Far-Infrared Technology for Spaceborne Applications

Michael Gaidis, Ph.D.

Submillimeter Wave Advanced Technology Group at JPL

Peter H. Siegel (Technical Supervisor)
Devices: Suzanne Martin (Group Leader): Tracy Lee, Barbara Nakamura, Peter O’Brien, James Velebir
Circuits: Imran Mehdi (Group Leader): Jean Bruston, Goutam Chattopadhyay, Robert Dengler,
Alain Maestrini, Frank Maiwald, Andrea Neto, Lorene Samoska, Erich Schlecht
Flight: John Oswald (Group Leader): Mike Gaidis, Karen Lee, Robert Lin, David Pukala,
Raymond Tsang, Tigran Karsian

Gaidis, IEEE Frequency June 7, 2000 JPL
Goals of this talk

• Convey the importance of the FIR/THz/Submm spectral region, and show its great potential for *breakthrough discoveries*
• Review the common *THz detectors* with an eye to the future (not enough time to cover sources today)
• Review what the *science community needs* from you
What can you do with FIR?

Cosmology

Astrophysics

Life on Extra-Solar Planets

Planetary

Galaxy Evolution

Atmospheres

T-Ray Spectroscopy

Goldilas, IEEE Frequency June 7, 2000 JPL
Astrophysics: Photons in the Far-Infrared

Common processes which produce FIR radiation:
- thermal emission from interstellar dust
- fine structure line emission from atoms and ions
- rotational line emission from molecules
- synchrotron and bremsstrahlung from hot electrons

98% of post-Big Bang photons are in the FIR!

D. Leisawitz, GSFC

COBE Spectrum of the Galaxy

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Energy of Photons in the Milky Way

\[ \text{Log (Intensity)} \]

\[ \approx 50\% \text{ of TOTAL energy is in the FIR!} \]

From D. Leisawitz, GSFC (and COBE)

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Astrophysics: What are the questions?

from “The Submm Frontier…” by J.C. Mather et al.

• When was “first light”? Did the first generation of stars form in early galaxies or before such systems existed? (Did star formation = galaxy formation?)

• What is the history of energy release and nucleosynthesis in the universe? How did carbon, oxygen, other heavy elements, and dust build up over time? What dispersed the metals?

• Did the process or rate of star formation change over the course of cosmic history? How might changes in the star formation process be attributed to the gradual enrichment of the interstellar medium with heavy elements? Are stars different today than they were at first light?

• What are the processes of structure formation in the universe? When and how did the first bulges, spheroids, and disks form? How did galaxies in today’s universe form?
Astrophysics: FIR sees the First Stars and Galaxies

Imagine the universe expanding like a balloon, and we are on the surface. This is a slice taken from the balloon showing the progression of the surface with time.

From J. Mather, GSFC
NGST web site

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Astrophysical Sources and their Spectra

<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>Wavelength Range (nanometers $[10^n m]$)</th>
<th>Radiated by Objects at this Temperature</th>
<th>Typical Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma rays</td>
<td>Less than 0.01</td>
<td>More than $10^8$ K</td>
<td>Few astronomical sources this hot; some gamma rays produced in nuclear reactions</td>
</tr>
<tr>
<td>X-rays</td>
<td>0.01 - 20</td>
<td>$10^6 - 10^8$ K</td>
<td>Gas in clusters of galaxies; supernova remnants, solar corona</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>20 - 400</td>
<td>$10^5 - 10^7$ K</td>
<td>Supernova remnants, very hot stars</td>
</tr>
<tr>
<td>Visible</td>
<td>400 - 700</td>
<td>$10^3 - 10^5$ K</td>
<td>Exterior of stars</td>
</tr>
<tr>
<td>Infrared</td>
<td>$10^5 - 10^6$</td>
<td>$10 - 10^5$ K</td>
<td>Cool clouds of dust and gas; planets, satellites</td>
</tr>
<tr>
<td>Radio</td>
<td>More than $10^6$</td>
<td>Less than $10^5$ K</td>
<td>Dark dust clouds</td>
</tr>
</tbody>
</table>

Gaitska, IEEE Frequency June 7, 2000 JPL
Atmospheric & Planetary Research in the FIR

- Ozone Depletion Studies on Earth
- Cloud Ice, Global Warming
- Aerosols, volcanic eruptions, dust...
- Search for H$_2$O in solar system bodies
- Chemical mapping of Venus, Titan, ... atmospheres
- Comet outflows and composition
Molecular Oxygen (O₂) Transitions

* note that the temperature of the observed object does not necessarily correspond to the frequency of emitted/absorbed radiation

≈ 70 K
Important Atmospheric Components Measured by EOS-MLS on NASA’s AURA Spacecraft

- Temperature and pressure
- 190 GHz → H₂O, HNO₃
- 240 GHz → O₃ and CO
- 640 GHz → N₂O, HCl, ClO, HOCl, BrO, HO₂, and SO₂
- 2.5 THz → OH

GHz Module

Spacecraft
THz Module

Spectrometer
Progress in Heterodyne Sensors for Atmospheric Studies

1991: 63 GHz to 205 GHz

UARS - MLS
prior to S/C integration

2003: 118 GHz to 2500 GHz

EOS - MLS
in thermal vacuum test chamber
T-Rays

Picometrix, Bell Labs, and Toshiba Cambridge Research Lab
## Energy/Temperature Scales

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Description</th>
<th>Energy Value</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6 THz</td>
<td>CMB $\approx 2.7$ K</td>
<td>$k_B T$</td>
<td>2.7 K</td>
</tr>
<tr>
<td></td>
<td>$\lambda = 500$ $\mu$m</td>
<td>$h\nu$</td>
<td>28 K</td>
</tr>
<tr>
<td></td>
<td>Nb Superconducting Gap</td>
<td>$2\Delta$</td>
<td>35 K</td>
</tr>
<tr>
<td></td>
<td>GaAs Donor Ionization</td>
<td>$E_d$</td>
<td>70 K</td>
</tr>
<tr>
<td>1.9 THz</td>
<td>Ionized Carbon (CII)</td>
<td>$h\nu$</td>
<td>93 K</td>
</tr>
<tr>
<td></td>
<td>Interstellar Clouds</td>
<td></td>
<td>10 - 100 K</td>
</tr>
<tr>
<td>2.5 THz</td>
<td>OH Radical</td>
<td>$h\nu$</td>
<td>120 K</td>
</tr>
<tr>
<td>6 THz</td>
<td>$\lambda = 50$ $\mu$m</td>
<td>$h\nu$</td>
<td>290 K</td>
</tr>
<tr>
<td>Room Temp</td>
<td>$\approx 295$ K</td>
<td>$k_B T$</td>
<td>295 K</td>
</tr>
<tr>
<td>SS Carbon</td>
<td>Ionization</td>
<td>$E_d$</td>
<td></td>
</tr>
</tbody>
</table>
THz devices: electrons or photons?  
waves or particles?

μ-Wave HEMTs  
**Electrons!**

500 μm  
600 GHz

Infrared CCDs  
**Photons!**

50 μm  
6 THz

at this time, *neither* approach works very well in the THz region!
Materials in the THz regime

Cannot assume *anything* is benign!

-/comment Superconductors: Cooper pairs are split by THz photons ($\Delta \approx \text{THz}$)
-/comment Metals: anomalous skin effect ($e^- \text{mfp} > \text{skin depth}$); acoustic phonons absorb
-/comment Semiconductors: free carriers and acoustic phonons absorb; plasma $f \approx \text{THz}$
-/comment Dielectrics: $n_{\text{optical}} \neq n_{\text{THz}} \rightarrow$ alignment difficult; strong phonon absorption
-/comment Polymers & Plastics: intermolecular modes absorb strongly (but $n_{\text{optical}} \approx n_{\text{THz}}$)
-/comment Liquids: molecules' vibration and rotation strongly absorb THz
-/comment Gasses: simple molecules vibrate/rotate at THz; water absorption is horrendous
-/comment Dust, Aerosols: grains the size of THz wavelengths scatter
-/comment Surfaces: conventional machining can be rough on $\lambda$ scales
-/smiley Absorbers: *this* is not too difficult to find!

*However, the savvy innovator can capitalize on these properties to create new applications and new instrument concepts*
## Capitalizing on Materials Properties

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Property</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconductor</td>
<td>THz breaks Cooper Pairs</td>
<td>Photon-based direct detector similar to diode</td>
</tr>
<tr>
<td>Semiconductor</td>
<td>Plasma frequency, free carrier absorption</td>
<td>Diagnostic in semiconductor processing (carrier concentration, etc.)</td>
</tr>
<tr>
<td>Polymers &amp; Plastics</td>
<td>Strong phonon absorption; characteristics different for different materials</td>
<td>Specific spectral signature can be used for analysis of materials (TDS)</td>
</tr>
<tr>
<td>Liquids</td>
<td>THz coupling to molecular excitations</td>
<td>Chemical analyses</td>
</tr>
<tr>
<td>Gas</td>
<td>THz vibrational/rotational modes</td>
<td>Remote sensing</td>
</tr>
<tr>
<td>Gas (H₂O)</td>
<td>Strong absorption</td>
<td>Minimize communication signal interference (LANs)</td>
</tr>
<tr>
<td>Biochemical</td>
<td>Strong absorption; characteristics vary widely for different materials</td>
<td>Medical imaging</td>
</tr>
<tr>
<td>Ice Crystals</td>
<td>Interaction with THz radiation depends on crystal size</td>
<td>Quantify cloud ice effects in Earth's thermal balance</td>
</tr>
</tbody>
</table>
Atmospheric Absorption

HF VHF Microwaves mm-Waves Far IR Infrared Vis UV

Wavelength

Ionosphere Opaque
Radio Window
Mountaintop Transmission is Acceptable
Atmosphere Opaque
Optical, IR Window
Atmosphere Opaque

from MIPAS

Gaidis, IEEE Frequency June 7, 2000 JPL
Avoiding Atmospheric Absorption

Stratosphere: SOFIA
≈ 41,000 feet

Mountaintop: Mauna Kea
≈ 13,000 feet

South Pole: AST/RO
≈ 1000 feet

Outer Space (L2): FIRST
≈ 1,000,000 miles

Mesosphere: Balloons
≈ 100,000 feet
Designing for Space

- Radiation, Space Environment
- Launch Vibration
- Deployable Structures
- Paperwork, Red Tape
- Vacuum Operation
- No Repairs
- Precise, Careful Engineering
- Light-Weight Structures

Gaidts, IEEE Frequency June 7, 2000 JPL
Detector Types: Tradeoffs

Note: the previous slides do not tell the whole story!
(very simplistic generalizations)
Many tradeoffs to consider:

1) observing frequency
2) background noise (telescope, object, atmosphere)
3) required sensitivity and dynamic range
4) integration time and detector fluctuations or response time
5) spectral resolution
6) spectral coverage
7) spatial resolution
8) spatial coverage and beam pattern
9) detector availability, complexity, and cost
10) instrument lifetime (cryogen use, opportunity for repair, ...)
11) instrument power requirements (local oscillators, coolers, ...)
12) instrument mass and volume
13) sensitivity to the environment (thermal, radiation, EMI, ...)
14) heritage; past successes and failures

Gaidis, IEEE Frequency June 7, 2000 JPL
Dominant FIR/Submm Detector Applications: Sensitivity vs. Wavelength

Wavelength (μm)

1000  300  30

highest

Galaxy Studies (Mixers)
CMB & SEU (Bolometers)
(Bolometers & Photoconductors)

SEU
CMB = Cosmic Microwave Background

Atmospheric & Planetary
(Mixers)

in situ Materials Studies
(T-Rays)

SEU = Structure & Evolution
of the Universe

lowest

0.3  1.0  10

Frequency (THz)

Gaidls, IEEE Frequency June 7, 2000 JPL
Dominant FIR/Submm Detector Niches:
Sensitivity vs. Wavelength

Wavelength (μm)

1000  300  200  60  30

Sensitivity

highest

Bolometers
(≤300 mK)

Photoconductors
(≈2 K)

Mixers

lowest

SIS (4 K)

HEB (4 K)

Schottky (20 K to 300 K)

Frequency (THz)

0.3  1.0  1.5  5.0  10

Gaidis, IEEE Frequency June 7, 2000 JPL
Dominant FIR/Submm Detector Niches:
Spectral Resolution vs. Wavelength

Wavelength (µm)

1000 300 200 60 30

SIS (4 K)  HEB (4 K)

Schottky (20 K to 300 K)  Mixers

Bolometers (< 300 mK)

Photoconductors (~ 2 K)

Spectral Resolution

$f/\Delta f$

Frequency (THz)

0.3 1.0 1.5 5.0 10
Noise Sources

- Photon noise (like shot noise)
- Confusion noise (infrared cirrus, high-Z objects)
- Atmospheric transmission noise (like attenuator at T>0)
- Optics noise (reflector loss or dielectric absorption is like an attenuator at T>0)
- Detector noise
  - Heterodyne Detectors: *i.e.* Electronic "wave" detectors
    - Quantum noise (associated with phase sensitive detection)
    - Shot noise
    - Thermal (Johnson) noise
    - Gain fluctuations
  - Direct Detectors: *i.e.* Photon "particle" detectors
    - Bolometers
      - Thermal (Johnson) noise
      - Phonon shot noise
    - Photoconductors
      - Shot noise
Passive Remote Sensing: Heterodyne Components

EOS - MLS Instrument

Back End Spectrometer / Filter Bank

Schematic Prepared by Dennis Flower, JPL
THz Heterodyne Mixers; Y2K

MOMED (JPL)
GaAs Schottky @ RT
≥ 800 GHz

HEB (JPL)
Nb Hot Electrons @ 4 K
≈ 1 THz and up

Quasi-optic coupling
with twin-slot antennas

SIS (Caltech, JPL)
NbTiN superconductor @ 4 K
≈ 100 GHz to ≈ 1.2 THz

Gaidis, IEEE Frequency June 7, 2000 JPL
OLD: Whisker contacted Schottky Barrier Diodes

used for both heterodyne downconversion (mixing) and local oscillator power generation (varactor multiplication) for UARS

UVa point-contact GaAs Schottky diode for 200 GHz mounted in metallic waveguide mixer block

UVa point-contact GaAs Schottky diode for 2 THz operation (submicron anodes)
NEW: T-Gate Schottky Anode Geometry

Reduces parasitic resistance by as much as 2X without increasing capacitance and allows submicron anode area (<.05 \( \mu \text{m}^2 \)) for >15 THz cutoff frequencies.

SEM's of JPL submicron T-gate style Schottky anode for 2.5 THz mixing applications.

Advances in planar diode and circuit topology have helped establish the credibility of THz space-borne heterodyne instruments – several of which are now in production.
JPL Mixer: Planar Diode on Membrane Devices
Monolithic Membrane Device (MOMED) Mixer at 2520 GHz

Top Right: Close up of 2.5 THz waveguide (50x100μm).
Below: Dual mode 2.5 THz feedhorn mandrel.
Below Right: Beam pattern of horn & MOMED at 2520 GHz.

Gaidis, IEEE Frequency June 7, 2000 JPL
Receiver Noise: JPL Schottky MOMED

Signal Resolution:
\[ \Delta T_{\text{sig}} \approx \frac{T_n}{\sqrt{B\tau}} \]

for \[ T_n = 6500 \text{ K} \]
\[ B = 10 \text{ MHz} \]
\[ \tau = 1 \text{ second} \]

\[ \Delta T_{\text{sig}} \approx 2 \text{ K} \]
EOS-MLS 2.5 THz Receiver Front End
# Summary of Submillimeter-Wave Receivers being built at JPL

<table>
<thead>
<tr>
<th>JPL INSTRUMENT</th>
<th>PURPOSE</th>
<th>RADIOMETER CHANNELS</th>
<th>KEY MEASUREMENTS</th>
<th>IMPLEMENTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>VESPER Venus Orbiter (proposal)</td>
<td>Atmospheric chemistry on Venus</td>
<td>2 Radiometer Bands: 470, 557 GHz</td>
<td>80 key lines: Water, CO, CO2, HD, Oxygen, ...</td>
<td>470: Schottky QUID Subharmonic mixer 557: Schottky QUID Sub harmonic mixer</td>
</tr>
</tbody>
</table>

prepared by Peter Siegel

Galile, IEEE Frequency June 7, 2000 JPL
Heterodyne Receiver Noise and LO Power: Y2K

Obvious need for better sources!
Direct or Heterodyne: How do I choose?

If you want sensitivity...

*Direct Detection: high frequency*
*Heterodyne: low frequency*

Crossover in techniques at frequency where source thermal noise ≈ quantization noise

\[ k_B T \approx h\nu \]

roughly, \( \lambda \approx 100 \mu \text{m} \) or \( \nu \approx 3 \text{ THz} \)

**Direct vs. Heterodyne involves many tradeoffs, and the specific application will often make the choice for you.**
How far behind is THz?

Angular Resolution

A 30 m baseline is needed to see individual high-z galaxies

A 1 km baseline is needed to resolve the young galaxies

from D. Leisawitz, GSFC
How far behind is THz? (continued)

Point Source Detectability

from D. Leisawitz

Galits, IEEE Frequency June 7, 2000 JPL
Pressing FIR/Submm Detector Needs:
Sensitivity vs. Wavelength

Wavelength (μm)

| 1000 | 300 | 30 |

Sensitivity

- Ultra-Sensitive Arrays of Bolometers
- Tunable LO Sources for Mixers
- Improved Mixers: HEB, Schottky
- High-Power, Tunable LO Sources
- Compact Instruments
- High-Power Sources

Frequency (THz)

0.3 1.0 10

Goldb, IEEE Frequency June 7, 2000 JPL
The Present State of FIR Technology

Present state: similar to optical astronomy in the 1950's!!

They've come a long way in 22 years!

- Huge increase in sensitivity, and angular resolution over current and proposed missions is possible, unique in the EM spectrum
- Simultaneous spectral information provides great potential for BREAKTHROUGH discoveries!
The LAST Viewgraph

This is a fun and exciting field!
- Revolutionary technology is being developed and will be rapidly implemented
- Factors of 2 to 10 improvement are common

It is challenging, but there is a BIG payoff

What legacy do YOU want to leave for future generations?

T-Rays can stop terrorism, cure heart disease and cancer, and alleviate traffic congestion (OK, maybe not “stop terrorism”)