5 Technology Maturation (4pg total)

Because the Probe concepts are under consideration for the next decade, they are forward looking and can recommend technologies that do not yet meet the criteria for NASA's Technology Readiness Level (TRL) 5, but that could be developed to that level by ~2023.

5.1 Technology Requirements

Technologies required for PICO have already been partially matured through complimentary sub-orbital experiments. Continued support from NASA through the APRA and SAT programs will be necessary for all technologies to reach TRL5 by Phase A.

5.1.1 Low frequency detectors

The baseline PICO instrument requires three-color dual-polarized antenna-coupled bolometers covering bands from 21 GHz to 462 GHz (§3.2.1, Table 1). Numerous teams have demonstrated detector sensitivity and stability at frequencies lower than that required for PICO (§3.2.3). The developments required to enable the PICO baseline design are the extension of existing detector technologies to lower and higher frequencies, demonstration of 3-color pixels across that spectrum, and beam line testing to simulate the cosmic ray environment at L2.

Generally, antenna-coupled bolometers receive different spectral ranges because their antennas have been geometrically re-scaled in proportion to wavelength, and the microstrip filters have been appropriately tuned. The extension to lower frequencies requires control of film properties and lithography over large areas, whereas scaling to higher frequencies often forces tighter critical dimensions and possible changes to the thickness of the films to keep these dimensions fabricable. Moreover, materials tend to exhibit higher losses at higher frequencies and denser wiring can be prone to reduced yield. Both of these challenges require tight control of cleanliness and full understanding of process parameters.

Trichroic (and dichroic) coupling schemes require antennas with desirable optical properties over a far wider bandwidth than single color pixels. For example, few antennas provide stable and real radiation impedance over more than an octave of bandwidth, making three-color designs challenging to implement. While the sinuous antenna does provide this bandwidth, it's polarization state "wobbles" log-periodically with frequency and we are still understanding the systematics impacts of this through suborbital experiments.

Several competing optical coupling technologies have matured over the past ten years through myriad suborbital experiments (Figure 9). This experience presents multiple options to PICO, including horn-coupling (Duff 2016), antenna-array coupling (BICEP2 2015), and sinuous antenna/lenslet-coupling (Edwards 2012). SPT-3G has deployed dual-polarized 3-color antenna-coupled bolometers utilizing sinuous antennas, all operating in the 90/150/220 GHz atmospheric windows (reference). Advanced ACT-pol has deployed dual-polarized two-color antenna-coupled bolometers coupled to horn-antennas with lithographed Orthomode Transducers (reference). To date, ACT-pol has deployed 90/150 GHz and 150/230 GHz focal planes, and will deploy 27/39 GHz shortly. Lab prototypes of dual-color antenna arrays have been demonstrated at 30/40 GHz and 220/270 GHz.

We propose the following schedule to mature these technologies:

1. 2019: Ground based field demonstrations of 30-40 GHz (already funded- Class, ACT, BICEP) and laboratory demonstrations of 15 GHz (not yet funded).
2. 2022: Balloon mission to demo 270-600 GHz range, to fly before 2022. BFORE and

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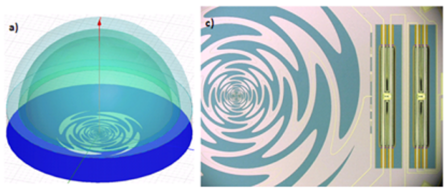
IDS are under study for this and would require funded through the APRA program (requires $5-10M for a flight).

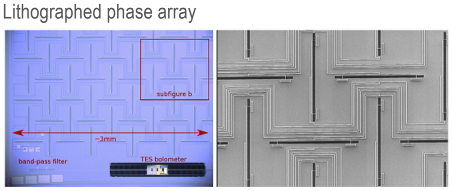
3. 2019-2023: continued support of ground telescopes to refine systematic control and test other frequency combinations.
4. 2018-2022. Cosmic rays studies culminating in a beam line test in 2022. These activities are currently supported by SAT and MOO funds, and require continued support.

Tasks 1 and 2 will need to demonstrate trichroic pixels in anticipation of PICO's baseline design.

Sinuous antenna



Lithographed phase array



Horn coupled

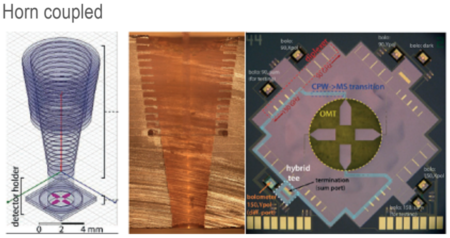


Figure 9: We may include some (TBD) pictures in the technology section to show that though development is required, we are building on existing technologies. Images from CMB-S4 Technology Book.

5.1.2 High frequency detectors

The highest frequency channels at or above the niobium band gap of 650 GHz (§3.2.1, Table 1) will need to be mapped through detectors that omit superconducting transmission lines, instead coupling power to absorbing films through horns. The development required to enable these detectors for PICO involves prototyping and testing monolithic arrays in these short wavelength bands for each polarization and developing a packaging scheme to position both polarizations in close proximity within an array of waveguide backed horns.

This development will build off of prior designs of unpolarized and dual-polarized horn/absorber-coupled NTD-Ge bolometers used in the Planck and Hershel flight missions. These were single detectors hand assembled into focal planes, while PICO calls for monolithic arrays. Additionally, SPT-pol deployed a camera of dual-polarized horn/absorber coupled TES bolometers for 90 GHz, but also as hand-assembled individual detectors. Finally, monolithic arrays of horn/absorber coupled unpolarized TES bolometers have been used in the APEX and SPT telescopes, as well as the EBEX balloon flights.

PICO's detectors will use a similar design as SPT-pol 90 GHz coupling each polarization to two gold bars co-centered in the back of a horn, but with a slight displacement along the optical axis. The community will need to generalize this design to monolithic arrays with pixels an order of magnitude smaller than SPT's. This task is well within the capabilities of many commercial and government fabrication facilities. The two polarizations will need to be separated by ~0.05 mm, which is easily accomplished if using commercial silicon wafers with DRIE etched holes.

There are no serious technical barriers to implementing this design, but NASA will need to invest in suborbital demonstrations. We propose the following schedule:

1. 2020: Lab demonstrations of prototypes (not yet funded), performing noise, stability, and optical tests.

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2. 2022: Balloon mission to demo 600 GHz-1000 GHz range, to fly before 2022. BFORE and IDS are under study for this and would require funded through the APRA program (requires $5-10M for a flight).
3. 2021-2022: Cosmic ray studies culminating in a beam-line test, to be done concurrently with the antenna-coupled bolometers.

5.1.3 Readout Electronics

While the detectors can be made background-limited, the readout is demanding. The sensitivity requirements of PICO dictate the use of ~13,000 transition edge sensor bolometers. Thus, sensor readout requires a highly multiplexed system.

Several architectures have been in active development through sub-orbital experiments. More than 10 experiments have used time division SQUID multiplexing (TDM). The 10,000 pixel bolometer camera SCUBA2 [1] on the JCMT is the largest array to use TDM. Recently, SPT-3G [2] fielded a 16,260 bolometer camera that utilizes MHz frequency division SQUID multiplexing [3]; however it is too early to assess the detailed performance. Several sub-orbital cameras in development with greater detector counts plan to use entirely different readout systems or alternative detectors to solve the readout challenge. The Simons Observatory, which in total will contain more than 60,000 sensors, plans to implement TES bolometers with microwave SQUID multiplexers [4]. BICEP Array [5] is investigating thermal kinetic inductance detectors [6] for the highest frequency channels of the instrument, which have the highest sensor counts.

Because of the relative maturity, the PICO design calls for time division multiplexing, however with 128 switched rows per readout column (TDM-128x). This multiplexing factor is beyond what has currently been demonstrated. The vast majority of deployed instruments have used TDM-32x. Advanced ACTPol has demonstrated TDM-66x [7,8].

Technical developments associated with achieving TDM-128x include 1) development of fast-switched room temperature electronics, 2) system engineering of room temperature to cryogenic row select cabling to ensure sufficiently fast row switch settling times, 3) demonstration of TDM-128x SQUID aliased noise below PICO detector sensitivity requirements. These technical advancements are readily achievable with modest investments. If invested in the near future, these developments can be made by 2020-2021. We recommend continued support of suborbital experiments with a preference to proposals that plan to implement 128x TDM over the existing state of the art. This research will require roughly $4M over the next three years, but we stress that this support can be of projects that will also advance the detector readiness articulated above.

5.2 Technology Descopes

Talk about probability of completing tech development. Talk about what mission opportunities would be available even if tech development doesn't go as planned.

Note: Jeff says we definitely need to talk about fall-back options if the Tech Development does not succeed in reaching the baseline design point.

5.3 Enhancing Technologies

The following technologies represent opportunities to extend PICO's scientific capabilities beyond the baseline mission described in this report (these technologies are not required or assumed by the baseline concept).

Microwave frequency SQUID multiplexing can increase the multiplexing density and reduce the number of lines between the 4K and ambient temperature stages. Kinetic Inductance Detectors (KIDs) and Thermal KIDs (TKIDs) can further reduce the complexity of wiring and

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integration at the sub-Kelvin cryogenic stages. These technologies could reduce risk in the final mission, and the cost to develop them is $3-4M/year, with a high chance of reaching TRL-5 before Phase A.

microwave frequency MUX (Dober 2017), kinetic inductance detectors (KIDs) (McCormick 2016), and thermal KIDS (TKIDs) (Steinbach 2018),

An alternative 100-mK (or colder) cooling technology on the edge of flight applicability is Closed-Cycle Dilution Refrigeration. Attractive for its lack of magnetic fields, truly continuous (non-cyclic) cooling, and commonality of mechanical pumps with the 4-K--class coolers, the CCDR has flight-demonstrated most of the required technology; only separation and recirculation of the ^{3}He and ^{4}He fluids remains below TRL-5 in the zero-G environment. We estimate that this could cost $2M/year to develop.

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