Some of the PICO science goals attempt to detect extremely faint signals. The most ambitious one is to reach the signals characterizing an inflationary gravity wave with $r \lesssim 0.001$, with a B-mode polarization peak signal $\lesssim$ 10nK in amplitude at $\ell = 80$. It has long been recognized that exquisite control of systematic uncertainties will be required for any experiment attempting to reach these levels, and it is widely accepted that the stability provided aboard a space platform makes it best suited to control systematic uncertainties compared to other platforms. This is one of the most compelling reasons to observe the CMB from space. As WMAP and *Planck* demonstrated, an L2 orbit offers excellent stability as well as the flexibility in the choice of scan strategy. PICO takes advantage of an L2 orbit, implementing scans that are crosslinked on many time scales and at many angles, without interference from the Sun, Earth, or Moon, thus reducing the effects of low frequency noise (1/f) without additional modulation. The redundancy of observations allows the checking of consistency of results and an improved ability to calibrate and to correct systematic errors in post-processing analysis.

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 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=6×10^{-3}[**?**]). In the near term, the ground based and suborbital CMB community will continue to develop new techniques in handling systematics, particularly in developing the CMB-S4 project.

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[**? ? ?**]. Particularly we note Fig. 3 of [**?**] which quantifies Planck's systematic error limits on the polarization power spectral measurements. Recently studied space missions, such as EPIC-IM, LiteBird and *CORE*, have placed systematic error mitigation at the forefront of the case for their mission and have developed tools and strategies for estimating and mitigating these[**? ? ?**].

Systematics are coupled with the spacecraft scan strategy, and the details of the data analysis pipeline. Thus, 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.

0.0.1 List of Systematics

The systematic errors faced by PICO can be categorized into three broad categories: 1) Intensity-to-polarization leakage, 2) stability, and 3) straylight, and are listed in Table **??**. These were prioritized for further study using a risk factor incorporating the working group's assessment of how mission-limiting the effect is, how well these effects are understood by the community and whether mitigation techniques exist.

The three highest risk systematic errors were studied further and are discussed in subsections below. The PICO team used simulation and analysis tools developed for Planck[**?**] and *CORE*, adapting them for PICO.

Name	Risk	Effect	
Leakage			
Polarization Angle Calibration	5	$E \to B$	See Sect. 0.0.2.
Bandpass Mismatch	4	$T \to$P, $E \to B$	
Beam mismatch	4	$T \to$P, $E \to B$	See Sect. 0.0.2
Time Response Accuracy and Stability	4	$T \to$P, $E \to B$	
Readout Cross-talk	4	spurious P	
Chromatic beam shape	4	spurious P	
Gain mismatch	3	$T \to$P	
Cross-polarization	3	$E \to B$	
Stability			
Gain Stability	5	$T \to$P, $E \to B$	See Sect. 0.0.3
Pointing jitter	3	$T \to$P, $E \to B$	
Straylight			
Far Sidelobes	5	spurious P	See Sect. 0.0.4.
Other			
Residual correlated noise (cosmic ray hits)	3	increased variance	

Table 1: Systematic errors expected in PICO's measurement of CMB polarization. Each source of systematic errors was given a rating of the risk that a given systematic error will dominate the B-mode measurement. A risk level of 5 indicates that a systematic effect is highly significant because it is design-driving, has limited past experiments, and/or isnÕt well understood. Risk level of 4 indicates a systematic that is either known to be large but is understood reasonably well or a smaller effect that requires precise modeling. Risk level of 3 indicates that we expect the effect to be small, but it isn't necessarily well understood enough that modeling it should be done in detail in a mission Phase A. This study investigated the systematics with risk levels of 5 via simulations.

0.0.2 Absolute polarization angle calibration

CMB polarization can be rotated due to 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 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.

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

The most recent constraints on cosmological birefringence **?**] were limited by uncertainties on the detector orientations. In Planck, the detectors were characterized pre-launch to $\pm 0.9^o$ (rel.) $\pm 0.3^o$ (abs.) [**?**]. For PICO, the relative rotation of the detectors will be measured to a few $0.1'$ using the CMB, but the overall rotation is unlikely to be known pre-launch to better than Planck. Known polarized sources, such as the Crab Nebula, are not characterized well enough independently to serve as calibrators; **?**] show that the current uncertainty of $0.33^o = 20'$ on the Crab polarization orientation, limits a B mode measurement to $r \sim 0.01$, far from PICO's target.

In the absence of other systematics and foregrounds, a polarization rotation error α of $10'$ degrades the error bar of r by 30%, while EB, TB and BB spectra can measure a rotation α at 3σ when $\alpha \sim 0.07, 0.2$ and $0.9'$ respectively on perfectly delensed maps, and $0.25, 0.9$ and $4.5'$ on raw maps.

In principle, the technique of using the TB and EB spectra can detect and measure a global polarization rotation error at levels ($0.1'$) below those affecting r measurements in BB ($> 1'$). However, a future mission should simulate additional aspects, such as delensing, the interaction with foregrounds, and $1/f$ noise in simulating and assessing the impact of an angle calibration error.

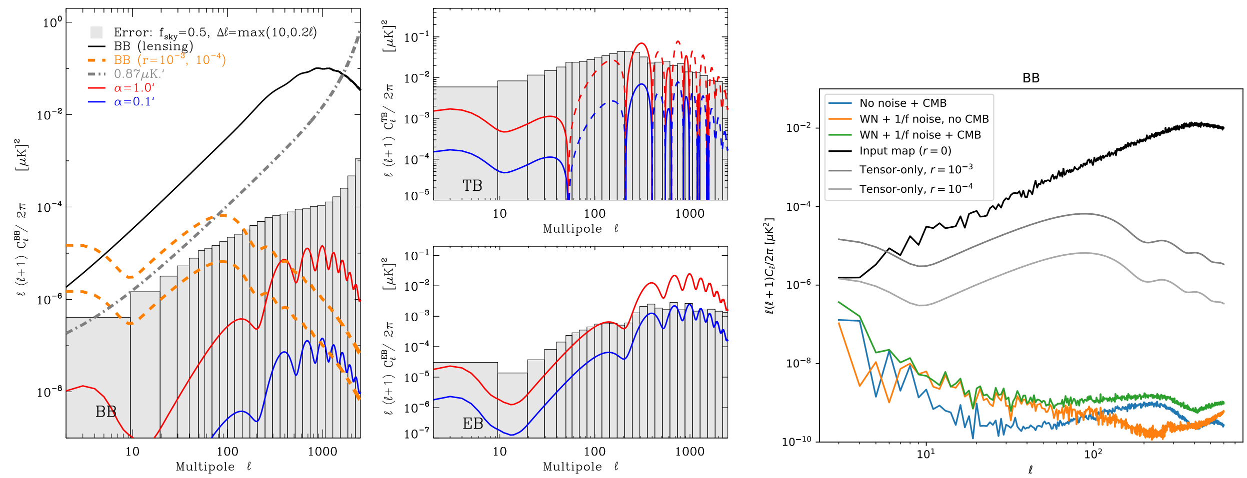

Figure 1: Effect of a rotation of the angle of polarization, assuming the Planck 2018 Λ-CDM best fit model [**?**] with $\tau = 0.054$ and expected PICO noise performance, assuming perfect delensing.

0.0.3 Gain Stability

Photometric calibration is the process of converting the raw output of the receivers into astrophysical units via the characterization of the *gain factor* $G(t)$ which we allow to vary with time. In space, $G(t)$ can be measured with the dipole. 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 receivers, but also on the details of the scanning strategy. To analyze the impact of calibration uncertainties on PICO, we performed the following analysis:1. We simulated the observation of the sky, assuming four receivers, the nominal scanning strategy, and $1/f$ noise. The simulated sky 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 again simulated the observation of the sky, this time using the values of G computed during step 2, which contain errors due to the presence of noise and the CMB signal.

The presence of large-scale Galactic emission features can bias the estimation of calibration factors. Ideally, a full data analysis pipeline would pair the calibration step with the component separation step, following a schema similar to Planck/LFI's legacy data processing[**?**]: the calibration code is followed by a component separation analysis, and these two steps are iterated until the solution converges.

Results of the simulation (neglecting foregrounds) are shown as power spectrum residuals in Fig. **??**. We estimate the gain fluctuations to better than 10^{-4} solving for the gain every 40 hours (4 precession periods). The scanning strategy employed by PICO allows for a much better calibration than Planck, thanks to the much faster precession.

0.0.4 Far Sidelobe Pickup

Measurement of each detector's response to signals off axis, which tends to be weak (–80dB less than the peak response) but spread over a very large solid angle, is difficult to do pre-launch, and may not even 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 software[1] was used to compute the PICO telescope's response over the full sky. The computed full-sky beams showed features peaking at about -70 dB of the on-axis beam. This full-sky beam was convolved with a polarized Galactic signal and a one-year PICO mission scan using the simulation pipeline and preliminarily shows that the far sidelobe pickup must be calculated accurately down to the 90 dB level in order to be removed from the measured B-mode signal to a level that does not appreciably increase the variance on the B-mode power measurement.

0.0.5 Key Findings

Properly modeling, engineering for, and controlling the effects of systematic errors in a next-generation CMB probe is critical. As of today, we conclude that there is 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. 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.

- In a PICO mission, a physical optics model of the telescope should be developed, enabling full-sky beam calculations, which should be validated as much as possible on the ground. This will be needed to characterize and remove far sidelobe pickup seen during the mission.

- 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