NASA PCOS Program Technology

- The Inflation Probe is part of NASA's Physics of the Cosmos (PCOS) program office
- PCOS has an annual process by which mission-related technology needs are prioritized by a Technology Management Board
- Anyone can submit "technology needs" related to the program goals- due date is **June 1**; prioritization happens in July-August
- The prioritization process results are listed in the Program Annual Technology Report (PATR), feeds into the language of the AO for the Strategic Astrophysics Technology (SAT) call (amended in December;proposals due March 2018)
- In addition, this is one way that NASA program offices and NASA HQ receives input from the science community

3 CMB-related technology gaps already tracked by PCOS

1. Advanced millimeter-wave focal-plane arrays for CMB polarimetry
2. Millimeter-wave optical elements
3. High efficiency cooling systems 20K to below 1K

- In the future, the direction of our Study may dictate new gaps/modifications of existing gaps
- My suggestion for this year: we submit a statement to PCOS along the lines of:
  - The Inflation Probe team supports maintaining these three gaps. As our study advances over the next year we may submit technology gaps or modify the requirements associated with the existing ones.

Gap Name		Advanced millimeter-wave focal-plane arrays for CMB polarimetry *Submitted by General Community*
Description		The Inflation Probe (IP) requires arrays of detectors with background-limited sensitivity, dual-polarization detection capability, and control of systematic errors at multiple frequencies between ~30 and ~600 GHz for foreground removal. Architectures must be scalable to large arrays for the requisite sensitivity. Simultaneous multiband operation, high multiplexing factors, and efficient detector and readout focal-plane packaging represent desirable design qualities. Detector systems must be compatible with the space environment. This includes low dielectric exposure to low-energy electrons and robust performance in the presence of cosmic rays. Continued deployment in ground-based and balloon-borne platforms will benefit development efforts.
Current State-of-the-Art (SOTA)		A great deal of progress has been made with a variety of approaches, including feedhorn and antenna-coupling waveguide probes, and filled absorber structures. TESs are currently the leading candidate technology for the detecting element in these integrated sensors. Arrays of several thousand detectors are operating in ground-based Cosmic-Microwave-Background (CMB) -polarization experiments. Balloon experiments E and B Experiment (EBEX) and Suborbital Polarimeter for Inflation Dust and the Epoch of Reionization (Spider) have demonstrated two TES architectures in the environment closest to space. Primordial Inflation Polarization Explorer (PIPER) will soon demonstrate a third. Fabrication of TES arrays on 150-mm diameter substrates, which addresses pixel-count scalability, is now maturing at multiple fabrication foundries. However, no fielded 150-mm arrays exist at this time.
TRL	**SOTA**	4
	Solution	3
Performance Goals and Objectives		The detectors must demonstrate high efficiency, background-limited sensitivity, and linearity over a wide spectral range (~30 to ~600 GHz), while at the same time controlling systematic errors to a level sub-dominant to the instrument statistical-noise floor. The technology must demonstrate extremely low levels of polarized-beam systematic errors to achieve this goal. The technology must be compatible with space-borne operation, and provide appropriate magnetic shielding, cosmic-ray immunity, vibration tolerance, and excellent noise stability. Process uniformity, high detector efficiency, and high yield are also important. One technical development that would have a large impact on instrument design is a reduction of the TES detector-to-readout interconnects at the milliKelvin stage. Current TES readout schemes demand a large number of additional hardware elements, which require interconnects and an associated mechanical support structure. Technical approaches that do away with additional readout hardware elements will reduce the mass, volume, and complexity of the entire instrument. Integrated fabrication of TES detectors and SQUID readouts represents one avenue to achieve this goal.

Scientific, Engineering, and/ or Programmatic Benefits	Measurement of CMB polarization to search for evidence of, and characterize, Inflation is a top NASA priority. Such detectors are a key enabling technology. A space-borne measurement can probe for a polarization pattern imprinted by a background of GWs generated at the time of Inflation in the early universe. Polarization measurements on finer angular scales probe large-scale structure sensitive to neutrino mass and dark energy.
PCOS Applications and Potential Relevant Missions	These are needed for measuring CMB polarization to search for and characterize the faint polarized signature of Inflation. The targeted mission is IP as recommended in the NWNH report. Other possibilities include Explorer and international CMB-polarization and absolute-spectrum experiments. Development also has technological overlaps with superconducting far-IR and X-ray detectors.
Time to Anticipated Need	**Named missions:** IP (2020s) **Development needed for 2020 Decadal:** Yes, IP **Other drivers:** IP technology development is a NWNH priority that was recently revisited by the mid-Decadal review. US contribution to the Japanese Aerospace eXploration Agency (JAXA) mission Lite (light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD) is already in a phase A study through the Explorer's program. An additional Explorer proposal to contribute to a European Space Agency (ESA) mission is likely this year.

Gap Name		Millimeter-wave optical elements *Submitted by General Community*
Description		High-throughput telescopes and optical elements with controlled polarization properties are required for the IP. These require development of cryogenic mm-wave filters and coatings. Measurement of CMB polarization on large scales may require rapid polarization modulation to separate sky-signal polarized intensity from instrumental effects. Employing modulators large enough to span the telescope primary aperture is an advantage in that sky polarization can be separated from instrumental effects.
Current State-of-the-Art (SOTA)		Single-layer anti-reflection (AR) coatings are in widespread use. Meta-material AR structures are in development and early use. Several experiments in the field are currently using rapidly spinning half-wave plates as the primary means of modulating the signal and separating it from longer time variations. More experiments are coming online using both half-wave plates and variable-delay polarization modulators that endeavor to measure larger areas of the sky.
TRL	**SOTA**	2 – 5
	Solution	
Performance Goals and Objectives		Develop robust multi-layer coatings for broadband applications for commonly used dielectrics (e.g., silicon, alumina, and sapphire). Develop thermal filtering technologies suitable for large Focal-Plane Arrays (FPAs) operating at sub-Kelvin temperatures. Develop space-compatible modulators, including work on frequency-selective surfaces and mechanisms compatible with the space radiation environment. Minimizing dielectric cross-section to low-energy electrons is a priority. Develop and compare strategies for instrument architectures with and without rapid modulators. A secondary goal is to ensure that the technology can be implemented in a cost-effective way for large optical elements. Large in this context is up to 100 cm in diameter.
Scientific, Engineering, and/or Programmatic Benefits		Broadband optics can reduce the necessary focal-plane mass and volume for CMB polarization measurements. This may open options for compact optical systems appropriate for lower-cost Explorer opportunities; an international mission concept using broadband refracting optics is in the planning stages. Modulators are potentially a key enabling technology.
PCOS Applications and Potential Relevant Missions		IP, Far-IR, Explorer, and international experiments to study CMB polarization and absolute spectrum.
Time to Anticipated Need		**Named missions:** IP (2020s) **Development needed for 2020 Decadal:** Yes, IP **Other drivers:** IP technology development is a NWNH priority that was recently revisited by the mid-Decadal review. International and Explorer implementations of the IP have proposed launch dates during the second half of the next decade.

Gap Name		High-efficiency cooling systems for temperatures covering the range 20 K to below 1 K *Submitted by General Community*
Description		Stable and continuous cooling systems with high thermal-lift capacity and efficiency are needed for the IP and planned X-ray and Far-IR missions. Refrigerators to reach 100 mK are needed, especially refrigerators that are stable, continuous, low mass, have long lifetimes, and are low cost. The cost of reaching 100 mK is an impediment to small or mid-size missions that incorporate sensors requiring such low operating temperatures.
Current State-of-the-Art (SOTA)		The Planck satellite demonstrated continuous cooling to 20 K and 4 K for four years, and continuous cooling to 0.1 K for 2.5 years. The demonstrated open-cycle dilution refrigerator on Planck does not scale to higher power loading. Approaches based on adiabatic demagnetization refrigeration (ADR), ^{3}He sorption cooling, or closed-cycle dilution offer avenues to provide improved performance.
TRL	**SOTA**	6
	Solution	
Performance Goals and Objectives		Continuous and stable cooling to 100 mK without cryogens. Cost reductions of 3-5× compared to 100 mK refrigerators demonstrated to date. Mass reductions of 2-3× compared to 100 mK refrigerators demonstrated to date. The cooling power must be increased beyond that provided by the Planck system for large focal planes, and the implementation simplified for lower-cost mission opportunities.
Scientific, Engineering, and/or Programmatic Benefits		Enables next-generation measurements of CMB polarization, Athena, and high-resolution photon counting. Enables improved sensor performance. Enables 100 mK sensors on small or mid-size missions. Extends mission lifetimes.
PCOS Applications and Potential Relevant Missions		IP, Explorer, and international CMB polarization and absolute spectrum experiments; X-ray applications with cryogenic detectors; and Far-IR instrumentation.
Time to Anticipated Need		**Named missions:** IP (2020s), Athena **Development needed for 2020 Decadal:** Yes, IP and XRS **Other drivers:** IP technology development is a NWNH priority that was recently revisited by the mid-Decadal review. International and Explorer implementations of the IP have proposed launch dates during the second half of the next decade.