Space-Based Applications of Far-Infrared Systems

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Abstract – **This paper discusses the applications of space-based far-infrared/terahertz sensors and systems. It also covers the needs and desires of scientists, discusses what has been done to date, and what is planned for the future.**

I. Introduction

As is the case in other spectral regions, astronomers and atmospheric scientists drive much of the cutting-edge technology development in the FIR. The dramatic attenuation of FIR radiation by water and other constituents of Earth's atmosphere forces many of the scientists' measurement platforms above the atmosphere, into space. Therefore, there is a strong correlation between the development of new FIR technology and the development of FIR spaceborne instrumentation.

Technologists working at microwave frequencies effectively utilize a "wave" and "electron" approach, while those working in the infrared effectively utilize a "particle" and "photon" approach. Unfortunately, given the state of technology today, neither approach is optimal for use in the FIR. With only marginal success, researchers toil diligently to stretch the boundaries of both wave and particle technologies to the FIR. The pessimist may complain about the state of FIR technology, but the optimist will note that this field is ripe for development, and possesses great potential for breakthrough discoveries.

Because there has been only minimal application of FIR technology in spacecraft to date, even the simplest FIR measurements offer great potential for breakthrough discoveries.

II. Far-Infrared Applications

A. Astronomy

Characteristic temperatures, molecular bond strengths, and dust grain sizes are responsible for filling the heavens (and Earth!) with FIR radiation. COBE spacecraft measurements showed almost half the luminosity and 98% of the post-Big Bang *photons* in a typical galaxy lie in the FIR spectral region [1]. This is shown in Fig. 1, along with the 1.9 THz carbon line – a single spectral line responsible for 0.25% of the energy radiated by a galaxy [2]! In addition to the wealth of photons in the FIR, we find the wavelength of FIR photons is such that one can probe deeply inside regions of gas and dust that surround stars, without the dramatic attenuation typically seen by near-IR photons. This gas and dust, in many places

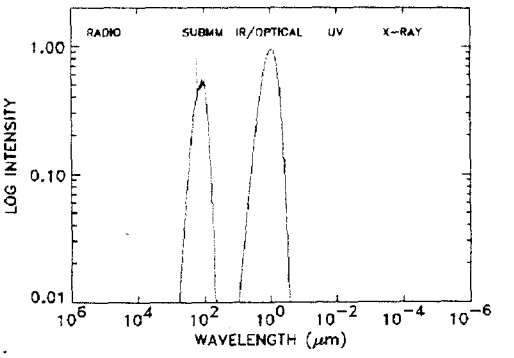

Fig. 1: COBE/DIRBE measured spectrum of the Milky Way galaxy [2]. Note the 158 μm CII line.

responsible for the birth of new stars and galaxies, is at temperatures that exhibit a peak in the Planck blackbody radiation spectrum in the FIR [3]. Using Doppler information collected by high-spectral-resolution heterodyne radiometers, the dynamics of galaxies new and old may be understood. Frequency resolution better than a part in a million is necessary for many of these studies.

With the sluggish advancement of FIR technology, there has been only one spacecraft to date which has successfully utilized FIR heterodyne radiometers: the Submillimeter-Wave Astronomy Satellite (SWAS) [4]. Launched in 1998, this spacecraft has generated impressive astrophysical measurements at frequencies near 490 and 550 GHz (where atmospheric attenuation is particularly strong). Several other spacecraft are due to launch in the near future with FIR heterodyne radiometers for astrophysical, atmospheric, and cometary studies. Most notable is the European Space Agency's Far-Infrared & Submillimeter Telescope (FIRST), which includes a significant contribution from NASA. Set to launch in 2007, it will utilize cold optics and state-of-the-art bolometers and superconducting mixers to make extremely sensitive measurements from the mm-wavelength region to frequencies exceeding 1 THz [5].

Among the more interesting possible space-based astronomy missions is a proposal for a single-aperture far-infrared (SAFIR) observatory. The National Academies' Astronomy and Astrophysics Survey Committee has recommended SAFIR as a follow-on to the Next-Generation Space Telescope (NGST) [6]. SAFIR is planned to utilize a cold 8-m space-based telescope that is diffraction limited at 30 μm, and will be more than 100 times as sensitive as FIRST. It will investigate the earliest stages of star and galaxy formation by penetrating into regions too dust-shrouded to be studied by NGST, and too warm to be effectively studied

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by ground-based facilities such as ALMA (Atacama Large Millimeter Array). Given its large size, low temperature, and sensitive detectors, SAFIR's "astronomical capability" will be of order 100,000 times that of previous missions. There is obviously tremendous potential for breakthrough discoveries!

In the following decade, attention will naturally shift to the creation of a FIR interferometer in space. A 30-m class space infrared interferometric telescope (SPIRIT) has been proposed as a precursor to a 1-km baseline interferometer, the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) [2]. Poor angular resolution has been a major limitation in FIR studies of the evolution of primordial structure in the universe, and the formation of galaxies, stars, and planets. Angular resolution on the order of 0.01 arcsec is needed to resolve distant galaxies or protoplanetary systems in nearby star-forming regions. The ground-based mm-wavelength ALMA will provide such resolution, and in the FIR, SPECS would perform similarly. SPIRIT would be used as technology validation, with compelling science objectives as well. Given the large number of FIR photons available, the sensitivity of filled-aperture telescopes is only necessary for certain measurements (e.g., high resolution spectroscopic observations of distant objects), and much science can still be performed with a sparsely-filled-aperture telescope.

While direct detection holds a sensitivity advantage over heterodyne radiometry for some applications in the FIR, the longest-baseline interferometers will require the phase-coherent techniques of heterodyne measurements to allow realistic combination of the numerous telescope signals. Very-large-aperture telescopes (perhaps tens of meters in diameter, from inflatable structures) will be required to make the sensitivity of such an interferometer of practical use for many astrophysical studies.

B. Atmospheric Chemistry

We all have been touched to some extent by regulations imposed to maintain a healthy atmosphere. We may notice the effects of reduced smog levels, trends in global warming, a potentially life-saving ozone layer, or the expense of a CFC-free refrigerator, but behind the scenes, governments make extremely difficult choices in balancing economic and environmental priorities. Atmospheric scientists strive to provide governments with unequivocal data that makes these choices obvious. As fate would have it, important molecules in the Earth's atmosphere exhibit vibration and rotation spectra in the FIR. By monitoring such molecules, one can gain a better understanding of atmospheric dynamics, obtain more realistic data for atmospheric models, and provide real-time feedback on atmospheric conditions [7].

Precise observation of molecular spectral line shapes, widths, and amplitudes are critical to extracting the relevant information from measurements. Doppler and pressure-broadening of the spectral lines typically results in linewidths of order 1 to 10 MHz [8]. For sufficient accuracy in data collection, one desires spectral resolution of better than a part in a million.

The Upper Atmosphere Research Satellite, Microwave Limb Sounder (UARS-MLS) instrument began operation in 1991, and has been consistently returning useful data of this nature to the present day [9]. Although the highest frequencies observed with UARS-MLS were only in the neighborhood of 200 GHz, it has laid the groundwork for the next generation Earth Observing System, Microwave Limb Sounder (EOS-MLS). Set for launch in 2003 in NASA's AURA spacecraft, EOS-MLS is presently the largest American FIR space mission, and will observe the atmosphere in five radiometer frequency bands from 100 GHz to 2.5 THz with semiconductor-based heterodyne receivers [10]. An additional follow-on mission to launch near the end of the decade is being proposed.

FIR heterodyne receivers also find application in cloud ice crystal observations, an important part of accurate global-warming models [11]. A DC-8 airplane-based instrument is presently being built at JPL to demonstrate the usefulness of this technique, and will hopefully lead to a space-based global application. Lastly, the effects of aerosols and dust spewed into the atmosphere by volcanoes are readily observed in the FIR, and are occasionally detected by the MLS radiometers.

C. Planetary Science

Earth's atmosphere is but one of many interesting atmospheres in our solar system. Remote or in-situ FIR measurements are particularly well-suited to intriguing atmospheres like those of Venus, Mars, the gaseous planets, and Saturn's moon Titan. By learning about the atmospheric composition and dynamics on remote planetary bodies, scientists can develop models of planetary evolution and suitability for future exploration. The sensitivity of FIR radiometry to emission from water molecules may lead to missions to Mars and Jupiter's moon Europa. Missions to Mars have been proposed, and a potential FIR study of Venus' atmosphere is presently receiving much attention. The reduced size of FIR antennas with respect to their millimeter-wave counterparts also makes them attractive for in-situ "weather stations" and sensor webs.

Other solar system bodies are realistic candidates for FIR study – comets and other Kuiper Belt objects (KBOs) offer clues to understanding the creation of our solar system, and possibly life on Earth as well. The molecular gas and dust outflows from heated comets offer much information in the FIR, from identification of molecular species to the size, quantity, and albedo of the ejected debris. Rosetta, another ESA-NASA collaboration, will contain the MIRO instrument for 236 and 562 GHz remote studies of the comet 46 P/Wirtanen as it orbits the comet. The instrument will remotely measure gas volatile composition, coma temperature, gas velocity, and subsurface temperatures of the cometary nucleus to a depth of 2 cm or more. Key measurements include CO and water in the head and tail of the comet, temperatures, and isotope ratios. Launch is in 2003, and rendezvous is expected in 2011, with observations lasting at least 2 years thereafter. Future FIR studies of the albedo, size, and position of KBOs will be useful for understanding the conditions that regulated the formation and evolution of the debris that coalesced into our solar system [3].

As many signatures of life (as we know it) can be found in the molecules detectable with FIR radiometers, one would envision that space missions in the distant future will include large-aperture, large-baseline interferometers for examining the chemistry of extra-solar planets. The ratio of planet to stellar flux increases significantly as one moves from the near-IR to the FIR, another reason for working in the FIR. Although extremely large telescopes (at this time unfeasible) would be required for the necessary sensitivity, the predicted molecular species and planetary atmosphere temperatures associated with life make FIR radiometers particularly well-suited to the task of detecting extraterrestrial life.

D. *In-Situ Studies*

The rapid advancement of terahertz imaging, based on terahertz time-domain spectroscopy, makes feasible a portable terahertz spectrometer [12]. With improvements in spatial resolution, signal processing, and penetration depths, terahertz imagers could be valuable in remote geological studies, in-situ atmospheric spectroscopy, and as medical diagnostic tools for humans in space. Presently, the processing time and the size of the instruments is inadequate for space flight use, but a dedicated technology development effort can solve these problems with reasonable cost.

E. *Non-Scientific Spaceborne Applications*

The information-carrying capacity of signals with terahertz bandwidths is obviously immense. Due to atmospheric absorption, one finds few applications of free-space FIR transmission at the Earth's surface. However, satellite-to-satellite communication can be achieved with the immense bandwidths offered by the FIR. Defense applications exist here as well because of the difficulty in eavesdropping through the atmosphere. Compact, low power FIR radiation sources, detectors, and filters must be developed before such applications become economically feasible.

III. Heterodyne Devices

A. *Why Heterodyne?*

Heterodyne technology offers highest sensitivity in the longer-wavelength region of the FIR. As wavelengths decrease, the attractiveness of direct detection instruments increases. Nonetheless, for most applications in the FIR that require high frequency resolution (a part in 10,000 or more), heterodyne receivers are most practical. While this is a useful guide, most often, the specific targeted application will make the choice of heterodyne vs. direct for you. For brevity, only heterodyne devices are discussed in this paper; we refer the interested reader to reference [13] for information on the present status of direct detectors.

B. *Mixers*

The highest-sensitivity applications requiring high frequency resolution utilize superconductor-insulator-superconductor (SIS) tunnel junction mixers operating at temperatures of 4 K or below. For frequencies above about 1 THz, one resorts to hot-electron bolometer (HEB) mixers if high sensitivity is needed. Again, these operate at temperatures near 4 K. For space applications, cooling technology becomes a very important issue. Even for spacecraft operation at the friendly L2 Lagrangian location, one cannot expect passive cooling to provide temperatures below 30 K [14]. For room-temperature operation, or simplicity in low-sensitivity applications, Schottky diodes are used. The convenience of operating at room temperature typically carries a penalty of a factor of 5 to 10 in sensitivity, but new advances in planar diode technology [15] are making Schottky diodes more attractive. Figure 2 shows recent measurements from our laboratory, with uncorrected receiver noise below 6500 K, DSB. Removing the effects of atmospheric loss and IF amplifier noise in the measurement setup gives room temperature *mixer* noise close to 4000 K, DSB.

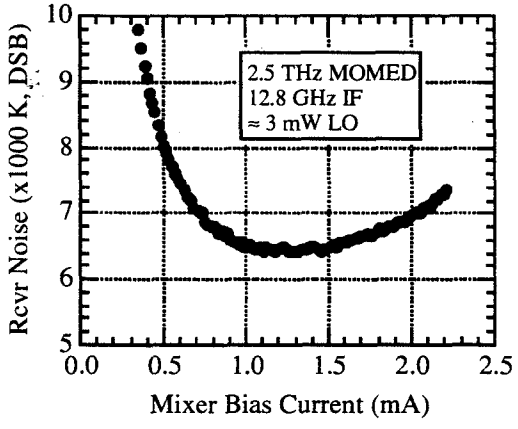

Fig. 2: Uncorrected receiver noise temperature with JPL's planar Schottky diode MOMED.

C. *Local Oscillators for Spaceborne Use*

Typical LO power requirements range from 100 nW (HEBs) to 1 μW (SIS) to 1 mW (Schottky), and has enormous consequences on the applications in which these mixers are used. Inefficiencies in diplexing and optical coupling can raise the actual LO source powers needed by a factor of 5. Note that arrays of such mixers are envisioned for the future, and the aforementioned LO power must be multiplied by the size of the array (assuming a very efficient LO power distribution scheme).

SIS and Schottky mixers enjoy an advantage over HEB mixers in the power stability requirements of the LO. The SIS and Schottky mixers operate in a region where fluctuations in LO power are compressed somewhat: fractional changes in LO power correspond to perhaps ten times lower fractional changes in IF output power. HEB mixers, however, operate in a regime where such compression is much less significant, and LO fluctuations are nearly indistinguishable from signal fluctuations. Requirements on power stability are typically 1% for the SIS and Schottky, but 0.1% for the HEB mixers.

There is a division of approaches used for LO technology, with electronic techniques generally used at

frequencies below 1 THz, and photonic techniques above 1 THz. While reasonable success has been achieved in the former regime, the latter frequency regime has only rarely been able to meet the demands of use in spacecraft.

IV. Space Flight Qualification

Lifting a radiometer into space is no easy task. The complexity and cost of such systems can easily be an order of magnitude larger than similar systems built for ground use. There must be a strong science driver and a friendly political climate to enable such missions. When given the necessary endorsement and funding, one must then take into account the need for:

1. minimal mass, volume, DC input power
2. thermal requirements and thermal stability
3. ability to withstand launch vibration, typ. 5-25 g, rms
4. radiation hardness; from ≈ 10 krad (Si) (in low Earth orbit) to > 1 Mrad (Si) (near Jupiter)
5. minimal EMI susceptibility; protection against ESD
6. adequate testing, given the improbability of repairs in space (including vacuum testing)
7. precise, careful engineering to ensure best instrument performance (justifying the cost of launch)
8. reliability and lifetime analyses and tests
9. materials choices (low outgassing, minimal mechanical stress in optics,...)
10. quality assurance, configuration control, documentation.

Although it is possible to create a low noise terahertz receiver in the laboratory, challenges exist in making it robust enough for practical use. Most electronic (but not optical) FIR components are relatively immune to launch vibration, as their small mass places resonant frequencies high above the few-hundred Hertz typical of launch vehicles. GaAs Schottky diodes are known to be relatively immune to total-dose effects resulting from the deposition of ionizing energy, but other devices now being introduced may suffer more from their use of minority carriers or nano-scale features [17]. To ensure radiometer lifetimes in excess of common 2-to-10 year mission durations, accelerated lifetests with fit to Arrhenius-lognormal or electromigration models are necessary. This is of particular importance with novel device designs and their high current densities.

V. Conclusion

While very few space missions have applied heterodyne FIR technology, it is quite clear that its utilization is of utmost importance in many fields of science. Many breakthrough discoveries in these fields can reasonably be expected, but are being hindered by a lack of FIR technology. Figure 3 outlines the pressing technology needs for FIR spaceborne applications.

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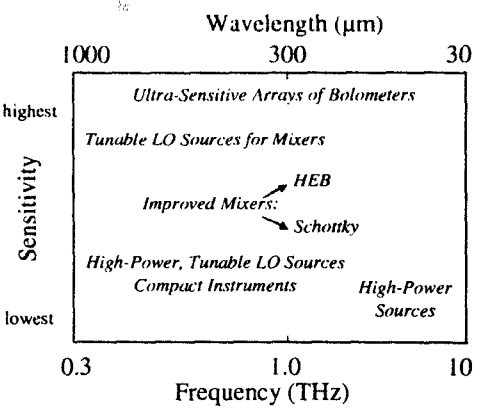

Fig. 3: Technology needs for the FIR.

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