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Report of the Heterodyne Submillimeter-Wave Sensors Panel

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INTRODUCTION

Heterodyne receiver technology for future NASA missions provides a particularly exciting development opportunity, in that entirely new areas of spectroscopy will be enabled if the frequency range of sensitive receivers can be pushed into the THz regime. In particular, the submm regime is rich with molecular transitions which can serve as signatures of cold gases and particles in planetary, stellar and interstellar objects. In addition, no array capability currently exists in the submillimeter wavelength regime, and this development offers enormous advantages for future imaging instruments. We stand at the threshold of realizing these capabilities through the implementation of advances in superconductor technology and semiconductor planar epitaxial growth and lithographic processing techniques. However, the development of these technologies in time to benefit the relevant missions will require an aggressive R&D program, and since NASA's needs in these areas are unique, the entire support for this effort will necessarily be borne by the agency.

The focus of the Heterodyne Submillimeter-Wave Sensors Panel was the heterodyne development required to meet the science goals of the Astrotech 21 mission set. The relevant missions include SMIM, NGOVLBI, LDR and SMMI, for which the specific requirements are summarized in Table I. Many of these performance specifications lie significantly beyond the capabilities of existing technology, and will require further advances. Previous development in this area has been supported by NASA and SDI. The NASA Office of Aeronautics, Exploration and Technology (OAET) has funded submillimeter heterodyne sensor development starting in 1988 under the Civil Space Technology Initiative (CSTI). The primary goal of this program is enhanced receiver performance above 200 GHz, where emission from molecular bands provides the most detailed information on the constituents and chemistry of the interstellar medium. Examples of emerging planar submillimeter receiver technology and of the richness of spectral information available in this frequency range are displayed in figures 1 and 2, respectively. The NASA Office of Space Science and Applications (OSSA) has also supported development in this area. In addition, one of the NASA University Centers of Excellence, the University of Michigan Space Terahertz Technology Center, was identified to carry out research in high-frequency devices and receivers. At about the same time, SDI started an effort in terahertz technology development for communications applications.

The shortcomings of existing heterodyne receiver capabilities vis-a-vis the performance specifications for the Astrotech 21 mission set fall into four categories; local oscillators (LO), mixers, focal-plane arrays, and spectrometers. In Table II a comparison is made of the specifications for (i) a recent submillimeter-wave space mission, Cosmic Background Explorer (COBE), (ii) an instrument on a mission to be launched this year, the Microwave Limb Sounder for the Upper Atmosphere Research Satellite (UARS/MLS), (iii) a mission to be launched in '95, the Submillimeter Wave Astronomy Satellite (SWAS), and (iv) for two representative Astrotech 21 missions, SMIM and LDR. COBE flew 50 and 90 GHz receivers, UARS/MLS has three heterodyne

Table I Astrotech 21 Mission Requirements Summary

Mission Technology Freeze Launch Date	SMIM 1996 2002	NGOVLBI 2000 2006	LDR 2006 2012		SMMI 2006 2012
Frequency Range (GHz)	400-1200	1-220	100-1200	1200-2000	1000 - 3000
Type of Receiver	SIS	HEMT/SIS	SIS	SBD	SIS
Sensitivity Specification (hv/k)	20	10	10	10	6
LO Power	50 μW	10 μW	1 mW	20 mW	100 μW
Number of Pixels	8 - 10	5	2 x 10 array	2 x 10 array	1 per antenna (12 antennas)
Operating Temperature	2-5 K	30 K & 4 K	2-5 K	40-60 K	2- 5 K
Heat Load (mW)	20	200/30-60	< 100	800	50
Operating Life (yrs)	2-4	10	10	10	10
Spectral Resolution	10^{-6}	---	10^{-6}	10^{-6}	10^{-6}
Spectral Channels	8000	---	2x10x1000	2x10x1000	1000 per receiver
IF Bandwidth	4 GHz	> 1 GHz	> 1 GHz	> 1 GHz	40 GHz
Preamp Noise Temperature	< 0.1 T_{sys}	< 3 K	< 0.1 T_{sys}	< 0.1 T_{sys}	< 0.1 T_{sys}
Special Requirements	Complete frequency coverage	VLBI-quality LO	Focal plane arrays and low-power, many-channel digital spectrometer		Phase stability

Table II Heterodyne Sensor Capabilities for NASA Missions

Development Status	Flown in Space for Space	Developed for Space	Under Development	Desired for Future Mission	Desired for Future Mission
Sample Mission Launch Date	COBE 1989	UARS/MLS 1991	SWAS 1995	SMIM ~ 2002	LDR ~2008
LO	5 mW @ 90 GHz GaAs Gunn oscillator	1 mW @ 205 GHz GaAs Gunn oscillator with x3 whisker-contacted varactor	3 mW @ 275 GHz InP Gunn oscillator with x3 whisker-contacted varactor	100 μW @ 1200 GHz	20 mW @ 2000 GHz
Mixers	Planar diode in waveguide mount @ 90 GHz	Fundamental whisker-contacted GaAs SBD in waveguide with 200 hv/k @ 205 GHz, Rm. T operation	Harmonic whisker- contacted GaAs SBD in waveguide with 120 hv/k @ 557 GHz, 150 K operation	Fundamental SIS with 10 hv/k @ 1200 GHz, 2-4 K operation	SIS to 1200 GHz, SBD to 2000 GHz, with 10 hv/k @ 2000 GHz
Focal Plane Array	None	None	None	None	2x10 array
Spectrometer	NA	6 filter banks with range of fixed-resolution varying from 1 to 200 MHz, 16 channels per filter bank	1 AOS spectrometer 1.4 GHz BW 1 MHz res. 1400 channels	8-10 AOS spectrometers each with 1000 channels, 2 GHz BW & 2 MHz res.	2x10x1000 channels AOS spectrometers, 2 GHz BW, 2 MHz res.

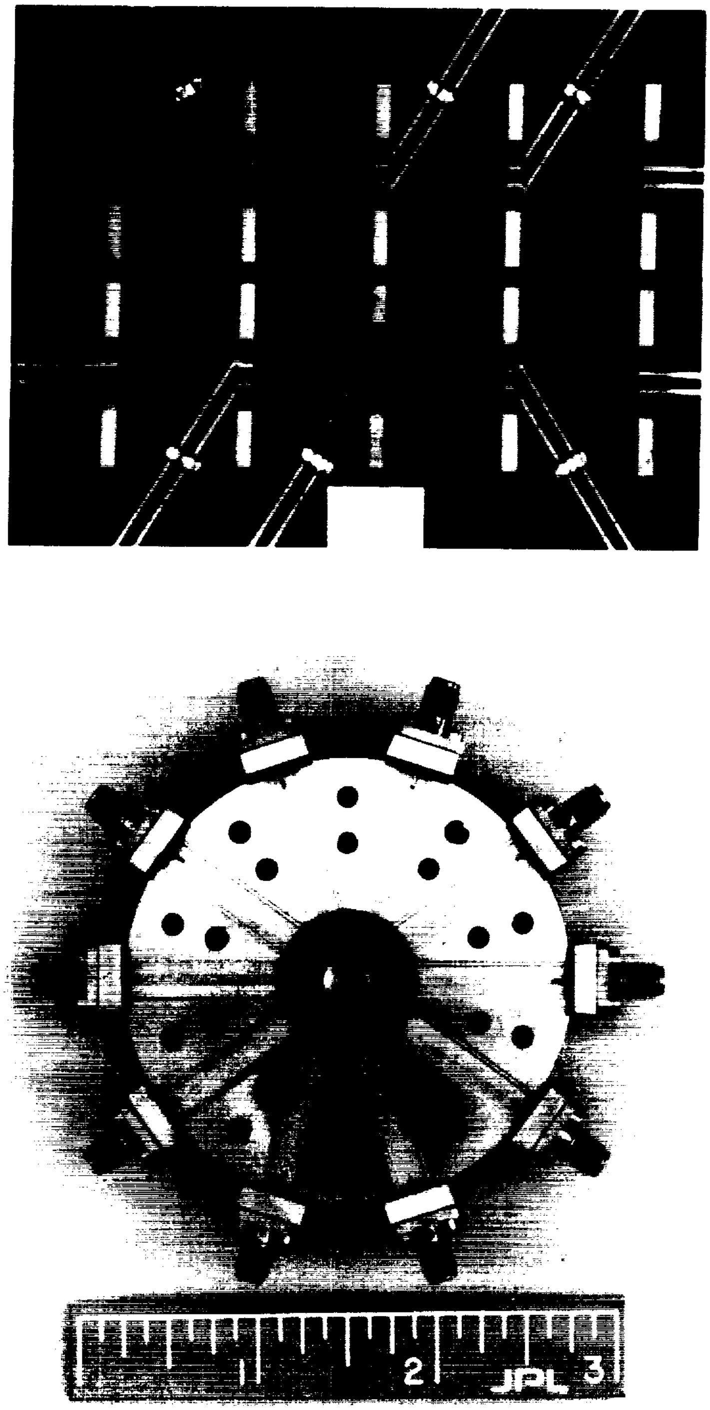

Figure 1. 230 GHz planar heterodyne array of superconducting tunnel junctions and dipole antennas on a dielectric-filled parabola (scale is in inches). This ten element array was fabricated at the Jet Propulsion Laboratory. The enlargement of the center region (top photo) shows the antenna elements.

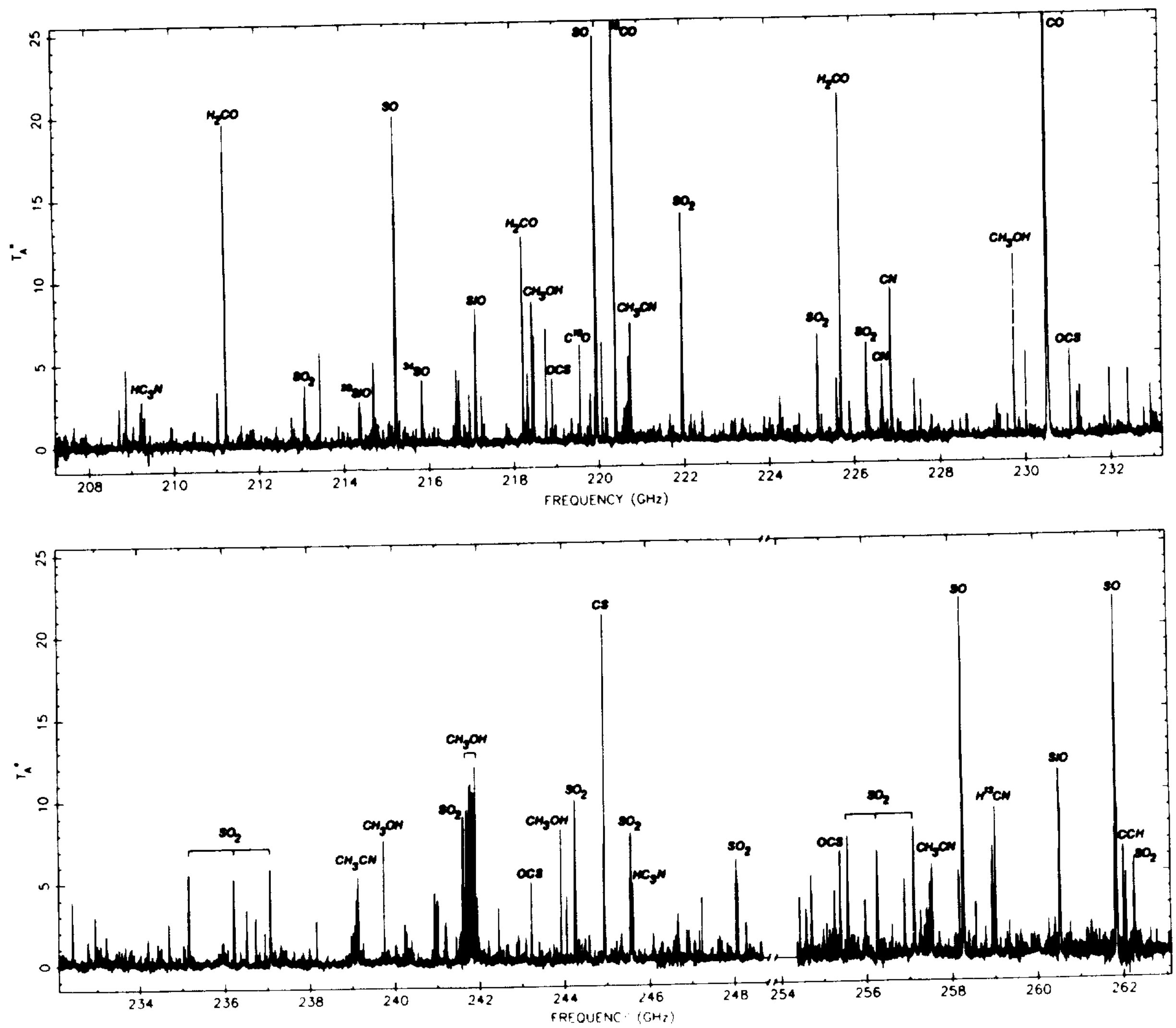

Figure 2. Emission spectrum of the Orion Nebula illustrative of the wealth of information on the molecular composition of interstellar clouds available in the millimeter and submillimeter wave range wave regime. This spectrum was obtained with a ground-based telescope.

radiometers at 63, 183 and 205 GHz, and SWAS will have two receivers at 480 and 560 GHz. This table clearly displays the progress that is being made in heterodyne detector capabilities, and highlights the advances that are still required. The remainder of this report addresses each of the four categories in turn, describing the emerging technologies which offer promise in meeting the measurement requirements of future astrophysics missions, and providing a development plan to achieve the desired performance on the required time scale.

LOCAL OSCILLATORS

A. Technology Assessment

As shown in Table II, SMIM, NGOVLBI, SMMI and LDR all require local oscillator (LO) performance which is beyond the current state-of-the-art. The current baseline technology for these missions is Gunn oscillators operating at 100 GHz coupled to a chain of whisker-contacted GaAs Schottky multipliers to reach the THz regime. However, to date no system with satisfactory output power has been demonstrated above 600 GHz. It is urgent that a satisfactory source be demonstrated above 1 THz as soon as possible; otherwise subharmonic mixers must be developed. From the panel's 1991 vantage point, there is also significant concern that the LDR requirement of 20 mW at 2 THz may not be possible to achieve with the baseline system, thus requiring the development of alternate technologies.

B. Development Plan

The panel recommends that the baseline technology be pursued vigorously, but that a number of innovative new concepts be tried also, as summarized in Table III.

The baseline design calls for whisker-contacted GaAs Schottky multipliers with factors of 2x2x3 to reach 1.2 THz. However, adequate conversion efficiency has not yet been demonstrated at THz frequencies, and multiple whisker-contacted devices are cause for serious concern in terms of system robustness. While the baseline technology needs to be pursued aggressively, the panel recommends additional support of emerging technologies based on bandgap engineered III-V heterojunction barrier structures offering the potential of higher conversion efficiency, especially at the highest frequencies, as well as a significant improvement in robustness. Higher order multipliers using symmetric CV diodes offer another possibility for increasing the conversion

Table III Local Oscillator Technology Development

Technology Area	Current Technology	Program Goals	Program Dates	Program Size
Frequency multiplier devices				
Baseline GaAs Schottky varactors	< 700 GHZ	1200 GHz	91 - 96	Moderate
Planar GaAs Schottky varactors	< 200 GHz	1200 GHz	91 - 96	Small
Novel III-V varactors	< 200 GHz	1200 GHz	91 - 96	Small
Higher order varactors	< 200 GHz	1200 GHz	91 - 96	Small
Develop best option for > 1 THz		2000 GHz	96 - 01	Moderate
Frequency multiplier circuits				
Baseline metallic waveguide	< 700 GHZ	10% fixed bandwidth	91 - 96	Moderate
Micromachined waveguides	Concepts	Feasibility	91 - 96	Small
Quasi-optical structures	Concepts	Feasibility	91 - 96	Small
Quintuplers	Concepts	Feasibility	91 - 96	Small
Develop best option for > 1 THz		2000 GHz	96 - 01	Moderate
Oscillators for driving multipliers				
Baseline Gunn oscillator	1000 GHz, 50 mW	300 GHz, 10 mW	93 - 96	Small
Other mm-wave oscillators	Concepts	0.3-3 THz, 10 mW	93 - 96	Several small
Submm fundamental oscillators				
Quantum well	< 700 GHz, 1 μW	1200 GHz, 50 μW	91 - 96	Small
Josephson junction arrays	≤ 450 GHz	1200 GHz, 50 μW	91 - 96	Small
Power combining arrays	Concepts	1200 GHz, 50 μW	91 - 96	Small
Develop best option for > 1 THz		2000 GHz, 50 μW	96 - 01	Moderate

efficiency to THz frequencies. There is also concern that the currently available metallic waveguide structures may reach their limit at ~ 700 GHz, and not be appropriate for higher frequency operation. Possible solutions include quasi-optical structures, micromachined waveguides, overmoded waveguides or corner cube architectures.

Higher THz powers can also be achieved by augmenting the power of the fundamental oscillator to drive the multiplier chain. Fundamental oscillators in the submillimeter range are inherently more efficient than multiplied sources, but the technology is much less mature. Pushing millimeter-wave oscillators such as Gunn oscillators or IMPATT oscillators to higher frequencies with moderate power would also be useful to reduce the multiplication factor required to achieve the desired final-stage frequencies. Promising approaches for submillimeter-wave fundamental oscillators include the development of QW and Josephson tunnel junction technologies. Compact, tunable gas lasers or semiconductor laser structures are also possibilities for the LDR Schottky receiver.

Overall, the panel recommends a program equivalent to about a 15 lead person effort be focused on the LO problem, with about 40% of the resources being used to pursue the baseline technologies, and 60% to explore and develop alternate emerging technologies. It is also noted that the LO and mixer development programs should be tightly coupled.

MIXERS

A. Technology Assessment

As shown in Table II, some important requirements for mixer performance are not met by existing technologies, including the high frequency needs of SMIM and LDR. The baseline design for these missions is for Nb or NbN SIS mixers in a waveguide architecture to 700 GHz, and planar structures to 1200 GHz. GaAs Schottky barrier diode (SBD) mixers are baseline for frequencies above 1200 GHz. The precise dividing frequency between SIS and SBD implementation will be determined by the crossover frequency in its performance at the technology freeze date. A critical question is the ability of SIS mixers to operate adequately at frequencies above the superconductor energy gap (725 GHz for Nb). Josephson currents and RF losses in the superconductor may make Nb mixers unusable above this frequency, and the larger energy gap NbN has not yet been shown to work as well as Nb at any frequency. At the highest frequencies, where GaAs SBDs are baseline, there is concern over achieving the required sensitivity, as well as doubts about the robustness of the whisker-contacted devices.

B. Development Plan

Working in the baseline technologies, a number of possibilities should be pursued to extend the performance of these approaches towards the required mission specifications. These include the investigation of new alloys and insulators, NbN superconductor/insulator/normal metal (SIN) structures, and various novel architectures. Properties of the superconductors should also be measured in the higher frequency ranges - a demonstration of satisfactory operation at 1 THz is urgently needed.

Given the uncertainties inherent in the baseline technology, a number of alternate and fall-back approaches should also be investigated in parallel. Planar GaAs Schottky diode mixers, photoconductors such as Ge blocked-impurity-band (BIB) devices, high Tc SIS, and superconducting photoinductor detectors are worthy of consideration. In addition, other mixer geometries such as balanced mixers and subharmonically pumped mixers should be developed to ease the requirements on LO frequency.

Overall, the panel recommends that a ~ 12 lead person effort be maintained in this area, with about 70% going towards support of the baseline program. As noted before, the mixer development program should be closely coupled to the LO effort. Existing mixer technologies and the recommended development plan are summarized in Table IV.

FOCAL PLANE ARRAYS

A. Technology Assessment

This is a new technology requirement in the submm-wave regime, and although the development is progressing on schedule, it will require sustained support for some years to come. State-of-the-art capabilities in this area are still in the developmental phase, with prototypes for ground-based telescopes only now being built, and only for frequencies below 250 GHz. Multiple-pixel arrays bring a number of new problems to be overcome that are not present in discrete receivers. At the current time, the number of pixels envisioned is limited by LO power and spectrometer channel count. Other array-specific concerns include the coupling strength between the elements and the antenna and LO, as well as undesired coupling among elements and other parasitic effects, and heat dissipation of the IF amplifiers. There is currently no definitive baseline design for the LDR arrays, and new ideas need to be explored as they emerge.

B. Development Plan

Overall, the panel recommends that a ~3 lead person effort in array technology development be sustained, with new concepts investigated promptly.

Table IV Mixer Technology Development

Technology Area	Current Technology	Program Goals	Program Dates	Program Size
Baseline Technology Devices				
Nb or NbN SIS mixers	Concepts	THz operation	91 - 93	Small
New alloys & insulators	Concepts	THz operation	91 - 94	Small
SIN structures	Concepts	THz operation	91 - 94	Small
Develop best option(s) for > 1 THz		Mission specs	93 - 98	Moderate
Alternate Device Approaches				
Planar GaAs mixers	200 GHz prototype	THz operation	91 - 94	Small
Ge BIB photoconductors	Concepts	THz operation	91 - 94	Small
Superconducting photoinductors	Concept	Feasibility	91 - 94	Small
High T_c SIS mixers	Concepts	THz operation	92 - 94	Small
Develop best option(s) for > 1 THz		Mission specs	93 - 98	Moderate
Baseline Mixer Circuits				
Metallic waveguide	200 GHz	THz operation	91 - 94	Small
Open structure mounts	Concepts	THz operation	91 - 94	Small
Develop best option(s) for > 1 THz		Mission specs	93 - 98	Moderate
Alternate Circuit Approaches				
Micro-machined waveguides	Concepts	Low losses	91 - 95	Small
Balanced mixers	< 200 GHz	THz operation	91 - 95	Small
Subharmonically pumped mixers	< 200 GHz	THz operation	91 - 95	Small
Develop best option (s) for > 1 THz		Mission specs	93 - 98	Moderate

Current ideas worth exploring include arrays of micromachined feedhorns, end fire slot antennas, and dielectric-filled parabola structures. The status of superconducting IF amplifiers and correlators being developed for other purposes should also be monitored, as they offer the potential for reduced power and heat loads. The suggested development plan is summarized in Table V.

SPECTROMETERS

A. Technology Assessment

Existing ground-based spectrometers would be adequate for SMIM and LDR except that they are stable only over a narrow temperature range, and have not been operated without human intervention over long periods of time. Smaller, lower-power designs with twice the bandwidth would be very desirable and should be possible. A considerable increase in the number of channels is also called for by the LDR array requirements.

B. Development Plan

The panel recommends that a 3 lead person effort be mounted to bring spectrometer technology to the required level of performance. This effort should include, in addition to the development of AOS technology, a monitoring of advances in digital circuits, since a digital spectrometer would ultimately be desirable to improve stability. The panel's recommendations are summarized in Table VI.

Table V Focal Plane Array Technology Development

Technology Area	Current Technology	Program Goals	Program Dates	Program Size
Early array development	Ground-based design	250 GHz	91 - 93	Small
Extension to THz	Concepts	LDR specs	93 - 00	Moderate
Explore new concepts		Feasibility	91 - 96	Small
Develop best option(s)		LDR specs	96 - 01	Moderate

Table VI Spectrometer Technology Development

Technology Area	Current Technology	Program Goals	Program Dates	Program Size
Baseline Spectrometers				
AOS filter	1000 channels 1 MHz resolution	20, 000 channels 1 MHz resolution	91 - 95	Small
Digital spectrometer				
Monitor this technology Develop for LDR if feasible	Concepts	Same as above Mission specs	91 - 95 95 - 00	No funding Small

SUMMARY

After reviewing the science goals of the Astrotech 21 mission set, and comparing the resulting receiver performance requirements with existing technology, the panel determined that there are significant unmet requirements in four areas; local oscillator power and mixer sensitivity in the THz regime, IF spectrometer channel count, and array technology in any form. A comprehensive development plan has been prepared to provide these capabilities in the time frame needed before technology freeze dates of the respective missions. It was also noted that the development of these capabilities has immense payoff for future astrophysics missions, as it opens entire new arenas of spectroscopy and imaging in the critical submm-wave regime rich in molecular transitions.