CMB Technology Roadmap for the NASA Inflation Probe

Developed for the NASA Physics of the Cosmos Program Analysis Group
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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 high sensitivity planned for the Inflation Probe. Other emerging (TRL = 1-3) technologies should also be supported, under the auspices of the current NASA R&A program. We support collaboration between a NASA-funded technology development program, incorporating NASA and federal laboratories with university-based researchers, and sub-orbital and ground-based CMB polarization experiments. This program will rapidly implement candidate technologies so they can be demonstrated in demanding scientific applications that approximate the space-borne Inflation Probe environment.

As described in the Astro2010 Decadal Report, the case for CMB measurements from space will be evaluated mid-decade. The results of this assessment will be used to plan technology development funding for the latter half of the decade. Depending on the outcome of this review, the Decadal recommended a directed technology program at the \$60M - \$200M level. Separately, the report recommended augmented funding to support technologies at medium TRL (Technology Readiness Level). **We recommend that NASA begin directed funding for CMB technologies in FY2012 as a necessary step to inform the mid-decade review.** Key CMB detector technologies are currently reaching the field and thus at medium readiness. Furthermore these same technologies are essential to the success of sub-orbital and ground-based CMB polarization experiments, which must provide critical information on the experimental case for detecting inflationary CMB polarization needed for the mid-decade review.

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. The roadmap also incorporates elements from the CMB community-based 2005 *Task Force on Cosmic Microwave Background Research* (the Weiss committee) planning document. The importance of CMB polarization 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*.

<u>The Astro2010 Decadal report endorsed a CMB technology program of \$60-\$200M over the decade in preparation for a mission beyond 2020</u>. The report 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. It could range between the notional ($60M) budget used here up to a significant (perhaps on the order of $200 million) mission-specific technology program starting mid-decade". Separately, the Astro2010 Decadal recommended that "medium-term technology development be augmented at the level of $2 million per year starting early in the decade, ramping up to an augmentation of $15 million per year by 2021".

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 similar to 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 expected to have a small departure that results from Inflationary physics.

In addition, Inflation predicts a stochastic background of tensor perturbations: gravitational wave radiation sourced by the same quantum fluctuations that produced scalar 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. Such 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, though in a limited range of angular scales. 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 and currently planned sub-orbital experiments. The Einstein Inflation Probe will carry out all-sky, multi-frequency observations with unprecedented sensitivity to comprehensively measure CMB polarization to fundamental limits, extracting all cosmologically available information on inflationary polarization. A space-borne measurement can completely characterize the polarization signal at the level predicted by large-field inflation models. Furthermore, the Inflation probe can constrain to 1 % a contribution to primordial fluctuations from cosmic strings (see the inflation white paper arXiv 0811.3919 for more information).

The plan for the future development of the Inflation Probe includes the construction of suborbital experiments that test and optimize techniques and technologies; these new experiments are 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. This development will utilize these technologies in demanding science applications, an approach that has proven successful in the past, as witnessed by early sub-orbital precursors that demonstrated key technologies for *COBE*, *WMAP*, and *Planck*.

4. Technologies for the Inflation Probe

Technology	Detectors			Optical system	Cryogenic system	Push Technology[b] 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 stable and continuous sub-Kelvin coolers appropriate in space for expected focal plane thermal loads.	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 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, and a new generation of ground-based and sub-orbital experiments are predicated on a rapid expansion in focal plane capability.			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.
[b]Near-term push technology from the PCOS TechSAG table, defined as emerging technologies needed for applications in the next decade.

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 sub-orbital and ground-based platforms, we will gain experience with them in a representative scientific environment, so that we understand the integration of each technology at an operating-system 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 considerations in the space-borne Inflation Probe.

Microwave Kinetic Inductance Detectors (MKIDs) are another direct (phase-insensitive) 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 recently emerged, e.g. TES detectors with RF multiplexed readouts and bolometers using MKID temperature sensors. Detector array technology has broad applicability to NASA X-ray and infrared space astronomy missions.

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 the 30-300 GHz frequency coverage goals that were recommended 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 frequencies less than 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 HEMT-MMIC 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.

Bare detector arrays are also being developed for CMB polarization experiments, and rely on classical optical components for beam control and polarization analysis. In all cases however CMB polarimetry critically depends on the optical properties of the full system. All the components of any implementation, including the detectors, optical elements, and polarization modulation optics, must also be shown to meet a demanding level of systematic polarized 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 (HWP) or Variable-delay Polarization Modulator (VPM). 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 at a base temperature of approximately 100 mK with continuous cooling and high temperature stability. *Planck* has realized an on-orbit performance that nearly meets the IP requirements using an open-cycle dilution refrigerator. We recommend a hybrid approach based on a combination of radiative and mechanical cooling to 4 K, with a 100 mK cooler based from 4 K. Cooling to 4 K can leverage from the mechanical cooling systems developed for *Planck* and the MIRI instrument on *JWST*. Designs for more cooling power at 100 mK than *Planck* are being developed using closed-cycle dilution and adiabatic demagnetization refrigeration (ADR) cooling.

Scientific progress and technologies are rapidly evolving, and thus the prioritization of technology development must be periodically monitored and re-planned. 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, which is shown in Fig.1, as the results from deep sub-orbital 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

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 shape the sensitivity and frequency coverage requirements for the Inflation Probe.

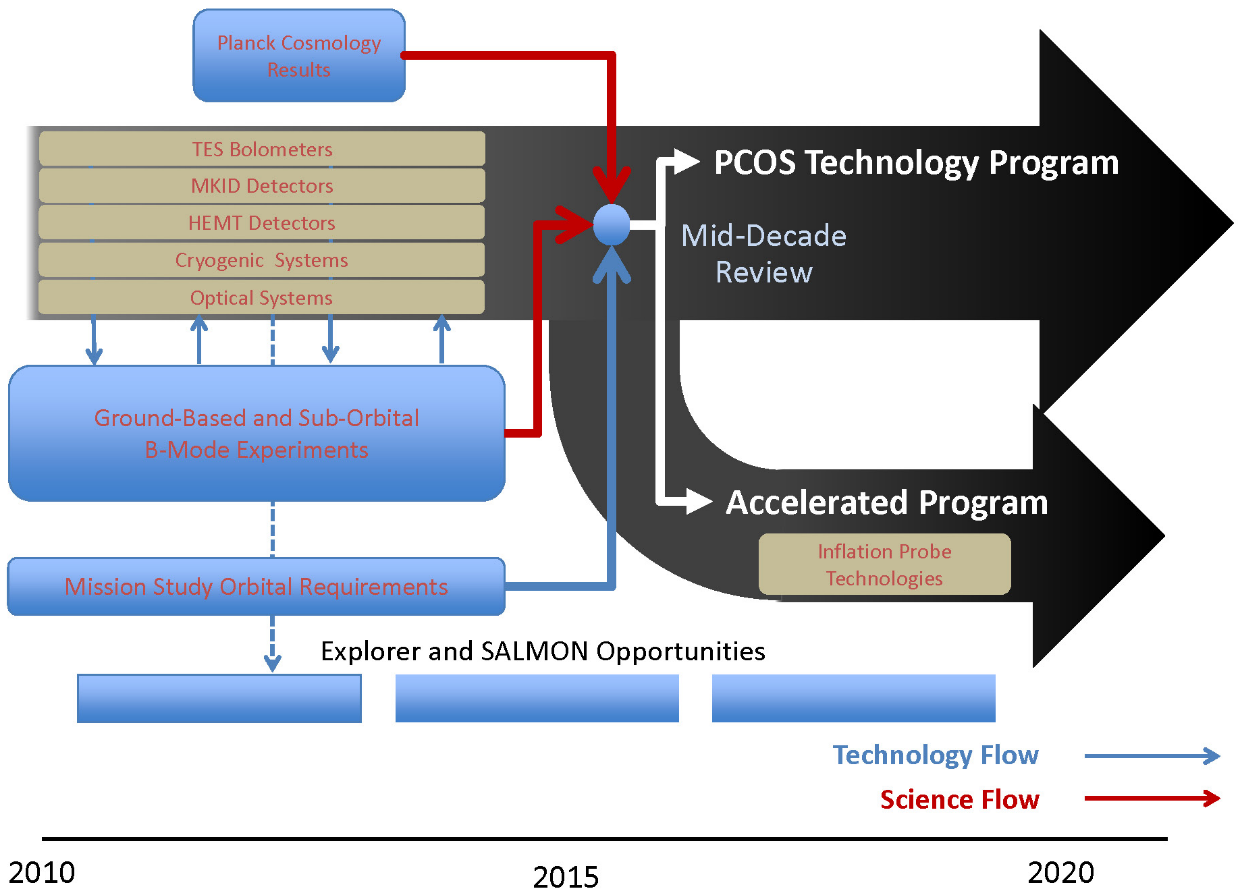

Figure 1. The relationship between the CMB technology program and associated scientific efforts. The Astro2010 Decadal Survey recognized that CMB science and technology are evolving quickly, and recommended a $60-$200M program with a mid-decade review, providing an accelerated technology effort leading to the Inflation Probe. We show this as a key milestone in the CMB technology program, at which point a down selection of current technologies may occur leading to a rapid development of the Inflation Probe mission, or alternatively continued development of technologies. The technology program interacts closely with ground-based and sub-orbital experiments to field candidate technologies. The scientific results of these experiments, generally carrying out deep polarization CMB measurements in small areas of sky, and the all-sky multi-band measurements of *Planck* will provide scientific input to the mid-decade review. A mission study program, a component of this CMB technology program, will investigate mission implementations and determine the technology requirements that are specific to a space mission. Technologies matured in this program may provide intermediate opportunities for use in the Explorer program.

The technology program operates synergistically with ground-based and sub-orbital 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*.

A mission studies component in the program is needed to develop specific space architectures, and set the technology requirements for a space experiment. Looking further forward, this component should grow over time to address technology challenges that are specific to the space that cannot be demonstrated in a sub-orbital environment.

While this development is progressing, it is likely that specific 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. 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 (see Table 2). In addition, 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.

In addition, the science return from these observational activities advances the field and generates a sharper focus on the scientific requirements for a space mission. 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. A detection of B-mode polarization from one or more of the experiments in Table 2 over a limited multipole range will set the stage for a comprehensive all-sky space-borne measurement. We note that scientific landscape continues to evolve, and we anticipate a role for new and more powerful ground-based and sub-orbital 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.

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	21/15/12/7	200/270/350/600	2560	VPM
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	80/34/22	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.
QUBIC	TES	60	90/150	256/512	Int.
QUIJOTE	HEMT	54-24	10-30	38	-

The quest for increased signal-to-noise that drives much of the detector development also has profound implications for handling the data. We have already seen the numbers of observations in a CMB data set grow 1000-fold over the last 15 years and can anticipate a similar growth over the next 15 years. Suborbital experiments currently being fielded will gather 10x the *Planck* data volume, proposed next generation suborbital experiments will gather 100x *Planck*, and a subsequent Inflation Probe satellite mission may gather 1000x *Planck*. High performance computing is also entering uncharted territory as we can no longer simply rely on increased clock speeds to support performance growth. Parallel development of the supporting data-handling technologies is a critical piece of the Inflation Probe roadmap. Much of the support for CMB computing has been supported by DOE to date. We encourage continued support and interaction of CMB computation with sub-orbital experiments to develop the new data-handling and computational algorithms that will be needed for the Inflation Probe.

The complementary effort of continuing mission studies is needed to assess the scientific and technical requirements for the Inflation Probe. A satellite experiment ultimately faces challenges in a space environment that go beyond what can be shown in a sub-orbital precursor experiment, e.g. particle interactions in the detectors, low-mass magnetic shielding, control of optical spillover using cold absorbers, and continuous 100 mK cooling systems. While the current program takes advantage of the synergy with ground-based and sub-orbital experiments to maximize technical and scientific development, the mission study program is needed to develop the technical requirements and implementations that are specific to space. The importance of the mission study wedge will gradually expand over the decade, as we begin to transition technologies proven in sub-orbital and ground-based experiments to meet space mission needs. These studies will provide useful input to the mid-decade review, determining specifications for detector sensitivity, band-coverage and systematic error control, and defining requirements for optics and cooling that are specific requirements for space. Mission studies will help guide technology down-selections to come. The overall program balance between technologies and mission studies should be assessed in the mid-decade review.

8. Conclusion

Technology capability must rapidly increase to meet the demanding requirements of ground-based and sub-orbital experiments. These experiments are necessary precursors to the Inflation Probe. Furthermore the scientific results from this program are needed to inform the scientific case for a dedicated CMB polarization satellite, and for the expanded technology program recommended by the Decadal Report that will be evaluated mid-decade. To illustrate the need for a directed CMB technology program, we note that as of mid 2011, operational CMB experiments are using a grand total of several hundred detector pairs. The current demands of funded ground-based and sub-orbital experiments in Table 2 are predicated on a massive increase in detector array capability, fielding more than ten thousand detector pairs, more than a factor of 10 increase in just a few years. Furthermore these experiments are based on several fundamentally different array technologies, and use diverse polarization methodologies that must deliver a large improvement in systematic error control. The expected sensitivity of the Inflation Probe exceeds the sum of the planned sub-orbital experiments by a large factor, by virtue of higher instantaneous sensitivity and continuous operation in space. A directed NASA CMB technology program is urgently needed to meet this scientific program, and to prepare the field for the mid-decade review put forth by the Decadal Survey. Fortunately the CMB field has a clear path to develop these technologies in representative experiments that will return scientific results, as has been successful in past with *COBE*, *WMAP* and *Planck*, and we expect rapid progress if this technology program is implemented.