

Aside from control of foregrounds, the most compelling reason to observe the CMB from space is the favorable environment of an orbit around Earth-Sun L2, and the opportunity for excellent control of systematic errors that affect CMB measurements from any platform. Compared with a ground-based, sub-orbital, or even a space mission in low-Earth orbit, the L2 environment offers excellent stability as well as the ability to observe large fractions of the sky on many time scales without interference from the Sun, Earth, or Moon. The redundancy of observations allows the checking of consistency of results and an improved ability to correct systematic errors in post-processing analysis.

As of today, we see a clear path to demonstrate that state-of-the-art technology and data processing can take advantage of the L2 environment and control systematic errors to a level that enables the science goals of PICO.

A rich literature investigates the types of systematic errors due to the environment, the instrumentation, observation strategies, and data analysis that confound the polarization measurement by creating a bias or an increased variance???. Every measurement to date has at one point reached a systematic error limit, and have advanced many sophisticated techniques to mitigate systematics, finding both new technological solutions and new analysis techniques. As an example, the BICEP’s systematics limited it to $r=0.1?$ while through additional effort within the program, BICEP2 achieved a systematics limit of $r=6\times 10^{-3}?$). In the near term, the ground based and sub-orbital CMB community will continue to develop new techniques in handling systematics.

All prior on-orbit measurements of CMB polarization were limited by systematic errors until an in-depth study of the systematics was performed and the post-processing data analysis suppressed them???. Additionally, recently proposed CMB missions, such as LiteBird and *CORE*, have placed systematic error mitigation at the forefront of the case for their mission???

During the course of the PICO Study, a systematics working group examined systematic errors affecting PICO (approximately 1 nanoKelvin in the map). Most systematic errors can be mitigated by careful design and engineering of the spacecraft and instrument, and the use of present-day state-of-the-art technology and data analysis tools. However, some systematic errors may limit the precision of the B-mode measurement and the group studied these in further detail. The work was based on the experience of the group’s involvement with past missions, in particular Planck, and in recent detailed studies of the *CORE* and LiteBird concepts.

End-to-end simulation of the experiment is an essential tool, including realistic instabilities and non-idealities of the spacecraft, telescope, instrument and folding in data post-processing techniques used to mitigate the effects. Systematics are coupled with the spacecraft scan strategy, and the details of the data analysis pipeline. During the study, the PICO team used simulation and analysis tools developed for the Planck mission? and the *CORE* mission concept, adapting them for PICO. These tools allowed a deeper examination of several key systematic errors.

0.0.1 List of Systematics

The systematic errors face by PICO can be categorized into three broad categories 1) Intensity-to-polarization leakage, 2) stability, and 3) straylight. These were prioritized for further study based on the team’s assessment of how well these systematics are understood by the community, whether mitigation techniques exist - either in instrument design or in data analysis.

In many cases the systematics are completely mitigated through the use of a polarization modulator such as a half-wave plate or a variable phase delay modulator. For the purposes of the cost constraints of PICO, in each case we investigated mitigation techniques that do not require a

modulator.

Name	Description	State-of-the-art	Additional Possible Mitigation
Leakage			
Bandpass Mismatch	Edges and shapes of the the spectral filters vary from detector to detector. leaks $T \rightarrow P$, $P \rightarrow P$ if the source's bandpass differs from calibrator's bandpass?	Precise bandpass measurement?; SROLL algorithm?; filtering technique?;	polarization modulation; full I/Q/U maps for individual detectors mitigates; additional component solution (see Banerji& Delabrouille (in prep)).Current techniques meet requirements.
Beam mismatch	Beam shapes differ between detectors that are combined to reconstruct polarization; leaks $T \rightarrow P$, $P \rightarrow P$	See Sect. 0.0.2	Current techniques meet requirements.
Gain mismatch	Relative gain between detectors that are combined to reconstruct polarization; error leaks $T \rightarrow P$	mission-average relative calibration demonstrated to 10^{-4} to 10^{-5} level ?	Sect. 0.0.3 describes effects of stability in time in relative gains.
Time Response Accuracy and Stability	Uncertainty of detector in time constants (measurement errors, time variability) biases polarization angle, pointing and beam size. In a constant spin-rate mission (PICO) is degenerate with the beam shape. leaks $T \rightarrow P$, $P \rightarrow P$	On-orbit reconstruction of time response to 0.1% across a wide signal band?, residuals corrected as part of beam and map-making algorithm?.	Treatment of residual time response as part of the beam meets requirements.
Readout Cross-talk	Power in one detector leaks into other detectors	<i>Planck</i> 's high-impedance bolometers with crosstalk measured at the level of 10^{-3} did not impact CMB polarization science?. Cross-talk low-impedance bolometers measured at XXX.	State-of-the-art (reconstruction and correction at map-making level) meets requirements.
Polarization Angle	Uncertainty in polarization calibration leaks $E \rightarrow B$.	Knowledge of astrophysical calibrators to 0.3° ?; ground measurement to 0.9° reconstruction to 0.2° using <i>TB</i> and <i>EB</i> demonstrated by <i>Planck</i> ?	Polarization modulation; See Sect. 0.0.2 for discussion; Must mitigate through developing further analysis techniques.
Cross-polarization	$Q \rightarrow U$ rotation by the optical elements of the instrument.	Degenerate with polarization gain calibration.	State-of-the-art polarization gain calibration meets requirement at .
Chromatic beam shape	Beam shape is a function of source SED: measured using a planet, used to build a window function to correct CMB power spectrum.	<i>Planck</i> simulations and parameterization as part of the likelihood.	Should be further investigated in Phase A of a mission using physical optics simulations.
Stability			
Pointing jitter	Random pointing error mixes T, E and B at small angular scale	Pointing reconstruction in <i>Planck</i> to	
Gain Stability	Time-variation of detector gain due to time variability of bath temperature variations, optical power.	Reconstruction of time variability of gain to 0.2% in <i>Planck</i> ?	See Sect. 0.0.3; Gain fluctuations in PICO on the level of XXX% on time scales of YYY can be corrected in post-processing.
Straylight			
Far Sidelobes	Pickup of Galactic signals at large angles from the main beam axis; Spillover can be highly polarized.	<i>Planck</i> validated straylight model in anechoic chamber to -80 dBi?.	Design of optical system and baffling, informed by telescope straylight simulations. See Sect. 0.0.4 for a study of beams calculated with a physical optics code for the PICO telescope and simulated Galactic pickup during the reference mission.
Other			
Residual correlated cosmic ray hits	detectors experience correlated cosmic ray hits below detection threshold resulting in misestimated noise covariance.	<i>Planck</i> /HFI found the 5% percent noise correlation due to this effect did not impact results?.	Detector design to reduce cosmic ray cross-section; Current analysis techniques (accounting for correlated noise) meet the needs.

Table 1: Systematic errors expected in PICO's measurement of CMB polarization, with assessment of currently known mitigation techniques. Those systematic errors found to be most likely to impact PICO are described further in the text. †[To be finished]†

0.0.2 Absolute polarization angle calibration

The rotation of the CMB polarization can have different causes, including 1. a birefringent primordial Universe, or a Faraday rotation due a primordial magnetic field (?), 2. birefringent foregrounds, or interaction with the Galactic magnetic field, 3. systematic effects in the instrument, and in particular an error on the actual direction of polarization measured by each detector. While the first two sources create a rotation that may depend on scale, position and/or frequency, the latter depends mainly on the detector considered.

A rotation α of the direction of polarization mixes the Q and U Stokes parameters via $Q \pm iU \rightarrow e^{\mp i2\alpha}(Q \pm iU)$ and thus mixes the the power spectra and their correlations as illustrated in Fig. 1.

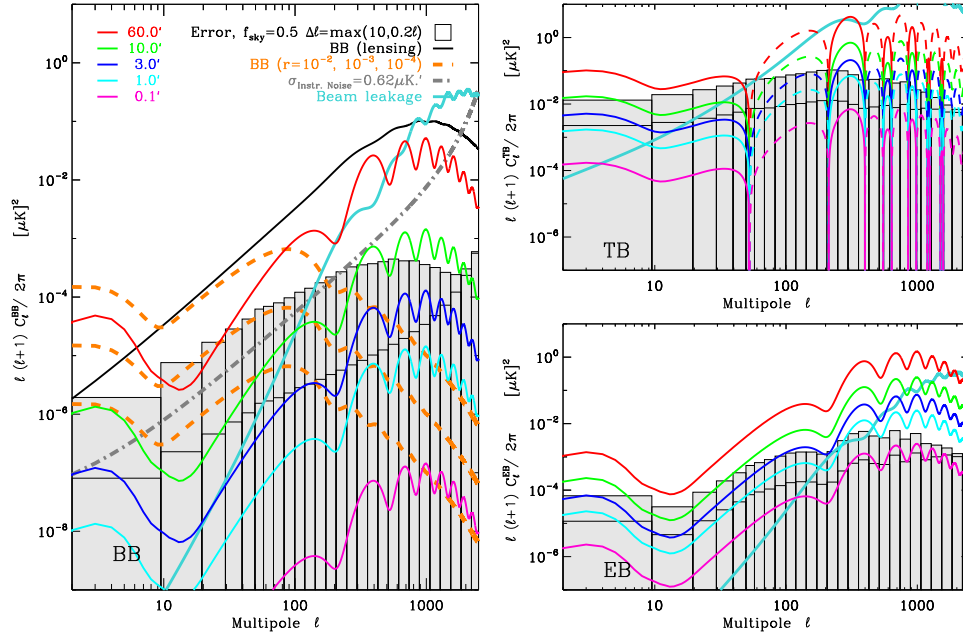


Figure 1: Effect of a rotation of the angle of polarization, assuming the Planck 2018 Λ -CDM best fit model (?) and expected PICO noise performance, assuming perfect delensing \dagger [Remove the $r=0.01$ curve; decide whether to keep beam leakage curve; perhaps remove 60' and 10'] \dagger .

In Planck, the ground measurements of the detectors orientation had an error of $\pm 0.9^\circ$ (rel.) $\pm 0.3^\circ$ (abs.) (?).

The most recent constraints on cosmological birefringence (or systematic rotation) was set in ?, looking for residual signal in TB and EB spectra, but are dominated by the uncertainties on the detector orientations.

For PICO, the relative rotation of the detectors, could be measured with a good accuracy (a few $0.1'$?, \dagger [refs?]) \dagger on the CMB, but the overall rotation is difficult to determine. Known polarized sources, such as the Crab Nebula, could be used to do that but ? show that the current uncertainty of $0.33^\circ = 20'$ on the Crab polarization orientation, obtained when combining all the available measurements, would not the measurement of tensorial B modes below $r \sim 0.01$ (assuming everything else to be nominal), far from PICO's target.

Figures 2 and 3 show how the measurement of r by PICO is degraded because of an overall rotation of polarization, and how TB and EB can be used to monitor this rotation, assuming that the only source of polarization rotation is instrumental. These results are obtained assuming the spectra to

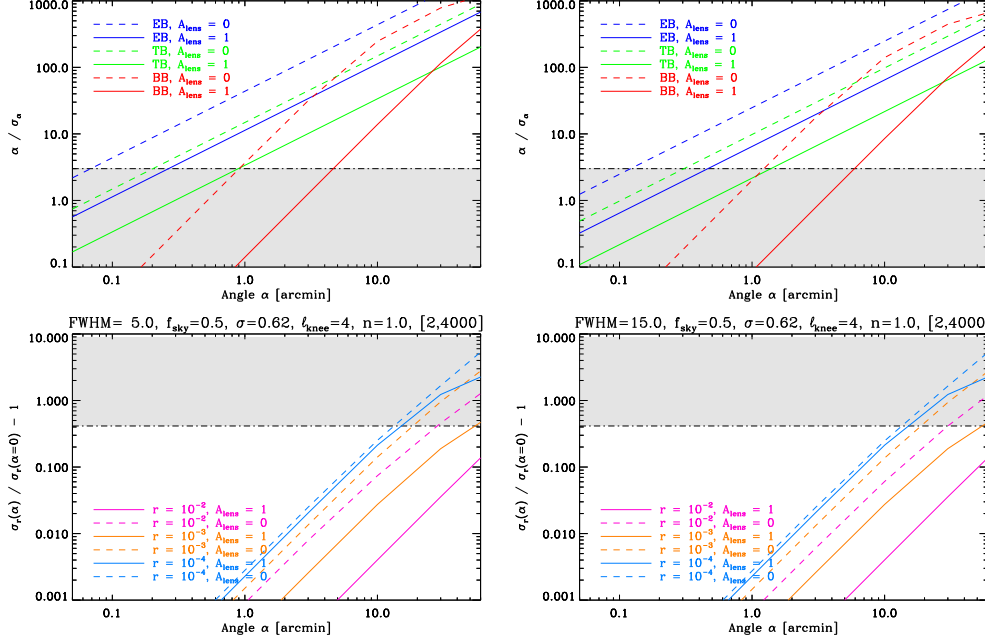


Figure 2: Upper panels: signal to noise ratio of the polarization angle α measurement by EB (blue lines), TB (green lines) and BB (red lines), assuming either no delensing (solid lines) or perfect delensing (dashes); the shaded area is $|\alpha|/\sigma_\alpha < 3$. Lower panels: degradation on measurement of r , for $r = 10^{-2}$, 10^{-3} , 10^{-4} (magenta, orange and cyan lines, respectively), either with no delensing (solid lines) or perfect delensing (dashes). The underlying cosmology is Planck 2018 Λ -CDM model (with $\tau = 0.054$), and assuming a polarized noise of rms = $0.62\mu K$ and power spectrum $(1 + (\ell_{\text{knee}}/\ell)^n)$ with $\ell_{\text{knee}} = 4$ and $n = 1$, with the analysis done on the multipole range $[2, 4000]$ over a sky fraction $f_{\text{sky}} = 0.5$. The beam FWHM= $5'$ on the *lhs* and $15'$ on the *rhs* panels. †[Probably remove this figure and summarize in text.]†

have a Gaussian likelihood, with a variance $\propto 1/f_{\text{sky}}$, and ignoring the foreground contributions. In principle, the technique of using the TB and EB spectra can detect and measure a global polarization rotation error at levels ($0.1'$) well below those affecting r measurements in BB ($> 1'$). However, a future mission should include additional aspects of the measurements of CMB polarization, such as delensing, the interaction with foregrounds, and $1/f$ noise in simulating and assessing the impact of an angle calibration error.

0.0.3 Gain Stability

Photometric calibration is the process of converting the raw output of the receivers into a physically-meaningful quantity, such as thermodynamic temperature or brightness. As CMB receivers are usually linear, this process reduces to the characterization of the *gain factor* G :

$$y(t) = G(t) \times T(\vec{x}(t)) + n(t), \quad (1)$$

where $y(t)$ is the timestream of raw samples produced by the detector, $G(t)$ is the gain factor (which we allow to vary with time), T is the sky temperature observed along direction $\vec{x}(t)$ (which varies with time as the spacecraft spins), and $n(t)$ is a noise term that includes both uncorrelated

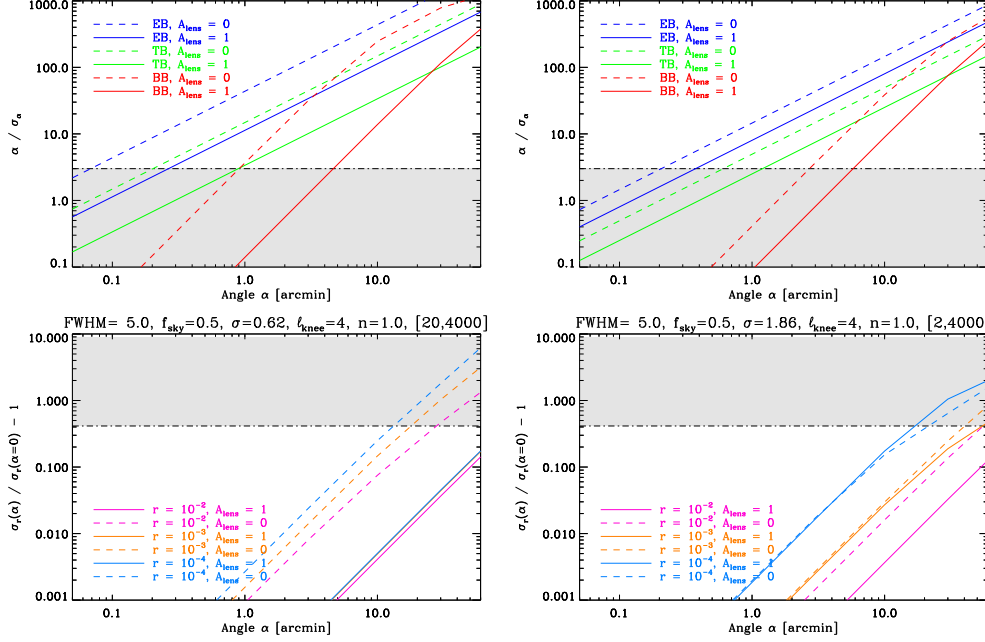


Figure 3: Same as Fig. 2, left panels, reducing the multipole range $[20, 4000]$ (*lhs*) or with a noise rms multiplied by 3 (*rhs*).[†][Probably remove this figure and summarize in text.][†]

and correlated noise. It is assumed that the timescale of variation in G (G/\dot{G}) is much longer than the typical timescale of variations in T : in the case of Planck, this was of the order of several days. In the case of space CMB experiments, the characterization of $G(t)$ is commonly done using the signal caused by the motion of the spacecraft with respect to the rest frame of the CMB itself. This signal is commonly called the *dipole*, as its most significant contribute is at multipole $\ell = 1$. For the PICO concept study, we evaluated the impact of noise in the estimation of $G(t)$ using the tools developed for the Planck/LFI instrument and the CORE mission proposal. The quality of the estimate depends on the noise level of the receiver, but also on the details of the scanning strategy. The Planck/LFI experiment, because of a poor choice of the scanning strategy parameters (namely, a too slow precession motion), was forced to avoid using one year out of four in the 2015 data release [REF]. We can anticipate that this problem is not expected in PICO, thanks to the significantly faster precession envisaged.

In order to test the impact of calibration uncertainties, we have run the following analysis:

1. We simulated the observation of the sky, assuming four receivers and the nominal scanning strategy. We included both white noise and $1/f$ noise. The sky only contained CMB anisotropies, plus the CMB dipole.
2. We ran the calibration code to fit the dipole against the raw data simulated during step 1.
3. We simulated again the observation of the sky, but this time we used the values of G computed during step 2, which contain errors due to the presence of $n(t)$ and the CMB signal in Eq. (1). The noise in the output map is therefore the sum of the noise in the error on G and the term n .

The presence of foregrounds in the sky signal would cause a bias in the estimation of the calibration constants, due to the presence of large scale features in the Milky Way at microwave frequencies. A

full data analysis pipeline for PICO should pair the calibration step with the component separation step, following a schema similar to what has been done by the Planck/LFI team for the 2018 data release [CITATION]: the application of the calibration code should be followed by a component separation analysis, and these two steps should be iterated until the result converge to a solution. In this analysis we assume to study the calibration at the last iteration, when the components have already been properly separated.

Results of the simulation are shown in Figures XXX and YYY. The scanning strategy employed by PICO allows for a much better calibration than in the case of Planck’s, thanks to the much faster precession.

0.0.4 Far Sidelobe Pickup

The main beam (within a few degrees of the axis of beam response) in a CMB mission can be measured to high precision using the planets as compact sources. Measurement of each detector’s response to signals more than a few degrees off axis, which tends to be at a very low level (more than -80dB less than the peak response) but spread over a very large solid angle, is difficult to do pre-launch, and may not be done accurately after launch. Nonetheless, this far sidelobe can couple bright Galactic signal from many tens of degrees off-axis and confuse it with polarized signal from the CMB off the Galactic plane.

To evaluate this systematic error, GRASP software¹ was used to compute the PICO telescope’s pickup over the full sky. This full-sky beam was convolved with a polarized Galactic signal and a full PICO mission scan using the simulation pipeline. The far sidelobe pickup was estimated to contribute less than XXX to the B-mode angular power spectrum and thus an error in r of YYY. In a real mission due to the difficulties of measuring this beam, physical optics simulation capabilities must be maintained and validated as well as possible with on-orbit data.

0.0.5 Key Findings

Properly modeling, engineering for, and controlling the effects of systematic errors in a next-generation CMB probe is critical. In particular we note:

- The raw sensitivity of the instrument should include enough margin that data subsets can independently achieve the science goals. This allows testing of the results in the data analysis and additional data cuts, if needed.
- NASA’s support of ground-based and suborbital CMB missions will mitigate risk to a future space mission as PICO by continuing to develop analysis techniques and technology for mitigation of systematic errors.
- In a PICO mission’s phase A, a complete end-to-end system-level simulation software facility would be developed to assist the team in setting requirements and conducting trades between subsystem requirements while realistically accounting for post-processing mitigation. Any future CMB mission is likely to have similar orbit and scan characteristics to those of PICO, thus there is an opportunity for NASA and the CMB community to invest in further development of this capability now.

¹<https://www.ticra.com>