

\[ P = 98 \left( \frac{N_{el}}{196} \right)^2 \left( \frac{\Delta \nu}{19.8 \text{ GHz}} \right) \left( \frac{n_{\text{bits}}}{2 \text{ bits}} \right) \text{ W.} \]

Additionally we need to consider the digitizers. If the IF bands are 1.4 GHz, then the digitizer needs to run at 2.8 GHz for Nyquist sampling. Low-voltage digitizers that operate at this clock speed have not yet been demonstrated, but a 1-bit digitizer clocked at 392 MHz has been demonstrated that dissipates 4 mW. Assuming that the power dissipation scales with clock speed, the power dissipation would be

\[ P = 40 \left( \frac{N_{el}}{2} \right) \left( \frac{\Delta \nu}{19.8 \text{ GHz}} \right) \text{ W.} \]

Clearly, sampling and full correlation of many hundreds of elements over tens of gigahertz bandwidth can now be contemplated for less than 1 kW.

5.3. Interferometer Design

The way that interferometers achieve separation of \( E \) and \( B \) modes is shown schematically in Figure 17. A cross-correlation between the circularly polarized states, one from each antenna, is formed. The visibilities that correspond to the cross-correlations are related to the Stokes parameters as follows (Kovac et al., 2002).

\[ V^{RR}(u_i) = \alpha_i \int d\mathbf{x} A(x, \nu_i) |T(x)| e^{-2\pi i u_i \cdot \mathbf{x}}, \]

\[ V^{LL}(u_i) = \alpha_i \int d\mathbf{x} A(x, \nu_i) |T(x)| e^{-2\pi i u_i \cdot \mathbf{x}}, \]

\[ V^{RR}(u_i) = \alpha_i \int d\mathbf{x} A(x, \nu_i) |Q(x) + i U(x)| e^{-2\pi i u_i \cdot \mathbf{x}}, \]

\[ V^{RR}(u_i) = \alpha_i \int d\mathbf{x} A(x, \nu_i) |Q(x) - i U(x)| e^{-2\pi i u_i \cdot \mathbf{x}}, \]

from which the \( E \) and \( B \) components can be reconstructed:
Figure 17. Schematic of the operation of an interferometer (from Staggs and Church). A single polarization state from one antenna (in this case circular) is correlated with the polarization state from a second antenna. Placing a OMT after the feedhorn to split the signal into left and right circular polarization states, with a separate amplifier chain for each, allows all four Stokes parameters to be measured.

\[
\tilde{Q}(u) = \cos(2\chi)\tilde{E}(u) - \sin(2\chi)\tilde{B}(u),
\]

\[
\tilde{U}(u) = \sin(2\chi)\tilde{E}(u) + \cos(2\chi)\tilde{B}(u).
\]

It is also possible to build an interferometer based on bolometric interferometry by combining the signals optically prior to detection on a bolometric array. Such an approach is discussed elsewhere in the workshop. However, coherent amplifier technology is more suited to interferometric measurements than bolometric technology because the former has the ability to replicate photons, once the quantum tax is paid, allowing the full polarization state of the incoming radiation from a single feed to be correlated with that from any number of other feeds without degrading the sensitivity. In contrast, a bolometric interferometer cannot simultaneously measure \( Q \) and \( U \) (and thus \( E \) and \( B \)), and cannot expand efficiently to a large number of interferometric elements. Instead the incoming polarization state must be optically modulated and split, a complicated technology development that is not required in a coherent amplifier interferometer and does not scale well to a large number of feeds/detectors.

The advantages of interferometry do not lessen the need for sensitivity. Large arrays of detectors operating near fundamental noise limits are required whether the detectors are treated independently or as part of an interferometer. Since a close-packed interferometer and a close-packed focal plane array with the same number of elements have the same sensitivity, a \( B \)-mode interferometer needs hundreds of array elements per frequency just like a focal plane array. Fortuitously, a close-packed interferometric array with hundreds of elements to satisfy the sensitivity requirement also has an extremely well-shaped synthesized beam with very low sidelobe levels. This is the kind of interferometer that we are discussing.

5.4. Systematics and Sensitivity: Advantages and Disadvantages of Interferometers

Because an interferometer directly measures the spatial correlation function of the incoming signal, the measurement technique is fundamentally different from that of focal plane arrays.

Features that make heterodyne interferometers particularly suited for \( B \)-mode polarization measurements include:

- insensitivity to large-scale offsets and drifts;
- accurate determination of the synthesized beam shape, which can be calculated with high precision based on the geometry of the interferometric elements;
• simultaneous measurement with low 1/f noise of temperature \((I)\) and polarization \((Q\) and \(U)\);
• sensitivity of each baseline to a particular Fourier mode on the sky, so measurements are made directly in Fourier space
• simultaneous measurement of the real and imaginary parts of the signal, which can be combined in a straightforward way to decouple the E and B mode signals accurately.

Advantages:

• Coherent-amplifier interferometric methods allow certain systematics to be greatly reduced or eliminated altogether without the need for complicated multi-parameter modeling. Table 3 shows a list of systematics and a comparison of their effect on an interferometer with a system based on a focal plane array of bolometers. Note that many of these advantages are lost in a system based on bolometric interferometry.

• The cross-correlation of a single polarization state from two different antennas measures a single Fourier mode on the sky. Uncorrelated signals, such as amplifier 1/f noise, are strongly suppressed.

• There is inherent differencing involved in the cross-correlation process. The fringe pattern that is formed on the sky filters the images in \(\ell\)-space in a well-understood way.

• A single Fourier mode is measured with just two detectors, which simplifies the mode-by-mode calibration in \(\ell\)-space. Note that this advantage is lost in a bolometric interferometer, where the fringes are projected onto a bolometer array and many detectors are required to measure a single mode.

• With hundreds of close-packed corrugated horn elements, the synthesized beam will be both extremely clean and calculable with high precision. Moreover, the radiation pattern of individual corrugated feeds, which adds up to the envelope of the “primary beam”, is better than that of any telescope. Beamshape uncertainties with telescopes are a major systematic affecting current experiments. WMAP, for example, continues to make beam corrections at the 1% level or so that affect science results directly. The impossibility of fully characterizing the feed+telescope patterns with high dynamic range in the post-launch, cold environment of space may provide an ultimate limitation to telescope+focal plane array experiments. An interferometer seems likely to avoid this problem (detailed analysis is needed to quantify this), and as a result seems to be the ultimate in low systematics for CMB polarization.

• The noise modeling is simplified by the interferometric strategy because the noise from a single baseline is localized to a specific point in Fourier space.

• Because the angular resolution requirements are modest, corrugated feed horns can be used as the antennas, with the result that sidelobes and cross-polarization will be the lowest that is possible for any of the proposed B-mode experiments at the present time.

• A heterodyne interferometer can be configured in a natural way as a broadband spectrometer by splitting the IF band into \(N_{\text{sub}}\) spectral bands. Depending on the requirements that this places on the downlink speed, this spectral information can be retained and used as a check on systematics from foregrounds.

Disadvantages:

• An interferometer filters out all angular scales larger than the primary beam. This sets a lower \(\ell\) limit to the interferometric measurement; however, the total power signal from the feeds could be used directly to measure the lowest multipoles. Work would be required to figure out the best way to do this, and this complication makes it appropriate to consider this a disadvantage of an interferometer. The silver lining is that the low \(\ell\)s would be measured without a telescope, which will reduce systematics.
Considerations & Practicalities:

- Crosstalk or mixing between polarization states in the same antenna can lead to leakage of $T$ into $Q$ and $U$. This can be mitigated by phase switching the two states at different frequencies. Unlike the complex phase modulation required for bolometric interferometer, a simple 180 degree phase switch—a mature, well understood technology—is used. Crosstalk that occurs between the antennas and the phase switch is mitigated by enclosing the low-noise amplifiers in separate metal housings. Crosstalk between antennas can be mitigated by scanning the instrument across the sky to modulate the sky signal with respect to the more slowly varying cross-talk.

- The number of pixels that can be accommodated in a space-based interferometer will be limited primarily by power dissipation and the capabilities of the correlator.

- At 150 GHz and above, the noise temperature of the heterodyne system will be significantly higher than a bolometric system, but the foreground signals, which are the primary target at higher frequencies, are also rising. As discussed in §3.2, preliminary indications from modeling of component separation are that optimum results are obtained when noise per channel is proportional to total signal, including foregrounds.

5.5. Technical Design and Technology Development Program

In order to achieve the noise levels required to measure $B$-modes, both the sensitivity and the number of individual detectors/interferometer elements must be increased. The sensitivity of a filled-array interferometer and a close-packed focal plane array with the same angular resolution and sensitivity per detector are the same. Therefore, from a detector standpoint the same basic requirements apply to interferometers and focal plane arrays, namely, better detectors, and more detectors. The number of interferometer elements must be increased from the dozen or so of past CMB interferometers (e.g., VSA, DASI, CBI) to hundreds. This simultaneously produces a synthesized beam with extremely low and symmetric sidelobes. Figure 18 shows the sort of building blocks that could be used in a large-$N$ interferometer.

The speed and power dissipation of sampling and multiplying chips will continue to advance at a rapid rate, driven by the needs of wireless communication. At present, development of 90 nm-technology digitizers is lagging behind that of multipliers. Based on the modeling projections made for the 90 nm multiplier/accumulator ASICs, near-term development can be expected to result in digitizers with maximum clock rates in the neighborhood of 1400 MHz. A 90 nm ultra-low power 0.5 CMOS ASIC digitizer can be expected to reduce the power dissipated by two orders of magnitude.

Table 3 shows the TRL level of essential components of a CMBPol interferometry.

5.6. Technological Readiness

A great deal of design and engineering work would be required to build a space CMBPol interferometer. As with any experiment to measure $B$-modes, control of systematics and the effectiveness of the overall scheme must be demonstrated in suborbital observations. Most of the key technologies are applicable beyond interferometry. The most important technology developments required are in ultra-low-noise cryogenic amplifiers and modules discussed in §4, and in the correlator digitizers and multipliers. The correlator technologies are driven by commercial demand, and science can piggyback on their development.
Figure 18. Schematic of a single pixel suitable for use in an interferometer to measure CMB polarization. Two MMIC modules (lower left) are used, one per polarization. The modules are mounted on the IF/LO distribution board (lower right), which further amplifies the IF signals. There are two boards, one each for left and right circular polarization, but only one is shown for clarity.

Acknowledgments
We thank John Kovac and Andrew Lange for data used in Figures 1 and 2, Lorene Samoska and Pekka Kangashalti for Figures 6–9 and 11, Matt Morgan for Figure 10, Josh Gundersen for the left panel of Figure 13, the University of Chicago QUIET team for Figure 14, and Laura Newburgh for Figure 15, and Amber Miller and Bruce Winstein for helpful comments.
Table 3. Key technologies for a CMBPol interferometer.

| Element                        | Heritage         | Development Needed for CMBPol | TRL | Comments                                                                 |
|--------------------------------|------------------|-------------------------------|-----|--------------------------------------------------------------------------|
| Feed horn array                | WMAP, Planck     | Test crosstalk on very small baselines | 6+  | Individual horns very well understood. QUIET will demonstrate latelet arrays. |
|                                | Platelet arrays for QUIET | Weight reduction              |     |                                                                          |
| Orthomode transducers          | WMAP, Planck, QUIET | Weight reduction, assembly of many units. | 6+  |                                                                          |
| 20 K Cooler                    | Planck           |                               | 8   |                                                                          |
| Heterodyne MMIC amplifier modules | QUIET, GeoSTAR   | Prototype pixel fabrication  | 4   | Prototype single polarization heterodyne module is under development. Paper design exists, fabrication expected by end 2008. |
|                                | Platelet arrays for QUIET | Weight reduction              |     |                                                                          |
| IF electronics                 |                  | Low power amplifiers          |     | Use HEMTs?                                                               |
| Correlator                     | GeoSTAR          | low power ASIC multipliers and digitizers | 4-6+|                                                                          |

Appendix: Sensitivity Comparison of Bolometric and HEMT-based systems
We give here details of the method used in §3.1 to compare the sensitivities of HEMT and bolometric systems for both space and ground.

Appendix A.1. Sensitivity of a bolometric system
The sensitivity of a bolometer to a single mode of polarization can be calculated from first principles based on the techniques in Zmuidzinas (2003). The Noise Equivalent Power (NEP) is given by:

\[
\text{NEP} = \sqrt{2 \left( \frac{P_{\text{det}}^2}{\Delta \nu} + P_{\text{det}} h \nu \right)} \text{ WHz}^{-1/2}. \tag{A.1}
\]

\(P_{\text{det}}\) is the power incident on the detector and is given by

\[
P_{\text{det}} = \Delta \nu h \nu \left( \eta n_{\text{CMB}} + \sum_i \epsilon_i n_{\text{back},i} \right), \tag{A.2}
\]

where \(\eta\) is the optical efficiency of the detection system, \(\epsilon\) is the emissivity of each contribution to the background, and \(\Delta \nu\) is the bandwidth of the system. The quantities \(n_{\text{CMB}}\) and \(n_{\text{back}}\) are the photon occupation numbers of the signal (CMB) and background, respectively, given by

\[
n(T) = \frac{1}{\exp(h \nu/kT) - 1}. \tag{A.3}
\]

For the Figures 1 and 2, the following assumptions have been made:
• For a perfect bolometric system from the ground, it is assumed that the signal is the CMB and the background is from atmospheric and telescope emission. A ground-based telescope is assumed to have a temperature of 280 K and an emissivity of ~ 2.9% (giving a telescope temperature of 8 K). The atmospheric emissivity is calculated for a high dry site.

• For a space-based system, the telescope is assumed to be cold so that its contribution to the background power can be ignored.

To convert NEP to sensitivity to $Q$ (or $U$) involves the following steps:

• First the bolometer NEP is converted to an NET

$$\frac{\text{NET}}{T_{\text{CMB}}} = \frac{\exp(x) - 1}{x \exp(x)} \times \frac{1}{\sqrt{2}} \times \frac{\text{NEP}}{T_{\text{CMB}}}$$  \hspace{1cm} (A.4)

where $x = h\nu/kT_{\text{CMB}}$ and the factor of $1/\sqrt{2}$ converts $\text{W Hz}^{-1/2}$ to $\text{W s}^{1/2}$.

• It is assumed that the detected signals from two bolometers, each sensitive to an orthogonal direction of polarization, are differenced to get $Q$. Then:

$$\text{NEQ} = \frac{\text{NET}}{\sqrt{2}}$$  \hspace{1cm} (A.5)

Appendix A.2. Sensitivity of a HEMT-based system

A similar procedure is followed for a HEMT system. The sensitivity of a single quantum-limited amplifier can be calculated from first principles (Zmuidzinas, 2003), and is shown to have an NEP of

$$\text{NEP} = \sqrt{\frac{2}{k\Delta\nu}} (P_{\text{det}} + h\nu\Delta\nu).$$  \hspace{1cm} (A.6)

We don’t normally think of amplifier sensitivities in terms of NEP, but there is no reason not to do so. To see this in the more familiar terms of system temperature, we divide by $k\Delta\nu$ and convert from $\text{W Hz}^{-1/2}$ to $\text{W s}^{1/2}$ to get

$$\Delta T_{\text{RJ}} = \frac{1}{\sqrt{k\Delta\nu}} \left(T_{\text{back,RJ}} + \frac{h\nu}{k}\right),$$  \hspace{1cm} (A.7)

where $P_{\text{det}} = k\Delta\nu\Delta T_{\text{back,RJ}}$ defines the Rayleigh-Jeans temperature of the radiation that is incident on the amplifier. The second term in Equation A.7 is then identified as the quantum noise introduced by the amplifier and defines a noise temperature of $T_{\text{amp}} = h\nu/k$ at the quantum limit. The sensitivity of a system with an amplifier that has noise higher than the quantum limit can be accomplished by modifying Equation A.7 to be

$$\Delta T_{\text{RJ}} = \frac{1}{\sqrt{k\Delta\nu}} \left(T_{\text{back,RJ}} + q\frac{h\nu}{k}\right),$$  \hspace{1cm} (A.8)

where $q$ is the ratio of the amplifier noise temperature to the quantum noise limit (e.g., a “five times quantum” amplifier would have $q = 5$.) This expression can then be converted back to NEP, giving

$$\text{NEP} = \frac{2}{k\Delta\nu} (P_{\text{det}} + qh\nu\Delta\nu),$$  \hspace{1cm} (A.9)

from which the NET for CMB measurements can be calculated using Equation A.4.
The NEQ of a HEMT-based system, whether it is a correlation radiometer, or an interferometer, is given by:

\[
\text{NEQ} = \frac{\text{NET}}{\sqrt{2}}
\]  

(A.10)

The difference is that these systems can measure \(Q\) and \(U\) simultaneously without noise penalty, so it is conventional when making comparisons between bolometric and HEMT based systems to include an extra factor of \(\sqrt{2}\) so that:

\[
\text{NEQ}_{\text{bolo}} = \frac{\text{NET}}{\sqrt{2}}
\]  

(A.11)

\[
\text{NEQ}_{\text{HEMT}} = \frac{\text{NET}}{2}
\]  

(A.12)

This convention has been adopted in the figures.

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