Optical Design of PICO, a Concept for a Space Mission to Probe Inflation and Cosmic Origins

Karl Young[a†], Marcelo Alvarez[b], Nicholas Battaglia[c], Jamie Bock[d], Jullian Borrill[e], David Chuss[f], Brendan Crill[g], Jacques Delabrouille[h], Mark Devlin[i], Laura Fissel[j], Raphael Flauger[k], Daniel Green[l], Kris Gorksi[g], Shaul Hanany[a], Richard Hills[m], Johannes Hubmayr[n], Bradley Johnson[o], Bill Jones[c], Lloyd Knox[p], Al Kogut[q], Charles Lawrence[g], Tomotake Matsumura[r], Jim McGuire[g], Jeff McMahon[s], Roger O'Brient[g], Clem Pryke[a], Xin Zhi Tan[a], Amy Trangsrud[g], Qi Wen[a], and Gianfranco de Zotti[t]

[a]University of Minnesota, USA
[b]University of California Berkeley, USA
[c]Princeton University, USA
[d]California Institute of Technology, USA
[e]Lawrence Berkeley National Laboratory, USA
[f]Villanova University, USA
[g]Jet Propulsion Laboratory, California Institute of Technology, USA
[h]Laboratoire AstroParticule et Cosmologie adn CEA/DAP, France
[i]University of Pennsylvania, USA
[j]National Radio Astronomy Observatory, USA
[k]University of California San Diego, USA
[l]University of Toronto, Canada
[m]Cavendish Laboratory, University of Cambridge, UK
[n]National Institute of Standards and Technology, USA
[o]Columbia University, USA
[p]University of California Davis, USA
[q]Goddard Space Flight Center, USA
[r]Kalvi IPMU, University of Tokyo, Japan
[s]University of Michigan, USA
[t]Osservatorio Astronomico di Padova, Italy

ABSTRACT

The Probe of Inflation and Cosmic Origins (PICO) is a probe-class mission concept currently under study by NASA. PICO will probe the physics of the Big Bang and the energy scale of inflation, constrain the sum of neutrino masses, measure the growth of structure in the universe, and constrain its reionization history by making full sky maps of the cosmic microwave background with sensitivity 70 times higher than the Planck space mission. With bands at 21-799 GHz and arcmin resolution at the highest frequencies, PICO will make polarization maps of galactic synchrotron and dust emission to observe the role of Galactic magnetic fields in galactic evolution and star formation. We describe the current state of the PICO instrument design. We will discuss the choice of optical system, present the design of the focal plane, and give the expected noise level.

Keywords: Cosmic microwave background, cosmology, mm-wave optics, polarimetry, instrument design, satellite, mission concept

[†]E-mail: kyoung@astro.umn.edu, Telephone: 1 612 626 9149

1. INTRODUCTION

Currently, NASA funded spaces missions in astronomy and astrophysics are either Explorer missions with $250M cost caps or flagship missions such as JWST which cost around $3-$5B. To study the science opportunities available at intermediate costs, NASA called for studies of 'Probe' class missions with $1B cost caps. The Probe of Inflation and Cosmic Origins (PICO) is one of these NASA funded studies. This paper describes the instrument optical design and focal plane approximately two thirds of the way through the study time line. The final PICO report will be sent to NASA at the end of 2018.

Astrophysical observations in the millimeter and sub-millimeter region of the electromagnetic spectrum contain a wealth of information about the formation, evolution, and structure of the Universe. The polarization and temperature anisotropies of the cosmic microwave background (CMB) encode fundamental physics information relating to the epoch of inflation, the mass of neutrinos, and the number of relic light particles in the early Universe. They also contain information about the formation of the first stars, galaxies, and clusters. Information about the role of magnetic fields in star formation and galactic evolution is obtainable by observing the polarized emission of Galactic dust, which traces magnetic fields, at high resolution. Targeting both of these regimes, PICO will survey the entire sky with unprecedented polarization sensitivity in 21 bands centered at 21–799 GHz. Details of these science targets and expected constraints from PICO are in a companion paper, Sutin et al.[1] In this paper we discuss the mission's optical system, focal plane, and sensitivity.

2. SPACECRAFT AND MISSION

PICO will conduct scientific observations for five years from the Earth-Sun L2 Lagrange point. The spacecraft design impacts the optical design and sensitivity in two primary ways; volume constraints limit the physical size of the telescope and optical component temperatures impact noise levels.

The maximum size of the spacecraft is limited by the launch vehicle, SpaceX's Falcon 9, which carries payloads up to 4.6 m in diameter. This diameter limit sets the V-groove size which, along with the scan strategy, defines the 'shadow cone' in Figure 1. The shadow cone is the volume protected from solar illumination, and all optical components must remain within it. The shadow cone and inner V-grooves define an available volume for the telescope.

The temperatures of all optical elements are given in Figure 1 The optics box, secondary, and focal plane are actively cooled, details of the thermal system are given in Sutin et al.[1]

3. OPTICAL SYSTEM

The PICO telescope is a 1.4 m aperture modified open-Dragone. This choice was driven by a combination of science requirements and the physical limits discussed in Section 2. The science requirements are: a large diffraction limited field of view (DLFOV) sufficient to support $\mathcal{O}(10^4)$ detectors, arcminute resolution at 800 GHz, low instrumental polarization, and low sidelobe response. Additionally, the transition edge sensor bolometers baselined for PICO require a telecentric focal plane which is sufficiently flat that it can be tiled by 10 cm detector wafers without reduction in optical quality.

More than 30 years ago Dragone analyzed the performance of several off-axis systems and found solutions with low cross-polarization at the center of the field of view and with astigmatism, or astigmatism and coma, canceled to first order.[2–4] A number of recent CMB instruments used off-axis systems, and several began the design optimization with systems based on designs by Dragone.[5–9] For PICO we began the optimization with a Dragone system that to our knowledge has not been implemented before. We call it an 'open-Dragone' because of its overall geometry, see Figure 2, and in contrast to the widely used 'cross-Dragone'.

We consider two additional Dragone systems; a Gregorian Dragone and a cross-Dragone. We compare their performance to an open-Dragone using 155 GHz diffraction limited area, measured in units of $(F\lambda)^2$, as our metric. With half the diffraction limited focal plane area of the open-Dragone,[8] the Gregorian Dragone is unable to support $\mathcal{O}(10^4)$ detectors, so it was rejected. The cross-Dragone has roughly $4\times$ the diffraction limited focal plane area of the open-Dragone, is that true? I didn't think it was that much of a difference true for our open vs a crossed of the same aperture and similar geometry to EPIC. This is only a factor of 2 in DLFOV diameter.

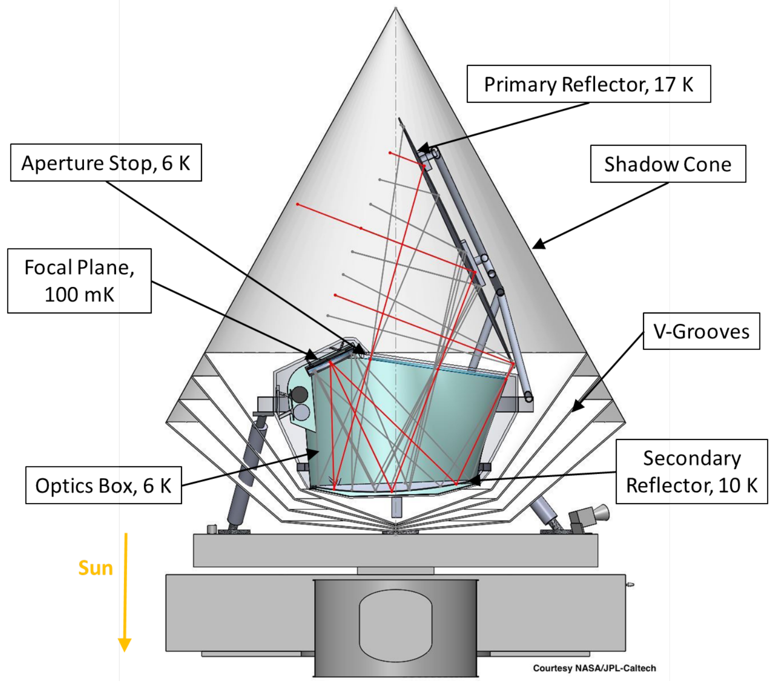

Figure 1. Mechanical design of the PICO satellite. Components relevant to this paper are labeled, for other details see Sutin et al.[1] The symmetry axis of the satellite precesses around the satellite-sun axis (orange arrow) with an angle of 26 degrees. This precession defines the shadow cone which is shown in light gray.

but it has significant sidelobes as shown in Figure 4. Additionally, a cross-Dragone will always have a larger F-number than a similar open-Dragone, because the cross-Dragone focal length must be long enough that the focal plane does not block the primary mirror. The larger F-number results in a larger telescope which fits poorly into the shadow cone. The largest cross-Dragone that meets the PICO volume constraints has a 1.2 m aperture while the largest open-Dragone aperture is 1.4 m. The large F-number of the cross-Dragone system also increases the physical focal plane size, and therefore mass and cost, for a fixed number of pixels. These disadvantages with the Gregorian Dragone and the cross-Dragone led us to use the open-Dragone as a starting point for the PICO optical design.

We design the initial open Dragone following Granet's method.[10] We find a solution with low f-number, $F = 1.42$, the largest aperture that satisfies the volume constraints, and a large DLFOV. We force a circular aperture stop between the primary and secondary mirrors and numerically optimize its angle and position to obtain the best optical performance. The stop diameter provides an effective 1.4 m aperture on the primary for the center feed. Adding a stop in this way increases the size of the primary mirror, because the primary is unevenly illuminated at various field angles. Actively cooling the aperture stop, however, reduces detector noise and the stop shields the focal plane from stray radiation. At this stage the system still meets the Dragone condition and is defined by the 'Initial Open-Dragone' parameters in Table 1.

In his publications Dragone provides a prescription to eliminate coma in addition to the cancellation of astigmatism in the baseline designs.[3] The reflector corrections involve adding distortions to the primary and secondary reflectors which are proportional to r^4 where $r = 0$ is at the chief ray impact point on each mirror. We thus attempt to increase the DLFOV using two methods.

In the first method, one of the coauthors (RH) uses Zemax to add Zernike polynomials to the base conics which describe the mirrors. These Zernike polynomials are offset from the symmetry axis of the conic by 624.2 cm for the primary and 76.1 cm for the secondary. This places the origin of polynomials at the chief ray impact point for each mirror. Inspired by the Dragone corrections, all Zernike terms up to fourth order and the first fifth order term are allowed to vary. The optimization metric is minimization of the rms spot diameter at the