A CMBPOL mission concept: feed farm on a simple spinner

Lyman Page[1], **Gary Hinshaw**[2], **and Jennifer Lin**[1]

[1] Dept. of Physics, Princeton University, Princeton NJ 08544-0708.

[2] NASA Goddard Space Flight Center, Greenbelt, MD 20771.

E-mail: `page@princeton.edu`

Abstract. We present a concept for a medium scale satellite mission to measurement the B-mode polarization in the CMB at large angular scales. The idea is to close pack a multifrequency array of ∼1500 corrugated feeds to make a "feed farm". The majority point along the spin axis of the satellite. The primary modulation is obtained by spinning the satellite. Thus, in any instant the polarization in one direction is measured very well. The spin axis is then smoothly precessed over the celestial sphere. An angular resolution of better than 2.5° is possible at 150 GHz. Little detector development is needed; indeed the requisite sensitivity has nearly been achieved. The technical challenges are in the cryogenics and in the manufacture of corrugated feeds above 200 GHz. The astrophysical challenge is in the foreground emission. In the absence of foreground emission the raw sensitivity of a simple feed farm observing for one year corresponds to $r < 0.005$ or 3.2 μK-arcmin.

1. Introduction

We briefly present the concept of a "feed farm" as a potential geometry for a CMBPOL mission. The design is conceptually simple and is quite different from more widely discussed options. All elements of the optical design can be computed from first principles and thus potential systematic effects can be identified early on. Its main limitation is that it works only for large angular scales. Its main benefit is that a technical phase-A study could commence immediately.

In the following, the picture to keep in mind is that of a 2.5 m diameter shroud completely populated by feeds. The diameter of a $\theta_{FWHM} = 2.4°$ at 150 GHz is 7.5 cm, and thus approximately 750 such feeds will fit in the shroud with room for additional smaller feeds. To our knowledge, such a feed has never been built. For a fixed angular resolution, the diameter scales inversely with frequency. One immediately sees two challenges: (1) How to optimize the available space in the shroud to maximally solve for and subtract foreground emission; (2) How to produce and maintain the 0.1 K required to cool the detectors over a 2.5 m diameter circle, while at the same time having the skyward part of the feeds at the radiatively cooled temperature of 40 K.

In addition to the practical aspects just mentioned, we have not been able to design "bare" feeds with enough resolution to measure both the reionization and decoupling B-modes. However, we note variations on the theme that we have not pursued that lead to improved resolution. One of these may make the design more attractive than the variant presented here.

Below, we follow the outline suggested by John Ruhl and Gary Hinshaw at the meeting on Inflation Probe Systematics Workshop in Annapolis, MD July 28-30, 2008.

2. Collaborators

The feed farm concept has been around since people began talking about a CMBPol mission. The following is one version that was spawned as a result of discussions with collaborators on the Hinshaw *et al.* Jan. 2004 proposal entitled "A Mission Concept Study for the Einstein Inflation Probe," (with C. Bennett, M. Devlin, D. Fixsen, W. Hu, K. Irwin, N. Jarosik, A. Kogut, A. Kosowsky, M. Limon, S. Meyer, A. Miller, S. H. Moseley, B. Netterfield, A. Oliveira-Costa, L. Page, J. Ruhl, U. Seljak, D. Spergel, S. Staggs, M. Tegmark, B. Winstein, E. Wollack, E. Wright, & M. Zaldarriaga). Additional developments came from the Staggs *et al.* proposal "Broadband Cryogenic Feedhorn Arrays for Cosmic Microwave Background Polarimetry," Jun. 2005 (with N. Jarosik and L. Page) and from a study of 150 GHz feeds by Jennifer Lin, and undergraduate physics major at Princeton, that was supported in part by the Meyer *et al.* NASA "CMBPol Mission Concept Study" award.

3. Summary table of mission

Table 1 gives a schematic outline of aspects of the mission. Keep in mind that the mission has not been studied in detail and so these should be viewed as little more than a starting point. For example, the results of the foreground workshop will inform the best choice of frequencies, a detailed study of corrugated feeds will inform us about the feasibility of the concept.

Table 1. Feed farm on a spinner

Attribute	Design Goals	Units
Angular resolution	180-360	arcmin
Frequency coverage	90-300	GHz
Sky coverage	40,000 (full sky)	square degrees
Multipole coverage	2-100	
Polarization modulation	Spin+OMT	
Types of detectors	Bolometers	
Location	e.g., L2	
Instrument NEQ	40/feed	$\mu\mathrm{K\,s}^{1/2}$
Expected limit on r	Need foreground analysis	
Status	Back of the envelope/future	

4. Instrument and observing strategy

We describe the simplest version of the feed farm, though many variations on the theme are possible. Outside of the cryogenics, the development of the instrument is straightforward. For the ∼750 150 GHz feeds, there are 750 copies of the basic unit. That unit consists of a feed, a detector system, and a readout. The units are then arranged in the S/C bus.

4.1. Feeds

The optics are simple. There are only corrugated feeds in the design. The beams are symmetric. One can compute the beam patterns, sidelobes, and polarization response to high accuracy and one can build what one designs. The code we have used is called CCORHRN which was developed by YRS Associates [4]. Examples of the comparison of prediction to measurement are given in Barnes *et al.* (2003)[1].

The feed is the element that determines the angular resolution. A typical corrugated feed has $\theta_{FWHM} \approx 10^\circ$ corresponding to a forward gain of ≈25 dBi. In any space mission, we consider it a requirement that both the reionization and at least the rise to the recombination peak in the B-mode spectrum be measured. The recombination peak is at the causal horizon at $z_{dec} = 1100$ and corresponds to $\ell = 90$ or $\theta \approx 2^\circ$. Figure 1 shows the scales. It would be far preferable to measure both peaks in one mission, but this cannot be done with the simple feed designs we have considered thus far.

In an effort to optimize the feeds, we ran the CCORHRN code, varying the profile, throat geometry, and grove spacing with an eye toward producing a robust design. We have found a 150 GHz design that is 49 cm long, has a 3.4 cm radius at the aperture, with $\theta_{FWHM} = 2.45^\circ$ and a VSWR is < 1.05 from 105-164 GHz. It has 1702 segments. We have designed a comparable profiled version that is just 29.5 cm long with input radius 3.9 cm. The design can be scaled to other frequencies.

We find that it is difficult to produce a reasonable length "bare" feed with $\theta_{FWHM} < 2.5^\circ$ at 150 GHz. Other options to consider are adding lenses, dielectric feeds, or dual frequency feeds.

There is a simple variant on the scheme described above. Instead of single large feeds, use multiple cross-Gregorians (or similar) telescopes of diameter $\approx$ 15 cm. Each mini telescope would then become the unit. Each could support a number of smaller feeds and would produce an array of beams on the sky. It is not as simple an optical system as the pure feed farm, and the packing of the telescopes is not as straightforward, but it has other advantages such as: there is much less mass to cool; the beam size could be tuned; and the design is more compact. The main disadvantage, however, is that the beams are no longer coaligned with the spin axis, though there may be telescope designs to ameliorate this.

4.2. Detectors

The detectors will not be a significant challenge for a feed-farm like concept. There is no need for detector arrays. At the base of each feed is one "detector unit." A detector unit is comprised of an OMT, stripline (or similar) filters, and bolometers. The bolometers are presumably semiconductors, TESs, MKIDS, or something similar. Various groups around the world are already building these units.

Unlike coherent systems, the basic unit still involves the dfference between two power detectors. The signals we seek are at the tens of nK level, and the background is the CMB at 3 K. Thus through modulation and spatio-temporal filtering one must ensure that power differences on the order of 1 in 10^8 are robust. This may require the addition of phase shifting in the detector unit but that is not yet clear. The stablity of space will be an enormous help here. A comparison may be made to WMAP which detects B-mode signals (from galactic foreground emission) at the μK level. The amplifier temperatures are $\sim$ 100 K and thus power differences are measured at a part in 10^8. However, WMAP relies on the coherent correlation of two inputs to get the first factor of $\sim 10^2$.

The TES detectors have been shown to be very stable with 1/f knees below 0.03 Hz, corresponding to a spin period of 33 seconds. In principle, if the detector unit were stable, spinning the spacecraft could provide the necessary modulation to get above the detector 1/f.

In a background limited system, one could expect to get NEQs of 40 $\mu\mathrm{K\,s}^{1/2}$ per feed (Bock *et al.* (2006)[2]). We assume this value in the plots given below. To achieve this will take 0.1 K cryogenics.

4.3. Layout & Scan

Polarization measurements are fundamentally different than temperature measurements. If the instrument were perfectly stable and the polarization measurement perfect (e.g., no temperature leakage, perfectly symmetric beams, no motion of the spacecraft etc.) one could measure the

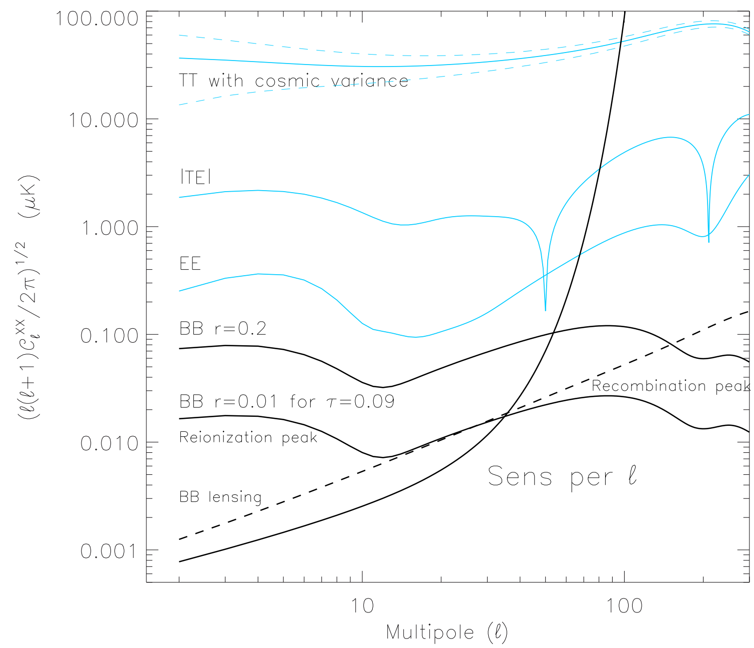

Figure 1. The CMB angular power spectrum at large angular scales. The top curves show the TT spectrum with the cosmic variance. The next one down shows the absolute value of the temperature polarization cross correlation. Next comes the EE spectrum. Below that are two versions of the BB spectrum, both for an optical depth of $\tau = 0.09$. The top curve has $r = 0.2$ (the current 95% upper limit, Komatsu *et al.* (2008) [3]) and the bottom one $r = 0.01$. The peak at $\ell \approx 5$ is due to reionization caused by the formation of the first stars. The peak at $\ell \approx 90$ corresponds to the causal horizon at the decoupling surface, B-modes inside the horizon are redshifted away with the expansion of the universe. The dashed line shows the B-modes due to lensing of the E-modes. The smooth line starting $\ell = 2$ and $(\ell(\ell+1))C_\ell/2\pi)^{1/2} = 8\times10^{-4}$ μK is the sensitivity per ℓ for 750 $\theta_{FWHM} = 2.4°$ feeds with an NEQ=40 μK s$^{1/2}$ observing 75% of the sky for one year.

polarization at each point and produce a map of the sky. No cross linking would be necessary. In reality no measurement is perfect and we suspect that one will want to measure the temperature anisotropy as well as the polarization anisotropy. In addition to the technical motivations, there are scientific motivations as well, such as searching for isocurvature modes and reionization through the TE correlation. The right balance between measuring T and E in the presence of foreground gradients and instrumental systematic errors may be determined with simulations. The approach we advocate, though, puts more emphasis on measuring the polarization in a single region of sky than on scanning the sky with uniform weighting.

In the feed farm, the feeds are mostly parallel with a few pointed off the spin axis by up to $\pm20°$. The off-axis feeds are for measuring the temperature anisotropy. The spacecraft spins at 2 RPM (4x WMAP) or at a frequency of ~ 0.3 Hz. Thus the measurement of the polarization along the spin axis is highly redundant.

In a 2.5 m diameter area, ~ 750 feeds may be fit. Higher frequency feeds can be nestled in between the 150 GHz feeds. If lower frequency bands are needed, they will have to have lower resolution or displace the 150 GHz feeds. Cold fingers are routinely run over 1.3 m distances and so such an area can be cooled. However, there is no doubt though that it will be a challenge.

J. Ruhl points out that the alignment of the feeds will be critical. Based on past experience, 1 arcmin is achievable. Simulations are needed to tell if this is good enough.

With such a design, the spin axis will have to be at 90° with respect to the earth sun line for some of the orbit. Using a simple ground screen and the Sommerfeld formula, we find that the sun can be shielded down to the 10 nK level. We view this as a proof-of-principle calculation. Greater rejection will be desired but this simple calculation suggests that the shielding is tractable. This also means that some "side mounted" solar panels will be needed.

Data rate: There is plenty of opportunity for on-board processing because of the large redundancy. The compound spin makes transmission difficult. Perhaps a 30 GHz transmitter is needed. This is a tough area but can probably be solved with enough DSN resources.

4.4. Orbit

Primarily because of its stability and geometry, the L2 orbit appears as a natural place for the feed farm. As with WMAP, some type of compound precession would seem beneficial, but the solution is not as straight forward. WMAP maintains a constant angle of insolation, leading to its remarkable thermal stability. With the feed farm requirement of observing at 90° with respect to the earth-sun line, this will not be possible. Since WMAP is passively cooled, the constant insolation angle is critical. The feed farm requires active cooling and so there may be some leeway. Again, simulations are needed.

5. Acknowledgments

We thank the organizers for a stimulating workshop on systematic errors in CMB polarization measurements.

6. References

[1] Barnes C, *et al.* 2002, *ApJS* **143** 567

[2] Bock J, *et al.* 2006, *Task Force on Cosmic Microwave Background Research*, or "The Weiss Report" arXiv:astro-ph/0604101

[3] Komatsu E, *et al.* 2008, Accepted in ApjS, arXiv0803.0547K

[4] Rahmat-Samii Y, Imbriale W, Galindo V, 1996 *Conical Corrugated Horn Analysis (CCORHRN)*, YRS Associates