1 Executive Summary (2 pg, Hanany)

Responsibility: Hanany

2 Science (30.5 pages)

2.1 Introduction (1 pg, Hanany)

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

To be included: State of the art in the field; Compelling outstanding questions; Needed capabilities for progress (Knox? + others)

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 16 to all the rest in 2.2.

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
- 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 (be qualitative. this isn't about reducing the sigma on a parameter. this 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)
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. 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 (τ = full sky) Some requirements derive from foregrounds (frequency coverage) and some from systematics (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)

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)

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

2.7 Systematic Errors (3 pgs, Crill)

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. Mitigation of systematic errors is the most important reason (along with the broad wavelength band) 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, based on the experience of past missions, in particular Planck. 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 do still present a risk that they may limit the measurement and the group studied these in further detail.

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. During the study, the PICO team used simulation and analysis tools developed for the Planck mission[**?**] and for the CORE mission concept, adapting them for PICO. While not fully developed, these tools allowed a deeper examination of the most worrisome 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.

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; **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

...

2.7.3 Gain Stability

...

2.7.4 Far Sidelobe Pickup

...

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, some margin for data cuts as needed, and

In a PICO mission's phase A, a complete end-to-end system-level simulation facility would be developed to assist the team to set requirements and conduct 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, and there is an opportunity for NASA and the CMB community to begin to develop this capability now.

3 Instrument (6 pgs, Trangsrud & Hanany)

Telescope, focal plane, cooling, readout

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

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