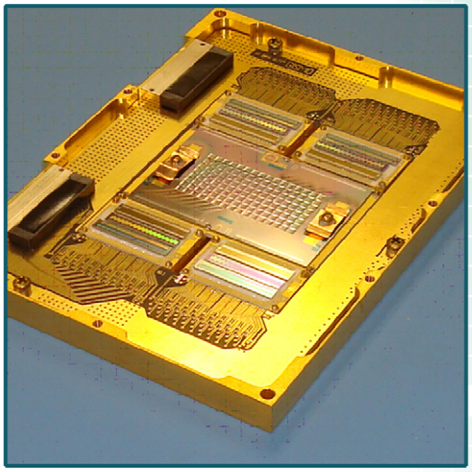
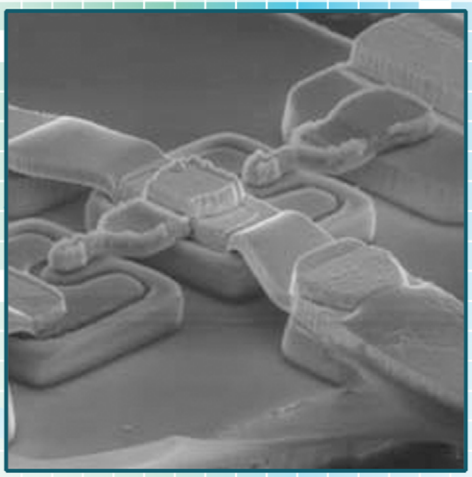
National Aeronautics and Space Administration

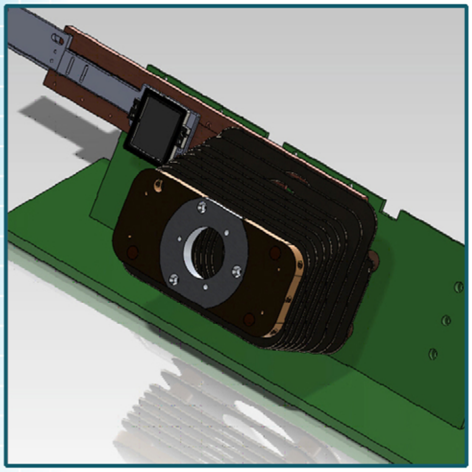
Cosmic Origins

Program Annual Technology Report

Cosmic Origins
Program Office
October 2011







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EXECUTIVE SUMMARY

This Program Annual Technology Report (PATR) is the annual summary of the technology development activities in support of the Cosmic Origins (COR) Program for the previous year (FY11). The COR Program Office was established in FY11, making this the first such report. The COR Program Office resides at the NASA Goddard Space Flight Center (GSFC) and serves as the implementation arm for the Astrophysics Division at Headquarters (HQ) for COR Program related matters. The COR PATR describes the state of the Program's technology management activities and summarizes the Program's technology development status for the prior year.

The PATR includes the community-provided technology needs and the Technology Management Board (TMB)-vetted prioritization and investment recommendations. This information will be referenced by the Program over the following year, as the calls for technology development proposals are drafted. Comments from the community are invited at every stage, and specific technology needs inputs are requested at the start of each summer to begin the prioritization cycle again. This process improves the transparency and relevance of technology investments, provides the community a voice in the process, ensures open competition for funding, and leverages the technology investments of external organizations by defining a need and a customer.

Goals for the COR Program envisioned by the National Research Council's (NRC) "New Worlds, New Horizons in Astronomy and Astrophysics" (NWNH) Decadal Survey report includes a 4m-class UV/optical telescope that would conduct imaging and spectroscopy as a post-*Hubble* observatory with significantly improved sensitivity and capability, a near-term investigation of NASA participation in the Japanese Aerospace Exploration Agency/Institute of Space and Astronautical Science (JAXA/ISAS) *Space Infrared Telescope for Cosmology and Astrophysics* (SPICA) mission, and future Explorers.

Recognizing that these goals present numerous technological challenges with varying time horizons, the NWNH report recommends that NASA maintain support for the development of technologies that feed into these projects. Additionally, the NWNH Electromagnetic Observations from Space (EOS) panel report went further to identify technologies needed for missions in the 2021-2030 timeframe that require investments in the present. It is the goal of the COR Program to shepherd all of these technologies to the tipping point where they can transition into project technology plans. In so doing, these technologies can serve as the foundation for robust mission concepts for review by the community such that the scientific relevance of proposed missions will be prioritized in subsequent strategic planning.

Consequently, to meet the challenge of the NWNH report in the coming decade, the COR element of the Strategic Astrophysics Technology (SAT) program is formulated to solicit investigations that will undertake focused development of technologies that feed into key COR science themes. A list of the technologies selected for FY12 SAT development is included in this report.

The COR Program and the community have a robust technology development history to draw from for this inaugural annual technology report. Responsibility for generating this PATR rests with the Advanced Concepts and Technology Office (ACTO), within the Program Office (PO). The ACTO has attempted to map the activities of the past year into an appropriate form to acknowledge important prior work and to describe the basis for the activities for the coming year.

The COR Program Office has been established, and the ACTO is fully staffed, to support the technology development activities for future COR missions. The initial mission development portfolio includes a future 4m-class UV/optical telescope, a potential participation in the Japanese SPICA mission, and the *Hubble Space Telescope* (HST) De-Orbit mission. The NWNH provides guidance for establishing the appropriate content for this newly established program.

The first step in the technology development process is to identify the technologies required to support COR science missions. This process involves the scientific and technological community that is defining the future missions, and the Cosmic Origins Program Analysis Group (COPAG). Once these technology needs are identified, they are prioritized by the TMB, based on a set of evaluation criteria that reflects the goals of the Program in the current programmatic environment.

A key part of this report is to address the progress in technology needs identification and prioritization. During the past year, the process of soliciting these needs from the community has been executed. A process for prioritizing these technology needs has been established by the Program TMB. The technology needs prioritization process was completed, and the results are categorized into three priority groups.

The TMB determined the following technology areas to be Priority 1, representing the highest interest to the Cosmic Origins Program at this time. The TMB recommends that they ***should*** be invested in first, when funding is available. The Priority 1 technology areas are:

- High quantum efficiency, large-format UV detectors
- Photon counting, large-format UV detectors
- UV coatings
- Ultra-low-noise far-IR direct detectors

The Board categorized the rest of the technology needs into Priorities 2 and 3. Priority 2 contains technology activities that the Board feels are worthy of pursuit and ***would*** be invested in, if additional funding allows. Priority 3 technologies are deemed to be supportive of COR objectives, but for various reasons they do not warrant investment at the present. However, they ***could*** be invested in, if significant additional funding is available.

The technology management planning for the Program Office is complete. The Program Office is ready to provide the leadership required to advance the technologies for the missions under its purview. As the FY12 activities progress, these plans may be adjusted as necessary to match programmatic needs. The Program Office remains committed to providing a transparent, merit-based, and balanced process for supporting the technologies needed to help ensure the success of the Cosmic Origins Program.

SECTION 1.0 PROGRAM OVERVIEW

The goal of the COR Program is to understand the origin and evolution of the universe from the Big Bang to the present day. On the largest scale, COR's broad-reaching science question is to determine how the expanding universe grew into a grand cosmic web of galaxies and how the stars, planets, and galaxies formed over time. COR also seeks to understand how stars create heavy elements that are essential to life, such as carbon, oxygen, and nitrogen, starting with the first generation of stars to seed the universe with the heavy elements we see on Earth today and continuing up through the formation of stars now.

The Science Mission Directorate of NASA Headquarters acknowledged the continued importance of the science by establishing the Cosmic Origins Program Office in 2009 within the Astrophysics Division. In May 2011, the COR Program Acceptance Review was conducted. On August 4, 2011, the Key Decision Point I (KDP-I) was held, and the Agency Program Management Council confirmed the COR Program to proceed into the implementation phase.

The COR Program Office is located at the NASA Goddard Space Flight Center. A primary function of the Program Office during the implementation phase is to develop and administer an aggressive technology program. In order to achieve this end, and along with the Physics of the Cosmos (PCOS) Program, an ACTO has been chartered to facilitate, manage, and implement the technology policies of both the COR Program and the PCOS Program. The ACTO will coordinate the infusion of technologies into COR and PCOS missions, including the crucial phase of transitioning a wide range of nascent technologies into targeted project mission technology programs, when a project is formulated.

The ACTO oversees technology developments applicable to COR missions, funding for which is supported by the COR Supporting Research and Technology (SR&T) budget. This PATR, Volume 1, is the first comprehensive document detailing the technologies currently being pursued and supported by COR SR&T. It also outlines a view, as of late 2011, of the COR roadmap for future technology needs.

1.1 Background

The COR Program encompasses a diverse set of science missions aimed at meeting Program objectives wherein each mission has unique science capability. The Program was established to integrate space, suborbital, and ground activities into a cohesive effort that enables each project within the Program to build upon the technological and scientific legacy of both its contemporaries and predecessors. At Program inception, the following current and future projects were placed within the Program to be shepherded commonly in support of the "Cosmic Origins" science goals. Each project operates independently to achieve its unique set of mission objectives, which contribute to the overall Program objectives. The initial operating missions in the COR Program Office portfolio are:

- *Hubble Space Telescope*
- *Spitzer Space Telescope*
- The U.S. component of the European Space Agency's *Herschel Space Observatory*

In support of the COR Program objectives, the Program Office is responsible for ensuring that NASA is positioned technologically to continue mission developments into the future to advance the broad scope of COR science goals. Accordingly, the Program is charged with overseeing the maturation of missions in formulation, implementation, and operations as well as technologies in development.

- COR Supporting Research and Technology (SR&T)
- Future Mission Concept Development
- *James Webb Space Telescope* – Science upon operations.

Since obtaining authorization to formulate the Program in 2009, fiscal constraints have become more restrictive and suppressed ambitions for the vigorous development of new missions and studies. Additionally, the NRC has released its decadal study for Astronomy and Astrophysics. The NRC's NWNH report has resulted in the COR Program shifting its focus to ardent technology development and prudent mission concept studies.

In its NWNH report, the NRC acknowledged that we have learned much about the history of the universe from the Big Bang to today and placed a high value on the COR science missions relating to Cosmic Dawn (the NWNH nomenclature closely identifiable with COR). The *James Webb Space Telescope* (JWST), the *Atacama Large Millimeter/submillimeter Array* (ALMA), and radio telescopes under development were identified as powerful tools for pursuing COR science goals. With these projects under way, the NRC-prioitized recommendations did not include a specific named NASA-led mission that fit within the COR Program; however, it did include a conspicuous NASA contribution to the JAXA SPICA. The NRC also ardently recommended an augmentation to the Explorer Program that supports Astrophysics with rapid, targeted, competed investigations. This recommendation provides an additional robust vehicle to accomplish COR science. The COR Program is committed to managing the available funds strategically and establishing partnerships, when possible, to maximize the benefits of its investments and to ensure that the Program will foster missions that continue to accomplish Program objectives. Key to this effort is tactically advancing enabling technologies to conduct COR science.

With the conclusion of the Space Shuttle Program in 2011, the safe re-entry or disposal of HST is a requirement for NASA. Accordingly, the COR Program Office is tasked with studying the options and developing the means of accomplishing this requirement. While this effort does not contribute to new COR science objectives, it is a necessary use of Program resources to conclude the life-cycle of this great observatory. The COR Program Office anticipates the resulting technology advancements can be designed into future missions for low-cost, end-of-life solutions.

The COR Program Office has initiated a second study to mature future ultraviolet/optical/infrared (UVOIR) space telescope capabilities. The NWNH report recommends the development of a large ultraviolet and optical mission to replace *Hubble* and will select amongst several conceptual missions that have been studied, including the *New Worlds Observatory* (NWO), the *Telescope for Habitable Exoplanets and Interstellar/intergalactic Astronomy* (THEIA), and the *Advanced Technology Large Area Space Telescope* (ATLAST). All of these and others call for UV imaging and spectroscopy, and general astrophysics in the visible and near infrared (IR). The ACTO plans to kick off a UVOIR mission study in FY12.

Recently, the COR Program Office has embarked on an additional study to determine the feasibility of participation with the Japanese on an instrument contribution to the SPICA mission, currently slated for launch in 2018. In accordance with the NWNH recommendation that a SPICA contribution be undertaken only if affordable, near-term budget uncertainties are currently a key factor in determining NASA's ability to participate. SPICA is currently planned to have a System Definition Review (SDR) in the April 2012 timeframe. The COR Program Office is conducting a study of a straw-man NASA contribution to SPICA. An instrument delivery has been requested by JAXA three years prior to launch, which requires a decision to be made soon on the presence and scope of a NASA contribution. The outcome of the concept study will be used to inform this decision.

1.2 COR Program Technology Development

In the future, the COR SR&T will fund a variety of technology developments that are determined to be necessary for the advancement of COR science missions. Strategically, the COR Program Office inherits the mantle of the NWNH via its adoption of the prioritized complement of missions and activities to advance the set of COR science priorities. This strategic vision comes principally from NWNH, but also from the following recent related NRC documents such as the "Report on the Panel on Implementing Recommendations from New Worlds, New Horizons Decadal Survey," "Panel Reports—New Worlds, New Horizons in Astronomy and Astrophysics," "Space Studies Board Annual Report 2010," and "An Enabling Foundation for NASA's Space and Earth Science Missions." The COR Program PATR will continue to be an open and available source for the public, academia, industry, and the government to learn about the status of those missions and the enabling technologies required to fulfill the COR Program science goals.

The PCOS/COR Technology Management Plan details the process that strategically identifies COR technology needs, enables the maturation of those technologies in a prioritized fashion, and inserts them into new missions responsively. The process diagram (Figure 1) illustrates the annual cycle by which this is achieved. Starting at the left, science needs and requisite technologies are derived from the current astronomy community environment, and are presented (by means of many public fora, but in particular the COPAG workshops) into the NASA advisory chain. The COR Program Office is aware of these science needs independent of the COPAG, as all such presentations and deliberations are public.

The COPAG provides analyses through the Federal Advisory Committee Act (FACA)-mandated process. Meanwhile, the COR Program Office convenes its Technology Management Board (TMB), which prioritizes the technologies and publishes them annually in this PATR. The TMB recommends these priorities to NASA HQ, which solicits proposals for technology development. Grants are awarded to technology developers, who submit annual reports that are reviewed by the TMB and become a portion of this PATR. Technological progress also changes the landscape of the requirements for the science needs, and so this process is repeated annually to ensure continued currency of the priorities.

Public outreach is conducted regularly by the COR Program Office to ensure that the broad astronomy community is informed of these developments. It is expected that new starts for missions will lead technologies out of this management process and into project-specific technology development efforts.

The external scientific and technology communities are key stakeholders for the program technology development activities. The community participates in the program technology process in multiple ways, including through the COPAG workshops held by the Program in conjunction with specific studies and as developers through responses to solicitations. These workshops provide a mechanism for including community input into the program technology process.

Technology Process Diagram

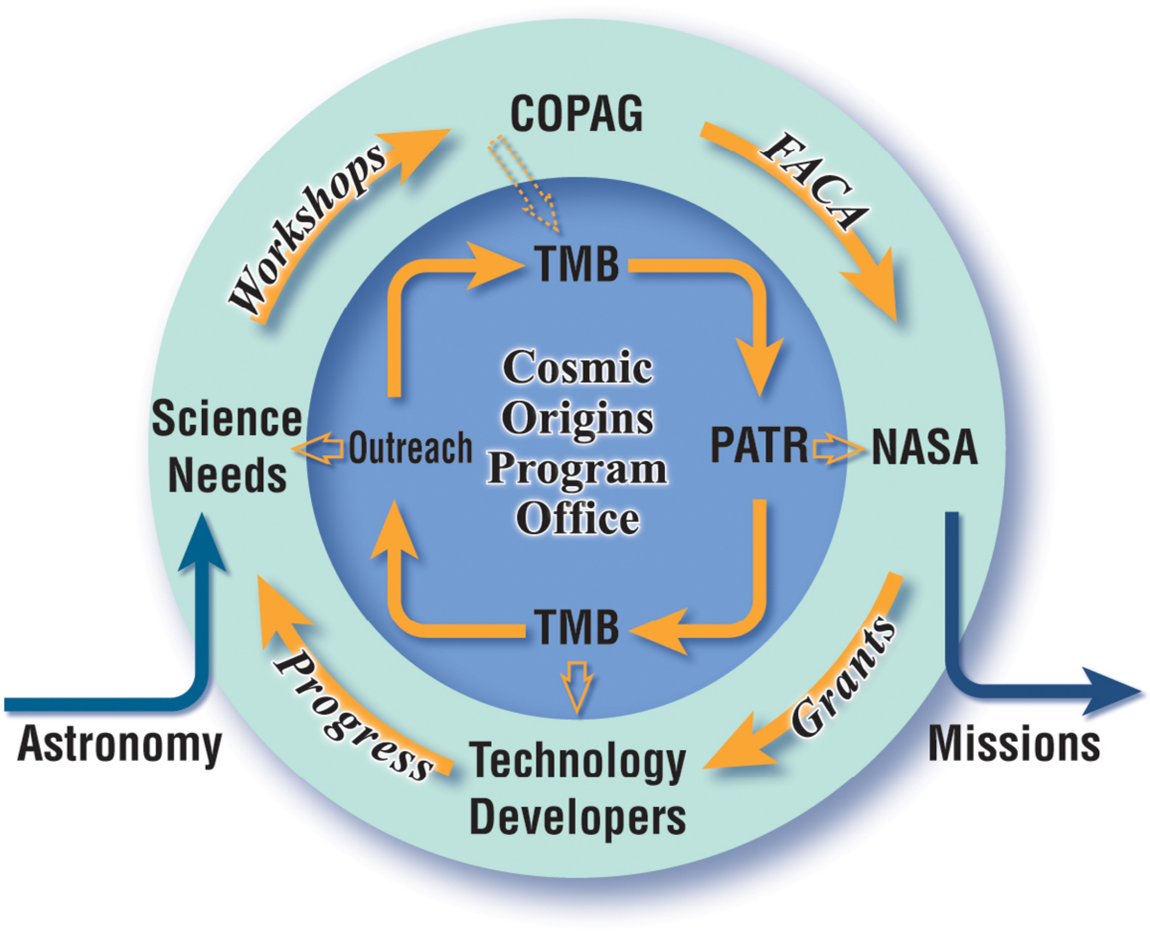

Figure 1. *The COR "Technology Turntable" illustrates the annual process by which science needs and their requisite technologies are indentified, prioritized, and matured.*

The COR TMB is a program-level functional group that enables the direct stakeholders in the technology portfolio to provide input to and review the program technology development activities. The TMB prioritized those technologies identified by the community and communicated via the COPAG. This prioritization provides crucial direction for the merit-based selection of technology development funding. This report, the annual COR PATR, is the means of disseminating this information publicly.

SECTION 2.0 TECHNOLOGY STATUS: STRATEGIC INSTRUMENT TECHNOLOGY DEVELOPMENT

Introduction

An important function of the COR Program Office is to develop and administer an aggressive technology program to support the infusion of technologies into missions that achieve COR science. In this PATR, the suite of technologies supported to date is based on legacy selections focused on detector development. These addressed the need for submillimeter heterodyne technology and far-infrared large-format direct detector arrays for the *Stratospheric Observatory for Infrared Astronomy* (SOFIA) mission and high quantum efficiency, electron-bombarded CMOS detectors for UV application.

Future volumes of the PATR will provide status reports on the technologies being developed by the COR Program, including those selected via the Research Opportunities in Space and Earth Science (ROSES) SAT proposal solicitation. Legacy SR&T activities relevant to the COR theme, funded through prior mechanisms, are summarized in Table 1, and details are provided in the subsequent sections. These activities are advancing the technology readiness level of detector technologies for UV, far-infrared, and submillimeter wavelengths.

Mission	Technology	PI and Institution
SOFIA	Submillimeter Heterodyne Receiver	Paul Goldsmith, NASA/JPL
Future UV/Opt	Electron-Bombarded High Quantum Efficiency UV CMOS Detectors	Bruce Woodgate, NASA/GSFC
SOFIA	Far-Infrared Large-Format Array Detectors	S. Harvey Moseley, NASA/GSFC

Table 1. *Current COR Technology Investments*

It should be noted that two of these efforts were directed at maturing technologies for use in instruments for SOFIA. Gratifyingly, both teams were involved in submitted SOFIA instrument proposals using the technologies supported by the COR Program funds.

Three new COR technologies have recently been selected for funding via the SAT proposal call in ROSES 2010. These have not yet begun serious work, and hence each project's status is not presented here, but their progress in the first year will appear in this section in the 2012 PATR. These new projects are listed in Table 2.

Mission	Technology	PI and Institution
Future UV/Opt	Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes	Phillip Stahl, NASA/MSFC
Future UV/Opt	High performance cross-strip micro-channel plate detector systems for spaceflight experiments	John Vallerga, U.C. Berkeley
Future UV/Opt	Enhanced MgF_2 & LiF Overcoated Al Mirrors for FUV Space Astronomy	Manuel Quijada, NASA/GSFC

Table 2. *New COR SAT Technologies Selected for FY12 Start*

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2.1 Heterodyne Technology for SOFIA

Prepared by: Paul Goldsmith/JPL and Imran Mehdi/JPL

Summary

Determining the structure and properties of the diffuse interstellar medium (ISM) is a key NASA strategic goal that can be achieved only with high-resolution spectroscopy. The SOFIA mission, with its robust instrumentation plan and high-altitude flight path, provides a platform for conducting investigations of galactic and extra-galactic sources using high-resolution submillimeter spectroscopy. The proposed task focuses on developing and demonstrating heterodyne technology that can be infused into future instruments for SOFIA. The goal is to deploy multi-pixel array receivers in the 1–5 THz range. Single-pixel, hot-electron bolometer (HEB) mixers will be designed, fabricated, and tested to optimize their sensitivity. The HEB mixers' IF bandwidth will also be optimized, along with high-velocity resolution, to provide adequate frequency coverage for observations of nearby galaxies and the center of the Milky Way galaxy. The optimized mixers and local oscillator (LO) chains will be combined in array receivers as necessary to take full advantage of each flight by mapping large portions of the sky. The technology will be focused on cosmologically important molecular and fine structure lines including such as the singly ionized carbon (CII), neutral atomic oxygen (OI), carbon monoxide (CO), methylidyne radical (CH), deuterated hydrogen (HD), and protonated helium (HeH+). Our approach will be focused on developing and characterizing the complete receiver front ends to ensure stability and optimum performance of the flight-borne instruments. Such instruments aboard SOFIA will allow the science community to exploit high-resolution spectroscopy to follow up the many exciting discoveries made using the Heterodyne Instrument for the Far Infrared (HIFI) instrument on the European Space Agency's *Herschel Space Observatory*.

Technology Description

In astrophysics, the far-infrared/submillimeter wavelength region of the spectrum (60–1,000 microns, 0.3–5 THz) is dominated by the continuum emission from warm dust with numerous spectral emission and absorption lines of atomic and molecular gas superimposed. A number of large spatial surveys using the *Herschel* Photodetector Array Camera and Spectrometer (PACS) and Spectral and Photometric Imaging Receiver (SPIRE) photometers have determined that the dust emission is filamentary in nature at all scales that have been observed. In spite of the universality of the dust structures, large differences in the rates of star formation are observed. The physical processes that give rise to this structure and facilitate the onset of star formation remain the subject of a contentious debate between the effects of turbulence and magnetic fields. The other open question is the details of transition between the atomic and molecular phases of the diffuse ISM and their spatial and chemical relationship to the observed denser material and their influence on the star formation rate. The velocity structure of atomic and ionized gas associated with dense regions remains largely unknown and can be obtained only through spectroscopy. Separation of components of the ISM requires velocity-resolved atomic, ionic, and molecular line profiles. The recent NWNH report has highlighted questions that will require heterodyne technology to resolve: i.e., how do stars form?; how do circumstellar disks evolve and form planetary systems?; what are the flows of matter and energy in the circumgalactic medium?; and what controls the mass-energy-chemical cycles within galaxies?

Resolution of these questions will require heterodyne studies of statistically significant areas of the ISM. The obvious targets are the brightest lines in the spectrum, CII and OI, which trace the interfaces between low- and high-extinction regions. Other species, including singly ionized nitrogen (NII) and CH, provide a direct connection to the total gas column and a means to separate the atomic and molecular gas. The ideal observational output with which to study these complex structures is a two-dimensional image with spectrum at every point—a data cube. But current state-of-the-art is only a single pixel. The urgent need for sensitive velocity-resolved images of regions spanning a wide range of spatial scales requires a heterodyne array for more rapid mapping.

Heterodyne spectroscopic instruments are the only technical possibility for obtaining velocity-resolved spectral resolution in the far infrared. Building on the HIFI hardware developed by Jet Propulsion Laboratory (JPL), the focus of this work is to increase frequency coverage, output power, and the Technology Readiness Level (TRL) of the next generation of receiver front ends (RFE) to enable the implementation of imaging array receivers at frequencies between 1.9 and 5 THz. A nominal heterodyne receiver system, based on HEB detectors, is shown in Figure 2. The HEB detector and the intermediate frequency (IF) amplifier are cooled to 4K. The local oscillator subsystem provides the LO signal that is mixed with the radio frequency (RF) signal from the spectra.

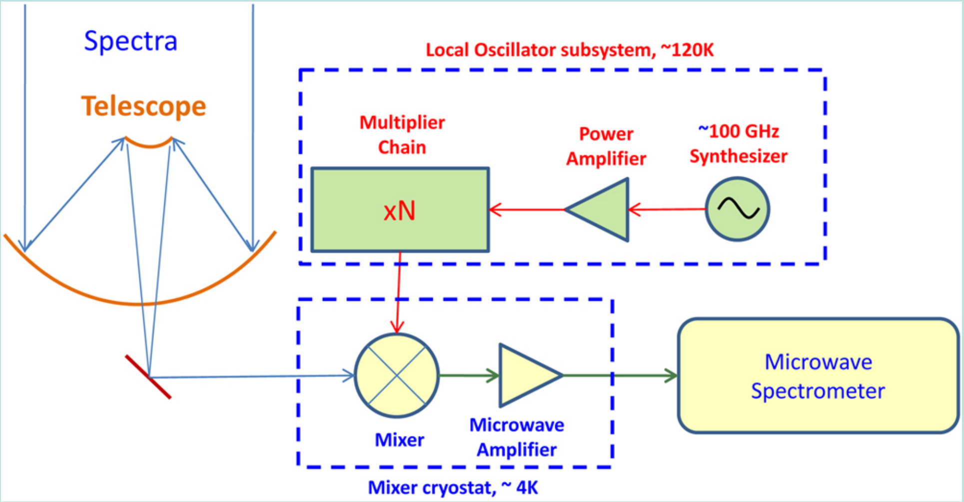

Figure 2. *Heterodyne detectors convert incoming photons to lower frequency by "mixing" them with a local oscillator signal. The down-converted signals are easy to amplify and analyze using standard microwave techniques, enabling spectral resolution as high as $\lambda/\Delta\lambda \approx 10$ million. Heterodyne spectrometers can be tuned by changing the frequency of the oscillator.*

To successfully test the mixer devices, a robust LO source at 1.9 THz will be needed. Figure 4 shows the measured output of the LO chains developed and delivered for the HIFI instrument from JPL. While these results enabled the higher bands on HIFI, the next generation of SOFIA heterodyne instruments will need better LO chains.

This task is focused on developing super-sensitive heterodyne array receivers in the 1.9 THz range and beyond. Receiver systems on HIFI operate to frequencies as high as 1.9 THz with a single pixel and system temperature equal to 2,400 single sideband (SSB). But the IF bandwidth on HIFI is less than 2 GHz for these receiver systems, which provides a velocity span of only 300 km/s at 1.9 THz. Moreover, the complicated optical path and poor thermal stabilization of the LO sources has resulted in the HIFI system having stability and calibration issues. The technology that will be developed and demonstrated under this task will correct for these shortcomings and show the feasibility of deploying heterodyne array receivers for future instruments.

Progress

Toward higher IF-bandwidth HEB detectors

One of the main objectives of this task is to verify the reportedly outstanding performance of NbN HEB mixers developed by the Moscow State Pedagogical University (MSPU) in a well-characterized JPL setup, which would be free of spurious signals due to the so called "direct detection" effect and other non-mixing artifacts affecting the Y-factor of the system. Another objective is to test JPL-made HEB mixers in the same configuration in order to understand whether the JPL mixer technology is behind and, if this is the case, to come up with a plan on closing the performance gap.

Figure 3. *Picture of the testbed at JPL.*

1. The experimental setup has been built (Figure 3). It features a ^{4}He receiver cryostat with a quasi-optical mixer block (Figure 5) and a low-noise broadband amplifier (T_{amp} = 3-7 K, Δf = 11 GHz) and a vacuum box with hot (295 K) and cold (90 K) loads inside (Figure 6). The local oscillator power is injected into the box through a Mylar window and is fed to the receiver through a thin beam splitter. A remote-controlled chopper wheel inside the box switches the signal path between the hot and cold loads. The use of a vacuum box eliminates atmospheric losses and air density fluctuations in the signal and LO paths, thus improving the receiver's stability. The mixer uses a 12mm elliptical silicon (Si) lens to form a narrow beam (Figure 5, center image). The spiral antenna is situated at the rear focus of the lens (Figure 5, right-hand image).

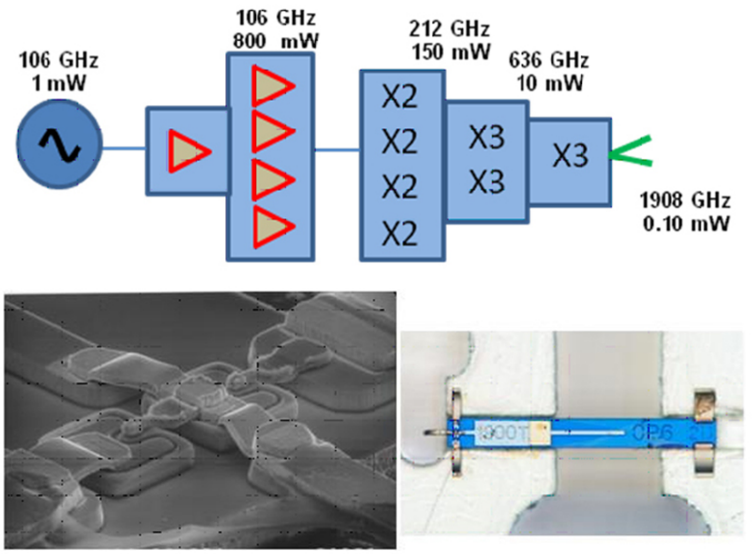

Figure 4. Top: *The proposed scheme for obtaining higher output power at 1.9 THz to pump array mixers is shown.* ***Bottom:*** *These scanning electron microscope (SEM) images show details of the 1,900 GHz tripler chip that has been designed and fabricated at JPL for HIFI.*

The overall setup has been characterized by measuring the output noise temperature across the IF bandwidth. In this case, a 50-Ohm resistor with variable temperature was used instead of the HEB device. The resistor Johnson noise was used as a test signal for the noise bandwidth characterization.

2. Several mixer-chip layouts have been obtained from MSPU (Figure 7). They all feature the spiral antenna integrated into a coplanar waveguide (CPW) structure (Figure 7, left-hand image), which provides a smooth broadband transition to the IF coax. The niobium nitride (NbN) device (0.1 μm × 1 μm to 0.2 μm × 2 μm) is placed at the feeding point of the antenna (Figure 7, right-hand image). These designs are being placed on a JPL photomask

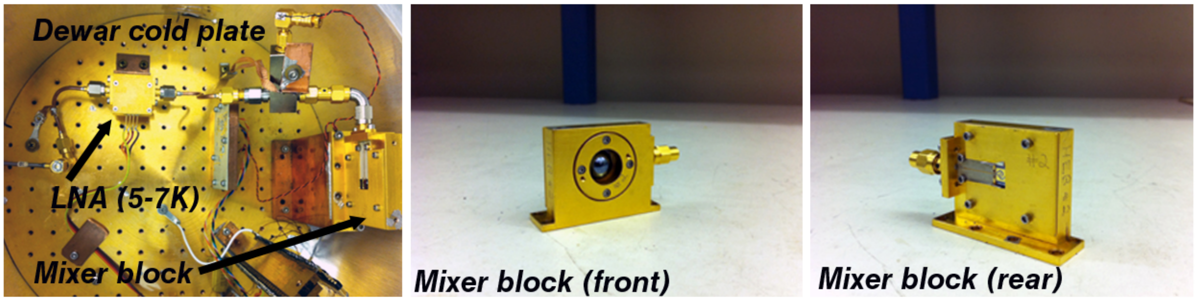

Figure 5. Left. *A close-up of the cryostat is shown.* ***Center:*** *Pictured here is the front of the mixer block.* ***Right:*** *The rear of the mixer block is shown. The mixer blocks (center, right) will be used to characterize HEB devices.*

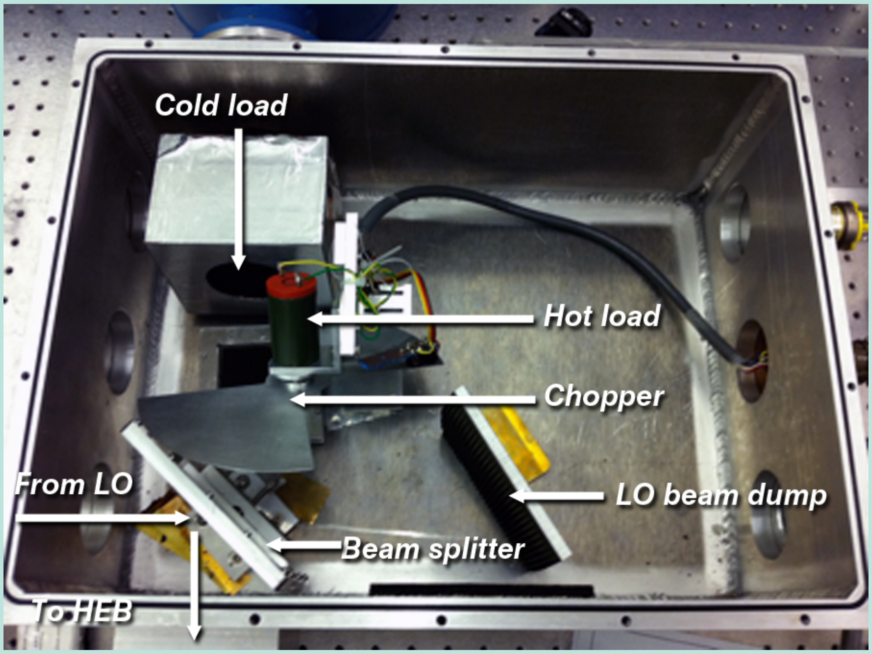

Figure 6. *The inside of the cryostat is pictured and shows the cold load required for proper calibration.*

for fabrication of HEB mixer chips using the current JPL technology. This will allow for the back-to-back comparison of the performance of the devices fabricated by MSPU and by JPL with all the antenna and test setup details being identical. The JPL devices are expected to become available in the first half of August 2011. Meanwhile, we will be testing the overall system performance (noise temperature at 1.9 THz and 1.4 THz and noise bandwidth) using the spiral antenna coupled NbN HEBs previously fabricated at JPL.

Progress toward the next generation of LO sources

The proposed architecture for the LO chain is shown in Figure 4. Multiplier chips for the three multipliers have been designed and are currently being fabricated at JPL. These chips will enable JPL to build a chain that covers the 1,900–2,060 GHz band. The second stage, which is a tripler, has to cover the 630–686 GHz range. A chip that covers this range has been designed, and the simulated efficiency of such a chip with 25 mW of input power has been done. The chip is currently being fabricated at JPL using our proprietary GaAs planar Schottky diode membrane process.

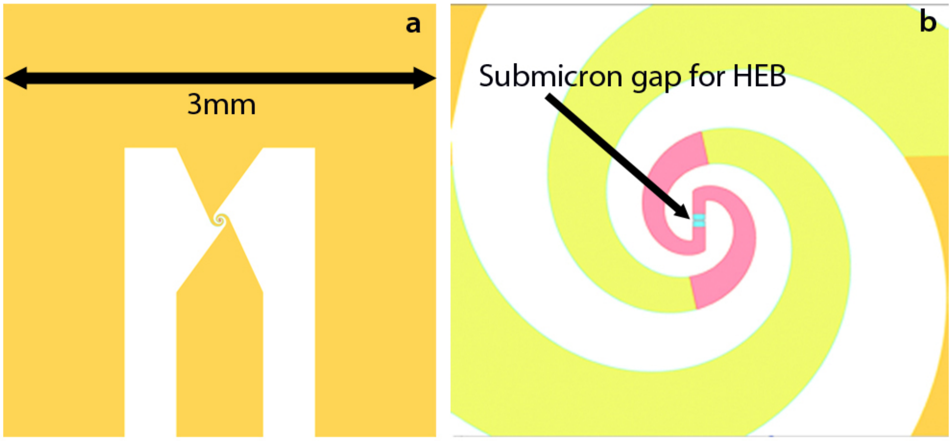

Figure 7. The device designs currently being investigated for performance are shown.

The first-stage doubler of the LO chain has been fabricated and tested in the last month. Although the appropriate amplifier block has not yet been completed, we can still characterize the quad-chip doubler over a limited bandwidth and with limited input power. The measured performance at room temperature is shown in Figure 8.

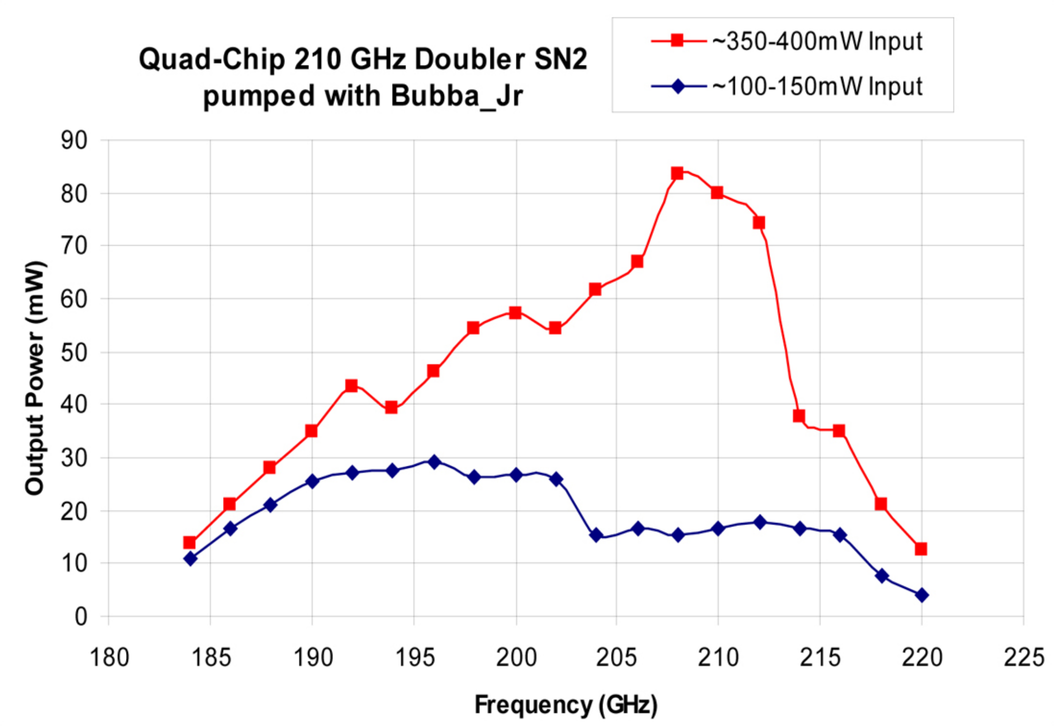

Figure 8. The measured performance of the quad-chip frequency doubler is shown.

Status and Plan

Status

Development of heterodyne technology in the submillimeter-wave region continues to be pursued by a number of groups worldwide. The leading applications for this technology are still driven by NASA needs, although recent work on utilizing submillimeter-wave technology for contraband detection has generated a lot of non-NASA interest.

Within the heterodyne realm, high-sensitivity detectors are mainly needed by the Astrophysics community. This is because the planetary science and Earth science remote-sensing communities are usually background limited and can accomplish their science goals by using room temperature detectors. For frequencies beyond 1 THz, the detector of choice for the Astrophysics community has been the HEB. Figure 9 shows the current status of the measured noise sensitivity of these detectors as a function of frequency. Most groups working on this technology from the U.S. and the rest of the world are shown in this figure. Recent results from MSPU have been very impressive, and JPL will try to verify these results based on our testbed. The other impressive characteristic of these devices is that they have been shown to possess higher IF bandwidth than any of the other devices reported so far. Again, this will be verified at JPL.

The proposed activities for the development are shown in Table 3. It has only been a few months since work was commenced on this task. However, the MSPU devices have already been demonstrated with higher IF bandwidth. All other technology developments are currently progressing.

Plan

A major goal for FY12 is to demonstrate a 4-pixel, 1.9 THz receiver. To accomplish this goal, the following activities are currently planned:

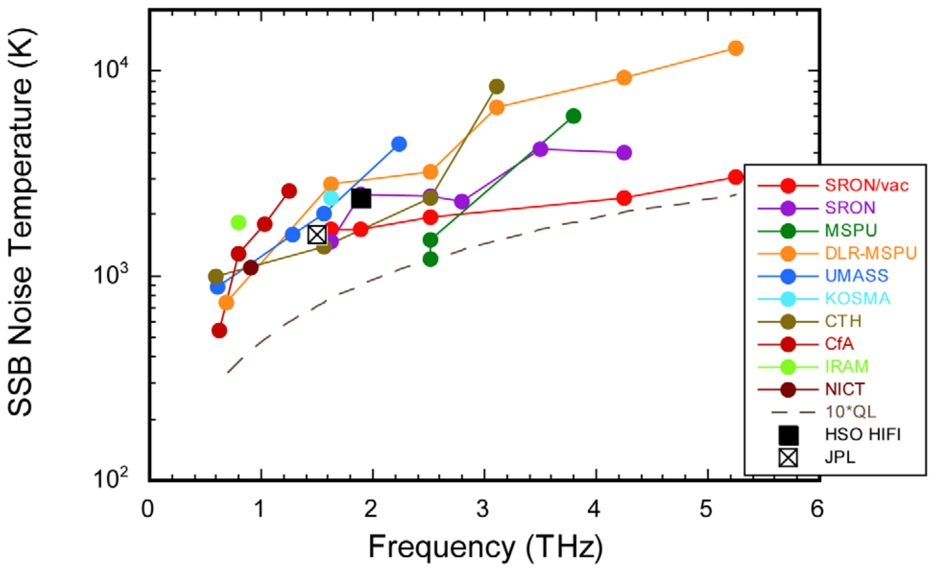

Figure 9. *The measured noise temperature of a wide variety of similar receivers made around the world has approached the quantum limit across a broad frequency range.*

Technology	Comments
HEB with IF>5 GHz	Concept validated at MSPU; under investigation at JPL
4-pixel LO at 1.9 THz	Work under progress
16-pixel LO at 1.9 THz	To be addressed in FY12/FY13
4-pixel RFE at 1.9 THz	To be addressed in FY12
16-pixel RFE at 1.9 THz	To be addressed in FY12/FY13

Table 3. *Proposed Technology Activities*

1. Design of 1,900–2,060 GHz-based HEB mixer devices with optimized IF bandwidth. This design will be based on the results obtained in FY11 from the MSPU-provided devices along with the devices that are fabricated at JPL. The device material structure will be optimized to provide optimum sensitivity along with maximum IF bandwidth. A single-pixel waveguide block will be designed, fabricated, and tested.

2. Demonstration of a 1,900–2,060 GHz LO chain. This chain will be based on a 2×3×3 implementation of frequency multipliers. All three chips are being fabricated in FY11 and will be available for use in FY12. All of the multipliers will first be packaged in individual blocks for testing. It will be important to show that the circuits can cover the full design bandwidth.

3. A 1,900-GHz receiver front-end module with 4 pixels will be designed and implemented. The mixers will be housed in waveguide circuits, and the LO will be coupled with external horns. Characterization of this receiver will be important to investigate the calibration and pointing capabilities of array receivers.

Technology Milestones

The development schedule and milestones are shown in Table 4. The major milestone for FY11 is to validate the high sensitivity and high IF bandwidth devices from MSPU. This task is currently under way.

Milestone	Date
Validation of Mixers with low noise and high IF	October 2011
Optimization of single pixel mixer performance (1.37,1.9, 2.7 THz)	June 2012
Build 1.37 and 1.9 THz LO Sources (post-HIFI technology)	March 2012
Demonstration of a 4-pixel 1900 GHz Front end	September 2012
Development of LO for 16 pixels (1.9 THz)	January 2013
Extension to a 16 pixel 1.9 THz RFE	June 2013

Table 4. *Proposed Technology Activities*

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2.2 UV EBCMOS Detectors

Prepared by: Bruce Woodgate/NASA GSFC

Summary

The goal of this task is to build and test high quantum efficiency, large-area, UV electron-bombarded complementary metal-oxide semiconductor (EBCMOS) imaging detectors. This work will accelerate this UV detector technology for potential application to the next generation of large, free-flyer UVOIR missions after the *Hubble Space Telescope*. In addition, the development of this detector technology will enable future Explorer and Stand Alone Missions of Opportunity (SALMON) missions for flight.

Detectors of the future in the UV will employ cesiated aluminum gallium nitride (AlGaN) and potassium bromide (KBr) as photocathodes. Because AlGaN requires high processing temperatures, the only detector architecture available that is realizable in the foreseeable future is that of a planar opaque photocathode and electron-bombarded silicon detector. Previous detectors with this architecture have employed a charge-coupled device (CCD) operating in frame transfer mode as the sensor. However, as will be described later, CMOS arrays provide numerous practical and performance advantages over CCDs for this application. We are developing detectors that incorporate large-area photocathodes with demagnifying electrostatic electron imaging to smaller CMOS detectors and testing their imaging and noise performance. We have started with demountable, windowless detectors with KBr photocathodes for simplicity and for wavelengths below 130 nm, and we will continue with sealed windowed detectors with AlGaN photocathodes for wavelengths greater than 105 nm. This work leverages a recent NASA Research Opportunities in Space and Earth Sciences (ROSES)/Astronomy and Physics Research and Analysis (APRA) award and Goddard Internal Research and Development (IRAD) funding to the Principal Investigator (PI). Funding for this task was received in June 2011.

Technology Description

The NWNH report has recommended the development of a large UVOIR mission to replace *Hubble* and will select amongst several conceptual missions that have been studied, including *New Worlds Observatory* (NWO), *Telescope for Habitable Exoplanets and Interstellar/intergalactic Astronomy* (THEIA), and *Advanced Technology Large Area Space Telescope* (ATLAST). All of these and others call for UV imaging and spectroscopy instruments, on the same missions as exoplanet imaging and spectroscopy, and general astrophysics in the visible and near IR. All three of these missions have adopted the Goddard telescope design strategy of a UV-sensitive Al/MgF$_2$ primary and secondary mirror telescope to a Cassegrain focus for wavelengths below 500 nm and an off-axis, three-mirror anastigmatic focus with additional silver-coated mirrors for high efficiency in the visible and near-IR. Included in the UV instrumentation is a very sensitive two-mirror, 3D spectrograph that could use the UV image slicer that was the subject of an FY10 internal research and development project at Goddard. Space UV imagers and spectrographs require detectors free of read noise to measure very faint objects, such as distant quasars, star-forming galaxies, and the intergalactic medium, where most of the baryons in the universe reside. UV photon-counting detectors are needed with high quantum efficiencies, zero read noise, and radiation hardness. While zero read noise UV detectors have been used in many space missions, their limited quantum efficiencies (QE) and small formats have reduced the effectiveness of their expensive host telescopes. Higher QE and larger-format radiation-hard photon-counting UV detectors are required. The technology pull from the large UVOIR mission for UV detectors would also benefit future Explorer and SALMON mission concepts that could fly and demonstrate the new UV detector arrays before a flagship mission.

A particularly important diagnostic of hot gas occurs in a wavelength region inaccessible to windowed detectors, ionized oxygen (OVI) at 103.2 and 103.8 nm, which is the best available diagnostic for the expected reservoir of most of the baryons in the universe at low redshift. Fortunately, opaque KBr photocathodes have very high QE (~80%) at these wavelengths when used in a windowless detector, such as the GSFC/Rutgers EBCMOS detector, which will be preferred to the current lower QE, higher noise microchannel-plate-based detectors, when ready for flight. In the nearer UV (130–300 nm), the highest QEs have been obtained with opaque cesiated p-doped GaN at GSFC and University of California, Berkeley (Figure 10, left-hand image). In comparison, the current UV detectors on HST have QEs ~10% in the near UV. For example, the lowest curve plotted in Figure 10 (left-hand image) is for the HST Space Telescope Imaging Spectrograph (STIS) and Cosmic Origins Spectrograph (COS) near-ultraviolet (NUV) CsTe photocathode multi-anode microchannel array (MAMA) detectors, which have a peak QE of 9%. The best combination of detectors for the wavelength range 90–300 nm is opaque EBCMOS detectors, with windowless KBr from 90–130 nm and windowed GaN from 130–300 nm.

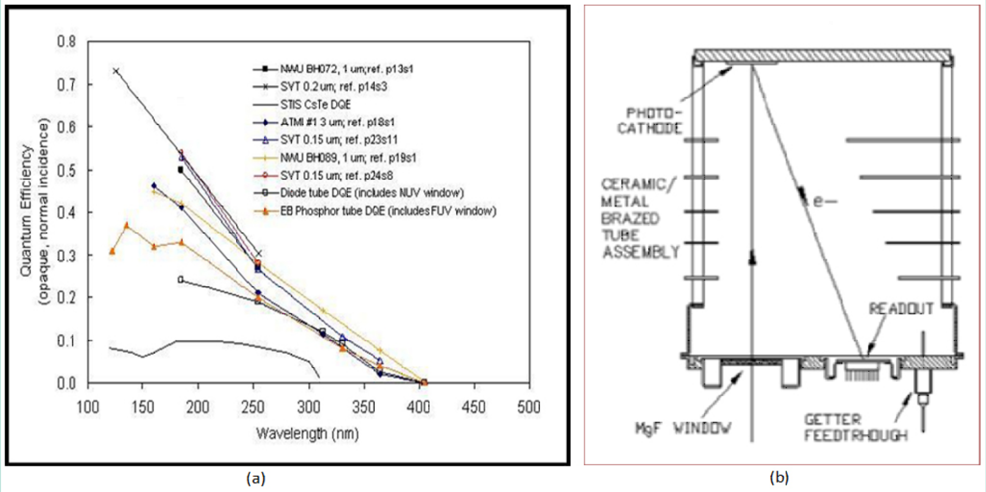

Figure 10. Left: *Quantum efficiency results as a function of wavelength, obtained by GSFC in prior APRA and IRAD programs.* ***Right:*** *A schematic of current Rutgers magnetic-focused EBCMOS detector is shown.*

In general, the best detectors for detecting faint objects at these wavelengths will be those with the highest sensitivity and improved resilience to loss of gain, compared to the HST/*Far Ultraviolet Spectroscopic Explorer* (FUSE)-era detectors. Recent improvements in the UV quantum efficiency (QE) using cesiated p-doped AlGaN, by GSFC's Code 667 and University of California, Berkeley, have obtained QEs of 68% at 122 nm and ~50% at 180 nm, a factor 3–5 better than the traditional CsI and CsTe (Figure 10, left-hand image), and so are the best hope for sensitivity improvements over most of the FUV and NUV spectral range for most of these medium- and long-term missions. However, these QEs are obtained on opaque planar and nanowire photocathodes on matched crystalline substrates and have not been demonstrated in microchannel plate (MCP)-based detectors. The only way to use the current improved photocathodes is to use them in windowed, sealed, electron-bombarded CCD or CMOS tubes (EBCMOS), which we are pursuing in our approved ROSES/APRA work (Figure

10, right-hand image). Demonstration of the EBCMOS method distinguishes the immediate applicability of the GSFC/Rutgers approach, rather than Berkeley's reliance on coating the MCPs with GaN. Use of GaN photocathodes requires the development of ceramic (silicon or alumina) MCPs because of the 900°C processing temperature of GaN. GaN photocathodes on MCPs also require other significant extra steps, which have yet to be demonstrated and which would reduce the quantum efficiency. The high voltage required for EBCMOS is similar to that of multi-MCP detectors.

While the main advantage of the high-QE EBCMOS detectors is to detect fainter objects, or to save the cost of larger telescopes, they are also more robust against high UV flux than MCP-based instruments. This problem is currently preventing many UV observations with the *Hubble Space Telescope*, including coronagraphic observations of planet-forming circumstellar systems, due to concerns for degrading the MCP gain, as has been observed on the COS and FUSE, and which was severe on the *Extreme Ultraviolet Explorer* (EUVE) and on many solar missions such as the *Solar and Heliospheric Observatory* (SOHO). The dark noise is also expected to be lower with EBCMOS due to removal of the dominant dark-noise source in MCP-based devices, the MCP itself. The narrow pulse height distribution with EBCMOS allows the rejection of most cosmic rays by pulse height discrimination.

The use of CMOS arrays in electron-bombarded detectors is now possible with the advent of back-thinned CMOS arrays. They have several advantages compared to the CCD detectors used in the previous electron-bombarded charge-coupled device (EBCCD) detectors flown in the *Interstellar Medium Absorption Profile Spectrograph* (IMAPS) mission. The Intevac CMOS arrays can be framed faster (~40 frames/s), have larger formats (with 1,280 × 1,620 pixel arrays), less electron bombardment damage, no charge transfer efficiency (CTE) losses, and require no mechanical shutter.

Progress

Preparatory steps have been made to install a back-thinned Intevac CMOS imager into a Rutgers University demountable EBCMOS magnetically focused detector with KBr photocathode in the Rutgers vacuum calibration chamber with UV illumination. The UV-illuminated photocathode will be re-imaged with ~10 kV electrons and magnetically focused onto the CMOS detector. Design concepts are shown for insertion of a CMOS detector into the Rutgers University's demountable electrode structure (Figure 11), and for an insertion feed-through for the Rutgers UV calibration vacuum chamber to bring the electronics closer to the CMOS readout detector for vacuum testing in the focusing magnet of the EBCMOS detector (Figure 12).

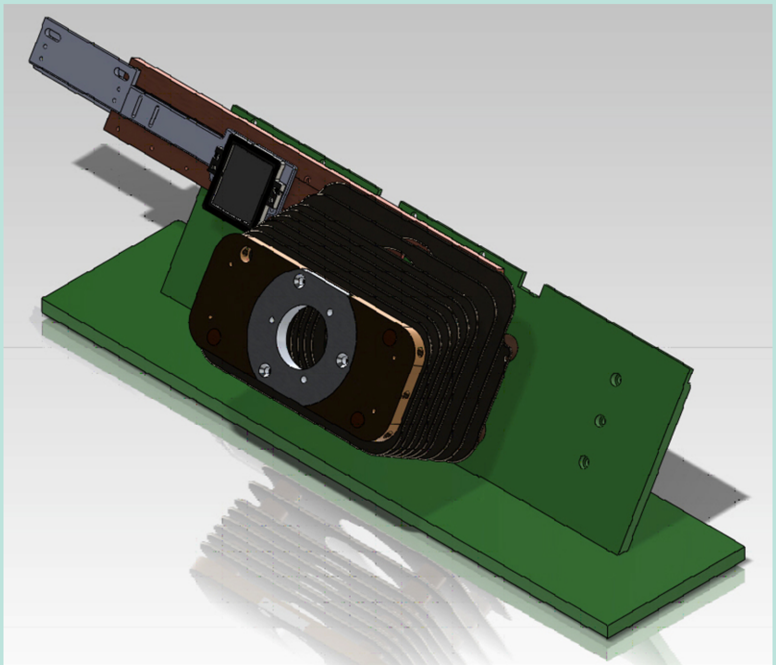

Figure 11. *The concept for a CMOS chip carrier on a Rutgers demountable electrode is shown.*

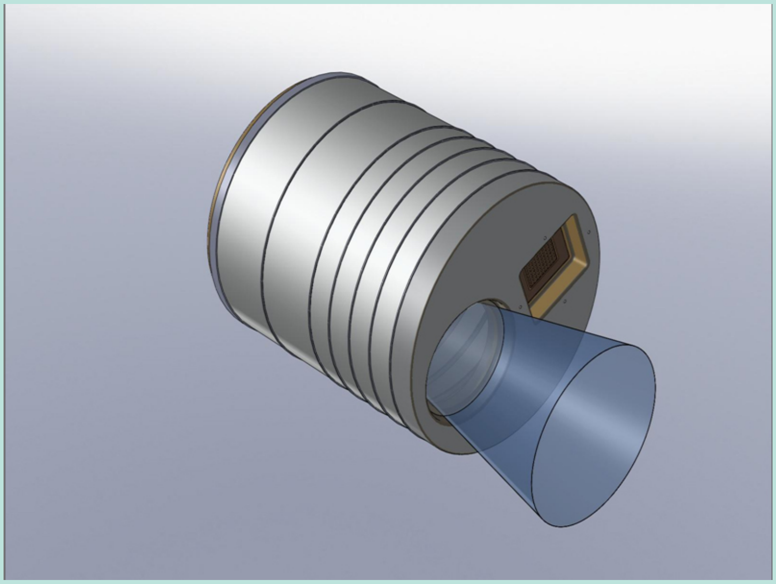

Figure 12. *A CMOS sensor electronics feed-through concept for a Rutgers "medium" calibration chamber is shown.*

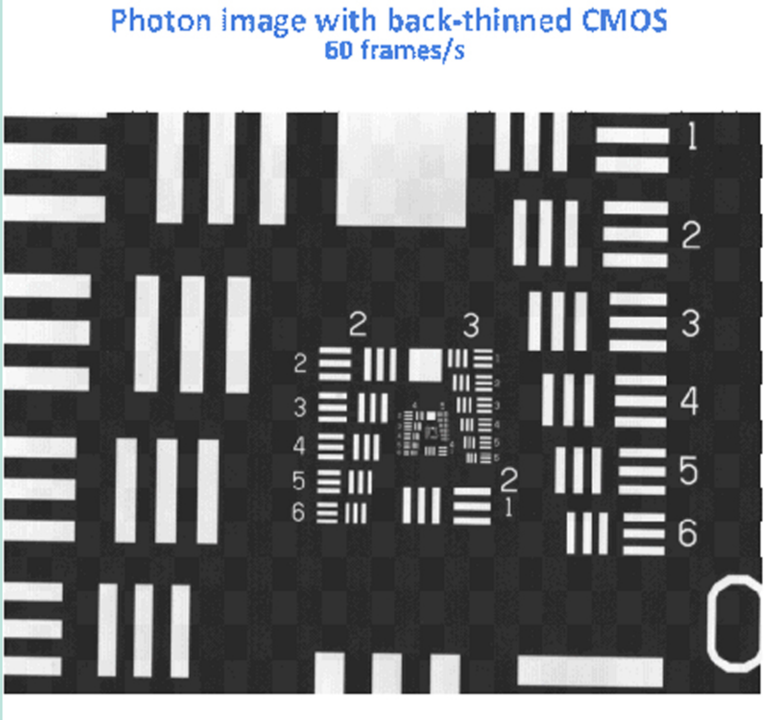

Figure 13. *The back-thinned CMOS detector with visible-light image input to show image quality and high speed prior to imaging with penetrating ionizing particles.*

A CMOS detector was illuminated with an Air Force target pattern to show image quality and high-speed function of the detector and electronics and data storage (Figure 13), and pulse height distribution with (x,y) location with X-ray input via an ^{241}Am source (Figure 14) to simulate electron input and individual event detection prior to installation into vacuum.

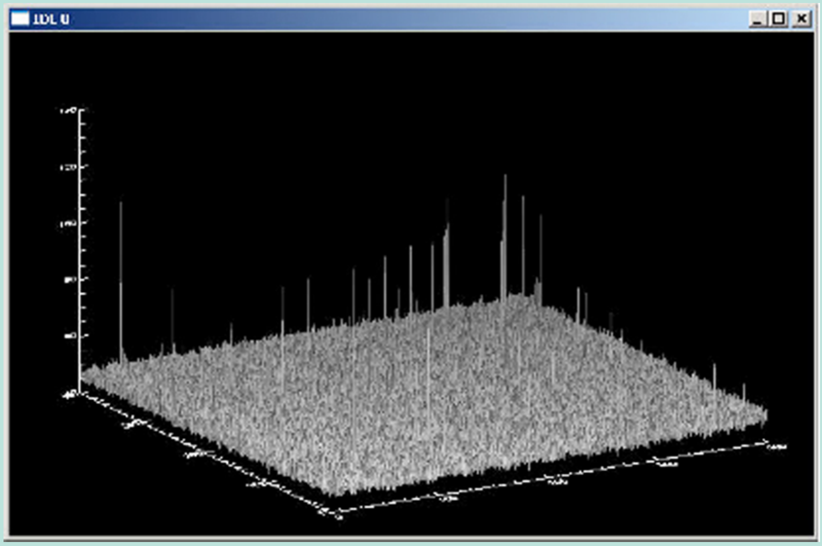

Figure 14. *Individual ionizing events (X-rays) with back-thinned CMOS imager, simulating electron input.*

Design work has been initiated for the large-area demagnifying electrostatic detector by: 1) the recruitment of a civil service detector engineer to apply SIMION® electron-optics design software to the electron focusing between photocathode and receiving CMOS anode; the recruitment of a civil service optics engineer to use optical ray-trace software to produce UV spectroscopic images compatible with the concave UV photocathode to explore large fast-UV spectroscopic imaging concepts for future Explorer and flagship missions.

Status and Plan

We will leverage our current efforts from APRA (FY11-14) and IRAD (FY11 small-area demonstration for magnetic focus), for two purposes:

1) To push the technology to higher TRL levels in time for future missions, closing the gap between early concept demonstration and flight readiness.
2) To create larger photocathode area detectors with the higher QEs needed for the 3D and other spectrographs featured in the studied NWNH report missions. (Packaging the three dimensions, two spatial and one spectral, onto two-dimensional photocathodes requires many pixels to cover the product of the range/resolution for each of the three dimensions.)

Prior work and Current status

In addition to the photocathode improvements shown in Figure 10, which will continue under the renewed APRA funding, we have acquired back-thinned Intevac CMOS devices and a data acquisition system and tested them in air optically, as shown in Figures 13 and 14. A number of back-thinned CMOS sensors designed specifically for electron-bombardment are commercially available from Intevac, Inc., in Santa Clara. We have prior lab experience with a 1,280 × 1,024 back-thinned device, ISIE10 with 10.8 micron pixels, which is included in their Night Vista 3010M imaging camera with a GaAs based photocathode in a proximity focusing configuration. The sensor operates at 30 frames per second with a nominal read noise of 35 e^- rms. The sensor employs rolling shutter readout with low-power, 3.3-volt operation. A version of this device has been evaluated at GSFC under an internal IRAD program. This was shown to exhibit good single photoelectron detection efficiency at the relatively low bombardment voltage of less than 4kV in a proximity focusing configuration. Intevac make a larger-format EBCMOS sensor (ISIE11), comprising 1,640 × 1,200 11 micron pixels, operating at 60 frames per second with lower read noise (typically 22 e^- rms). We have already procured four of these sensors, along with a number of dummy ceramic packages (to perfect our Indium sealing technique) from Intevac with our current funding, and these will be incorporated into the first tubes. At the higher electron-bombardment energy (8–10 keV) of the magnetically and electrostatically focused tube configurations, the expected signal-to-noise ratio (SNR) per photon event (taking into account any dead layer energy loss) is expected to be less than 100:1, allowing very efficient discrimination against system noise. In addition, advances in intra-pixel technology at Intevac have been designed to limit charge-spreading within the device, further improving photon-event SNR.

Planned Work

Leverage of APRA: A four-year proposal has been accepted by NASA for FY11-14 to cover generic development of the UV photocathodes, including p-doped AlGaN and ZnMgO, both planar and nanowires. This includes detector tube development, including tube sealing of both photocathodes and CMOS anode arrays into current design, magnetically focused Rutgers tubes and low-TRL efforts toward larger-format photocathodes and anode arrays for larger field of view coverage. The APRA work provides for partial funding of our small, highly skilled team to advance these concepts to about TRL-3 levels at a rate consistent with APRA funding.

We will install the CMOS into a Rutgers demountable electrode structure, install this into a Rutgers vacuum test system with magnetic focusing, for electron input and test it for QE as a function of wavelength, dark noise, read noise (which as a photon counter should be zero), and image quality.

This COR work will increase the level of effort, primarily by increasing the amount of time the current team can spend on this work, using their skills in UV optics, electron-optics, low-noise analog electronics, real-time programming, magnetic/mechanical design, and ultra-high vacuum (UHV) operations. We will also supplement this team with special skills and facilities required to advance to the higher TRL levels, such as more detailed electron optics, optics design to simulate the imagers and spectrographs to illuminate the photocathodes, and structural design and fabrication. Representative detector designs suitable for imager and spectrograph applications will be developed, fabricated, and tested. This effort will include detailed design of the electron optics and the electrical, mechanical, and thermal design of the detector will be appropriate for a flight environment. Actual qualification testing is not planned as part of this program but could be performed at a later date. Performance testing will include: measurements of quantum efficiency as a function of wavelength; spatial resolution across the area format using patterned photocathodes, and then by photon imaging onto the photocathodes; dark noise using long exposures, including rejection of ion events by an upper-level discriminator, and; rejection of read noise by lower-level discriminator thresholding for each frame.

Technology Development Milestones

Milestone	Date
Electro-optical design and modeling	April 2011
Ceramic/metal cage electrode design and fabrication	May 2011
Specify and procure vacuum test system for demagnifying tube testing, and custom modifications required	July 2011
Specification and procurement of test hardware, including monochromator and calibration sources	August 2011
Photocathode deposition - uniform and patterned	September 2011
Annual Report	October 2011
Performance testing of electro-optics system in vacuum	November 2011
Structural design to hold electrode cage and CMOS, highly transparent to input beam	December 2011
Fabrication of launchable electrode and CMOS housing	March 2012
Mid-year Report	April 2012
Performance testing of ruggedized system in vacuum	June 2012
Annual Report	October 2012

Table 5. *Technology Development Milestones*

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2.3 Far-Infrared Large-Format Array Detectors

Prepared by: S. Harvey Moseley/NASA GSFC, Dominic Benford/NASA GSFC, Christine Jhabvala/NASA GSFC, and Johannes Staguhn/NASA GSFC and JHU

Summary

The goal of this Cosmic Origins technology development project is to demonstrate the key component technologies required to produce space-worthy, far-infrared (far-IR) to submillimeter, high-sensitivity bolometer arrays on a large scale of 1,280 pixels. This objective is in direct support of one of the three Astrophysics Science Area Objectives in the 2011 NASA Strategic Plan:

"…improve understanding of the many phenomena and processes associated with galaxy, stellar, and planetary system formation and evolution from the earliest epochs to today."

Existing mission concept plans and community priorities convey the need for large-format, far-IR arrays containing thousands of pixels as an enabling technology required for future NASA missions. However, for wavelengths longer than 40 µm, there is no existing detector that can meet this requirement. This project builds on the results of previous APRA-funded research and leverages related Goddard-funded process improvements to prepare large-format, far-IR detector arrays for a suborbital demonstration in 2013.

Technology Description

In preparation for the NWNH report, several large groups self-organized in support of highly capable future missions. One of these groups, consisting of 72 scientists from NASA centers, U.S. universities, and abroad, submitted a broad community endorsement entitled "Far-Infrared/Submillimeter Astronomy from Space: Tracking an Evolving Universe and the Emergence of Life" (Harwit et al., 2010). This document draws from over a dozen other separately submitted decadal survey white papers related to science and instrumentation of far-infrared missions and was, in turn, submitted as a community consensus for consideration to the NWNH committee. This white paper held a clear recommendation:

"We will need, in 2010 – 2020, to: (i) prepare the scientific and technical prerequisites and (ii) conduct full phase-A studies of both a 10-m class cryogenically cooled Single Aperture Far-Infrared Telescope, SAFIR, and a similarly cooled Space Infrared Interferometric Telescope, SPIRIT, before the end of the decade."

There are many technologies needed for these two NASA missions spanning nine categories, of which only three were slated to derive from low-level R&A investments, and only one was specifically called out as being a low technology readiness level. This high-priority development need is the production of large-format, sensitive arrays of far-infrared detectors.

Several publications derived from mission concept studies contain the array requirements for future NASA missions. The best-studied of these is probably SAFIR, which requires detector arrays with on the order of 10^4 pixels and sensitivity of 10^{-19} W/√Hz (Benford and Moseley, 2004). CALISTO, the *Cryogenic Aperture Large Infrared Space Telescope Observatory* (Goldsmith et al., 2008), is a somewhat scaled-down version of SAFIR, and its instrument suite includes a six-band camera with 4,096 pixels per band, in addition to echelle-type

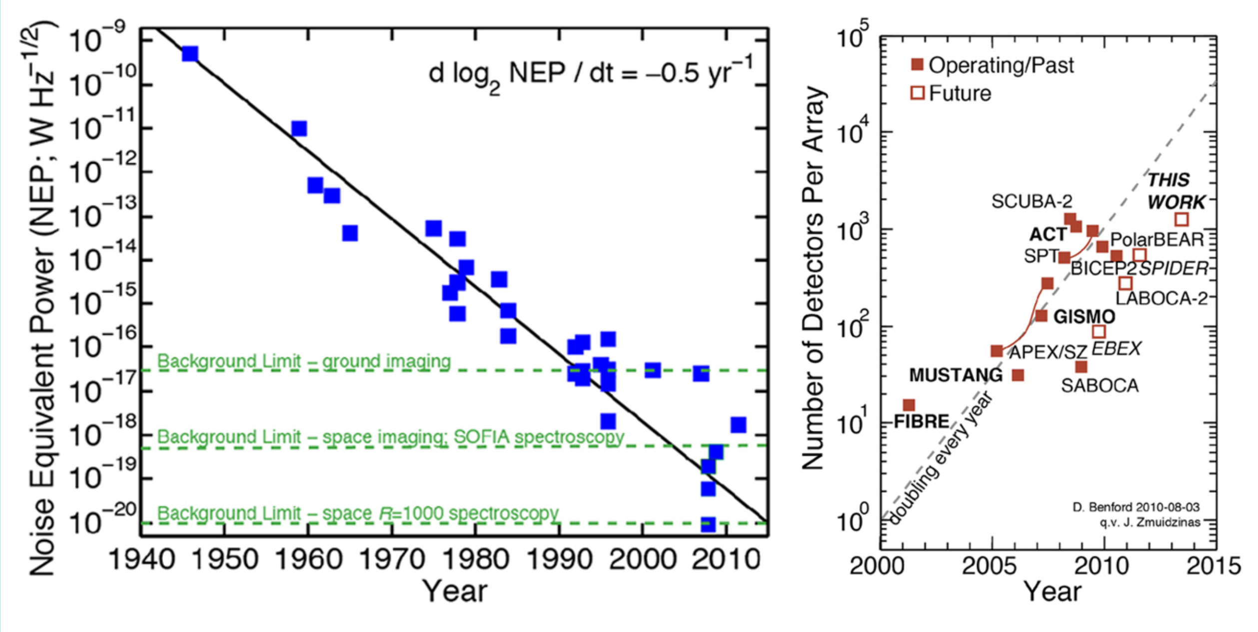

Figure 15. Left: *The Noise Equivalent Power (NEP) of individual bolometers has been improving rapidly for decades, and is now limited only by the applications for which they are developed.* ***Right:*** *Similarly, TES bolometer array formats did improve rapidly, but have stagnated for several years and have not been developed for spaceworthiness. Suborbital applications, which generally require higher sensitivity and overall Technology Readiness Level (TRL), are italicized. TES bolometer arrays developed at GSFC are shown in bold.*

spectrometers with up to 12,000 pixels per band. CALISTO's operational plan includes a six-month or more period of sky mapping designed to produce a confusion-limited survey in its longest wavelength bands (Goldsmith et al., 2010). However, at a representative wavelength of 70 µm, this size of camera can survey only approximately 0.7% of the sky in a year. In response to this, a more recent technology plan for far-IR detectors (Bock et al., 2010) slates a detector pixel count of 10^5, which permits this deep survey to be conducted over one-sixth of the sky. It is to satisfy the above goals—*over a thousand pixels in a single bolometer array*—that we have been developing the technology described here.

The use of such large-format detector arrays in the near future is well-suited to a high-profile application: far-infrared polarimetry on SOFIA. SOFIA has a focal-plane field of view of over 8 arcminutes in diameter and, at a wavelength of 40 µm, its 2.5m telescope provides an angular resolution of 4 arcseconds. The mapping of magnetic fields in nearby molecular clouds requires a map size of at least 5 arcminutes (Dotson et al., 2010), and the polarization fraction is several times larger at 40 µm than at longer submillimeter wavelengths (Hildebrand and Vaillancourt, 2009). A large-area imaging polarimeter would be ideal for this science case, as an entire region could be imaged simultaneously, significantly improving on the systematics control necessary for sensitive polarimetric measurements. The requirement on the detector array is a format of approximately 64 pixels on a side, with a noise-equivalent power (NEP) of only about 7×10^{-17} W/$\sqrt{\text{Hz}}$. This sensitivity has been demonstrated and surpassed with our detector array architecture (Staguhn et al., 2006). Upon completion of this project, the detector technologies needed to make the largest-area, most-sensitive polarimeter that SOFIA can accommodate will have been produced. Confidence is high that new ground-based facilities, such as the *Large Millimeter Telescope* (LMT) and C*erro Chajnantor Atacama Telescope* (CCAT), will provide ample opportunity for the demonstration and maturation of this technology.

Cosmic Origins Mission Traceability:

- SOFIA second generation instruments
  - Require capability by mid-2011
  - Array format must be much larger than current
- U.S. SPICA instrument
  - Needs maturity by 2012 or earlier
- Future balloon proposals
  - Will directly assist with BETTII Far-IR interferometry experiment
- Explorer call in 2012+
- Next major far-IR mission—the *Single Aperture Far Infrared Observatory* (SAFIR), CALISTO, or the *Space Infrared Interferometric Telescope* (SPIRIT)—will need concentrated effort

How This Supports Technology Development

COR Needs—to demonstrate the maturity of current technology:

- Fabricate protoflight detector arrays
- Use in suborbital applications as frequently as possible
- Progress supports long-term enabling technologies
- Far-IR future mission is the strongest driver and a likely high scientific priority

Progress

Goddard has developed a far-infrared bolometer device architecture named the Backshort Under Grid (BUG) array that is shown in Figure 16. A BUG array having 16 × 8 pixels was first demonstrated in a Goddard-built ground-based instrument for the Institut de Radioastronomie Millimetrique (IRAM) 30m telescope, GISMO (Goddard IRAM Superconducting 2-Millimeter Observer) (PI: Johannes Staguhn, GSFC/JHU). GISMO accomplishments will be described further in the text that follows.

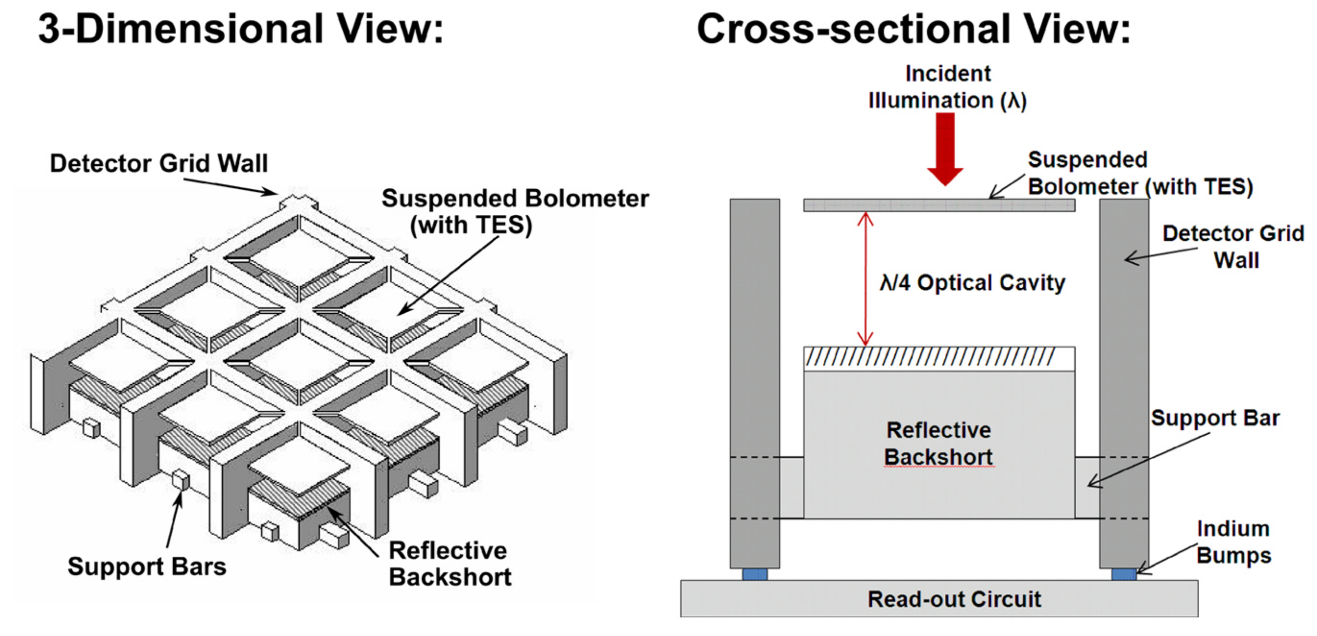

Figure 16. *This conceptual drawing of the BUG array architecture highlights the components that enable high filling factor and high optical efficiency.*

The current evolution of this technology has been scaled up to achieve 1,280-pixel arrays suitable for a SOFIA second-generation instrument. A set of four such arrays are now in development for the balloon-borne instrument known as PIPER (Primordial Inflation Polarization Explorer, PI: Alan Kogut, GSFC). These kilopixel arrays will be described in the section that follows. In addition, small-format BUG arrays are slated to fly on the balloon instrument, BETTII (Balloon Experimental Twin Telescope for Infrared Interferometry, PI: Stephen Rinehart, GSFC).

The BUG array architecture's inherent versatility and extensibility can fulfill a wide variety of detector instrument needs, including space applications. The BUG array is a three-component detector system: 1) superconducting Transition Edge Sensor (TES) bolometer pixels designed for background-limited sensitivity; 2) a tuned (norminally λ/4-wave, but optimized) backshort under each pixel to provide high optical efficiency, and; 3) a 2-D Superconducting Quantum Interference Device (SQUID) multiplexer to read out signals from the pixels. The detector array, designed as a grid of suspended, 1 μm–thick silicon bolometers with superconducting TES thermistors, is bump-bonded directly to the SQUID multiplexer. The backshort is a separately fabricated, wafer-scale component that forms an optical cavity under each pixel. A key advantage of our BUG architecture is the versatility to tune its performance for specific wavelengths of operation by changing the dimensions of the optical cavity and the surface impedances of the absorber and reflector layers. The spacing of the backshort is adjustable (from about 30–300 μm) by independently adjusting the depths of two silicon deep-etch processes needed to produce the grid. Additionally, this element can act as a reflective backshort or as a terminating load, depending on the needs of the optical design.

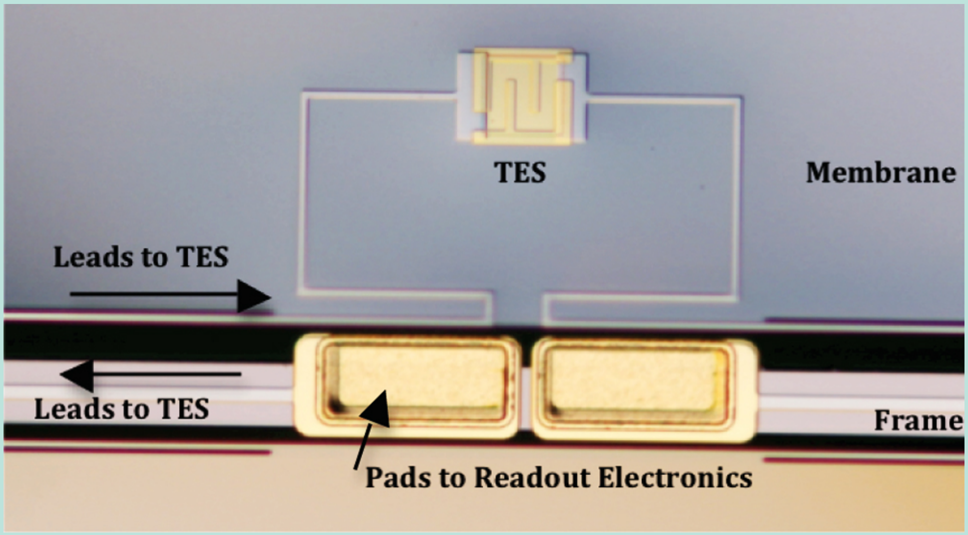

Figure 17. *This microscope image of a TES shows superconducting leads, a portion of the detector membrane, and contact pads to readout circuit. Wrap Around Vias, located on the detector support frame and discussed later in this report, are identified as "pads to readout electronics."*

Goddard is uniquely capable of the continued development of this bolometer architecture because of its advancement of three technical challenges: 1) the development of low-noise superconducting transition-edge sensors; 2) pixel lead routing from the top surface to the bottom to enable scaling, and; 3) hybridization to mate TES arrays with the SQUID multiplexers.

Transition Edge Sensor

Under prior funding, GSFC and the National Institute of Standards and Technology (NIST) worked together to produce a SQUID multiplexer design that features more than two orders of magnitude less magnetic field susceptibility (in fact, the first-stage SQUIDs now have an unmeasurably low pickup) and an order of magnitude reduction in dead (unaddressable) pixels. The new generation of time-domain multiplexer allows inductors roughly half the value of the 475 nH used for the Submillimetre Common-User Bolometer Array (SCUBA-2) design (Irwin et al, 2004) and a significant reduction of the resistance of the 300-mOhm TES normal-state resistance. We have optimized the normal-state resistance of our Zebra-striped TES thermisters (visible in Figures 16 and 20) to 5–20 mOhm, which is appropriate for the newly designed SQUIDs. The TES, shown in Figure 17, operates in the range of 100–150 mK.

TES to SQUID Interface—the Wrap-Around Via and the Through-Wafer Via Solutions

In order to scale up the number of pixels that can be placed in a detector array, the TES leads for each pixel (shown in Figure 17) must be routed from the top surface to the bottom surface for attachment to the SQUID readout in the most efficient manner possible. Two methods have been invented two methods to do this: the Wrap-Around Via (WAV) and the Through-Wafer Via (TWV). Routing superconducting wires that demonstrate high critical current and are three-dimensional, rather than planar, is a significant technical challenge that we has overcome.

While the WAV has been demonstrated by plating metal strips down the existing sidewalls, it requires a long fabrication cycle with two high-risk processes. Therefore, work is being performed to aggressively mature a routing method through the frame itself with TWVs in which high-aspect ratio micro-vias (measuring 10 × 20 μm) are etched through thick wafers,

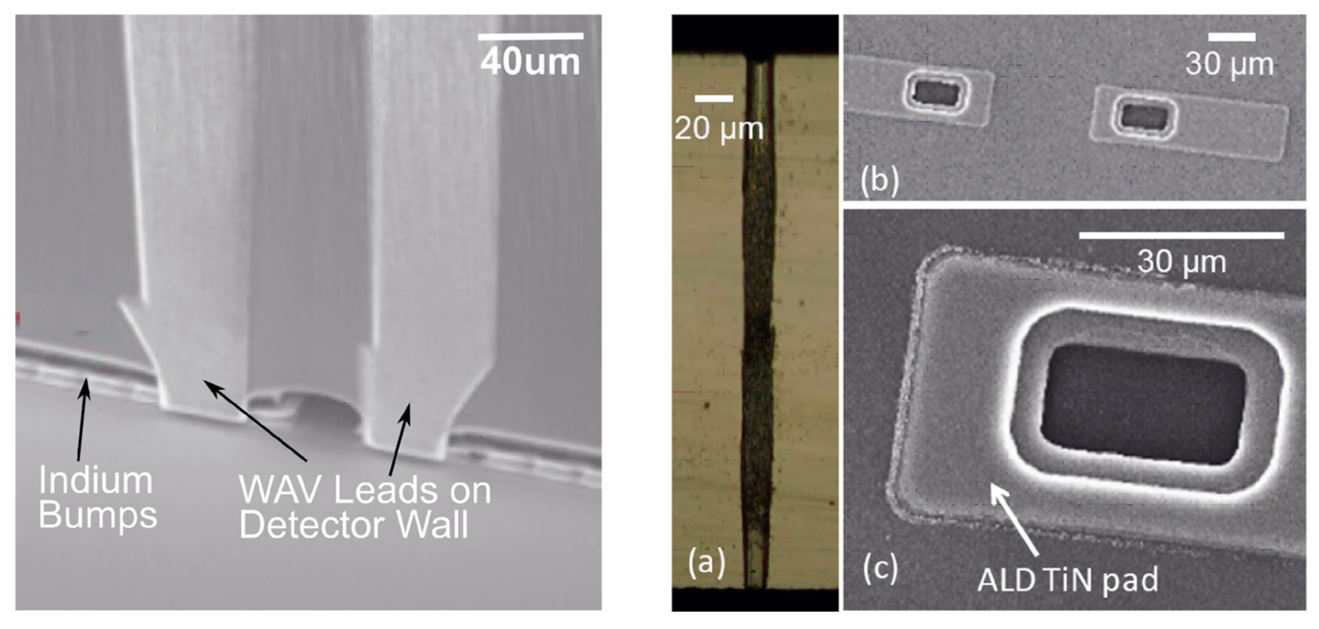

Figure 18. Left: *A Scanning Electron Microscope shows two WAV leads deposed on the sidewall of a BUG pixel and making contact to indium bumps on the detector substrate.* ***Right:*** *This sequence of images shows: a) a cross-section of a microvia cut through a silicon wafer; b) the top view of two microvias with atmoic layer deposition (ALD) metallization patterned into contact pads for the detector, and; c) a close-up of the top of a microvia, showing the superconducting TiN pad deposited over and into the opening of the via.*

as shown in Figure 18. After drilling, the vias are conformally coated with superconducting titanium nitride (TiN) using Atomic Layer Deposition (ALD). Pads around via openings are then patterned; the vias are plugged with SU-8 polymer to provide wafer planarity for the remaining detector processing. Compare this new approach (shown in Figure 19 with the WAV image shown in Figure 17. The TWV is now being carried as a secondary path to the WAV, as we mature it and ultimately expect it to replace the WAV for all future BUG array

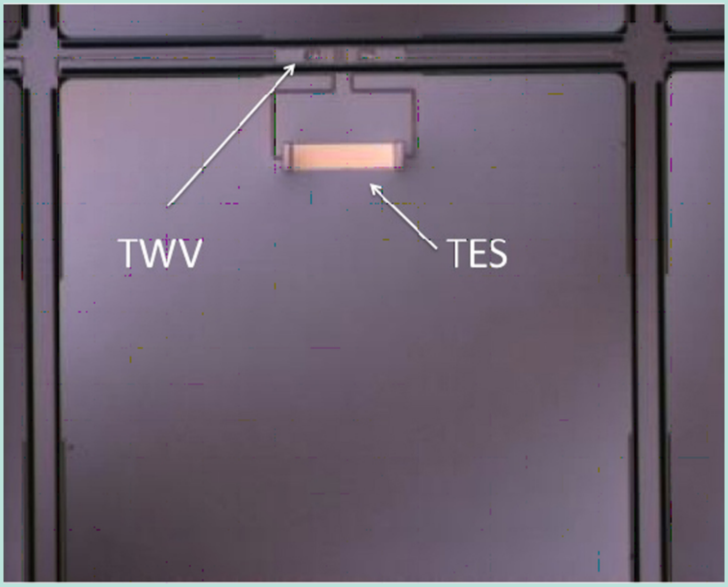

Figure 19. *A single BUG pixel is shown with TWV interconnects, which can be seen where they emerge from the back-side of the wafer along the supporting grid wall. Compare this with the WAV image shown in Figure 3.*

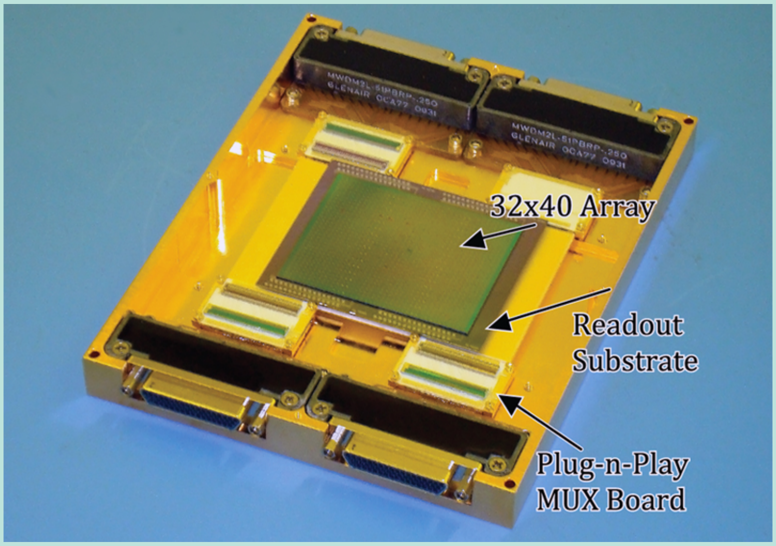

Figure 20. *A kilopixel array hybridized to a fanout substrate and wired to 1 × 32 SQUID readouts is shown. The array has 32 unique pixel designs to optimize sensor and leg geometries.*

designs. Significant improvements in the ease of fabrication and pixel yield with the new TWV method of interconnection have been observed. Both processes are now running in parallel. The most recent production resulted in a pre-hybridization yield of 98% good pixels with TWV technology, compared to 95% with WAV technology. Post-hybridization results are currently pending.

Hybridizing Detector Arrays to Multiplexers

GSFC has established an indium bump bonding capability with broad applications for detector integration. This process allows for the addition of more functionality per unit area and the ability to optimize the two major components (the bolometer array and the SQUID readout) separately.

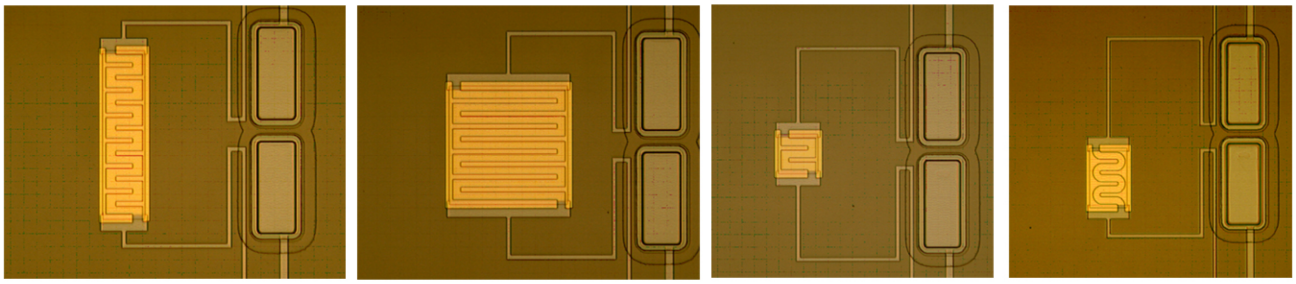

Figure 21. *Four of the sixteen TES designs incorporated into the Calibration Array are shown in the microscope images above.* ***a)*** *Version 1: A TES design used in the GISMO instrument.* ***b)*** *Version 2: A large-area TES, with a 1x1 aspect ratio.* ***c)*** *Version 3: Small-area TES with 1:1 aspect ratio. d) Version 4. Small-area TES with 2:1 aspect ratio.*

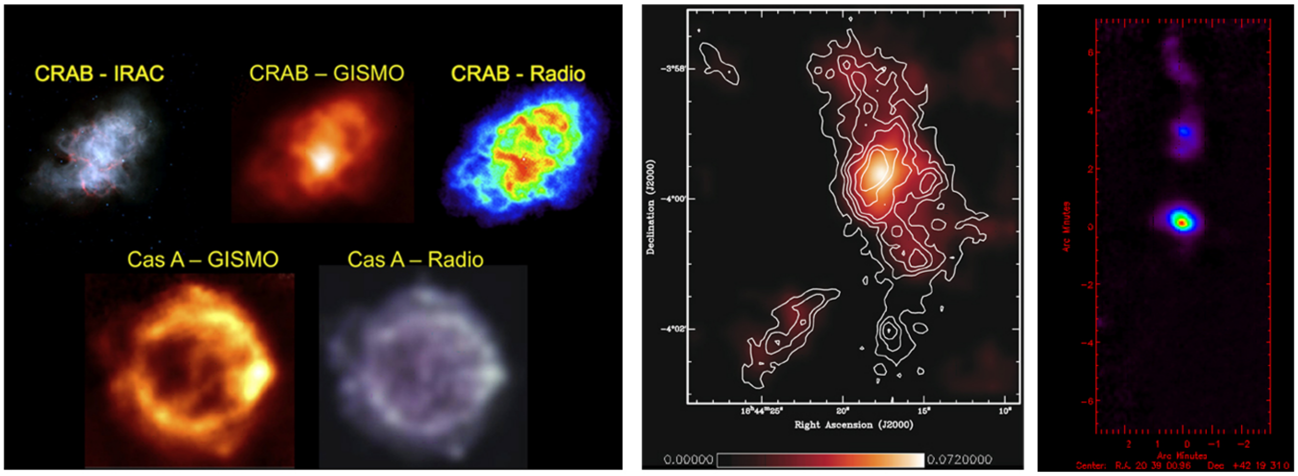

Figure 22. Left: *GISMO observations of supernova remnants are compared with observations at other wavelengths and show excellent agreement.* ***Center:*** *A GISMO observation of the infrared dark cloud IRDC 30 overlaid with 1.25-mm contours is shown.* ***Right:*** *A large field in the DR 21 region is shown.*

We have hybridized a 32 × 40 BUG array to a dummy fanout substrate for functional tests. Figure 20 shows a photograph of a hybridized array, with a subset of the available 1,280 pixels wirebonded for testing using 1 × 32 linear SQUID readout chips. The array contains the angle-deposited WAV's shown in Figure 18, and also contains varieties of suspended 1.4 µm-thick detector elements, with superconducting sensors (as already described). The detectors in this "Calibration Array" have 16 parametric variants of TES designs and 16 parametric variants of leg geometry designs, which allows for choosing the optimal design parameters for current programs and future missions. A subset of the TES designs is shown in Figure 21.

Operating BUG Arrays in the Field on Telescopes

The first operational SQUID multiplexer was developed at NIST (Chervenak et al., 1999) to read out superconducting bolometers and is the forerunner of the devices in GISMO. Shortly thereafter, our group achieved the first demonstration of an operational SQUID-multiplexed detector (Benford et al., 2000; Benford et al., 2002). This was followed by the demonstration that SQUID multiplexers can perform at the Johnson noise limit of TES bolometers (Staguhn et al., 2002). These steps provided the necessary demonstration of basic technologies to permit an expansion in array size and limited astronomical demonstrations. At the same time, individual bolometers were being optimized for more reliable processing (Allen et al., 2004). These featured repeatable DC performance parameters (Benford et al., 2004). However, their most important feature was that their noise was very close to the thermodynamic limit (Staguhn et al., 2004). The combination of these elements and advances in architectures for two-dimensional arrays (Benford et al., 2003) allowed other instruments to be developed along similar timelines to GISMO. These include the Atacama Cosmology Telescope (ACT)(Fowler et al., 2004; and Niemack et al., 2006) and the Multiplexed SQUID TES Array at Ninety Gigahertz (MUSTANG) for the Green Bank Telescope (Benford et al., 2004; and Dicker et al., 2006).

In addition to those, we undertook to build our own BUG-based technology demonstration astronomical instrument, the 2mm camera GISMO for the IRAM 30m telescope. GISMO was built as a pathfinder instrument, using high-temperature transition-edge sensor detectors (transition temperature = 450 mK). GISMO enables a variety of scientific projects, ranging from observations of cold dust in the local universe to observations of the earliest starburst galaxies in the universe. Figure 22 demonstrates our ability to successfully reduce extended source observations, ranging from observations of supernova remnants to infrared dark clouds and star forming regions. Figure 23 shows GISMO observations of point sources

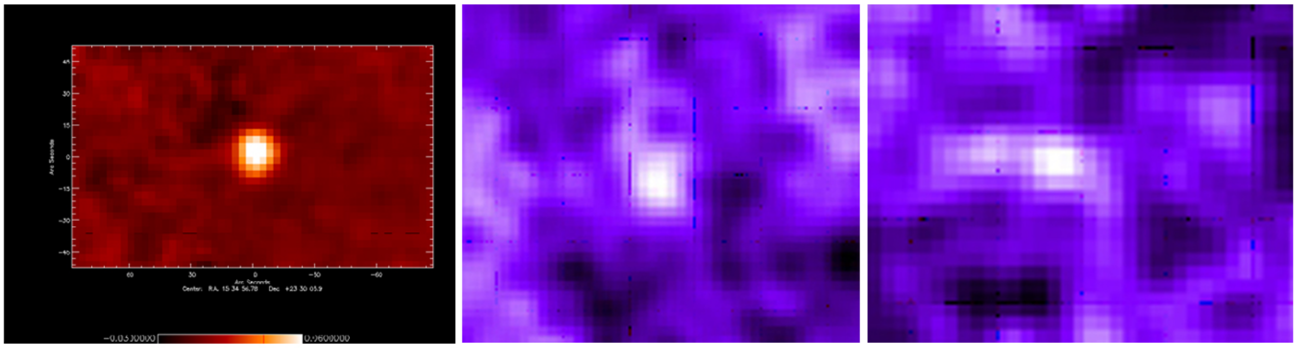

Figure 23. Left: *A GISMO 2-mm map of Arp220 is shown.* ***Center:*** *the z=3.9 quasar APM 08279+5255 is shown.* ***Right:*** *The z=5.3 Submillimeter galaxy AzTEC-3 (Capak et al., 2011) is shown.*

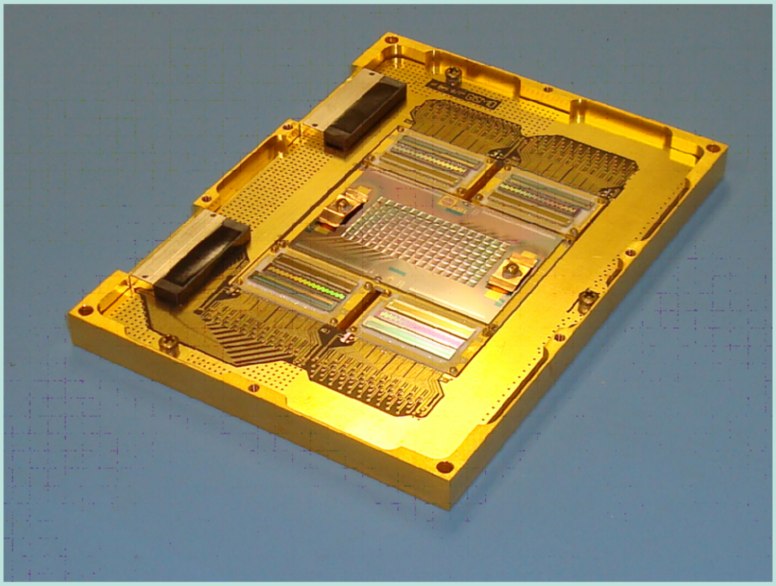

Figure 24. *This photograph of a GISMO detector shows an array of 8 x 16, 2mm-pitch TES pixels with SQUID multiplexed readout.*

with decreasing fluxes from left to right. The left panel of the figure shows the high signal-to-noise GISMO map of the prototypical Ultra-Luminous Infrared Galaxy (ULIRG) Arp 220, demonstrating GISMO's performance for point source observations. The center panel shows the detection of the massive high-redshift (z = 3.87) quasar APM 08279+5255, while the right panel shows the z = 5.2 submillimeter galaxy AzTEC-3; these demonstrate the ultimate sensitivity achieved by the BUG-based instrument.

The core of the GISMO instrument is its 8 × 16 BUG, array shown in Figure 24. Its size is dominated by the large coplanar readouts and wiring layers, which are greatly reduced in the new hybridized detector architecture detailed above.

Status and Plan

1. Address the immediate needs by completing a flight-like prototype, 32 × 40 detector array for SOFIA/balloon platform requirements; FY11 (Under this program)
2. Address maturity for future missions and instruments by deploying large-format arrays in suborbital instruments; namely, the Primordial Inflation Polarization Explorer (PIPER); FY13 (Funded project)
3. Produce small-format arrays for the Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII); FY12–13 (Funded project)

We are maturing a very promising Through-Wafer Via technology that was mentioned in earlier in this report. In the very near term, we will hybridize a Calibration detector array having TWV interconnects. We have observed a significant improvement in the yield of pixels using the new technology, although at present we do not have cryogenic test data to show our results. Our latest array, as yet not hybridized, has a fabrication yield of 98% good pixels. We will be pushing this technology very rapidly to replace the Wrap-Around Via technology. (WAV fabrication yield demonstrated to date is 95%—acceptable, but neither as convenient a process nor as promising a result as with the TWV technology.) Goddard has recently acquired an ALD system to support our TWV development. This tool was purchased through a cost-sharing plan, partially funded through this program. When this system becomes operational later this year, we will be able to advance our TWV technology rapidly, as we will no longer be dependent on sources in Finland for deposition of material on our TWV wafers. Goddard is continuing support of the development of BUG arrays through IRAD funds to push the successful completion of this project and others.

Technology Development Milestones

FY10/11/12

Milestone	Date
Develop processes for TWV and WAV connection	September 2010
Produce characterization hardware for 1,280-pixel arrays	September 2010
Deliver and test kilopixel "Calibration" detector arrays.	October 2011
Mature TWV technology to replace WAV.	May 2012
Deliver functional kilopixel array for characterization/validation	September 2012

Table 6. *Major milestones for FY 10/11/12 technology development.*

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SECTION 3.0 PROGRAM TECHNOLOGY NEEDS

As input to the technology development process, the scientific stakeholders in the missions that will be supported by the new technologies are canvassed to provide a summary of the perceived needs by this community. Because the scientific community is largely responsible for initiating missions based on certain technologies, this is an effective way to initiate the process. One formal route for inputs from the scientific community is through the COPAG. The COPAG is constituted by the NASA Astrophysics Subcommittee to support community coordination and analysis of scientific and technological issues impacting NASA's COR Program. The Program Office will accept inputs from anyone at any time. These inputs will be solicited continually and compiled annually, and are provided in the form of a technology needs table. The technology needs assessed in 2011 are shown in Tables 7 and 8, which consist of 12 technologies that the community has identified as being needed to enable or enhance a future COR strategic mission.

For each technology shown in the technology needs tables, descriptions are provided in the following categories:

Brief Description: This is a summary of the key performance criteria for the technology.

TABS Category: Each technology includes a Technology Area Breakdown Structures (TABS) number that indicates where it fits into the hierarchy of NASA's Space Technology Roadmap, developed by the Office of the Chief Technologist.

Goals and Objectives: This further details the specific goals of a potential technology development effort.

TRL: This specifies the currently estimated Technology Readiness Level(s) of the technology.

Tipping Point: This provides a timeframe during which the technology can be brought to a level where its eventual viability can be assessed.

NASA Capability: This details NASA's current capability to implement and/or access the technology.

Benefit: This describes the eventual impact of the technology to the mission concepts that have identified it.

NASA Needs: This describes the specific needs and performance requirements for NASA mission concepts.

Non-NASA but Aerospace Needs: This describes the specific needs and performance requirements for applications outside of NASA mission concepts and within the aerospace sector.

Non-aerospace Needs: This describes the specific needs and performances requirements for all other needs (those not covered in the previous two categories).

Technical Risk: This describes the known technical risks in developing the technology.

Sequencing/timing: This describes the desired availability timeframe for the technology.

Time and Effort: This estimates the duration and scope of the technology development effort.

COR Techology Needs Table

Name of technology	**High QE, large format UV detectors**	**Photon counting UV large-format detectors**	**UV coatings**	**Large, low-cost, light-weight precision mirrors for Ultra-Stable Large Aperture UV/Optical Telescopes**	**Deployable light-weight precision mirrors for future Very Large Aperture UV/Optical Telescopes**	**Very large format, low noise Optical/IR detector arrays**
Brief description (1024)	Future NASA UV missions, require high quantum efficiency (>70%), large-format (>2k x 2k) detectors for operation at 100-400nm or broader.	Future NASA UV missions, particularly those devoted to spectroscopy, require high quantum efficiency (>50%), low noise (<1e-7 ct/pixel/s), large-format (>2k x 2k) photon-counting detectors for operation at 100-400nm or broader	High reflectivity, highly uniform UV coatings are required to support the next generation of UV missions, including explorers, medium missions, and a UV/optical large mission. High reflectivity coatings allow multiple reflections, extended bandpasses, and accommodate combined UV and high-contrast exoplanet imaging objectives.	Future UV/Optical telescopes will require increasingly large apertures to answer the questions raised by HST, JWST, Planck and Hershel, and to complement the ≥ 30-m ground-based telescopes that will be coming on line in the next decade. For diffraction limited performance, the pointing budget gets tighter as aperture grows and wavelengths shrink, requiring $\theta \sim 0.1\ \lambda/D$ pointing accuracy. Technologies are therefore required that provide a high degree of thermal and dynamic stability, and wave front sensing and control	Future UV/Optical telescopes will require increasingly large apertures to answer the questions raised by HST, JWST, Planck and Hershel, and to complement the ≥ 30-m ground-based telescopes that will be coming on line in the next decade. For diffraction limited performance, the pointing budget gets tighter as aperture grows and wavelengths shrink, requiring $\theta \sim 0.1\ \lambda/D$ pointing accuracy. Technologies are therefore required that provide a high degree of thermal and dynamic stability, and wave front sensing and control	Future NASA Optical/near-IR missions require large format detector arrays mosaicable in formats of ~Gpix, covering wavelengths from the optical to 1.7µm.
TABS category	8.1.1	8.1.1	8.1.3	8.1.3	8.1.3	8.1.1
Goals and Objectives	The goal is to produce large-format, high QE, low-noise UV-sensitive detectors routinely that can be employed in a variety of explorer, medium, and strategic missions.	The goal is to produce large-format, high QE, low-noise UV-sensitive detectors routinely that can be employed in a variety of explorer, medium, and strategic missions.	Development of UV coatings with high reflectivity (>90-95%), high uniformity (<1-0.1%), and wide bandpasses (~100 nm to 300-1000 nm). New coating technologies such as Atomic Layer Deposition are particularly promising. Some will be required for large optics (0.5-4m), many for smaller instrument optical elements.	Develop lightweight UV and optical mirrors with Areal density <20kg/m2, surface roughness 5 to 10 nm rms, cost <\$2M/m2, for telescopes with ~50 m2 aperture,<1 mas pointing accuracy, and < 15 nm rms stability	Develop deployable lightweight UV and optical mirror architectures with areal density <20kg/m2, surface roughness 5 to 10 nm rms, for telescopes with > 100 m2 aperture,<1 mas pointing accuracy, and < 15 nm rms stability	Develop high QE, low noise optical/IR arrays that can produce focal planes of a gigapixel.
TRL	Silicon-CCD detectors are TRL4-5. Other technologies (MCP, APD) are TRL2-4.	Silicon-CCD detectors are TRL4-5. Other technologies (MCP, APD) are TRL2-4.	Depending on the coating and approach these range from TRL3-5.	Lightweight 1.3-m Be and SiC mirrors are TRL 6. Borosilicate glass mirrors are TRL 5. Larger mirrors are TRL 2-3	Lightweight 1.3-m Be and SiC mirrors are TRL 6. Borosilicate glass mirrors are TRL 5. Larger mirrors are TRL 2-3	CCDs and HgCdTe arrays in megapixel formats are TRL >6.
Tipping point (100 words or less)	TRL6 with Si-CCD detectors can be achieved in ≈2 years with modest funding investment; in APDs later.	TRL6 with APDs detectors can be achieved in ≈3 years with moderate funding investment.	Relatively modest investment can determine the best approaches and scalability of various coatings and coating techniques.	One or more mirror technologies can be matured to meet requirements with reasonable investments in 3-5 years.	One or more mirror technologies can be matured to meet requirements with reasonable investments in 3-5 years.	Credible path to gigapixel imager can be achieved in ≈2 years with very modest funding investment with an industry partner.

Table 7. *COR Technology Needs for Technologies 1-6 (Page 1 of 3).*

COR Techology Needs Table

Name of technology	High QE, large format UV detectors	Photon counting UV large-format detectors	UV coatings	Large, low-cost, light-weight precision mirrors for Ultra-Stable Large Aperture UV/Optical Telescopes	Deployable light-weight precision mirrors for future Very Large Aperture UV/Optical Telescopes	Very large format, low noise Optical/IR detector arrays
NASA capability (100 words of less)	NASA is partnering with industry to produce these detectors.	NASA is partnering with industry to produce these detectors.	NASA has capabilities for UV coatings at GSFC and JPL to ~10 cm for ALD coating development. Large optics will require more significant investments. NASA-private industry partnerships are possible and likely particular for matured coating techniques.	NASA has the necessary capabilities at GSFC, MSFC and JPL to develop these UV/Optical mirror technologies in partnership with industry	NASA has the necessary capabilities at GSFC, MSFC and JPL to develop these UV/Optical mirror technologies in partnership with industry	NASA has partnered with industry to produce these detectors.
Benefit	High performance detectors can increase the science impact of missions by 10-1000.	High performance detectors can increase the science impact of missions by 10-1000.	High coating reflectivity in UV make possible high-performance optical systems that can be highly-multiplexed, significantly increasing the potential impact of future missions High uniformity will allow a combined general UV/ optical and exoplanet imaging mission, which could provide a natural follow-on to JWST.	Low-cost, light-weight optics are required to enable the development of large aperture UV / Optical telescopes in the 2020 decade. Large aperture telescopes are required to provide the spatial resolution and sensitivity needed to follow up on discoveries with the current generation of space telescopes.	Low-cost, ultra-light-weight optics are required to enable the development of very large aperture UV / Optical telescopes in the 2030+ decades. Large aperture telescopes are required to provide the spatial resolution and sensitivity needed to follow up on discoveries with the next generation of space telescopes.	Future missions with large area imaging or multiobject spectroscopic drivers operate ~100 times faster than present.
NASA Needs	Current MCP-based UV detectors obtain ~5-20% QE, require high voltage, and can be difficult to fabricate. The science impact of cost-constrained, aperture-constrained future missions is dramatically improved by reaching near-perfect detector performance. 2010 Astro Decadal survey noted importance of technology development for a future 4-m class UV/optical mission for spectroscopy and imaging. Benefits will also accrue to Planetary, Heliospheric, and Earth missions in the UV band.	Current UV detectors obtain ~5-20% QE, require high voltage, and can be difficult to fabricate. The science impact of cost-constrained, aperture-constrained future missions is dramatically improved by reaching near-perfect detector performance. 2010 Astro Decadal survey noted importance of technology development for a future 4-m class UV/optical mission for spectroscopy and imaging. Benefits will also accrue to Planetary, Heliospheric, and Earth missions in the UV band.	2010 Astro Decadal survey noted importance of technology development for a future 4-m class UV/ optical mission for spectroscopy and imaging. Benefits will accrue to Planetary, Heliospheric, and Earth missions utilizing the UV band.	This technology is a key enabling technology for NASA's next large UV/ Optical mission.	This technology is a key enabling technology for a far future very large UV/ Optical mission.	This technology is a key technology of benefit for NASA's next large UV/ Optical mission.

Table 7. *COR Technology Needs for Technologies 1-6 (Page 2 of 3).*

COR Techology Needs Table

Name of technology	**High QE, large format UV detectors**	**Photon counting UV large-format detectors**	**UV coatings**	**Large, low-cost, light-weight precision mirrors for Ultra-Stable Large Aperture UV/Optical Telescopes**	**Deployable light-weight precision mirrors for future Very Large Aperture UV/Optical Telescopes**	**Very large format, low noise Optical/IR detector arrays**
Non-NASA but aerospace needs	High performance UV detectors can have numerous aerospace applications, remote-sensing, situational awareness, etc.	High performance UV detectors can have numerous aerospace applications, remote-sensing, situational awareness, etc.	UV sensors require high-performance optical systems that benefit greatly from UV coating improvements.	This technology is critically important for many remote sensing missions sponsored by other government agencies	This technology may connect with many remote sensing missions sponsored by other government agencies	High performance optical/IR detector mosaics can have numerous aerospace applications, remote-sensing, situational awareness, etc.
Non-aerospace needs	High performance UV detectors may have applications in bio and medical imaging.	High performance UV detectors may have applications in bio and medical imaging.	Unknown but could be important.	Ground based, airborne, balloon and sounding rocket telescopes could all benefit from this technology	Unknown but could be important.	High performance optical/IR detectors may have applications in bio and medical imaging.
Technical risk	Technical risk of Si-CCD detectors is low-moderate because of prior investments in Si detector and CCD processing.	Technical risk of Si-CCD detectors is low-moderate because of prior investments in Si detector and CCD processing.	Technical risk is low-moderate. Facilities and techniques exist for small optical elements. Moderate risk in scaling to large optics.	Technical risk is moderate because the development effort is an extension of activities currently planned or underway at several government, academic and industrial facilities	Technical risk is moderate because the development effort is an extension of activities currently planned or underway at several government, academic and industrial facilities	Technical risk is low, as basic technology is mature.
Sequencing/ timing	Should come as early as possible since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.	Should come as early as possible since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.	Should come as early as possible since mission definition and capabilities are built around coating performance. There is a clear plan to achieve this technology. Users identified.	Should come as early as possible since technology is applicable to small, medium and large missions. By 2020 for the next large UV astrophysics mission.	Must follow developments for near-term lightweight mirror segments. By 2030 for the far future large UV astrophysics mission.	Should come early since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.
Time and effort	5 year collaboration between NASA, university groups, and industry.	5 year collaboration between NASA, university groups, and industry.	5 year collaboration between NASA, university groups, and industry.	5 year collaboration between NASA, university groups, and industry.	5 year collaboration between NASA, university groups, and industry.	3 year collaboration between NASA, industry, and other government agencies.

Table 7. *COR Technology Needs for Technologies (Page 3 of 3).*

COR Techology Needs Table

Name of technology	Photon counting Optical/IR detector arrays	Large format, low noise Far-IR direct detectors	Ultralow-noise Far-IR direct detectors	Large, cryogenic far-IR telescopes	Interferometry for far-IR telescopes	Sub-Kelvin Coolers
Brief description (1024)	Future NASA Optical/near-IR missions require high QE, fast response time photon counting detector arrays to cover the optical and near-infrared.	Future NASA Far-IR missions require large format detectors optimized for the very low photon backgrounds present in space. Arrays containing up to tens of thousands of pixels are needed to take full advantage of the focal plane available on a large, cryogenic telescope. Detector sensitivity is required to achieve background-limited performance, using direct (incoherent) detectors to avoid quantum-limited sensitivity.	Future NASA Far-IR missions require detectors optimized for the very low photon backgrounds present in space for spectroscopy. Arrays containing up to thousands of pixels are needed to take full advantage of the spectral information content available. Detector sensitivity is required to achieve background-limited performance, using direct (incoherent) detectors to avoid quantum-limited sensitivity.	Large telescopes provide both light gathering power, to see the faintest targets, and spatial resolution, to see the most detail and reduce source confusion. To achieve the ultimate sensitivity, their emission must be minimized, which requires that these telescopes be operated at temperatures that, depending on the application, have to be as low as 4K. Collecting areas on the order of 10m are needed.	Interferometry in the far-IR provides spatial resolution to see the most detail and reduce source confusion. Structurally-connect or free-flying Interferometric telescope systems are required for far-future missions in the far-IR. Telescopes are operated at temperatures that have to be as low as 4K.	Optics and detectors for far-IR and certain X-ray missions require very low temperatures of operation, typically well below 1K. Compact, low-power, lightweight coolers suitable for space flight are needed to provide this cooling.
TABS category	8.1.1	8.1.1	8.1.1	8.1.3	8.1.3	8.1.3
Goals and Objectives	Develop high QE photon counting detectors for wavelengths of around 400nm-1.7μm.	Detector format of at least 32x32 with high filling factor and with sensitivities (noise equivalent powers) of 10^{-19} W/√Hz are needed for photometry.	Detector sensitivities with noise equivalent powers of $\approx 3 \times 10^{-21}$ W/√Hz are needed for spectroscopy, arrayable in a close-packed configuration in at least one direction.	The goal is to develop a feasible and affordable approach to producing a 10m-class telescope with sufficiently high specific stiffness, strength, and low areal density to be launched, while maintaining compatibility with cryogenic cooling and far-IR surface quality/figure of ~1μm RMS.	The goal is to develop a feasible and affordable approach to producing a 40m-class interferometer capable of launch and operation, while maintaining compatibility with cryogenic cooling and far-IR surface quality/figure of ~1μm RMS.	A cryocooler operating from a base temperature of ~4K and cooling to <0.1K with a continuous heat lift of 10μW is required for several mission concepts. Features such as compactness, low power, low vibration, intermediate cooling and other impact-reducing design aspects are desired.
TRL	APDs for the near-IR are under development in industry, but are low TRL (~2).	Single detectors are at ~TRL5, but demonstrated array architectures are lagging at ~TRL3.	Single detectors are approaching TRL3.	JWST Be mirror segments may meet requirements now, so TRL5 with an extremely expensive technology; TRL3 exists for other materials.	Interferometry demonstrated at visible wavelengths in labs; far-IR interferometry on a balloon expected in ~4 years. TRL~3.	Existing magnetic refrigeration demonstrations have achieved TRL3-4.
Tipping point (100 words or less)	TRL6 will be achieved via substantial military investments, but optimization for low-background purposes could be a modest NASA effort.	TRL5 with transition edge sensors could be achieved within 3 years with moderate investment; with MKIDs within 4-5 years.	TRL4-5 with transition edge sensors could be achieved within 3 years with moderate investment; with MKIDs within 4-5 years.	TRL4 could be achieved within 3 years with modest investments using existing materials.	TRL5 could be achieved within 5 years with moderate investments building on existing efforts.	TRL5 could be achieved within 3 years with modest investments based on existing demonstration.
NASA capability (100 words or less)	NASA will likely have to partner with industry to produce these detectors.	NASA has laboratory fabrication facilities at GSFC and JPL currently working at a low level on these technologies.	NASA has laboratory fabrication facilities at GSFC and JPL currently working at a low level on these technologies.	NASA has cryogenic mirror testing capabilities at GSFC, MSFC, and JPL; mirror production would likely rely on industry partnerships.	NASA has performed cryogenic Interferometric testbed work.	NASA has cryogenic refrigerator fabrication and testing capabilities at GSFC, with some relevant experience at JPL.

Table 8. *COR Technology Needs for Technologies 7-12 (Page 1 of 3).*

COR Techology Needs Table

Name of technology	Photon counting Optical/IR detector arrays	Large format, low noise Far-IR direct detectors	Ultralow-noise Far-IR direct detectors	Large, cryogenic far-IR telescopes	Interferometry for far-IR telescopes	Sub-Kelvin Coolers
Benefit	Future missions with spectroscopic drivers operate ~100 times faster than present. Distant missions (beyond the Zodiacal dust cloud) will observe significantly (>10x) faster even in imaging applications.	Sensitivity reduces observing times from many hours to a few minutes (≈100x improvement), while array format increases areal coverage by a 10x-100x. Overall mapping speed can increase by factors of thousands.	Sensitivity reduces observing times from many hours to a few minutes (≈100x improvement). Overall observing speed can increase by factors of thousands.	Low-cost, light-weight cryogenic optics are required to enable the development of large aperture far-IR telescopes in the 2020 decade. Large apertures are required to provide the spatial resolution and sensitivity needed to follow up on discoveries with the current generation of space telescopes.	Large baselines are required to provide the spatial resolution needed to follow up on discoveries with the next generation of space telescopes.	Sub-Kelvin cryocoolers are required to enable the use of far-IR telescopes in the next decade, and are similarly necessary for certain X-ray detectors.
NASA Needs	This technology is a key technology of benefit for NASA's next large UV/Optical/IR mission.	Far-IR detector technology is an enabling aspect of all future far-IR mission concepts, and is essential for future progress. This technology can improve science capability at a fixed cost much more rapidly than larger telescope sizes. However, the development serves Astrophysics almost exclusively (with some impact to Planetary and Earth studies).	Far-IR detector technology is an enabling aspect of all future far-IR mission concepts, and is essential for future progress. This technology can improve science capability at a fixed cost much more rapidly than larger telescope sizes. However, the development serves Astrophysics almost exclusively (with some impact to Planetary and Earth studies).	This technology is a key enabling technology for any future NASA-built far-IR mission.	This technology is a key enabling technology for a far future NASA-built far-IR mission.	This technology is a key enabling technology for any future NASA-built far-IR mission.
Non-NASA but aerospace needs	High performance optical/IR photon counting detectors have numerous aerospace applications, remote-sensing, situational awareness, etc.	This technology is primarily needed and supported by NASA.	This technology is primarily needed and supported by NASA.	Lightweight telescopes are critically important for remote sensing applications.	Unknown but could be important.	This technology is primarily needed and supported by NASA.
Non-aerospace needs	High performance optical/IR photon counting detectors may have applications in bio and medical imaging.	Large format arrays are needed by suborbital astrophysics missions, and similar technologies find application in airport screening devices for DHS.	Unknown but could be important.	Ground based, airborne, balloon and sounding rocket telescopes could all benefit from this technology	Unknown but could be important.	Ground based, airborne, balloon and sounding rocket telescopes could all benefit from this technology; other laboratory needs could be fulfilled with commercialization.

Table 8. *COR Technology Needs for Technologies 7-12 (Page 2 of 3).*

COR Techology Needs Table

Name of technology	Photon counting Optical/IR detector arrays	Large format, low noise Far-IR direct detectors	Ultralow-noise Far-IR direct detectors	Large, cryogenic far-IR telescopes	Interferometry for far-IR telescopes	Sub-Kelvin Coolers
Technical risk	Technical risk is moderate, as basic technology has significant prior investment.	Technical risk for individual detectors is low, as the approach is relatively mature. Large format array technologies include integrated readout devices, which have moderate development risk.	Technical risk for individual detectors is low, as the approach is relatively mature. Large format array technologies include integrated readout devices, which have moderate development risk.	Technical risk is low, as development of many other mirror materials leverages large existing investments in industry; NASA needs in the near term can be demonstrated by testing existing technologies.	Technical risk is moderate, as maturity is lacking.	Technical risk is low, as development leverages previous investments at NASA.
Sequencing/timing	Should come early since mission definition and capabilities are built around detector performance.	Should come as early as possible since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.	Should come as early as possible since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.	Should come as early as possible since technology is applicable to small, medium and large missions. By 2020 for the next large far-IR astrophysics mission.	Must follow further results from prototype efforts. Underway by 2020 for the next large far-IR astrophysics mission.	Would be beneficial to undertake soon since technology is applicable to small, medium and large missions. By 2020 for the next large far-IR astrophysics mission.
Time and effort	5 year collaboration between NASA, industry, and other government agencies.	3 year collaboration between NASA, university groups, and other government agencies.	3 year collaboration between NASA, university groups, and other government agencies.	3 year collaboration between NASA and industry.	5 year collaboration between NASA and industry.	3 year effort at NASA.

Table 8. *COR Technology Needs for Technologies 7-12 (Page 3 of 3).*

SECTION 4.0 PROGRAM TECHNOLOGY PRIORITIZATION AND RECOMMENDATIONS

The technology needs table discussed in Section 3 provides a starting point for the next step in the process, which is to prioritize the needs according to a set of evaluation criteria. This prioritization is published each year in the PATR. This PATR summarizes the results of the TMB prioritization of the technology needs identified by the community. The COR program of the Astrophysics Division will use the information in this PATR as input over the following year as the calls for technology proposals (e.g., Strategic Astrophysics Technologies) are drafted.

The TMB was established to prioritize technology needs from the inputs provided by the community. Membership of the TMB includes senior members of the Astrophysics Division at NASA Headquarters, the COR Program Office, subject matter experts, consultants, and internal/external personnel as needed.

In order to prioritize the needs of these technologies, the Board developed a set of evaluation criteria that consists of 11 categories. These categories address the strategic alignment, benefits and impacts, risk reduction, timeliness, and effectiveness of each technology. The evaluation criteria are shown in Table 9.

For each criterion, a weight is assigned that is intended to reflect the importance that the COR program places on that criterion. These weights may be adjusted from year to year to reflect the changing needs of the Program. Each criterion receives a score of 0 to 4 in the evaluation. The score is multiplied by the established weight for the criterion, and this product is summed across all categories for each technology.

The 11 categories are described below, providing rationale and intent.

1. **Scientific ranking of applicable mission concept:** The intent is that a mission ranked highly by a major review process should receive a higher score for its related technologies. The NWNH report is the main source of the ranking for this year, although, in some cases, specific community-based reviews, other peer reviews, or a programmatic assessment may also be considered.

2. **Overall relevance to applicable mission concept:** If a technology is tied to a mission concept and it is key to that concept, then its score should be higher than for a technology that is of only minor importance to the mission concept. This category may be somewhat redundant with some of the more specific categories below, but this allows for capturing any unanticipated aspects of mission applicability.

3. **Scope of applicability:** If a technology is generally useful to many missions, it is scored higher. For example, some cases like optics or detector technologies clearly span more than one mission, whereas an ultra-high-precision timekeeping technology may have only limited applicability.

4. **Time to anticipated need:** If a mission concept is not planned for implementation for a long time, its technologies should receive a lower score than more immediate needs.

5. **Scientific impact:** If a technology improves the scientific return from a mission, then it should be scored higher. If it is absolutely required for the mission to be successful, it is scored highest.

6. **Implementation impact:** If a technology increases mission implementation efficiency or reduces the need for critical resources, then it should be scored higher.

7. **Schedule impact:** If a technology drives mission schedule, then it should receive a higher score for development. The intent is that this will help focus resources during technology development in areas where a technology is perceived to be able to contribute to schedule cost growth during mission implementation.

8. **Risk reduction:** If a technology reduces mission risk compared to the baseline mission concept, then it is scored higher. If the technology is already in the mission concept baseline, then it has no additional risk reduction benefits.

9. **Definition of required technology:** If the required technology is well defined and described, then it is scored higher than vague or inconsistent statements of need. This category again provides motivation for clarity in the identification phase.

10. **Other sources of funding:** A technology that is likely to receive funding from other sources should be scored lower than one that has no other potential sponsors. This includes other U.S. agencies and commercial and foreign investments, where they are known. The intent is to focus resources in those areas that need them the most.

11. **Availability of providers:** If there are few providers or a single provider, then the score should be higher to maintain this capability as well as to provide resources to potentially enable developing additional providers.

#	Criterion	Weight	Score (0-4)	Weighted Score	General Description/Question	4	3	2	1	0
1	Scientific Ranking of Applicable Mission Concept	4	4	16	Scientific priority as determined by the Decadal Review, other community-based review, other peer review, or programmatic assessment. Captures the importance of the mission concept which will benefit from the technology.	Highest ranking	Medium rank	Low rank	Ranking not known	No clear applicable mission concept
2	Overall Relevance to Applicable Mission Concept	4	4	16	Impact of the technology on the applicable mission concept. Captures the overall importance of the technology to the mission concept.	Critical key enabling technology - required to meet mission concept goals	Highly desirable technology - reduces need for critical resources and/or required to meet secondary mission concept goals	Desirable-offers significant benefits but not required for mission success	Minor implementation improvements	Unknown
3	Scope of Applicability	3	4	12	How many mission concepts could benefit from this technology? The larger the number, the greater the reward from a successful development.	The technology applies to multiple mission concepts across multiple agencies	The technology applies to multiple mission concepts across multiple NASA programs	The technology applies to multiple mission concepts within a single NASA program	The technology applies to a single mission concept	Unknown
4	Time To Anticipated Need	3	4	12	How much time is available before the technology is needed to be at TRL6?	4 to 8 years (this decade)	9 to 14 years (early 2020s)	15 to 20 years (late 2020s)	Greater than 20 years (2030s)	Unknown
5	Scientific Impact to Applicable Mission Concept	2	4	8	Impact of the technology on the scientific harvest of the applicable mission concept. How much does this technology affect the scientific harvest of the mission?	Needed for baseline	Major improvement (> ~2x) to primary scientific goals	Only enables secondary scientific goals	No scientific improvements	Unknown
6	Implementation Impact to Applicable Mission Concept	2	4	8	Impact of the technology on the implementation efficiency of the applicable mission concept. How much does this technology simplify the implementation or reduce the need for critical resources?	Needed for baseline	Enables major savings in critical resources (e.g., smaller launch vehicle, longer mission lifetime, smaller spacecraft bus, etc.) or reduces a major risk	Enables minor savings in critical resources or reduces a minor risk	No implementation improvements	Unknown
7	Schedule Impact to Applicable Mission Concept	2	4	8	Impact of the technology on the schedule of the applicable mission concept. How much does this technology simplify the implementation to bring in the schedule?	Technology drives the mission concept critical path	Technology drives the critical path for a key component	Technology drives the critical path for a minor component	Technology is not likely to be on critical path	Unknown
8	Risk Reduction to Applicable Mission Concept Baseline	2	4	8	Impact of the technology on the risk of the applicable mission concept. How much does this technology reduce the risk?	Major mission concept risks directly mitigated by this technology, workarounds not currently known	Major mission concept risks directly mitigated by this technology, workarounds currently known	Minor mission concept risks mitigated by this techology	No risk benefits or technology is already in mission concept baseline	Unknown
9	Definition of Required Technology	1	4	4	How well defined is the required technology? Is there a clear description of what is sought?	Exquisitely defined	Well defined, but some vagueness	Well defined, but some conflicting goals not clarified	Not well defined, lacking in clarity	Poorly defined, not clear at all what is being described
10	Other Sources of Funding	1	4	4	Are there other sources of funding to mature this technology? If funding is expected to be available from other sources, this will lower the prioritization.	No, the Program is the only viable source of funding.	Interest from other sources can be developed during the development time of the technology	Interest from other sources is likely during the development time of the technology	Already being developed by other programs, agencies, or countries.	Unknown
11	Availability of Providers	1	4	4	Are there credible providers/developers of this technology? Where providers are scarce, there may be a compelling need to maintain continuity for the technology in the event there are no replacement technologies.	Single competent and credible provider/developer known	Two competent and credible providers/developers known	Multiple competent and credible providers/developers known	Providers/developers known but no assurance of competence or credibility	Unknown
	Total Possible Score:			100						

Table 9. *Evaluation Criteria for Technology Prioritization*

The TMB completed the evaluation process for each of the 12 technology needs. The Board analyzed the rankings to assure that the final results reflect the current strategic thinking and the COR programmatic environment. The technology rankings are then categorized into three priority groups. Technologies within any single group are ranked equally.

Priority 1: Contains technology activities that the Board has determined to be of the highest interest to the Cosmic Origins program and recommends that they ***should*** be invested in first, when funding is available. This priority level consists of technologies in the following areas:

- High-QE, large-format UV detectors – Future NASA UV missions require high-QE (>70%), large-format (>2k × 2k) detectors for operation at 100–400 nm or broader. The goal is to produce large-format, high-QE, low-noise UV-sensitive detectors routinely that can be employed in a variety of suborbital, Explorer, medium-class, and strategic missions.

- Photon-counting, large-format UV detectors – Future NASA UV missions, particularly those devoted to spectroscopy, require high-QE (>50%), low-noise ($<10^{-7}$ ct/pixel/s), large-format (>2k × 2k) photon-counting detectors for operation at 100–400 nm or broader.

- UV coatings – Development of UV coatings with high reflectivity, high uniformity, and wide bandpasses, ideally operating from the visible to wavelengths below 100 nm.

- Ultra-low-noise far-IR direct detectors – Future NASA far-IR missions require detectors optimized for the very low photon backgrounds present in space for spectroscopy at wavelengths between ~30 µm and ~300 µm. Detectors' sensitivities with noise-equivalent powers of $\approx 3 \times 10^{-21}$ W/√Hz are needed for spectroscopy, arrayable in a close-packed configuration in at least one direction.

Priority 2: Contains technology activities that the Board feels are worthy of pursuit and ***would*** be invested in, if funding allows. Priority 2 technologies include:

- Large, low-cost, lightweight, precision mirrors for ultra-stable large-aperture UV/optical telescopes in ≈4m-class sizes
- Deployable, lightweight, precision mirrors for future very-large-aperture UV/optical telescopes
- Large-format, low-noise far-IR direct detectors
- Sub-Kelvin cryocoolers

Priority 3: Contains technologies that are deemed to be supportive of COR objectives but, for various reasons, do not warrant investment at the present, although they ***could*** be invested in, if significant additional funding is available. Priority 3 technologies include:

- Photon-counting optical/IR detector arrays
- Large, cryogenic far-IR telescopes
- Very-large-format, low-noise optical/IR detector arrays
- Interferometry for far-IR telescopes

SECTION 5.0 CLOSING REMARKS

This Cosmic Origins 2011 Program Annual Technology Report serves as the first snapshot of the state of technology development under the COR Program Office and future directions for technology maturation. The PATR captures the technology needs as identified by the COPAG, which are based on community input for science drivers and technology opportunities. The Technology Management Board established rankings for the technology needs. The priorities are intended to serve as the recommendation from the COR Program Office to NASA HQ for resultant future technology investments to serve program goals optimally.

This report will be produced annually and will reflect the continuing changes in the landscape of scientific needs and their requisite technologies, incorporating novel developments to allow for the dynamic nature of the field. The COR Program Office annual activities, leading to the release of the PATR, provide a continuity of overall vision and process for strategic purposes, while retaining the flexibility to adapt tactically to new opportunities. Over time, this report will track the status of all technologies being matured to serve Program goals and will identify the next generations of technologies yet to be developed.

The Program Office will continue to interact with the broad scientific community—through the COPAG, workshops, public conferences, and public outreach activities—to identify and incorporate the community's ideas about new science and new technology needs in a sustained process. The Cosmic Origins Program Office welcomes continued input from the community in developing the 2012 Program Annual Technology Report.

We welcome community feedback. For more information about the Cosmic Origins Program, or to provide community feedback to NASA or through the COPAG, please visit: http://cor.gsfc.nasa.gov/copag.

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6.0 ACRONYMS

ACT	*Atacama Cosmology Telescope*
ACTO	Advanced Concepts and Technology Office
ALD	Atomic Layer Deposition
ALMA	Atacama Large Millimeter/submillimeter Array
AO	Announcement of Opportunity
APRA	Astronomy and Physics Research and Analysis
ATLAST	*Advanced Technology Large Area Space Telescope*
BETTII	*Balloon Experimental Twin Telescope for Infrared Interferometry*
BUG	Backshort Under Grid
CALISTO	*Cryogenic Aperture Large Infrared Space Telescope Observatory*
CCAT	*Cerro Chajnantor Atacama Telescope*
CCD	Charge-Coupled Device
CMOS	Complementary Metal-Oxide Semiconductor
COPAG	Cosmic Origins Program Analysis Group
COR	Cosmic Origins
COS	Cosmic Origins Spectrograph
CPW	Co-Planar Waveguide
CTE	Charge Transfer Efficiency
EBCCD	Electron-Bombarded Charge-Coupled Device
EBCMOS	Electron-Bombarded CMOS
EOS	Electromagnetic Observations from Space
ESA	European Space Agency
EUVE	*Extreme Ultraviolet Explorer*
FACA	Federal Advisory Committee Act
Far-IR	Far Infrared
FUSE	*Far Ultraviolet Spectroscopic Explorer*
FUV	Far Ultraviolet
FY	Fiscal Year
GISMO	Goddard IRAM Superconducting 2-Millimeter Observer
GSFC	Goddard Space Flight Center
HEB	Hot-Electron Bolometer
HIFI	Heterodyne Instrument for the Far Infrared
HQ	Headquarters
HST	*Hubble Space Telescope*
IF	Intermediate Frequency
IMAPS	Interstellar Medium Absorption Profile Spectrograph
IR	Infrared
IRAD	Internal Research and Development
IRAM	Institut de Radioastronomie Millimétrique
ISAS	Institute of Space and Astronautical Science
ISM	Interstellar Medium
JAXA	Japanese Aerospace Exploration Agency
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
JWST	*James Webb Space Telescope*

KDP-I	Key Decision Point I
LMT	Large Millimeter Telescope
LO	Local Oscillator
MAMA	Multi-Anode Microchannel Array
MCP	Micro-Channel Plate
MSPU	Moscow State Pedagogical University
MUSTANG	Multiplexed SQUID TES Array at Ninety Gigahertz
NASA	National Aeronautical and Space Administration
NEP	Noise-Equivalent Power
NIST	National Institute of Standards and Technology
NRC	National Research Council
NUV	Near Ultraviolet
NWNH	New Worlds New Horizons
NWO	New Worlds Observatory
PACS	Photodetector Array Camera and Spectrometer
PATR	Program Annual Technology Report
PCOS	Physics of the Cosmos
PI	Principal Investigator
PIPER	Primordial Inflation Polarization Explorer
PO	Program Office
QE	Quantum Efficiency
RF	Radio Frequency
RFE	Receiver Front Ends
rms	Root Mean Square
ROSES	Research Opportunities in Space and Earth Science
SAFIR	*Single Aperture Far Infrared Observatory*
SALMON	Stand Alone Missions of Opportunity Notice
SAT	Strategic Astrophysics Technology
SCUBA	Submillimetre Common-User Bolometer Array
SDR	System Definition Review
SNR	Signal-to-Noise Ratio
SOHO	Solar and Heliospheric Observatory
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPICA	Space Infrared Telescope for Cosmology and Astrophysics
SPIRE	Spectral and Photometric Imaging Receiver
SPIRIT	*Space Infrared Interferometric Telescope*
SQUID	Superconducting Quantum Interference Device
SR&T	Supporting Research and Technology
SSB	Single Sideband
TABS	Technology Area Breakdown Structures
TES	Transition Edge Sensor
THEIA	*Telescope for Habitable Exoplanets and Interstellar/intergalactic Astronomy*
TMB	Technology Management Board
TRL	Technology Readiness Level
TWV	Through-Wafer Via
UHV	Ultra-High Vacuum
ULIRG	Ultra-Luminous Infrared Galaxy
UV	Ultraviolet
UVOIR	Ultraviolet/optical/infrared
WAV	Wrap-Around Via

Chemical Elements

AlGaN	Aluminum Gallium Nitride
Al/MgF_2	Aluminum/Magnesium Fluoride
^{241}Am	Americium-241
CII	Singly Ionized Carbon
CH	Methylidyne Radical
CO	Carbon Monoxide
CsI	Cesium Iodide
CsTe	Cesium Telluride
GaAs	Gallium Arsenide
GaN	Gallium Nitride
HD	Deuterated Hydrogen
HeH+	Protonated Helium
KBr	Potassium Bromide
LiF	Lithium Fluoride
MgF_2	Magnesium Fluoride
NII	Nitrogen II
NbN	Niobium Nitride
OI	Neutral Atomic Oxygen
OVI	Quintuply Ionized Oxygen
Si	Silicon
TiN	Titanium Nitride
ZnMgO	Zinc Magnesium Oxide

Units

C	Celsius
GHz	Gigahertz
Hz	Hertz
k	Kilo, or Thousand
K	Kelvin
keV	Kiloelectronvolt
km	Kilometers
kV	Kilovolt
λ	Wavelength
mm	Millimeters
mW	Milliwatts
nH	Nanohenries
nm	Nanometers
µm	Micrometers, or Microns
s	Seconds
THz	Terrahertz

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