THz Technology and its Applications
with emphasis on
Multiplier Frequency Chains

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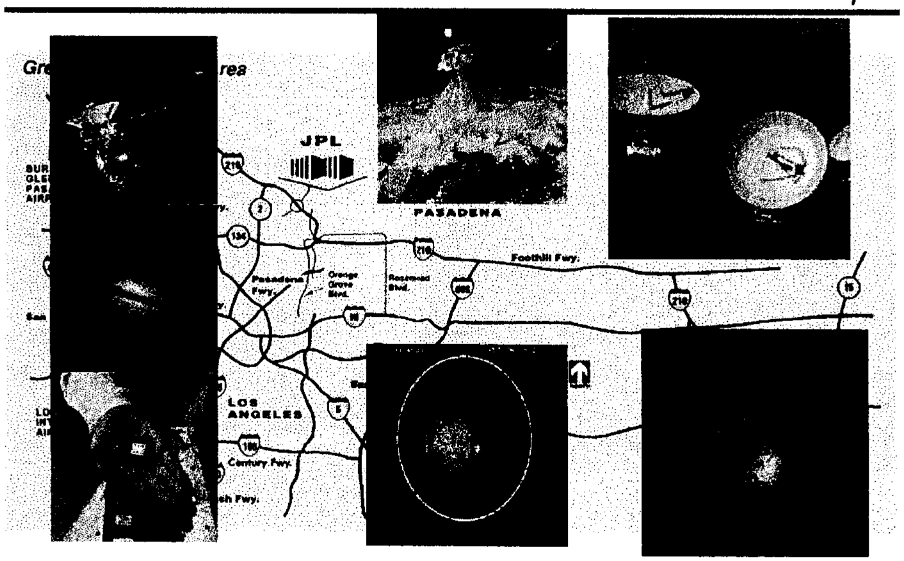
Motivation

Development of components for space-based heterodyne sensor technology at submillimeter wavelengths 125µm to 110µm (2.4THz to 2.7THz)
for
Astrophysics, Earth and Planetary Heterodyne and Direct-detection Remote Sensing Instruments (Herschel Space Observatory, EOS-MLS, ROSETTA).

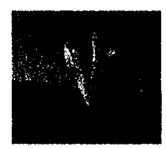
Detection of molecular species in space and in the laboratory
HD (1-0) transition line at 112µm to determine H/D ratio
High resolution spectroscopy
CII and NII hyperfine structure chemistry in InterStellar Medium (ISM)

Solving of Specific Technology Goals
Fabrication of circuits at JPL
Micromachining

Exploration of the Solar System



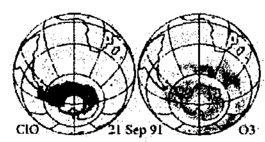
Submillimeter Wave Observation Platforms


High Altitude Balloon


Airborne Platform (DC8/SOFIA)

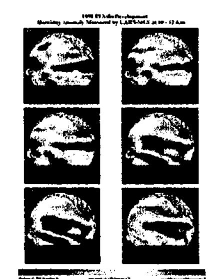

Earth Orbiter/Sounder


Planetary Sounder



First UARS-MLS measurement of correlation between ozone depletion and chlorine enhancement from September 1991.


NASA's Upper Atmospheric Research Satellite


Water vapor during 1997 El Nino from UARS-MLS

THz Bands & Atmospheric Transmission

Space Platforms are Necessary in the Submillimeter Due to water/oxygen absorption in the atmosphere

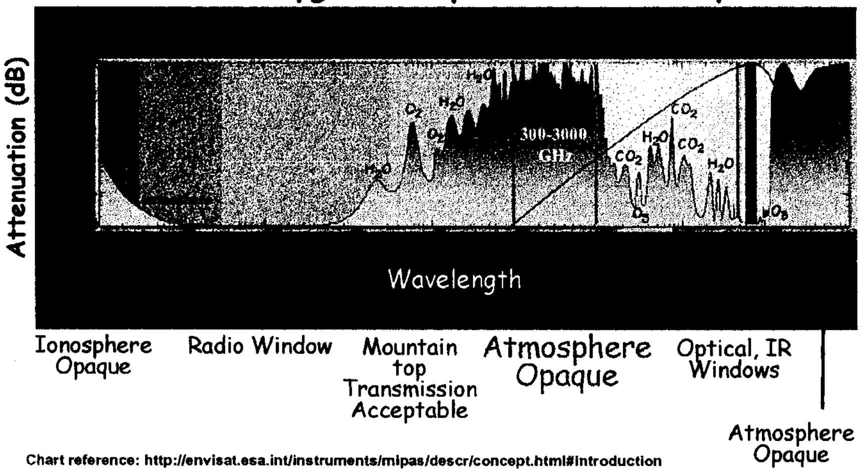
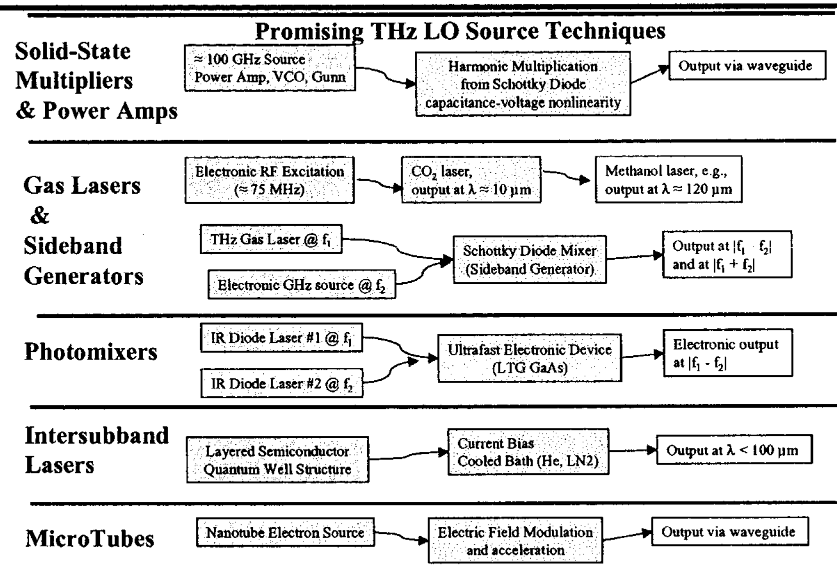
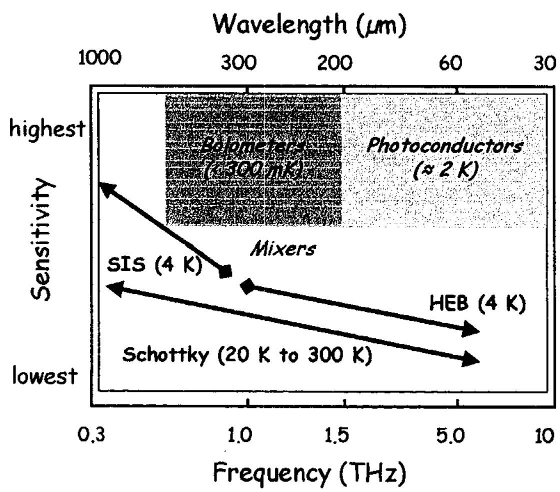


Chart reference: http://envisat.esa.int/instruments/mipas/descr/concept.html#introduction

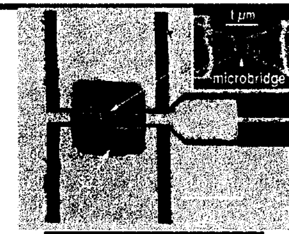
How to generate THz power?



Critical Technology: THz Detectors

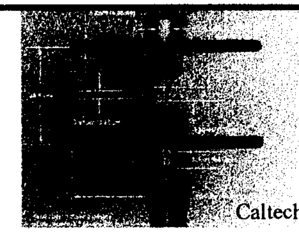


Heterodyne Superconducting Detectors for Astrophysics



Nb HEB @ 4 K 500 GHz - 5 THz

Sensitivity:
$\Delta T \approx T_n / \sqrt{(B\tau)}$
for... $T_n = 1000$ K
$B = 10$ MHz
$\tau = 1$ second...
$\Delta T \approx 0.3$ K
Interstellar clouds
≈ 10 - 100 K

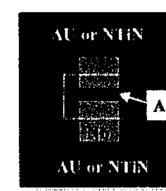


SIS, NbTiN @ 4 K 100 GHz - 1.2 THz

Source Velocity Resolution:
$\Delta v \approx c/R$
for... $R = 10^6$
$\Delta v \approx 0.3$ km/s

Jupiter & Sun	≈ 10 km/s
Earth & Sun	≈ 30 km/s
Sun & Milky Way	≈ 220 km/s

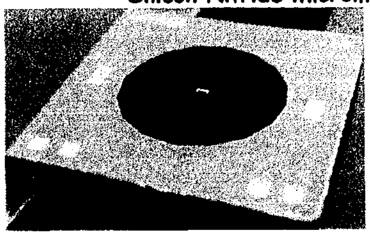
Quasi-optic coupling with twin-slot antennas

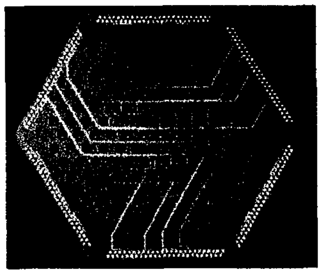


SWAS uses whisker contacted 600 GHz GaAs Schottky mixers and multipliers

Superconducting Detectors for Astrophysics Direct Detectors

Silicon Nitride Micromesh 'Spider-web' Bolometers





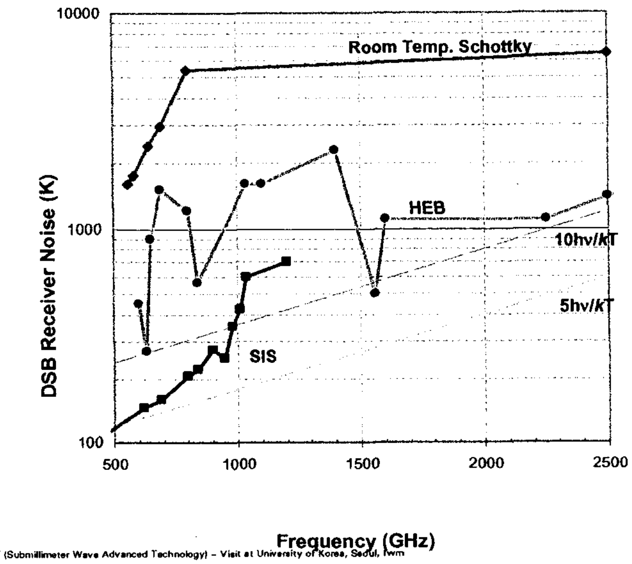
Spider-web architecture
- low absorber heat capacity
- low mass
- low-cosmic ray cross-section
- low thermal conductivity

Sensitivity:
NEP = 1.5×10^{-18} W/ $\sqrt{}$ Hz, at 100mK

To be used in Planck/HFI, FIRST/SPIRE

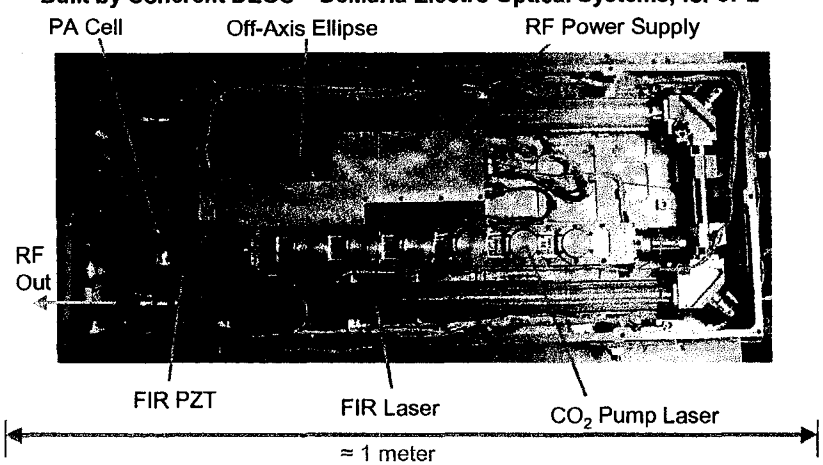
Example:
100 GHz bw, 1 sec integ., 10^{-18} NEP:
$\Delta T < 1\ \mu K$

THz Heterodyne Receiver Performance



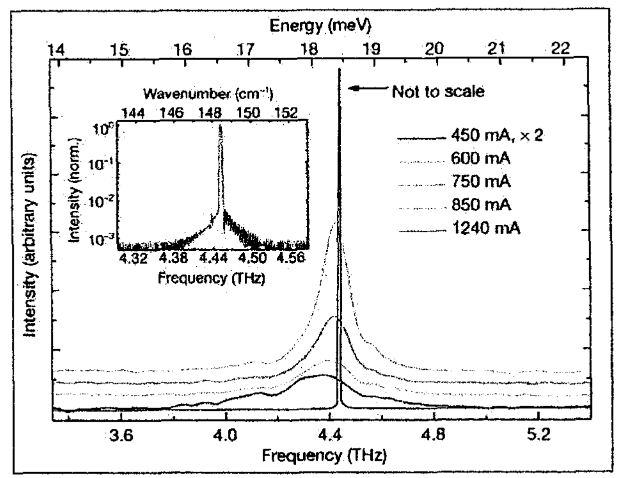
Flight Qualified CO_2 Pumped Methanol Gas Laser

Compact 2.5 THz gas laser system: RF power>20mW, DC power~100W
Built by Coherent DEOS – DeMaria Electro Optical Systems, for JPL



Slide Courtesy Eric Mueller (DEOS)

THz Generation with Intersubband Lasers



Direct THz intersubband solid-state laser emission showing power at ~4.44 THz .

The data shown is for a laser operated pulsed and cooled to 8K. Output power was reported to be about 2mW. At 50K ambient power dropped to 120 microwatts.

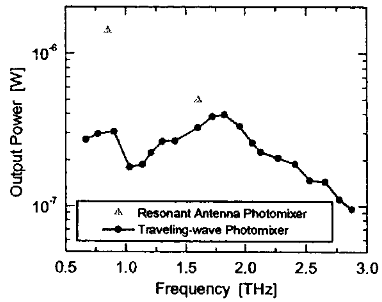
More recent results have shown CW operation and at higher ambient temperature.

(Slide courtesy R. Giles Davies, Cavendish Labs, Cambridge, UK)

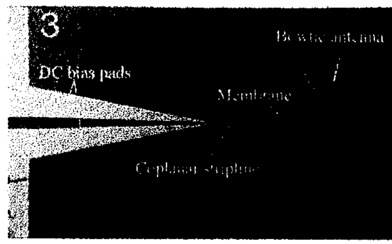
Ref. R. Kohler, A. Tredicucci, F. Beltram, H. Beere, E. Linfield, A. Giles Davies, D. Ritchie, A. Lotti and F. Rossi, Nature, vol. 417, May 9, 2002, p. 156

Photomixer Technology Developments at JPL

- Membrane-supported, or arrayed-antenna distributed gain region:
  - Low RF losses, high output power, avoid thermal burn-out
- Novel materials for 1.55 μm: GaAs:ErAs and InAlGaAs:ErAs



Collaboration of: JPL, UCSB, Caltech

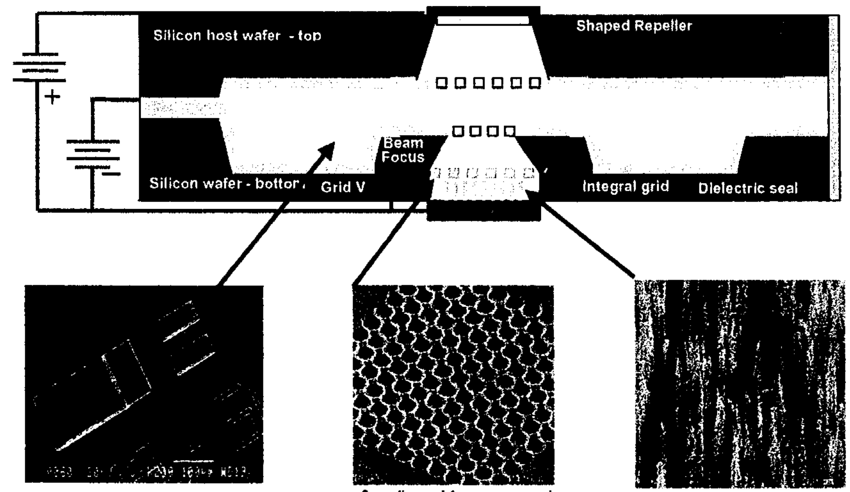


Courtesy of R. Wyss

THz Technology and its Applications

Nanoklystron: THz Generation from Vacuum Tubes

SCHEMATIC CONSTRUCTION WITH REALIZED STRUCTURES



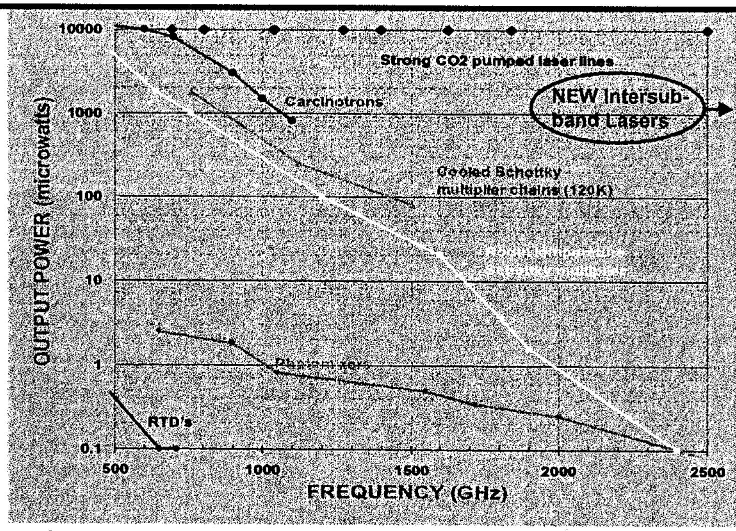
Silicon micromachined cavity (JPL)

2-mm line and 4-mm space mesh with micro-etch masks

High density silicon nanotips made with RIE

THz Technology and its Applications

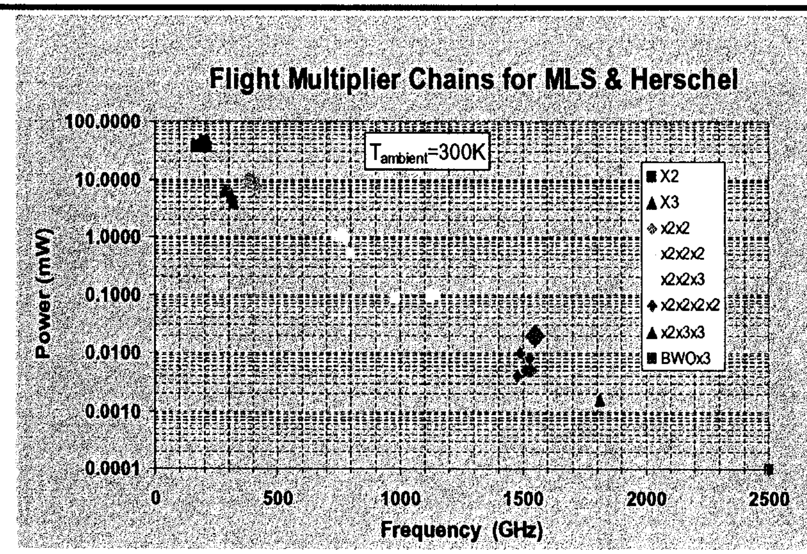
Summary of THz Source Performance



Data collected from assorted references (see MTT50, no. 3, March 2002. pp. 910-928)

THz Technology and its Applications

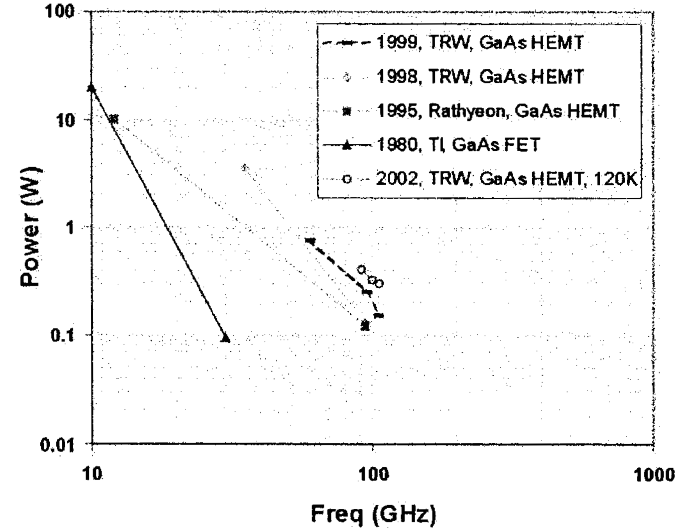
THz Source Performance: Multiplier Chains at RT



Why THz generation with planar Schottky diodes?

- Availability of high power power amplifier from 75-110GHz
- Micromachining of low loss waveguide structures
- Technology Development of fabrication processes for planar Schottky diodes fro the THz range (MoMeD)

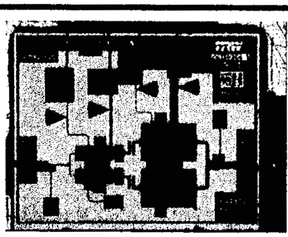
MMIC Power Amps

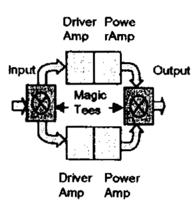


RF power of several 100mW in the 75-100GHz range

Ref: "THz Local Oscillator Sources: Performance and Capabilities," Imran Mehdi, E. Schlecht, G. Chattopadhyay, Lorene Samoska, P. H. Siegel, SPIE 2002.

MMIC Power Amps





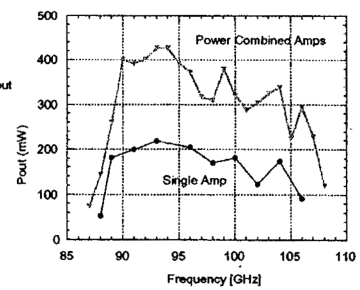


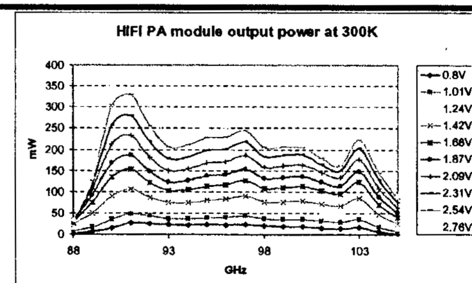
Figure 2. Power output from single and dual power combined packaged TRW MMIC amplifiers at W-band.

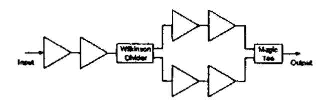
- 0.1 um PHEMT process
- 50 um thick substrate
- f_t = 200 GHz
- 64 finger device cell (output)
- on-chip bias network
- 50 ohm matching in/out
- 2.3 mm x 1.8 mm

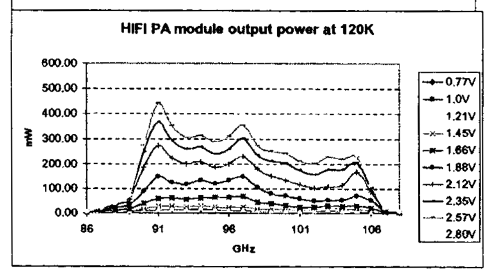
Ref: R. Lai et. al, "A high efficiency 0.15 um 2-mil thick InGaAs/AlGaAs/GaAs V-band power HEMT MMIC," IEEE GaAs IC Symposium Digest, Nov. 1996.

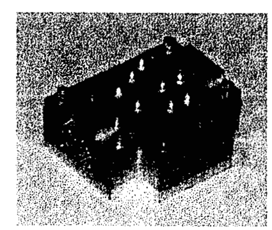
M. D. Biedenbender et al, "A 0.1 um W-band HEMT production process for high yield and high performance low noise and power MMIC's," 16th GaAs IC Symposium, 1994.

MMIC Power Amps



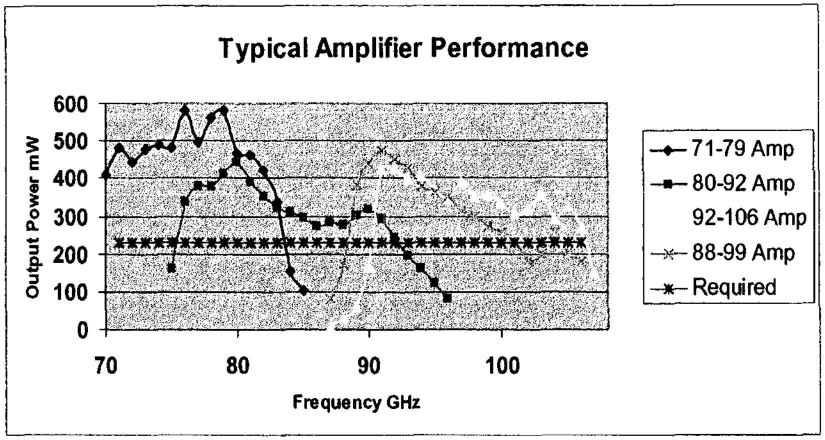






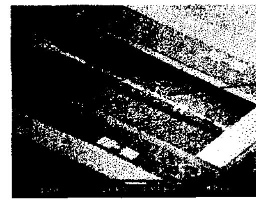
MMIC Power Amps Performance

Herschel Amplifier Performance versus System Requirements

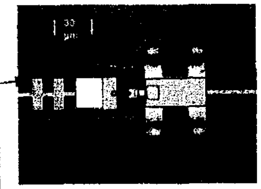


- Full frequency range covered by four amplifier types

Planar GaAs devices

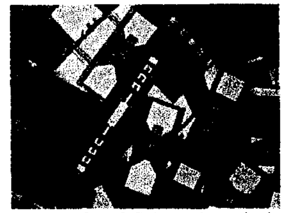


MOMED tripler circuit for 2.7 THz

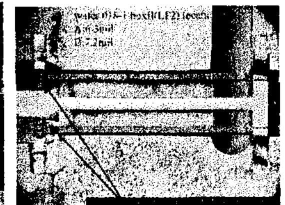


MOMED device blowup. Anode is 0.1x0.5 microns!

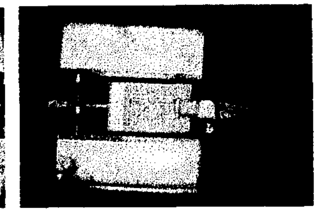
JPL Monolithic Membrane Diode (MOMED) process for ultra high frequency Schottky mixers and multipliers



JPL Submm-λ GaAs membrane circuits



100-200 GHz 6 diode, drop-in doubler yielding 50% efficiency and 25mW

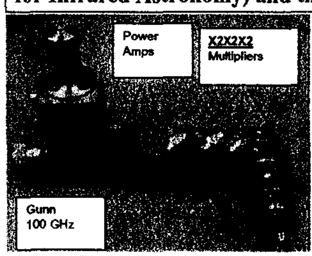


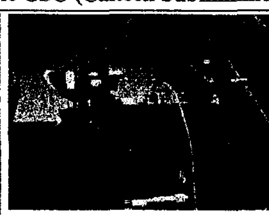
1200 GHz tripler circuit on GaAs membrane

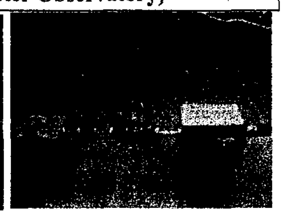
Sponsors: CodeR, Code Y (EOS-MLS), Code S (FIRST)
Devices work by: I. Mehdi, J. Gill, S. Martin, B. Nakamura, A. Fung, M. Dickie, T. Jun - JPL

Frequency Multiplier Chains Application

Solid-state THz sources based on power amplifiers and planar diode frequency multipliers are being developed to support a range of scientific instruments including the Herschel Space Telescope (HIFI), the South Pole's AST/RO (Astronomical Radio Obs.), NRAO's ALMA (Atacama Large Millimeter Array), SOFIA (Stratospheric Obs. for Infrared Astronomy) and the CSO (Caltech Submillimeter Observatory)





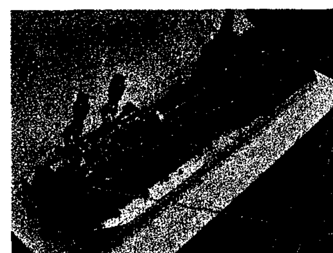


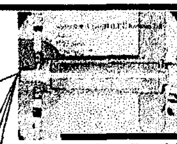
An all-solid-state 805 GHz Local Oscillator (LO) chain assembled for AST/RO (South Pole Radio Telescope). This compact submillimeter wave source produces over 150 microwatts of RF power - 4 times more power than the existing AST/RO LO system. The JPL components enable a new 4x4 submillimeter wave array receiver being assembled by U of Arizona.

An all-solid-state broad band 1500 (left) and 800 GHz (right) Local Oscillator (LO) chains assembled for the HIFI instrument on the Herschel Space Telescope. These sources are two of several frequency chains being readied for flight delivery on this ESA cornerstone observatory mission. The power output of the 800 GHz unit is over 1 mW and has 12% conversion efficiency from 100 GHz. The 1500 GHz unit produces about one half microwatt. A 1200 GHz unit, also being developed, produces over 150 microwatts across a band from 1100-1200 GHz. These are the highest reported power levels produced by solid-state sources to date.

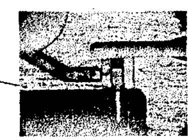
THz Frequency Multiplier Chain

DM Band 5a Local Oscillator Chain





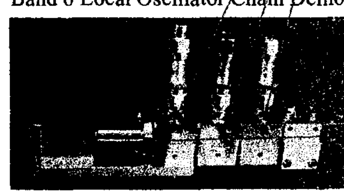
Substrateless Doubler Mounted in Multiplier

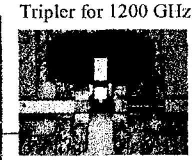


Frameless Membrane Tripler for 1200 GHz

Band 5 Chain
- World Record Bandwidth (1080-1220 GHz)
- World Record Power (250µW at 1135 GHz)
- First planar THz device
- DM meets flight performance Requirements

Band 6 Local Oscillator Chain Demo



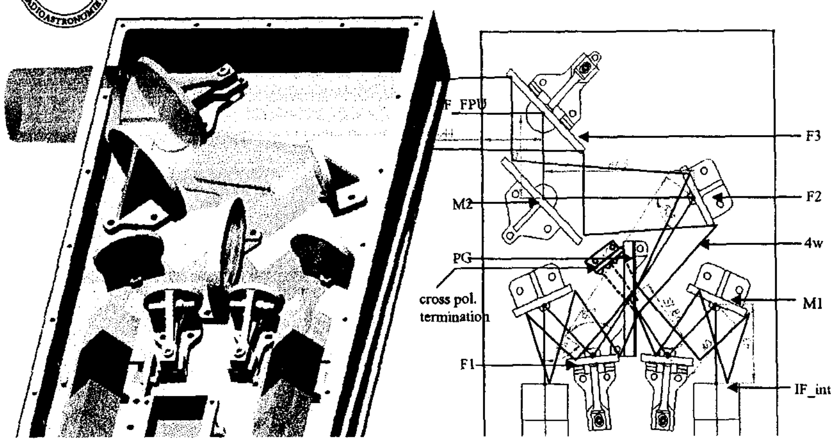


Framed Membrane Doubler for 1550 GHz

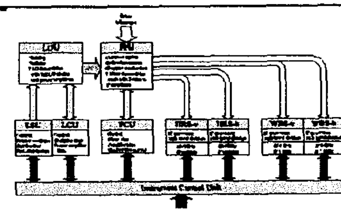
Band 6 Chain
- World Record chain frequency (1550 GHz)
- First 4 stage multiplier chain
- Exceeds 2.1mW required Without cooling
- Pumped HEB mixer

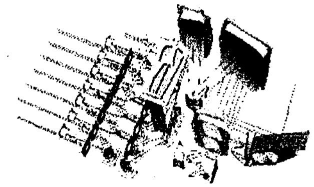
THz Frequency Multiplier Chain Optical Interface

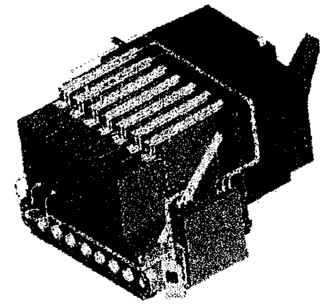
LOU -Optical Design (Courtsey of T. Klein, MPIfR)



The Heterodyne Instrument for Far Infrared



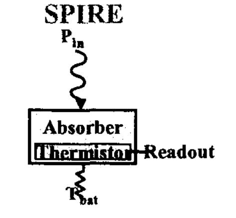


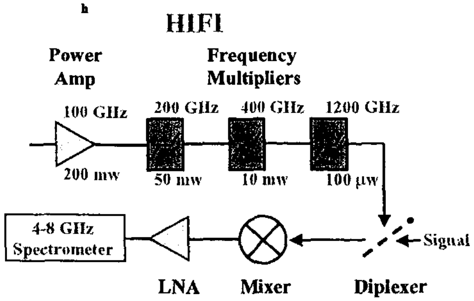


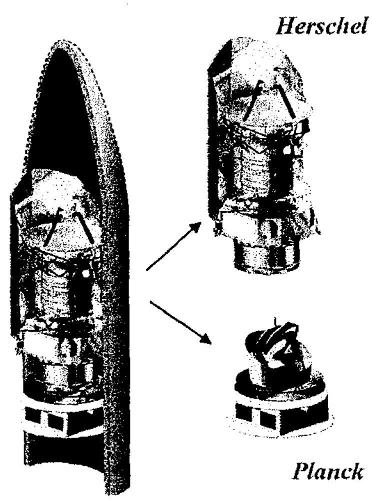
Focal Plane Unit

Optical paths for the 7 receivers

Herschel and Planck



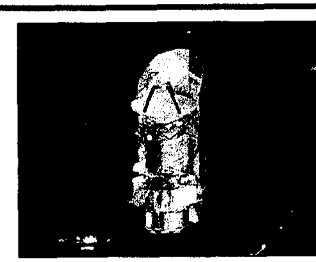




Herschel and Planck

Mission Overview

- ESA Cornerstone Mission (Great Observatory)
- Far Infrared Observatory with 3.5-m Telescope
- U.S. Participating in Two of Three Instruments
- U.S.Technology Input
  - High Frequency Heterodyne Receivers
  - Large Bolometer Arrays
- Launch Date: Mid-2007 to L2 orbit

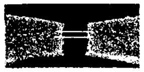


Science

- Investigate the dynamical and chemical evolution of galaxies and stars and the exchange of matter and energy among stars and the interstellar medium
- Study the complete lifecycle of a star and the relationship with interstellar matter
- Study structure, energetics and dynamics of the interstellar medium
- Study star formation by high-resolution observations of protostars, disks, an outflows
- Study the origin and evolution of the elements
- Investigate how stars and planetary systems form together
- Study early evolution of large scale galactic clusters and early galaxy formation
- Observe and study galaxies near the time of their formation at very high red-shift

NASA Contribution to Herschel

Far-Infrared Devices



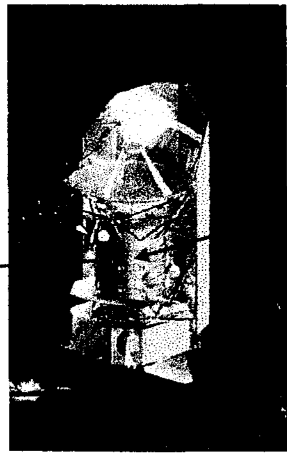
HEB Mixer

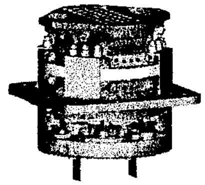
Twin slot SIS Mixer

92 GHz MMIC Amplifier

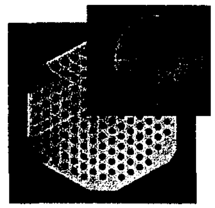
MMIC Multiplier

HIFI





Focal Plane



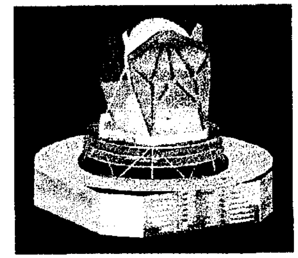
Bolometer Array

SPIRE

Planck Project Overview

Mission Overview

- ESA Mid Sized Mission
- Millimeter Cosmology Mission with 1.5-m Telescope
- U.S. Participating in Both Instruments
- U.S.Technology Contribution
  - Bolometer Detectors
  - Cryogenic HEMT Amplifiers
  - Sorption Cryocooler
- Launch Date: Mid-2007 to L2 orbit



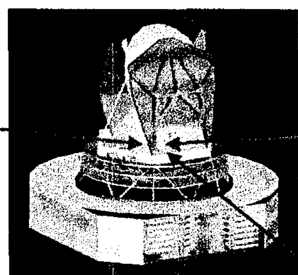
Science

- CMB anisotropy with sensitivity and resolution set by astrophysical limits
- Determine how structure in our Universe emerged from the Big Bang
- Cosmological parameters to unprecedented accuracy
  - Curvature of space (equivalent to knowing total energy of the universe, Ω_0)
  - Total non-relativistic matter density (cold dark matter + baryons)
  - Upper limit on on the energy scale of inflation
- Investigate how dark and luminous matter determine the geometry and fate of the Universe
- All-sky surveys of IR the most luminous cm-farIR objects in the universe
- All sky surveys of galaxy clusters, including the first clusters formed

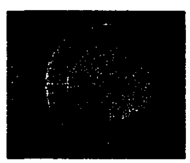
NASA Contribution to Planck

LFI

Cryogenic low-noise amplifier technology and radiometer expertise

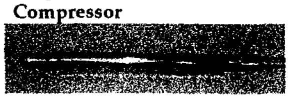


HFI

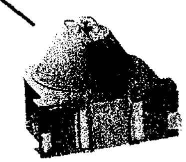


Spider Web Bolometers

Single Cryocooler Compressor



Cryocooler Compressors



Cryocooler Cold End

Astrophysics Drivers for THz Sensors

Key Science Programs	Required Measurements
Origin of Galaxies	Ang resolution @80 μm <5" Imaging: λ/Δλ~3, 80–670 μm Spectroscopy: λ/Δλ~1x10⁴, 80–670 μm
Evolution of Stars and Galaxies	Ang resolution @80 μm <5" Imaging: λ/Δλ~3, 80–670 μm Spectroscopy: λ/Δλ>10⁵, 111–620 μm
Origin of Stars and Planets	Ang resolution @80 μm <5" Imaging: λ/Δλ~3, 80–670 μm Spectroscopy: λ/Δλ > 10⁷, 111–620 μm

Engineering Implications

Telescope
~ 3.5m, diffraction-limited at 130 μm (80 μm goal).

Heterodyne Instrument
0.48–2.7 THz (111-620μm)
$\lambda/\Delta\lambda > 10^7$
Physical temp 1.7K

Bolometer Instrument
>1000 pixels
Physical temp ~ 0.3K
Fourier Transform Spectrometer
200–670 μm
$\lambda/\Delta\lambda$ >20-1000
Imaging Photometer
200–670 μm
$\lambda/\Delta\lambda \sim 3$

Photoconductor Instrument
European instrument

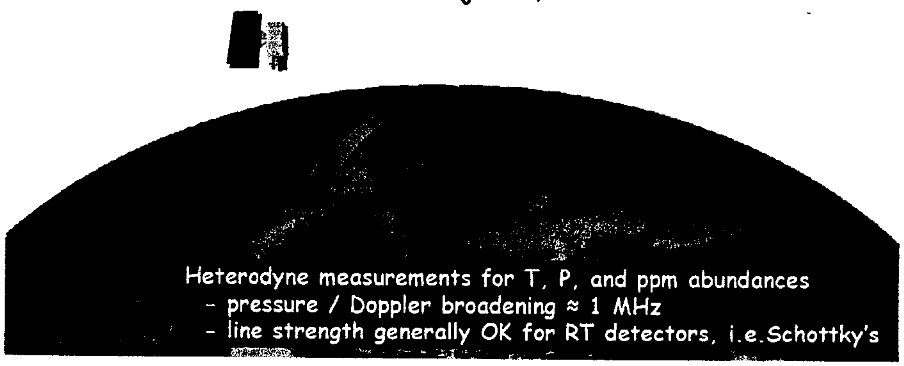
Key Technologies

Photomixers & MMIC Amplifier Driven Multiplier LO Sources
P > 50 μW
ν < 1.25 THz
P > 1 μW for
ν > 1.41 THz
Tuning range > 10%
SIS, HEB Mixers
$T_{noise} < 5\ h\nu/k$ (Goal)
0.48–2.7 THz

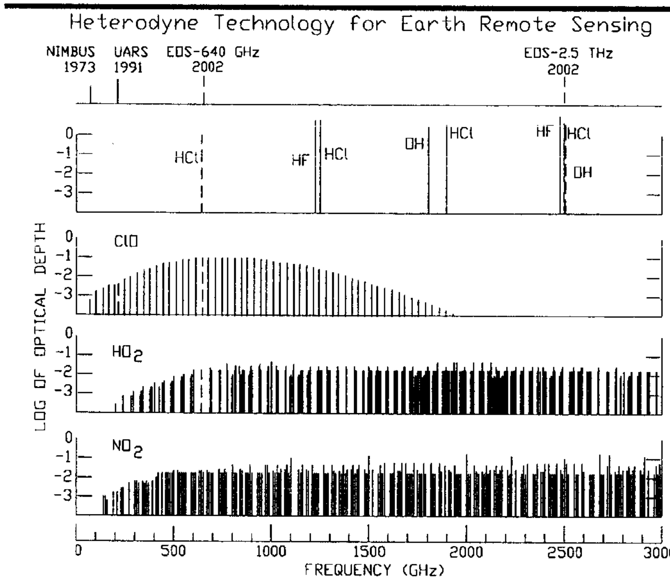
Spider or Pop-up Bolometer Arrays
32 x 32
Response > 10 Hz
NEP < 10^{-17} W/Hz$^{1/2}$

Application: Earth Remote Sensing of the Upper Atmosphere

- Stratospheric and Tropospheric Chemistry
  - ozone layer modeling
  - economics vs. environment
  - water distribution/pollutants
- Clouds: Global Warming
  - ice crystals: size and distribution
- Aerosols, Volcanic Ejecta, Dust

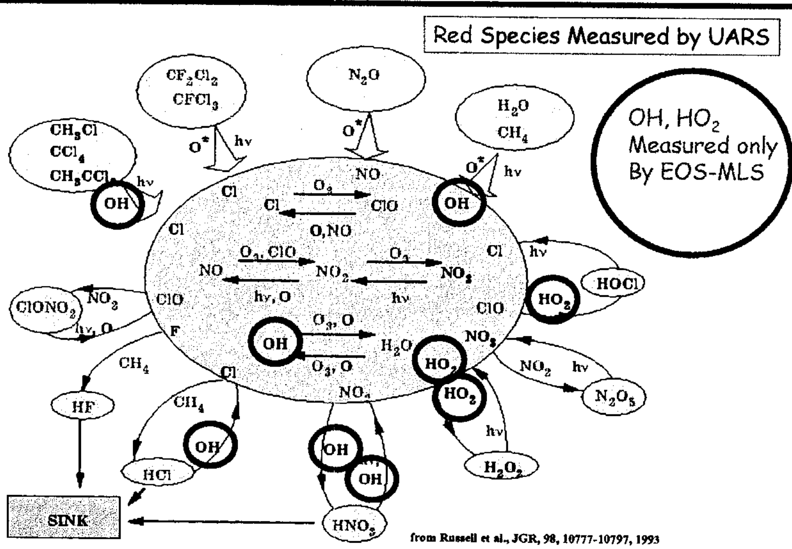


Submillimeter Spectra for Earth Remote Sensing



Spectra of some important molecules in the Earth's upper atmosphere and measurements being addressed by NASA heterodyne instruments. The peak power or minimum frequency for many emission lines occurs in the THz region. *(From: J. Waters, EOS Atmospheres presentation, Goddard Space Flight Center, 1991)*

Ozone Cycles

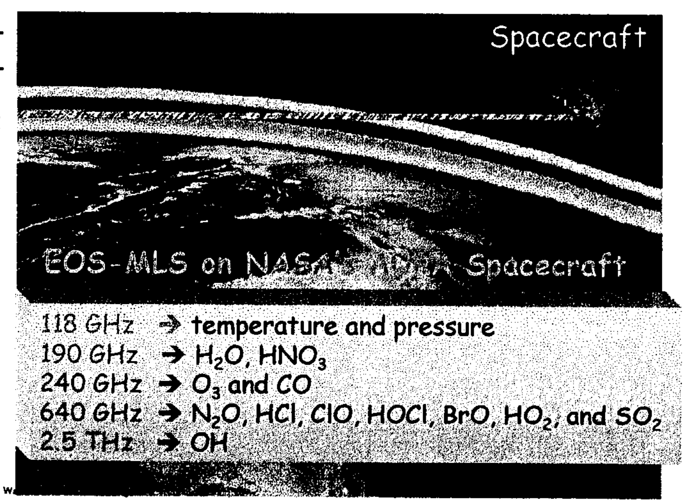


from Russell et al., JGR, 98, 10777-10797, 1993

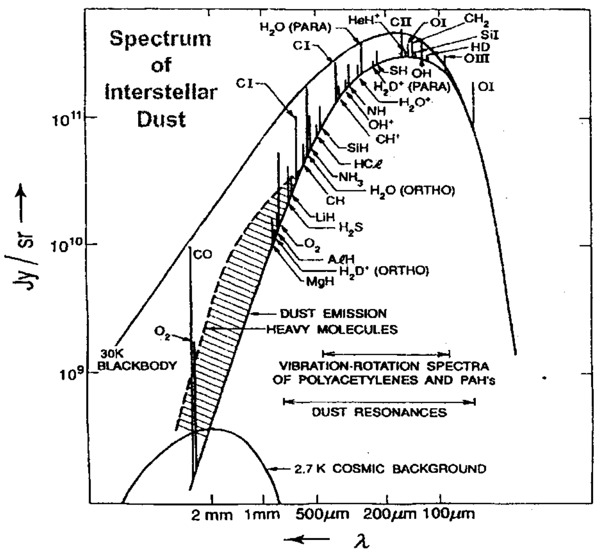
Applications: Microwave Limb Sounding

Remote Sensing with Fine Height Resolution (≈ 1 km)

Tangent Height ↕



Astrophysics Drivers for THz Sensors



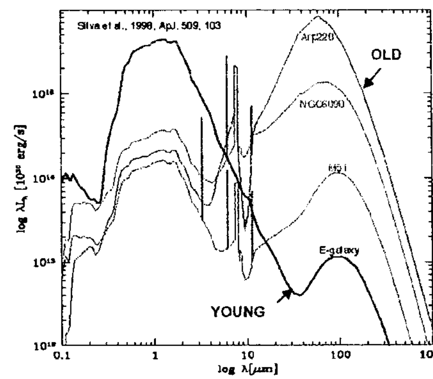
THz is the primary freq. for line and continuum radiation from cool (5-100 K) gas (atoms and molecules) and dust.

Useful for Studying Stellar and Galactic Constituents and Evolution, Cosmology, Dust & Gas Chemistry, Cosmic Background Physics.

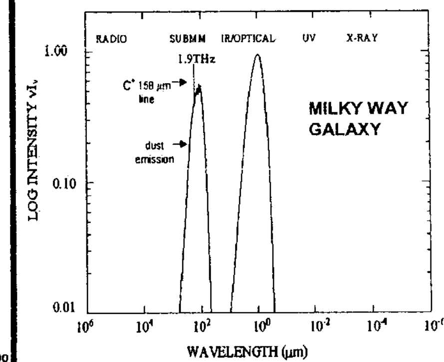
LEFT: Radiated Energy vs. Wavelength showing 30K blackbody, interstellar dust and key molecular line emissions *(from Tom Phillips, IEEE Proc., 80, no. 11, 1992).*

Galactic Emission at THz Frequencies

Half the luminosity and 98% of the photons released since the Big Bang fall into the Submillimeter and Far IR regions



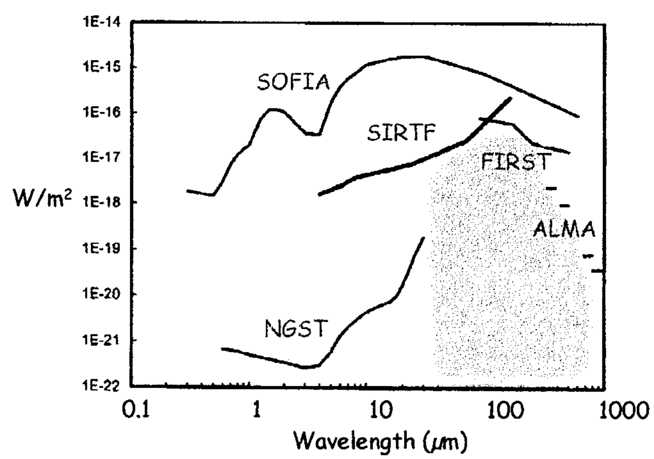
Energy output vs. wavelength for galaxies of ascending ages showing advantages of THz detection for probing the early universe (*Courtesy Bill Langer – Herschel Sp. Obs. Archives*)



Spectrum of Milky Way galaxy showing luminous power output vs. wavelength. Almost 50% of the power is emitted at THz frequencies! *(From D. Leisawitz, SPIE Proc.,* ***4013****, Mar 2000)*

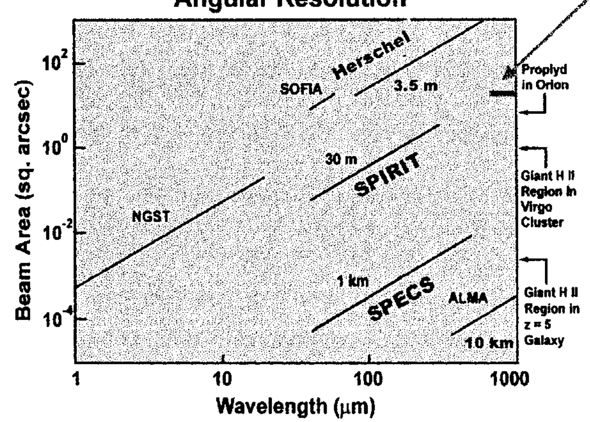
Planned Sensitivity and Wavelength Coverage

Detectable Flux in 3 Hour Integration (5σ)

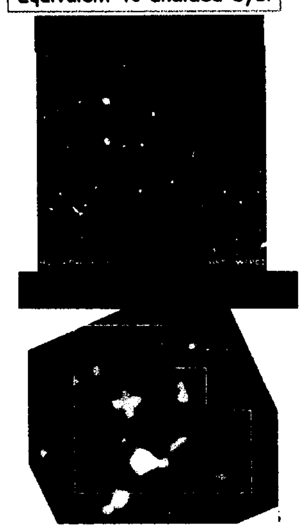


from G. Rieke and S. Beckwith in the McKee-Taylor Decadal Review

Antenna Drivers for Space Astrophysics



15m aperture @ 300 GHz
Equivalent to unaided eye!



30 m baseline required for resolving star-forming regions

1 km baseline needed to resolve protoplanetary disks & high-Z galaxies!

Slide courtesy of D. Leisawitz, GSFC

Planetary Science Drivers

- Comets
  - * Oceans on earth? Life on earth?
- Kuiper Belt objects
  - * Origin & evolution of solar system
- Planetary Atmospheres
  - * Remote studies of gas giant planets
  - * Venus orbiter (VESPER)
  - * In situ studies of atmospheric dynamics
    - atmosphere - regolith interaction (e.g., on Mars) & evolution of atmospheres
    - in situ weather stations on remote planets (e.g., Mars)
- Planetary Volcanism and Life Signatures
  - * Remote studies of subsurface gas emission from organic and volcanic sources (e.g. Mars/Europa, Callisto)
- Long-Term
  - * Large-baseline interferometers for atmospheric chemistry of extra-solar planets

- **The authors would like to thank the many contributors who provided slides or material for this presentation, especially Dave Leisawitz, Bill Langer, Tom Phillips, George Reike, Eric Mueller, Giles Davies, Jonas Zmuidzinas, Rick LeDuc, Rolf Wyss, John Ward,Lorene Samoska, Jamie Bock, Rob McGrath, Joe Waters and Jim Russell.**

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