# THz Sources for Space

Peter H. Siegel, Caltech
Frank Maiwald/Imran Mehdi/John Ward, JPL

Submillimeter Wave Advanced Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

**Department of Defense**
**Advisory Group on Electron Devices**
Special Technology Area Review on
**COMPACT THZ SOURCES**
**ONR/AFOSR Headquarters, Feb 28 -Mar 2, 2007**

# Outline

- Drivers for Terahertz Space Applications
- Terahertz Space Missions:

  Past, Present and Future
- Terahertz Source Requirements

  Examples of some JPL instruments
- Case Study for Flight Deliverable:

  THz Local Oscillators for ESA's Herschel Space Telescope

# Motivations

## TRADITIONAL

- ASTROPHYSICS: Molecular Spectroscopy, Continuum Black Body, Cosmic Background
- EARTH: Water, ozone, pollutants, aerosols, ice
- PLANETS: Atmospheric composition, winds

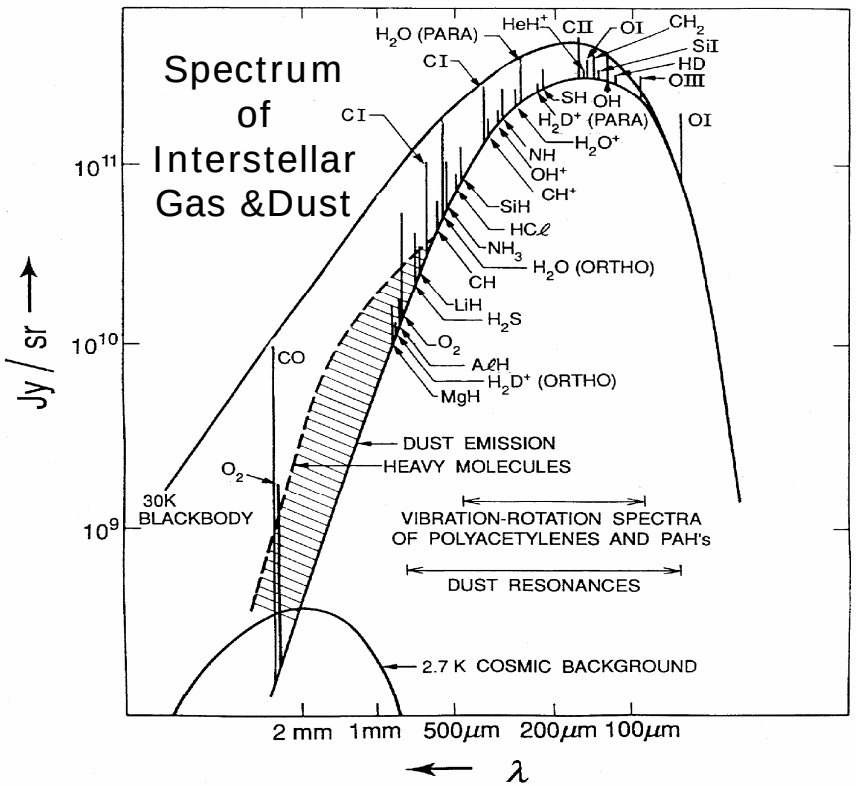
## NEW

- ASTROPHYSICS: Extra Solar Planets (5-10 THz)
- EARTH: Meteorology/Climate (mm/submm)
- PLANETS: Thermal mapping, Astrobiology (submm)

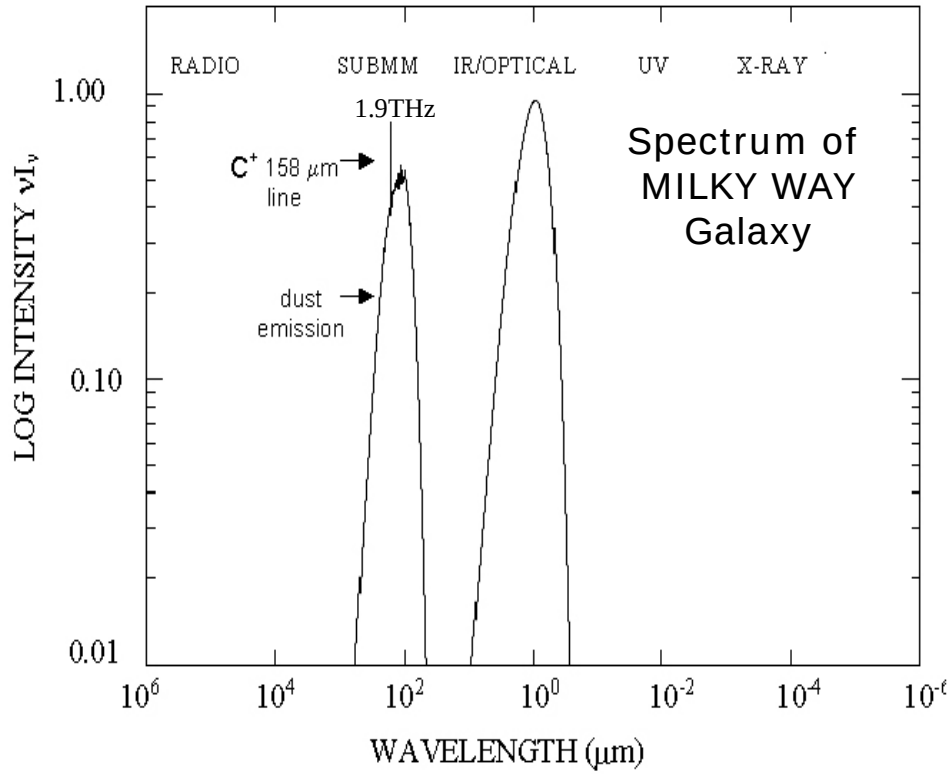
# THz Space Science Drivers

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

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




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




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

# New Space Science Missions

**Despite large funding cuts in core technology & the shift to human exploration at the expense of many NASA science missions, THz remote sensing instruments still occupy prominent places in several mission queues. *These include:***

- CAMEO: A comprehensive Earth/weather sounder (mission of opportunity, including potential NOAA queue)
- Vesper: A Venus orbiter for atmospheric limb scanning (Discovery class)
- Marvel/Signal: A Mars sounder looking for volcanic and bio signatures as well as performing atmospheric chemistry (Scout Mission or Mars Express class)
- TOAM: Titan orbiter & balloon borne probe (Observatory class)
- TRACE: New active radar spectrometer for Europa (Obs. Class)
- SAFIR and SAFIR lead-ins: Observatory class astrophysics instrument for full millimeter-to-infrared coverage
- TIP: A new terrestrial planet finder concept using far-IR interferometer and direct detection techniques (Obs. Class)

# Types of THz Space Sensors

- Direct Detection
  - Broadband, high sensitivity, low spectral res.
  - Typical technologies (100 GHz-10 microns):
    - Spectrophotometers, cooled bolometers (.001-4K), photoconductors (100 GHz to 10 microns)
- Heterodyne Detection
  - Narrow band, mid-to-high sensitivity, high res.
  - Typical technologies (100-5000 GHz):
    - Schottky diode mixers, hot electron bolometers (4K), superconducting tunnel junctions (4K)

# THz Instrument Parameters

## TYPICAL REQUIREMENTS for SPACE APPLICATIONS

- FREQUENCY RANGE: 100 GHz-5 THz (most spectral lines)
- FREQUENCY RESOLUTION: 100kHz-10MHz & 2-20GHz for continuum
- RF FREQUENCY COVERAGE: 10-100 GHz (greater if possible)
- RECEIVER SENSITIVITY: 1-100X Quantum Limit ($h\nu/2k \sim 0.05K/GHz$)
- SOURCE POWER: 0.1-10mW for heterodyning, 10-1000mW for radar
- ANTENNA DIMENSIONS: 50 cm-to-30 meters plus interferometry
- COOLING REQUIREMENTS: 1milliKelvin–to-Earth Ambient
- POWER/MASS/VOLUME: 20-150W / 5-50kg / 1x1x1m
- RADIATION HARDNESS: 10-100 kRad (1 MegaRad some cases)
- THERMAL/VIBRATION: -55C to +70C/14g's 20-2000Hz, 1000g shock
- LIFETIME IN SPACE: 2-15 years
- TECHNOLOGY READINESS LEVEL: 5 to 9
- OTHERS: Completely autonomous, failsafe operation, low data rates and minimal data storage/compression (kb/s max), extreme thermal environments, complete performance traceability, *unimaginable oversight & documentation!*

# Technology Readiness

| NASA's Technology Readiness Level Index | | |
|---|---|---|
| **Stage** | **TRL** | **Hardware Status** |
| Basic Technology Research | 1 | Observe and report basic principles or new results that are more fundamental in nature. |
| Feasibility Research | 2 | Formulate concept or application. |
| | 3 | Prove the concept through analysis or experiment. |
| Technology Development | 4 | Validate the concept using components or breadboards in the laboratory |
| Technology Demonstration | 5 | Validate the component or breadboards in a relevant environment. |
| | 6 | Demonstrate a model or prototype in the relevant environment, ground or space. |
| System/Subsystem Development | 7 | Demonstrate a prototype in the space environment. |
| System Test, Launch and Operations | 8 | "Flight qualification" of the actual system through ground or space test. |
| | 9 | "Flight proven" through successful mission operations. |

# Survey of Space Instruments 1

## Completed THz Space Instruments

| Mission or Instrument | Launch Year | Agency or Country | Application | Frequency Coverage | Instrument Description | Status |
|---|---|---|---|---|---|---|
| Mariner 2 | 1962 | NASA | Venus Flyby | 15.8/22.2 GHz | Earliest μwave observations | Complete |
| Cosmos 243<br>Cosmos 384 | 1968<br>1970 | Soviet Union | Earth | 3-37 GHz | Water vapor and temperature sounding | Complete |
| Nimbus 5 | 1972 | NOAA | Earth | 22-60 GHz | Water vapor, temperature profiling, ice/snow | Complete |
| Cosmos 669 | 1974 | Soviet Union | Earth and Astrophysics | ≈300 GHz to <60 μm | 1st Earth & space IR measurements using cooled bolometers | Complete |
| Salyut 6 | 1978 | Soviet Union | Astrophysics | ≈200 GHz to <20 μm | Space station telescope with active 4K cooler and bolometric detectors | Complete |
| IRAS | 1983 | NASA | Astrophysics | 8-120 μm | Helium cryogen & cooled beryllium antenna | Complete |
| COBE | 1989 | NASA | Astrophysics | 30 GHz-3 THz and 1-240 μm | Cosmic background and IR mapper with high resolution interferometer & photometer | Complete |
| UARS-MLS | 1991 | NASA | Earth | 63,183,205GHz | 1st heterodyne receivers for high resolution spectroscopy of stratospheric | Complete |
| SSM/T-2 | 1991 | NOAA/DoD | Earth | 91,150,183GHz | Heterodyne for water vapor | Complete |
| ISO | 1995 | ESA | Astrophysics | 2-240 μm | Superfluid He, Fabry Perot, photometers and photoconducting detectors | Complete |

# Survey of Space Instruments 2

## Operational THz Space Instruments

| Mission or Instrument | Launch Year | Agency or Country | Application | Frequency Coverage | Instrument Description | Status |
|---|---|---|---|---|---|---|
| SWAS | 1998 | NASA | Astrophysics | 490,550 GHz | 1st submillimeter wave heterodyne instrument: water, O2 and CO | Completed |
| Odin | 2001 | Sweden | Astrophysics & Earth | 118, 490-500, 540-580 GHz | Heterodyne space & Earth sounder with Sterling cooler | Operational |
| WMAP | 2001 | NASA | Astrophysics | 90 GHz | Cosmic background w/MMIC's | Operational |
| Spitzer | 2003 | NASA | Astrophysics | 5-140 μm | Cooled telescope, multiband photometers & spectrograph | Operational |
| MIRO | 2004 | ESA | Comet | 188, 560 GHz | 1st submm-$\lambda$ heterodyne planetary mission. $H_20$,CO,$NH_3$, $CH_3OH$ | Operational Rendezvous in 2014 |
| Aura MLS | 2004 | NASA | Earth | 118, 180, 240, 640, 2520 GHz | 1st THz heterodyne mission: ozone & climate change | Operational |
| AKARI | 2006 | JAXA | Astrophysics | 1-180 μm | Cryogen plus active cooler 6K telescope, all sky survey | Operational |

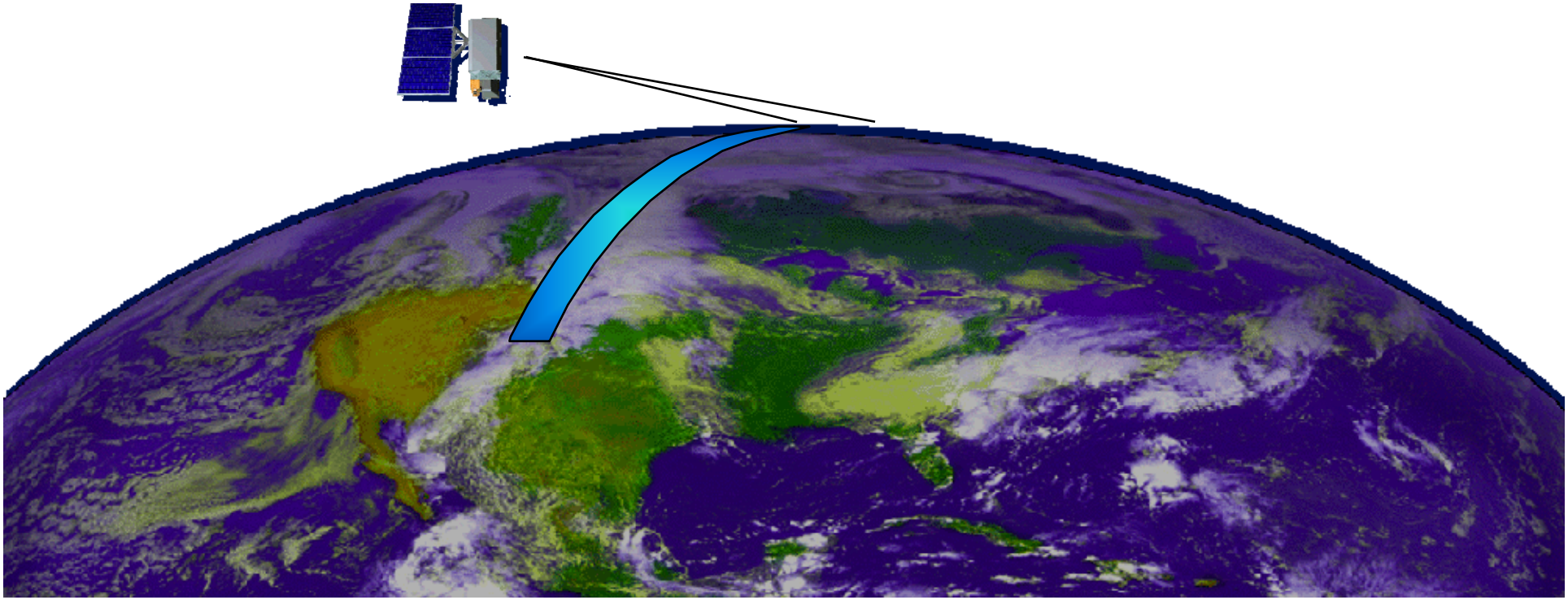
# Future THz Space Instruments

| Mission or Instrument | Launch Year | Agency or Country | Application | Frequency Coverage | Instrument Description | Status |
|---|---|---|---|---|---|---|
| Herschel | 2008 | ESA | Astrophysics | 480-1900 GHz and 60-200 μm | Heterodyne & direct detect, cooled telescope, multiple instruments | In Construction |
| Planck | 2008 | ESA | Astrophysics | 30-70 GHz, 100-850 GHz | Cosmic background with high & low freq. channels | In Construction |
| SMILES | 2008? | JAXA | Earth | 625-650 GHz | 1st superconducting heterodyne system for Earth observations | Completed, awaiting launch |
| Vesper | 2012+ | NASA | Venus | 460-560 GHz | High res. spectroscopy for clouds and winds | Approved Concept |
| Submilli-metron | 2015? | Russia | Astrophysics | 150-1500 GHz | Int. Space Station, cooled dish, He bolometers | Approved Concept |
| Future Astronomy | >2015 | NASA/ESA | Astrophysics | mm-to-IR | SAFIR, SPIRIT, SPECS, ESPRIT, STO, TIP… | Proposal Concepts |
| Future Earth | >2012 | NASA/ESA | Earth | mm-submm | CAMEO, ACECHEM, meteorological interfer. | Proposal Concepts |
| Future Planets | >2015 | NASA/ESA | Planets | mm-submm | Mars, Titan, Europa … | Proposal Concepts |

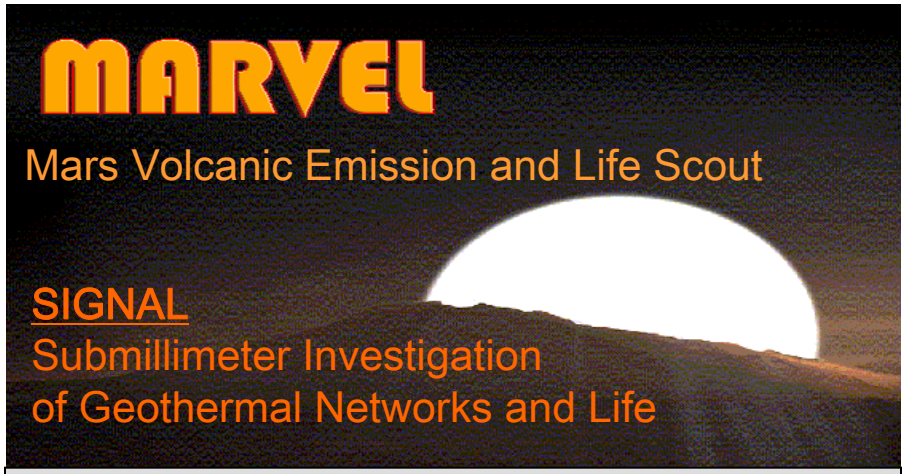
# Earth Remote Sensing for Climate and Ozone

**CAMEO:** Composition of the Atmosphere from Mid Earth Orbit: Pollution Monitoring, Ozone monitoring, Tropospheric chemistry, Water distribution, Cloud ice size and distribution, Radiation Balance through LIMB SCANNING

3 Instruments: (1) Submillimeter Limb Scanner – Superconducting Heterodyne Radiometers at 100, 200, 600 GHz, (2) AIRS - broadband thermal IR imaging spectrometers from 3-15um, (3) TROPI - UV, visible and near IR grating spectrometers



# Heterodyne Remote Sensing: Life, Volcanism, Chem. Composition, Wind, Temp., Pressure

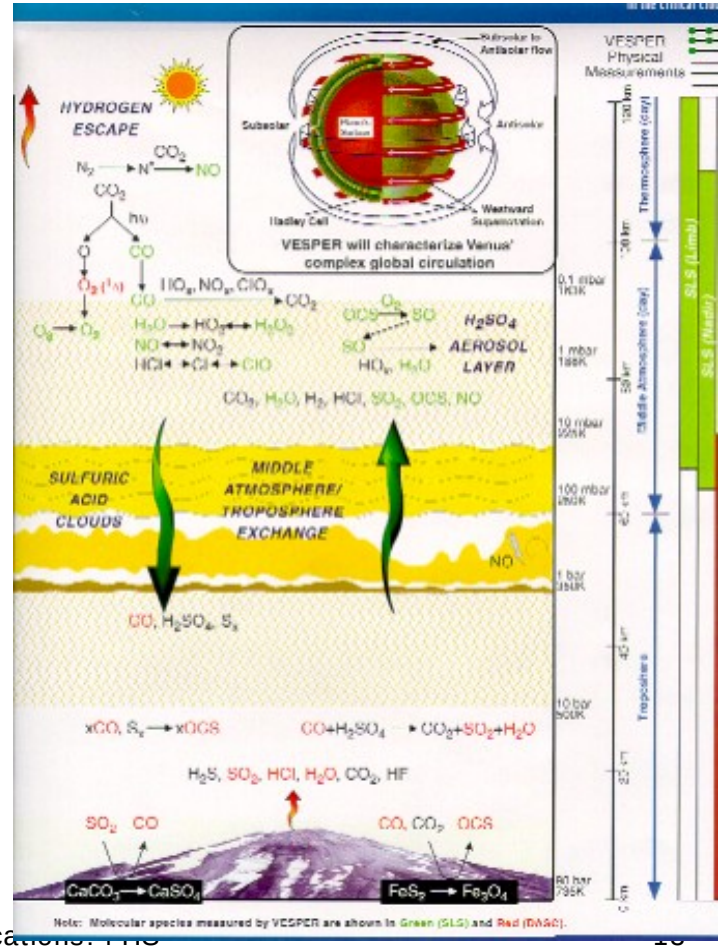



**SIGNAL Measurement suite and sensitivity for 15sec integration, 10 MHz BW, 5000K SSB noise temperature:**

| Molecule | Frequency | SIGNAL Sensitivity (pptv) | |
|---|---|---|---|
| | | Nadir | Limb grazing |
| HCN | 531.716388 | 1400 | 5 |
| HNO3 | 531.761329 | 419600 | 1399 |
| OCS | 534.7278 | 119900 | 400 |
| N2O | 552.487036 | 863300 | 2878 |
| H2O | 556.936002 | 5000 | 17 |
| SO | 560.178331 | 16700 | 56 |
| H2CO | 561.899318 | 12100 | 40 |
| O3 | 566.293689 | 681500 | 2272 |
| NH3 | 572.498068 | 23900 | 80 |
| CO | 576.267931 | 781000 | 2603 |
| H2S | 579.799042 | 112900 | 376 |
| H2O2 | 582.05595 | 33600 | 112 |
| HO2NO2 | 587.816003 | 3215700 | 10719 |
| SO2 | 589.271422 | 118100 | 394 |

**Vesper:** Venus Sounder

- Constituent Detection Above Clouds
- Direct Wind Velocity Measurements
- Temperature/Pressure Altitude Profile



# … and possibly for atmospheric insertion

**Orbiter & Balloon Borne Probe**

# TITAN ORBITER AERORover MISSION (TOAM)


E. C. Sittler Jr.[1], M. Acuna[1], M. Allen[2], G. Bjoraker[1], J. Brasunas[1], M. J. Burchell[3], M. Burger[1], G. Chin[1], A. J. Coates[4], J. F. Cooper[1], J. Esper[1], D. Fairbrother[5], W. Farrell[1], M. Flasar[1], B. Gerlach[6], S. Gorevan[7], J. Green[1], R. E. Hartle[1], Eastwood Im[2], D. Jennings[1], R. E. Johnson[8], W. T. Kasprzak[1], D. R. Kojiro[9], H. W. Kunow[10], S. Livi[11], H. Niemann[1], J. Nuth[1], P. Mahaffy[1], D. J. McComas[12], R. MacDowall[1], B. McKibben[13], R. Pfaff[1], J. Pitman[14], F. Raulin[15], D. Reuter[1], F. Robb[16], D. Schulze-Makuch[17], R. Wimmer-Schweingruber[10], P. Siegel[2], D. E. Smith[1], A. Steele[18], J. Trombka[1], Y. Yung[19], and J. C. Zarnecki[20].

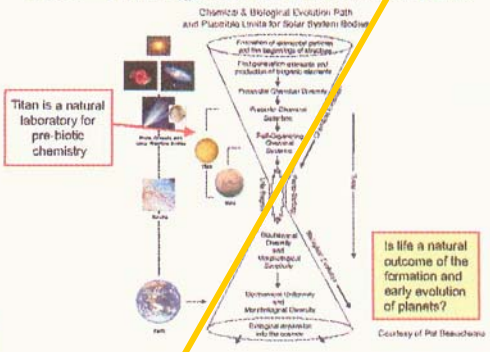
1. NASA Goddard Space Flight Center, Greenbelt, MD, USA, 2. Jet Propulsion Laboratory, Pasadena, CA, USA, 3. University of Kent, Canterbury, Kent CT2 7NH, UK, 4. Mullard Space Science Laboratory, University College London, Dorking, UK, 5. GSFC/Wallops Flight Facility, Wallops, VA, USA, 6. Rockwell Collins Deutschland GmbH, Grenzhöfer Weg 36, D-69123 Heidelberg, Germany 7. Honeybee Robotics, Ltd., New York, NY, USA, 8. University of Virginia, Charlottesville, VA, USA, 9. NASA Ames Research Center, Mountain View, CA, USA, 10. University of Kiel, Keil, Germany, 11. Applied Physics Laboratory, Laurel, MD, USA, 12. Southwest Research Institute, San Antonio, TX, USA, 13. University of New Hampshire, NH, USA, 14. Lockheed Martin Space Systems Company, USA, 15. LISA- University of Paris, France, 16. University of Maryland Biotechnology Institute, MD, USA, 17. Washington State University, Pullman, WA, USA, 18. Carnegie Institution of Washington, D.C., USA, 19. California Institute of Technology, Pasadena, CA, USA, 20. Open University, Milton Keynes, UK.



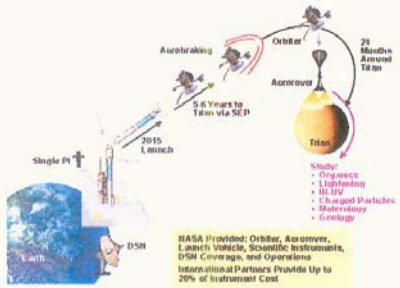
## Abstract

We propose to develop a new mission to Titan called Titan Orbiter Aerorover Mission (TOAM). This mission is motivated by the recent discoveries of Titan, its atmosphere and its surface by the Huygens Probe, and a combination of in situ, remote sensing and radar mapping measurements of Titan by the Cassini orbiter. Titan is a body for which Astrobiology will be the primary science goal of any future missions to it. TOAM is a multi-faceted mission with launch using a Delta IV Heavy for high C3 interplanetary orbit injection, possible Jupiter flyby, Solar Electric Propulsion (SEP), orbit injection via aerobraking at Titan, probe entry with balloon technology (i.e., Aerorover phase) and finally a landing phase. The cruise phase can last between 5-9 years, orbiter reconnaissance phase of ~ 6 months, Aerorover global reconnaissance phase ~ 6 months, Aerorover global surface science phase ~ 6 months and Aerorover landing phase ~ 6 months, with possibility of an extended mission. The orbiter will be powered by 3 MMRTGs and Aerorover by a single MMRTG. The Aerorover will probably use a hot air balloon concept using the waste heat from the MMRTG ~ 500-1000 watts. Our strategy to use an orbiter is contrary to some studies using just a single probe with balloon. Autonomous operation and navigation of the Aerorover around Titan, which will include descent near to the surface to collect surface samples for analysis, is in itself a very complex process and will require nearly continuous tracking and navigation updates. Only an orbiter can provide this capability as a relay station and GPS role so that the Aerorover will be able to navigate safely within Titan's environment, while maintaining nearly continuous communication with ground stations. Although very complex, our goal is to keep the Aerorover as simple as possible in order to enhance the likelihood of success. Experience has shown that such complex missions will develop unexpected problems, for which a balloon concept allows for it to safe itself by going to high altitudes and thus allow teams on the ground the necessary time needed to work around such problems. New technologies will need to be developed and miniaturization will be required to maintain functionality while controlling mass, power and cost. Duty cycling will be used. The orbiter will combine altimetry, radio science and remote sensing instruments to measure the global topography, sub-surface structure and atmospheric winds during its recon phase so that the Aerorover can use this information to navigate safely around Titan and identify prime sites for surface sampling and analysis. In situ instruments will sample the upper atmosphere which may provide the seed population for the complex organic chemistry on the surface. The Aerorover will have all the instruments needed to sample Titan's atmosphere, surface, possible methane lakes/rivers, use multi-spectral imagers for recon phase of surface and take close up surface images and during landing phase take core samples and use seismometers.

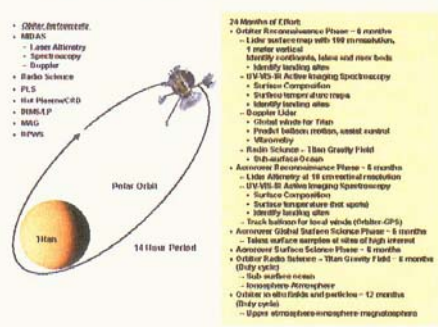

## Titan – An Organic-rich Environment




## Mission Concept

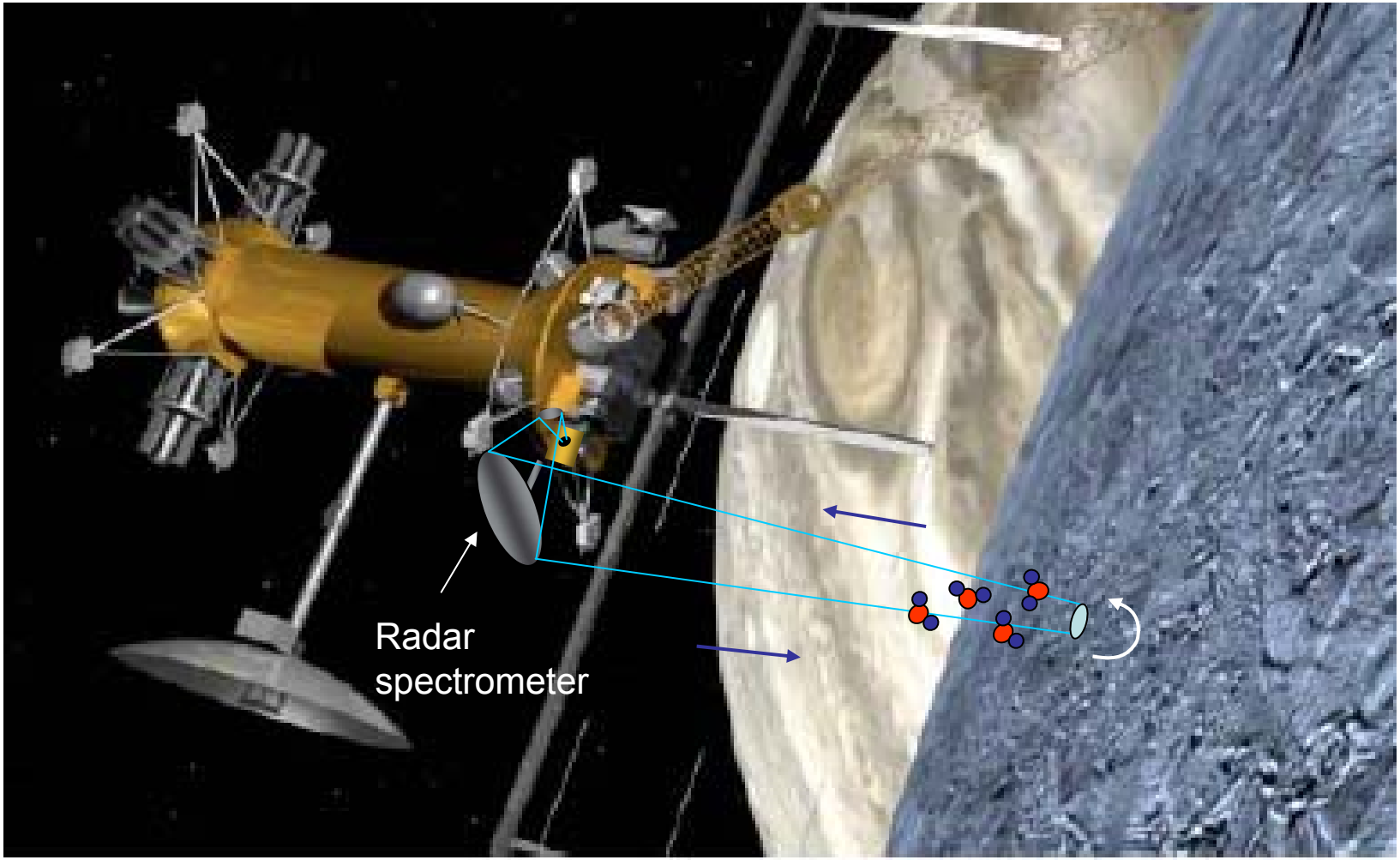



## Orbiter Operational Concept




## Aerorover Operational Concept

## **TRACE:** THz Radar Astrobiology and Chemistry Experiment (EUROPA)



# Future Astrophysics Driver for Technology Development

Jet Propulsion Laboratory and Goddard Space Flight Center
California Institute of Technology

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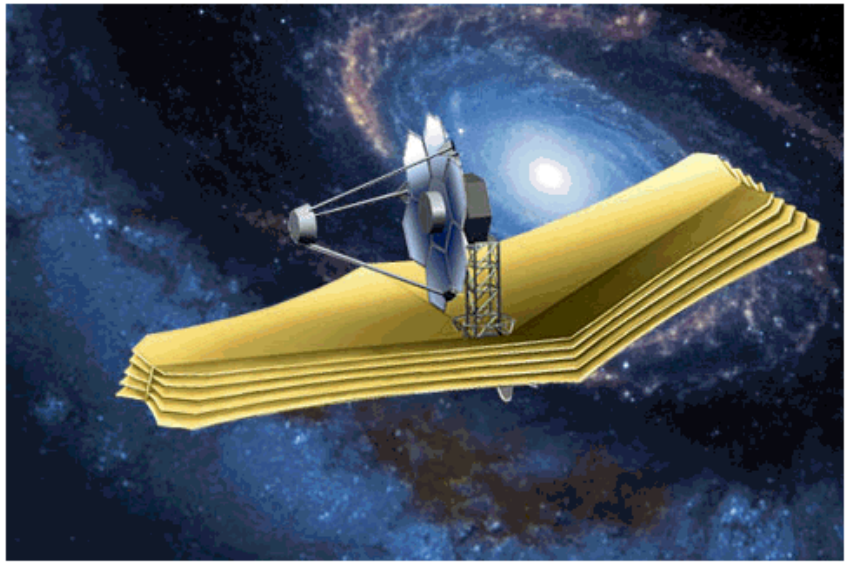
JPL HOME | EARTH | SOLAR SYSTEM | STARS & GALAXIES | TECHNOLOGY

## SAFIR SINGLE APERTURE FAR-INFRARED OBSERVATORY

HOME SITEMAP

- WHAT IS SAFIR?
- SCIENTIFIC POTENTIAL
- TECHNOLOGIES
- ASTRONOMICAL CONTEXT
- QUICK FACTS
- TEAM
- NEWS



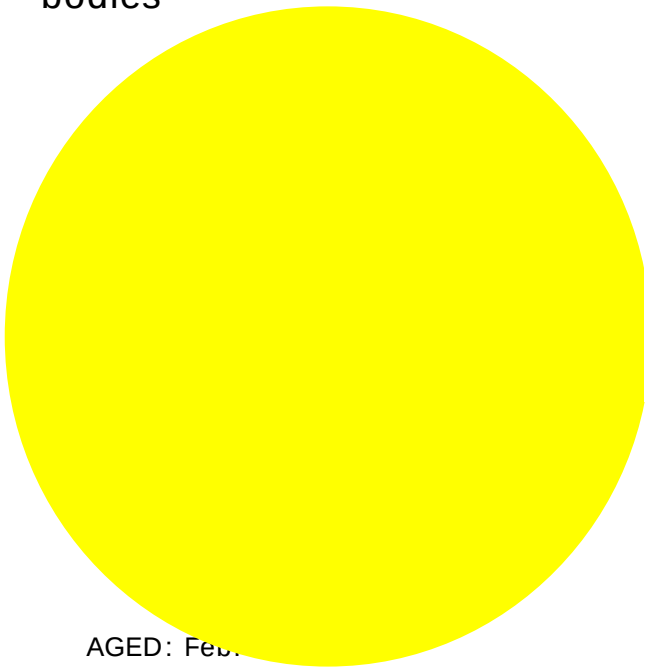
*The Single Aperture Far-Infrared Observatory (SAFIR) is a large cryogenic space telescope envisioned as a follow-on to the Spitzer Space Telescope (Spitzer) and the Herschel Space Observatory. SAFIR will provide unprecedented sensitivity in the important range between infrared wavelengths probed with the James Webb Space Telescope, and the microwave wavelengths observable with telescopes on the ground. SAFIR will explore the formation of the first stars and galaxies in the universe's distant past, and will pierce the veils of obscuring dust to reveal planetary system formation in our own Galaxy.*

*The SAFIR mission is currently being studied by NASA in a collaboration between the Jet Propulsion Laboratory (JPL) and Goddard Space Flight Center (GSFC).*

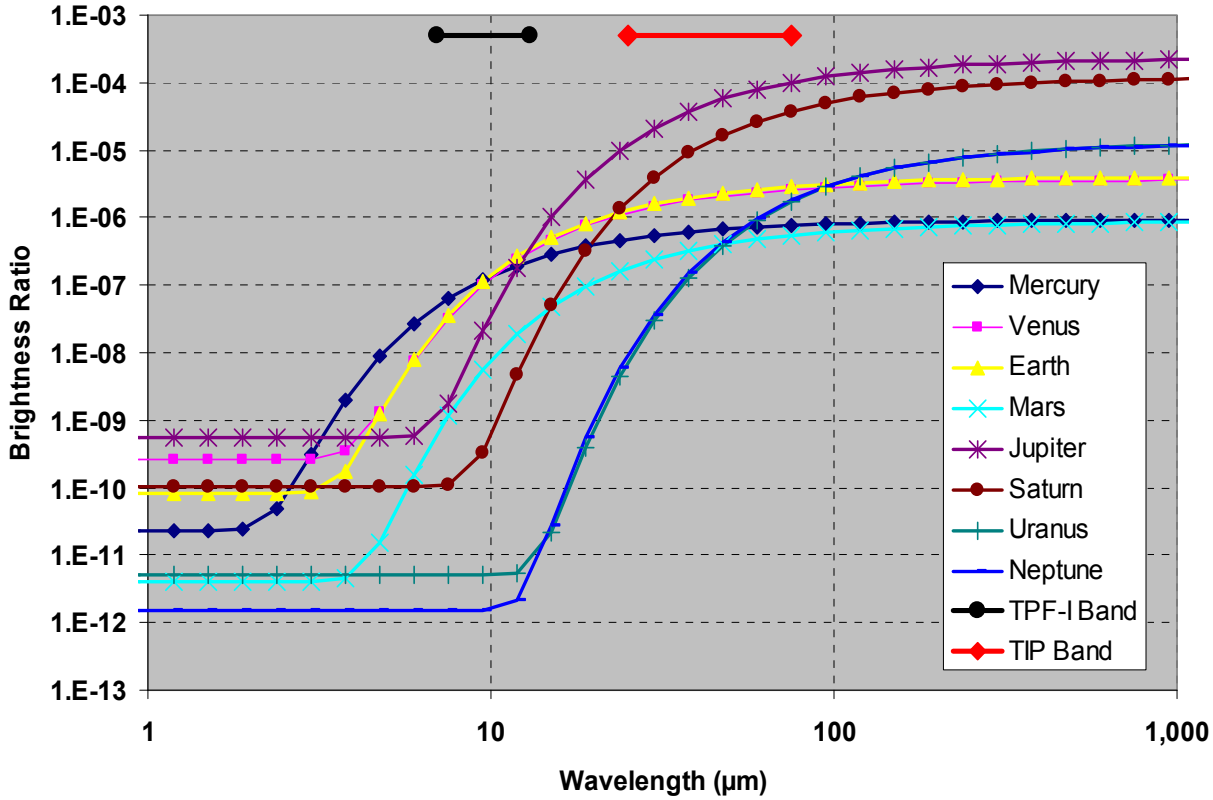
# Planet Finding & Search for Life

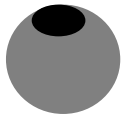
## TIP: Terahertz Interferometer for Planets

Take advantage of blackbody emission curve (Rayleigh-Jeans regime) to dramatically reduce contrast between hot star and possible orbiting planetary bodies



Contrast between STAR and PLANET vs. Wavelength



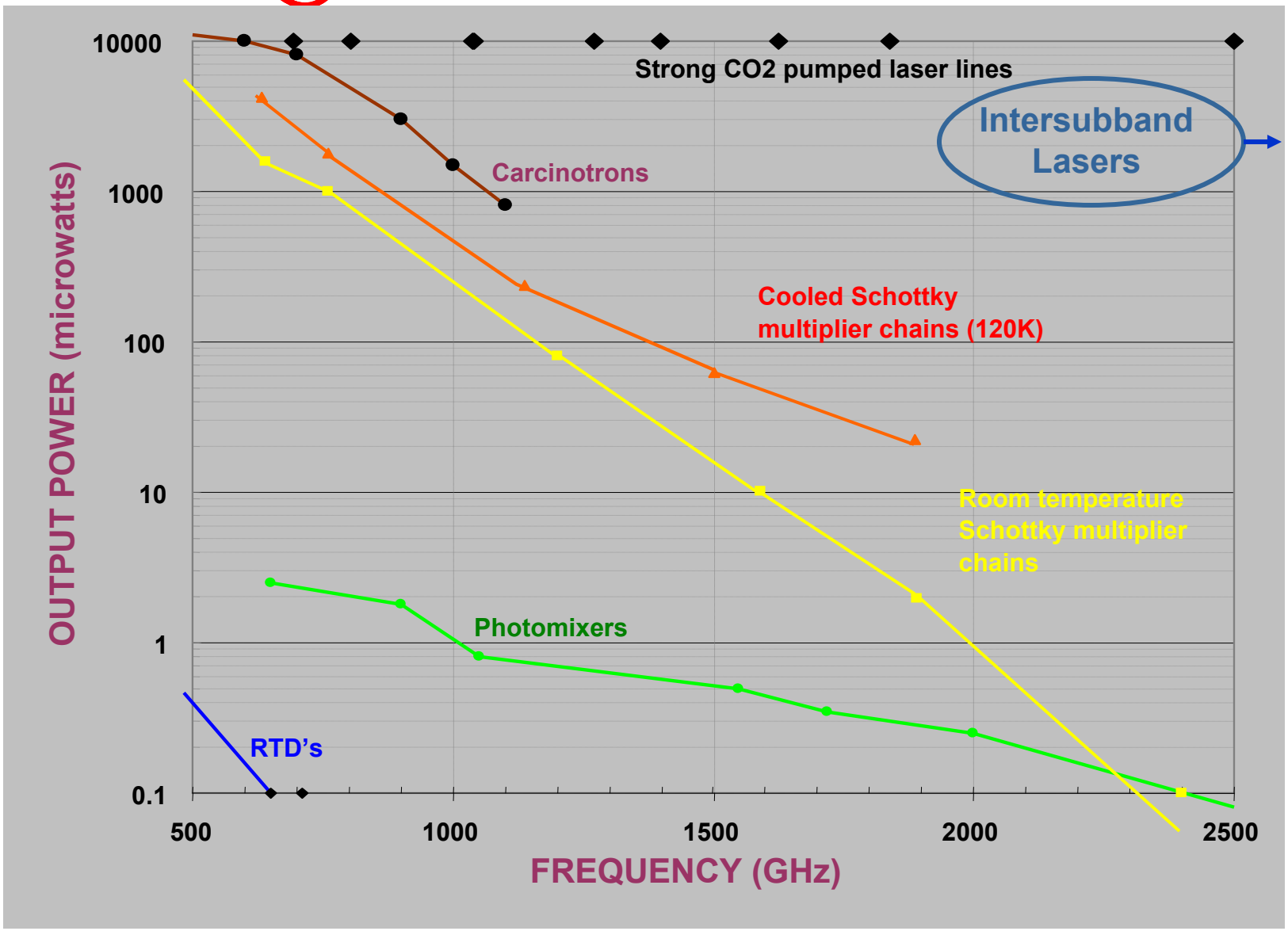



Interferometric techniques needed to cancel out star radiance, and VERY large apertures (30m) needed to achieve desired S/N at frequencies from 1-5 THz.

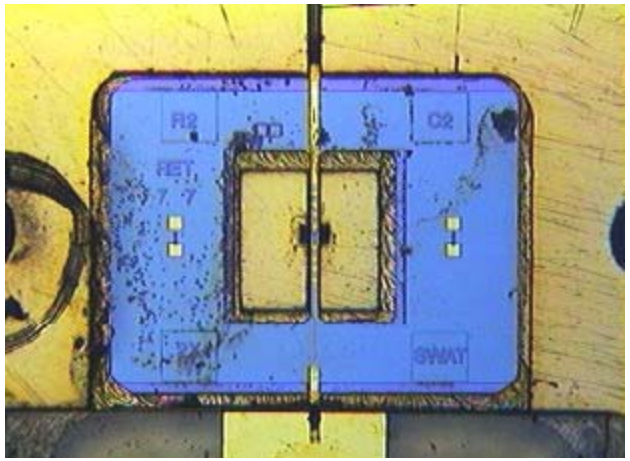
# Source Needs

- Heterodyne Systems: Passive
  - Superconducting: 1-100 uW/pixel
  - Semiconducting: 1-10mW/pixel
- Heterodyne Systems: Active
  - 1-1000mW transmit plus above requirements
- Direct Detection Systems: Active
  - 1-1000W transmit: semiconducting
  - 1-100mW transmit: superconducting
- High purity, phase stable, ($f/\Delta f = 10^7$-$10^8$)

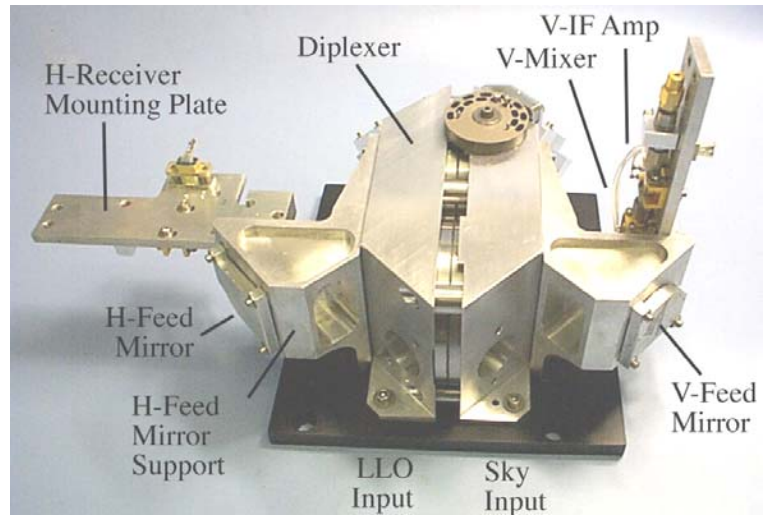
# THz Source Performance



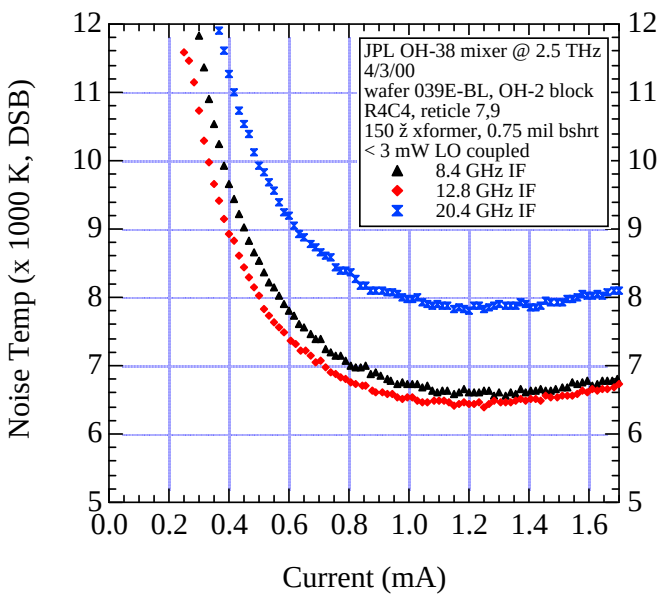
# 2.5 THz Receiver for EOS-MLS



**JPL 2 .5 THz mixer chip in waveguide mount**

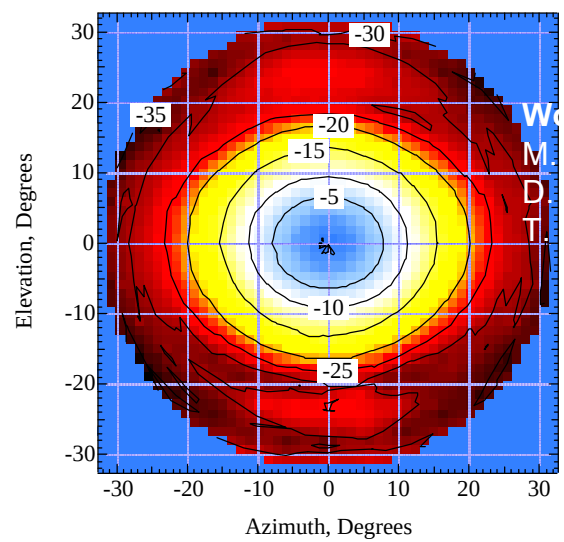



**Two channel receiver for 2.5 THz flight application**




Required LO power 6-8 mW

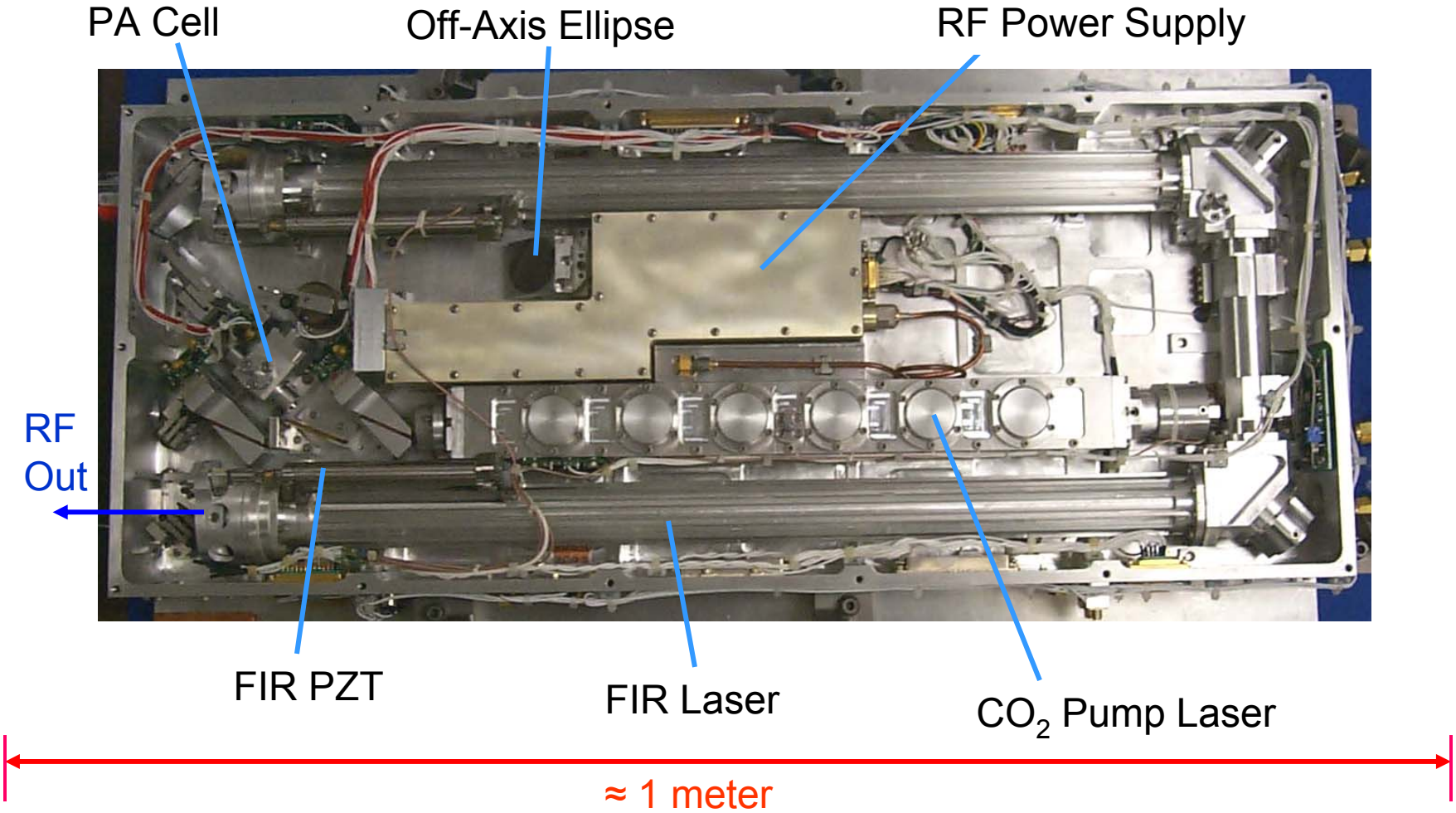
**Receiver performance vs. LO Power at 2.5 THz**




**Beam pattern of 2.5 THz dual mode horn**

# Local Oscillator for 2.5 THz

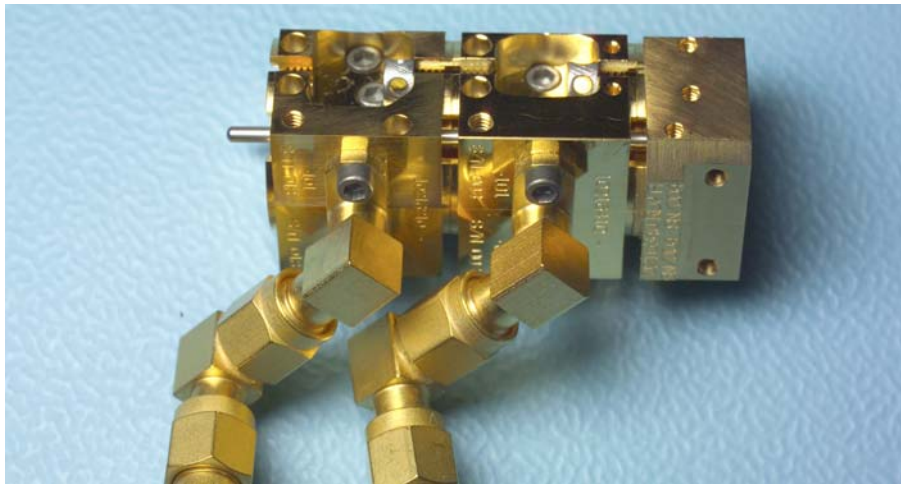
**Compact 2.5 THz gas laser system: RF power>20mW, DC power~100W**
**Built by Coherent DEOS for JPL**



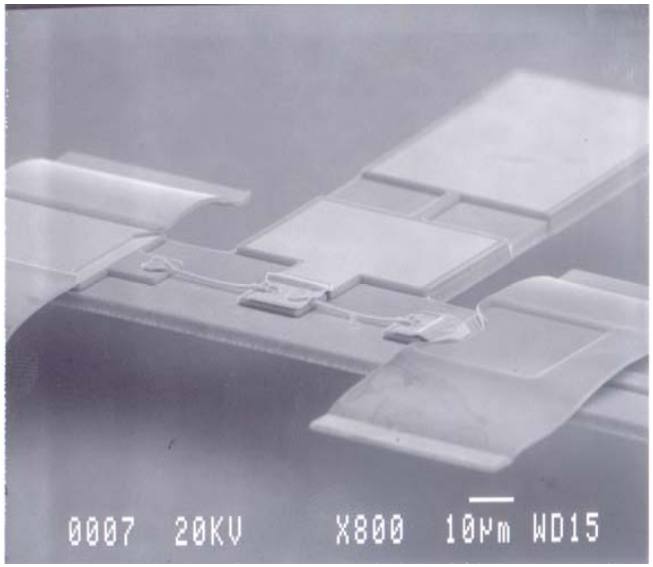
# Multiplier Based LO's for Herschel

**Recent JPL Flight Amp/Multiplier Performance**

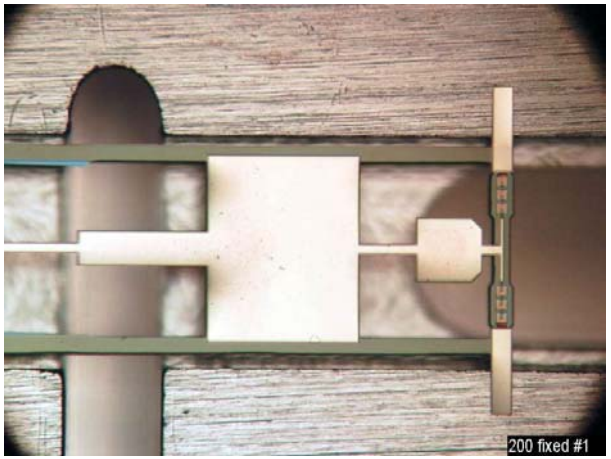
- **Power Amps: 400mW at 94GHz; 200mW 90-105 GHz; 40mW 65-145GHz; 15mW with 85-90 GHz VCO, 20mW 145-170 GHz (HRL)**
- **Multipliers: 30mW @200 GHz (X2) & 6mW at 400 GHz (X2X2);**
- **2 mW @ 800 GHz (X2 X2)**
- **250μW @ 1200 GHz (X2X2X3)**
- **100 μW @ 1600 GHz (X2 X2 X3)**
- **40 μW at 1900 GHz (X2 X3 X3)**
- **0.1 μW @ 2500 GHz (tripler)**



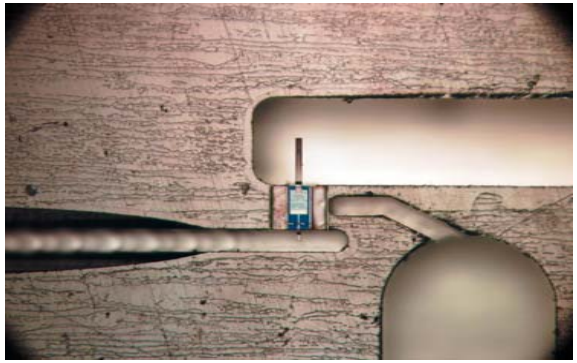
**1200 GHz X2X2X3 flight multiplier source: 250uW, 10% bandwidth**




**SEM photograph of the anode area for a balanced 1500 GHz doubler chip**




**Drop-In Substrateless 200 GHz Balanced Doubler Circuit in waveguide split-block**

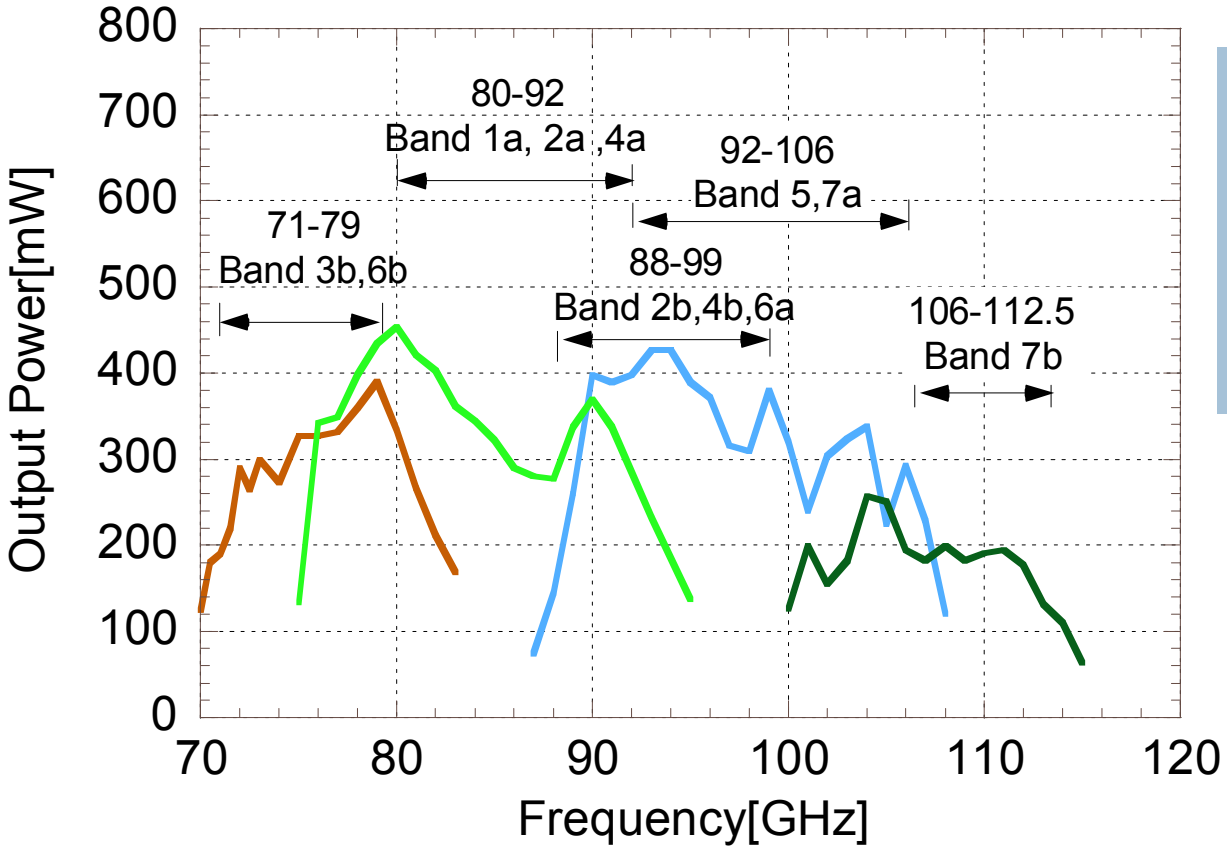


**1500 GHz Tripler with integrated output feed horn**

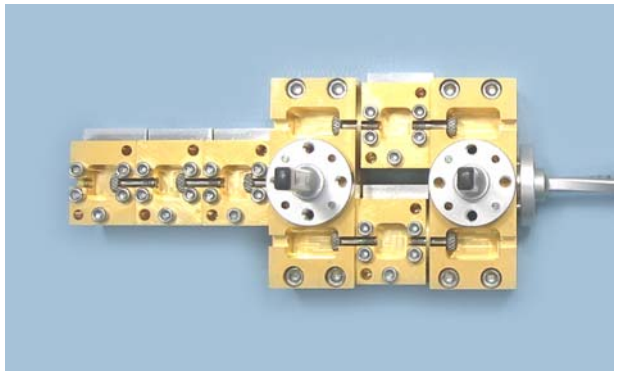
*Work by SWAT LO Team: Imran Mehdi, Frank Maiwald, Alain Maestrini, Erich Schlecht, Goutam Chattopadhyay, Dave Pukala, Ray Tsang, John Gill, Suzi Martin, William Chun, Brad Finamore, Lorene Samoska and HRL (VCO), TRW (power amps)*

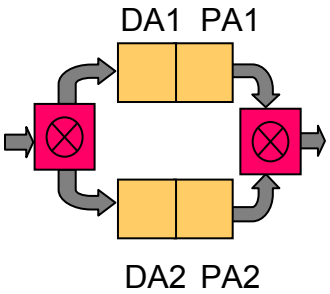
# Millimeter-Wave Power Amps for Herschel

Power Amplifier Output Power & Frequency Bands for Herschel




**Power Combining for >400 mW Output**





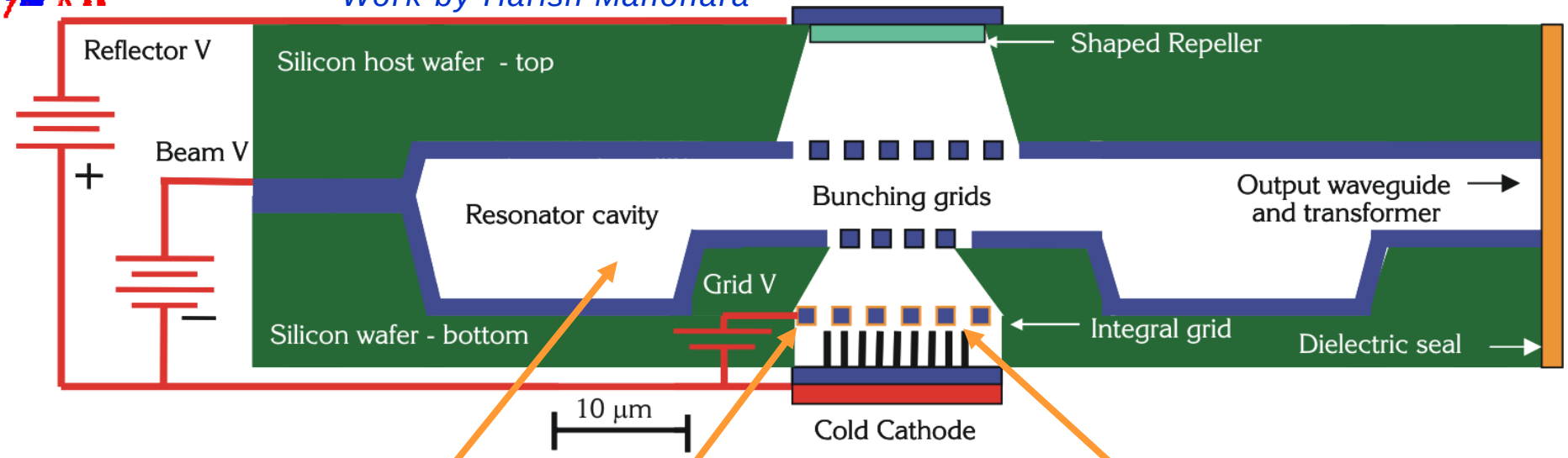

* With TRW

JPL & NGST. Work by L. Samoska, A. Peralta, T. Gaier, M. Wells (JPL), Rich Lai et.al. NGST

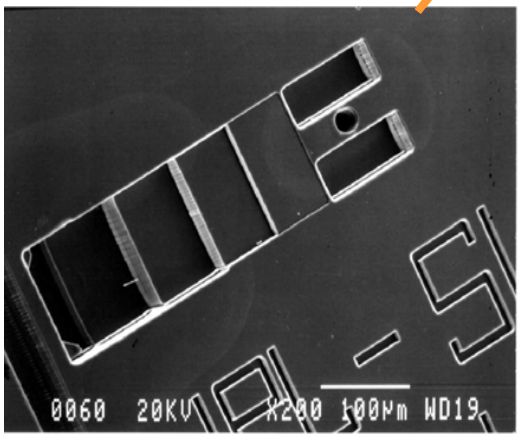
# Vacuum Tube Sources for THz?

## Emission Performance to date: 16A/cm$^2$ at 20 uA/V unfocussed

*Work by Harish Manohara*

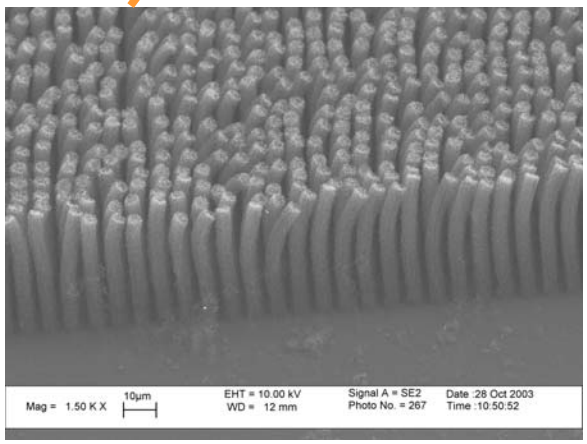



**Vacuum sealed split block**



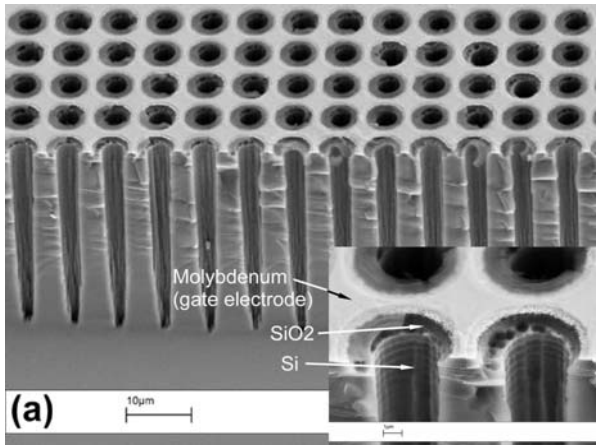

**Silicon micromachined cavity (JPL)**

**CNT Bundles**



**High density carbon nanotube bundles**

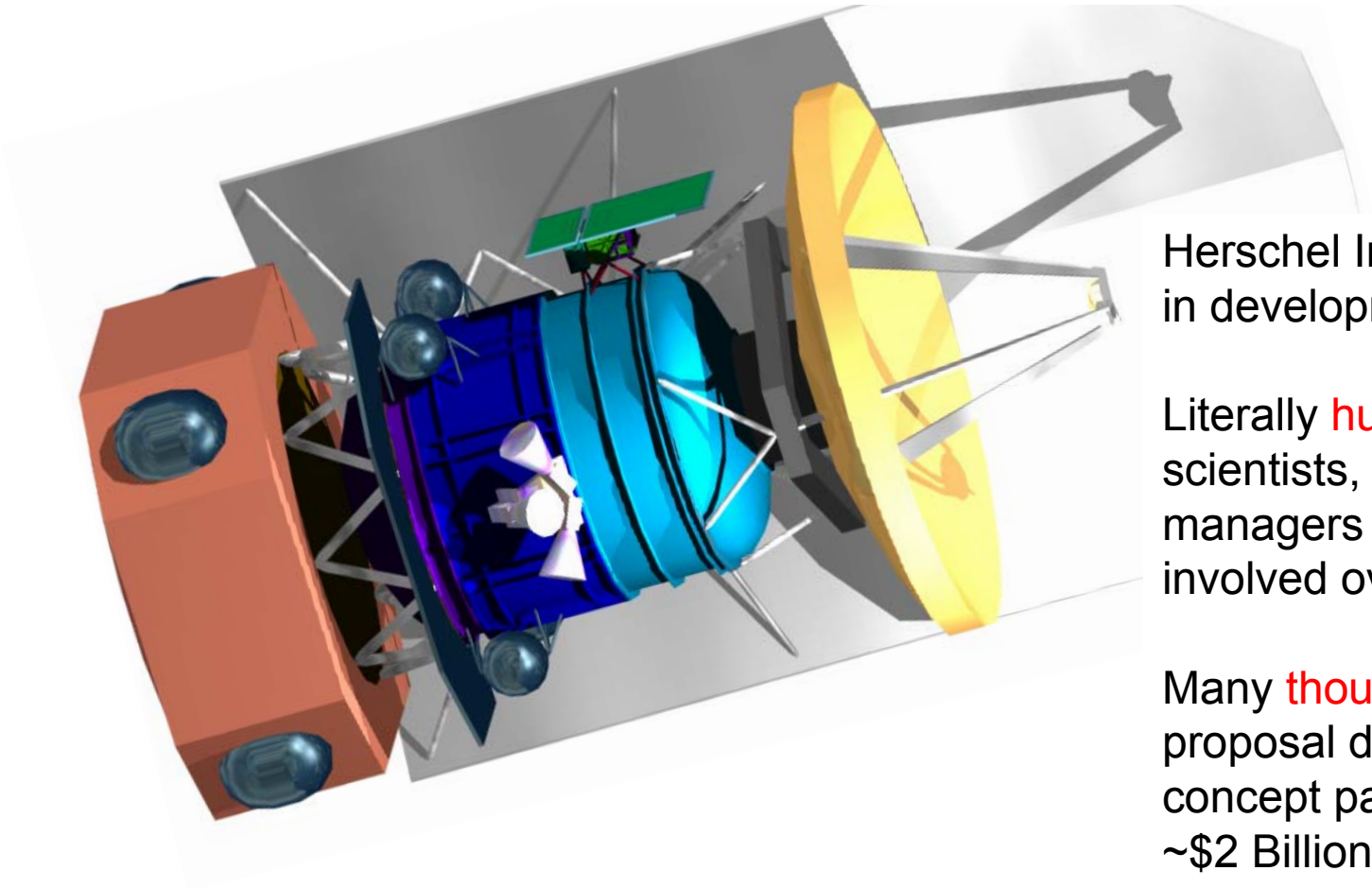
**New CNT Bundles with Grid**




**CNT Bundles with emission and focusing grid**

# Case Study: THz Sources for Herschel HIFI

Herschel Space Telescope with Heterodyne Instrument for the Far Infrared (HIFI). HIFI: All Solid state electronically tunable sources and superconducting heterodyne receivers from 400 GHz to 1.9 THz



Herschel Instrument Concept in development since 1985!!!

Literally hundreds of scientists, technologists and managers have been involved over the years.

Many thousands of pages of proposal documents and concept papers went into this ~$2 Billion mission.

# 1200 GHz Multiplier Based Source

## Top Level Flight Requirements/Deliverables
## Low Frequency THz Band Only

- Bandwidth: Two separate modules
  - Band 5a: 1127-1178 GHz continuous,
  - Band 5b: 1192-1242 GHz continuous
- Output Power
  - 37μW into a linearly polarized fundamental Gaussian beam
- Interfaces
  - Mechanical: envelope, support for assembly in subsystem
  - Thermal: power dissipation of 6Watts @120K
  - Optical: z: +/- 100um, x,y: +/- 50um, Diagonal Horn
  - RF: K-band waveguide flange
  - Electrical: bias/DC for power amp and multiplier modules
- Power Leveling: Via Power amplifier and Multiplier bias
- Deliverables: 3 Flight Models, 3 Mounting plates, flight release component & interface drawings, performance verification documents

# 1200 GHz Multiplier Based Source

## Environmental Requirements Matrix (80 page document!)

| | | Herschel/Planck JPL Hardware - Test & Analysis Requirements | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Static Load | | Earth Handling | | | Dynamics | | | | Thermal | | | | | | | | | | | | | EMC | | | | | | |
| HARDWARE ITEM | Test Program Type | Static Loads | Quasi-static acceleration | Package Drop & Trans Vibration | Humidity | Explosive Atmosphere | Acoustic | Vibration - sine | Vibration - Random | Pyro. Shock/Simulated Drop Shock | Contamination | Temp. ground handling | Thermal Shock | Launch Press Profile | Temp./ Atmosphere | Thermal Vac. | Ionizing Dose | Displacement Damage | Low Dose Rate | EUV | Single Event Effects | Solid Particles | Orbital Debris Generation | EMC Conducted susc. Note 3 | EMC Radiated susc. | EMC Cond Emissions | EMC Radiated Emission | ESD Susceptibility | Magnetic | EMC Isolation |
| **Herschel** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Telescope (Eri Cohen) | PF | X | A | Z | Z | Z | X | X | X | X | Z | A | A | A | | X | A | A | A | A | A | A | A | X | X | X | X | X | X | X |
| Primary Mirror (m1) | PF | H | A | Z | Z | Z | H | H | H | H | A | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| Secondary Mirror (m2) | PF | H | A | Z | Z | Z | H | H | H | H | A | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| Actuator Motor and Controls | PF | H | A | Z | Z | Z | H | H | H | H | A | H | H | H | H | H | H | H | H | H | H | H | H | X | X | X | X | X | X | X |
| Flexures | PF | H | A | Z | Z | Z | H | H | H | H | A | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| Metering Struts "Tripod legs" | PF | H | A | Z | Z | Z | H | H | H | H | A | H | H | H | H | H | H | H | H | H | H | H | H | X | X | X | X | X | X | X |
| Support Structures,etc. | PF | H | A | Z | Z | Z | H | H | H | H | A | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| MLI, Heaters,Al Shield,etc. | PF | H | A | Z | Z | Z | H | H | H | H | A | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| **HIFI (John Pearson)** | | | | | | | | | | | | A | A | A | | | A | A | A | A | A | A | A | | | | | A | | |
| Development SIS Mixer | D | N | N | Z | Z | Z | N | H | H | N | Z | Z | H | H | N | Note 1 | N | N | N | N | N | H | H | H | H | H | H | Z | H | H |
| Devemopment HEB Mixer (OPT*) | D | N | N | Z | Z | Z | N | H | H | N | Z | Z | H | H | N | Note 1 | N | N | N | N | N | H | H | H | H | H | H | Z | H | H |
| Flt SIS Mixer Block (1 & 2) | PF | A | A | Z | Z | Z | N | C | C | X | Z | X | H | H | N | Note 1 | Note4 | N | Note4 | Note4 | Note4 | H | H | H | H | H | H | Z | H | H |
| Flt HEB Mixer Block (1 & 2) (OPT*) | PF | A | A | Z | Z | Z | N | C | C | X | Z | X | H | H | N | Note 1 | Note4 | N | Note4 | Note4 | Note4 | H | H | H | H | H | H | Z | H | H |
| Development Power Amps | D | N | N | Z | Z | Z | N | Z | Z | Z | Z | Z | H | H | N | Note1 | N | N | N | N | N | H | H | H | H | H | H | Z | H | H |
| LO Power Amps (1-4) (TRW) | PF | A | A | Z | Z | Z | N | X | X | X | Z | X | H | H | N | Note 1 | N | N | N | N | N | H | H | H | H | H | H | Z | H | H |
| Diodes | PF | N | N | Z | Z | Z | N | N | N | N | Z | Z | H | H | N | Note 1 | N | N | N | N | N | H | H | H | H | H | H | H | H | H |
| Development Band 5 LO Multiplier Chain | D | N | N | Z | Z | Z | N | H | H | N | Z | Z | H | H | N | Note 1 | N | N | N | N | N | H | H | H | H | H | H | Z | H | H |
| Flt Band 5 LO Multiplier Chain | PF | A | A | Z | Z | Z | N | X | X | X | Z | X | H | H | N | Note 1 | N | N | N | N | N | H | H | H | H | H | H | Z | H | H |
| Flt Band 6a LO Multiplier Chain (OPT*) | PF | A | A | Z | Z | Z | N | X | X | X | Z | X | H | H | N | Note 1 | N | N | N | N | N | H | H | H | H | H | H | Z | H | H |
| **SPIRE (Jerry Lilienthal)** | | | | | | | | | | | | A | A | A | | | A | A | A | A | A | A | A | | | | | | | |
| Qual Cold Electronics JFET Module | Q | A | A | Z | Z | Z | N | X | X | SD | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | X |
| Proto Flt Cold Electronics JFET Module | PF | A | A | Z | Z | Z | N | X | X | N | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | X |
| Flt Spare Cold Electronics JFET Module | FA | A | A | Z | Z | Z | N | X | X | N | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | X |
| Qual Photometer Assembly | Q | A | A | Z | Z | Z | N | X | X | SD | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | X |
| Flt Spare Photometer Assembly | PF | A | A | Z | Z | Z | N | X | X | N | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | X |
| Proto Flt Photometer Assembly | FA | A | A | Z | Z | Z | N | X | X | N | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | X |
| Qual Spectrometer Assembly | Q | A | A | Z | Z | Z | N | X | X | SD | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | X |
| Proto Flt Spectrometer Assembly | PF | A | A | Z | Z | Z | N | X | X | N | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | X |
| Flt Spare Spectrometer Assembly | FA | A | A | Z | Z | Z | N | X | X | N | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | X |
| **PLANCK** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 20K Cryocooler (Al Nash) (Parker Cowgil) | | | | | | | | | | | | A | A | A | | X | A | A | A | A | A | A | A | H | H | H | H | H | H | X |
| Cold End | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Flight Unit 1 | PF | A | A | Z | Z | Z | H | X | X | X | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| Flight Unit 2 | PF | A | A | Z | Z | Z | H | X | X | X | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| Piping | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Flight Unit 1 | PF | A | A | Z | Z | Z | H | H | H | H | Z | H | H | H | N | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| Flight Unit 2 | PF | A | A | Z | Z | Z | H | H | H | H | Z | H | H | H | N | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| Compressor | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Flight Unit 1 | PF | A | A | Z | Z | Z | H | X | X | X | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| Flight Unit 2 | PF | A | A | Z | Z | Z | H | X | X | X | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| **HFI (Jerry Lilienthal) (Jamie Bock)** | | A | A | | | | | | | | | A | A | A | | | A | A | A | A | A | A | A | | | | | | | |
| CQM Bolometer Module (Cryo Qual Model)note 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Low Frequency (3 units) | PF | H | H | Z | Z | Z | N | X | X | SD | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| High Frequency (3 Units) | PF | H | H | Z | Z | Z | N | X | X | SD | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| Flight Bolometer Module | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Low Frequency (217, 143, 100 gHz) | FA\PF | H | H | Z | Z | Z | N | X | X | SD | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | H |
| High Frequency (857, 545, 353 gHz) | FA\PF | H | H | Z | Z | Z | N | X | X | SD | Z | H | H | H | N | X | H | H | H | H | H | H | H | H | H | H | H | H | H | H |

| | |
|---|---|
| PT= | Pressure Testing |
| SD = | Simulated Drop Shock |
| C= | Cold Vibration Test (4 deg K) |
| OPT*= | This Hardware may be built, but is not yet Approved |
| Z= | No Test or Analysis Required if Approved Procedures are Followed and Acceptable Environmental Conditions are Maintained |
| N= | Neither Test or Analysis Required |
| H= | Test or Analysis Req at the Higher Level of Assembly or One Analysis Performed for The Group |
| X= | Test Required |
| A= | Analysis Required |
| Note 1 | Normal Operation is cold and in vacuum |
| Note 2 | Cyro Qual Bolometers Will be Tested at Proto Flight Levels and Delivered for Use in the Instrument Qualification Tests |
| Note 3 | Test in 4.9.4.1.2 and 4.9.4.1.3 will be omitted |
| Note 4 | Need for test will be determined, Test if Necessary or No Test |
| | Termp. Ground Handling is thermal cycles for HIFI |

# 1200 GHz Multiplier Based Source

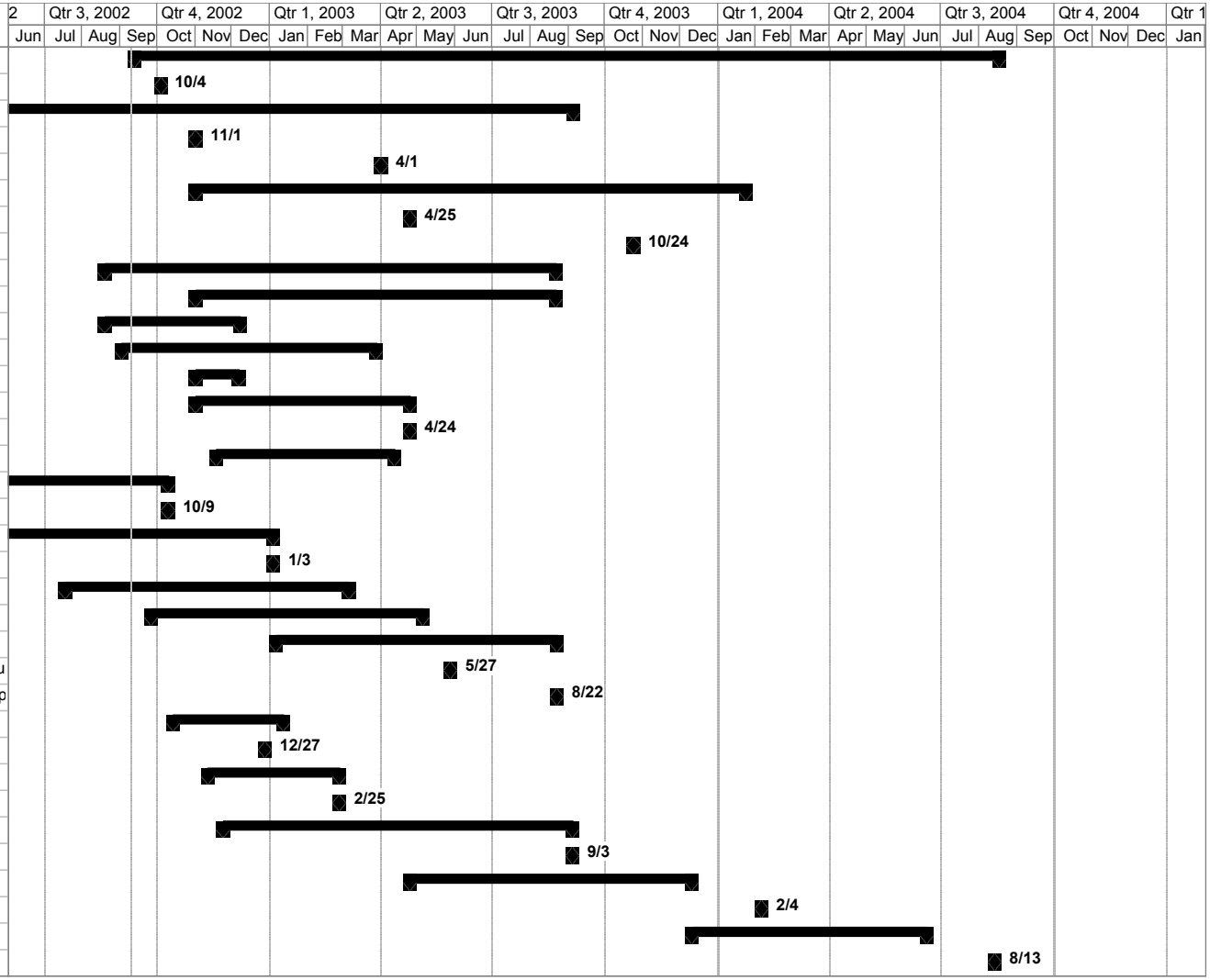
## Specification Matrix: 1 of 12 pages!

| Band 5 Specification Document | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| JPL D-20525revA, Issue 3, 30 July, 2002 | | | | | | | | | |
| ***Functional Requirement*** | ***Section*** | ***Comply*** | | | | ***Validation*** | ***FM*** | ***status*** | ***Comments*** |
| | | ***Low*** | ***Nom.*** | ***High*** | ***Unit*** | | ***&FS*** | ***DM*** | |
| **RF Verification Conditions** | 3.2 | 100 | **120** | 150 | **K** | Calibrated temperature sensor | M | done | Cryo test bench, test log |
| | | | | | | vaccum, pressure gauge | M | done | Cryo test bench RF input power level +0.6 dBm to +3.0 dBm at WR-10 band, power amplifier saturated |
| **RF range Band 5a LO** | 3.2.1 | **1127** | | **1178** | **GHz** | Calorimeter or Keating Meter | M | done | Band 5 LO chain |
| **RF range Band 5b LO** | 3.2.1 | **1192** | | **1242** | **GHz** | Calorimeter or Keating Meter | M | done | Band 5 LO chain |
| **RF power** | 3.2.2 | **37** | | | **uW** | Calorimeter or Keating Meter | M | done | operation temperature @120K, linearly polarized Gaussian beam |
| | | | **>18** | | **uW** | Calorimeter or Keating Meter | M | done | three frequencies @295K for beam measurements |
| **RF Output Power Adjustment** | 3.3.3 | | **13** | | **dB** | relative to 3.2.2 with Bolometer | M | limited shown | adjustable between the max. output power and –13dB from the required value specified in 3.2.2 |
| **Optical Performance** | 3.4 | | **>10** | | **dB** | Bolometer | M | no | signal to noise >= 10 |
| **Location of Output Beam** | 3.4.2 | | **295** | | **K** | Location of feed horn | M | mech. Done | mechanically and optically at 295K |
| **Polarizaton** | 3.4.3 | | **45** | | **deg.** | | D | done | |
| **Polarization purity** | 3.4.4 | | **90.9** | | **%** | Wire grid extinction at 1185GHz | M | no | (opt.three frequencies @295K for beam measurements) |
| | | | | | | | M | = | **M**easurement |
| | | | | | | | D | = | **D**esign |

# 1200 GHz Multiplier Based Source

## Schedule: 2 Year delivery (1 of 5)

| ID | Task Name |
|---|---|
| 1 | **HIFI BAND 5 LO SCHEDULE (DRAFT)** |
| 6 | Delivery Band 5b chain to CalTech |
| 7 | **Device Fabrication** |
| 19 | Milestone Delivery HF2 |
| 20 | Milestone Delivery LF3 |
| 21 | **Receivables** |
| 29 | Delivery Flight Power Amplifier |
| 30 | Delivery Spare Flight Power Amplifier |
| 31 | **Solving technical issues** |
| 32 | **RF-stress test on 200GHz** |
| 36 | **RF beam measurement** |
| 39 | **Reliability measurement** |
| 43 | **Qualifications** |
| 46 | **LF3 design for band 5?** |
| 49 | Decission: LF3 |
| 50 | **Drawings/Release for flight hardware** |
| 61 | **<1THz block machining** |
| 66 | Machined 200GHz and 400GHz blocks |
| 67 | **THz block machining** |
| 72 | Machined 1200GHz block |
| 73 | **184-212 GHz doubler assy and test** |
| 153 | **368-424 GHz doubler assy and test** |
| 233 | **1200 GHz tripler assy and test** |
| 314 | Readyness of first Band 5 LO chain (only mu |
| 315 | Readyness last Band 5 LO chain (only multip |
| 316 | **machine mounting hardware** |
| 321 | Delivery of mounting hardware |
| 322 | **Shipping container** |
| 327 | Delivery of shipping container |
| 328 | **QM chain Band 5** |
| 340 | QA chain tested |
| 341 | **5a and 5b flight chains** |
| 350 | Delivery of flight chains |
| 351 | **spare flight chains** |
| 362 | Delivery of spare flight chains |



# 1200 GHz Multiplier Based Source

## Hardware Delivery Review HRCR (150 pages!)

**Hardware Requirements Certification Review – HIFI Element** **JPL D-31542**

| Assembly/Subsystem | PEM | Phone | Section | Date |
|---|---|---|---|---|
| HSO-Planck, HIFI | John Pearson | 4-6822 | 3850 | 14 March 2005 |

| Drawing/ Part No | Dwg. Rev. | Nomenclature | Serial No.s | | | Final IR No. | Mass (grams) As Meas. / Req. |
|---|---|---|---|---|---|---|---|
| 10215890 | C | Band 5 Local Oscillator | SN 100 | | | 925905 | 446+/-15g/626g |

| Check applicable answer and give necessary explanation in remarks column | Yes | No | N/A | Remarks |
|---|---|---|---|---|
| 1. Are all drawings and specifications complete, approved, released and frozen? | x | | | This unit is being delivered to assist in test of the flight HIFI instrument prior to the Local Oscillator Subsystem delivery. It is being delivered as a potential flight spare, with the knowledge that another fully tested spare is available. |
| 2. Do the released drawings and specifications reflect all approved changes? | x | | | |
| 3. Is hardware identical to other hardware delivered? If no, provide difference list. | x | | | |
| 4 Does the hardware meet the requirement of its functional requirements, specifications, waivers and/or ICDs ? If no, provide difference list. | | x | | This unit has not been fully characterized as would be required for a flight unit. It cannot be concluded that all specifications are met without completing the tests. |
| 5. Have all IR discrepancies and MRBs been dispositioned and agreed to by Engineering/ QA ? | x | | | |
| 6. Is complete as-built list information included in the build book? | x | | | |
| 7. Have all required environmental tests & analyses been completed? | | x | | This unit has not seen the required three thermal cycles in test yet. It has passed acceptance vibration. |
| 8. Is all required assembly and/or subsystem level functional testing completed ? | | x | | Unit is not characterized at 120K. |
| 9. Have all piece parts, processes and materials been approved by JPL? | x | | | |
| 10. Does this hardware meet all contamination control requirements? | x | | | |
| 11. Are all required shipping containers, shipping procedures, and special handling procedures ready? | x | | | |
| 12. Is additional work required to bring this hardware to flight readiness? | x | | | Characterization tests should be completed before unit is flown. |
| 13. Is this hardware acceptable for flight ? | | x | | See previous comment. |

| Data Attachments | Signature Approval & Date |
|---|---|
| 14. Latest Top Assembly Drawings ☒ Attached ☐ None | Cog E 03/15/05 |
| 15. List of open ECRs ☐ Attached ☒ None | PEM 3/14/05 |
| 16. Waivers ☐ Attached ☒ None | QA Engineer 3/31/05 |
| 17. Open MRBs ☐ Attached ☒ None | Mission Assurance Mgr. 3/14/05 |
| 18. Open P/FRs on this H/W ☐ Attached ☒ None | Environments/Reliability 3/14/05 |
| 19. Open P/FRs on similar H/W ☐ Attached ☒ None | EEE Parts 3/21/05 |
| 20. Handling Document ☒ Attached ☐ None | Project 3/14/05 |
| 21. Shortage List ☐ Attached ☒ None | |
| 22. Requirements Verification Matrix ☒ Attached ☐ None | |

# 1200 GHz Multiplier Based Source

Some of the Documents Required/Produced for 1 Source Chain!
(approximately 75% of total)

# 1200 GHz Multiplier Based Source

## Completed 1200 GHz (upper) & 1900 GHz (lower) Flight Assemblies!

# Summary

- We are in a Space Terahertz Renaissance
  (*Someone please let NASA know this!*)
- Significant space flight experience is already in hand from missions dating back to the 1970's
- Lots of new programs are being proposed in Earth, planetary and Astrophysics arenas
- However almost no RF components are off-the-shelf
- More component vendors are desired to reduce costs and increase range of available RF parts
- Sources need major improvements in power and bandwidth as well as efficiency (array applications)
- Higher TRL levels are desired for mission insertion
- Custom work must continue within NASA facilities to meet rigorous flight requirements and environments
- Flight development, components and instruments have synergy and spin-off with DoD requirements