

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

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## 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 discuss the choice of optical system, which is based on an open-Dragone telescope that, to our knowledge, has not been used for mm-wave astrophysical observations. We also present the focal plane design, a white noise model of the instrument, and the expected noise level.

did you review the abstract? does it accurately represent the contents of the paper? Is it highlighting the unique and new things you are reporting? Is it quantitative? In order; yes, yes, I think so, and somewhat.

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need to distinguish between Current Best Estimate and Required Sensitivity. Added one sentence on this at end of 1st paragraph of intro. Does it need to be more prominent?

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

## 1. INTRODUCTION

Currently, NASA funded space missions in astronomy and astrophysics are either Explorer missions with \$250M cost caps or flagship missions, such as JWST, which cost roughly \$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 status of the instrument optical design and focal plane approximately two thirds of the way through the study time line. Values in this paper, such as component temperatures and detector noise levels, are current best estimates. They are not finalized mission requirements. 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, as well as information on emission from the innermost regions of radio source jets. . 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.<sup>1</sup> 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 an orbit around 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 mirror, and focal plane are actively cooled, details of the thermal system are given in Sutin et al.<sup>1</sup>

## 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.<sup>2–4</sup> A number of recent CMB instruments used off-axis systems, and several began the

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\* We consider an area in the FOV diffraction limited when the Strehl ratio is larger than 0.8.

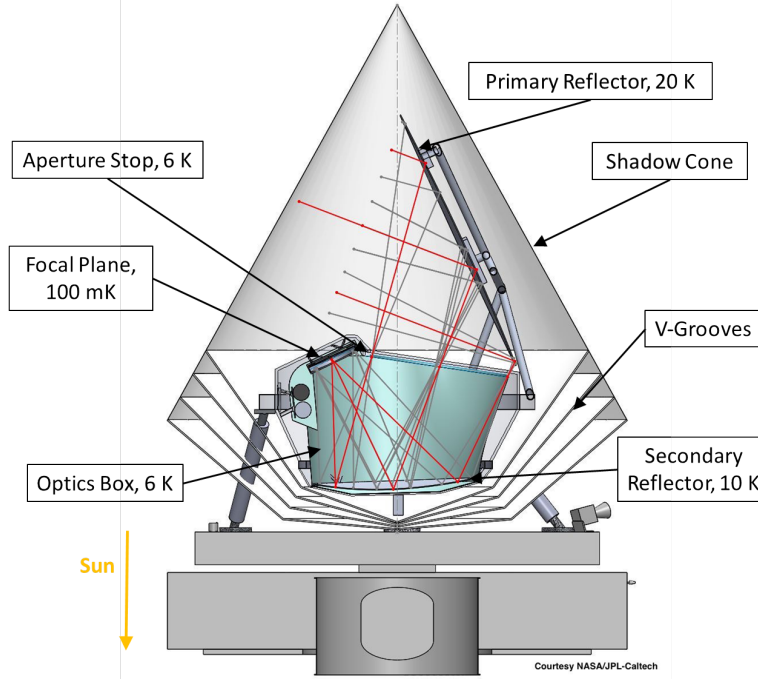


Figure 1. Mechanical design of the PICO satellite. Components relevant to this paper are labeled, for other details see Sutin et al.<sup>1</sup> The symmetry axis of the satellite precesses around the satellite-sun axis (orange arrow) with an angle of 26 deg. This precession defines the shadow cone which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

design optimization with systems based on designs by Dragone.<sup>5–10</sup> For PICO we begin the optimization with a Dragone system that to our knowledge has not been implemented in CMB instruments before. We call it an ‘open-Dragone’ because of its overall geometry and in contrast to the widely used ‘cross-Dragone’, see Figure 3.

We consider two additional Dragone systems, a Gregorian Dragone and a cross-Dragone, and compare the relative performance of all three systems in terms of DLFOV, compactness, and rejection of sidelobes. Compared to the open-Dragone, the Gregorian has half the DLFOV for the same  $F$ -number and cannot support  $\mathcal{O}(10^4)$  detectors. It is therefore rejected. The cross-Dragone has roughly  $4\times$  the DLFOV of the open-Dragone, but is more difficult to pack inside the spacecraft volume while avoiding the known sidelobes shown in Figure 2. We find the largest cross-Dragone which meets the PICO volume constraints has a 1.2 m aperture and an  $F$ -number of 2.5, while the largest open-Dragone aperture is 1.4 m with an  $F$ -number of 1.42. The larger  $F$ -number of the cross-Dragone system implies a larger physical focal plane, and therefore higher mass and cost, for the same number of pixels. For the PICO case, we conclude that the advantages of a low  $F$ -number and easily baffled sidelobes make the open-Dragone a good starting point for further optimization.

We design the initial open Dragone following Granet’s method.<sup>11</sup> 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.<sup>3</sup> 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.

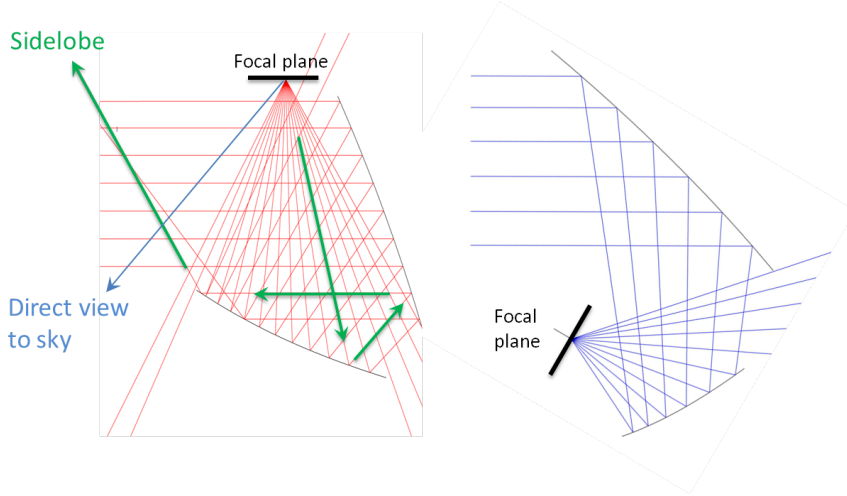


Figure 2. Comparison of sidelobes for a cross-Dragone (left) and an open-Dragone (right). Rays are traced from the center of the focal plane toward the sky. For both systems spillover around the secondary is straightforward to mitigate with absorptive baffles. However, the sidelobe and direct sky view in the cross-Dragone system require a long forebaffle or large  $F$ -number to mitigate, both of which are problematic in the PICO case.

In the first method, one of the coauthors (RH) used 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 following locations: the center of the FOV,  $\pm 2$  deg in Y, and  $\pm 4$  deg in X. The center of the FOV is given a weight of 100 while each outer point is given a weight of 1. To constrain the optimization, the X and Y effective focal lengths are held fixed as is the impact point of the chief ray on the focal plane. This optimization step increases the DLFOV by factors of 1.15, 2.4 and 10.5 at 21, 155 and 799 GHz, respectively. We improve the DLFOV at all frequencies by approximately 50% by rerunning the optimization and including a curved focal surface. A small ( $\sim 4\%$ ) additional gain in DLFOV is achieved by adding Zernike terms up to sixth order, allowing the secondary to focal surface distance to vary, adding a weighted constraint on the effective focal length, and adding fields with weight of 0.01 to the rms spot diameter metric at  $\pm 7.5$  deg in Y and  $+15$  deg in X. These additional fields are necessary to constrain the corrections at the mirror edges.

In the second optimization method, another coauthor (JM) uses CodeV and allows more of the geometric parameters of the system to vary. To adjust the mirror shapes, we add Zernike polynomial corrections to the conic surfaces which define the two mirrors. The Zernike polynomials are defined on the same coordinates as the base conics. We vary the 4th and 9th-13th terms of the Zernike polynomials. We allow the focal surface curvature and focal surface to secondary distance  $L_s$  to vary. The primary-secondary distance  $L_m$ , primary offset  $h$ , and the primary and secondary rotation angles,  $\alpha$  and  $\beta$ , are varied as well. The optimization metric is the rms spot diameter across the field of view, with weighted constraints requiring telecentricity and maintaining the X- and Y-focal lengths. We add Lagrange constraints to enforce beam clearances and place an upper limit on overall system size. Once the optimization converges to an acceptable optical system, we add higher order Zernike terms, 19th-25th, and refine the mirror shapes using the same metric and constraints. The current PICO optical design is from this optimization procedure.

Figure 4 shows that the second optimization method greatly increases the DLFOV relative to the initial open-Dragone design. The DLFOV is increased by factors of 1.9, 3.8, 4.3, and 4.6 at 21, 129, 155, and 799 GHz, respectively. The most important gain is at 129 and 155 GHz where the extra area allows us to add many more ‘C’ and ‘D’ pixels, see Figure 5 and Section 4, which contain the bands most sensitive to the CMB. Being able to pack 100’s of ‘C’ and ‘D’ pixels into the focal plane is what allows PICO to reach unprecedented levels of

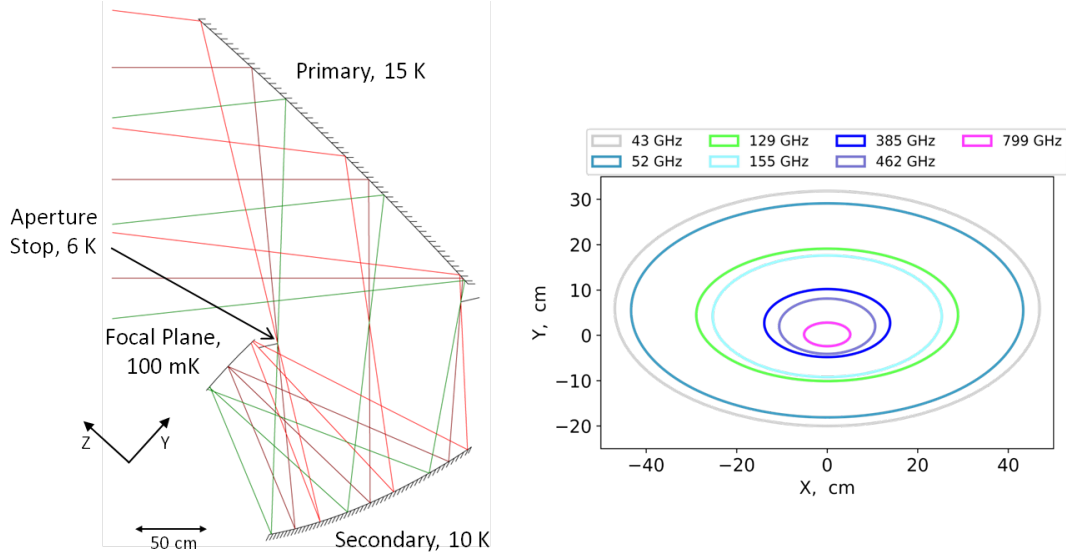


Figure 3. Raytrace (left) and Strehl = 0.8 contours (right) for the PICO optical design.

Table 1. Telescope geometric parameters

| PICO optical system           |           |           |                                   |         | Initial Open-Dragone <sup>b</sup> |       |
|-------------------------------|-----------|-----------|-----------------------------------|---------|-----------------------------------|-------|
|                               | Primary   | Secondary | Telescope parameters <sup>b</sup> |         | Fundamental design parameters     |       |
| Mirror size <sup>a</sup> (cm) | 270 × 205 | 160 × 158 | Aperture (cm)                     | 140     | Aperture (cm)                     | 140   |
| Radius of curvature (cm)      | ∞         | 136.6     | <i>F</i> -number                  | 1.42    | θ <sub>0</sub> (deg)              | 90    |
| Conic constant, <i>k</i>      | 0         | -0.926    | h (cm)                            | 624.2   | θ <sub><i>e</i></sub> (deg)       | 20    |
| Normalization radius (cm)     | 524.8     | 194.1     | α (deg)                           | 74.2    | θ <sub><i>p</i></sub> (deg)       | 140   |
| 4th Zernike Coefficient (cm)  | 2018.4    | -61.1     | β (deg)                           | 62.3    | L <sub><i>m</i></sub> (cm)        | 240   |
| 9th Zernike Coefficient (cm)  | -37.0     | 16.7      | L <sub><i>m</i></sub> (cm)        | 229.3   |                                   |       |
| 10th Zernike Coefficient (cm) | -2919.8   | -15.1     | L <sub><i>s</i></sub> (cm)        | 140.5   |                                   |       |
| 11th Zernike Coefficient (cm) | -1292.7   | 22.3      |                                   |         | Derived parameters                |       |
| 12th Zernike Coefficient (cm) | 120.6     | -3.8      |                                   |         | <i>F</i> -number                  | 1.42  |
| 13th Zernike Coefficient (cm) | -74.5     | 4.9       | Focal Surface                     |         | h (cm)                            | 624.2 |
| 19th Zernike Coefficient (cm) | -75.8     | 3.4       | Ellipse major axes (cm)           | 69 x 45 | α (deg)                           | 38.6  |
| 20th Zernike Coefficient (cm) | -398.9    | 6.3       | Ellipse major axes (deg)          | 19 x 13 | β (deg)                           | 101.4 |
| 21st Zernike Coefficient (cm) | -319.5    | 23.3      | Radius of curvature (cm)          | 455     | L <sub><i>s</i></sub> (cm)        | 122.2 |
| 22nd Zernike Coefficient (cm) | -276.6    | -8.5      |                                   |         | Primary, <i>f</i> (cm)            | 312.1 |
| 23rd Zernike Coefficient (cm) | -201.6    | -3.2      |                                   |         | Secondary, <i>a</i> (cm)          | 131   |
| 24th Zernike Coefficient (cm) | -127.4    | -1.9      |                                   |         | Secondary, <i>e</i>               | 1.802 |
| 25th Zernike Coefficient (cm) | -55.0     | 0.1       |                                   |         |                                   |       |

<sup>a</sup> The maximum physical size of the mirrors.

<sup>b</sup> Telescope parameters follow the definitions in Granet 2001.<sup>11</sup>

CMB sensitivity. Compared to the first optimization method, the second gives somewhat better performance at the lower frequencies, with 1.11 and 1.15 times large DLFOV at 21 and 155 GHz, respectively. Method two gives a smaller DLFOV at 799 GHz, only 0.3 times the method one area, but the DLFOV is still sufficient for the number of 799 GHz detectors we require. Figure 4 also shows the second optimization method reduces the overall telescope volume, allowing it to fit more easily within the shadow cone.

do you mean if we had only optimization method 1 we wouldn't reach our goals? not really, because the goals are poorly defined. But total CMB sensitivity would be lower with method 1 only.

The geometric parameters of the PICO optical system are given in Table 1. The system is diffraction limited for 799 GHz at the center of the field of view. At 155 GHz the DLFOV is 82.4 deg<sup>2</sup> and the total throughput for all frequencies is 910 cm<sup>2</sup>sr. Figure 3 shows Strehl of 0.8 contours for all pixel types. The slightly concave

focal surface, which has a radius of curvature of 4.55 m, is telecentric to within 0.12 deg across the entire FOV.

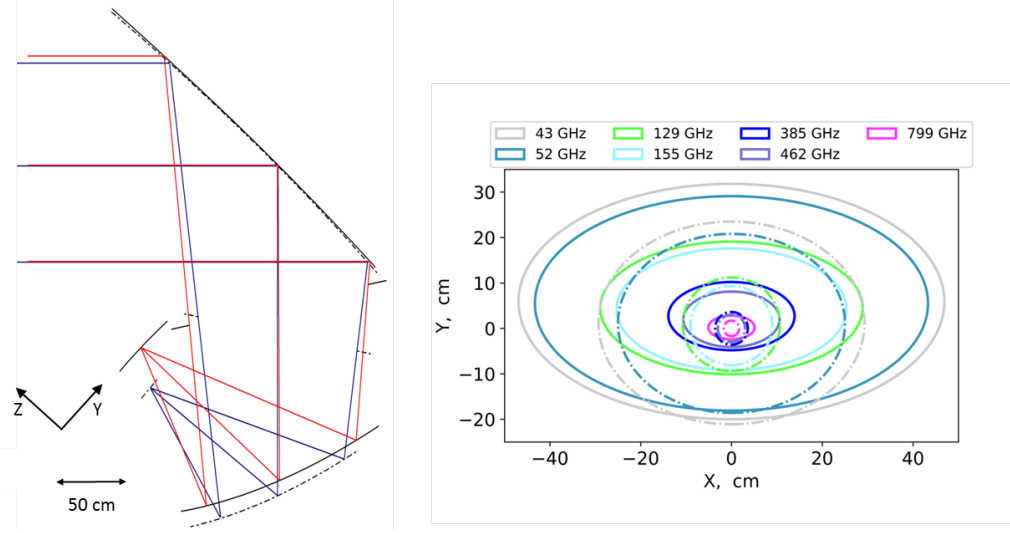


Figure 4. Comparison between the open-Dragone optimized using method two and the initial open-Dragone. The ray traces (left) are aligned at the chief ray impact point on the primary. The optimized system (red rays, solid mirrors) is smaller in the vertical direction than the unoptimized version (blue rays, dash-dot mirrors). The overlaid Strehl = 0.8 contours (right) show the improvement at all frequencies in the optimized (solid lines) system over the unoptimized (dash-dot lines) system.

An additional benefit of the optimization is the concave focal surface. The open-Dragone’s focal surface is naturally curved. Matching this curvature reduces defocus and increases the DLFOV as well as increasing telecentricity. The unoptimized system is telecentric to within 2.5 deg while the optimized version is telecentric to within 0.12 deg. If the focal surface is too strongly curved tiling it with flat detector wafers would result in large defocus at the edges of these wafers. This is not the case for PICO. The focal surface radius of curvature, 4.55 m, results in a defocus of 0.1 mm for the edge of a 10 cm wafer.

#### 4. FOCAL PLANE

Modern mm/sub-mm detectors are photon noise limited, therefore the primary way to increase sensitivity is to increase the number of detectors. **are there additional secondary ways?** The PICO focal plane has 12,996 detectors, 175 times the number flown on *Planck*. PICO achieves this by having a large DLFOV and using multichroic pixels (MCPs).<sup>12,13</sup> The MCP architecture assumed for PICO has three bands per pixel with two single polarization transition edge sensor (TES) bolometers per band and therefore six bolometers per pixel. We assume the MCPs are coupled to free space using lenslets and sinuous antennae,<sup>12</sup> but the focal plane layout, including pixel sizes, numbers, and spacing would not change significantly if horn or phased array coupling was used instead.

PICO has 21 overlapping bands with centers spanning the range 21–799 GHz. The bands are divided amongst nine pixel types labeled A to I; see Figure 5. The 25% fractional bandwidth is broader than the interband spacing causing neighboring bands to overlap and requiring them to be in separate pixels. The exceptions to the MCP architecture are the highest three bands, because they are above the superconducting band gap of niobium which is used for the transmission lines, antennae, and filters of the MCPs. For bands G, H, and I, we will use feedhorn-coupled polarization sensitive bolometers. The technology has high TRL as it has already been used successfully with *Planck*<sup>14</sup> and Herschel SPIRE.<sup>15</sup>

Figure 6 shows the PICO focal plane. We optimize the diameter of each MCP by calculating the array sensitivity for that pixel type. The calculation includes the increased illumination of the aperture stop as the pixel diameter decreases, as described in Section 5.1. We choose a pixel diameter of  $2.1F\lambda_{\text{mid}}$ , where  $\lambda_{\text{mid}}$  refers



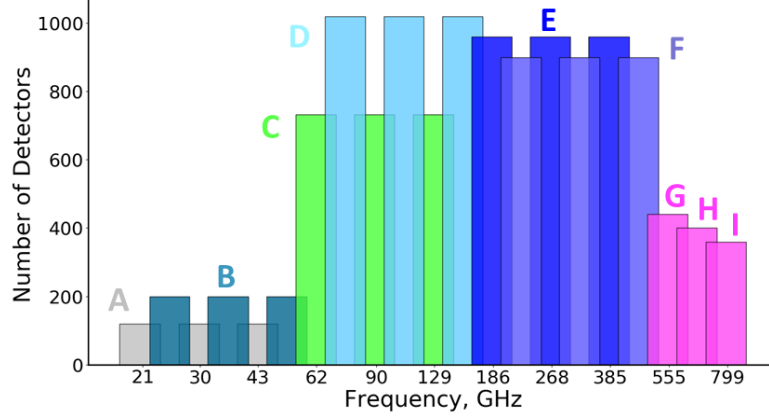


Figure 5. Frequency coverage of the PICO bands. Each color (excluding magenta) denotes a different MCP, labeled A-F. The bar height indicates the number of detectors per band. Bar width gives the bandwidth. All bands are top-hats with 25% fractional bandwidth; the  $x$ -axis is logarithmic. The three highest frequencies (magenta) are the single color pixels G, H, and I.

to the center band of each pixel. This gives an edge taper,  $T_e$ , on the stop of 10 dB for the center band of each pixel.

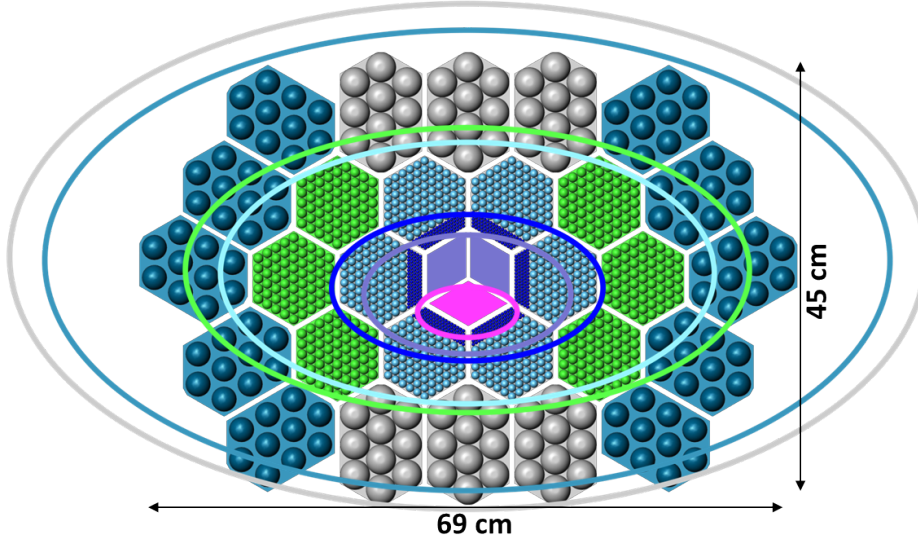


Figure 6. PICO focal plane layout with Strehl = 0.8 contours for each pixel type. The pixel and Strehl contour colors match the band colors, A-I, in Figure 5

Differencing detectors that are sensitive to orthogonal polarization states enables each pixel to make a measurement of a particular Stokes parameter. Pixels that are sensitive to the  $U$  Stokes parameter are rotated by 45 deg relative to those that are sensitive to  $Q$ . This Q/U measurement is in the instrument reference frame with the  $x$ -axis parallel to the scan direction; see Figure 7.

The PICO focal plane readout has been designed around  $\times 128$  time domain multiplexing (TDM), but this choice is not a significant driver for the focal plane layout or overall noise budget.

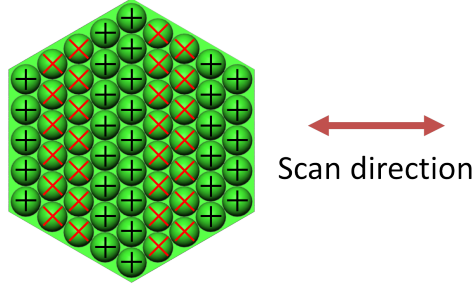


Figure 7. Layout of pixels sensitive to Stokes Q (black crosses) and Stokes U (red exes) for an example wafer.

## 5. INSTRUMENT NOISE

We develop an end to end noise model of the PICO instrument to predict full mission sensitivity and provide a metric by which to evaluate mission design trade-offs. This model assumes white noise at all frequencies. The overall sensitivity does not include calibration uncertainties or estimates of other possible systematic effects. To construct the model we estimate the optical load, calculate noise equivalent power (NEP) by source, combine all NEP terms to get detector noise, combine all detectors to get noise per frequency band, and then include total mission time to find overall mission sensitivity.<sup>16,17</sup> Each of these steps includes various assumptions and design decisions, which are discussed in this section. The assumptions are summarized in Table 2.

what's important here is how do we know that the model is correct. How was it checked and validated? See following. An aside, what is the normal or natural way to refer to work done by coauthors on the paper? Saying 'we' all the time seems odd, but so does talking about work done by coauthors as if it is separete from the main work written up in this paper.

To validate our model we compare to an independent calculation done by collaborators at JPL. The calculations agree within 1% for individual noise terms and for overall mission noise. We also use our model to calculate CORE and LiteBIRD noise using published system parameters. The results are consitent with published values. Additionally, we compare PICO detector noise to CORE and LiteBIRD detector noise. The lower PICO noise is explained by the cold system and differing optical efficiency. From these test we conclude that our model is correct and our assumptions are reasonable. I'm not a huge fan of this paragraph. It is fairly wishy-washy, but is the best I can do for now.

### 5.1 Single bolometer noise

#### 5.1.1 Model

The sources of optical load are the CMB, the primary and secondary mirrors, the aperture stop, and a low pass optical filter. These elements are shown schematically in Figure 8. The total load absorbed at the bolometer is the sum of the power emitted by each element reduced by the transmission efficiency of the elements between the emitting surface and the bolometer. The absorbed power is

$$P_{\text{abs}} = (((P_{\text{CMB}}\eta_{\text{PRI}} + P_{\text{PRI}})\eta_{\text{stop}} + P_{\text{stop}}(1 - \eta_{\text{stop}}))\eta_{\text{SEC}} + P_{\text{SEC}})\eta_{\text{filter}} + P_{\text{filter}})\eta_{\text{bolo}}, \quad (1)$$

where  $P_{\text{elem}}$  is the in band power emitted by a given element for a single polarization and  $\eta_{\text{elem}}$  is the transmission efficiency of the element. Power emitted by the stop is a special case. We multiply  $P_{\text{stop}}$  by  $(1 - \eta_{\text{stop}})$  because  $\eta_{\text{stop}}$  is the spillover efficiency, the fraction of the throughput which passes through the stop. Therefore  $(1 - \eta_{\text{stop}})$  is the fraction of the throughput which views the stop.

For PICO, the CMB and stop account for the majority of the optical load at all frequencies. The jumps in load between neighboring bands, seen in Figure 9 around 70 and 200 GHz, are due to  $\eta_{\text{stop}}$  changing with frequency which is a consequence of using MCPs. The MCP angular beam width depends on the wavelength and pixel diameter as<sup>16</sup>

$$\theta_{1/e^2} = \frac{2.95\lambda}{\pi D_{\text{px}}}. \quad (2)$$



Table 2. Noise model parameters, see text for details.

|   |   |
|---|---|
| Throughput  | single moded, $\lambda^2$   |
| Fractional Bandwidth                                | 25%   |
| Mirror emissivity                                   | $\epsilon = \epsilon_0 \sqrt{\nu/150 \text{ GHz}}, \epsilon_0 = 0.07\%$ |
| Aperture stop emissivity                            | 1   |
| Low pass filter reflection loss                     | 8%  |
| Low pass filter absorption loss <sup>a</sup>        | frequency dependent, 0.2%–2.8%  |
| Bolometer absorption efficiency                     | 70%   |
| $T_e$ of low, middle, and high bands (dB)           | 4.8, 10.0, 20.7   |
| $\eta_{\text{stop}}$ of low, middle, and high bands | 0.68, 0.90, 0.99  |
| Bose noise fraction, $\xi$                          | 1   |
| Bolometer yield                                     | 90%   |
| Bath temperature, $T_o$ (mK)                        | 100   |
| TES critical temperature, $T_c$ (mK)                | 187   |
| Safety factor, $P_{\text{sat}}/P_{\text{abs}}$      | 2   |
| Thermal power law index, $n$                        | 2   |
| Intrinsic SQUID noise (aW/ $\sqrt{\text{Hz}}$ )     | 3   |
| TES operating resistance, $\Omega$                  | 0.03  |
| TES transition slope, $\alpha$                      | 100   |
| TES loop gain                                       | 14  |
| Mission length (years)                              | 5   |
| Observing efficiency                                | 95%   |

<sup>a</sup>Assumes separate metal mesh in polypropylene filters for each wafer.

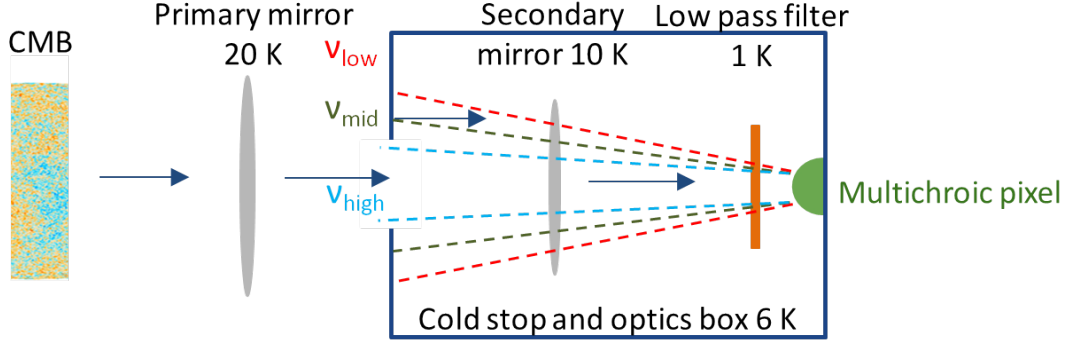


Figure 8. Schematic representation of the prediction of optical load. Power emitted by each element is modified by the efficiency of the following elements and added to the total expected load. The multichroic pixel illuminates the stop differently for each of the three bands.

The edge taper,  $T_e$ , of the middle frequency band in each pixel is chosen to be 10 dB. For the upper and lower bands  $T_e$  is calculated using Equation 2. This changing illumination of the stop is shown schematically by the dashed rays in Figure 8. For each MCP in pixels A-H  $T_e$  is 4.8, 10, and 20.7 dB for the lower, middle, and upper bands, respectively. These edge tapers correspond to  $\eta_{\text{stop}}$  of 0.68, 0.90, and 0.99. The changing  $\eta_{\text{stop}}$  has two main effects; changing optical efficiency between bands, which affects optical load and the NEP to noise equivalent temperature (NET) conversion, and telescope beam size not scaling smoothly with  $\lambda$ .

We consider four noise sources per bolometer; photon, phonon, TES Johnson, and readout. Photon noise depends on the absorbed power,<sup>18</sup>

$$NEP_{\gamma}^2 = \int_{\text{band}} 2h\nu p_{\nu} d\nu + 2\xi \int_{\text{band}} p_{\nu}^2 d\nu, \quad (3)$$

where  $p_{\nu}$  is the power spectral density for a single polarization absorbed at the bolometer and  $\xi = 1$  is the fraction

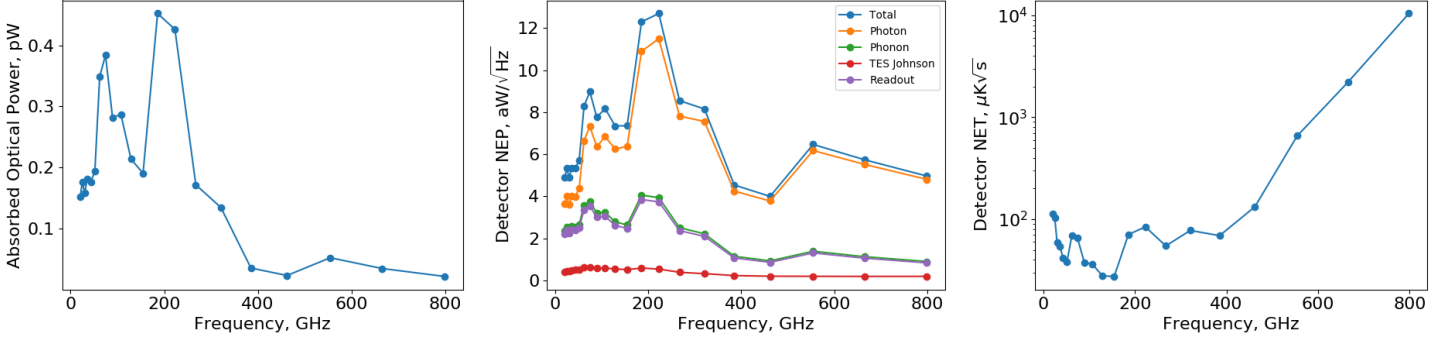


Figure 9. Left: Expected optical load as a function of frequency for single polarization PICO bolometers. Center: Breakdown of NEP across the PICO frequency range. Photon noise dominates even at the lowest frequencies. Right: Single detector NET, temperature sensitivity **what does that mean? as opposed to polarization sensitivity which is lower by  $\sqrt{2}$ . Although maybe that is obvious as it is for 1 detector?**, across the PICO bands.

of correlated Bose photon noise. We include a factor of 2 in the Bose noise term because the bolometers receive the power from a single polarization. From  $P_{\text{abs}}$  we calculate the TES bolometer properties and phonon noise.<sup>19</sup> The last noise term intrinsic to the bolometer is the TES Johnson noise **aren't we using the same Johnson noise for all bolos? I don't understand this question. All bolos have Johnson noise, but it depends on voltage bias, so it varies band to band..** All noise sources in the cold and warm readout electronics are lumped under the readout term. The NEPs for each noise source as a function of frequency are shown in Figure 9.

### 5.1.2 Results

The primary driver of noise levels is the optical load. The combination of the CMB and aperture stop make up the majority of the load in all bands. The load from the mirrors is greatest at 799 GHz where it is 47% of the total optical load. The CMB provides more than half the load in the middle and upper bands of the multichroic pixels, but the stop dominates the load in the lowest band of each pixel. Load from the stop in the lowest band of each pixel ranges from 1.2 times the CMB load at 21 GHz to a maximum of 4.7 times the CMB load at 223 GHz.

For PICO, photon noise dominates at all frequencies as shown in Figure 9. Bose noise is most significant at lower frequencies with  $\text{NEP}_{\text{Bose}}/\text{NEP}_{\text{Poisson}} = 1.5$  in the lowest band. However, Poisson noise increases as  $\sqrt{P_{\text{abs}}\nu}$  while Bose is proportional to  $P_{\text{abs}}$ , so Poisson noise equals Bose noise at 30 GHz and dominates at higher bands;  $\text{NEP}_{\text{Bose}}/\text{NEP}_{\text{Poisson}} < 10\%$  at 321 GHz. Phonon noise is the second most significant source,  $\text{NEP}_{\text{phonon}}/\text{NEP}_{\text{photon}}$  ranges from 65% at 21 GHz to 19% at 799 GHz.

For TDM readout, phonon and readout noise are roughly equal with TES Johnson noise being insignificant. We also modeled frequency domain multiplexing (FDM) readout. For FDM the TES Johnson noise is higher, 2/3 of the readout NEP, but the readout noise is lower. Comparing the combined TES Johnson and readout NEPs for TDM and FDM we find essentially identical performance with total noise differing by less than 3% across all bands. For both systems we require a focal plane temperature,  $T_o$ , of 100 mK and a bolometer safety factor of 2 to remain photon noise dominated at the lowest bands. **should we have Dobbs review this? I don't think it is necessary. But you're more familiar with the politics of this one. Dobbs isn't a co-author, if that matters.**

### 5.2 Combined array noise

Using single detector NEPs from Section 5.1 and the detector counts from Section 4 we calculate the combined NEP of the detector array for each band. Combining detectors simply reduces noise by  $\sqrt{N}$  except for Bose photon noise. For the lowest band of each MCP the pixels over sample the PSF, pixel spacing is  $0.4F\lambda$ , resulting in correlated Bose noise between pixels. Accounting for this effect gives a 26% increase in the combined array NEP of the lowest band, 21 GHz, and a 0.003% increase in array NEP at the highest band, 799 GHz.

From the array  $NEP$  we convert to  $NET$  per band,

$$\frac{NEP}{NET} = \sqrt{2} \eta_{\text{opt}} \int_{\text{band}} \left. \frac{dp_\nu}{dT} \right|_{T_{\text{CMB}}} d\nu. \quad (4)$$

The  $\eta_{\text{opt}}$  term contributes to the ‘jumps’ in  $NET$  seen in Figure 9, because  $\eta_{\text{opt}}$  varies band to band.

All the above calculations are for sensitivity to temperature and are given in Table 3. Assuming evenly weighted observations of the full sky and 5 years observing at 95% efficiency, we calculate full mission map sensitivities in polarization; final column in Table 3. Combining all bands gives a total CMB map depth for the entire PICO mission of  $0.62 \mu\text{K}_{\text{CMB}}\text{-arcmin}$ .

Table 3. PICO frequency channels and noise.

| Pixel Type | Band GHz | FWHM arcmin | Bolometer NEP $\text{aW}/\sqrt{Hz}$ | Bolometer NET $\mu\text{K}_{\text{CMB}}\sqrt{s}$ | $N_{\text{bolo}}$ | Array NET $\mu\text{K}_{\text{CMB}}\sqrt{s}$ | Polarization map depth                   |       |
|------------|----------|-------------|-------------------------------------|--|-------------------|--|--|-------|
|            |          |             |                                     |  |                   |  | $\mu\text{K}_{\text{CMB}}\text{-arcmin}$ | Jy/sr |
| A          | 21       | 38.4        | 4.89                                | 112.2  | 120               | 13.6   | 19.2                                     | 6.69  |
| B          | 25       | 32.0        | 5.33                                | 103.0  | 200               | 9.56   | 13.5                                     | 7.98  |
| A          | 30       | 28.3        | 4.92                                | 59.4   | 120               | 5.90   | 8.31                                     | 7.93  |
| B          | 36       | 23.6        | 5.36                                | 54.4   | 200               | 4.17   | 5.88                                     | 9.59  |
| A          | 43       | 22.2        | 5.33                                | 41.7   | 120               | 4.01   | 5.65                                     | 13.9  |
| B          | 52       | 18.4        | 5.73                                | 38.4   | 200               | 2.86   | 4.03                                     | 16.8  |
| C          | 62       | 12.8        | 8.29                                | 69.2   | 732               | 3.13   | 4.42                                     | 37.0  |
| D          | 75       | 10.7        | 8.98                                | 65.4   | 1020              | 2.47   | 3.47                                     | 48.1  |
| C          | 90       | 9.5         | 7.76                                | 37.7   | 732               | 1.49   | 2.10                                     | 44.5  |
| D          | 108      | 7.9         | 8.18                                | 36.2   | 1020              | 1.21   | 1.70                                     | 57.0  |
| C          | 129      | 7.4         | 7.35                                | 27.8   | 732               | 1.09   | 1.53                                     | 69.7  |
| D          | 155      | 6.2         | 7.36                                | 27.5   | 1020              | 0.91   | 1.28                                     | 84.6  |
| E          | 186      | 4.3         | 12.30                               | 70.8   | 960               | 2.52   | 3.54                                     | 383   |
| F          | 223      | 3.6         | 12.70                               | 84.2   | 900               | 3.05   | 4.29                                     | 579   |
| E          | 268      | 3.2         | 8.55                                | 54.8   | 960               | 1.87   | 2.62                                     | 369   |
| F          | 321      | 2.6         | 8.16                                | 77.6   | 900               | 2.73   | 3.84                                     | 518   |
| E          | 385      | 2.5         | 4.54                                | 69.1   | 960               | 2.35   | 3.31                                     | 318   |
| F          | 462      | 2.1         | 4.00                                | 132.6  | 900               | 4.66   | 6.56                                     | 403   |
| G          | 555      | 1.5         | 6.47                                | 657.8  | 440               | 33.1   | 46.5                                     | 1569  |
| H          | 666      | 1.3         | 5.74                                | 2212   | 400               | 117  | 164                                      | 1960  |
| I          | 799      | 1.1         | 4.97                                | 10430  | 360               | 560  | 816                                      | 2321  |
| Total      |          |             |                                     |  | 12996             | 0.46   | 0.65                                     |       |

## 6. CONCLUSIONS/SUMMARY

The PICO optical system is a simple two mirror open-Dragone which we numerically optimize to maximize the DLFOV. The addition of a cold aperture stop and cold mirrors minimize optical load and reduce noise. The focal plane takes advantage of the large DLFOV and MCP technology to implement 12996 polarization sensitive detectors in 21 bands from 21-799 GHz. When combining all bands, our instrument noise model predicts full mission polarization map depth of  $0.62 \mu\text{K}_{\text{CMB}}\text{-arcmin}$ .

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