Contents

1 Scientific, Technical, and Management Section

1.1 Baselines and Observables

We are proposing to study a probe-scale mission to extract the wealth of cosmological information contained in the spectrum and polarization of the cosmic microwave background (CMB). The starting points for our study of this CMB Probe are two current-decade space missions, EPIC-IM and Super-PIXIE [1, 2]. EPIC-IM was presented to the 2010 decadal panel as a candidate CMB imaging polarization space mission. It was based on a 1.4 m effective aperture telescope and 11,094 bolometric transition edge sensors. PIXIE is a proposed Explorer-scale mission focused on a measurement of the spectrum and polarization of the CMB on large angular scales. Super-PIXIE is envisioned to be a scaled up, more capable version of PIXIE. It consists of 4 spectrometers, each operating between 30 and 6000 GHz with 400 $\sim$15 GHz-wide bands. Improvements in technology by the next decade will enable the design of a mission that is more capable compared to EPIC-IM and Super-PIXIE. Therefore, all quantitative predictions presented in this proposal, which are based on EPIC-IM and Super-PIXIE, represent *minimum* capabilities for the CMB Probe.

The best measurements of the CMB spectrum – made by COBE/FIRAS approximately 25 years ago – show that the average CMB spectrum is consistent with that of a blackbody to an accuracy of 4 parts in 10^4 [3, 4]. Distortions in this spectrum encode a wealth of new information. The distortion shapes are commonly denoted as μ- and y-types [5, 6]. The μ-distortion arises from energy release in the early universe and can only be produced in the hot and dense environment present at high redshifts. This makes μ-distortions a novel messenger from a redshift range $z \geq 5 \times 10^4$. The y distortions are caused by energy exchange between CMB photons and free electrons through inverse Compton scattering. These originate at lower redshifts and are sensitive to the evolution of the large scale structure of the universe.

Thomson scattering at the surface of last scattering is the source of the polarization of the CMB. It is useful to decompose the polarization field to two modes that are independent over the full sky, E and B modes. Together with the pattern of temperature anisotropy T, the CMB thus gives three auto- and three cross-spectra. The *Planck* satellite and larger aperture ground-based instruments measured the T spectrum to cosmic variance limit for $\ell \leq 1500$. Much information remains encoded in the E and B spectra, whose full exploration has just begun [7, 8**? ?**].

A future CMB Probe-scale mission will address the physics of the big bang and of quantum gravity; it will measure the sum of the neutrino masses, and constrain the effective number of light particle species and the nature of dark matter; it will probe the existence of new forms of matter at the early universe; it will give new insights on the star-formation history across cosmic times, and it will provide information about the processes that control structure formation. In addressing these broad array of fundamental questions the Probe firmly fits into NASA's strategic plan as articulated by its Strategic Goal 1 "Expand the frontiers of knowledge", and specifically Objective 1.6 "Discover how the universe works, [and] explore how it began and evolved".

1.2 Science Objectives

1.2.1 The Primordial Universe and Cosmic Inflation

The observed temperature and E-mode polarization of the CMB imply the existence of primordial density perturbations generated long before recombination, providing a remarkable observational link to the dynamics of the universe near the big bang. Inflation, a primordial era of accelerated expansion, provides a compelling dynamical origin for the observed nearly scale-invariant spectrum of the primordial perturbations [9, 10, 11, 12, 13]. In addition to primordial density perturbations inflation predicts an as yet unobserved spectrum of primordial gravitational waves sourced directly by quantum fluctuations of the tensor component of the metric. These gravitational waves leave a distinct B-mode imprint on the polarization of the CMB. Any detection of degree-scale B-mode polarization, whether generated by the primordial gravitational waves of inflation [14, 15] or any other source of vector or tensor perturbations, would reveal completely new information about the primordial era. The results would either provide additional confirmation for current models or could overturn them. A detection would also have implications for fundamental physics by providing evidence for a new energy scale near the GUT scale. For example, in single-field inflation the potential energy V of the inflaton is related to the tensor-to-scalar ratio r by $V^{1/4} = 3.7 \times 10^{16}\, r^{1/4}$ GeV.

To test inflation, the largest scales $\ell \leq 10$ are particularly important because they reveal the presence of B-mode correlations on scales that were super-horizon at the time of recombination [17], and because the signal on large scales is strongest relative to the lensing B mode and instrumental noise. Figure 1 shows current CMB data, B modes from vacuum fluctuations of the metric during an inflationary era for two representative values of r, as well as forecasts for the determination of the CMB spectra for EPIC-IM and the lensing residual and noise.

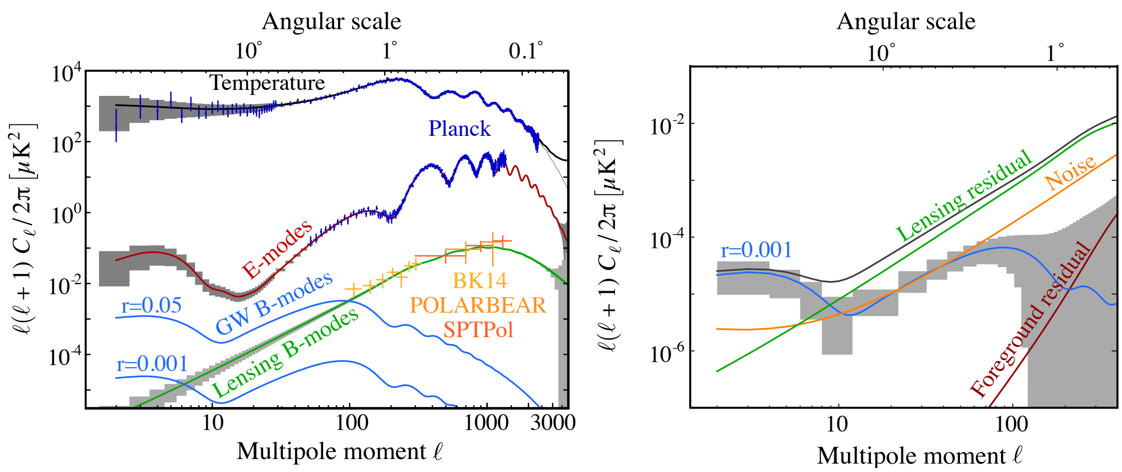


Figure 1: Predicted determination of the CMB power spectra for EPIC-IM (grey boxes) after foreground removal for $r = 0$ (left) and after foreground removal and delensing for $r = 0.001$ (right) overlaid on theoretical predictions (solid lines) and including Planck measurements of the temperature and E modes (dark blue) and of several ground-based measurements of the lensing B modes. The tensor B mode predictions (blue) are shown for two representative values of the tensor-to-scalar ratio: $r = 0.001$ and $r = 0.05$.

No sub-orbital platform has yet produced B mode measurements at $\ell < 40$, and a satellite is by far the most suitable platform for the all sky observations necessary to reach the lowest modes, $\ell < 20$. In its recent report New Worlds New Horizons (NWNH), the decadal survey committee strongly endorsed searches for B modes from inflation saying, "The convincing detection of B-mode polarization in the CMB produced in the epoch of reionization would represent a watershed discovery." [18].

In slow roll inflation there are only two classes of models that naturally explain the measured value of the spectral index n_s. One is the set of potentials $V(\phi) \propto \phi^p$, which contains many of the canonical inflation models. This set is already under significant observational pressure. If the error bars on the spectral index tighten by a factor of about 2, and the 95% C.L. upper limit on r is pushed to even ~ 0.01, all such models would be ruled out. The most recent constraint on the tensor-to-scalar ratio is $r < 0.07\,(95\%)$; see Figure 2 [16].

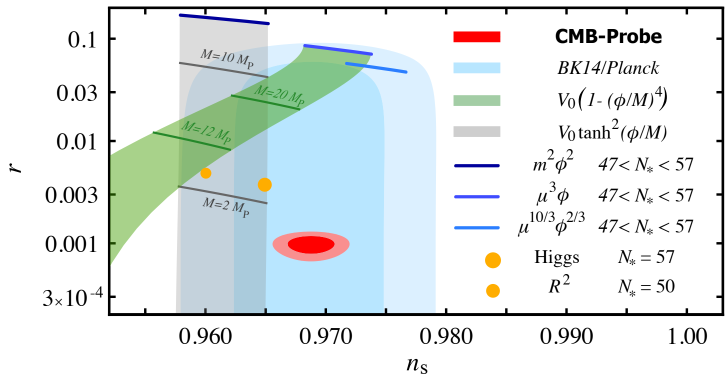


Figure 2: Current 1 and 2σ limits on r and n_s (blue) [16] and forecasted constraints for a fiducial model with $r = 0.001$ for EPIC-IM. Also shown are predictions for the models of the inflaton potential discussed in the text: Chaotic inflation (blue lines); Higgs and R^2 (large and small dots, respectively); quartic hilltop (green band); and a sub-class of α-attractor models [19]

The other class of models includes Starobinsky and Higgs inflation, which both have $r \sim 0.003$. A future mission capable of reaching $\sigma_r \sim \mathcal{O}(10^{-4})$ would provide significant constraints on virtually all models that naturally explain n_s. For a simple foreground model with spatially uniform spectral dependence assuming synchrotron emission that is well described by a power law and dust emission well characterized by a two-component model, EPIC-IM would achieve $\sigma(r) \sim 1.3 \times 10^{-4}$ assuming $r = 0.001$ and delensing with data from EPIC-IM itself.

A detection of B modes consistent with a primordial spectrum of vacuum fluctuations would be the first observation of a phenomenon directly related to quantum gravity. In addition, any detection with a next generation satellite would be evidence for *large-field* inflation [20], in which a smooth potential that supports inflation extends over a distance in field space $\Delta\phi \gtrsim M_p$. Studies of inflation in the context of quantum gravity give a generic expectation $\Delta\phi \lesssim M_p$ [21, 22, 23, 24], although there are some mechanisms to realize large-field inflation [25, 26, 27, 28]. A detection of r would therefore provide strong motivation to better understand how large-field inflation can be naturally incorporated into quantum gravity.

All inflation models predict a B mode spectrum with the shape shown in Figure 1, but inflation need not be correct [29, 30, 31] and does not preclude additional sources of B-mode polarization either during or after inflation. To be confident of the implications of a detection, the shape and Gaussianity of the B mode spectrum must be characterized. The vast majority of inflation scenarios predict an extremely Gaussian and nearly scale-invariant spectrum for gravitational waves. A target constraint of $\sigma(n_t) < 1$ at $r = 0.01$, easily achievable with a Probe mission, would significantly constrain non-vacuum inflationary sources [32, 33].

Deeper mapping of E-mode polarization will also test inflationary models. Large scale E modes will provide new tests of isotropy, a prediction of most models of inflation; for example, the observations can reject at 99% confidence models in which low multipoles are aligned in the temperature maps [34]. Together with continued improvements at high ℓ from the ground, these modes will also improve constraints on the scalar spectral index, its changes with scale, and on primordial non-Gaussianity by factors of about two.

Spectral distortion measurements give additional tests of inflation. The dissipation of small-scale perturbations through Silk-damping leads to μ-distortions [35, 36, 37, 38]. In ΛCDM the distortions are predicted at a level of $\mu = (2.0 \pm 0.14) \times 10^{-8}$, a level that is readily accessible to a Probe class mission, see Fig. 3 [38, 39]. A Probe may also give the sensitivity to detect the signature of recombination radiation imprinted by recombination of hydrogen and helium at redshift $z \simeq 10^3 - 10^4$; see Fig. 3 [40, 41]. The detailed physics is sensitive to the values of n_s, which is a direct probe of inflation.

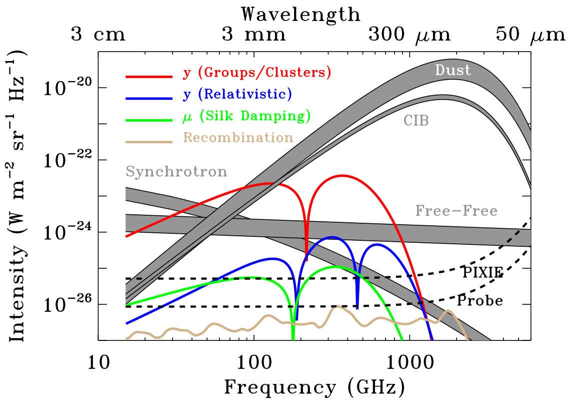


Figure 3: Anticipated y and μ spectral distortions (solid), the signature of resonant recombination lines (solid), and anticipated foreground signal levels relevant for spectral distortion measurements (grey bands). The simplest extension of a proposed Explorer class mission (Probe, dash grey) gives approximately 10 times the Explorer sensitivity (PIXIE). A better optimized Probe may give detections of all anticipated distortions.

1.2.2 Light Relics and Dark Matter

After inflation, the universe was reheated to temperatures of at least 10 MeV and perhaps as high as 10^{10} GeV. At these high temperatures, even very weakly interacting or very massive particles, such as those arising in extensions of the Standard model of particle physics, can be produced in large abundances [42, 43]. As the universe expands and cools, the particles fall out of equilibrium, leaving observable signatures in the CMB power spectra. Through these effects the CMB is a sensitive probe of neutrino and of other particles' properties.

One particularly compelling target is the effective number of light relic particle species $N_{\rm eff}$, also called the effective number of neutrinos. The canonical value with three neutrino families is $N_{\rm eff} = 3.046$. Additional light particles contribute a change to $N_{\rm eff}$ of $\Delta N_{\rm eff} \geq 0.027\, g$ where $g \geq 1$ is the number of degrees of freedom of the new particle [44, 45]. This defines a target of $\sigma(N_{\rm eff}) < 0.027$ for future CMB observations. Either a limit or detection of $\Delta N_{\rm eff}$ at this level would provide powerful insights into the basic constituents of matter.

Forecasts for $N_{\rm eff}$ are shown in Figure 4. The two most important parameters for improving constraints are the fraction of sky observed $f_{\rm sky}$ and the noise. Achieving both larger $f_{\rm sky}$ and lower noise are strengths of the CMB Probe compared to other platforms. Our baseline mission nearly reaches the target constraint with $g = 1$, already exceeding constraints from other astrophysical probes and planned CMB observations. A newly designed mission is could reach $\sigma(N_{\rm eff}) < 0.027$ and provide a window back to the time of reheating.

Many light relics of the early universe are not stable. They decay, leaving faint evidence of their past existence on other tracers. The relics with sufficiently long lifetime to survive few minutes, past the epoch of light element synthesis, leave a signature on the helium fraction Y_p. If they decay by the time of recombination, their existence through this period is best measured through the ratio of $N_{\rm eff}$ to Y_p. The Probe's cosmic variance limited determination of the E-mode power spectra will improve current limits for these quantities by a factor of five thus eliminating sub-MeV mass thermal relics. Spectrum distortion measurements give additional constraints on the lifetime and abundance of such relics [47, 48, 49, 50]. A future Probe's μ-distortion constraint gives a two orders of magnitude improvement on the abundance and lifetime of early universe relics [51, 52] compared to current constraints derived from measurements of light element abundances [53, 54].

Cosmological measurements have already confirmed the existence of one relic that lies beyond the Standard Model: dark matter. For a conventional WIMP candidate, the CMB places very stringent constraints on its properties through the signature of its annihilation on the T and E spectra [55, 56, 57]. Planck currently excludes WIMPs with mass $m_{\rm dm} < 16$ GeV and a future CMB mission could reach $m_{\rm dm} < 45$ GeV for $f_{\rm sky} = 0.8$. The CMB provides the most stringent constraints on the dark matter annihilation cross section for dark matter in this mass range. The

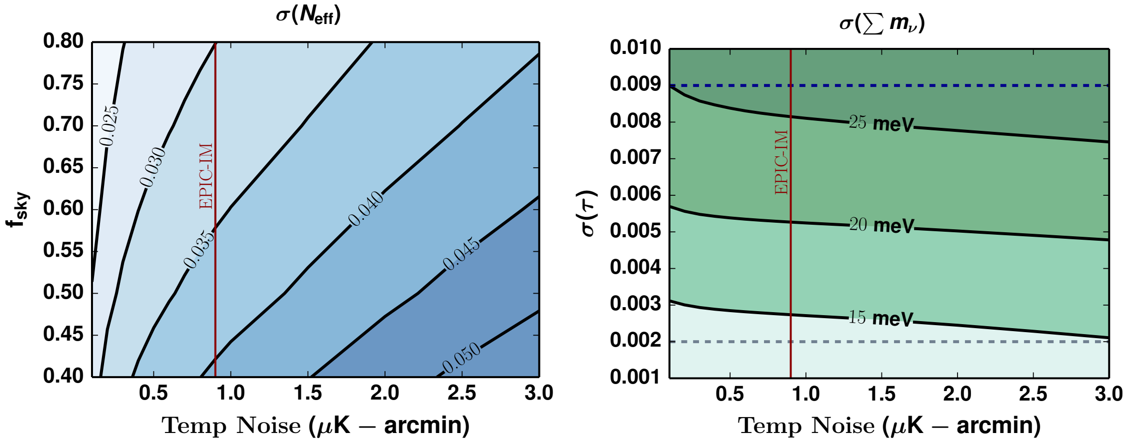


Figure 4: $N_{\rm eff}$ as a function of noise and sky fraction (left) and Neutrino mass constraints as a function of uncertainties in measurement of τ, noise, and sky fraction of $f_{\rm sky} = 0.7$. The resolution assumed is 5'. Vertical lines denote the expected performance of EPIC-IM. The blue dashed line is the current *Planck* limit; the grey dashed line is the limit from cosmic variance measurement of τ. All forecasts assume internal delensing of the T and E-maps [46], including residual non-Gaussian covariances. The $\sum m_\nu$ forecasts include DESI BAO.

CMB is complimentary to direct detection experiments which probe the scattering cross-section of dark matter with Standard model particles.

A particle-independent approach is to constrain dark matter interactions that would affect the evolution of the effective dark matter fluid and its interactions with baryons or photons. The simplest example is to constrain the baryon-dark matter cross section through its effective coupling of the two fluids [58]. These couplings affect the evolution of fluctuations and ultimately the T and E spectra. The current limits of $\sigma \gtrsim 10^{-31} - 10^{-34}\,{\rm cm}^2 \times (m_{\rm dm}/{\rm MeV})$ can be competitive with direct detection for sub-GeV masses. More exotic dark sectors that include long-range forces can produce an even richer phenomenology in the CMB and in the large-scale structure without necessarily producing an associated signature in direct detection experiments or indirect searches (e.g. [59, 60, 61]).

Interactions of dark matter with standard model particles can also be constrained through measurements of spectral distortions [62]. Current constraints from FIRAS are most sensitive to small dark matter mass, $m_{\rm X} \lesssim 0.2\,{\rm MeV}$, but these could be extended to $m_{\rm X} \lesssim 1\,{\rm GeV}$ with a Probe-class mission, testing DM interaction down to cross-sections $\sigma \simeq 10^{-39} - 10^{-35}\,{\rm cm}^2$ [62]. This provides new constraints on the low mass end, $m_{\rm X} \lesssim 10\,{\rm MeV}$ and improve existing limits [63, 64] by up to a factor of $\simeq 50$. Distortion measurements furthermore open a new avenue for testing dark matter-proton interactions [62].

A host of other physical phenomena including the existence and properties of axions, primordial magnetic fields, and superconducting strings, leave signatures on the spectrum of the CMB and can therefore be constrained by the sensitive measurements of a future Probe [e.g., 65, 66, 67, 68, 69].

1.2.3 Neutrino Mass

One of the last unknowns of the Standard model of particle physics is the absolute mass scale of the neutrinos. Cosmology presents a unique opportunity to measure the sum of neutrino masses $\sum m_\nu$ through the suppression of the growth of structures in the universe on small scales. The sensitivity to $\sum m_\nu$ from suppression of power is limited by our knowledge of the primordial amplitude of fluctuations A_s, which is strongly degenerate with the optical depth τ. The current limit on τ from *Planck* of $\sigma(\tau) = 0.009$ [70] limits $\sigma(\sum m_\nu) \gtrsim 25$ meV. Forcasts for an internal CMB measurement of $\sum m_\nu$ via CMB lensing [71] are shown Figure 4 but the conclusion is the same for any proposed cosmological probe. Therefore, a cosmological detection of the minimum value expected from particle physics $\sum m_\nu = 58$ meV at more than 2σ will require a better measurement of τ. The best constraints on τ come from E modes with $\ell < 20$ which require measurements over the largest angular scales. To date, the only proven method for such a measurement is from space. The CMB Probe will reach the cosmic variance limit of $\tau \sim 0.002$ and will therefore reach $\sigma(\sum m_\nu) < 15$ meV when combined with DESI's measurements of baryon acoustic oscillations [72]. A detection of $\sum m_\nu$ at this level is not possible with any other existing survey.

1.2.4 Cosmological structure formation

Understanding the evolution of cosmological structures from small density perturbations through the formation of the first stars to present day galaxies and cluster is a key goal of cosmology [73]. Cosmological reionization, the transition of the universe from dominated by neutral to ionized hydrogen, is a cornerstone of this evolution because it encodes information about the star formation history and the physical processes that formed the galaxies of various luminosities and masses we see today. But when did the epoch of reionization start? How long did it last? Are early galaxies enough to reionize the entire universe or is another source required?

Measurements of the CMB E-mode power spectrum over large angular scales are sensitive to the optical depth to reionization τ, a key parameter for all reionization models that attempt to answer these questions. The *Planck* team reported recently a value of $\tau = 0.055 \pm 0.009$ [70, 74]. The level is significantly lower than previous estimates and reduces the tension between CMB-based analyses and constraints from other astrophysical sources. The CMB Probe's cosmic variance limited measurement of E-mode polarization will improve the 1σ error by a factor of 4.5 to reach a cosmic variance limited measurement of τ, thus setting stringent constraints on models of the reionization epoch.

The anisotropy in the cosmic infrared background (CIB) produced by dusty star-forming galaxies in a wide redshift range, are an excellent probe of both the history of star formation and the link between galaxies and dark matter across cosmic time. The *Planck* collaboration derived values of the star formation rate that, at redshifts z~ 3, are three times larger than constraints from number counts measurements ([75, 76, 77]). By measuring CIB anisotropy with 100 times higher signal-to-noise ratio the CMB Probe will shed light on this intriguing discrepancy. Specifically, it will constrain the star formation rate with one tenth of *Planck*'s uncertainty.

A key parameter in simulations of the angular power spectrum of the CIB is $M_{\rm eff}$, the galaxy halo mass that is most efficient in producing star formation activity. Comparing measurements of the power spectrum to simulations constrains this parameter, which informs structure formation models. Current models and measurements find $M_{\rm eff} \sim 10^{12}$ solar masses with about 10% uncertainty. The CMB Probe will constrain this parameter at the percent level.

Reionization of the universe and the onset of structure formation inject energy into the sea of CMB photons. This injection is detectable through a distinct spectral distortion. This is the largest expected distortion – marked 'y Groups/Clusters' in Figure 3 – and will be clearly detected by the CMB Probe. A detection will give information about the total energy output of the first stars, AGNs, and galaxy clusters, an important parameter in structure formation models.

Group-size clusters that have masses $M \simeq 10^{13}\, M_\odot$ contribute significantly to the signal. With temperature $kT_{\rm e} \simeq 1\,{\rm keV}$ these are sufficiently hot to create a relativistic temperature correction to the large y-distortion. This relativistic correction, denoted 'y relativistic' in Figure 3, will also be detected with high signal-to-noise ratio by the CMB Probe, and will be used to constrain the currently uncertain feedback mechanisms used in hydrodynamical simulations of cosmic structure formation [78].

The CMB spectrum varies spatially across the sky. One source of such anisotropic distortion is due to the spatial distribution clusters of galaxies and has already been measured by Planck [79]. A combination of precise CMB imaging and spectroscopic measurements will allow observing the relativistic temperature correction of individual SZ clusters [80, 81, 82], which will calibrate cluster scaling relations and inform our knowledge of the dynamical state of the cluster atmosphere.

Resonant scattering of the CMB photons during and post last scattering leads to spectral-spatial signals that can be used to constrain the abundance of metals in the dark ages and therefore the make-up of the first, and subsequent generations of stars [83, 84, 85, 86, 87].

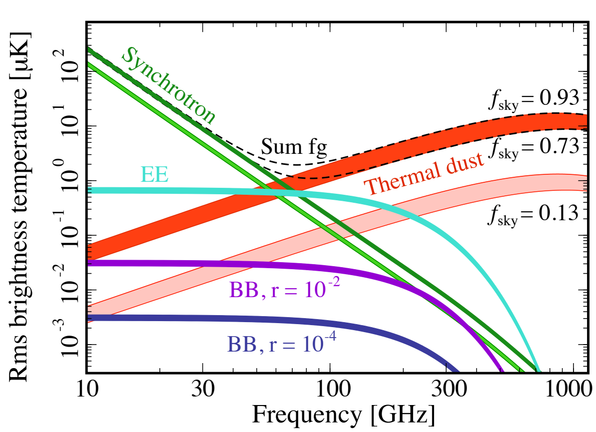
1.3 The Challenges: Foregrounds and Systematics

The search for primordial B modes poses the most stringent requirements on foreground removal and control of systematic effects. A tentative target for the CMB Probe is to constrain the tensor-to-scalar ratio with an uncertainty that is a factor of 100 smaller than the current upper limit $r < 0.07$ at 95% CL, that is, to reach $\sigma(r) \lesssim 0.0003$. According to data from *Planck* and sub-orbital experiments, foregrounds currently already dominate the signal. A 100-fold improvement on the final error will require exquisite measurements and modeling of foregrounds.

To ascertain that the uncertainty on the measurement of r is dominated by statistical rather than systematic error, the mission design, execution, and data analysis will have to be dominated by the need to control systematic uncertainties to unprecedented, and not yet achieved, levels.

1.3.1 Foregrounds

Whereas the CMB temperature anisotropy signal dominates Galactic sources of emission over much of the sky, this is not the case for polarization. Figure 5 compares the expected RMS brightness temperature of polarized emission from Galactic sources to E and B modes as a function of frequency and gives the expected signal levels as a function of angular scale ℓ.



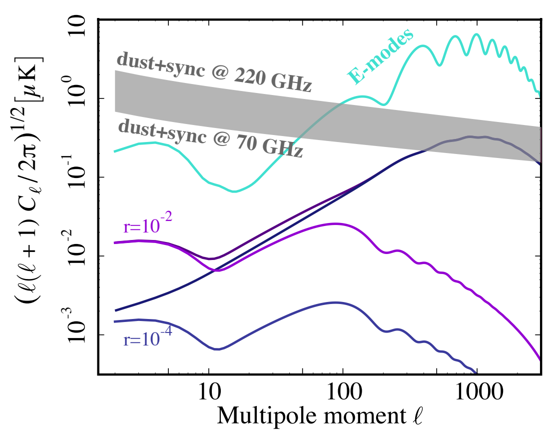


Figure 5: *Left:* Brightness temperature as function of frequency for the polarized CMB (cyan, purple, blue) and Galactic foreground signals: dust (red) and synchrotron (green). The darker bands correspond to sky fractions between 73% and 93%; the lighter bands to the cleanest 13%, with the width indicating the uncertainty. *Right:* Angular power spectrum for E-mode polarization and B-mode polarization for $r = 10^{-2}$ and $r = 10^{-4}$, and for foreground emission between 70 and 220 GHz.

The conclusions are that:

- over the largest angular scales (lowest ℓs), which are crucial for a range of science goals and where inflationary B modes would be largest relative to those from lensing and instrument noise, foreground sources of confusion will need to be measured and subtracted to a level better than 1 part in 10 for E and in 100 for B;
- foregrounds dominate the potential inflationary B mode signal on *all* angular scales by an order of magnitude or more.

Known signals can be accounted for and removed with multi-frequency observations even if their amplitude is large. But the best measurements to date, from *Planck*, fall far short of the fidelity envisioned for the Probe. This is visually demonstrated by Figure 6, which compares the level of B modes at low ℓ for $r = 0.001$ to the *Planck* 353 GHz noise, extrapolated to 150 GHz, a frequency band in which the signal is among the strongest.

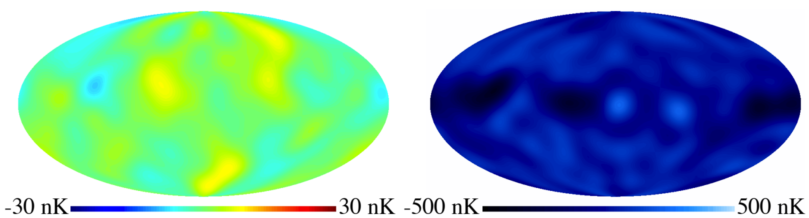


Figure 6: *Left:* Stokes Q for inflationary B modes for $\ell < 12$ and $r = 0.001$. *Right:* Noise in the $Planck$ 353 GHz map of Stokes Q for $\ell < 12$ extrapolated to 150 GHz assuming the (sky average) spectral properties of dust.

Removal of foregrounds based on multi-frequency data in a number of frequency bands relies on extrapolations between frequencies based on an assumed spectral dependence. At the current level of precision a power law dependence for synchrotron radiation and a modified black body spectrum for dust emission provide a reasonable fit to CMB data. At the level of precision required for a probe mission, this description will no longer be sufficient. The complex composition of dust leads to departures from a simple modified black body spectrum because different components may emit at different temperatures. The different components are in general not perfectly correlated with each other, leading to decorrelation between frequency bands. Furthermore, the spectral dependence of synchrotron and dust emission is spatially varying. The spectral dependence must ultimately be measured with the Probe mission. The challenge is to design the frequency coverage to do so optimally.

While the search for primordial B modes leads to the strictest constraints on foreground residuals, exquisite control of foregrounds is also necessary for the other science objectives. Detailed information about the reionization history, available by a cosmic variance limited measurement of the E power spectrum, is buried below the foregrounds at $\ell < 10$. In addition, one must understand the foreground requirements to successfully delens the data at the required level. Recovering *all* of the spectral distortions signals from the raw data will require proper accounting for emission by dust grains, synchrotron emission from electrons spiraling in the Galactic magnetic field, Coulomb scattering of charged particles ('free-free') (see Figure 3), as well as anomalous microwave emission and CO emission.

1.3.2 Systematic Errors

The latest experience with *Planck* points to the following systematic error categories likely to be important for the CMB Probe, or for that matter, for any instrument striving to map the polarization over large portions of the sky to the levels targeted by the CMB Probe [70]: 1. Intensity-to-polarization leakage, 2. stability, and 3. straylight. Each of these is considered in light of polarimetry measurements through differencing the signals of two detectors that are sensitive to orthogonal polarization states.

Leakage The CMB anisotropy signal is a factor of 1000 larger than the strongest possible inflationary B modes (see for example Fig. 1). Therefore instrumental effects that can leak even a small fraction of an intensity fluctuation into spurious polarization and must be understood and controlled. The main effects are differences between gains of detectors, their frequency bandpass mismatch, their differential pointing on the sky, and their differential antenna patterns. Currently, the most sensitive sub-orbital experiments have shown control of systematics at a level of $r \lesssim 0.006$; approximately half of the contribution was from intensity to polarization leakage [**?**]. These differential effects need to be controlled, through instrument design, characterization, and data analysis to levels that are another factor of 10-100 more stringent so that the contributions of systematic uncertainties to the Probe's total error budget is negligible.

Leakage-related effects will drive: requirements on the optical system, and the uniformity of the bandpass of each polarimeter; calibration requirements on the level of cross-polar leakage and its angle; and measurements of the the beam shape as a function of source spectrum. These systematic effects can potentially be mitigated by modulation of the sky signal in such a way that allows complete reconstruction of the polarized sky signal using each photometer, for example, using a half-wave plate.

Stability. The reconstruction of deep, full sky polarization maps involves a combination of measurements made at times separated by months, requiring stability of the response of the instrument on corresponding time scales. Random deviations from stability are a source of noise; systematic deviations are a source of systematic error. This type of systematic error puts requirements on control of thermal drifts of spacecraft temperatures, to mitigate thermal emissivity changes and thermoelastic deformation of telescope structures. The cryogenic operating temperatures of detectors or reference calibration loads must be controlled adequately as well. Careful design of the scan strategy can shorten the time scales needed for stringent stability, for example Planck's scan strategy traced out great circles which overlapped on 1 minute timescales, giving a shorter effective time scale for stability requirements.

The spacecraft's ambient radiation environment is modulated by the solar activity and can introduce temperature drifts in the cryogenic stages and lead to correlated transients in detectors and readout electronics. For example, cosmic ray energy deposition in the Planck/HFI focal plane was a source of correlated noise between detectors and created a factor $\sim$5 additional noise at ℓ=2 [70]. The design of the instrument must account for these effects.

Straylight. When the brightest sources in the sky – the Sun, Moon, planets, and Galaxy – are passing through the far sidelobes of the telescope they create a spurious polarization signal. If they are passing in repeated, scan synchronous pattern, the spurious signal becomes a source of systematic error. This far sidelobe response can be reduced through careful optical design and baffling, but will always be present at a non-trivial level. Detailed modeling of the *Planck* telescope, convolved with sky sources, gave a predicted sidelobe contamination at a detectable level of tens of micro-Kelvin in the 30 GHz maps. This contamination has been observed in *Planck* difference maps. As a result an estimate of the sidelobe contamination was removed from some of the *Planck* time ordered data as part of the mapmaking process. The more stringent requirements for CMB-probe will necessitate at least this level of mitigation.

1.4 The CMB Probe in Context

1.4.1 Current and Forthcoming Sub-Orbital Efforts

The remarkable forthcoming scientific yield has motivated significant agency investments in current and future sub-orbital experiments which are designed to realize the full potential of this unique probe of fundamental physics and astrophysics. These experiments are designed to exploit the comparative advantages of the sub-orbital platforms, while providing the design heritage and experience necessary to maximize the probability of success of an orbital mission.

For the ground-based efforts, these include combinations of *i)* provision for large apertures and therefore high angular resolution, *ii)* flexibility to rapidly deploy new technologies, and *iii)* allowance for detector formats that are relatively unconstrained by mass and power limitations. To date, these have demonstrated low noise measurements of small and intermediate angular scale E and B polarization structures over less than 2% fractional areas of the sky.

The balloon-borne missions *i)* extend the frequency reach of the ground based telescopes, *ii)* enable high fidelity measurements on larger angular scales than can be probed from the ground, and *iii)* grant access to an environment with similar requirements and constraints as in orbit, providing heritage for future space missions as well as experience in dealing with the analysis of data that are representative of a space mission. In this way, the sub-orbital programs complement and multiply the scientific return of the proposed orbital mission, while reinforcing its technical preparedness.

The 2010 Decadal Panel strongly recommended supporting sub-orbital efforts in preparation for a possible space mission to follow sub-orbital detections of inflationary gravity waves. As a result, the US has clear leadership in the field, both in terms of ground- and balloon-based experiments and results.

This leadership will continue into the foreseeable future. In aggregate, funded, now-being-built 'Stage 3' CMB experiments will deploy approximately 100,000 detectors on various sub-orbital experiments within the next 3-5 years. Ground-based experiments plan to extend measurements from few percent of the sky to few tens, although in a limited frequency range between 30 and 300 GHz. Balloon-borne payloads operating at even higher frequencies strive to cover even larger fractions.

1.4.2 Proposed Efforts: LiteBIRD, COrE, and CMB-S4

Japan, in collaboration with NASA, is now considering whether to proceed with LiteBIRD, a space mission designed to search for B modes from inflation. The US Team has submitted its Phase A report to NASA; Phase A in Japan will conclude in about a year check. LiteBIRD is a smaller, more focused mission compared to the CMB Probe. It is an imager based on a 0.4 m aperture telescope. Therefore it has a resolution 3.5 times lower compared to the 1.4 m aperture of EPIC-IM. Its reach in ℓ space is correspondingly 3.5 times lower making the science available at ℓ's above few hundred in both E and B modes unreachable. It has no spectroscopic capabilities and thus not sensitive to any of the spectral distortion science goals.

For the Japanese space agency JAXA, LiteBIRD is meant to fit within the $300M class of missions. Although there are uncertainties about comparing JAXA's cost calculations to NASA's, LiteBIRD's overall size and more limited science reach is commensurate with it being below, or just at the lower margin of the Probe's cost window.

A collaboration of scientists in Europe has just recently proposed COrE to ESA as part of the M5 round of space mission proposals. The team includes a number of US collaborators; the PI of this proposal is a member of COrE's Executive Board. COrE is a CMB polarization imager that is based on a 1.2 m aperture telescope and thus intended to reach 3 times the resolution of LiteBIRD. It will reach a resolution of 5-10 arcmin in the 100-200 GHz bands. ESA has capped the M5 proposals to EU550M, the equivalent of $610M. Member countries are expected to contribute an additional ∼$150M making the total cost close to $750M. Selection of missions for Phase A studies is expected in June 2017, and end of Phase A in summer 2019.

The US CMB community has proposed, and the Particle Physics Project Prioritization Panel (P5) has recommended to the DOE, the establishment of a 4th generation CMB experiment called CMB-S4. This is an ambitious program to field approximately 5 times the number of detectors fielded by Stage 3 experiments. If and when funded, CMB-S4 will enable unprecedented sensitivity at frequency bands accessible from the ground, and with telescopes that enable high resolution.

1.4.3 Why Study a CMB Probe?

Learning from the successes of COBE/FIRAS, COBE/DMR, WMAP, and *Planck*, a CMB Probe is the single most suitable vehicle to deliver complete sky coverage and therefore information on the largest angular scales, comprehensive frequency coverage, and exquisite control of systematic effects. Some of the science goals described in Section 1.2 are reachable only through mapping of the largest angular scales. No sub-orbital experiment has yet produced any polarization results on more than 2% of the sky, let alone on scales requiring 70% of the sky. The broad frequency coverage of the space mission is best suited to mitigate the foregrounds expected on a broad range of angular scales, including those important for removing the effects of B-modes from lensing. The mission will provide a single self-consistent and self-calibrated data set; and it will provide legacy maps at many frequency bands that will become the basis for hundreds of new papers.

If the inflationary signal is detected by sub-orbital experiments any time soon, a space mission to characterize the signal in full detail is equally compelling. The existence of ambitious sub-orbital programs is a complementary strength. How to make the best use of this complementarity is an explicit goal of our study; see Section 1.6.

1.4.4 Does the CMB Probe Fit Within the Cost Window?

The total cost estimate for the EPIC-IM mission, as generated by JPL's Team X, was $920M in 2009 []. The mission had a 1.4 m effective entrance aperture. When the mission was assessed by the 2010 Decadal Panel, the independent cost estimate was $1200M check. The COrE mission, that had just been proposed to ESA and has an aperture of 1.2 m, was estimated by the proposing team to have a total cost $773M. The cost estimate for LiteBIRD, which has a 0.5 m aperture, is within the $300M class.

When NASA proposed to initiate studies for next-decade flagship missions that had a cost exceeding $1B there was consensus within the CMB community that a compelling CMB mission can be constructed for less than this amount. The aperture size and science goals we are envisioning for the CMB mission are most akin to EPIC-IM and COrE and we therefore believe it fits within the Probe class.

1.4.5 This Study in the Context of Previous Mission Studies

The EPIC-IM summary paper and a report to the decadal panel from a NASA mission study, both from 2009, represent the US community's most recent view of the anticipated science reach and the path to implementation of a possible future US space mission. The landscape has changed since. There is a need to present an updated view to the next decadal panel.

Theoretical advances and progress in physics and astrophysics gave updated goals for the fidelity of measurements of E and B modes, including measurements of inflationary gravitational waves, the properties of light relics, and structure formation in the universe. A slew of sub-orbital experiments together with the *Planck* mission have transformed our view of the mm-wave polarized sky, highlighting the requirement on thorough understanding of the foregrounds. Advances in detector technologies, multiplexed readouts, and optical components now enable a significantly more capable mission than the one envisioned ten years ago. And the community has vastly more experience with designs of polarimeters and the control of their systematic uncertainties. A new study, based on this accumulated information and experience, is timely; this is the study we are proposing here.

The US LiteBIRD team has proposed participation in LiteBIRD and recently generated its Phase A report. The proposal and report were conducted by a subset of the community for the purpose of supporting a specific mission design, within specific cost caps, that match JAXA plans.

Work on our proposal, and the subsequent mission study, represent a collaborative effort by all interested members of the CMB community, including US members of the LiteBIRD team. We have also reached out to our international partners and invited them to participate. The final report will present a consensus view of the US CMB community. This would be the proper input for the deliberations of the next US decadal panel.

1.5 State of Technologies

2 pages. Discuss the technologies, their TRL, and what will be studied

1.6 Mission Study and Management Plan

1.6.1 Study Plan

The mission study is open to the entire CMB community and includes more than 50 scientists. To gain maximum benefit from *Planck*, LiteBIRD, and CORE we invited international members to participate. The work is organized into Working Groups (WG) that represent each of the main themes of the study; see Figure 7. Working groups are led by members of the study's Executive Committee, as listed in the Figure. Although Figure 7 suggests distinct boundaries between the WGs we expect and encourage significant overlap and feedback. It is not practical to enumerate all the interdependencies.

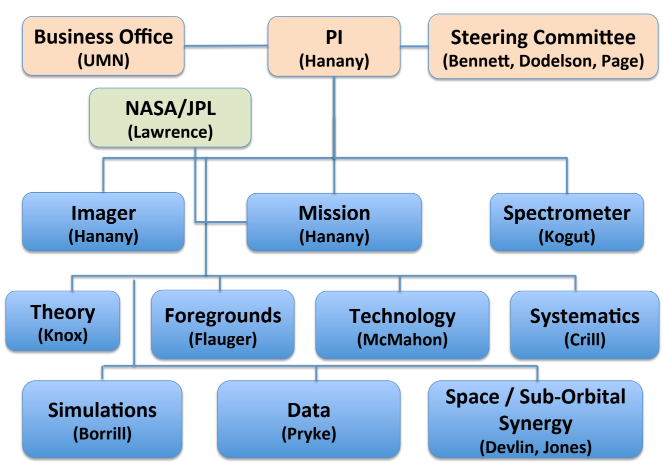


Figure 7: Management structure of the CMB Probe. A steering committee advises the PI. The study is led by the PI through an Executive Committee. Each member of the committee is in charge of a specific Working Group (blue boxes). Significant overlap and feedback is expected between the working groups. Participation in the Working Groups is open to all members of the CMB community.

The study will be carried out through intra- and inter-WG teleconferences; mission design teleconference with JPL engineers; mission design meetings at JPL; and a community workshop that is described in more detail below under the 'Space / Sub-Orbital Synergy' WG. We now describe the planned work for each of the WG.

• **Theory (Knox)** This WG will survey, summarize, and prioritize the set of science goals for the Probe. Given input on target frequency bands, assumptions about foregrounds, instrument systematics, and instrument noise levels the group will generate forecasts for the impact of the Probes products and their ultimate significance for physics and astrophysics. This group will also investigate how to optimally combine and cross-correlate the Probe's data with other data sets. This is an area of strong overlap with the Data and Foreground WGs.

• **Mission (Hanany) and connection with JPL (Lawrence)** The Mission WG is responsible for defining the overall mission architecture including telescope implementation, cooling, telemetry, mass, power, and cost. The WG will work closely with the JPL lead scientist (Lawrence) and JPL mission engineers.

• **Imager (Hanany) and Spectrometer (Kogut)** The imager and spectrometer WGs will translate the science goals to mission requirements and to a set of optional designs. The designs will include telescopes of various configurations, focal planes with several candidate detector technologies and readout schemes, optical elements, and cooling strategies. These groups will similarly consider the options for spectrometers. Both groups will interact frequency and work closely with the Mission WG and with the JPL team to assess the relative merits of the designs. The WG will consider an imager-only design, a spectrometer-only design, and a combined instrument.

• **Technology (McMahon)**

• **Space / Sub-Orbital Synergy (Devlin, Jones)** By the time the CMB probe is likely to fly, significant advances will have been made on the ground. This is true regardless of the state of the proposed CMB-S4 effort, and even more so should funding for S4 becomes available soon. This WG will assess and recommend the most appropriate design parameters such that the data sets from the Probe and sub-orbital measurements complement each other. Pertinent questions include: to what extent should the aperture size of the Imaging Probe rely on delensing capabilities provided by high resolution measurements from the ground? What is the optimal resolution of a space-based mission from the point of view of providing foreground subtraction capabilities to sub-orbital missions? What is an optimal overlap in ℓ-space coverage? Does the design of a spectrometer depend on the specifics of data available from sub-orbital measurements?

We are planning a community workshop to address these question, including forming a community consensus on the question of the need for a space mission if CMB-S4 is funded.

• **Data Analysis and Exploitation (Pryke)** The full sky nature, the broad frequency coverage, and the high sensitivity of the CMB-Probe will generate a legacy data set surpassing that of *Planck*. This WG will plan for the extraction of cosmological and astrophysical products from the Probe's data. This includes exploring component separation techniques and the resulting core science analysis performance, as well as exploring synergies with sub-orbital measurements at CMB frequencies and cross-correlations with orbital and sub-orbital data at other wavelengths. It will assess whether specific synergies suggest preferring some mission parameter values over others. Examples include adjusting the resolution, and frequency coverage.

• **Systematics (Crill)** This WG plans to build an end-to-end simulation pipeline that will generate simulated measurements at an instrumental level, and feed them into the notional analysis pipeline, including foreground/CMB component separation and power spectral analysis. With this simulation pipeline the WG will explore mitigation of systematic errors by design, for example implementing modulation schemes and modulator technologies, and mitigation of systematic errors by analysis techniques. This pipeline will be used to define requirements for a notional mission, and would be helpful in prioritizing the Probe's technology development needs.

• **Foregrounds (Flauger)** High fidelity measurement and subtraction of foregrounds will permeate all aspects of the study plan. This WG will construct foregrounds models that encompass all the known and expected emission complexities. The models will be informed by physical inputs [**? ?**] and measurements, for example the spatial variations of the spectral dependence, decorrelation between frequencies, and departures from a simple modified black body law for galactic dust [**?**]. The models will be inputs for the process of instrument optimization and for tests of algorithms for foreground removal. During instrument optimization they will inform an optimal selection for the number of frequency bands, their central frequencies and bandwidths, all subject to the constraint of finite focal plane area. This optimization is also informed by choices of detector technology. To carry out exercises in foreground subtraction, we will implement a simulation pipeline that will test the efficacy of different component separation methods including Commander, SMICA, SEVEM and NILC, which have been used with the *Planck* data [**?**]. The WG will extract cosmological and astrophysical information from the component maps and their power spectra, and compare to the input values to assess the residual errors. During this stage too, we will benefit from the experience of the *Planck* data including its use of specific power spectral and parameter estimation approaches (e.g. Master [], XFaster [], and CosmoMC []).

• **Simulations (Borrill)**

1.6.2 Study Team

The study consists of more than 50 scientists representing hundreds of years of experience with CMB theory, data analysis, and measurements on all platforms including satellite missions that have already flown (WMAP, and *Planck*) and the two proposed (LiteBIRD and CORE). The PI Hanany, who has more than 20 years of CMB ballooning experience, co-led MAXIMA and Archeops, was the PI of MAXIPOL and EBEX, and is a member of CORE's Executive Board, will have ultimate responsibility for the study. He is advised by a Steering Committee – Bennett (Johns Hopkins), Dodelson (Chicago), and Page (Princeton) – and assisted by a business office at the University of Minnesota. An Executive Committee (EC) is in charge of the daily operation of the collaboration. The members of the Steering and Executive Committees led and are leading operating CMB experiments that have produced the most compelling CMB polarization results. They include leaders and members of the WMAP, US *Planck*, US LiteBIRD, and US CORE teams. They include initiators and implementors of new millimeter-wave technologies, and of recognized experts in data analysis and theory.

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2 Curriculum Vitae

3 Summary of Work Effort

4 Current and Pending Support

5 Letters of Support

6 Budget Details - Narrative

6.1 Team, and Work Effort

6.1.1 Funded Team Members

6.1.2 Non-Funded Team Members

6.2 Costing Principles

- **Summer Salaries:**
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6.3 University of Minnesota Budget

6.3.1 Direct Labor

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6.3.4 Other Direct Costs

Publications and Teleconferencing
Other Subcontracts

6.3.5 Facilities and Administrative Costs

7 Budget Sheets

ACS attitude control system

ADC analog-to-digital converters

ADS attitude determination software

AHWP achromatic half-wave plate

AMC Advanced Motion Controls

ARC anti-reflection coatings

ATA advanced technology attachment

BRC bolometer readout crates

BLAST Balloon-borne Large-Aperture Submillimeter Telescope

CANbus controller area network bus

CIB cosmic infrared background

CMB cosmic microwave background

CMM coordinate measurement machine

CSBF Columbia Scientific Balloon Facility

CCD charge coupled device

DAC digital-to-analog converters

DASI Degree Angular Scale Interferometer

dGPS differential global positioning system

DfMUX digital frequency domain multiplexer

DLFOV diffraction limited field of view

DSP digital signal processing

EBEX E and B Experiment

EBEX2013 EBEX2013

ELIS EBEX low inductance striplines

ETC EBEX test cryostat

FDM frequency domain multiplexing

FPGA field programmable gate array

FCP flight control program

FOV field of view

FWHM full width half maximum

GPS global positioning system

HDPE high density polyethylene

HIM high index materials

HWP half-wave plate

IA integrated attitude

IP instrumental polarization

JSON JavaScript Object Notation

LDB long duration balloon

LED light emitting diode

LCS liquid cooling system

LC inductor and capacitor

LZH Lazer Zentrum Hannover

MCP multi-color pixel

MSM millimeter and sub-millimeter

MLR multilayer reflective

MAXIMA Millimeter Anisotropy eXperiment IMaging Array

NASA National Aeronautics and Space Administration

NDF neutral density filter

PCB printed circuit board

PE polyethylene

PME polarization modulation efficiency

PSF point spread function

PV pressure vessel

PWM pulse width modulation

RMS root mean square

SLR single layer reflective

SMB superconducting magnetic bearing

SQUID superconducting quantum interference device

SQL structured query language

STARS star tracking attitude reconstruction software

SWS sub-wavelength structures

TES transition edge sensor

TDRSS tracking and data relay satellites

TM transformation matrix

UHMWPE ultra high molecular weight polyethylene

UMN University of Minnesota