The Probe of Inflation and Cosmic Origins

A Space Mission Study Report
December, 2018

Principal Investigator:
Steering Committee:
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Contributors:
Endorsers:

1 Executive Summary (2 pg, Hanany)

2 Science (31 pages)

48 pages are currently distributed as 31/17: 31 pages for science (including foregrounds and systematics), 17 for instrument, technology, mission, technology, management and cost. References are extra. Should rebalance to 28/20?

2.1 Introduction (1.5 pgs, Hanany + (Flauger? Green? +?)

NASA suggested table of contents says Science Intro or Landscape section should include:

- State of the Art in the Field
- Compelling Outstanding Questions
- Needed Capabilities for Progress

2.2 Science Objectives (17.5 pgs)

The PICO Science Traceability Matrix (2pg, Hanany&Trangsrud) will be inserted around here. It is an 11x17 foldout, so it counts as 2 pages, which leaves 15.5 to all the rest in 2.2. Currently allocating 15 pages.

FOR EACH OF THE BELOW SUBSECTIONS:

- Introduce and elaborate on the applicable PICO "Science Objectives" from the STM table (what do they mean and why are they important)
- Observations/Measurements that enable PICO to accomplish each Science Objective (tell the data analysis story that connects the Observations column of the STM to the Science Objective column)
- Contextualize relative to sub-orbital and other space missions. *Emphasize where capabilities are unique to space.*
- Science yield estimate (be quantitative. how well will PICO do at Baseline/Required performance? at Current Best Estimate performance?)
- Include a summary plot or table which demonstrates PICO's performance against the Science Objective as written (e.g. how it discriminates between different theories)
- Perceived science impact. (The impact isn't reducing sigma on a parameter. It is about what we will learn about nature.)

2.2.1 Fundamental Physics (6 pgs, Flauger, Green)

To include: Cosmic Inflation, Particle Physics (Neutrinos and Light Relics), primordial EM fields
Should address these Science Objectives from the STM:

- "Probe the physics of the big bang by detecting the energy scale at which inflation occurred if it is above 4×10^{15} GeV, or place an upper limit if it is below" [r]
- "Probe the physics of the big bang by excluding classes of potentials as the driving force of inflation" [n_s, n_{run}]
- "Determine the sum of neutrino masses, and distinguish between inverted and normal neutrino mass hierarchies" [Σm_ν]
- "Detect departures from or tightly constrain the thermal history of the universe" [N_{eff}]
- Origin of magnetic fields and cosmic birefringence

2.2.2 Cosmic Structure Formation and Evolution (4 pgs. Hill, Battaglia (& Alvarez))

Should address these Science Objectives from the STM that relate to reionization + ??

2.2.3 Galactic Structure and Star Formation (5 pgs, Chuss & Fissel)

Should address these Science Objectives from the STM:

- "Determine whether the interstellar medium of our galaxy is unique by comparing the ratio of energy in magnetic field to turbulence to that in nearby galaxies."
- "Determine if magnetic fields are the dominant cause of low star formation efficiency in our Galaxy."
- "Determine whether radiative torque is responsible for the alignment of dust grains with magnetic fields"
- "Determine the influence of the magnetic field on Galactic dynamics within the Milky Way."

2.3 Measurement Requirements (2 pgs, Hanany & Trangsrud)

Some requirements derive from the science (e.g. τ = full sky, r = depth, lensing = resolution)
Some requirements derive from foregrounds (e.g. frequency breadth) and some from systematics (e.g. particular scan pattern)

2.4 Additional Science (2 pgs, de Zotti)

Describe science that we get for free.

2.5 Complementarity with other Measurements and Surveys (1 pg, Lawrence? Schmidt?)

Should describe complementarity with sub-orbital CMB measurements and with other surveys, both in space and on the ground. This is summary text (more detail in subsections about specific objectives)

2.6 Foregrounds (4 pgs, Jacques and Clem)

The state of knowledge and known challenges; how does PICO address the challenges; forecast of performance.

2.7 Systematic Errors (3 pgs, Crill)

Note:include a review of previous work of the community on systematics, going way back to the Hu papers. (Tasked to Brendan)
Note: Calculate a defensible level of acceptable systematics. For example, integrate r 10^{-3} and 10^{-4} power from ell 2-10, 10-50,(do a signal to noise calculation), then state what map rms that corresponds to.
A CMB mission aiming for the unprescedented sensitivity of PICO must control systematic errors to avoid bias or an increased variance of the science measurement. Systematics must be controlled or corrected to a level that enables the PICO science goals (better than 1 nanoKelvin (**Note: make sure this is a correct statement - also be careful about reducing a complicated concept such as systematic errors to a single map rms number, could also quote this as a δr error**) in the map). Mitigation of systematic errors is the most important reason (along with the availability of broad wavelength coverage) to perform a measurement of the CMB polarization from a space telescope; 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. This redundancy of observations allows the checking of consisitency of results and an improved ability to correct systematic errors in post-processing analysis.
During the course of the PICO Study, a systematics working group examined systematic errors affecting PICO, 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 on 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[1] and the CORE mission concept, adapting them for PICO. These tools allowed a deeper examination of several key systematic errors.

2.7.1 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.

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 leakage 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 may be adequate**
Beam mismatch		See Sect. 2.7.2	
Gain mismatch			
Time Response Accuracy and Stability			
Readout Cross-talk			
Polarization Angle			See Sect. 2.7.2
Cross-polarization			
Chromatic beam shape			
Stability			
Pointing jitter			
Gain Stability			See Sect. 2.7.3
Straylight			
Far Sidelobes			See Sect. 2.7.4
Other			
Residual correlated cosmic ray hits			

Table 1: Systematic errors expected to affect PICO.

2.7.2 Absolute polarization angle calibration

Eric H to write up

2.7.3 Gain Stability

Maurizio to write up

2.7.4 Far Sidelobe Pickup

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2.7.5 Key Findings

Understanding and controlling the effects of systematic errors in a next-generation CMB probe is critical.
The raw sensitivity of the instrument should include enough margin that data subsets can independently archieve the science goals. This allows testing of the results in the data analysis and additional data cuts, if needed.
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.

3 Instrument (6 pgs, Hanany & Trangsrud)

Telescope (Hanany / Young), focal plane (Hanany / Young), cooling (Trangsrud), readout (O'Brient)
Review: Bock, Hubmayr, Suzuki,

4 Mission (3 pgs, Trangsrud)

To be included: mission architecture, spacecraft and subsystems, orbit, attitude control and determination (Trangsrud)

5 Technology Maturation (4 pgs, O'Brient & Trangsrud)

Requirements, planned activities, schedules and milestones, estimated cost (O'Brient?)
For each technology include:

- Requirements
- Planned activities
- Schedule and Milestones
- Estimated Cost

6 Management, Risk, Heritage, and Cost (4 pgs, Trangsrud)

cost, risk, heritage (Trangsrud)

References

[1] Planck Collaboration, P. A. R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, and et al. Planck 2015 results. XII. Full focal plane simulations. *Astron. Astrophys.*, 594:A12, September 2016.