CMB Technology Roadmap for the NASA Inflation Probe

Developed for the NASA Physics of the Cosmos Program Analysis Group
July 2011

James Bock (Jet Propulsion Lab), Todd Gaier (Jet Propulsion Lab), Shaul Hanany (U. Minnesota), Kent Irwin (National Institute of Standards), Adrian Lee (U. California at Berkeley), Steve Meyer (U. Chicago) and Harvey Moseley (Goddard Space Flight Center)

1. Executive Summary

This roadmap describes a program for developing the technologies necessary for NASA's Inflation Probe satellite. For the next 5 years we recommend funding for three critical technologies currently at mid technology readiness (TRL = 4-6): detector arrays, optics, and coolers. Of these, the highest priority should be placed on the development, testing, and characterization of detector arrays, which are needed to realize the sensitivity required by the Inflation Probe. Detector array technology has broad applicability to NASA X-ray and infrared space astronomy missions. Emerging (TRL = 1-3) technology should also be supported, under the auspices of the current NASA R&A program. We support collaboration between NASA-funded technology development between NASA and federal laboratories with university-based researchers, and endorse a program implementing candidate technologies in sub-orbital and ground-based experiments, so they can be demonstrated in a space-representative environment. The CMB technology program will be evaluated mid-decade as recommended by the Astro2010 Decadal Report in order to assess the rapidly developing scientific and technological case for the Inflation Probe and plan technology development for the latter half of the decade.

2. Introduction

This technology roadmap is based on the recommendation of the Astro2010 Decadal Report for directed technology funding leading to a space-based measurement of Cosmic Microwave Background (CMB) polarization, for a fourth-generation CMB satellite experiment termed the Einstein Inflation Probe. This roadmap also incorporates elements from the CMB community-based 2005 *Task Force on Cosmic Microwave Background Research* (Weiss committee) planning document. The importance of this research has been recognized in national reports including the 1999 National Academy report *Gravitational Physics: Exploring the Structure of Space and Time*, the 2001 Decadal survey *Astronomy and Astrophysics in the New Millennium*, and the 2003 National Research Council report *Connecting Quarks with the Cosmos*.

The Decadal report endorsed a CMB technology program of $60M over the decade in preparation for a mission beyond 2020. The report however noted that "the level of late-decade investment required is uncertain, and the appropriate level should be studied by a decadal survey independent advice committee review. It could range between the notional budget used here up to a significant (perhaps on the order of $200 million) mission-specific technology program starting mid-decade".

Therefore our roadmap charts the path forward for the next 5 years, leading to a mid-decade review that will inform planning for the subsequent 5 years. Our plan incorporates the unique strengths of the CMB research field, infusing NASA-led technologies into a vigorous and diverse sub-orbital and ground-based observational program that provides rapid technology demonstration in an environment representing the ultimate application in orbit. This program combines university-based research groups, with NASA technology support and important contributions from the NSF, DOE, and DOC agencies. Scientific results from these ground-based and sub-orbital experiments, as well as all-sky polarization measurements from the current ESA *Planck* satellite, will inform the mid-decade review foreseen by the Decadal survey for planning technology funding in the latter half of the decade.

3. Science

There is mounting evidence that the entire observable universe was spawned in a dramatic superluminal Inflation of a sub-nuclear volume. Inflation provides beautiful solutions to outstanding problems in cosmology, connects the physics of the largest and smallest phenomena, and challenges the very foundation of modern physics. During Inflation, quantum fluctuations were stretched to astronomical size, producing the scalar fluctuations that are well observed in the CMB temperature anisotropy and forming the seeds for all the structures in the universe. The spectrum of these fluctuations is nearly scale-invariant, but with a small departure that depends on Inflationary physics.

In addition, the simplest versions of Inflation robustly predict a stochastic background of tensor perturbations: gravitational wave radiation sourced by the same quantum fluctuations. Inflationary gravitational waves leave a unique pattern imprinted on the CMB polarization discernible from primordial scalar density fluctuations present during the recombination era. That pattern has been labeled B-mode polarization, akin to a magnetic field being the curl part of a vector field in electromagnetism. A sufficiently sensitive and careful measurement of the polarization anisotropy of the CMB could detect the presence of these gravitational waves. That detection would confirm the overall theory of Inflation and provide a measure of the energy scale of Inflation that would constitute the first quantitative clues to the physical laws that govern the universe at these highest energies.

The amplitude of the B-modes is quantified by the ratio of the tensor to scalar perturbation amplitude, r, which is directly related to the Inflationary energy scale, $V^{1/4} = 1.06 \times 10^{16} (r/0.01)^{1/4}$ GeV. A detectably large tensor amplitude $r > 0.01$ would convincingly demonstrate that Inflation occurred at a tremendously high energy scale, comparable to that of Grand Unified Theories (GUTs). It is difficult to overstate the impact of such a result. To date physicists have only two indirect clues about physics at this scale: the apparent unification of gauge couplings, and experimental lower bounds on the proton lifetime. Detection of tensor fluctuations would be to Inflation what the discovery of the CMB was to Big Bang cosmology. Indeed its impact may be broader as Inflation directly bears on the current frontiers of fundamental physics: the union of general relativity and quantum mechanics, string theory, and the highest accessible energies.

Today, experimenters are testing instrumentation with the sensitivity and precision needed to make a detection of the B-mode pattern with amplitude of $r < 0.1$, where B-mode measurements begin to overtake constraints on r from other observables. These experiments are on a trajectory to push down to $r \sim 0.01$ in the coming years. Bringing the full potential of the CMB B-mode anisotropy signal to bear on the physics of Inflation and the early universe requires measurements well beyond a simple detection. This is the basis of the Astro2010 Decadal Survey recommendation to prepare for a space-based mission having more than ten times the sensitivity of the *Planck* satellite or what is possible from coming ground-based experiments. The space mission will be strengthened by a B-mode detection from current and planned experiments.

The plan for the future development of the Inflation Probe includes the construction of suborbital experiments that test and optimize techniques and technologies with the experiments being motivated by the requirement for more sensitive measurements. The suborbital program is paralleled by concurrent development of instrumentation aimed specifically at the unique problems of a space environment: high-sensitivity multiplexed focal-plane arrays, high-throughput mm-wave optics, and specialized cryogenic cooling systems. These parts of the program converge to the initialization of a space-based probe capable of fully extracting virtually all the cosmological information available in the CMB in a comprehensive all-sky high-sensitivity measurement in multiple frequency bands.

4. Technologies for the Inflation Probe

Technology	Detectors			Optical system	Cryogenic system	Push Technology: Advanced mm-wave / far-IR Arrays
	Sensor Arrays	Multiplexing	Optical Coupling			
Brief Description of Technology	The Inflation Probe requires arrays of polarization-sensitive detectors with noise below the CMB photon noise at multiple frequencies between ~30 and ~300 GHz for foreground removal[a]; up to 1 THz for Galactic science.	Multiplexed arrays of 1,000 - 10,000 low- temperature detectors will be required for the Inflation Probe.	The Inflation Probe requires coupling the light to the detectors with exquisite control of polarimetric systematic errors.	High-throughput telescope and optical elements with controlled polarization properties are required; possible use of active polarization modulation using optical elements.	The Inflation Probe requires cryogenic operation, passive radiators, mechanical cryo-coolers, and sub-Kelvin coolers.	Detector arrays with higher multiplexing factors and multi-color operation may provide simplified implementation for the Inflation Probe, and have diverse space-borne applications in X-ray calorimetry and far-infrared astronomy.
Goals and Objectives	Demonstrate arrays in sub-orbital instruments, and demonstrate the background-limited sensitivity appropriate for a satellite-based instrument in the laboratory.	Demonstrate multiplexed arrays of thousands of pixels in ground- and balloon-based instruments.	Demonstrate arrays of polarization-sensitive receivers with sufficient control of polarization systematics in sub-orbital and ground-based instruments.	Demonstrate all elements of an appropriate optics chain in sub-orbital and ground-based instruments.	Develop mature sub-Kelvin coolers appropriate for space.	Develop higher multiplexing factors with micro-resonators; demonstrate multi-color operation with antenna-coupled detectors to reduce focal plane mass.
TRL	**TES:** (TRL 4-5) Noise equivalent power (NEP) appropriate for a satellite has been demonstrated in the laboratory, and TES instruments have been deployed and used for scientific measurements in both ground-based and balloon-borne missions. **HEMT:** (TRL 4) Flight heritage, but extension to 3 QL noise, access to higher frequencies and lower power dissipation requires demonstration.	**TDM:** (TRL 4-5) Ground based arrays of up to 10,000 multiplexed pixels are working on ground-based telescopes. Kilopixel arrays will shortly fly in balloons. **FDM:** (TRL 4-5) Ground based arrays of up to 1,000 multiplexed pixels are working on ground-based telescopes, and initial balloon flights have occurred.	**Planar antenna polarimeter arrays:** (TRL 4-5) Ground based arrays deployed and producing science, balloon-borne arrays will soon be deployed. **Lens-coupled antenna polarimeter arrays:** (TRL 4-5). Ground based arrays deployed. **Corrugated feedhorn polarimeter arrays:** (TRL 4) Corrugated feeds have extensive flight heritage, but coupling kilopixel arrays of silicon platelet feeds to bolometers requires maturation. Ground-based arrays in this configuration are soon to be deployed.	**Millimeter-wave AR coatings:** (TRL 2-5) multi-layer to single-layer coatings. **Polarization modulators:** (TRL 2-4) half- wave plate modulators, variable polarization modulators, or on-chip solid-state modulators	Technology options for the sub-Kelvin coolers include He-3 sorption refrigerators, adiabatic demagnetization refrigerators, and dilution refrigerators. TRL for all options varies considerably from TRL 3 to TRL 9. Planck and Herschel provide flight heritage for some of these systems.	**MKID:** (TRL 3) Appropriate sensitivity needs to be demonstrated, small ground-based instruments are in development. **Microresonators:** (TRL 3) 2,000-channel ground-based MKID instruments are in preparation. Laboratory systems using microwave SQUIDs have been developed for small TES arrays. Hybrid combinations are possible. **Multi-color pixels:** (TRL 2) Multi-band lens-coupled antennas have shown proof of concept, but must meet exacting CMB requirements.
Tipping Point	For the TES, demonstrate appropriate sensitivity at all relevant wavelengths. For HEMTs, improved noise performance and low power dissipation.	For TDM and FDM, demonstrate full- scale operation on a balloon-borne instrument.	Extensive analysis of data from ground-based and balloon experiments is required to demonstrate control of systematics. Demonstrations required at all wavelengths of interest.	Demonstrate relevant optical system designs, including reflective and refractive optics, millimeter AR coatings, and half-wave plate polarization modulators.	Space cooling system can be leveraged on current technology efforts, but must provide extremely stable continuous operation	MKID instruments must demonstrate sensitivity in full sub-orbital instrument. For microresonators, a breakthrough is required on the room- temperature readout electronics. Multi-band pixels must be used in sub-orbital instrument.
NASA Capabilities	National labs (JPL, GSFC, NIST, and Argonne) and University groups (Berkeley) have extensive experience with the design and fabrication of arrays that have been used in previous missions in this wavelength range.			NASA and many University groups have developed and deployed optical systems as described here.	NASA has extensive heritage appropriate to the task, and some elements are commercially available.	National labs (JPL, GSFC, NIST, and Argonne) and University groups (Berkeley) have extensive experience with the design and fabrication of arrays.
NASA needs	The technology developed would leverage many other missions requiring low-temperature superconducting detectors, including **IXO**, **Generation-X**, and future far-infrared missions such as **SPIRIT**, **SPECs, or SAFIR.**		Pixel optical coupling technologies are candidates for future far-infrared missions such as **SPIRIT**, **SPECs, or SAFIR**.	Improvements in optical systems will benefit **SPIRIT**, **SPECs, or SAFIR**.	Developments will benefit any other future satellite mission requiring sub-Kelvin cooling, including **IXO**, **SPICA**, **SAFIR**, etc.	The technology developed would leverage many other missions requiring low-temperature superconducting detectors, including **IXO**, **Generation-X**, and future far-infrared missions such as **SPIRIT**, **SPECs, or SAFIR.**
Non-NASA aerospace needs	Arrays of sensitive bolometers may have national security applications either in thermal imaging of the earth, or in gamma spectroscopy of nuclear events.					
Non aerospace needs	Sensitive mm-wave bolometer arrays have applications in remote sensing, including concealed weapons detection, suicide bomber detection, medical imaging, and sensing through fog.					
Sequencing/Timing	Should come as early as possible. The entire Inflation Probe system is dependent on the capabilities of the sensors.			Early test of optical elements needed to gauge system issues.	The cryogenic system is specialized for space and not as time-critical.	These advanced options should be pursued in parallel to reduce cost and implementation risk.
Time and Effort to Achieve Goal	5-year collaboration between NASA, NIST, and university groups.				Leverage current development for space-borne coolers.	5-year collaboration between NASA, NIST, and university groups.

[a]Information on foregrounds across a broader range of frequencies (5 GHz to 1 THz) from sub-orbital and ground-based experiments is essential for optimizing the choice of bands for the Inflation Probe.

5. Prioritization

The program shown in Table 1 incorporates multiple independent approaches to each critical technology required by the Inflation Probe. This gives us confidence that at least one technology will be available for selection, and very likely it will be possible to select the best technology among multiple competing options. Furthermore since most of these technologies will be operated from a sub-orbital or ground-based platform, we will gain experience with them in a representative scientific environment, so that we understand the importance of each technology at a systems level. This systems knowledge is critical for the design of a space-borne instrument.

Technologies for the Inflation Probe fall under 3 broad categories: detectors, including their readouts and optical coupling schemes, optics, and cryogenics. As shown in Fig. 1, we plan for multiple technologies to go forward in the first half of this decade, leading to a prioritized selection mid-decade for enhanced development in the second half of the decade. However, at the beginning of this decade we can assign prioritization guidelines as follows.

1) Detectors

The current search for B-mode polarization is sensitivity-driven, so the development of detectors must be the highest development priority. Bolometers using a (TES) transition-edge superconducting film voltage-biased at the transition are currently the leading detector technology, in use in the large majority of CMB experiments. TES bolometers may be read out with multiplexed readouts, either based on time-domain or frequency-domain multiplexing with SQUID (superconducting quantum interference device) current amplifiers. SQUID-based readouts are currently in use with arrays of $\sim 10^4$ detectors, which is likely to be the size of the focal plane allowed by optical design in the space-borne Inflation Probe. Microwave Kinetic Inductance Detectors (MKIDs) are another direct detector technology, based on the change in inductance in a superconductor in the presence of photon-induced quasi-particles. MKIDs are read out using RF multiplexing which offers advantages of simplicity and larger multiplexing factors. While MKIDs do not yet demonstrate the sensitivity needed for CMB polarimetry, rapid progress is being made. Potential combinations of these approaches have been recently emerging, e.g. TES detectors with RF multiplexed readouts and bolometers using MKID temperature sensors. High electron mobility transistor (HEMT) amplifiers are used for coherent (phase-sensitive) detection. HEMTs are being combined with monolithic microwave integrated circuits (MMICs) to develop polarization modules that amplify and detect all the available polarization Stokes parameters.

Based on the 2005 Weiss report and the community-based plan assembled for the Decadal review in 2008 (see http://cmbpol.uchicago.edu/workshops/technology2008), direct detectors offer the highest potential for meeting the sensitivity and frequency coverage needed for the Inflation Probe. Thus highest priority should be placed on the development of direct detectors, and indeed the current balance of CMB detector research in the U.S. is currently based on these detectors (see Table 2). HEMT amplifiers are arguably the favored technology for operation at $\nu \leq 100$ GHz, and fulfill an important role in ground-based observations. Furthermore amplifiers can be operated at higher temperatures, which may offer a simplified space-borne implementation if the science can be accomplished with restricted spectral coverage. Support for all viable options for a space mission should be maintained at least until the mid-decade review.

Current focal plane designs integrate polarization detection, beam collimation, and band-pass filtering that is completely integrated with photon detection and readout. Current approaches include antenna-coupled bolometers combined with feedhorns, lenses, or planar antennas. A similar integrated approach is being developed for HEMTMMIC amplifiers combined with feed horns. These all offer a compact and modular design that scales to mass production, with obvious advantages for a space experiment. CMB polarimetry critically depends on the optical properties of the detection system, and these designs must be shown to meet the demanding levels of polarimetric control needed for the Inflation Probe.

2) Optics

The Inflation Probe will need a high-throughput optical system to accommodate the large focal planes needed for sensitivity, with demanding requirements on polarization purity and stray light control. Control of systematic errors can be enhanced by the use of polarization modulation by an optical element such as a half-wave plate. Broad-band anti-reflection coatings for optics or focal planes enable multi-band operation and a more compact instrument.

3) Cryogenics

Direct detectors require operation on a 100 mK focal plane with continuous cooling and high temperature stability. *Planck* has realized close to the necessary performance on-orbit using an open-cycle dilution refrigerator. Designs with more heat lift are being developed to operate from 4 K using close-cycle dilution and adiabatic demagnetization refrigeration (ADR) cooling. A combination of radiative cooling with a mechanical refrigerator could be used to achieve a 4 K base temperature, a simplification on the *Planck* cooling system.

The scientific field and technologies are rapidly evolving, and thus the prioritization of technology development must be periodically monitored and replanned. The mid-decade review offers the next milestone to assess the state of technology and to chart the course forward for the latter half of the decade. We believe further prioritization will become evident at this juncture, shown in Fig.1, as the results from deep sub-orbital and ground-based searches for tensor modes become known, and the all-sky measurements of polarized foreground with *Planck* will inform the sensitivity and band coverage needed for the Inflation Probe.

6. Technology Timeline

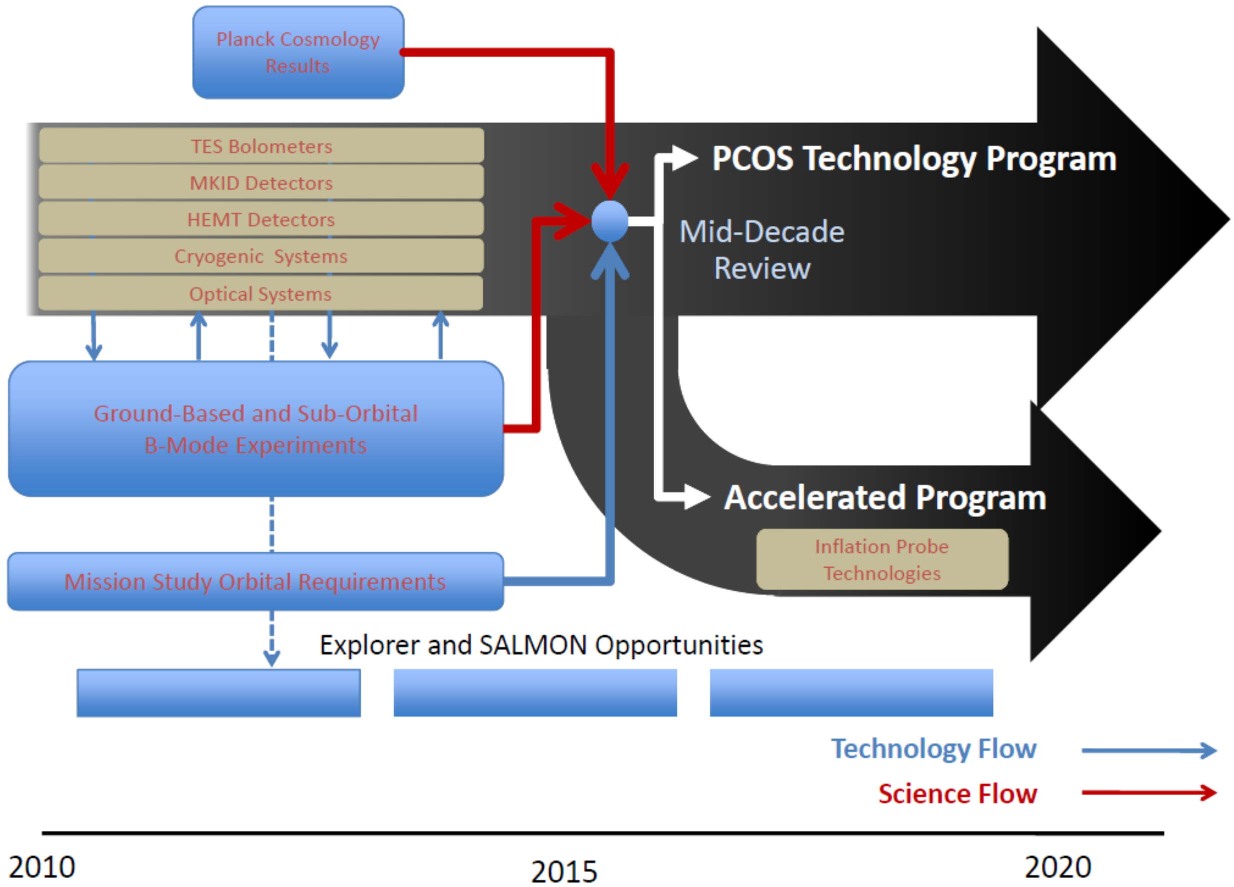

Figure 1. The relationships between the CMB technology program and other science and technology related efforts. The Astro2010 Decadal Survey recognized that CMB science and technology are evolving quickly, and recommended a mid-decade review, with the option of an accelerated technology effort with augmented funding leading to the Inflation Probe. We show this as a key milestone in the CMB technology program at which point, a down selection of technologies may occur leading to a rapid development of the Inflation Probe mission, or alternatively continued development of technologies at the current level of funding.

The first major input to the program will be the release of cosmological results from *Planck*. While *Planck* does not have the polarization sensitivity to achieve the CMB polarization goals described in the Decadal Survey, it does have unique capabilities in its all-sky observations of polarization over a wide range of wavelengths. *Planck* will influence our understanding of Inflation by its improved measurements of departure from scale invariance, non-Gaussianity, and constraints on B-mode polarization. Significantly, *Planck* will map polarized foreground emission over the full sky, which will serve to shape the technical requirements for the Inflation Probe.

The technology program operates synergistically with ground-based and suborbital experiments targeting deep B-mode observations. The experiments, funded under NASA's R & A program as well as NSF grants, are crucial for the success of the CMB technology program. These efforts test candidate technologies in the field, revealing limitations and systematic behavior, serving as prototypes for potential Inflation Probe architectures. The scientific results of these experiments will feed back into the mid-decade review. With extraordinary B-mode sensitivity, these experiments may reveal initial evidence for primordial gravity wave induced fluctuations, much as a series of experiments in the late 1980's and 90's provided initial evidence for the Doppler peaks in the intensity power spectrum, a necessary step prior to WMAP and *Planck*.

While this development is progressing, it is likely that technologies developed under the CMB technology program will be proposed for missions that seek to answer one or more of the science objectives of the Inflation Probe under the auspices of the Explorer and SALMON programs.

7. Implementation

The technologies most in need of development (see in Table 1) are at the mid-TRL range, and must be advanced by a new dedicated technology program. This program can be carried forward most efficiently using the existing strengths of the CMB scientific field. Detectors are currently developed in a few micro devices labs supported by NASA, DOE, and DOC. These centralized facilities should continue to engage university-based researchers, both to infuse new technologies into active ground-based and sub-orbital experiments, and to provide capabilities and share resources for developing new devices. Emerging low-TRL technologies are best developed under the current auspices of NASA APRA program as separate efforts.

Ground-based and sub-orbital experiments offer a uniquely valuable means to test and mature the key technologies for the Inflation Probe. These applications provide an opportunity to engineer the elements of the experiment and to apply them in environments with many of the features of a space mission. The careful analysis of the data will reveal features of the system operation that would be difficult or impossible to detect in the lab. Balloon-borne instruments offer a unique probe of the foregrounds and test technologies in space-like conditions. In addition, the science return from these observational activities advances the field and generates a sharper focus on the requirements for a space mission. Indeed the science results from deep ground-based and sub-orbital B-mode searches will help shape the scientific design of a space mission.

Table 2: Summary of Active Ground-Based and Sub-Orbital CMB Polarization Experiments

Experiment	Technology	Resolution (arcmin)	Frequency (GHz)	Detector Pairs	Modulator
US-led balloon-borne					
COFE	HEMT/MMIC	83/55/42	10/15/20	3/6/10	wire grid
EBEX	TES	8	150/250/410	398/199/141	HWP
PIPER	TES	21/15	200/270	2560	HWP
SPIDER	TES	60/40/30	90/150/280	288/512/512	HWP
US-led ground-based					
ABS	TES	30	150	200	HWP
ACTpol	TES	2.2/1.4/1.1	90/145/217	~1000	-
BICEP2	TES	40	150	256	-
C-BASS	HEMT	44	5	1	ϕ-switch
CLASS	TES	??	40/90/150	36/300/60	VPM
Keck	TES	60/40/30	96/150/220	288/512/512	HWP
POLAR	TES	5.2	150	2000	-
POLARBeaR	TES	7/3.5/2.4	90/150/220	637	HWP
QUIET	HEMT/MMIC	42/18	44/90	19/100	ϕ-switch
SPTpol	TES	1.5/1.2/1.1	90/150/225	~1000	-
International ground-based					
AMiBA	HEMT	2	94	20	Int.
BRAIN	TES	60	90/150	256/512	Int.
QUIJOTE	HEMT	54-24	10-30	38	-

There is presently a range of programs probing the polarization characteristics of the CMB, working at a wide range of frequencies and spatial scales, and using different technical approaches for detection, readout, and modulation of polarization (Table 1). The present generation of ground based and balloon-borne experiments are designed with sensitivities to B-mode polarization sufficient for detection if the tensor to scalar ratio is $r > 0.01$, in the range predicted by many theories. In addition to their advancement of our understanding of the CMB, these efforts are of great technical importance, in that it is through these experiments that we will develop the techniques for control of systematic errors at the level required for the detection and mapping of B-mode CMB polarization. The range of approaches allows us to identify the most robust approaches, refining our vision of the technical approach for the Inflation Probe. We note that scientific landscape continues to evolve, and anticipate a role for new and more powerful experiments to further probe Inflation and gravitational lensing effects in CMB polarization. This progression is supported by the Astro2010 Decadal Review, which recommended ground-based CMB polarization measurements as a compelling project for a medium class ($12M - $40M) Mid-Scale Innovations Program supported by NSF.

Finally, we plan a complementary effort of continuing mission studies (see Fig. 1) to assess the scientific and technical requirements for the Inflation Probe. These studies will provide valuable input to the mid-decade review, determining specifications for detector sensitivity, band-coverage and systematic error control, defining requirements for optics and cooling, and evaluating any technology down-selections to come mid-decade. While implementing candidate technologies in sub-orbital experiments provides a high-degree of technological confidence, ultimately CMB technologies must be guided by requirements for a space-borne measurement.