Future Focal Plane Technology Challenges for NASA's Origins Missions

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ABSTRACT

Recent advances in astronomical research have led to a much-improved understanding of the evolution of the physical Universe. Recent advances in biology and genetics have led to a much-improved understanding of our biological Universe. Scientists now believe that we have the research tools to begin to answer one of man's two most compelling research questions: "are we alone?" and "how did we get here?" This paper reviews the requirements and challenges we face to engineer and build the large area and very sensitive focal planes for interferometers and innovative single aperture telescopes to detect and characterize Earth-type planets around stars other than our sun.

1. INTRODUCTION

Alan Dressler[1] reported the results of a three-year science study to identify the highest scientific priorities in the NASA Origins program. These questions are summarized below:

1. Emergence of the Modern Universe
    a. How did the cosmic web of matter organize into the first stars and planets?
    b. How do different galactic ecosystems (of stars and gas) form and which can lead to planets and living organisms?
2. Stars and Planets
    a. How do gas and dust become stars and planets?
    b. Are there planetary systems around other stars and how do their architectures and evolution compare with our own solar system?
3. Habitable Planets and Life
    a. What are the properties of giant planets orbiting other stars?
    b. How common are terrestrial planets?
    c. What are their properties?
    d. Which of them might be habitable?
    e. Is there life on planets outside the solar system?

2. SYSTEM VISIONS FOCUS COHERENT TECHNOLOGY PROGRAMS

The process NASA uses to focus a technology program creates a detailed system vision or model of the space astrophysics sensor system required to make a scientific measurement of critical importance. Iterating with experts creates the system vision.

The hardware and software aspects of this system vision are then analyzed to create technology development roadmaps for systems engineering, systems modeling, structures, focal planes, materials, and thermal and wavefront controls. These system visions are used to drive and focus technology programs. As the technology evolves, specific system visions change and subsystem requirements change. Vigorous science programs in parallel with the technology programs continuously clarify the science measurement objectives and balance the science within the framework of a system that can be built.

Technology and science are being developed for several science measurement vision systems. There are three approaches for the Terrestrial Planet Finder (TPF): the coronagraph, the connected interferometer, and the formation-flying interferometer. There are several approaches for the Terrestrial Planet Imager (TPI). Characteristic of the TPI are 100-m+ clear-aperture optical telescopes, large-area, low-noise focal planes, and a cold telescope. The Single Aperture Far-Infrared (SAFIR) observatory currently has two visions: A segmented telescope, not unlike the James Webb Space Telescope (JWST), and the very innovative dual anamorphic reflecting telescope (DART) design.

The list below shows the family of missions that enable the origins program.

1. Ground testbeds
    a. Keck Interferometer
    b. Large Binocular Telescope Interferometer (LBTI)
2. Flight testbeds
    a. Stratospheric Observatory for Infrared Astronomy (SOFIA)
3. Space-flight systems
    a. Hubble Space Telescope (HST), new instruments
    b. Space Infrared Telescope Facility (SIRTF)
    c. Space Interferometer Mission (SIM)
    d. JWST
4. System visions
    a. TPF Free Flyer
    b. TPF Connected Interferometer
    c. TPF Coronagraph
    d. SAFIR
    e. Life Finder
    f. TPI
5. Supporting advanced technologies
    a. Advanced mirror system demonstration (AMSD)
    b. Coronagraph test bed
    c. DART
    d. Coronagraph mirror
    e. Cryocoolers program

3. ENABLING TECHNOLOGIES

Technologies that will enable the astrophysical search for origins (ASO) are largely considered in two groupings:

1. Those technologies responsible for image brightness and acuity: tasks in the design and engineering of large mirrors, large stable structures, adaptive controlled optics, wavefront sensing, cryogenics, and super smooth mirrors for very-high-authority control of scattered light within the optical system. These technologies require knowledge in the technical disciplines of mechanics, radiative transfer, structures, dynamics, materials science, deployment, alignment, and optical aberration control.

2. Those technologies responsible for recording the image with the highest possible fidelity for the purpose of signal processing and scientific interpretation. These technologies require knowledge in photo-electronic processes in materials, radiative transfer, image processing, microelectronic fabrication, and cryogenics.

This paper focuses on the needs of the infrared focal plane scientific community to complete the goals of the Origins program.

4. INFRARED FOCAL PLANE DEVELOPMENTS

A team of NASA science and technology experts has been writing and rewriting a coherent science and technology road map during the past three years. This ORIGINS[1] roadmap outlines a program of science coupled with technology development, and space flight experiments to achieve the space astronomy and physics goals for the next 20 years.

The ORIGINS[1] roadmap defines detectors as "the single most important technology which determines the ultimate performance of our observatories." For the whole range of future Origins IR missions, spanning short- to long-wave IR wavelengths, imaging and spectroscopic observations, the achievement of advanced focal plane technologies will be critical, if we are to fully benefit from the inherent sensitivities being designed into future astronomical mission concepts. The general needs and development trends are toward longer IR wavelengths, where the technology is less mature, toward larger-format arrays of both direct and coherent detectors, and toward improved sensitivity[2]. The SOFIA system will provide a very useful platform for many cycles of early demonstration and optimization of promising focal plane technologies that could ultimately be applied in space-based telescopes. Furthermore, competed missions in NASA's Explorer and Discovery programs will directly benefit from advanced focal plane capabilities.

Present development efforts represent a clear technological progression, in terms of establishing important technological heritage and incremental advances essential to successful implementation of future missions. For example, the (<30 μm) IR detector-array capability established for SIRTF and HST has directly supported the advances in format and sensitivity achieved for the JWST (see Figure 1), and these in turn will provide an excellent foundation for arrays needed for more distant applications, such as the TPF and others. Also, early coherent receiver systems (e.g., those demonstrated on the Kuiper Airborne Observatory and the Submillimeter Wave Astronomy Satellite) feed into systems to be demonstrated on SOFIA and in space (Planck, Herschel, SAFIR, and beyond).

Technologically, a number of evolutionary—and also revolutionary—advances are being pursued, and ongoing support for these efforts is needed. The need for larger and larger formats (10^3–10^4 and higher[2]) can be met by advances in material growth capability (size and quality of detector substrates), but also through new approaches for close packing far-IR detector arrays of far-IR photoconductors and bolometers. Powerful detection mechanisms, like the physical mechanisms exploited in superconducting transition-edge bolometers and hot-electron bolometers[3] (see Figure 2), are being investigated to provide improved sensitivity and speed of response. Demonstration of improved photon-coupling schemes (e.g., close-packed integrating cones, or planar antenna structures) will help achieve the goal of large-format, large-fill-factor (ideally, "gapless") focal-plane arrays.

The Origins missions will also rely upon certain selected NASA-unique technologies that need to be preserved and improved to satisfy future requirements. Two examples[2] of these are the antimony-doped silicon (Si:Sb) impurity band conduction IR detector arrays which were developed for SIRTF and SOFIA applications. Also, specialized cryogenic CMOS readouts for low (<10 K) temperatures are extremely important for a range of applications in the IR and far-IR, and this becomes increasingly key as wavelengths of interest increase (and corresponding readout operating temperatures decrease).

For all focal plane systems, the need for improved readout technology is a recurring theme. The noise, multiplexing speed, and power dissipation of integral readouts are key development issues which frequently define overall focal-plane sensitivity. Major progress has been made recently in adapting superconducting quantum interference device (SQUID) readout technology to multiplexing configurations of bolometer arrays, with multiplexing implemented in either the frequency- or time-domain. Analogous improvements have demonstrated in heterodyne or coherent systems, where the supporting elements (local oscillator (LO), and back-end spectrometer) often provide limits to achieved performance. In particular, such systems need to improve key parameters like intermediate frequency bandwidth, frequency coverage (esp. in the 1–3 THz range), improving LO power and efficiency. Even for the more mature <40 μm extrinsic and intrinsic array technologies, continuing improvements in readouts are needed to reduce noise, leakage currents, and power dissipation and improve yields, so that technologies that more closely reach fundamental performance limits can be demonstrated.

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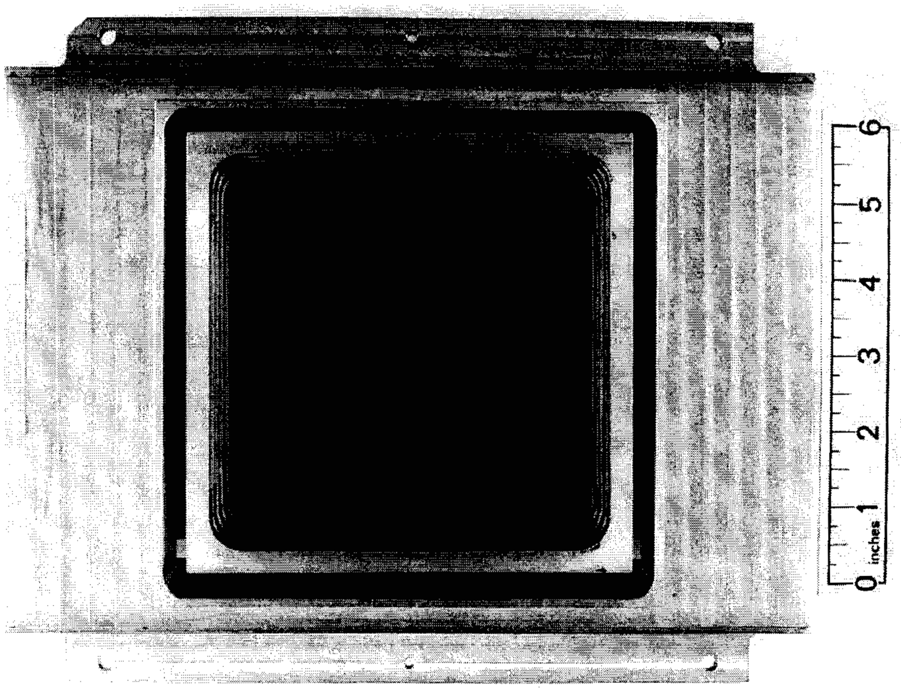

Figure 1. 4 k × 4 k pixel candidate JWST near-IR focal-plane array (four Raytheon SB-304 InSb arrays) (courtesy Raytheon Vision Systems)

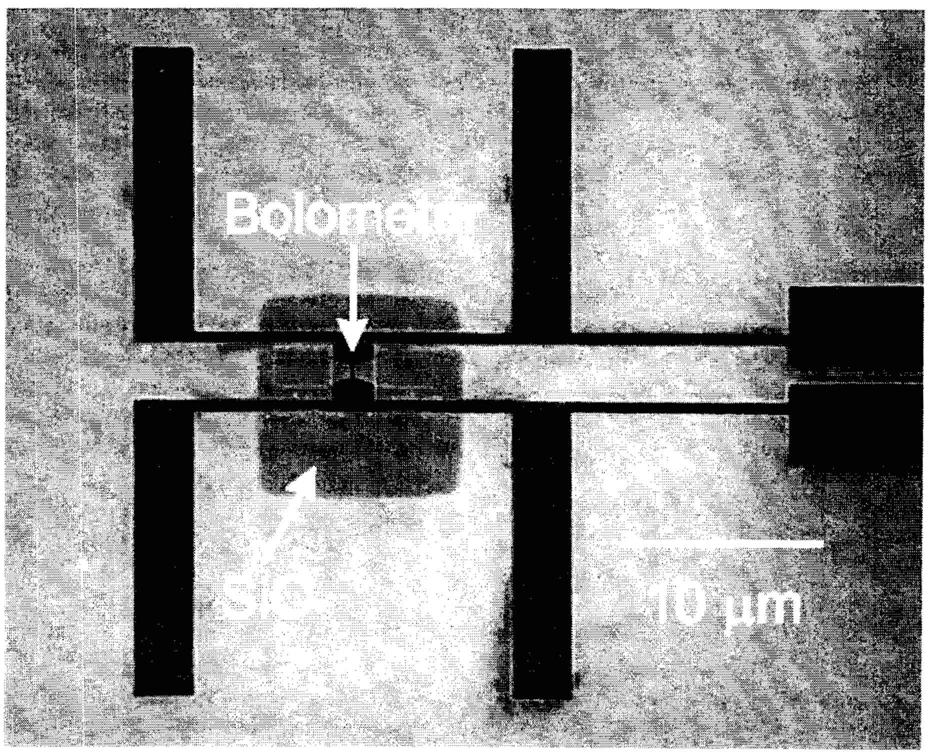

Figure 2. Microbridge hot-electron bolometer mixer designed to operate at frequencies as high as 2.5 THz. (courtesy JPL)

REFERENCES

1 A. Dressler et al., *Origins 2003: Roadmap for the Office of Space Science (NASA)*, JPL 400-1060 10/02 (http://origins.jpl.nasa.gov/library/scienceplan03/)

2 E. T. Young et al., "Detector Needs for Long Wavelength Astrophysics" *A Report by the NASA Infrared, Submillimeter, and Millimeter Detector Working Group*. June 2002. (http://sofia.arc.nasa.gov/det_workshop/report/report.html)

3 J. Wolf, J. Farhoomand and C. McCreight, eds., "Far-IR, Sub-mm, and Millimeter Detector Technology Workshop" NASA Conference Publication 211408. *Proceedings of April 2002 Detector Technology Workshop*, Monterey, CA. 2003.