Request for Information
Astro2020 Decadal Survey – Early Stage Space Concepts Questionnaire

Overview

Your project is being sent this request for information to help assess its technical readiness and required funding levels for development and implementation. For projects not ready for a start in the next decade, the survey wishes to understand the funding needs for technology maturation, or any technology demonstration activities required to prepare for future implementation.

The National Academies of Sciences, in consultation with the survey committee chairs, have contracted with the Aerospace Corporation to provide an independent Technical, Risk and Cost Evaluation (TRACE). In some cases, the information requested here may be used as input to this evaluation.

Projects being considered by the survey are at different stages of definition, and so we ask that you complete the request for information below to the best of your ability. If you do not have the detail in the format requested, please provide the information you have.

We are not providing strict page allocations for your response -- these should be dictated by project readiness and what you feel you require. We do, however, urge you to be as succinct as possible. We outline the basic structure for the document to guide you in your response. If the requested information exists in publicly available documents you may point to the pages where the information is provided. If you do refer to other documents, please provide copies of them, or links to the location where they can be downloaded.

We also request that you ensure that any written responses or diagrams that you include do not include ITAR/EAR-controlled information, as these responses must be made public if requested.

1. Executive Summary

Introduction: An “Inflation Probe” was competitively selected by NASA for Probe mission study. The Probe of Inflation and Cosmic Origins (PICO) is the result of this study. Both this response to the RFI and the 10-page PICO APC whitepaper rely on, and draw from the 50-page mission study report, which we henceforth refer to as the PICO Report (**PR**). Throughout this response we point the reader to the relevant sections in the **PR**; in some of our responses we assemble information that is otherwise scattered throughout the **PR**, or was not provided for lack of space.

The **PR** is posted on the arXiv (https://arxiv.org/abs/1902.10541), on NASA Decadal Survey webpage (https://science.nasa.gov/astrophysics/2020-decadal-survey-planning), and on the PICO website, which has additional supporting documents (https://z.umn.edu/picomission). The PICO APC white paper is Hanany et al. 2019 (https://arxiv.org/abs/1908.07495).

1. **Summarize your science objectives and your technical implementation at a high level.**

   The Executive Summary of the **PR** (Section 2, Pg. 1) gives a high-level summary of the science objectives (SOs) and the technical implementation.

2. **Summarize the technology maturity of your implementation, listing the demonstrated technologies and the technologies requiring development.**

   Technology maturity of the PICO focal plane detectors and readout is discussed in Section 5 of the **PR** (pg. 43, “Technology Maturation”); Cooling Technology requires only standard engineering and is discussed in Section 3.4 (pg. 37, “Thermal”, which is a sub-section of the instrument description).

   PICO utilizes focal plane and readout technologies that are available today, many of which are in-use by sub-orbital experiments. Adaptation of these detector technologies to the low optical background of space is required; repackaging of previously used technologies is required for the high frequency bands ($\nu > 500$ GHz). No basic physics challenges are anticipated, and current NASA technology development funding in the context of the LiteBIRD project already aims to mature the low frequency detector technologies ($\nu < 400$ GHz) for space applications. A recently-funded NASA 2019 SAT grant has begun maturing some of the PICO technologies.

3. **Summarize areas where the data to support this RFI are not currently available.**

   NASA funding for this Probe study supported significant mission concept maturation through the combined efforts of the PICO team and Team X (JPL’s concurrent design facility), therefore the majority of the data to support this RFI is available and provided here and in the **PR**. However, PICO is a pre-Phase A concept study, and a subset of the data requested in this RFI are neither standard Team X products, nor were requested or funded by the NASA study.

   <u>Definitions of Institutional Responsibilities</u>: There are multiple organizations capable of managing the PICO mission, and of delivering its subsystems (including the instrument,

spacecraft, and mission/ground system). The PICO study keeps these options open, and doesn't name definitive institutional responsibilities.

<u>Schedule</u>: We provide an overall schedule with mission phase durations and notional review dates (**PR** Table 6.1). These are based on actual schedule durations from similarly sized missions. This schedule was used by Team X for cost estimation. However, Team X does not produce, and we do not have available a detailed mission-specific schedule with instrument and spacecraft development time and critical path.

<u>Risks</u>: The **PR** has discussion of important risks (**PR** §6.4). The scope of the mission study did not support specification of these risks in great detail, nor rating them against the standard NASA 5×5 Likelihood and Consequence matrix.

<u>TRL</u>: Neither the PICO team nor JPL's TeamX conducted a formal review of TRL levels for the mission elements. Where appropriate, we provide estimated TRLs.

2. Science Overview

1. Briefly describe the scientific objectives and the most important measurements required to fulfill these objectives. Feel free to refer to science whitepapers or references from the literature.

The PICO SOs are described in Section 2 (Science) of the **PR** (pg. 4). The report also includes a science traceability matrix (Table 1.3, pg. 3) that provides a listing of the seven objectives together with required quantitative constraints, the derived mission requirements, and the instrument and mission that respond to these requirements. We provide the SOs here together with a succinct summary, placing the PICO measurements in the astrophysical context of the next decade as supported by recent whitepapers.

SO1: "Probe the physics of the big bang by detecting the energy scale at which inflation occurred if it is above 5×10^{15} GeV, or place an upper limit if it is below".

In their inflation science whitepaper Shandera et al. set target thresholds for B-mode experiments in the next decade. They write *"If these thresholds are passed without a detection, most textbook models of inflation will be ruled out; and, while the possibility of an early inflationary phase would still remain viable, the data would then force a significant change in our understanding of the primordial Universe."* (Shandera et al. 2019, https://arxiv.org/abs/1903.04700). PICO is the **only** instrument proposed for the next decade that can confidently reject the target thresholds set by Shandera et al.

If the currently-favored Starobinski model is the correct model of inflation, PICO is the only next decade experiment that would make independent 5σ detections in distinct patches of the sky, and with different independent sub-sets of frequency bands, for the entire range of possible models.

SO2: "Probe the physics of the big bang by excluding classes of potentials as the driving force of inflation" (Shandera et al., Slosar et al. 2019, https://arxiv.org/abs/1903.09883 and Meerburg et al. 2019, https://arxiv.org/abs/1903.04409).

PICO's constraints on classes of inflation potentials will be the strongest of any CMB experiment proposed for the next decade (Lee et al. 2019BAAS...51g.286L, Lee et al. 2019BAAS...51g.147L, Carlstrom et al. 2019BAAS...51g.209C).

SO3: "Determine the sum of neutrino masses" (Dvorkin et al. 2019, https://arxiv.org/abs/1903.03689).

Dvorkin et al. write: "*Our understanding of the clustering of matter in the presence of massive neutrinos has significantly improved over the past decade, yielding cosmological constraints that are tighter than any laboratory experiment, and which will improve significantly over the next decade, resulting in a guaranteed detection of the absolute neutrino mass scale*."

PICO would constrain the sum of neutrino masses at a level of $\sigma(\Sigma m_\nu) = 14$ meV, a constraint that will not be surpassed in the next decade. It will determine the sum of neutrino masses with three independent techniques: CMB lensing, cluster counts, and galaxy-lensing cross-correlations. For the CMB lensing technique, PICO is the only CMB experiment to measure both the lensing map and the optical depth to reionization τ, which are required for determination of $\sigma(\Sigma m_\nu)$. All cosmological surveys striving to constrain $\sigma(\Sigma m_\nu)$ at this precision will require a constraint on τ at the level provided by PICO.

SO4: "Tightly constrain the thermalized fundamental particle content of the early Universe" (Green et al. 2019, https://arxiv.org/abs/1903.04763).

Quoting from Green et al. "*Measurements in the coming decade will be sensitive to decoupling temperatures that are orders of magnitude higher than current experiments, and able to reveal new physics that will be inaccessible in any other setting*."

PICO will be more sensitive to light relics than all cosmic surveys planned in the next decade except for CMB-S4 that has equal sensitivity.

SO5: "Distinguish between models that describe the formation of the earliest luminous sources in the Universe" (Alvarez et al. 2019, https://arxiv.org/abs/1903.04580).

Alvarez et al. state that measurements of τ, the optical depth to reionization, "constrain the early reionization 'tail' which would place significant constraints on theories of early star formation, including X-ray binaries and massive Population III stars."

PICO will measure the optical depth to reionization to cosmic variance limit.

SO6: "Test models of the composition of Galactic interstellar dust" (Hensley et al.

2019BAAS...51c.224H).

Hensley et al. write "*Observations of polarized dust emission are an important window into the material composition of interstellar grains, and new data will enable definitive tests of dust modeling paradigms that remain unsettled despite decades of effort*."

PICO's 21 frequency bands and high polarimetric sensitivity will discriminate between competing models for the physics of the diffuse dust emission in the Galaxy at fidelity unmatched by any other experiment in the next decade. The full sky coverage, which only PICO can provide, enables these critical tests to be done along all possible sightlines thereby testing the variation in dust properties in the entire Milky Way.

SO7: "Determine if magnetic fields are the dominant cause of low Galactic star-formation efficiency" (Fissel et al. 2019, https://arxiv.org/abs/1903.08757).

In their science whitepaper Fissel et al. write "*Understanding the physics of how stars form is a highly-prioritized goal of modern Astrophysics, in part because star formation is linked to both galactic dynamics on large scales and to the formation of planets on small scales*."

PICO is the only next decade mission that will provide the requisite combination of full sky coverage, angular resolution, and frequency breadth to develop a complete picture of interstellar magnetic fields and magnetized turbulence over spatial scales from cloud cores (0.1 pc) to the diffuse ISM (10^4 pc).

Broader Impact: The science PICO will deliver extends beyond the seven science objectives to include placing constraints on dark matter (https://arxiv.org/pdf/1903.05140.pdf), tracing the evolution of structures in the Universe (https://arxiv.org/pdf/1904.04531.pdf, https://arxiv.org/pdf/1903.04944.pdf) probing feedback mechanisms in galaxy formation (https://arxiv.org/pdf/1903.04647.pdf) , understanding of the nature of radio sources and of anomalous microwave emission (https://arxiv.org/pdf/1904.05769.pdf, https://ui.adsabs.harvard.edu/abs/2019BAAS...51c.430M/abstract), and forming the cosmological paradigm of the 2030s (**PR** Section 2.4, pg. 16).

Measurements Required: PICO will achieve these science goals by conducting 10 redundant full sky surveys with combined required map depth of 0.87 μK·arcmin (0.61 μK·arcmin current best estimate), with 21 frequency bands spread between 20 and 800 GHz, and diffraction limited resolution between 38 and 1 arcminute full-width-half-maximum, respectively; see **PR** Table 1.3.

2. Of the objectives, which are the most demanding? Why?

The most demanding objective is SO1. The tensor-to-scalar ratio r is a parameter that quantifies SO1. Reaching an error $\sigma(r) = 1 \times 10^{-4}$ in the measurement of r will require accounting for Galactic foregrounds, for confusion between primordial CMB B-modes and B-modes from other sources (lensing), and for systematic errors at levels that have not yet been demonstrated.

Measurements required for SO1 drive most of the design of the mission.

Galactic foregrounds are known to be stronger than the expected signal, and there are no data available about the foregrounds at the precision required; see **PR** Section 2.7 (pg. 23). Simulations described in the **PR** indicate that PICO's combination of sensitivity and 21 frequency bands are adequate to reach the level required.

PICO's map of the B-modes from lensing, which will have higher signal-to-noise ratio than any other survey up to angular scale $\ell \sim 1000$ (see **PR** Section 2.3.2, Fig. 7, pg. 13), will be used to separate the lensing signal from that generated by an inflationary epoch.

The **PR** (Section 2.8, pg. 27) describes our analysis of several sources of systematic uncertainties; we chose to investigate this subset because of their potential impact on the science results. We conclude that due to PICO's high sensitivity they can be mitigated to the levels required.

We make the following additional comments in regard to mitigation against Galactic foregrounds and systematic effects.

Simulations: In the **PR** we advocate for continued effort of simulations that include more extensive modeling of Galactic foregrounds and systematic effects. We refer to this simulator package in this RFI, for example, in Section 4 (Technical Implementation – Mission Design), Question 2, and Section 4 Question 5.[1]

Foregrounds: PICO's high sensitivity and broad frequency coverage make PICO better suited than other experiments to reach any r goal targeted for the next decade. Ultimately, direct high-fidelity measurements, such as those provided by PICO, are the only way to account for foreground confusion.

Systematics: PICO is the only next decade survey that can detect r=0.001 in two independent patches of the sky, or using independent subsets of its frequency bands; each of the independent detections would have 5σ confidence. Independent, high confidence measurements give the strongest immunity against foregrounds and systematic error biases.

3. **Present the highest-level technical requirements (e.g. spatial and spectral resolution, sensitivity, timing accuracy) and their relation to the science objectives.**

   The technical requirements are summarized in Tables 1.2 and 1.3 of the **PR** (pg. 3), and they are described in more detail in Section 2.10 of the **PR** ('Measurement Requirements', pg. 32). Technical requirements are placed on depth, sky coverage, frequency bands, resolution, and the sky scan pattern.

4. **For each performance requirement, present as quantitatively as possible the sensitivity of your science goals to achieving the requirement. For example, if you fail to meet a**

[1] Hyperlinks to internal document locations are active only with Word.

key requirement, what would be the impact be on achieving the science objectives?

Depth: 'Depth' is a combination of inherent instrument noise and integration time per sky pixel. The required and current best estimate (CBE) RMS polarization measurement noise for a 1x1 arcminute^2 pixel at the end of the mission life-time are 0.87 and 0.61 μK·arcmin, respectively. All mission requirements will be achieved with the required depth, which has a factor of $\sqrt{2}$ margin relative to the CBE.

The *Planck* space mission, which also used bolometric detectors, demonstrated that detector noise levels predicted on the ground have been achieved in flight. PICO has 13,000 detectors. The conservative margin between the required and CBE depth levels is equivalent to the loss of 6500 detectors, or to a survey lasting only 2.5 years instead of the scheduled 5. Reduction in depth beyond the required value will gradually degrade PICO's abilities to achieve its SOs, with most initial impact occurring for SO1.

Sky Coverage: Achieving PICO's science goals does not require full sky coverage. There is negligible degradation for 90% sky survey. We did not investigate sensitivity to lower sky fractions because with the mission's single observing mode, 50% of the sky is covered within two weeks, and the entire sky is scanned over 6 months. The mission has ten such redundant surveys.

Frequency Bands: PICO's lowest and highest frequency bands near 20 and 800 GHz provide mitigation from Galactic foregrounds. PICO's highest frequency band at 800 GHz gives the angular resolution that is required for achieving SO7. Loss of information from an entire frequency band is unlikely as it represents loss of information from hundreds of independent detectors. Even in that unlikely case, foreground mitigation relies on the combination of several frequency bands and performance degradation is estimated to be mild. However, simulations shown in the **PR** (Section 2.7.3, pg. 26) indicate that simultaneous loss of information from several low and high frequency bands, leaving only frequency coverage between 40 and 400 GHz, would be detrimental to achieving SO1. Loss of the highest frequency band would degrade the mission's capability to achieve SO7.

Sky Scan Pattern: The repetitive scan pattern is composed of only three parameters: the spin rate of the instrument, precession rate of the spacecraft about the anti-sun direction, and the angle α of the precession cone (see **PR** Section 4.1.2, pg. 40). Varying these parameters within 30% of their nominal values will not adversely affect the mission. Larger deviations may also be possible, with the following caveats: (1) The spin rate can be slowed by a factor of 2, but effects of 1/f noise on the final results would have to be re-simulated and evaluated; The spin rate could be accelerated by a factor of 2 (or more), but effects on total power consumption and spacecraft attitude control will need to be evaluated. (2) The precession rate could be slowed or accelerated by a factor of 2, but effects on spacecraft dynamics, and mitigation of systematic uncertainties will need to be re-evaluated.

3. Technical Implementation - Instrumentation

1. **Describe the proposed science instrumentation, and briefly state the rationale for its selection. Discuss the specifics of each instrument (Inst #1, Inst #2 etc) and how the instruments are used together.**

   PICO meets all of its science-derived instrument requirements with a single instrument: an imaging polarimeter with 21 logarithmically spaced frequency bands centered between 21 and 799 GHz. The instrument is described in **PR** §3 (“Instrument”), including §3.1 (“Telescope”), §3.2 (“Focal Plane”), §3.3 (“Detector Readout”), §3.4 (“Thermal”), and §3.5 (“Instrument Integration and Test”). The instrument was selected based on science requirements flow down, technology readiness, and technical heritage. The PICO instrument builds on experience with the *Planck* HFI instrument. Similar instruments are currently used in ground and balloon-borne experiments giving extensive community technical heritage.

2. **Indicate the technical maturity level of the major elements and the specific instrument TRL of the proposed instrumentation (for each specific Inst #1, Inst#2 etc), along with the rationale for the assessment (i.e. examples of flight heritage, existence of breadboards, prototypes, mass and power comparisons to existing units, etc). For any instrument rated at a Technology Readiness Level (TRL) of 5 or less, please describe the rationale for the TRL rating, including the description of analysis or hardware development activities to date, and its associated technology maturation plan.**

   All technologies at TRL less than 5 are discussed in **PR** §5 (“Technology Maturation”). These technologies are in the TRL 4-5 range. The **PR** discusses taking these technologies to TRL 5. All of the required developments are straightforward evolutionary steps from existing technologies. TRL 5 technologies will be developed to TRL $\geq$ 6 in Phases A and B, prior to the Preliminary Design Review (PDR).

   *Please note: there is a typo in **PR** Table 5.1: Task 2 should read “Direct absorbing arrays ν>550 GHz.”*

   The 4.5 K cooler (**PR** §3.4.2) is a direct extension of the JWST MIRI design. Standard engineering is required to adapt it for PICO’s requirements. The MIRI cooler has demonstrated precooling and J-T loop cooling to 6.5 K; modifications to reach 4.5 K entail optimizing the design for the different material properties of the working fluids (3He and 4He) at the appropriate temperature. Distributed cooling following J-T expansion in a circulated-gas loop was demonstrated on *Planck* in a two-phase system, which is a significantly more challenging architecture. As described in **PR** §3.4.2, there are at least two potential industry sources for 4.5 K coolers (Ball Aerospace and NGAS) who have relevant systems and are actively developing them in a direction that would meet PICO’s requirements with >100% margin. The NGAS cooler has completed PDR-level development and is expected to reach CDR before PICO would begin Phase A.

3. **In the area of instrumentation, what are the top five technical issues or risks?**

   The PICO design meets the requirements associated with the NASA Class B risk classification. PICO's healthy contingencies, margins, and reserves provide flexibility to address risks realized during mission development and operations. PICO carries >40% instrument sensitivity margin, >100% heat lift margin, 43% system power contingency, and 31% instrument mass contingency. The PICO budget includes 30% cost reserves for Phases A–D.

   Risk: Technologies included in the PICO baseline are not matured to TRL 5 prior to Phase A due to funding limitations or technical challenges. *Consequence:* Technology development is performed prior to the beginning of mission development, and is outside of the mission cost (per NASA direction), therefore this risk does not represent threat to the cost of mission development. Rather, the technology development risk affects the availability of components for the baseline mission. Technology-related mission descopes, which can accomplish PICO science objectives, are described in **PR** §5.5. *Mitigation*: A technology maturation plan has been developed that is within the scope of the APRA and SAT programs (**PR** §5). Multiple US institutions have the relevant expertise to pursue the technology development program.

   Risk: Delivery of flight detectors is delayed due to production challenges. *Consequence*: Schedule and/or cost impact. Or, accept detector tiles with lower yield or reduced performance (with some reduction in instrument sensitivity margin; see **PR** §3.2.4, or this RFI Section 2, Question 4). *Mitigation*: Begin fabrication early in the project life cycle and fabricate a generous number of detector wafers to ensure adequate yield. Multiple institutions (including, for example, JPL, GSFC, NIST, and ANL) would be capable of producing the PICO detectors.

   Risk: Design and implementation of the thermal system adds unforeseen complexity as the project progresses. *Consequence*: Cost and possibly schedule impact. Or, an increase in the temperatures of the reflectors might be accepted (with some reduction in instrument sensitivity margin; see **PR** §3.2.4). *Mitigation*: Extensive thermal modeling and review in Phase A, and design for early test verification. Existing design provides > 100% heat lift margin (**PR** Table 3.3).

   Risk: Completion of required integration and test activities for the (cryogenic) instrument take longer than expected. *Consequence*: Schedule and cost impact. *Mitigation*: Advanced planning and allocation of appropriate budget, schedule and schedule margin. See Instrument I&T plan in **PR** §3.5. The PICO budget conservatively includes $29M for Instrument I&T (18% of the total Instrument budget), and $24M for Observatory-level Assembly, Test, and Launch Operations (ATLO). The PICO I&T plan was designed based on experience with *Planck*.

4. **Fill in entries in the Instrument Table. Provide a separate table for each Instrument (Inst #1, Inst #2 etc). As an example, a telescope could have four instruments that**

comprise a payload: a telescope assembly, a NIR instrument, a spectrometer and a visible instrument each having their own focal plane arrays. Please identify the basis for the CBE (Current Best Estimate).

An overview of the PICO instrument is presented in Section 3 of the **PR** (pg. 33). Detailed diagrams are provided there and in Section 4.4 of this RFI.

PICO's payload is comprised of a single instrument, which is defined to include the telescope, imager/camera, and cryocoolers (4 K and sub K). The V-Groove radiation shields and the main bipods (which support the instrument structural ring) are part of the spacecraft.

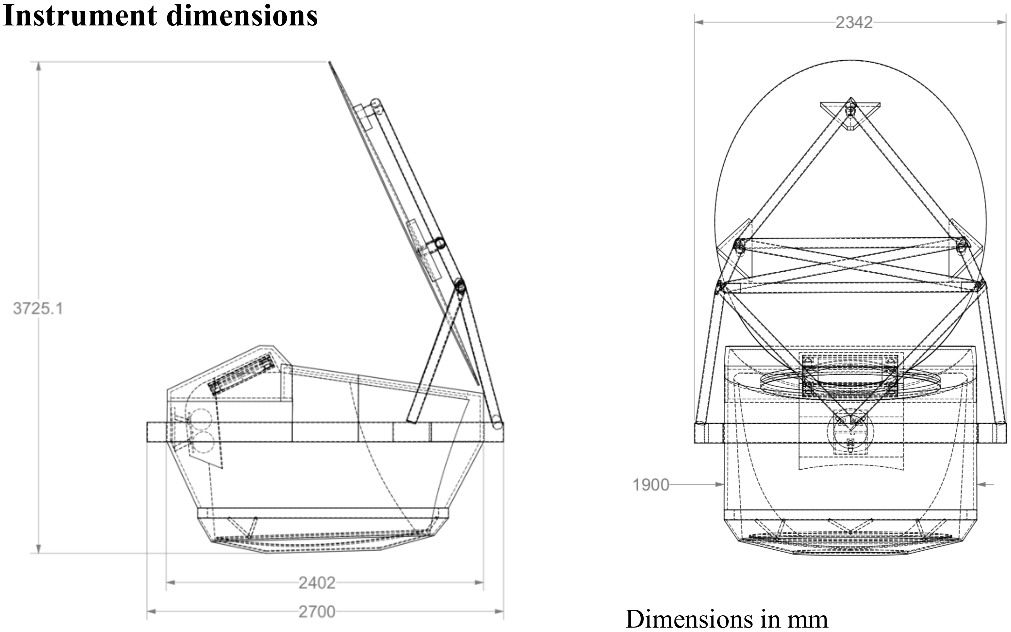
Instrument Table (Imaging Polarimeter)

Item	Value	Units
Type of Instrument	Imaging Microwave Polarimeter	
Number of channels	21	
Size/dimensions (for each instrument)	2.342 × 2.700 × 3.725 (see Figure "Instrument dimensions" below)	m x m x m
Instrument mass **without** contingency (CBE*)	544.5 (as 379 Telescope 165.5 Imager 81 Cryocoolers)	Kg
Instrument mass contingency (MEV-CBE)/CBE	31%	%
Instrument mass **with** contingency (MEV=CBE+reserve)	712.8 (as 508.7 Telescope 204.1 Imager 95.2 Cryocoolers)	Kg
Instrument average power without contingency (CBE)	406 (as 89 Imager 317 Cryocoolers)	W
Instrument average power contingency (MEV-CBE)/CBE	43%	%
Instrument average power with contingency (MEV)	581	W
Instrument average science data rate^ without contingency	70,600 uncompressed becomes 17,400 compressed	Kbps
Instrument average science data rate^ contingency	N/A (See response to question #5 below)	%
Instrument average science data rate^ with contingency		Kbps
Instrument Fields of View (if appropriate)	19 x 13	Degrees
Pointing requirements (knowledge)	10″ (3σ, each axis) from spacecraft attitude; 1″ (1σ, total) final reconstructed	Arcsec

Pointing requirements (control)	Spin axis direction controlled to 1° (3σ, radial); Spin rate of 1±0.1 rpm (3σ)	Degrees
Pointing requirements (stability)	Drift of spin axis < 1 arcmin/min (3σ, radial)	arcmin/min

*CBE = Current Best Estimate.
^Instrument data rate defined as science data rate prior to on-board processing

Instrument dimensions



Dimensions in mm
Note: V-groove radiation shields and main bipods are defined as part of the spacecraft.

Basis for CBE: The PICO CBE estimates were generated by Team X (JPL's concurrent design facility).

Basis for CBE: Mass

A more detailed instrument mass breakdown is included in the table below:

Component/ Assembly Name	Cost Model	Number of Flight Units #	CBE Unit Mass kg	CBE Mass kg	Mass Contingency %	MEV Mass kg
		8		379.0		508.7
Primary reflector (2.69 m x 2.04 m)	Telescope	1	80.0	80.0	50%	120.0
Secondary reflector	Telescope	1	42.0	42.0	30%	54.6
Filter (1 K)	Telescope	1	10.0	10.0	30%	13.0
Primary reflector support structure	Telescope	1	35.0	35.0	30%	45.5
Secondary structural ring	Telescope	1	10.0	10.0	30%	13.0
Main structural ring	Telescope	1	50.0	50.0	30%	65.0
Secondary bipods	Telescope	1	2.0	2.0	30%	2.6
Telescope box	Telescope	1	150.0	150.0	30%	195.0
		68		18.6		24.0
Frames (Copper of Invar)	NICM - Electronics	1	10.0	10.0	30%	13.0
Lenslet wafers + detector wafers (Si)	NICM - Electronics	31	0.2	5.0	30%	6.5
TDM chips (Si, if 2 mm thick)	NICM - Electronics	1	1.0	1.0	30%	1.3
Backshort bonding wafers (Si)	NICM - Electronics	1	0.1	0.1	30%	0.1
Metal-mesh filters (1 layer)	NICM - Electronics	1	1.0	1.0	30%	1.3
4K SQUID Modules	NICM - Electronics	15	0.1	1.5	20%	1.8
		2		21.4		27.8
Warm Electronics	NICM - Electronics	2	9.5	19.0	30%	24.7
DPU-IO	NICM - Electronics	2	1.2	2.4	30%	3.1
		6		44.5		57.1
Thermal Straps	NICM - Thermal	1	2.0	2.0	30%	2.6
Cooler Support	NICM - Structure	1	5.0	5.0	30%	6.5
Telescope box liner	NICM - Structure	1	14.0	14.0	30%	18.2
Telescope box liner tie-downs	NICM - Structure	1	10.0	10.0	30%	13.0
Focal plane enclosure (1 K)	NICM - Structure	1	9.5	9.5	30%	12.4
Focal plane enclosure supports	NICM - Structure	1	4.0	4.0	10%	4.4
		13		81.0		95.2
4K Cooler	Cryocooler model	1	31.3	31.3	10%	34.4
4K Cooler Electronics	Cryocooler model	1	8.7	8.7	30%	11.3
2-stage CADR	Cryocooler model	1	12.0	12.0	10%	13.2
3-stage CADR	Cryocooler model	1	7.0	7.0	10%	7.7
ADRC	Cryocooler model	1	22.0	22.0	30%	28.6

Instrument mass equipment list detailing the instrument elements included in the instrument mass estimate, and contingencies applied. The models that Team X used to model instrument cost are also called out (see **PR** §6.5.1).
The equipment list is based on requirements for NASA Risk Class B. The detector readout electronics ("Warm Electronics") and data compression ("DPU IO") are redundant and cross-strapped. The 4 K Cooler Electronics include internal functional redundancy (similar to the MIRI cooler). The cADR sub-Kelvin cooler electronics ("ADRC") are also internally redundant. The 2-stage and 3-stage CADR make one cADR unit.

In estimating masses, materials assumed were as follows (compiled for >10 kg components):

Component	***Material***
Primary reflector	Aluminum (1 cm thick)
Secondary reflector	Aluminum (8 mm thick)
Primary mirror support structure	Aluminum / fiberglass
Main structural ring	Aluminum
Telescope box	Aluminum honeycomb and facesheet
Telescope Box Cold Liner	Aluminum sheet metal
4 K Cooler and 4 K Cooler Electronics	Mass estimate based on the as-built MIRI cooler and electronics
2- & 3-stage cADR units, ADRC (electronics)	Mass estimate provided by Goddard Space Flight Center (based on experience delivering similar systems)

Basis for CBE: Power

Detectors are read out using Time Domain Multiplexing (TDM), as described in **PR** §3.3, with a matrix of 128 rows and 102 columns. In the warm electronics, a multiplexing (MUX) card can support 8 columns, so 13 MUX cards are required. Each electronics string is therefore comprised of:
1 cPCI Backplane + 13 MUX Cards + 1 combined Clock Card and Housekeeping Card + 1 Power Card + DPU IO (data compression)

Power used = (13 MUX cards)×(3.4 W) + (1 Clock card)×(12 W) = 56.2 W
Assuming a power conversion efficiency of 75%, the power consumed = 56.2W/0.75 = 75 W + 14 W power to DPU = 89 W total while operating

The cryocoolers are described in **PR** §3.4.1 ("cADR Sub-Kelvin Cooling") and §3.4.2 ("The 4.5 K Cooler"). The CBE power consumption for the cryocoolers is calculated based on MEV heat lifts. The MEV heat lifts carry >100% contingency relative to the modelled loads (see **PR** Figure 3.4).

Basis for CBE: Science Data Rate

The instrument data rate (70.6 Mbps = 6.1 Tbits/day) is calculated based on 16 bits/sample, the sampling rate for each tile type, and the associated number of bolometers, from the table below:

Tile type	Bandcenters [GHz]	FWHM of Smallest Beam	Sampling rate	Number of Bolometers	Uncompressed Data Rate
1	21,30,43	22.2'	45 Hz	360	0.02 Tbits/day
2	25,36,52	18.4'	55 Hz	600	0.05 Tbits/day
3	62,90,129	7.4'	136 Hz	2196	0.41 Tbits/day
4	75,108,155	6.2'	163 Hz	3060	0.69 Tbits/day
	186,268,385	2.5'	403 Hz	2880	1.61 Tbits/day
5	223,321,462	2.1'	480 Hz	2700	1.79 Tbits/day
6	555	1.1'	917 Hz	440	0.56 Tbits/day
	666			400	0.51 Tbits/day
	799			360	0.46 Tbits/day
				TOTAL (uncompressed):	**6.1 Tbits/day**

Spinning at 1 rpm, pointing 69 deg off the spin axis → Scan speed = (360°/min)*sin(69°) = 336' / sec
Sampling rate = (Scan speed)*(3 samples / FWHM of Smallest Beam)
Uncompressed data rate = (Number of bolometers)*(16 bits / sample)*(Sampling rate)

5. **If you have allocated contingency please describe it, along with the rationale for the number chosen.**

   Team X allocated **mass** contingencies at the component level based on design maturity (see table above). The total instrument mass contingency (31%) meets ANSI/AIAA-G-020-1992 mass contingency guidelines.

   Team X allocated **power** contingency at the instrument system level. The instrument power contingency (43%) meets JPL best practices. The majority (78%) of the CBE instrument power consumption is for the cryocoolers (250 W for the 4 K cooler and 67 W for the cADR). The cryocoolers are described in **PR** §3.4.1 and §3.4.2. The CBE power consumption for the cryocoolers is calculated based on MEV heat lifts. The MEV **heat lifts** carry >100% contingency relative to the modelled loads (see **PR** Figure 3.4).

   The instrument has a single operating mode with a fixed **data rate**. Team X does not traditionally apply contingency on data rate. PICO's conservative assumption of compression is similar to contingency (**PR**, §3.3, last paragraph). PICO also carries downlink time margin (**PR**, §4.2).

   PICO **instrument sensitivity** margin is discussed in **PR** §3.2.4.

6. **If known, provide a description of what organization is responsible for each instrument and summarize relevant past experience with similar instruments.**

   PICO has completed a funded concept study. It is premature to distribute responsibilities for providing hardware elements. However, for most instrument elements there is more than a single source capable of providing the necessary technologies, or the R&D required to elevate the TRL, where necessary.

   The continuous-ADR (cADR) sub-K cooler is the single instrument element that can currently be supplied by a single source, Goddard Space Flight Center. GSFC has an active cADR development program including elevating some of their coolers to TRL 9 (see also **PR** Section 3.4 "Thermal"). If necessary, PICO could employ a "single-shot" ADR (ssADR), for which there are additional vendors world-wide (including GSFC). With an ssADR there may be small impact on overall observing efficiency, which would mildly reduce mission sensitivity margin.

7. **For the science instrumentation, describe any concept, feasibility, or definition studies already performed.**

   PICO was competitively selected by NASA for a funded concept study. The **PR** is the final report from that study, and the study itself is briefly discussed in **PR** §6.1 ("PICO Study Participants").

   The PICO science instrumentation is a result of experience with the *Planck* mission, several previous mission studies in the US and Europe, as described below, and significant community heritage from active sub-orbital instruments.

The first phase of the PICO study (May-December 2017) focused on:

- Defining driving science objectives for the mission
- Conducting a key payload trade (see below)
- Defining a mission architecture that is likely to fit in the $1B cost cap including:
    - Number and type of instruments
    - Aperture size
    - Sensitivity
    - Basic survey concept of operations
- Producing a preliminary design

The team conducted a payload trade, selecting amongst three options based on science return. The options were scoped based on engineering ROMs:

- Imager-only (~1.5 m class telescope with modern detectors)
- Spectrometer-only ("Super-PIXIE": ~ 3x the size of the *PIXIE* Explorer concept)
- Small Imager + Small Spectrometer
  (~0.5 m imaging telescope + 2x20cm "Mini-PIXIE" spectrometer)

The Small Imager + Small Spectrometer architecture was rejected by the PICO Executive Committee because the science return from the combination of the two small instruments was judged to be too weak. Study funding only allowed for development of one concept, and the Imager-only concept was selected over the Spectrometer-only concept on the basis of science return.

In architecting and scoping the (Imager-only) PICO mission concept, the mission study leveraged experience from:

- *Planck* (ESA mission with NASA participation)
    - https://arxiv.org/abs/1807.06205
    - https://www.aanda.org/articles/aa/pdf/2010/12/aa12983-09.pdf
- CORE (proposed in response to ESA "M5" call)
    - https://arxiv.org/abs/1705.02170
    - https://arxiv.org/abs/1706.04516
- Design study by ESA's Concurrent Design Facility
    - https://sci.esa.int/web/trs/-/57795-cmb-polarisation-mission-study
- EPIC-IM (developed for Astro2010)
    - https://arxiv.org/abs/0906.1188

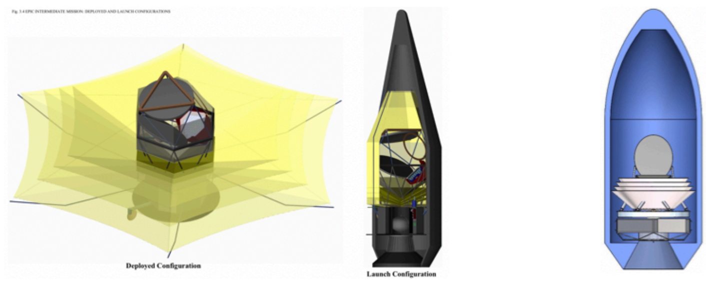
Planck provided PICO with a highly relevant benchmark:

	Planck
Frequency range	30 – 857 GHz
Effective aperture	1.5 m
Destination	Earth-Sun L2
Instruments	2 (LFI, HFI)
Detector temperature	100 mK (HFI), 20 K (LFI)

Total wet mass	1912 kg
Mission power	1300 W
Survey duration	4 yr
Cost **(including launch, operations)**	~ €700M FY12 = ~ $1B FY18

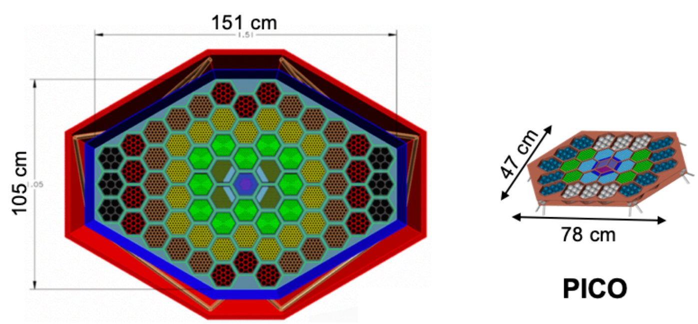
The team used EPIC-IM as an architecture reference, but made significant changes to reduce cost relative to EPIC-IM, including:

- EPIC-IM required a 4-layer 15.3-m diameter *deployable* sun shield system. The PICO design uses 4-layer 4.5-m diameter *static* system. This reduces development and test costs substantially, and removes a mission risk associated with deployment. This change was made possible by adapting the survey and optical designs, and by utilizing a larger available fairing size.



EPIC-IM 4K PICO

- PICO leverages modern (multichroic) detectors to reduce focal plane size while providing equivalent sensitivity. PICO has 13,000 bolometers, EPIC-IM had 11,100. PICO's bolometers fit on 31 detector tiles, EPIC-IM required 73 tiles.
The smaller, less massive focal plane places less thermal load on the 100 mK stage.



PICO

EPIC-IM 4K

Cost scoping and conservatism in the PICO architecture phase proved effective. The concept brought to Team X in December 2017 was found to be appropriate for the Probe cost cap. This enabled Team X and PICO team effort for the remainder of the study to focus on concept refinement, minor subsystem trades, and risk identification & mitigation.

The PICO team performed a trade study of various telescope designs, considering field of view, aperture size, physical volume, and resulting signal-to-noise ratio. See Young et al. (https://arxiv.org/pdf/1808.01369.pdf).

The PICO team performed extensive thermal modeling of the nominal PICO observatory design, including Thermal Desktop modeling, in order to confirm that temperature and thermal stability requirements were met, as well as to derive required heat loads to the cryocooling system (**PR** Table 3.3).

8. **For instrument operations, provide a functional description of operational modes, and ground and on-orbit calibration schemes. Describe the level of complexity associated with analyzing the data to achieve the scientific objectives of the investigation. Describe the types of data (e.g. bits, images) and provide an estimate of the total data volume returned.**

Operational Modes

The instrument has modes that are only planned to occur once in the baseline mission, during preparations for survey operations:

- Decontamination: Active heaters mounted on the optics hold the temperature at ~170 K, like the *Planck* implementation (https://arxiv.org/abs/1101.2023). The coolers are turned off.
- 4 K Cooler Cooldown: Decontamination heaters are turned off. The 4 K cooler is turned on. The sub-K cooler (cADR) is still off.
- cADR Cooldown: Both coolers are turned on, but detector readout is not required.

After cooldown is complete, the instrument is ready to begin science operations. The instrument has a single science mode: imaging.

- Imaging: Both coolers are turned on, maintaining instrument temperatures. The detector warm readout electronics and data compression electronics (DPU-IO) are active, reading the detectors out at a fixed rate, compressing the data, and outputting it to the spacecraft.

During normal operations, the instrument is in Imaging mode 24 hours a day. In the event of a safe mode event, the spacecraft would command the instrument to enter Standby mode.

- Standby: Both coolers remain on. The detector warm readout electronics and data compression electronics are off.

The instrument does not require a separate calibration mode; the data taken in Imaging mode during the science surveys will be processed for calibration.

Driving instrument power modes are detailed in the table below:

Subsystem	Component/ Assembly Name	Imaging	Standby	Cool-down	Peak Cool-down	FOR NICM
		24	24	24	< 1	
		Power Consumed MEV (W)				
		580.58	470.47	543.4	674.96	127.27
		System Level Power Contingency				
		43%	43%	43%	43%	43%
		Power Consumed CBE (W)				
		406	329	380	472	89
Electronics		89	12	12	12	89
Electronics	Warm Electronics	75	12	12	12	75
Electronics	DPU-IO	14	0	0	0	14
Thermal		317	317	368	460	0
Thermal	4K Cooler					
Thermal	4K Cooler Electronics	250	250	368	460	
Thermal	2-stage CADR					
Thermal	3-stage CADR	0	0	0	0	
Thermal	ADRC	67	67	0	0	

Driving instrument power modes: The maximum instrument power usage occurs when the 4 K cooler power spikes briefly in its pitch-point transition during the 4 K Cooler Cooldown (prior to survey operations). The Imaging mode sets the instrument average power. Decontamination mode is not shown in this table because the power draw from the decontamination heaters is expected to be much smaller than that required by the coolers for cool down, so decontamination is not a driving power mode. In this table, the "DPU-IO" is the data compression, and the "ADRC" is the electronics that control the cADR sub-Kelvin cooler.

Ground and On-Orbit Calibration Schemes

The data are calibrated using maps of point sources, information about the angular response of the telescope and the polarization response of the instrument, and comparison to available maps of the cosmic microwave background from the WMAP and Planck space missions. Ground testing and calibration activities are discussed in **PR** §3.5 ("Instrument Integration and Test"). Calibration is also discussed in **PR** §2.8 ("Systematic Uncertainties").

Data Analysis Complexity

PICO data will be analyzed in a manner similar to that of *Planck* and of several sub-orbital experiments including EBEX, SPIDER, AdvancedACT, SPT3G, and BICEP Array. There is substantial community heritage with data analysis approaches and techniques.

The key steps are as follows. Time domain detector data are cleaned from cosmic ray events and other glitches. They are synchronized with attitude information data using common on-board time stamps, and binned in sky stationary coordinates to produce maps of the Stokes I, Q, and U parameters at each frequency band. The data are calibrated using maps of point sources, information about the angular response of the telescope, the polarization response of the instrument, and comparison to available maps of the cosmic microwave background from WMAP and *Planck*. Calibrated maps, each at a different frequency band, are used to estimate the different sources of sky emissions, and as input to final analyses, each customized for its own SO.

The PICO data types, analyses, and products are described in our response below, Section 7, Question #4 ("Describe science and data products in sufficient detail that Phase E costs can be understood compared to the level of effort described in this section.").

Data Volume

As described in the **PR** in the last paragraph of §3.3 ("Detector Readout"), the instrument generates 6.1 Tbits/day of raw data, which is compressed to 1.5 Tbits/day for storage on the spacecraft and transmission to the ground (compression is the only on-board data processing). Uncompressed on the ground, this totals to 11,000 Tb of raw Level 0 data over the 5-year mission. Precedents for managing this data volume are described in the **PR** in the last paragraph of §6.3 ("Heritage").

9. **Describe the level of complexity of the instrument flight software.**

   The instrument flight software is relatively simple, only performing detector readout, lossless data compression, thermal control, and housekeeping. These tasks have been demonstrated onboard by operating suborbital instruments.

10. **Describe any instrumentation or science implementation that requires non-US participation for mission success.**

    There is no element in PICO's instrumentation or science implementation that requires non-US participation.

    Nevertheless, there are potential international partners in Europe and Japan that have technical expertise in elements of PICO's instrumentation. Colleagues in Europe have experience in science implementation from the Planck mission. Contributions from non-US participants could be considered to benefit PICO and reduce US mission cost.

11. **Describe the flight heritage of the instruments and their subsystems. Indicate items that are to be developed, as well as any existing hardware or design/flight heritage. Discuss the steps needed for space qualification. Describe any required deployments.**

    Instrument heritage is discussed in **PR**, §6.3 ("Heritage"). Technologies to be developed are discussed in **PR** §5 ("Technology Maturation"), including all steps required to take instrument technologies to TRL 5 prior to Phase A.

4. Technical Implementation - Mission Design

1. **Provide a brief descriptive overview of the mission design (launch, launch vehicle, orbit, pointing strategy) and how it achieves the science requirements (e.g. if you need to cover the entire sky, how is it achieved?).**

   The mission design is described in **PR** §4.1 ("Concept of Operations"), including §4.1.1

(“Mission Design and Launch”) and §4.1.2 (“Survey Design”).

2. **Describe all mission software development, ground station development and any science development required during Phases B and C/D.**

On-board flight software was discussed in Section 3 Question 9.

The PICO Mission Operations System (MOS) and Ground Data System (GDS) can be built using NASA’s standard Advanced Multi-Mission Operations System (AMMOS) tools with minimal adaption as needed to address mission specific features (e.g. to command and telemetry dictionary changes and S/C dependent behavior models). AMMOS tools are maintained by NASA and are kept current for security and general reliability.

The PICO science team will develop a mission simulation software package in Phase A (or earlier, if funded). The package will generate simulated PICO data that will include systematic effects and reflect knowledge about astrophysical sources of emission. (Elements of this package already exist from work with *Planck* data, through preparation of the CORE and PICO mission concepts (https://arxiv.org/abs/1707.04224, https://z.umn.edu/picomission/), and with existing experimental teams.) In Phase B, this package will enable algorithmic trade studies in the science data processing. It will also assist in development and validation of requirements, especially for the instrument and science processing.

Phase B

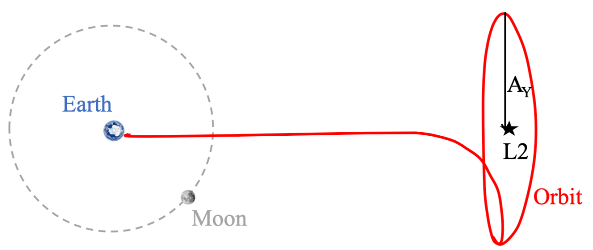
- Requirements will be developed for each of the software components.
- Available software from prior projects will be identified and evaluated for usability by PICO.
- Each step of the science data processing will be planned, from the telemetered time ordered detector data to science data products. Algorithms will be selected. For processing steps for which the optimal algorithm may not be known until data is available, multiple algorithms will be carried into phases C and D for implementation, enabling cross checks of key science results.
- The simulation software package will continue to be refined.

Phases C/D

- The MOS, GDS, and science processing pipeline detailed designs will be developed and the software will be implemented and fully tested.
- The simulator software package will be used to validate the science data processing modules individually as they are developed and will enable end-to-end testing of the entire pipeline prior to launch.
- Prior data on the astrophysical sky (synchrotron, dust, etc.) will be gathered to be used as part of the calibration and the sky component separation software to be used during mission operations.

3. **Provide entries in the Mission Design Table. For mass and power, provide contingency if it has been allocated. If not, use 30% contingency. To calculate margin, take the difference between the maximum possible value (e.g. launch vehicle capability) and the maximum expected value (CBE plus contingency).**

Mission Design Table

Parameter	**Value**	**Units**
Orbit Parameters (apogee, perigee, inclination, etc.)  	Sun-Earth L2 Quasi-Halo Orbit size A_Y < 400,000 km Sun-Probe-Earth angle < 15°; Orbital period 6 months	
Mission Lifetime	60	mths
Maximum Eclipse Period	N/A	min
Launch Site	KSC	
Observatory* Dry Mass without contingency (CBE)	1519	kg
Observatory* Dry Mass contingency (MEV-CBE)/CBE	27	%
Observatory* Dry Mass with contingency (MEV)	1934	kg
Propellant Mass without contingency	Team X does not provide explicit propellant contingency.	kg
Propellant contingency		%
Propellant Mass with contingency	213 (77% tank fill)	kg
Observatory* Wet Mass with contingency (MEV)	2147	kg
Observatory* Wet Mass MEV Plus L/V-side Adapter	2174	kg
Launch Vehicle	Falcon 9	Type
Launch Vehicle Mass Margin (based on MEV mass)	3195 – 2174 = 1021 for an escape C3 = -0.7 km^2/s^2 with ocean (barge) recovery (more margin if no recovery)	kg
Launch Vehicle Mass Margin (Capability-MEV)/MEV	52%	%
Observatory* Power without contingency (CBE)	759 (standard = Science Mode) 905 (peak = Science+Telecom)	W
Observatory* Power contingency (MEV-CBE)/CBE	43	%
Observatory* Power with contingency (MEV)	1085 (standard = Science Mode) 1294 (peak = Science+Telecom)	W

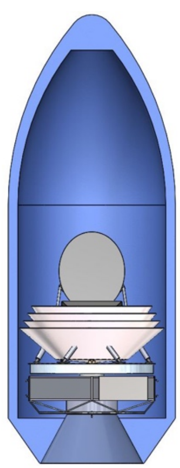
* Observatory = “Spacecraft” + “Instrument” = everything that flies

Power table

Subsystem/Instrument	Mode #	1	2	3	4	5	6	7
	Mode Name	Cruise	Launch	Cooldown	Cooldown Peak	Science	Science+Telecom	Safe
ACS	W	23	16	16	16	187	194	100
C&DH	W	44	44	44	44	44	44	44
Instrument	W	0	0	368	460	406	406	0
Propulsion System	W	27	27	8	8	8	8	58
Structures	W	10	0	10	10	10	10	10
Telecomm	W	40	40	12	12	12	148	40
Thermal	W	75	75	75	75	45	45	75
Power Subsystem	W	33	32	41	44	46	50	35
TOTALS		**252**	**235**	**574**	**669**	**759**	**905**	**362**
Systems Contingency	%	43%	43%	43%	43%	43%	43%	43%
Subsystem Contingency	W	**108**	**101**	**247**	**288**	**326**	**389**	**156**
Subsystems with Contingency	W	**361**	**336**	**821**	**957**	**1,085**	**1,294**	**517**

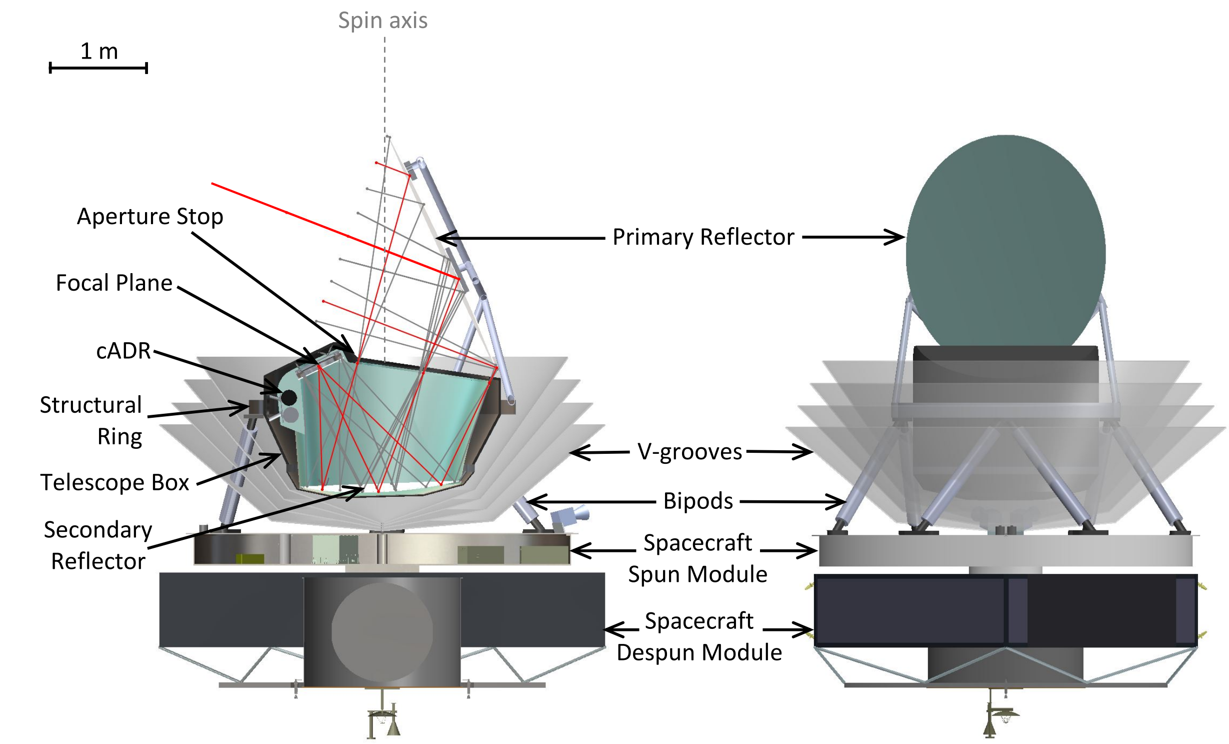
4. **Provide any existing block diagrams or drawings showing the observatory (payload and spacecraft) with the instruments and other components labeled and a descriptive caption. Provide a diagram of the observatory in the launch vehicle fairing indicating clearance if you have it.**

   Below we compile **PR** figures 4.1, 3.1, 3.2, and 4.3, and provide captions with text sourced (with some reordering) from the original captions and from §3. Launch vehicle fairing clearance is added to the caption of the first figure.

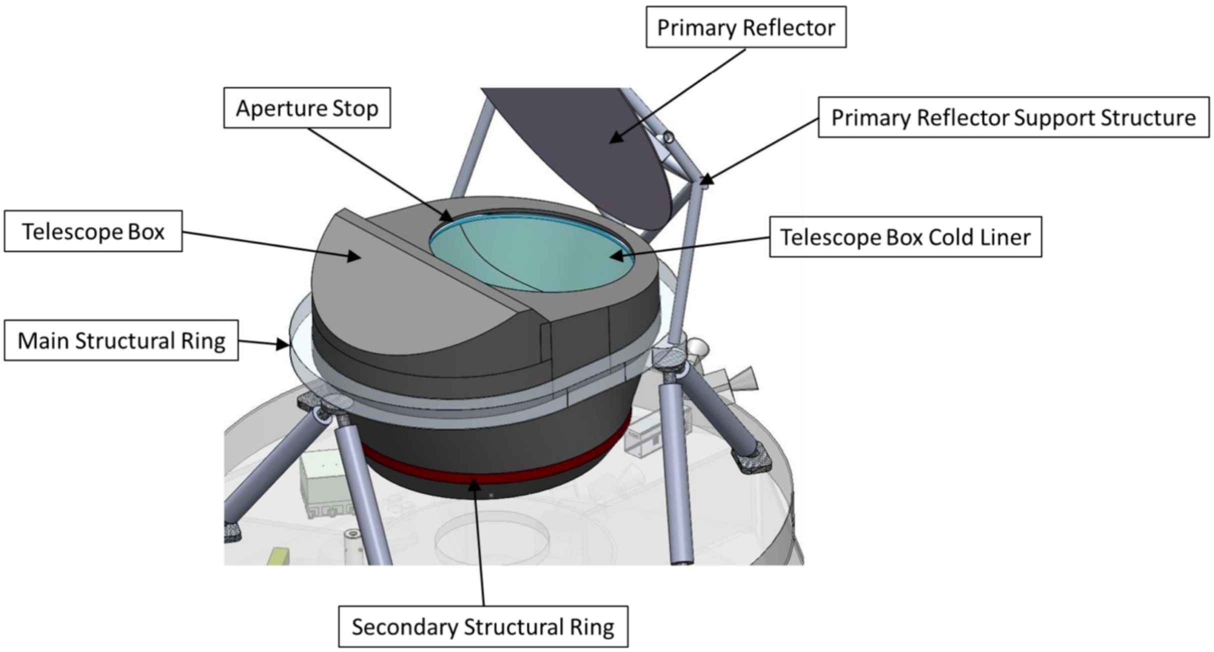


Observatory in the launch vehicle

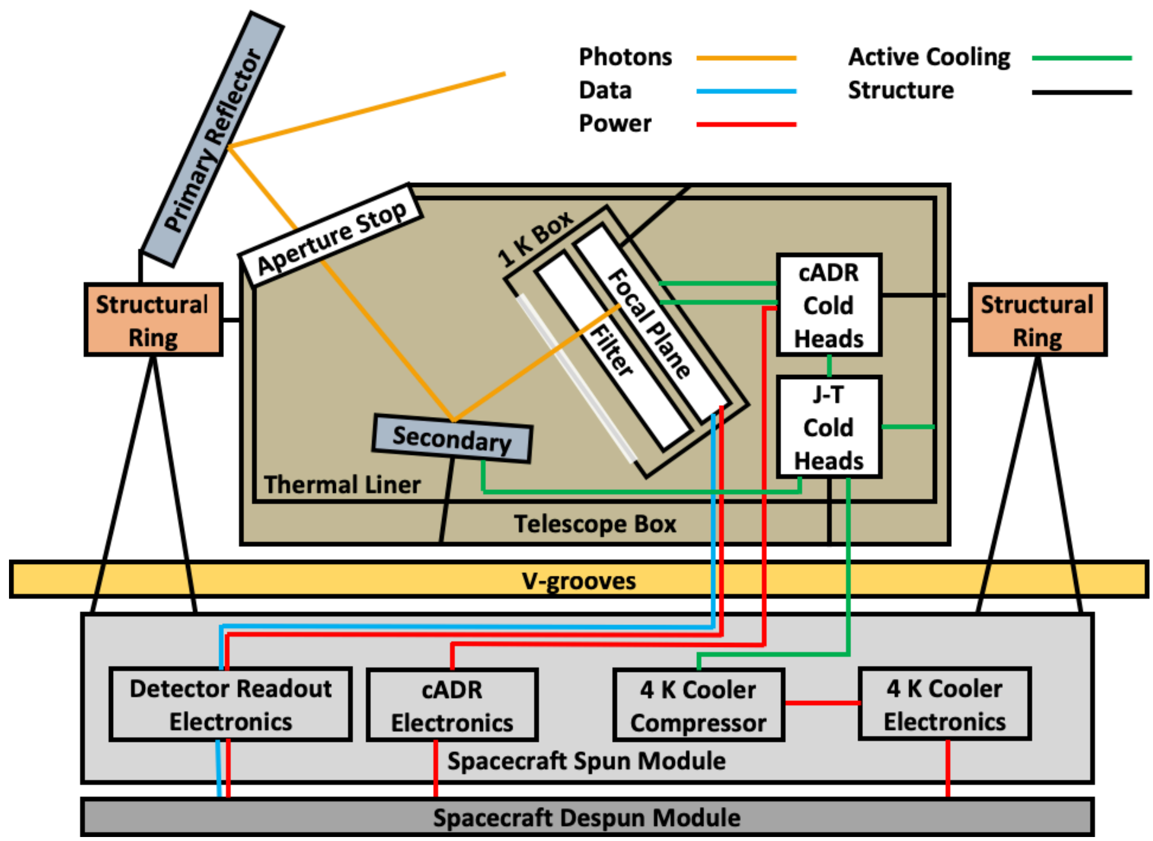
The PICO Observatory is compatible with the Falcon 9 fairing. The maximum diameter of the Observatory (at the largest V-Groove) is 4.5 m (5 cm radial clearance to the 4.6 m envelope). The vertical distance from the Spacecraft/Launch Vehicle separation plane to the top of the Observatory (at the top of the primary reflector) is 5.6 m.



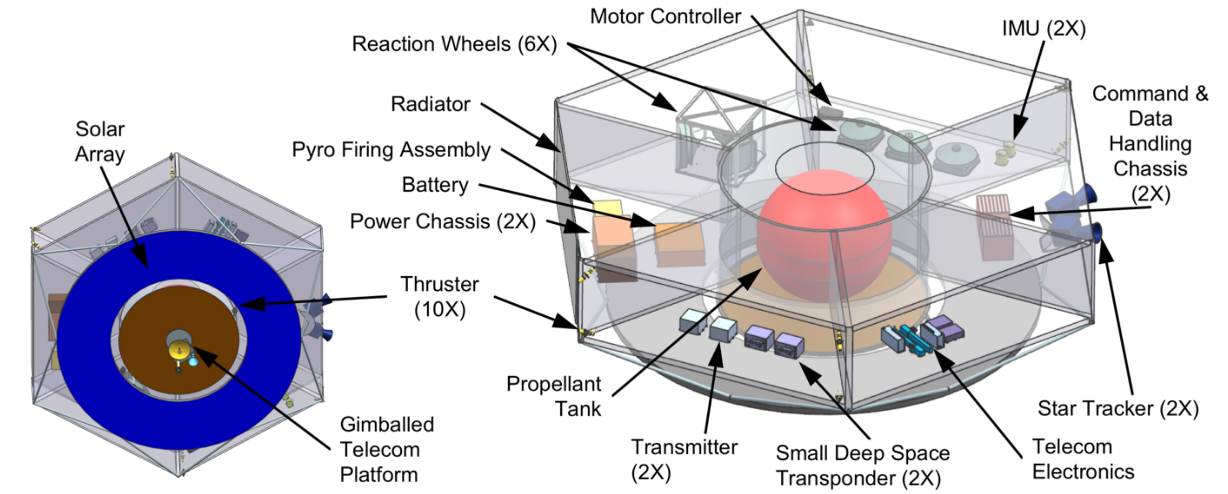
PICO overall configuration in side view and cross section (left), and front view with V-Groove assembly shown semi-transparent (right). The single science instrument is mounted on a spacecraft module which is spun at 1 rpm to perform the survey. A non-spinning module (labeled 'despun' in the figure) houses most spacecraft subsystems. Only power and digital data lines cross between the spinning and non-spinning modules (see block diagram below). A V-groove assembly thermally and optically shields the instrument from the Sun. The V-groove assembly is attached to the bipod struts that support the instrument structural ring. The structural ring supports the passively-cooled primary reflector and the telescope box, which contains actively cooled components including the secondary reflector, the focal plane, and sub-kelvin refrigerator (cADR); see also next Figure below.



The Telescope box, structural ring, and bipods. The telescope box contains actively cooled components (see previous Figure). Just inside it is a thermal liner that serves as a cold optical baffle and aperture stop.



PICO instrument block diagram. Active coolers provide cooling to the 100 mK focal plane, the surrounding 1 K box, the 4.5 K secondary reflector, and the 4.5 K thermal liner that also acts as a cold aperture stop. V-grooves provide passive cooling. The instrument, V-grooves, and spacecraft spun module spin together at a rate of 1 rpm. The spacecraft spun module hosts the 4K cooler compressor and its drive electronics, the sub-K cooler drive electronics, and the detector warm readout electronics. Only power and digital data lines cross to the spacecraft despun module.



The spacecraft despun module hosts the spacecraft power, telemetry, attitude control, and communication systems. Modular equipment bays provide easy access to all components and enable parallel integration of spacecraft subsystems. A cylindrical core provides a direct interface to the Launch Vehicle adapter ring. The fixed solar array is aft-mounted to optimize Sun pointing. High, Medium & Low Gain Antennas are mounted on a 2-axis gimballed platform to support Earth pointing.

5. For the mission, what are the three primary risks?

Risks are described in **PR** §6.4 ("Risk Assessment"). The content that is most relevant to the mission system is found in §6.4.3 ("Operations Risks").

Risk: insufficient progress, or unforeseen complexity with the foregrounds and systematic-effect simulation package. *Consequence*: Cost and possibly schedule impact. *Mitigation*: Allocate sufficient resources early-on in the program; include expertise from *Planck* and from currently operating sub-orbital experiments' experts.

6. Provide an estimate of required propellant, if applicable.

139 kg for delta-V
\+ 60 kg for attitude control
\+ 14 kg residual trapped ullage
----
213 kg total (Hydrazine)

5. Technical Implementation - Spacecraft Implementation

1. Describe the spacecraft characteristics and requirements. Include a preliminary description of the spacecraft design and a summary of the estimated performance of the

key spacecraft subsystems. Please fill out the Spacecraft Mass Table and Spacecraft Characteristics Table.

The spacecraft is described in **PR** §4.3 (“Spacecraft”), including §4.3.1 (“Attitude Determination and Control”).

Spacecraft Mass Table (kg)

Note: The masses of the V-Groove assembly and main bipods are included within Structures & Mechanisms, with respective masses of 221.4 kg CBE (287.8 kg MEV) and 40.7 kg CBE (53.0 kg MEV). The V-Groove assembly is discussed in **PR** in the third paragraph of §6.3 (“Heritage”).

Spacecraft Bus	Current Best Estimate (CBE)	Percent Mass Contingency	CBE Plus Contingency
Structures & Mechanisms	607.1	30%	789.1
Thermal Control	54.2	28%	69.2
Propulsion (Dry Mass)	42.7	7%	45.6
Attitude Control	88.4	10%	97.3
Command & Data Handling	23.3	8%	25.2
Telecommunications	30.1	18%	35.7
Power	62.8	17%	73.7
Cabling	65.5	30%	85.2
Total Spacecraft Dry Bus Mass	974.1	25%	1220.9

Spacecraft Characteristics Table

Spacecraft bus	Value/Summary, Units
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum honeycomb
Number of articulated structures	2 (1 rpm spin motor, 2-axis telecom gimbal)
Number of deployed structures	0
Thermal Control	
Type of thermal control used	Passive radiators - 1.2 m^2 on despun module - 1.1 m^2 on spun module - V-groove assembly (see **PR** §3.4.3)
Propulsion	
Estimated delta-V budget, m/s	132 m/s for orbit insertion + 15-20 m/s for TCMs + (2 m/s/yr)×(5 yr) for station keeping

	--------- 160 m/s Total
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Hydrazine
Number of thrusters and tanks	2 – 22 N thrusters pointed aft for delta-v; e.g. Aerojet MR-106L 8 – 4 N thrusters (in four clusters of two) for attitude control (reaction wheel desaturation, and safe mode slewing); e.g. Aerojet MR-111C 1 - tank
Specific impulse of each propulsion mode, seconds	235-229 sec for 22 N 229-215 sec for 4 N
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.)	3-axis control; Zero net angular momentum; See **PR** §4.3.1 ("Attitude Determination and Control")
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Star trackers (primary), Inertial (backup) See **PR** §4.3.1
Attitude control capability, degrees	Spin axis direction control to <1° (3σ, radial), achieved using RWAs mounted on despun module normal to spin axis, based on knowledge from star trackers and IMUs on despun and spun modules. Spin rate control to better than 0.1 rpm (3σ), achieved using the spin motor based on knowledge from the spin motor drive electronics (encoder).
Attitude knowledge limit, arcsec	<10″ (3σ, each axis), achieved using star trackers and IMUs on the spun and despun modules
Agility requirements (maneuvers, scanning, etc.)	See **PR** §4.1.2 ("Survey Design"). Single observing mode: spinning instrument at 1 rpm, precessing spin axis every 10 hr on 26° (radius) cone.
Articulation/#-axes (solar arrays, antennas, gimbals, etc.)	1 rpm spin motor: 1-axis Telecom gimbal: 2-axis

Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	Single fault tolerant architecture; 3 reaction wheel assemblies (RWAs), all on the despun module, normal to spin axis (in triangle configuration) for spin axis control (e.g. Honeywell HR-12) 3 reaction wheel assemblies (RWAs), all on the despun module, parallel to spin axis for momentum cancellation (e.g. Honeywell HR-16, 150 N m s) 4 star trackers (SRUs), two each on the spun and despun module (e.g. Sodern Hydra 3-head) 4 inertial measurement units (IMUs), two each on the spun and despun modules (e.g. Honeywell MIMU) 2 sun sensors on despun module (e.g. Adcole 2-axis coarse sun sensor) Spin motor electronics on despun module (e.g. MOOG 2-channel Electronic Control Unit)
Command & Data Handling	
Spacecraft housekeeping date rate, kbps	< 5 kbps
Data storage capacity, Mbits	4.6 Tbit (3 days of data)
Maximum storage record rate, kbps	655 Mbps (capability)
Maximum storage playback rate, kbps	655 Mbps (capability)
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Rigid, body mounted
Array size, meters x meters	Flat annular shape with 5.8 m^2 array area
Solar cell type (Si, GaAs, Multi-junction GaAs, concentrators)	GaAs
Expected power generation at Beginning of Life (BOL) and End of Life (EOL), watts	1477 W BOL 1320 W EOL (at 26° solar off point, per conops)
On-orbit average power consumption, watts	353 W CBE + 43% contingency = 505 W MEV
Battery type (NiCd, NiH, Li-ion)	Li-Ion
Battery storage capacity, amp-hours	74 A-hr For launch phase, sized to support 3 hr with 44% depth of discharge. No eclipses.

2. **Provide a brief description and an overall assessment of the technical maturity of the spacecraft subsystems and critical components. Provide TRL levels of key units, and in particular, identify any required new technologies or developments or open implementation issues.**

   Most requirements on the PICO spacecraft are well within typical ranges and can be met with standard high heritage systems. PICO's spin architecture and data volume requirements are less typical, and are discussed in **PR** in the last two paragraphs of §6.3 ("Heritage"). The PICO spacecraft design meets all requirements with TRL ≥ 6; no new technology development is required.

3. **Identify and describe the three lowest TRL units; state the TRL level and explain how and when these units will reach TRL 6. Summarize the TRL of all units less than TRL 4.**

   Not applicable.

4. **What are the three greatest risks with the spacecraft?**

   The PICO design meets the requirements associated with the NASA Class B risk classification. Essential functions are redundant (**PR** §4.3). PICO's healthy contingencies, margins, and reserves provide flexibility to address risks realized during mission development and operations. The PICO budget includes 30% cost reserves for Phases A–D.

   Risk: Design and implementation of spun and despun platforms adds unforeseen complexity as the project progresses. *Consequence*: Cost and possibly schedule impact. Or, a reduction in spin rate might be acceptable (by a factor of ~2), depending on the 1/f noise of the system, and subject to science simulations. *Mitigation*: Include JPL engineers who were involved in the SMAP mission in PICO design and review teams.

5. **If you have required new spacecraft technologies, developments, or if there are open issues, describe the plans to address them (to answer you may point to technology implementation plan reports or concept study reports, but please enumerate the relevant pages.**

   PICO does not rely on any new spacecraft technologies.

6. **Describe subsystem characteristics and requirements to the extent possible. Describe in more detail those subsystems that are less mature or have driving requirements for mission success. Such characteristics include: mass, volume, and power; pointing knowledge and accuracy; data rates; and a summary of margins. Comment on how these mass and power numbers relate to existing technology and what light weighting or power reduction is required to achieve your goals.**

   The spacecraft is described in **PR** §4.3 ("Spacecraft"), including §4.3.1 ("Attitude Determination and Control"), and in the "Spacecraft Characteristics Table" above.

There is no need for mass reduction. The Falcon 9 launch capability for ocean recovery exceeds PICO's 2147 kg total launch mass (including contingency) by a 50% margin. Current Best Estimate masses for each subsystem, and associated contingencies, are provided in the "Spacecraft Mass Table" above.

An opportunity exists to reduce spacecraft mass and the moment of inertia about the spin axis. In the PICO thermal model, the V-Grooves were (conservatively) modelled as non-conductive (like mylar). In the mechanical mass model, the (4.5 m diameter) V-Groove assembly was (conservatively) modelled to be more massive, like the *Planck* mission's honeycomb V-Groove assembly, with an area mass density comparable to a solar array substrate, totaling 221.4 kg CBE for the assembly (287.8 kg with contingency). The *SPHEREx* mission (a NASA mission with a planned launch date in 2023) has baselined a small-diameter (~1 m) rigid V-Groove assembly which extends to larger mylar photon shields (~4 m) with supports. This architecture would meet PICO's thermal requirements, and could substantially reduce its moment of inertia about the spin axis, easing requirements on the attitude control system. A V-Groove material trade will be considered during PICO Phase A, informed by the *SPHEREx* experience.

There is no need for power reduction. The spacecraft power system has positive power margin in all Observatory power modes (except during the Launch phase, before the solar arrays begin generating power). 43% power contingency is carried at the system level. Further, the solar array could grow (radially) by a factor of 125% in area before it would conflict with the Falcon 9 fairing. Current Best Estimates of power use by each spacecraft subsystem are compiled below.

Subsystem	Mode #	1	2	3	4	5	6	7
	Mode Name	Cruise	Launch	Cooldown	Cooldown Peak	Science	Science+Telecom	Safe
ACS	W	23	16	16	16	187	194	100
C&DH	W	44	44	44	44	44	44	44
Propulsion System	W	27	27	8	8	8	8	58
Structures	W	10	0	10	10	10	10	10
Telecomm	W	40	40	12	12	12	148	40
Thermal	W	75	75	75	75	45	45	75
Power Subsystem	W	33	32	41	44	46	50	35

7. **Describe the flight heritage of the spacecraft and its subsystems. Indicate items that are to be developed, as well as any existing hardware or design/flight heritage. Discuss the steps needed for space qualification.**

Spacecraft heritage is discussed in **PR** in the last three paragraphs of §6.3 ("Heritage").

8. **Address to the extent possible the accommodation of the science instruments by the spacecraft. In particular, identify any challenging or non-standard requirements (i.e. Jitter/momentum considerations, thermal environment/temperature limits etc.).**

The instrument structural ring is designed to mechanically mount to the main bipods (provided by the spacecraft). The instrument mass, with contingency, is 712.8 kg.

The instrument average power, with contingency, is 581 W. The instrument warm electronics compress the science data. After compression, the data rate is 17.4 Mbps (1.5 Tb/day). The spacecraft stores 3 days of data (4.5 Tb); see discussion in **PR** in last paragraph of §6.3.

The spacecraft provides a V-groove assembly which thermally and optically shields the instrument from the Sun. Provision of the appropriate thermal environment via passive V-groove radiators is a 30-year-old technology (**PR** §3.4.3).

The following items, included in the instrument scope (and instrument mass budget), are physically accommodated by the spacecraft on the spacecraft spun module:

- 4 K Cooler
  - 34.4 kg mass (including contingency)
  - 30 cm × 15 cm × 12 cm (including all attachment fixtures)
- 4 K Cooler Electronics
  - 11.3 kg mass (including contingency)
  - Assumed to be roughly the same volume as the 4 K Cooler (including built-in functional redundancy)
- ADRC (cADR electronics)
  - 28.6 kg mass (including contingency)
- Detector warm electronics and DPU-IO (data compression)
  - Dual string
  - Each string 13.9 kg mass (including contingency)
  - Each string 15 cm × 18 cm × 48 cm

Most requirements on the PICO spacecraft are well within typical ranges and can be met with standard high heritage systems (**PR** §4.3). The less typical requirements are the spin architecture and data volume requirements. They are discussed in the **PR** in the last two paragraphs of §6.3. The attitude and control system designed to support the spin architecture is described in more detail in **PR** §4.3.1.

9. Provide a schedule for the spacecraft, indicate the organization responsible and describe briefly past experience with similar spacecraft buses.

The PICO spacecraft provider will be selected during mission formulation. Multiple organizations are capable of providing a spacecraft bus to meet PICO's requirements. A detailed spacecraft delivery schedule has not yet been developed.

10. Describe any instrumentation or spacecraft hardware that requires non-US participation for mission success.

None.

11. Provide any special requirements such as contamination control or electro-magnetic controls (EMC).

None.

6. Enabling Technology

1. **For any technologies that have not been demonstrated by sub-scale or full-scale models, please provide a description of the technical maturity, including the description of analysis or hardware development activities to date, and the associated technology maturation plan.**

   The response to this question follows closely the response already provided above in Section 3 (Technical Implementation – Instrumentation), Question 2.

   All technologies at a TRL less than 5 are discussed in **PR** §5 ("Technology Maturation"). These technologies are in the TRL 4-5 range. The discussion covers taking these technologies to TRL 5. All of the required developments are straightforward evolutionary steps from existing technologies. TRL 5 technologies will be developed to TRL ≥ 6 in Phases A and B, prior to the Preliminary Design Review (PDR).

   *Please note: there is a typo in **PR** Table 5.1: Task 2 should read "Direct absorbing arrays ν>550 GHz."*

   The 4.5 K cooler (**PR** §3.4.2) is a direct extension of the JWST MIRI design, with only standard engineering required to adapt it for PICO's requirements. The MIRI cooler has demonstrated precooling and J-T loop cooling to 6.5 K; modifications to reach 4.5 K entail optimizing the design for the different material properties of the working fluids (3He and 4He) at the appropriate temperature. Distributed cooling following J-T expansion in a circulated-gas loop was demonstrated on Planck in a two-phase system, which is a significantly more challenging architecture. As described in **PR** §3.4.2, there are at least two potential industry sources (Ball Aerospace and NGAS) for 4.5 K coolers who have relevant systems and are actively developing them in a direction that would meet PICO's requirements (with >100% margin). The NGAS cooler has completed PDR-level development and is expected to reach CDR before PICO would begin Phase A.

2. **Describe the aspect of the enabling technology that is critical to the mission's success, and the sensitivity of mission performance if the technology is not realized or is only partially realized.**

   In the following paragraphs we discuss the implications of not-realized, or partially realized technology development of items enumerated in the **PR** Section 5 "Technology Maturation".

   Detectors for bands between 21 and 462 GHz:
   PICO uses arrays of transition edge sensor (TES) bolometric detectors. Such detectors are currently used extensively with sub-orbital experiments at frequencies between 30 and 300 GHz. Evolutionary development is required to adapt the technology to the lower background loading in space, and to the lower and higher frequencies that PICO would use.

   The goal of the technology development is to demonstrate detectors that have expected noise levels under space-like optical loading. Partial realization of the development implies elevated detector noise levels. Because PICO has 40% margin in detector noise, partial realization would represent lowering, or in extreme cases, eliminating this margin. An 'un-realized technology development' represents failure to achieve the required sensitivity, which would gradually degrade the science output of PICO. The *Planck* space mission has already demonstrated successful technology development for space-based bolometric detectors. The development anticipated for PICO relies on extensions of known technologies.

The baseline technology for PICO uses three-color pixels on the focal plane; each pixel has six TES bolometers. Sections 5.1 and 5.5 of the **PR** provide descope options if the technology development for the baseline three-color pixels is only partially realized, or deemed at risk. We present options with 2-color pixels and with single color pixel. Both descope options still achieve the PICO requirements.

Detectors for bands between 555 and 799 GHz:
For these frequencies the baseline technology relies on single-color, polarization sensitive, directly absorbing pixel with two TES bolometers (see more details in the **PR**). The majority of the development involves re-packaging of pixel elements that use already-proven technologies. Similar to the lower frequency case, the metric for partially realized or un-realized development is the noise level of the detectors, with similar consequences: partial realization would represent lowering, or in extreme cases, eliminating this margin; An 'un-realized technology development' represents failure to achieve the required sensitivity, which would gradually degrade the science output of PICO.

The **PR** presents an alternative technology for our baseline approach, see **PR** Section 5.2.

Time Domain Multiplexing (TDM):
The **PR** (Section 5.4) describes the largely standard engineering required to develop the multiplexing factor of the detector readout from its current value of 68x to PICO's 128x. Partially or fully unrealized technology development would require more wiring reaching the 0.1 K stage, imposing larger cryogenic heat loads on the sub-K cooler, and reducing the heat-lift margin.

An alternative technology, frequency domain multiplexing, can replace TDM, and would present smaller heat loads on the sub-K stage at the expense of higher ambient temperature power dissipation. This technology can be considered in the unlikely case that development of the TDM is only partially realized.

Beam Line Testing
Planck observed a cosmic-ray (CR) flux that was higher than expected. Data analysis was more complex because of diversity of CR energy deposition mechanisms into the detectors and their substrate. The goal of this development is to test the effects of CRs on modern planar arrays of TES detectors, to develop CR mitigation mechanisms, and to develop early familiarity with energy deposition mechanisms. The main goals of this development are early assessment, and identification of mitigation mechanisms.

3. **Provide specific cost and schedule assumptions by year for all developmental activities, and the specific efforts that allow the technology to be ready when required, as well as an outline of readiness tests to confirm technical readiness level.**

   Specific cost and schedule assumptions are listed in **PR** Table 5.1. Development activities and readiness tests are enumerated in the three milestone columns in that table.

4. **Please indicate any non-US technology that is required for mission success and what back up plans would be required if only US participation occurred.**

   None.

7. Mission Operations Development

1. **Provide a brief description of mission operations, aimed at communicating the overall complexity of the ground operations (frequency of contacts, reorientations, complexity of mission planning, etc.). Analogies with currently operating or recent missions are helpful. If the NASA DSN network will be used, provide time required per week as well as the number of weeks (timeline) required for the mission.**

   Mission operations are described in **PR** §4.1 ("Concept of Operations") and §4.2 ("Ground Segment").

   During the first two weeks after launch we plan fourteen 8-hr tracks per week using the DSN 34 m Beam Wave Guide (BWG). During weeks three and four, we plan daily 8-hr tracks. For the remainder of the mission we plan daily 4-hr tracks. As stated in **PR** §4.2 ("Ground Segment"), the daily 4-hr DSN passes return PICO data in 3.1 hr, with the remaining 0.9 hr available as needed for retransmission or missed-pass recovery. The mission sensitivity budget (**PR** §3.2.4) assumes that 95% of the science survey data is returned. This requirement should be easily met without extraordinary measures.

Mission Operations and Ground Data Systems Table

Ka-band is used for high-rate return of science data.
X-band is used to transmit spacecraft commanding, return engineering data, and provide navigation information (S-band is a viable alternative, and could be considered in a future trade).
All downlink links use Convolutional K=7, R = ½ coding with Reed-Solomon (I=5) outer code.

Ka-Band Downlink Information	Value, units
Number of contacts per day	One 4-hr contact per day (to DSN 34-m BWG)
Downlink Frequency Band	Near-Earth Ka-band (25.5-27 GHz)
Telemetry Data Rate(s)	150 Mbps (130 Mbps after CCSDS encoding)
S/C Transmitting Antenna Type(s) and Gain(s)	0.3 m Ka-band High Gain Antenna (HGA) 35.7 dBic
Spacecraft Transmitter peak DC power consumption	~75 W

Downlink Receiving Antenna gain	77 dBi
Transmitting Power Amplifier Output	35 W (TWTA)
X-band Downlink Information	**Value, units**
Number of contacts per day	One 4-hr contact per day, simultaneous with Ka-band (supported by DSN 34-m BWG)
Downlink Frequency Band	Near-Earth X-band (8.45-8.5 GHz)
Telemetry Data Rate(s)	900 kbps
S/C Transmitting Antenna Type(s) and Gain(s)	X-band Low Gain Antenna (LGA) 9 dBi X-band Medium Gain Antenna (MGA) 17 dBi
Spacecraft Transmitter peak DC power consumption	~15 W
Downlink Receiving Antenna gain	68 dBi
Transmitting Power Amplifier Output	5 W (SSPA)
X-Band Uplink Information	**Value, units**
Number of Uplinks per day	One 4-hr contact per day, simultaneous with Ka-band (supported by DSN 34-m BWG)
Uplink Frequency	Near-Earth X-Band (7.19-7.23 GHz)
Telecommand Data Rate	2 kbps
S/C receiving antenna type(s) and gain(s)	X-Band Medium Gain Antenna (MGA) 16 dBi, X-Band Low Gain Antenna (LGA) 8 dBi

2. **Identify any unusual constraints or special communications, tracking, or near real-time ground support requirements.**

   None.

3. **Identify any unusual or especially challenging operational constraints (i.e. viewing or pointing requirements).**

   None.

4. **Describe science and data products in sufficient detail that Phase E costs can be understood compared to the level of effort described in this section.**

   The PICO science data products consist of four levels:

   Level 1 data are time ordered data (TOD) from the detectors calibrated into engineering units (i.e. volts).

   Level 2 are calibrated TOD: these data will have cosmic ray hits and other glitches masked, detector time response function deconvolved, and will be calibrated into science units appropriate to the science objectives (for example micro-Kelvin, or MJy/sr).

   Level 3 are calibrated all-sky intensity and polarization (Stokes I, Q, and U parameters) maps at each measurement frequency.

Level 4 consist of temperature and polarization angular power spectra, the associated noise covariances and likelihood distributions, and all-sky component maps such as synchrotron, dust components, and the CMB.

In support of SO1-SO5, Level 4 products will also include the results of cosmological science interpretation, including model parameter estimates (such as τ, r, n_s, N_{eff}, and $\sum m_\nu$), their likelihood distributions, and all Monte Carlo Markov chains used to derive them.

For SO6, we will compare our measurements of the total and polarized spectral energy distributions (SEDs) to theoretical models predicting such SEDs as a function of Galactic dust composition. These will give constraints on the number of dust components and their properties.

For SO7 we will compute dust angular power spectra (both temperature and polarization), and will create maps of the projected magnetic field orientation in the dust for comparison with models and with ancillary data.

The Levels 1, 2, and 3 data are produced at a centralized PICO Science Data Center. Level 4 products are produced by the distributed PICO Science Team. All of the products will be delivered to the LAMBDA archive (https://lambda.gsfc.nasa.gov) at GSFC for distribution to the public.

5. **Describe the science and operations center for the activity. Will an existing center be expected to operate this activity? How many distinct investigations will use the facility? Will there be a guest observer program? Will investigators be funded directly by the activity?**

PICO is a survey mission with a single observing mode and a repetitive scan strategy (**PR** §4.1.2), therefore the operations center can be lean. It will be modeled after other NASA survey missions such as WISE, and SPHEREx, and WMAP.

The science objectives described in the PR (summarized in **PR** Table 1.3) will be funded by the project and performed by the PICO Science Team. PICO produces full sky survey data that will be made public through the LAMBDA archive. PICO does not require a Guest Observer program.

A PICO Science Data Center will execute the software that creates the Levels 1, 2, and 3 data products. In addition to generating Level 1 and Level 2 data, the Science Data Center will perform data quality assessment and feedback to the operations team on the health and performance of the instrument. Level 3 data will be generated after each (6 month) full sky survey has been completed. The Science Data Center will also manage computational resources on behalf of the Science Team for carrying out the Level 4 analysis.

The Level 4 data products will be generated by the distributed Science Team.

The host for the Science Data Center has not been decided. It would ideally be located at an existing institution such as a NASA center or NASA-funded data processing center (such as IPAC), and thus leverage existing infrastructure and knowledge base.

6. **Will the activity need and support a data archive?**

   PICO will use the services of LAMBDA, an existing NASA-sponsored data archive (https://lambda.gsfc.nasa.gov). PICO doesn't need to create its own archiving capabilities. LAMBDA is part of the NASA's High Energy Astrophysics Science Archive Research Center. LAMBDA is a multi-mission NASA center of expertise for cosmic microwave background radiation research. It provides CMB researchers with archive data from cosmology missions, software tools, and links to other sites of interest.

8. Programmatics and Schedule

1. **Provide an organizational chart showing how key members and organizations will work together to implement the program.**

   PICO's organization follows standard NASA Procedural Requirements (NPRs), and does not have any unusual attributes. Foreign contribution is not required. PICO consists of a single flight element with a single instrument with a single observing mode. PICO naturally provides full sky survey data which can be leveraged by the scientific community; a guest observer program is not required. Coordination with other missions is also not required. Project organization is described in **PR** §6.2.

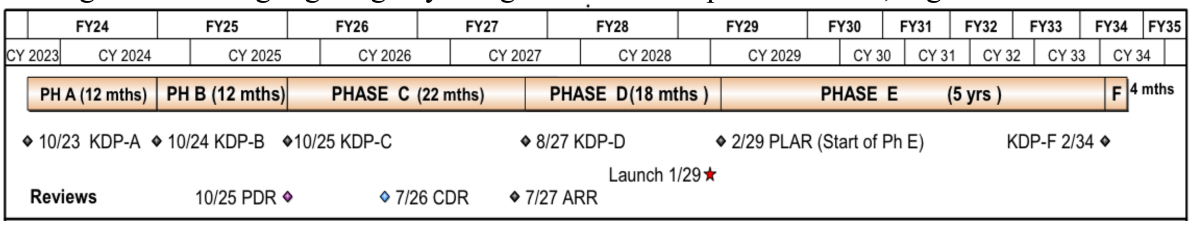
2. **Provide a table and a 5x5 risk chart of the top 3 risks to the program. Briefly describe how each of these risks will be mitigated and the impact if they are not. (Mass, power, schedule, cost, science, etc.).**

   Risks are described in **PR** §6.4 ("Risk Assessment"). Risks have not been rated against the NASA Likelihood and Consequence definitions.

   The top 3 risks are:
   - *Technologies included in the PICO baseline are not matured to TRL 5 prior to Phase A due to funding limitations or technical challenges*. Consequences and Mitigations for this risk are described in our response to Instrument question #3 above ("In the area of instrumentation, what are the top five technical issues or risks?").
     Note: Actively funded and relevant technology development efforts are underway at multiple institutions in support of suborbital projects. However, some of the technology development required for PICO is specific to a flight mission. Prioritization of this technology development will be important to ensure its readiness for the PICO mission.
   - *Design and implementation of spun and despun platforms adds unforeseen complexity as the project progresses*. Consequences and Mitigations for this risk are described in our response to Spacecraft question #4 above ("What are the three greatest risks with the spacecraft?").
   - *Design and implementation of the thermal system adds unforeseen complexity as the project progresses*. Consequences and Mitigations for this risk are described in our response to Instrument question #3 above ("In the area of instrumentation, what are the top five technical issues or risks?").

3. **Provide an overall (Phase A through Phase F) schedule highlighting key design reviews, the critical path and the development time for delivery required for each instrument, the spacecraft, development of ground and mission/science operations etc. Include critical on-orbit events such as maneuvers, instrument deployments, etc.**

   The figure below highlighting key design reviews is copied from **PR**, Figure 6.1.



   The PICO baseline schedule is based on historical actuals from similarly-sized missions such as Juno and SMAP. Per NASA direction, Probe studies assume a Phase A start in October 2023.

   Team X does not provide a schedule critical path nor the development time for delivery required for individual tasks in the schedule. We expect that the critical path will likely begin with either the detectors (**PR** §3.2) or the instrument thermal system (**PR** §3.4) before proceeding through instrument I&T (**PR** §3.5) and observatory I&T.

   On-orbit events and maneuvers are described in **PR** §4.1. There are no deployments.

Maneuver	Reason	Type	Epoch
Halo Manifold Insertion	Getting on L2 Halo Gateway	Deterministic	L+12 hr
TCM1	Insertion Clean-up	Statistical	L+10 days
TCM2	Before Halo orbit Insertion	Statistical	L+30 days
Station Keeping	To maintain the spacecraft halo orbit	Statistical	4 times / Year

4. **Provide a description of any foreign contributions and their extent.**

   No foreign contributions are assumed, nor required.

   There is strong interest in Europe and Japan in a next decade mission that has strong overlap in its science objectives with PICO. Contributions from non-US participants could be considered to reduce US mission cost.

9. Cost

1. **Provide FTE estimates and cost by year/Phase for all expected science personnel.**

Staffing:

		Phase A		Phase B		Phase C		Phase D		Phases E,F	
		Number	*Duration*	*Number*	*Duration*	*Number*	*Duration*	*Number*	*Duration*	*Number*	*Duration*
WBS 4	*NASA scientist*	1	12 months	2	12 months	6	22 months	6	18 months	8	60+4 months
	University faculty	1		4		6		10		15	
	University postdoc	1		8		12		20		25	
	Meetings/year	1		2		2		2		2	
WBS 9B	*SDS Scientist & Hardware*	1		2		4		4		4	
	SDS Programmer	0		3		7		7		7	

Below costs are in FY18$ (per NASA direction to funded Probe studies).

Assumed costs for staffing:

		Assumed cost (in FY2018$)
WBS 4	*NASA scientist*	$260k/person/year
	University senior faculty	$32k/person/year (1 month of summer salary)
	University postdoc	$100k/person/year
	Meetings/year	$2k/person/meeting
WBS 9B	*SDS Scientist & Hardware*	$250k/person/year
	SDS Programmer	$80k/person/year

Cost/yr and total cost (in FY2018$) for each mission phase:

	Phase A		Phase B		Phase C		Phase D		Phases E,F	
	Cost/Yr	*Total*	*Cost/Yr*	*Total*	*Cost/Yr*	*Total*	*Cost/Yr*	*Total*	*Cost/Yr*	*Total*
WBS 4	$402k/yr	$402k	$1,532k/yr	$1,532k	$3,100k/yr	$5,683k	$7,596k/yr	$11,394k	$5,064k/yr	$27,008k
WBS 9B	$250k/yr	$250k	$740k/yr	$740k	$1,560k/yr	$2,860k	$1,560k/yr	$2,340k	$1,560k/yr	$8,320k

Note: The Total Phase E-F costs presented here are different from those presented in the ***PR****. There was a spreadsheet error in the preparation of costs for the* ***PR*** *(wrong number of Phase E-F months assumed for WBS 4 (Science) and WBS 9b (Science Data System) only). The above tables and the Mission Cost Funding Profile table below use the corrected numbers.*

2. **If a foreign agency is assumed to be a partner or a major contributor, provide an estimate by year and Phase for the cost breakdown between NASA and any foreign contributions. This should be separate, but consistent with Total Mission Cost Funding Table.**

Not applicable.

3. **Provide a description and cost of what will be performed during Phase A by year. Also include total length of Phase A in months and total Phase A estimated costs.**

Phase A is 12 months and takes place only in FY2024. The estimated Phase A costs are FY2024$7.8M (FY2020$7.6M). In addition to standard Phase A activities (including development of a detailed Project schedule) the following tasks will be emphasized:

- A simulation software package will be developed, capable of generating simulated PICO data that will include instrumental systematic effects and reflect knowledge about astrophysical sources of emission.
- Technologies will be matured towards TRL 6 (to be completed prior to PDR, late in Phase B).
- Extensive thermal modeling and design trades will be performed, including a trade study examining an opportunity to reduce the spin moment of inertia by changing the materials used for the V-Groove assembly; see the response above to Section 5, Question #6).

4. Please fill out the Mission Cost Funding Profile table assuming that the mission is totally funded by NASA and all significant work is performed in the US.

PICO costs are discussed in **PR** §6.5 ("Mission Cost"), including §6.5.1 ("Payload Cost"). Costs in the **PR** are presented in FY2018$ because Probe studies supported by NASA were required to present costs in FY2018$. In the table below, we provide total costs in RY$, FY2018$ and FY2020$. The Phase E-F costs are different than those presented in the **PR** for reasons described in our response to Question #1 above (in this section).

Item	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	FY2032	FY2033	FY2034	Total	Total	Total
Cost	(Real Yr.)												(FY18$)	(FY20$)
Phase A Concept Study	7.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.8	7.2	7.6
Phase A Tech Dev														
Phase B-D Development	0.0	71.1	151.9	211.1	290.3	81.1	0.0	0.0	0.0	0.0	0.0	805.4	717	754
Launch Services	0.0	0.0	49.7	50.4	51.1	17.3	0.0	0.0	0.0	0.0	0.0	168.5	150	158
Phase E-F														
Science	0.0	0.0	0.0	0.0	0.0	4.1	6.3	6.4	6.5	6.5	2.2	32.0	27	28
Other Phase E-F Cost	0.0	0.0	0.0	0.0	0.0	8.5	13.0	13.2	13.3	13.5	4.6	66.1	56	59
Phase E-F Reserves	0.0	0.0	0.0	0.0	0.0	1.7	2.6	2.6	2.6	2.7	0.9	13.1	11	12
Total Phase E-F	0.0	0.0	0.0	0.0	0.0	14.4	21.9	22.2	22.4	22.7	7.7	111.3	94	99
Education/Outreach														
Other (specify)														
Total NASA Cost	7.8	71	202	262	341	113	22	22	22	23	8	1093	968	1019

5. For those partnering with foreign or other organizations, provide a second Mission Cost Funding Profile table, Table 5, and indicate the total mission costs clearly indicating the assumed NASA and contributed costs.

Not applicable.