PILOT: the Primordial Inflation Telescope

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Abstract. Coherent systems offer significant advantages in simplicity, testability, and cost. The PILOT mission concept, based on HEMT amplifiers, is designed to be a low-cost option for a future space mission.

1. Introduction to PILOT

PILOT, the Primordial InfLatiOn Telescope, is designed to search for evidence of primordial inflation by measuring B-mode polarization, determine the ionization history of the Universe, and map the CMB polarization at large angular scales. It is based on HEMT amplifiers, and designed to be a low-cost option for a future space mission. The basic mission parameters are:

- L_2 halo orbit
- Five frequency bands between 30 and 150 GHz
- Launch vehicle: TBD
- Mission duration: 4 years nominal
- Instrument cold end temperature: 20 K
- Pointing control: $5'$ rms
- Reconstructed pointing knowledge: $10''$
- Daily data volume: 7.5 Gb/day
- Estimated instrument mass: 500 kg
- Estimated instrument power: 1500 W
- Cost target: <$350 M

Figure 1 shows the design of the polarimeters, which measure both Q and U simultaneously. Figure 2 shows the basic thermal configuration, with a deployable Sun shield/solar panel, warm spacecraft bus, two-stage V-groove radiator for thermal isolation and radiative cooling, and cold instrument and telescope. Figure 3 gives the geometry of the telescope axis, spin axis, and Sun-Earth line, and describes the scan strategy.

Table 1 gives the number of feeds per frequency, and the power dissipation and noise characteristics of the instrument. Preliminary indications from simulations of foreground separation suggest that the optimum way to divide precious focal plane real estate is to achieve roughly uniform signal-to-noise ratio on the total signal, that is, CMB + foregrounds. Synchrotron and dust emission rise steeply with frequency away from the foreground minimum

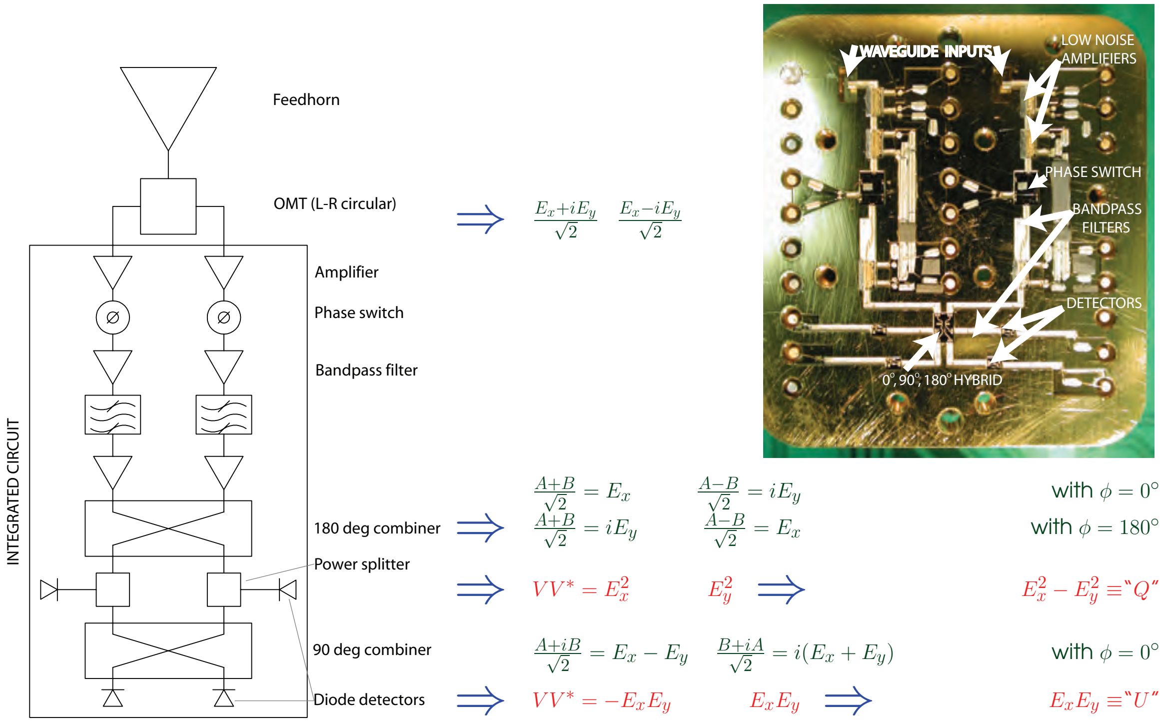

Figure 1. Block diagram of a pseudo-correlation polarimeterss that measure Q and U simultaneously. The incoming signal is split into left and right circular polarization, amplified, and passed through a phase shifter. The phase shifter in one arm is switched rapidly between 0° and 180°. After additional amplification, the two signals pass through a 180° combiner, and a power splitter. Detector diodes then measure either E_x^2 or E_y^2 (depending on the position of the phase switch), so that $E_x^2 - E_y^2 = Q$ can be calculated after readout. The second half of the split power is passed through an additional 90° combiner, leading similarly to a measurement of $E_xE_y = V$. Since both linear polarizations have passed equally through both amplifier chains before the signals in the two arms are subtracted, $1/f$ noise and common-mode systematic effects are highly suppressed. This scheme takes advantage of the fact that in a coherent (i.e., phase preserving) system, once the "quantum tax" is paid further processing adds negligible noise. In addition to highly effective suppression of $1/f$ noise and systematics, the simultaneous, continuous measurement of Q and U through one feed allows maximum efficiency in the use of valuable focal plane real estate.

Table 1. Number of feeds per frequency, power, and noise.

Frequency [GHz]	N	Power [mW]	$T_{\rm rcvr}$ [K]	$T_{\rm sys}$ [K]	NEQU [μK s$^{1/2}$]	NEQU/freq [μK s$^{1/2}$]	4-yr Noise/1 deg^2 [nK]
30	4	4	7	10	81.6	40.8	750
40	50	7	8	11	87.0	12.3	230
70	160	10	10	13	77.7	6.1	125
100	75	12	12	15	75.0	8.7	200
150	75	15	20	23	93.9	10.8	500
Total N	364		Total power dissipated = 4 W				

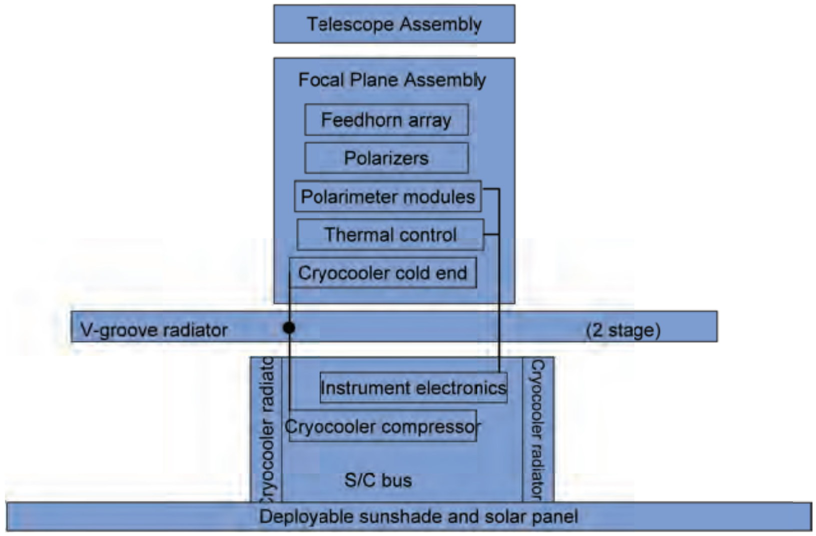

Figure 2. Block diagram of PILOT. The V-groove radiators provide excellent isolation of the warm and cold parts of the system, intercepting conducted heat from spacecraft bus and radiating it into space, as well as providing efficient precooling at $< 50\,\mathrm{K}$ for the cryocooler.

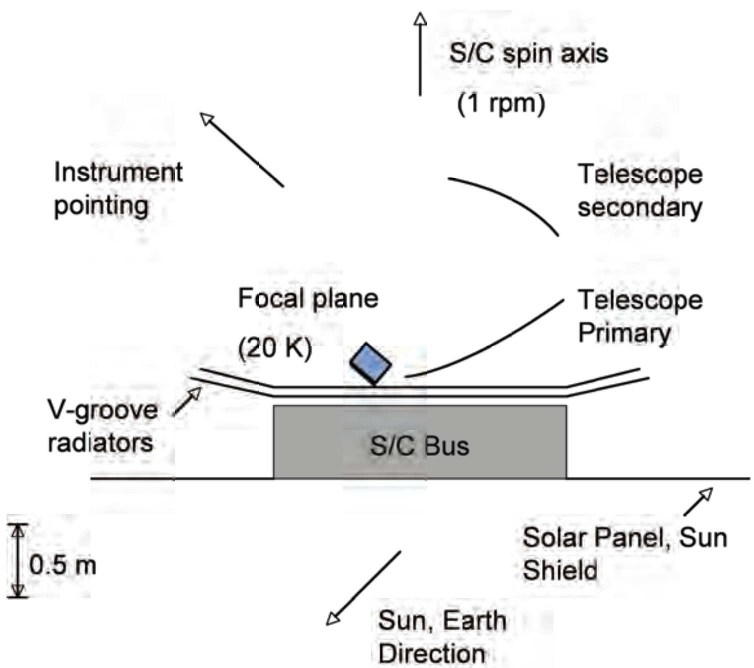

Figure 3. Schematic of PILOT, showing the basic configuration. The spacecraft spins at about 1 rpm about the symmetry axis of the spacecraft, which is at an angle of ∼45° to the Sun-Earth line, and which precesses about a cone of opening angle ∼45° in a few hours. Half the sky is observed every few hours. This scanning strategy provides highly uniform coverage of the sky as well as highly uniform polarization angle coverage at each point on the sky. A large and deployable sun shade/solar panel is required to keep everything else in shadow.

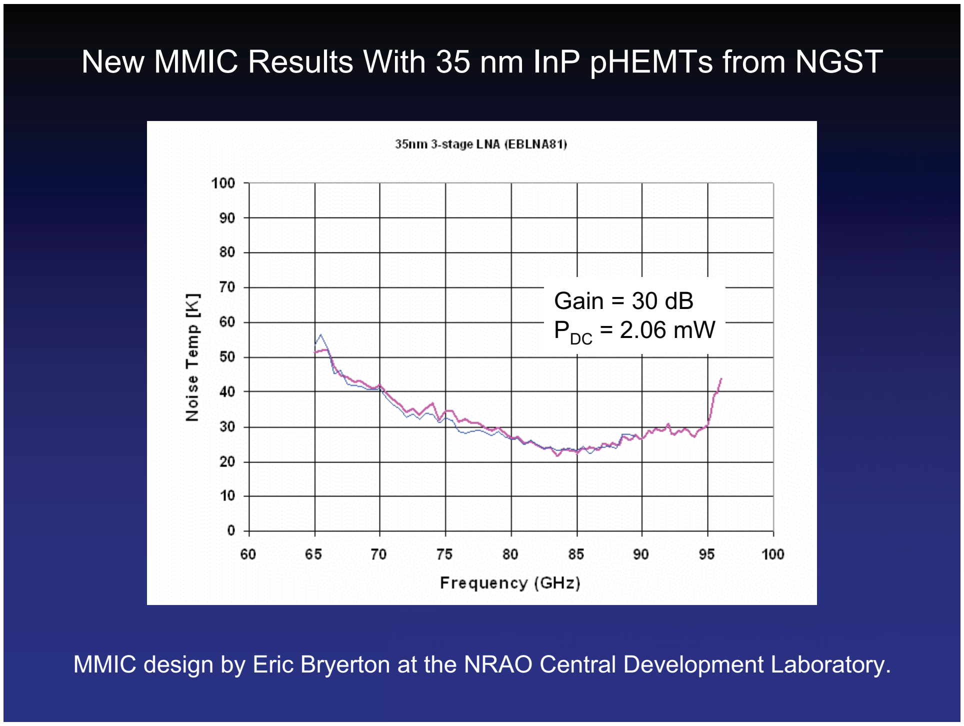

Figure 4. Noise as a function of frequency for the first 35-nm-gate HEMT MMIC amplifier at W band. The physical temperature of the MMIC was about 15 K. Although this is the lowest noise ever measured for a W-band amplifier, a noise model for the 35-nm devices based on room temperature performance at higher frequencies up to 350 GHz predicts that noise of less than 12 K at 100 GHz, a factor of 2.5 or so below this first realization, should be achievable with these devices. Based on past experience, a couple of years of technology development effort could be expected to realize this spectacular promise. Figure provided by M. Morgan.

(see Fig. 7), which occurs at about 70 GHz for temperature fluctuations. Recent evidence incorporated into the Planck Sky Model (PSM; Leach et al. 2008) used to generate Figure 7 suggests that the foreground minimum in polarization depends on the fraction of sky covered, but is above 100 GHz except in the Galactic plane. If this is confirmed by Planck (see *Planck: The Scientific Programme 2005*), the relative number of detectors per frequency for PILOT would be adjusted to move the minimum noise to higher frequencies. I'll return to the subject of foregrounds later.

The noise noise and power values assume the latest 35 nm-gate transistors (Dawson et al. 2005; Deal et al. 2006, 2007; Gaier et al. 2007; Kangaslahti et al. 2008; Pukala et al. 2008; Samoska 2006; Samoska et al. 2008). Noise values are extrapolated from room temperature measurements at 250–350 GHz using a noise model tied to the high frequency measurements (P. Kangaslahti, private communication). The model assumes that noise decreases by roughly a factor of ten between room temperature and 20 K. Power is scaled from a recent measurement in W band. The current best cryogenic noise performance achieved in the W band is shown in Figure 4, and is a factor of 2.5 or so higher than assumed in Table 1. However, this is the *first* cryogenic measurement in W band with the new 35 nm gate MMICs. Moreover, the cryogenic noise of this amplifier was indeed a factor of 10 lower than at room temperature, confirming one of the important parts of the noise model. Based on past experience, a couple of years of development effort could be expected to realize the great promise of these transistors, reducing the noise by the factor of 2.5 between current measurements and the noise model.

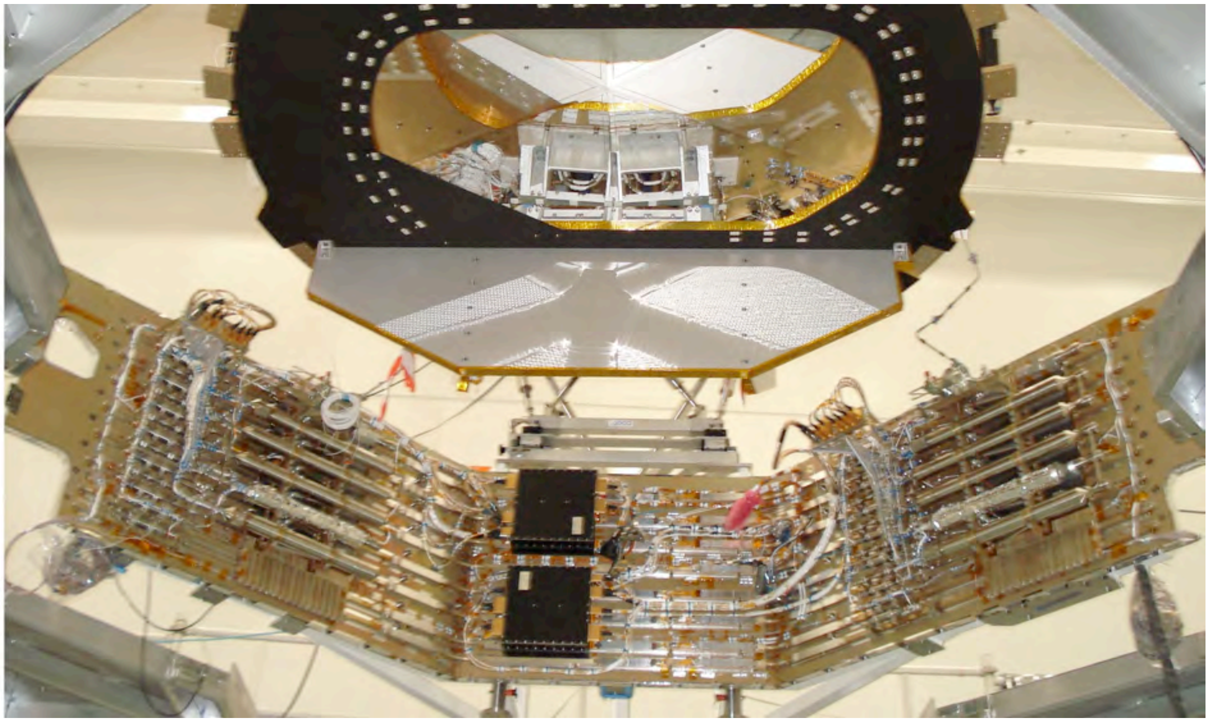

Figure 5. The 20-K hydrogen sorption cooler for Planck. Reconfigured to supply a single JT expansion valve, appropriately sized for a 45 K precool temperature, the Planck cooler would provide over 4 W of heat lift at 20 K. It therefore provides a high TRL existence proof for the viability of cooling a large array of amplifiers in space.

2. Cooling

The power dissipation of amplifiers is much higher than the negligible dissipation of bolometers. But it is not so high that a CMB polarization mission based on cryogenic amplifiers is precluded based on cooling considerations. Two factors are involved. First, the power dissipation of the latest generation of InP transistors is substantially less than for earlier devices. The active dissipation of the PILOT polarimeters is 4 W at 20 K. Second, the 20 K sorption cooler system about to fly on Planck (Fig. 5) is already large enough to do the job, with minor modifications, for about 1 kW of input power and a radiative precool temperature provided by the V-grooves of 45 K. Detailed system design studies are required to determine whether a sorption cooler is the best option, but the Planck cooler provides a TRL 8 existence proof that cooling requirements are not a showstopper.

3. Scientific Performance

Figure 6 compares the performance of PILOT with that of Planck, and shows that subject to the usual assumptions about systematics and foreground separation PILOT can reach the level of $r = 0.01$ recommended by the Task Force on Cosmic Microwave Background Research (TFCR; Weiss et al. 2005).

4. Foregrounds and Frequency Range

The requirement that will determine the viability of an amplifier mission for CMB polarization is that of foregrounds and the frequency coverage necessary to deal with them. Specifically, given that quantum noise in coherent detectors increases linearly with frequency, the key question

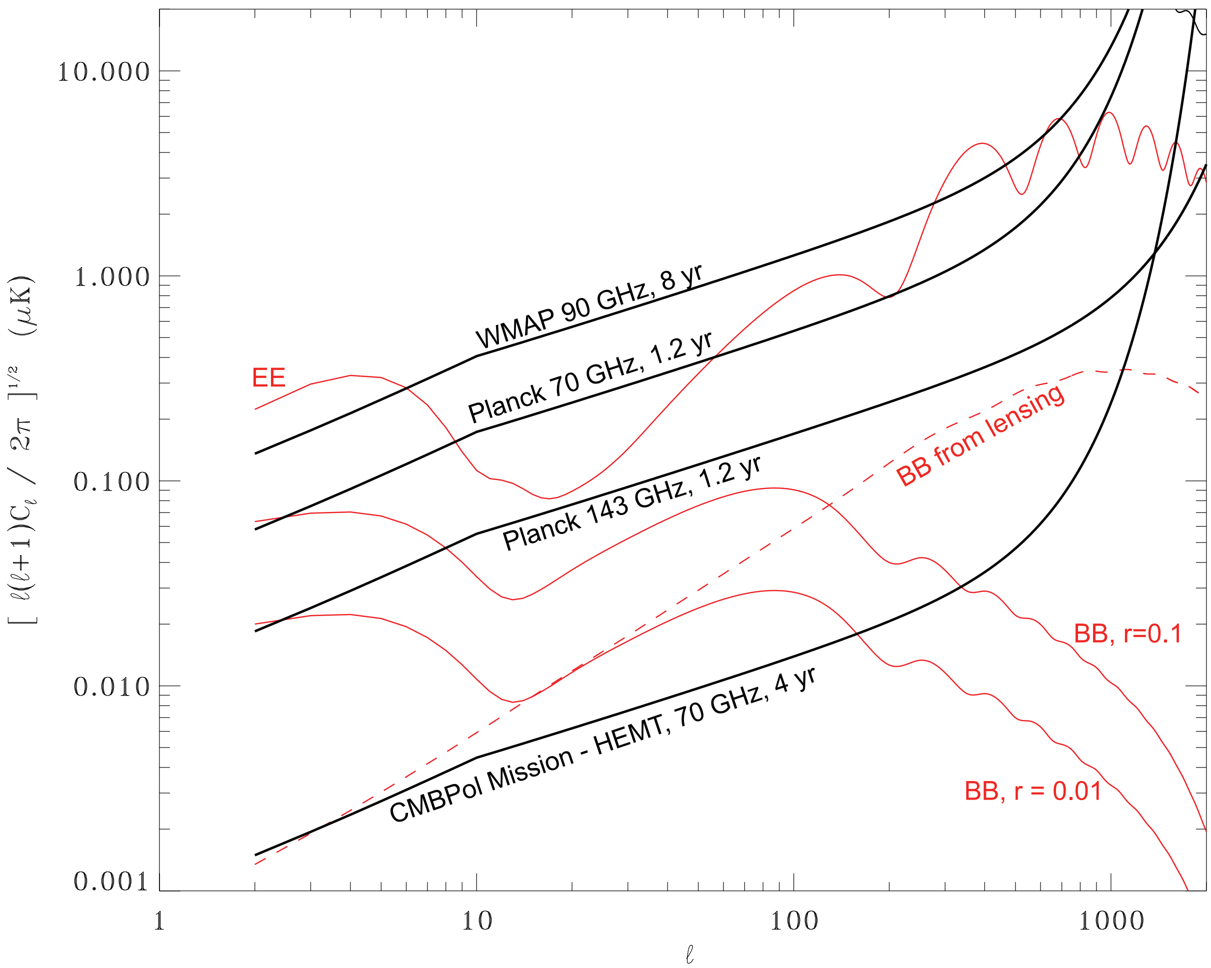

Figure 6. Comparison of noise levels in the 70 GHz band of PILOT with *WMAP* at 90 GHz and *Planck* at 70 GHz (amplifiers) and 143 GHz (bolometers). We follow the TFCR (2005, Fig. 6.1) and plot $\sqrt{\frac{2}{f_{\rm sky}(2\ell+1)}}N_\ell$ for the noise, so that at the intersection of a noise curve and a power spectrum (EE or BB) the noise per ℓ and the CMB signal are equal. BB is plotted for two values of the tensor to scalar ratio r, 0.1 and 0.01. The dashed curve shows the confusing BB signal due to weak lensing that peaks at about $\ell = 1000$. Too little is known about polarized foregrounds to support reliable simulations of the effects of foreground separation on ultimate CMB noise level. We therefore make the usual assumption that the noise level in one frequency channel near the foreground minimum is a reasonable standin for the noise to be expected after foreground separation using all frequency channels of the experiment. PILOT is more than an order of magnitude more sensitive to polarization than *Planck*, and achieves the sensitivity to B-modes recommended by the TFCR.

for an amplifier mission is how high in frequency must we observe in order to deal with high frequency foregrounds?

Figure 7 shows the level of synchrotron and dust temperature fluctuations in absolute units and relative to the CMB, calculated over different regions of the sky as indicated. A detailed discussion of foreground issues is available in "Prospects for Polarized Foreground Removal" (Dunkley et al. 2008) in another part of the CMBPol Mission Concept Study. Inadequate knowledge of foregrounds currently limits the certainty of conclusions that we can draw from simulations. Planck and current and planned suborbital experiments will solve that problem. In the meantime, we can say that if measurements above 150–200 GHz are unnecessary for foreground separation, an amplifier mission can do the job.

5. Sensitivity, Noise, and Systematics

Sensitivity, usually expressed in $\mu\mathrm{K\,s}^{1/2}$, is an ingredient of an experiment, but noise (which takes integration time into account) is more fundamental. In any case, CMB polarization measurements are certain to be limited by something other than instrument noise. The leading candidates are foregrounds, systematics, and money.

Figures 8 and 9 compare sensitivities and noise levels for amplifiers and bolometers for space and ground-based observations, respectively. The sensitivities of a "perfect" (i.e., quantum-noise-limited) amplifier and a "perfect" (i.e., 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 (Fig. 1, whereas direct detectors can measure either 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 9 with the curve in Figure 8.

In Figures 8 and 9, sensitivity curves are shown also for amplifiers at 3 and 5 times the quantum limit. In Figure 8, discrete points show:

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

The horizontal green, blue, and magenta lines in Figure 8 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. This is the target noise level recommended by the Task Force on Cosmic Microwave Background Research. 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.

In Figure 9, 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 9 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)

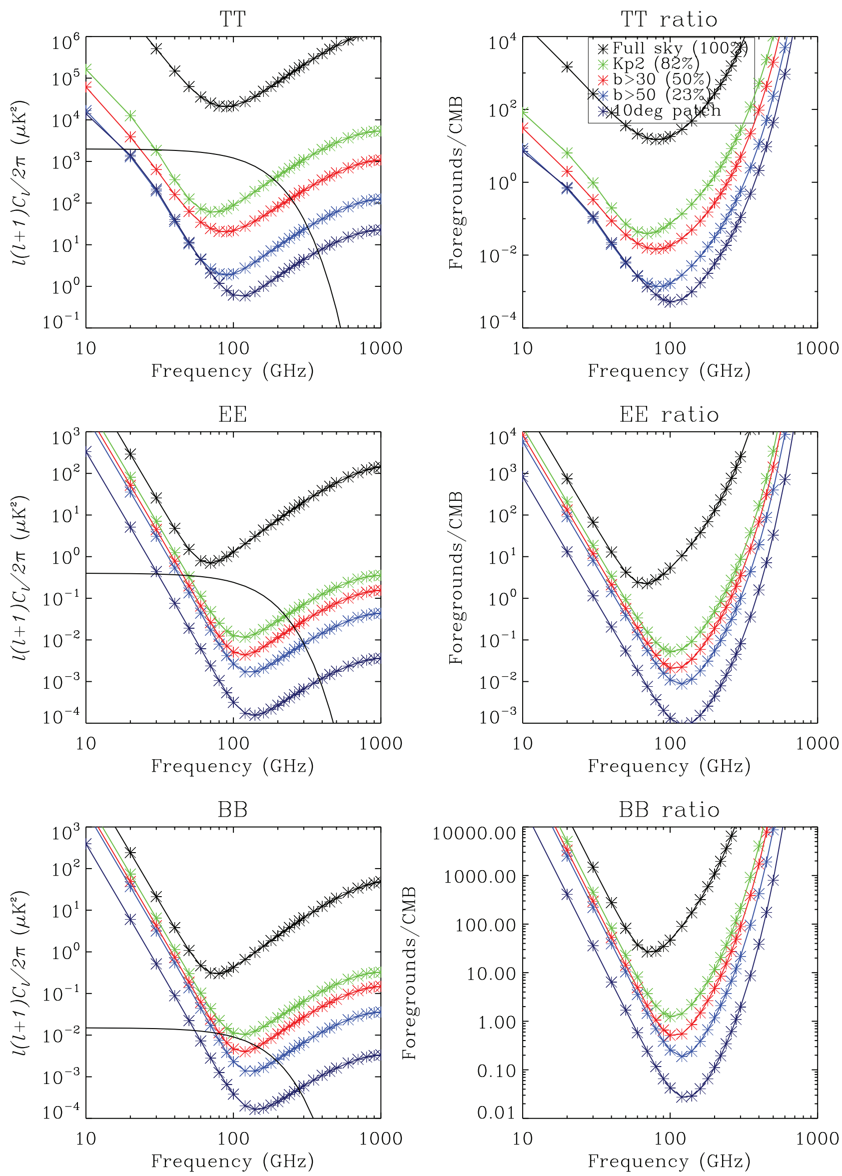

Figure 7. Synchrotron and dust temperature fluctuations in absolute units (*left*) and relative to the CMB (*right*), calculated over different regions of the sky (see upper right panel) from the Planck Sky Model (Leach et al. 2008) by Clive Dickinson (private communication). A B-mode space mission would surely measure the whole sky; the lower curves representing small sky fractions are relevant only for suborbital experiments. 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 70 GHz. At 30 and 180 GHz they are up by a factor of 25. By 300 GHz, dust fluctuations are up by three orders of magnitude compared to CMB fluctuations. If foreground spectra are complicated, a very wide frequency range may be disadvantageous. For EE the foreground data are much more uncertain, especially concerning dust. The green curve in the EE ratio plot reaches the same values at about 50 and 240 GHz.

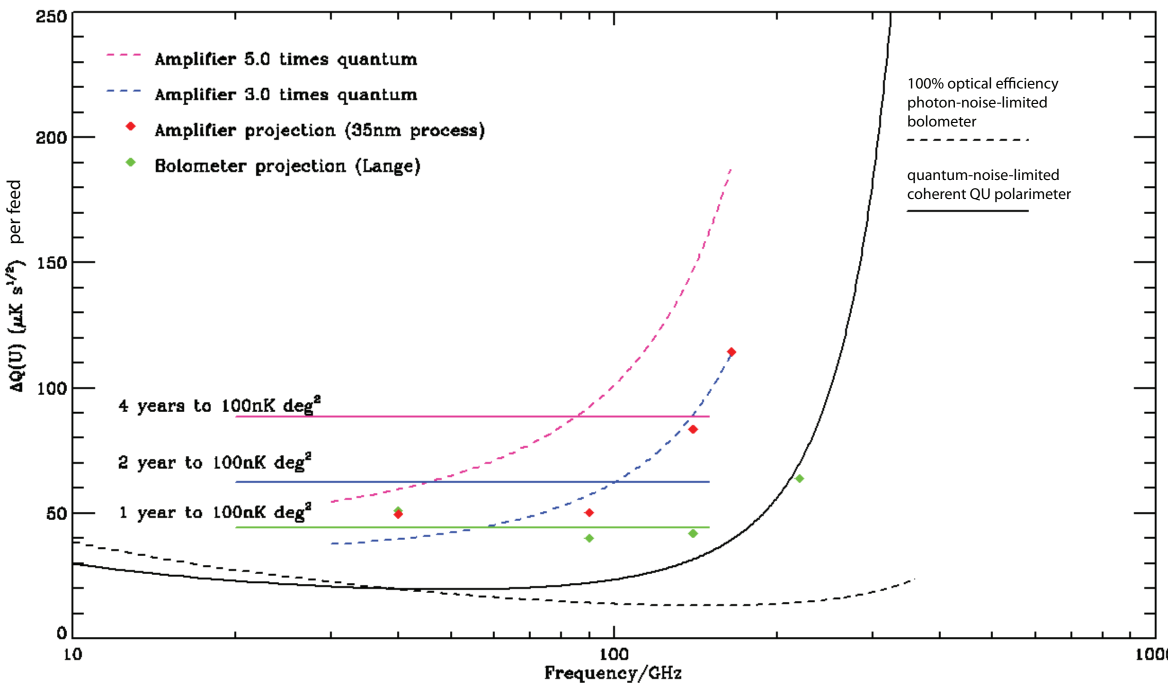

Figure 8. Sensitivity of a quantum-limited amplifier compared with the sensitivity of a photon-noise-limited bolometer (i.e., "perfect" amplifier and bolometer, respectively), in space. Below 40 GHz photon noise would dominate quantum noise for the amplifier. We have not added the two together so that 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.

from the ground. Such an array of amplifiers at the noise levels projected for 35-nm gate process HEMTs 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 forseeable future, both can reach the recommended noise level over a small patch of sky in a reasonable experimental lifetime from the ground. As mentioned before, the work required to bring amplifiers to the projected level of performance will take several years. But if an instrument with $3 \times q$ amplifiiers 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, assess in a real and stressful environment.

I believe that we should work towards this situation, that a down-select between the two technologies should not take place before this comparison can be made, and that the design of a space mission to measure the BB power spectrum in all its glory can then be made optimally.

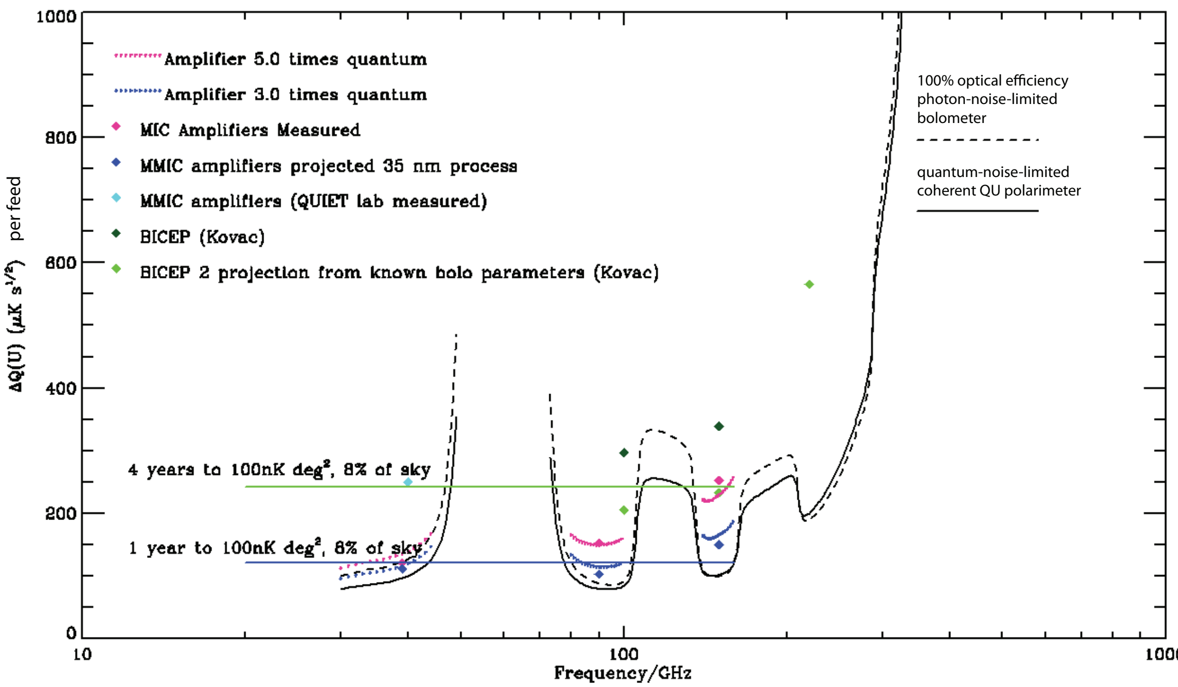

Figure 9. Sensitivity of a quantum-limited amplifier compared with the sensitivity of a photon-noise-limited bolometer (i.e., "perfect" amplifier and bolometer, respectively), from the ground at a high, dry, site. The dramatic effect of the atmospheric loading on bolometer sensitivity even in the good 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. 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.

6. Characteristics of Coherent Systems, Complexity, and Cost

Table 2 lists a number of essential technology characteristics of CMB polarimetry experiments and gives an assessment of the current status of the technology. Many of these are the subject of intense development. Although there are significant differences in approach between coherent and bolometric systems, a credible case can be made that both technologies can do the job, i.e., that there are no show-stopping systematic effects that will limit either technology.

Nevertheless, there are significant practical differences. Complexity is expensive. Testing in non-ambient conditions is expensive, and testing at 0.1 K is more expensive than testing at 20 K. A mission with amplifiers would be significantly simpler in many ways (e.g., no half-wave plates or other pre-detector modulators, no 0.1 K) and easier to test and validate before launch. It would therefore cost less.

7. Interferometers

Greg Tucker listed many advantages of interferometers ((Tucker, this workshop, *"MBI"*)). I second those, but believe that the way to achieve them is with a coherent, multiplicative interferometer. A large number of interferometer elements will be needed, both for sensitivity and for beam quality. The inherent difficulties of combining beams from multiple elements in

Table 2. Technology Characteristics

Requirement	MMIC HEMTs	Bolometers
Response time	Excellent	Adequate, can be modeled
Linearity	Excellent	Adequate, can be modeled
Dynamic range	Large	Small
Gain stability	Excellent with modulation	Excellent for Planck (NTD Ge technology), not yet public for TES
Offset stability	Excellent with modulation	Good
Polarization systematics	Excellent, Q and U from same pixel	Good, Q and U from different pixels, or complicated modulation
B-field, microphonic, EMI, RFI susceptibility	Good	Adequate (?)
Device uniformity	Not established	Good for Planck, not yet public for TES
	PRACTICALITIES FOR SPACE	
Cooling requirements	Passive + passive (?40 K?) or	0.1 K operation requires multi-stage cooling chain. Loading per detector depends on parasitics. Complicated.
	Passive + active (20 K). Heat lift requirement large but achievable.	
System testability & risk reduction before flight	Easier	Harder
MUX	Not needed	Adequate

an incoherent interferometer will become prohibitive for large N.

If foregrounds are indeed the limit to CMB polarization measurements, as is widely suspected, then space is required. We will have to observe throughout the frequency range where foregrounds are lowest, and that includes regions of the spectrum unavailable even from balloons. However, until now large space interferometers have been precluded by the power requirements for correlators. **This is no longer the case!** A funded ASIC development starting this month for GEOSTAR using 90 nm geometry will produce chips that multiply all pairs of 196 elements over 1400 MHz bandwidth for 1.68 W. To form all quadrature correlation products, four chips are needed for every 1400 MHz. Thus for 196 elements, all products over 40 GHz of bandwidth requires only

$$4 \times 29 \times 1.68 = 195\,\mathrm{W!!}$$

Of course, a correlator consists of more than multiplier chips, and the other components dissipate power as well. However, the N^2 dependence in multiplier power dominates for large correlators, and has been the limiting factor in the contemplation of large space correlators. No more. The systematic advantages of interferometers will be available to a CMB polarization space mission if necessary.

8. Summary

A space mission based on amplifiers is feasible. Noise levels required for Weiss-report B-mode sensitivity seem likely to be achieved with continued development of MMICs and modules. The cooling requirement of a handful of watts at 20 K, daunting at first glance, can be met with existing technology for a reasonable amount of power. Thermal/mechanical engineering of the flight system needs to be done.

The first realistic opportunity for a CMBPol mission may be the planned 2011–2012 Midex AO. Depending on the cost limit, a coherent mission may be possible on that timescale. The most important open question is that of foreground subtraction. An amplifier mission can perform extremely well up to 150 or perhaps 200 GHz, but quantum noise would make it uncompetitive with bolometers if higher frequencies are required.

The key open question for space is the necessary frequency coverage to deal with foregrounds. On the ground, in contrast, even raw sensitivity favors coherent systems.

Acknowledgments

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