Electronic approaches to sensor applications in the THz spectral region: The intersection of physics and technology

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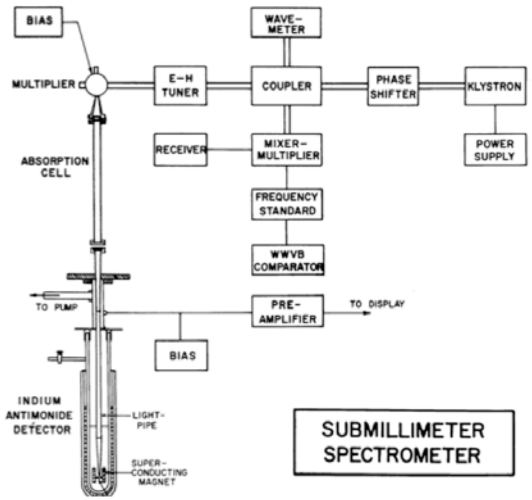
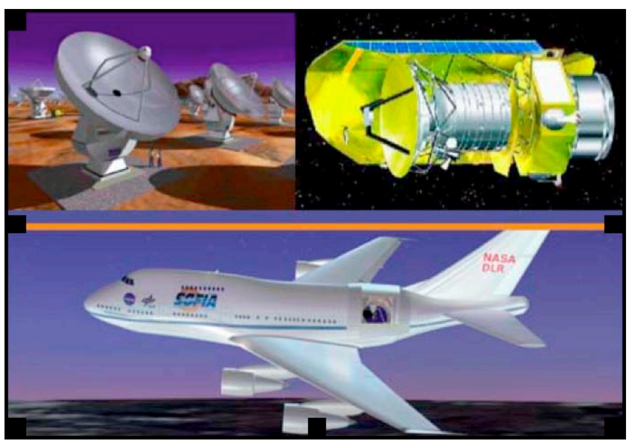
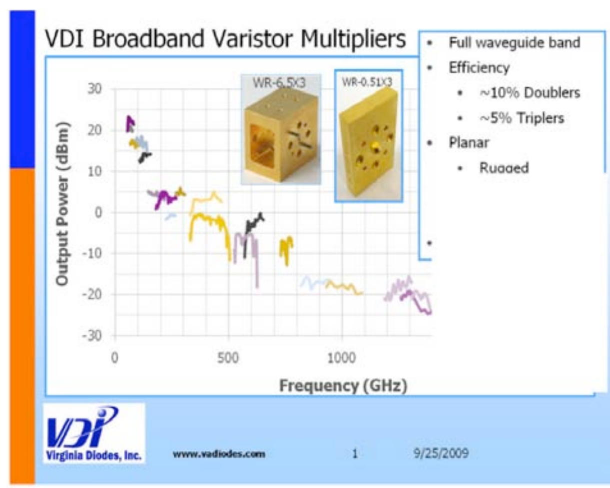
Battelle
Chris Ball

The THz has Come a Long Way (Incrementally)







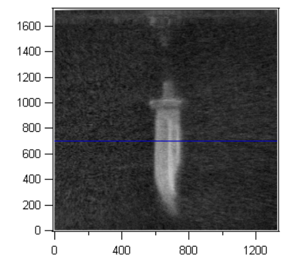
WSC: Imaging at mm-wave and beyond.

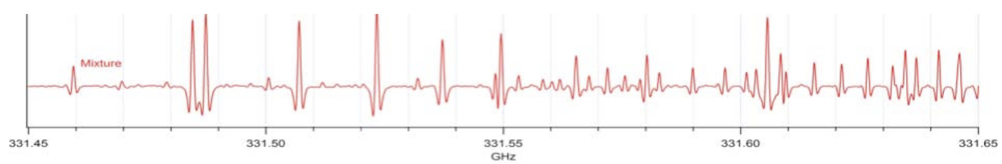
Applications
(From 'One-off' Science to Mass Market Technology)

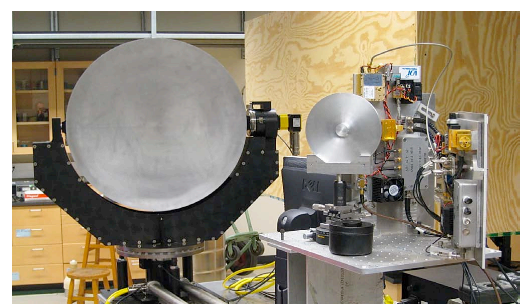
Existing 'One-off'
- Astrophysics
- Atmospheric

Expansion from lower frequency
- Communications

New for microwave
- Sensors/spectroscopic
- Imaging/radar
- Chemical Plasma Diagnostics

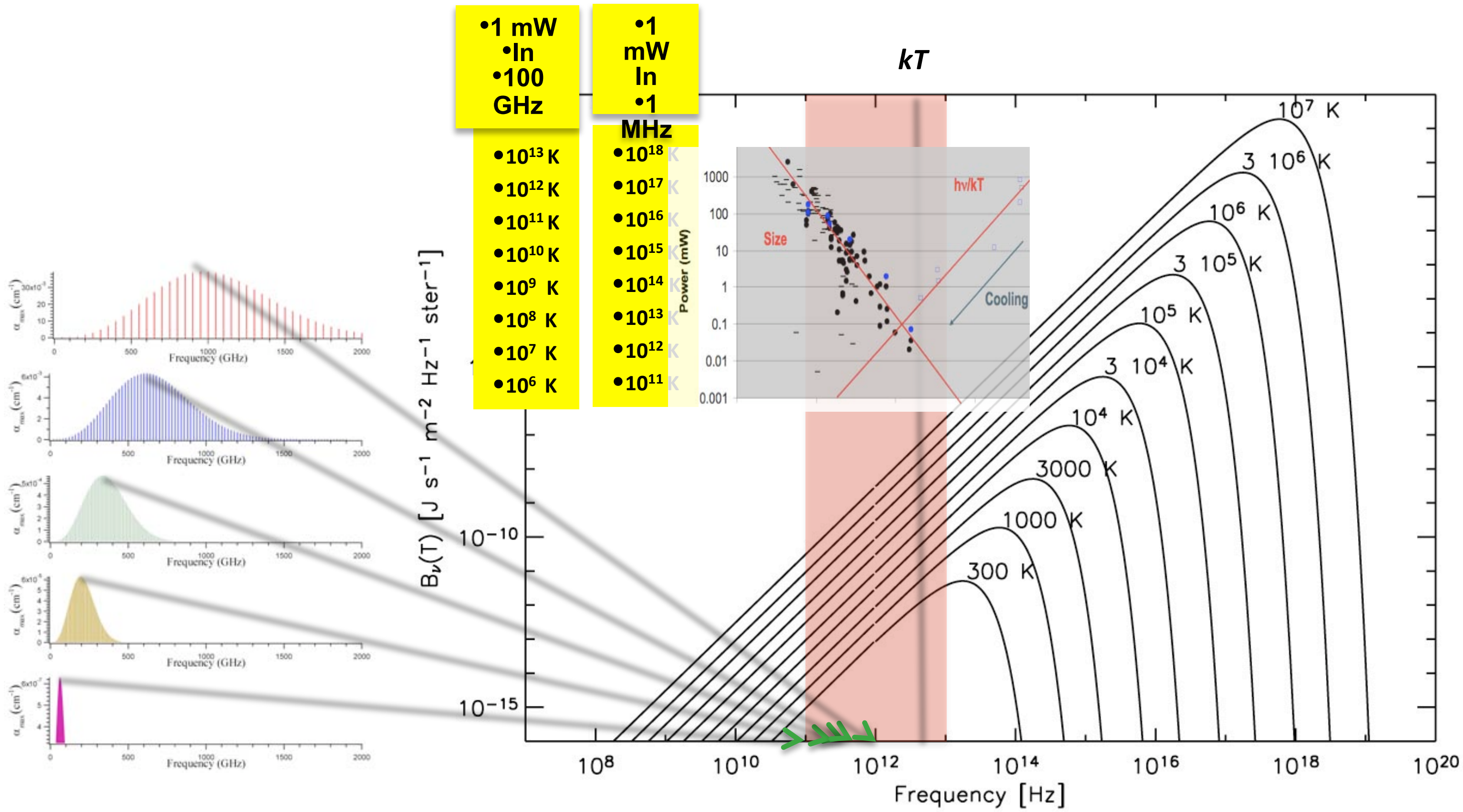






The Physics

Radiation and Interactions: Orders of Magnitude



The THz has defined itself broadly and spans *kT*

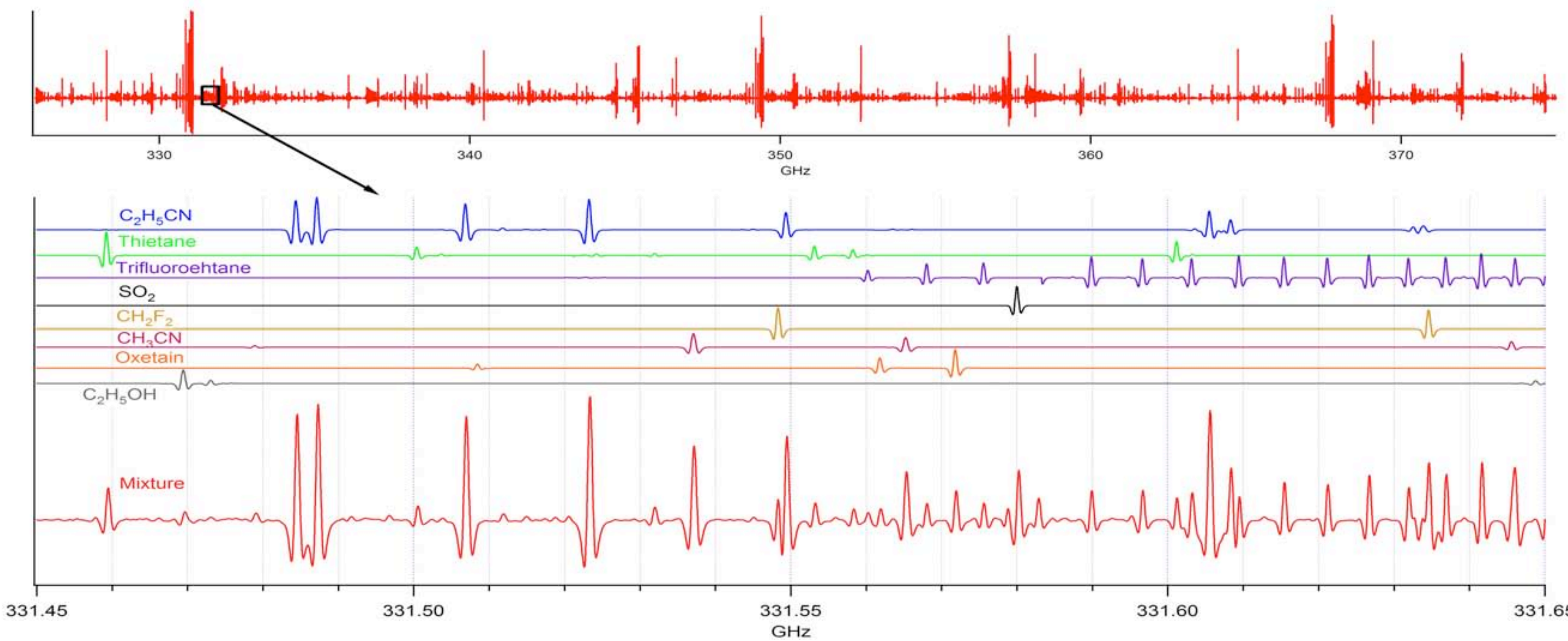
Jumping the 'gap in the electromagnetic spectrum is not the same as closing it

Bandwidth matters: Figures of Merit

For samples in thermal equilibrium, Doppler broadening is proportional to frequency

THz Fingerprint of a Mixture of 20 Gases

Three seconds of data acquisition: expands to 1 kilometer at scale of lower panel



Electronic Sources:

Spectral Brightness - Spectral Purity - Absolute Frequency Calibration - Frequency Agility

Physics and Consequences

Electronic sources are essentially delta functions

Small power provides high brightness
(1 mW in 1 MHz corresponds to 10^{14} K)

=> path to very small and inexpensive SMM/THz technology

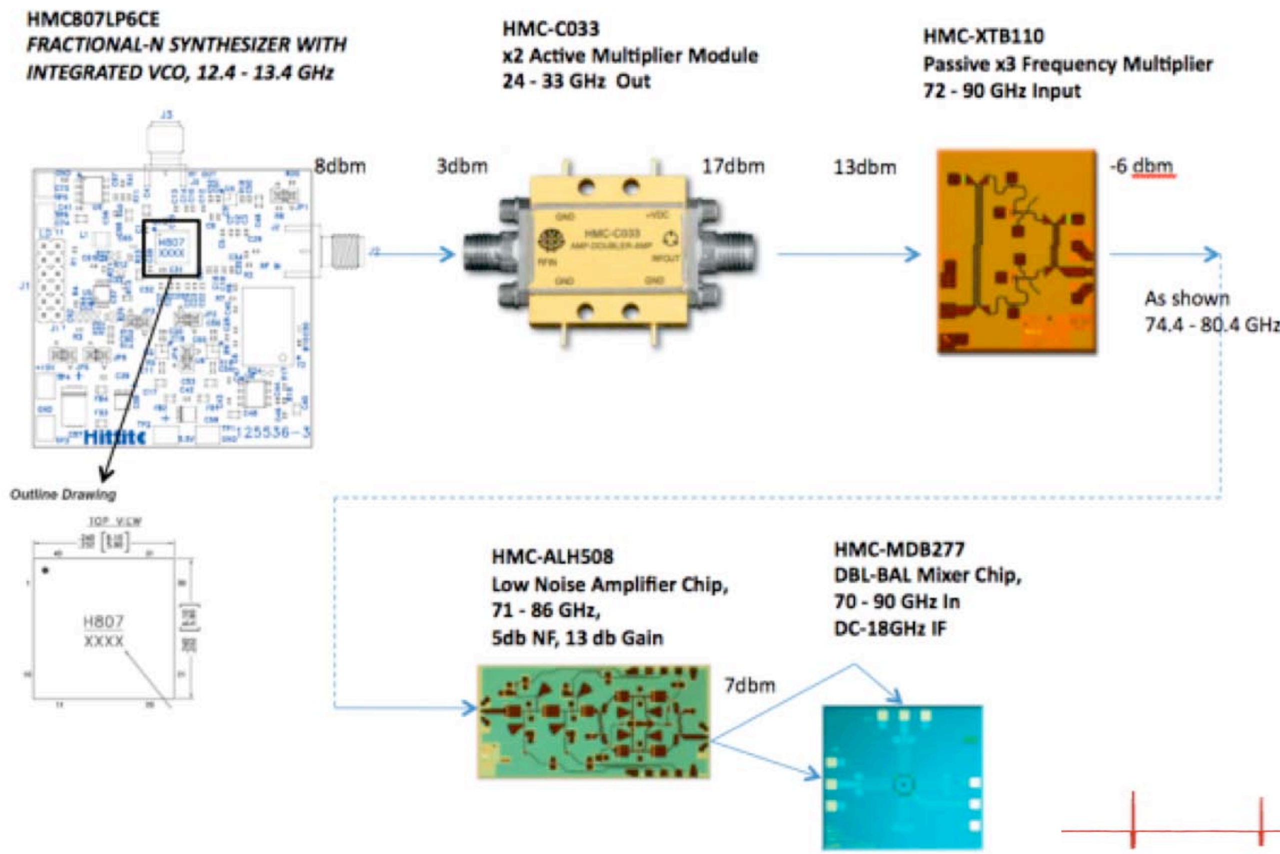
Spectral linewidth is Doppler (proportional to frequency)
=>Optimum pressure is ~ 10^{-5} atmospheres and sample is static
=> very small sample requirements
=> sampling volumes for preconcentration gains small (1 liter gives 10^{5} gain)

Heterodyne receivers can also have very narrow bandwidth

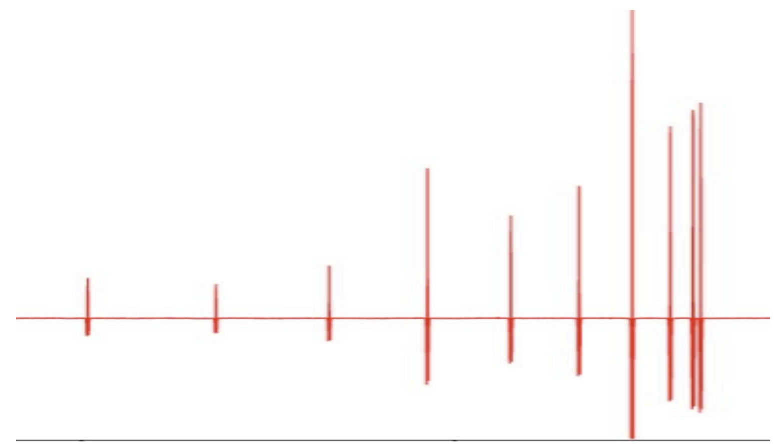
Near Term Technology Advances and their Impact on Applications

(The move from ‘one-off’ to the mass market)

Broad Line of Chip Level IC Through 100 GHz Commercially Available in Large Quantity

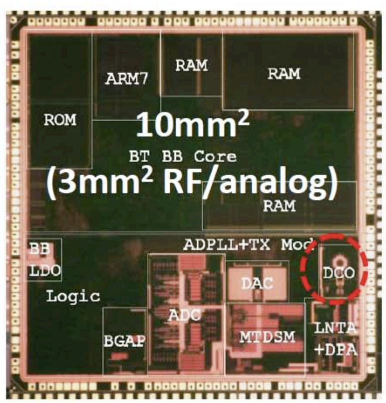


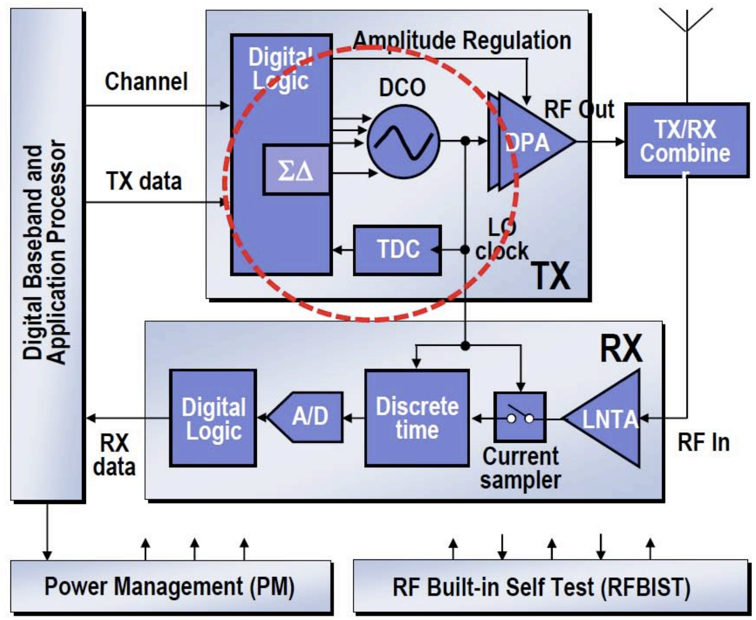
Experimental demonstration at 600 GHz of spectral purity of chip level synthesizer



Fully Integrated Synthesizer Technology in CMOS for Cell Phones*

- Factory auto-calibrations
- Power-up auto-calibrations
- Per-burst calibration
- RF BIST





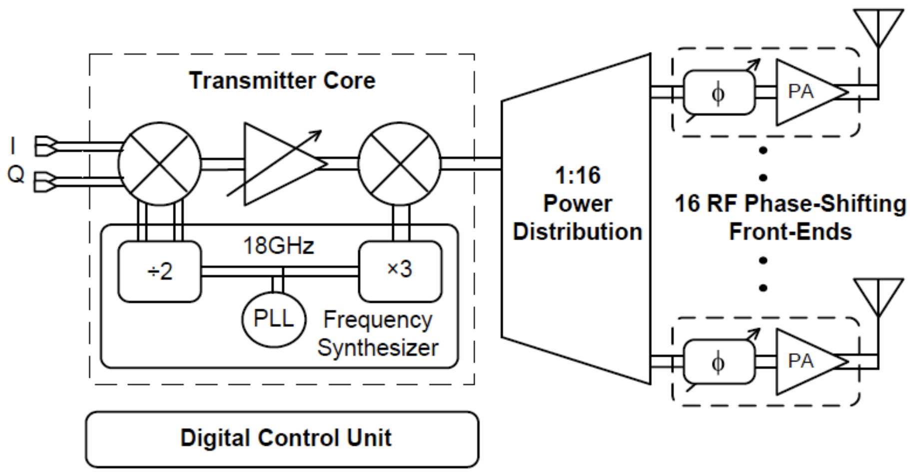
- Heavy digital assistance
  - described in detail later

6/15/2010 VLSI Short Course – Chih-Ming Hung 9

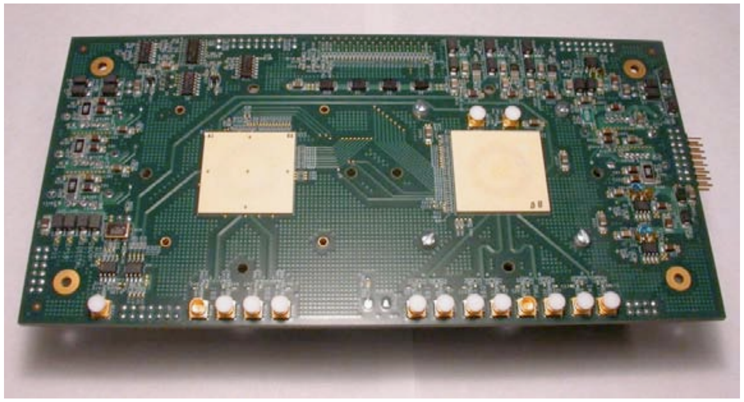
*Courtesy of Chih-Ming Hung, Kirby Laboratories, Texas Instruments

A SiGe BiCMOS 16-Element Phased-Array Transmitter for 60GHz Communications*

16 Element Phased Array TX Architecture



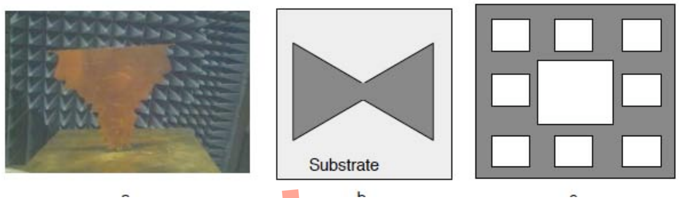
The IC integrates 2240 NPNs, 323,000 FETs and is fabricated in IBM 8HP 0.12um SiGe BiCMOS (f_T=200GHz)



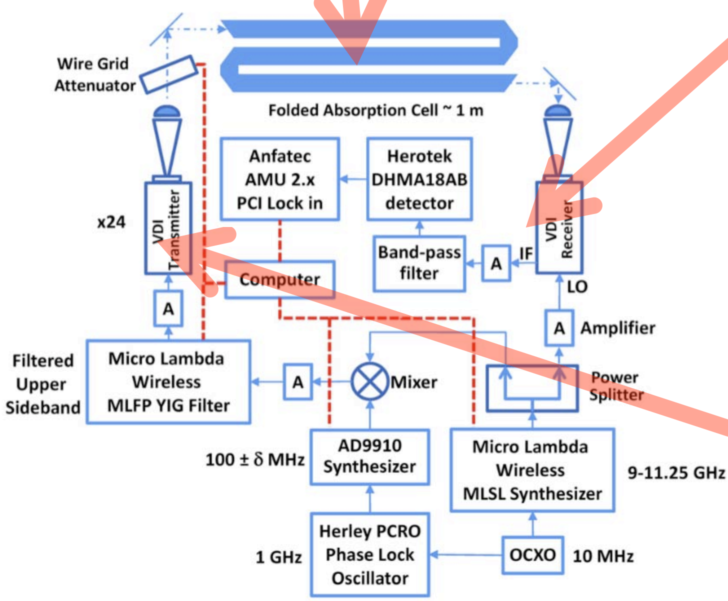
Combined Tx/Rx 16 Channel Evaluation Board

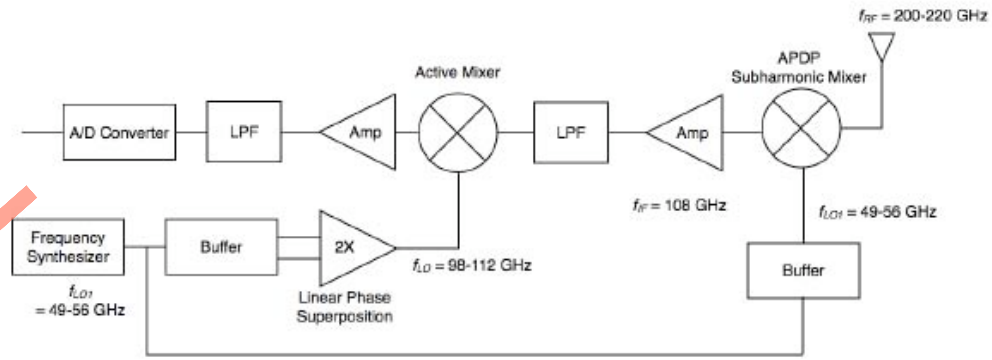
***Courtesy of Alberto Valdes-Garcia and Arun Natarajan, Watson Laboratory, IBM**

CMOS Integration for 240 GHz*

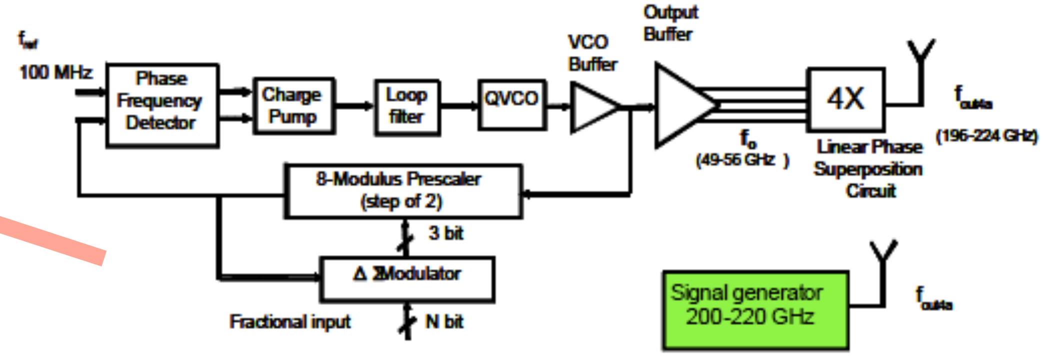


Antennas: Rashaunda Henderson





Receiver: Bhaskar Banerjee (UT-D)

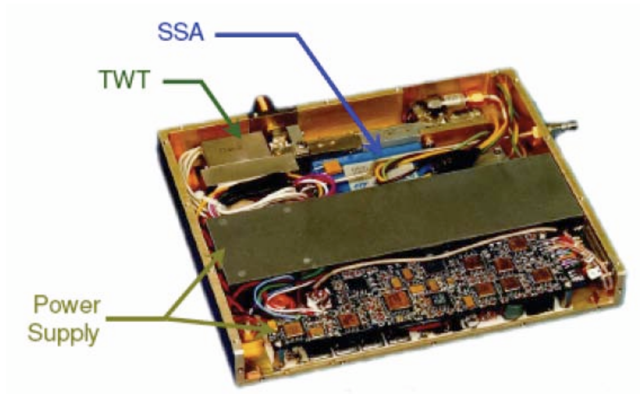


Transmitter: Kenneth O (UT-D)

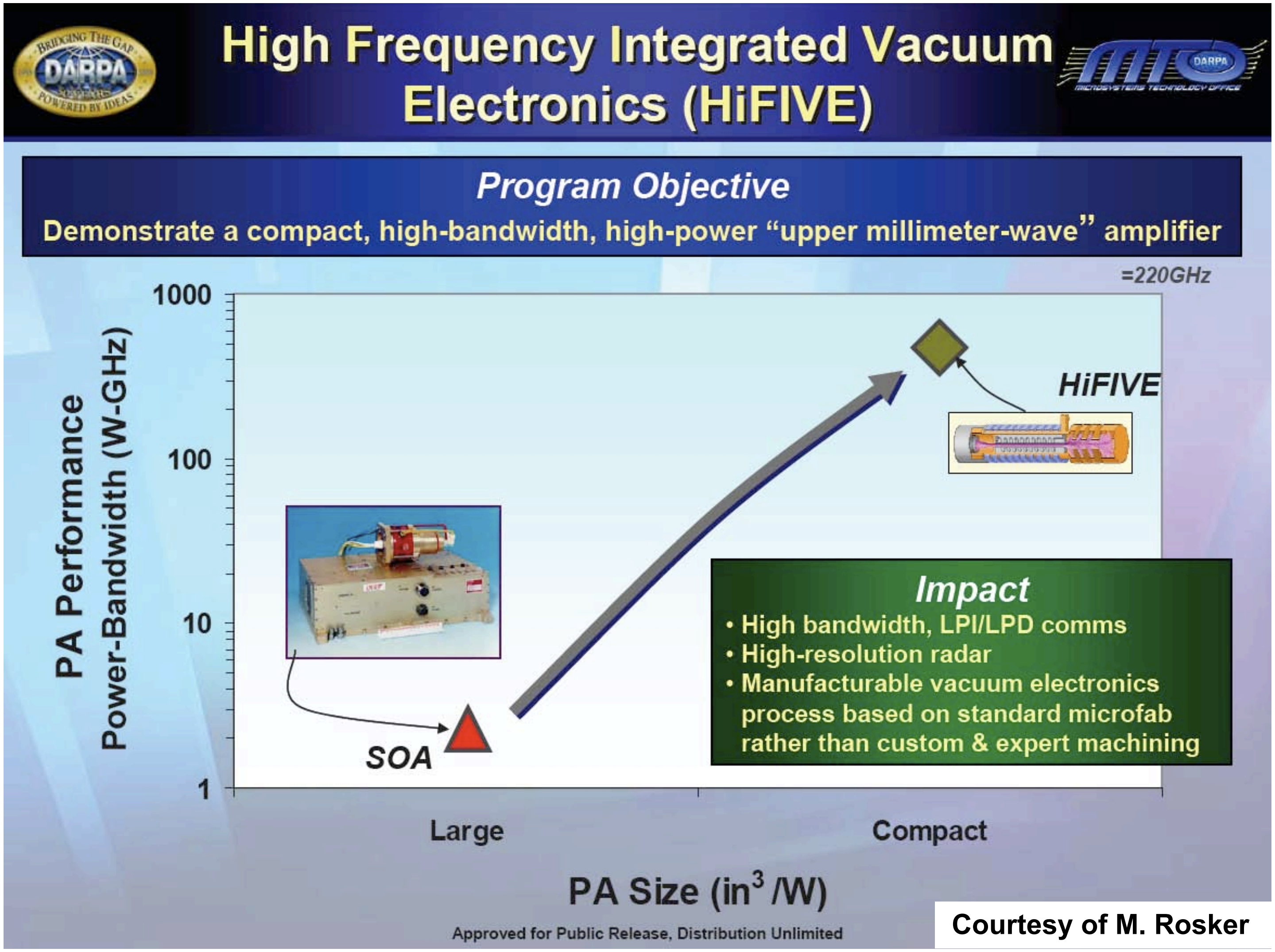
*Sponsored by the Semiconductor Research Corporation

WSC: Imaging at mm-wave and beyond.

Game Changers in Vacuum Electronics



Microwave Power Module (MPM) at 240 GHz



Courtesy of M. Rosker

Paths Forward to Meet HIFIVE Goals

Modeling of large signal electron beam dynamics

Magnet design

Broadband interaction and coupling structures for multiple/sheet beams

Long lived cathodes

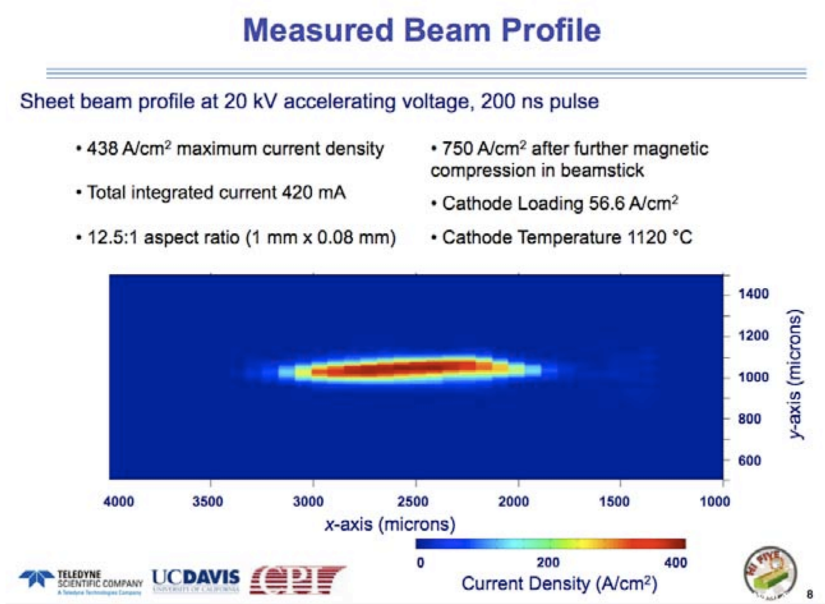
Fabrication and materials strategies

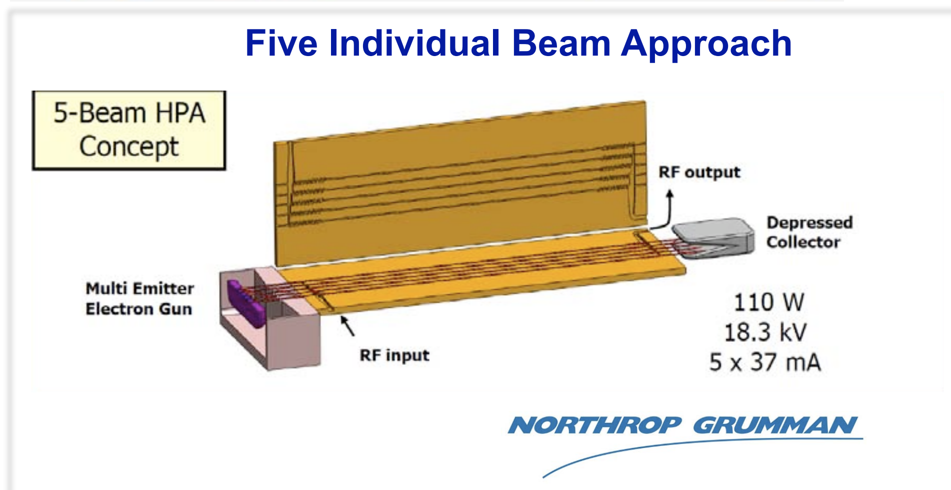
Electron Beams: The Heart of Vacuum Electronics

Extended sheet beam (top)

Combined pencil beams (bottom)

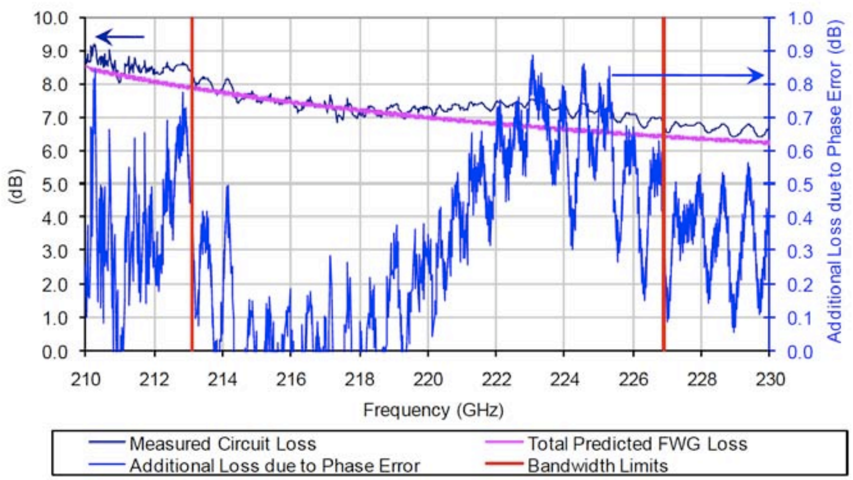
Significantly increases power while maintaining the required small dimensions of the microwave structures



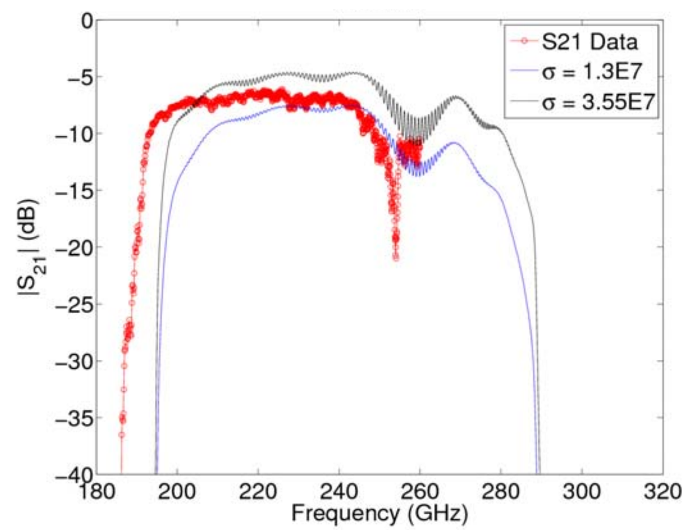


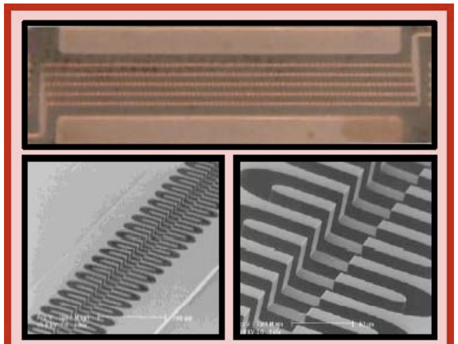
Cold Tests of Broadband Circuits

Circuit Losses



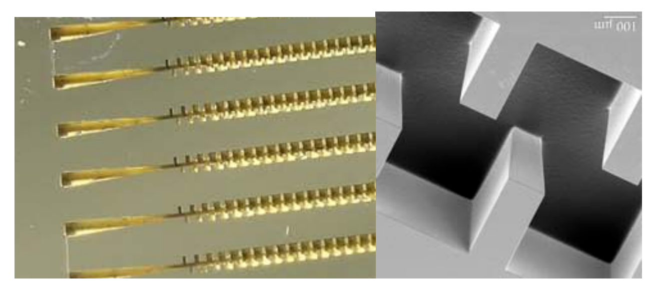
50 GHz raw bandwidth centered on 220 GHz





Micromachined RF Circuits

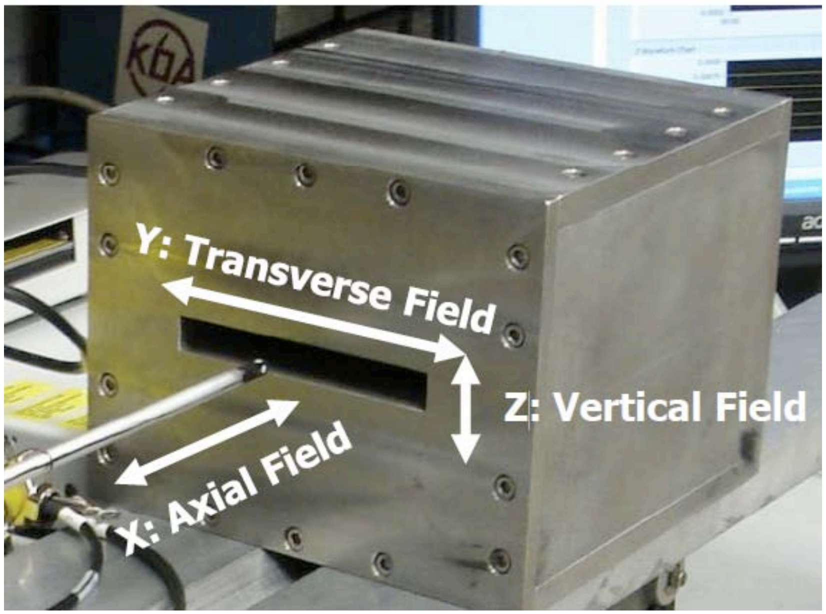
MEMS Interaction Structure

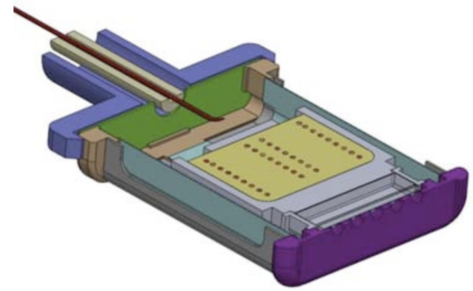


ging at mm-wave ar

Component Development and Testing at an Advanced Stage

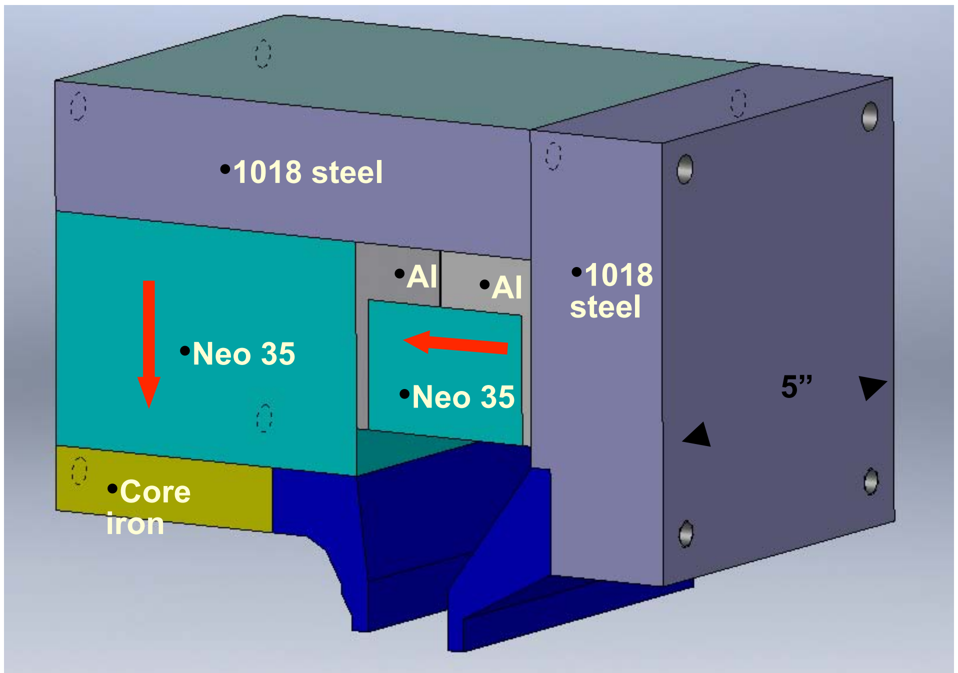
High-Aspect Ratio Magnet



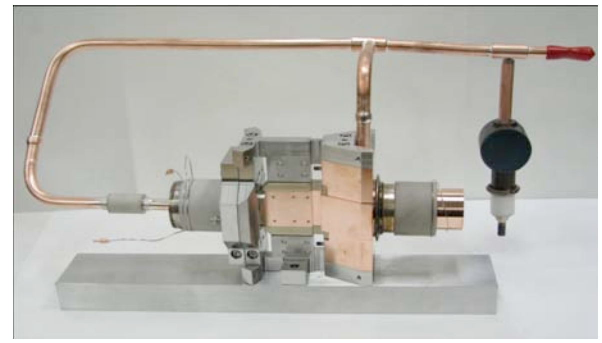


NORTHROP GRUMMAN

Component Development and Testing at an Advanced Stage



Beamstick



Beamstick in magnet

TELEDYNE SCIENTIFIC COMPANY
A Teledyne Technologi
UCDAVIS
ERSITY OF CALIFORNIA
eyond.

Vacuum Electronics

HIFIVE will provide 2 – 3 orders of magnitude increase in gain-bandwidth product for TWTs around 240 GHz

Additional programs at 670 GHz, 850 GHz, and 1030 GHz

Driven by advances in materials, fabrication technology, cathodes, simulation, and support

Still substantial up side in the infant* tube technology

*Compared with person-years and $ invested in solid state source research and development

Applications and Comparisons*

Comparisons at technology level

Optical frequency control can be heroic (Nobel Prize)
THz/TDS – low resolution, low brightness

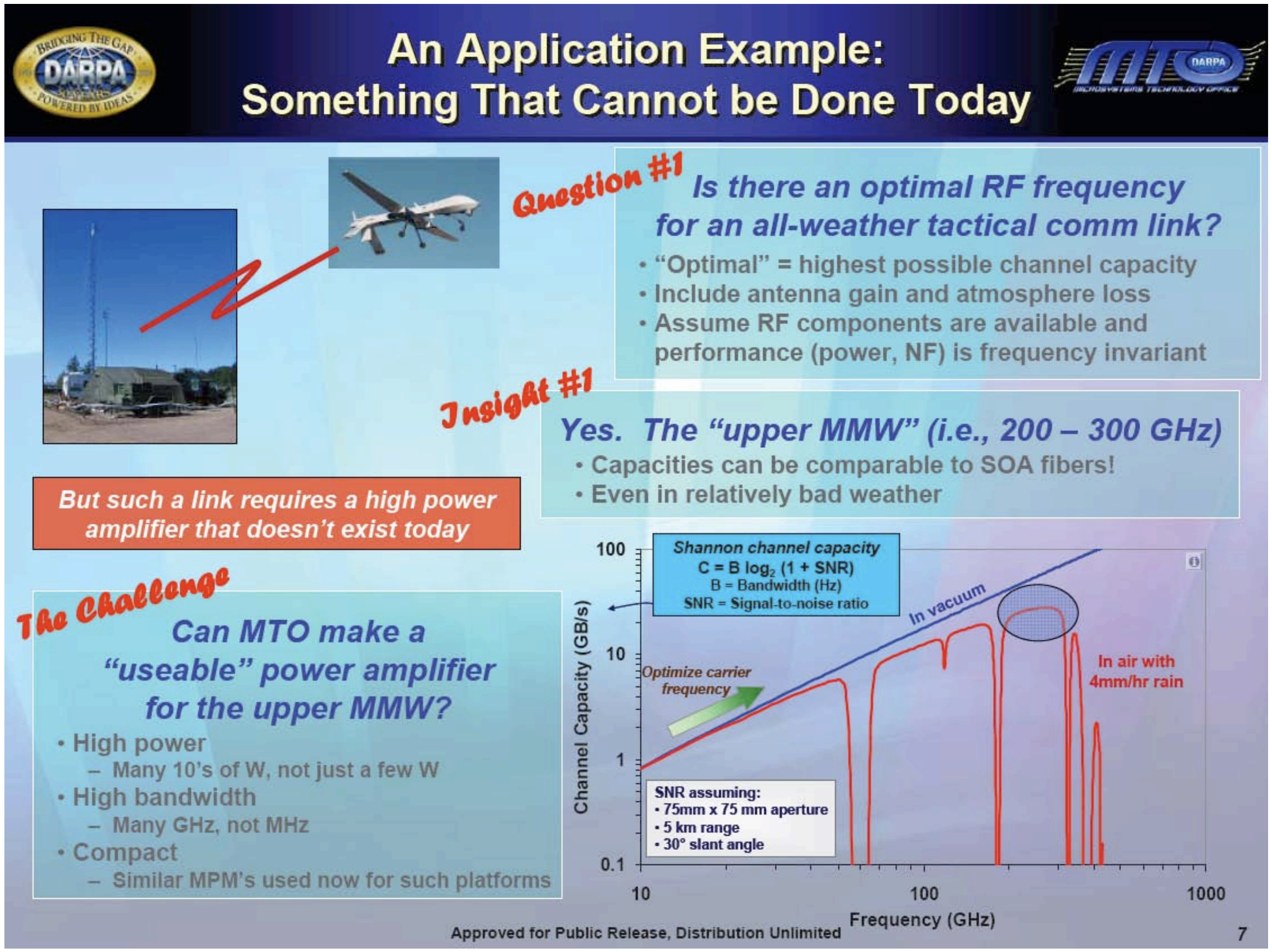
Comparisons of gas sensor systems

IR/Optical Comb
THz-TDS
Photomixers

Imagers

Transmission / materials and atmosphere

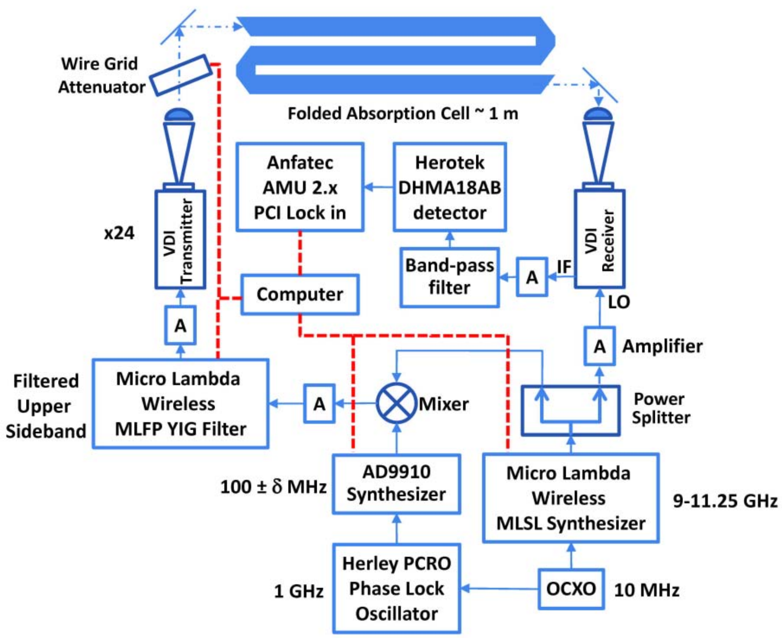
*Electronic THz systems are broadly very competitive



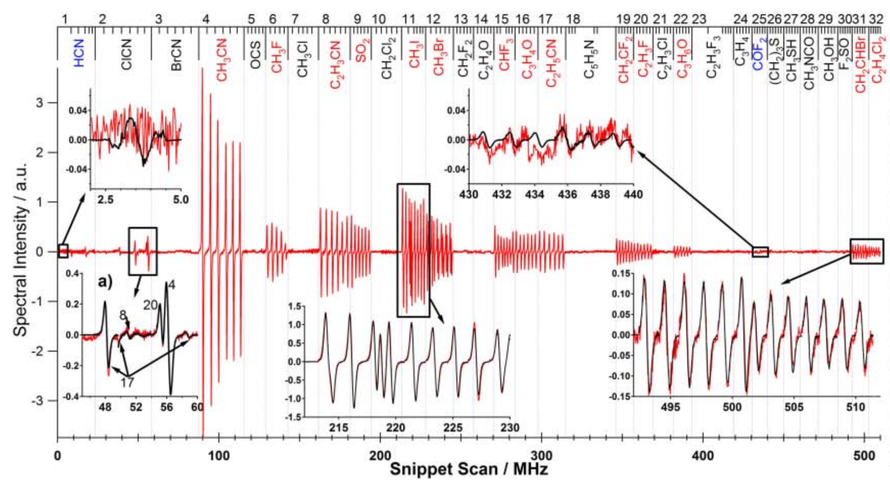
Courtesy of M. Rosker

Point Sensors

A Packaged Sensor



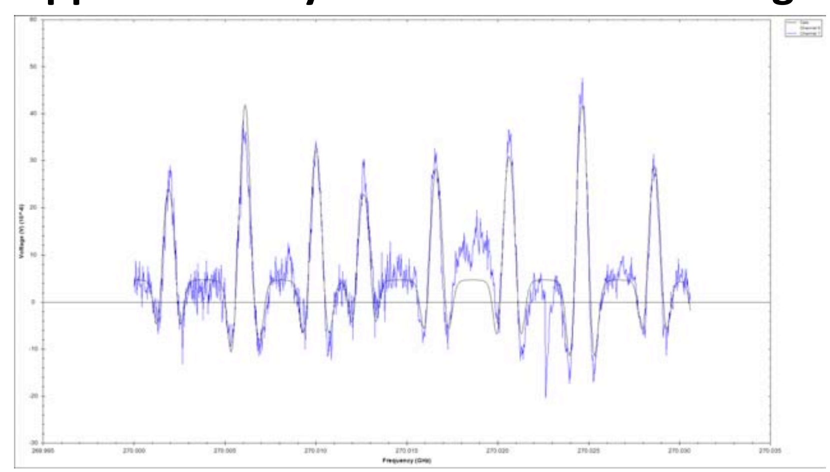
Absolute' specificity on mixture of 32 gases



	Pressure /µtorr	S/N
1	0.06	5.0
2	0.00	0.4
3	0.02	1.3
4	61.79	598.2
5	-0.02	0.5
6	26.97	304.7
7	0.00	0.1
8	66.09	432.5
9	54.13	323.8
10	0.12	1.2
11	130.10	404.2
12	85.04	390.4
13	0.16	1.0
14	-0.02	0.1
15	70.05	273.0
16	58.93	281.2
17	60.61	321.7
18	-0.12	0.8
19	55.67	192.8
20	40.31	161.3
21	-0.55	2.0
22	30.09	92.8
23	-0.07	0.3
24	-0.16	0.5
25	4.68	9.5
26	-0.90	1.8
27	0.10	0.2
28	0.81	1.5
29	0.27	0.6
30	-0.63	1.1
31	71.78	123.2
32	73.12	82.6

∑ = 0.89 mtorr

2 ppt sensitivity demonstrated on one gas



- 1 Cubic Foot Package
- Demonstrated that atmospheric clutter insignificant

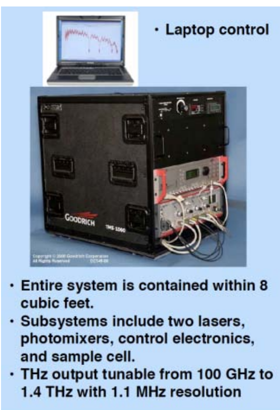
The U. S. Army Center for Health Promotion and Preventive Medicine Toxic Industrial Chemical (TIC) List

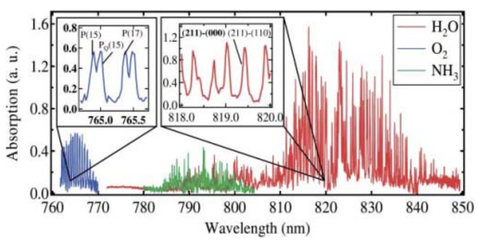
Allyl alcohol
Acrolein
Acrylonitrile
Ammonia
Arsine
Chlorine (HCl)
Diborane
Ethylene oxide
Formldehyde
Hydrogen bromide
Hydrogen chloride
Hydrogen cyanide
Hydrogen fluoride
Hydrogen selenide
Hydrogen sulfide
Methyl hydrazine
Methyl isocyanate
Methyl mercaptan
Nitrogen dioxide
Nitric acid
Parathion (not a gas)
Phosgene
Phosphine
Sulfuric acid (not a gas)
Sulfur dioxide
Toluene

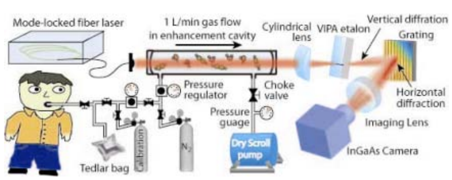
Green indicates a highly favorable gas
Orange indicates not a highly favorable gas
Red indicates not observable

Where are we Relative to Alternatives?

	Optical Comb/Cavity 100 Torr[1]	SMM 1.5 m Cell 10 mTorr	THz-TDS 5 m White Cell 7.5 mTorr[2]
$\Delta\nu_{system}$	1600 MHz	0.5 MHz	3000 MHz
$\Delta\nu_{instrument}$	800 MHz	0.001 MHz	3000 MHz
NH_3	18 ppb 9.6×10^{-11} mole	52 ppb 2.7×10^{-14} mole	---
CO	900 ppb 4.8×10^{-9} mole	280 ppb 1.5×10^{-13} mole	---
HCN	---	10 ppb 5.3×10^{-15} mole	---
CH_3CN	---	50 ppb 2.7×10^{-14} mole	---
CH_3Cl	---	---	$10^9/10^4$ ppb[5] $4\times10^{-7}/10^{-12}$ mole







Optical Comb/Cavity:

- Similar ppx sensitivity
- requires 10^4 more sample – sorbent difficult
- has $>10^4$ lower resolution
- orders of magnitude more atmospheric clutter
- much larger and more complex

THz-TDS:

- has $>10^3$ less ppx sensitivity
- requires 10^6 more sample – sorbent difficult
- has $>10^4$ lower resolution
- very sensitive to water interference
- somewhat larger and more complex

THz Photomixer:

- has $>10^4$ less ppx sensitivity
- requires 10^8 more sample – sorbent difficult
- demonstrates > 1000 less resolution
- orders of magnitude more atmospheric clutter
- somewhat larger and more complex (8 cu ft)

•SMM offers ‘absolute’ specificity
•SMM requires orders of magnitude less sample
=> Sorbents very advantageous, but spectroscopic optimizations unknown
•SMM has unknown limits wrt large molecules
•SMM has clear path to small and inexpensive

Plasma Diagnostics for Semiconductor Processing Diagnostics and Control

Can we give back to the semiconductor industry?

Results for Example Processing Plasma

Molecule*	Calculated Concentration/cm^3	Detectable Concentration/cm^3	Prognosis
CF_2	10^{13}	5×10^9	Easy
CF	10^{12}	2×10^8	Easy
CF^+	10^8	10^8	Marginal
C_3F_4	10^{13}	$\sim 5 \times 10^9$	Easy
Ar	10^{15}	--	No – atom
O	10^{13}	- -	No – atom
O_2	10^{13}	??	?? – magnetic dipole
F	10^{12}	- -	No – atom
C_4F_6	10^{12}	- -	No – zero dipole

*Molecular list and typical concentrations courtesy of Phillip Stout of Applied Materials

Quantitative detection limits are straightforward to calculate from first principles and/or previous work. This is a 'no risk' application. It will work! Is it useful?

The Millimeter and Submillimeter Spectrum of CF_2 and Its Production in a dc Glow Discharge

ARTHUR CHARO AND FRANK C. DE LUCIA

Department of Physics, Duke University, Durham, North Carolina 27706

The millimeter and submillimeter spectrum of CF^{+} a)

Grant M. Plummer, Todd Anderson, Eric Herbst, and Frank C. De Lucia
Department of Physics, Duke University, Durham, North Carolina 27706

(Received 7 October 1985; accepted 12 November 1985)

Plasma Diagnostics Summary

The low pressure plasmas of semiconductor etching processes are near ideal environments for SMM/THz analysis

Plasmas are noise and background free and 100% transparent in the SMM/THz

Optimum pressure because Doppler and Pressure broadening widths nearly equal

The rotational interaction between SMM/THz radiation and molecules is very strong

Diffraction limited beam will allow some location information to be derived, but will not be nearly as good as in the optical/infrared

However, inexpensive CMOS implementation with synthesized frequency and phase should make tomography possible

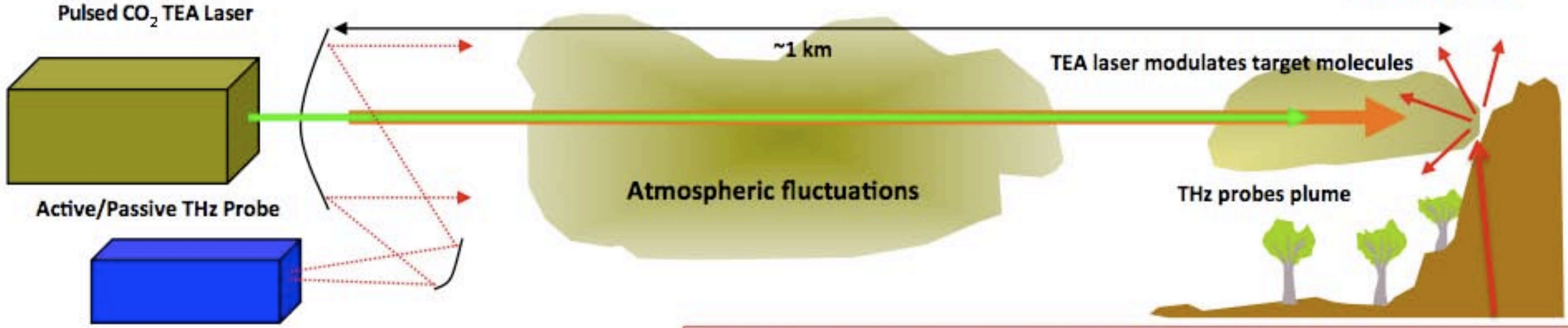
The critical issue is if there is enough concentration for detection
Spectroscopic calculations show for a number of species of interest that the concentrations will be sufficient

A dipole moment is required

If a species can be detected, this detection will be 'absolute', quantitative, and will provide measurement of the translational temperature as well

Stand Off Sensors

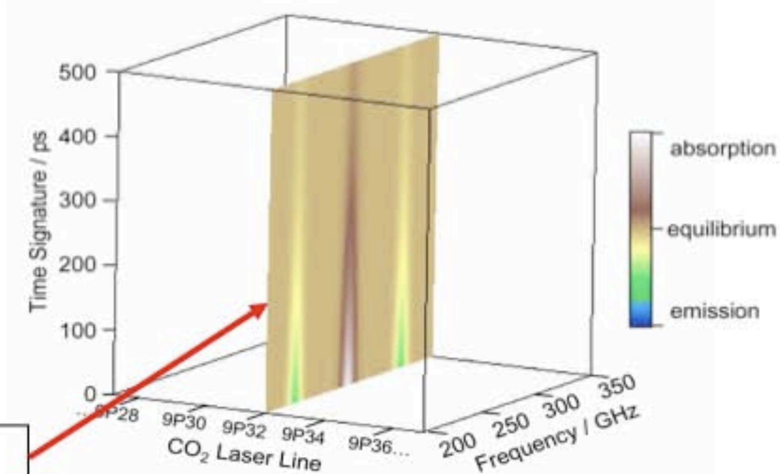
A New Approach:
Double Resonance Modulation for Remote Sensing



Single Mode to MultiMode Conversion
Vacuum Electronic to help with $10^5 – 10^7$ factor

Problem # 1: Specificity
Dimension 1: Choose IR pump frequency
Dimension 2: Monitor the SMM/THz probe frequencies
Dimension 3: Match pump pulse to relaxation of atmosphere (~100 ps)
=> 3-D to increase specificity

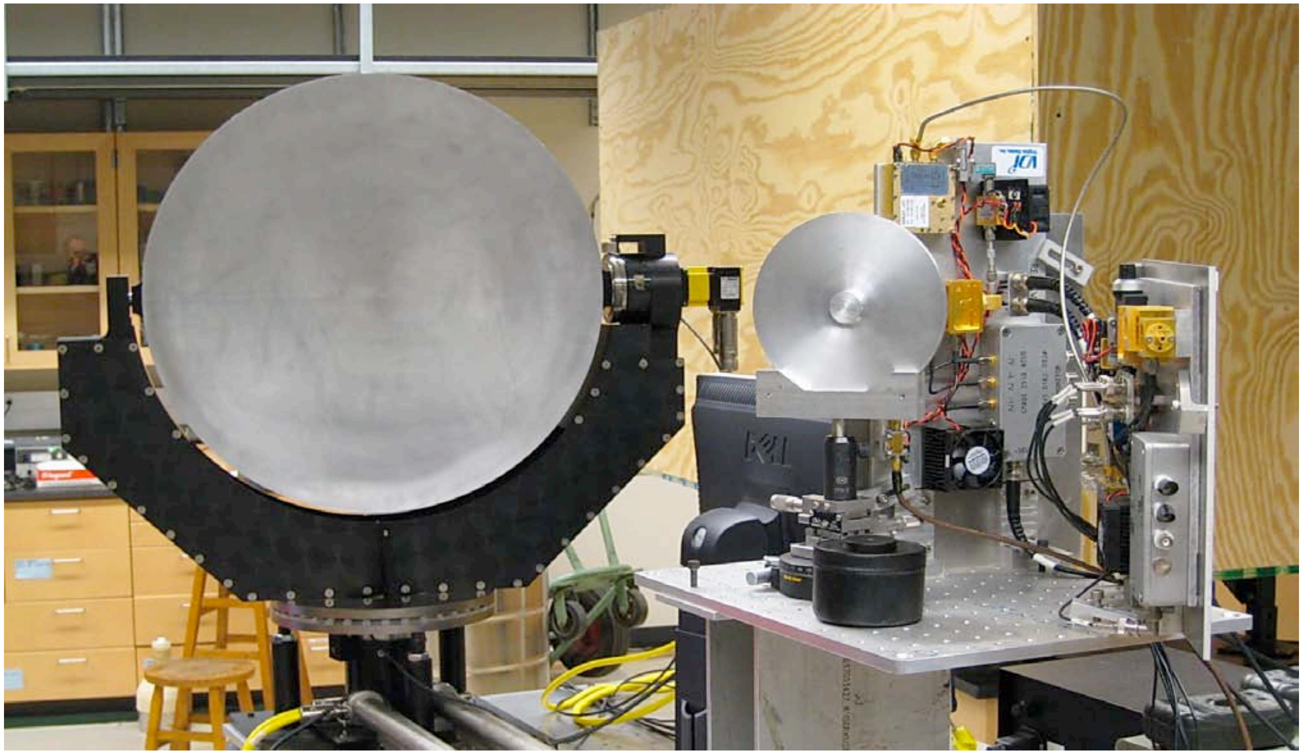
Problem # 2: Separation of target signature from baseline and clutter
Lock on to IR pulse sequence to reject of atmospheric clutter -
=> The 10^6 factor



Probe slice for a *particular* pump

Imaging

640 GHz Active Imager from DARPA TIFT Program



Incoherent 'Passive' Images: Angular Diversity

Cold Sky Illumination at 94 GHz

Incoherent Target Illumination

Multimode above

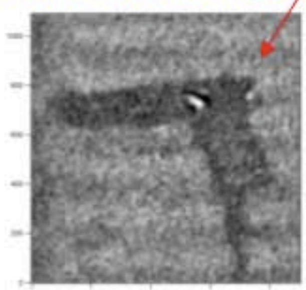
Multimode side

From ~blackbody room

Target emission into 2π steradians of modes

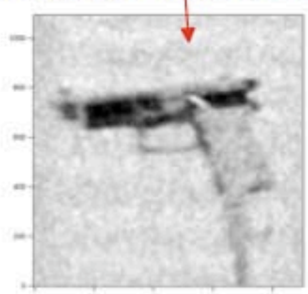
'Uniform' Passive Illumination at 94 GHz

Thermal Emission on Warm at 650 GHz Background



Shadow gram of metallic object reflecting diffuse colder room

~15 Degree Thermal Illumination at 650 GHz



Contrast of metal within angular diversity of illuminator

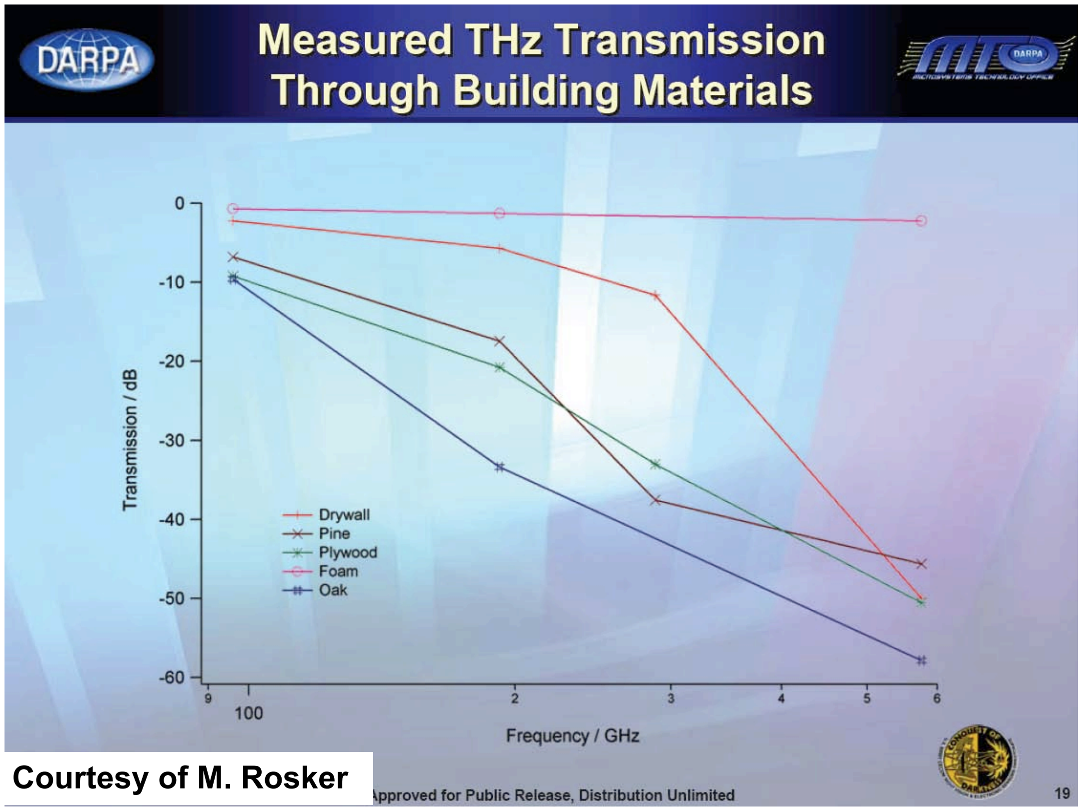
THz Passive Thermal Emission

Thermal Radiation no special angle

MTT-S

WSC: Imaging at mm-wave and beyond.

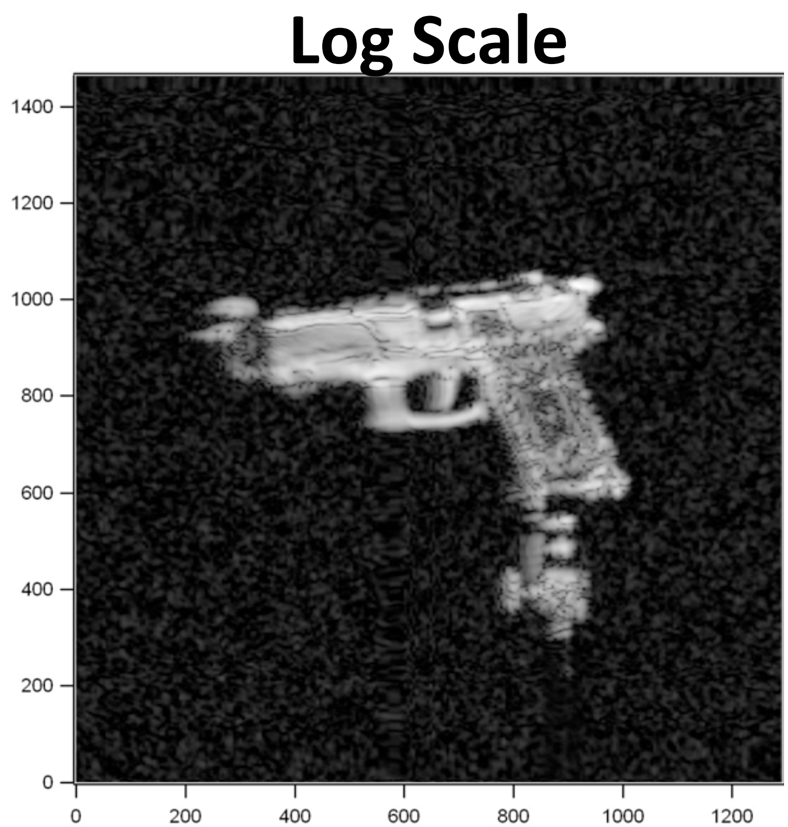
Will THz photons generated by electronic techniques 'see through walls'?

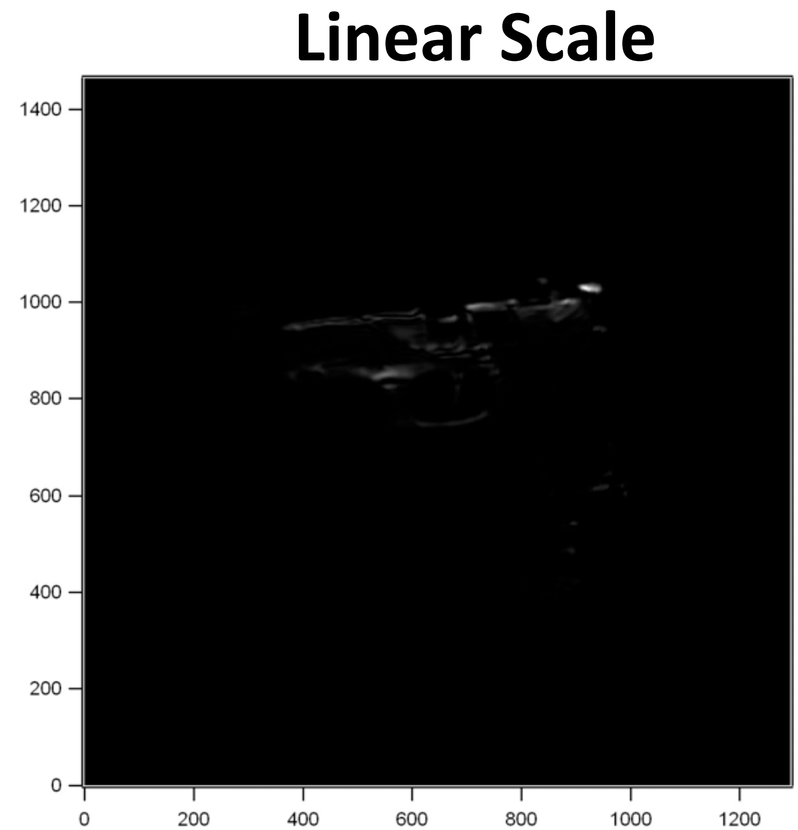


Courtesy of M. Rosker

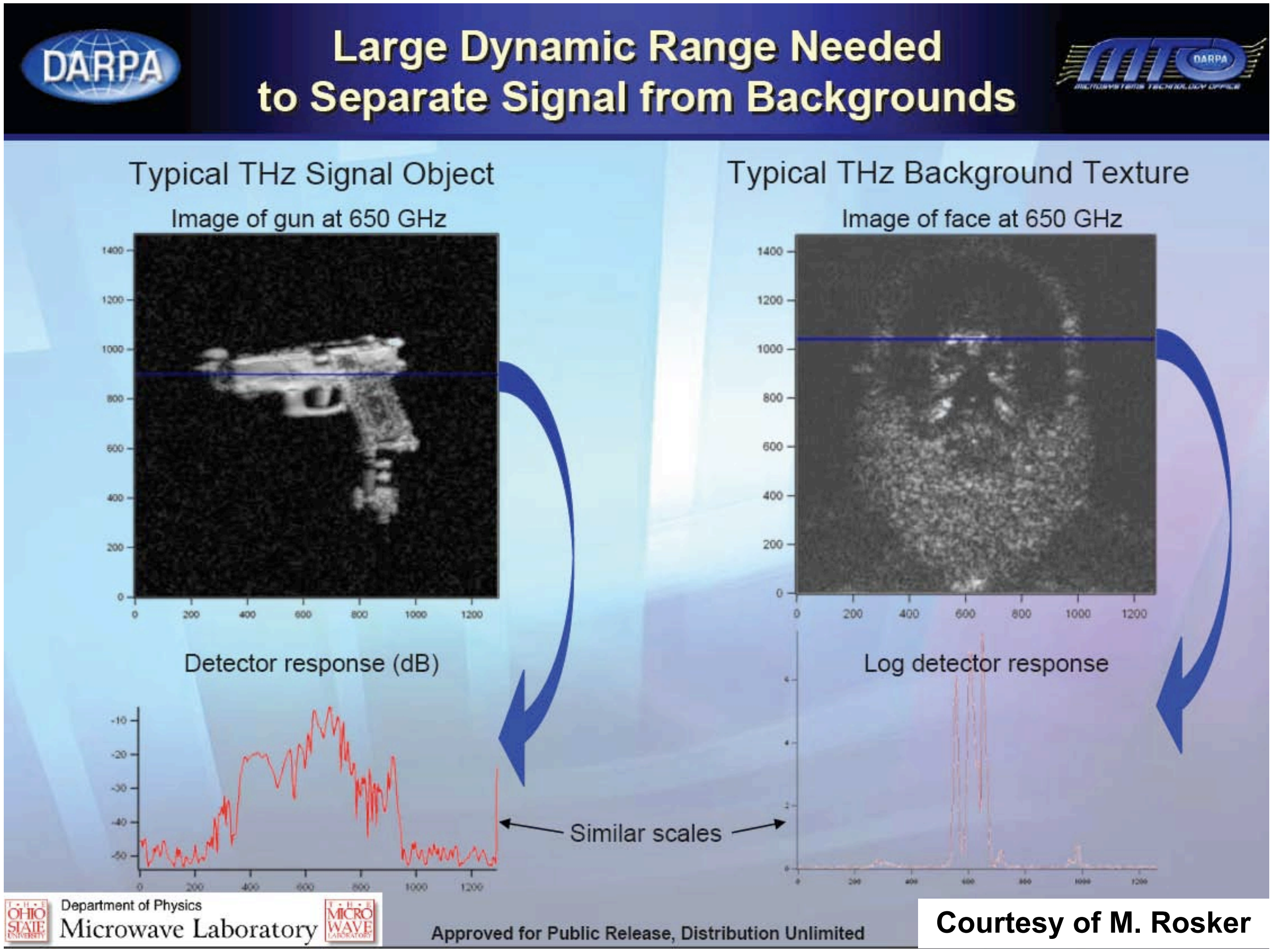
No, unless you live in a foam house!

What if Target is not at the 'Special Angle?' Log and Linear Scales (Problems and Solutions)



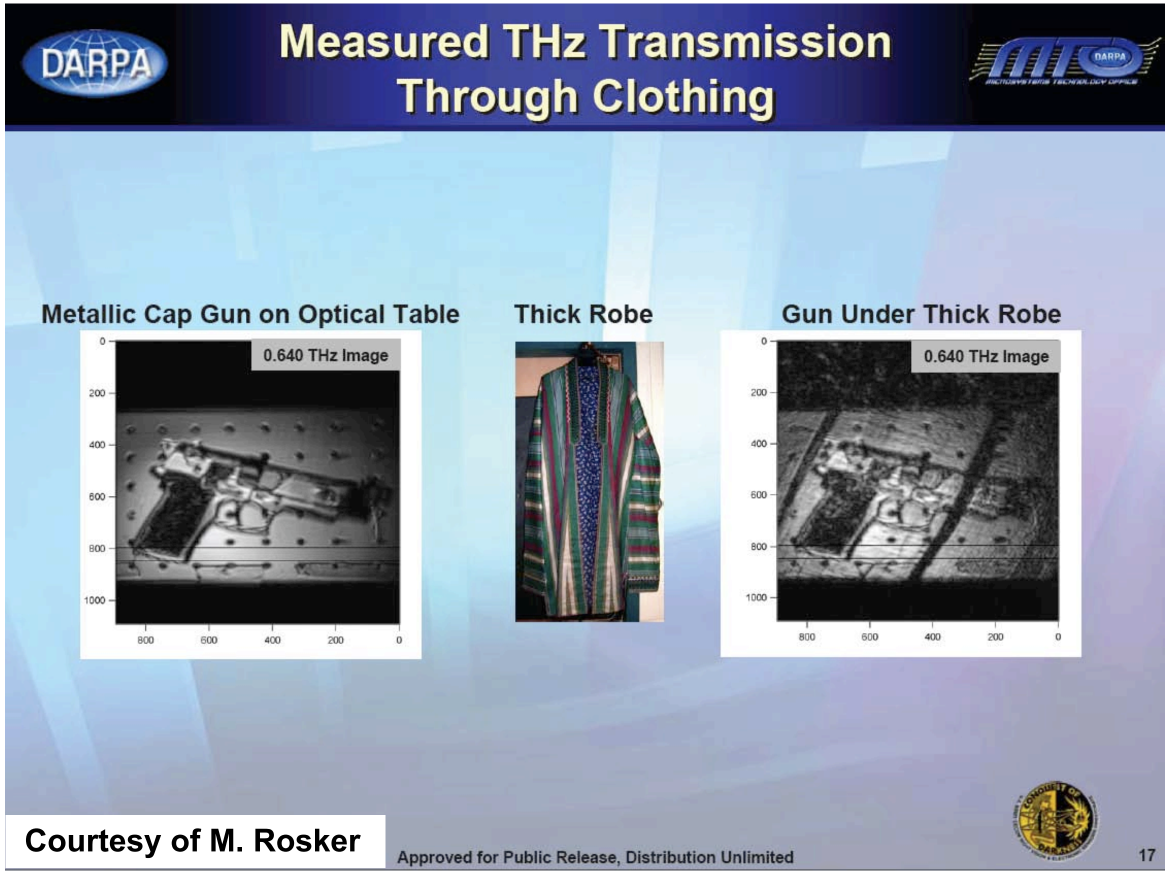


Small target rotation against non-specular background significantly reduces linear target contrast



This high dynamic range is available because of high spectral brightness in heterodyne receiver

What about Transmission?



With Gun and background are strategically angled, targets stand out under obstruction.

What if not statically angled and target down ~30 db?

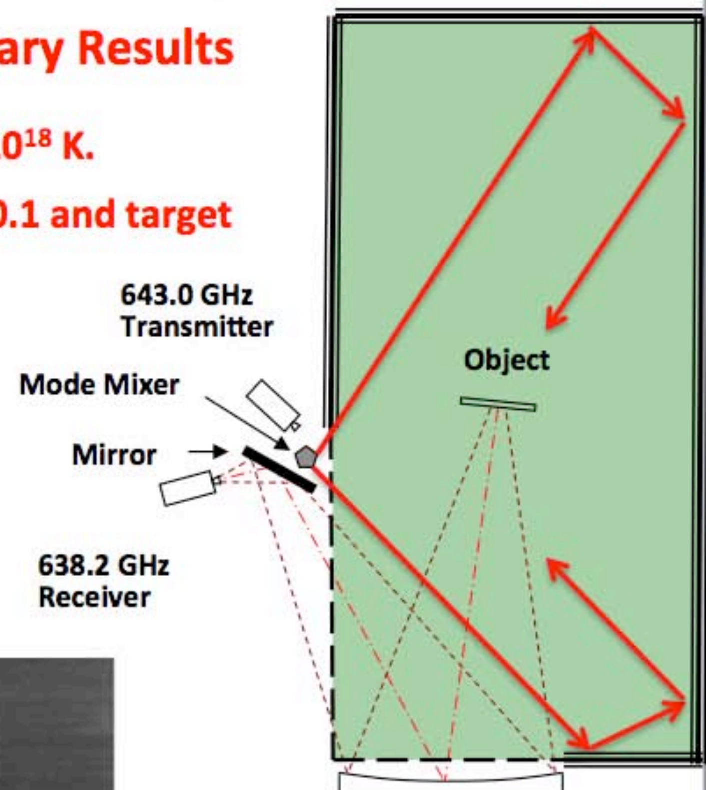
Can we use active illumination to make very hot 'passive' pictures and remove the need for 'special orientation: Multimode Illumination – Preliminary Results

1 mW in 100 Hz in a single mode corresponds to a temperature of 10^{18} K.

For a 'room/canyon' of scale l = 100 m, with 'wall' reflectivity R_w = 0.1 and target reflectivity R_o = 0.1

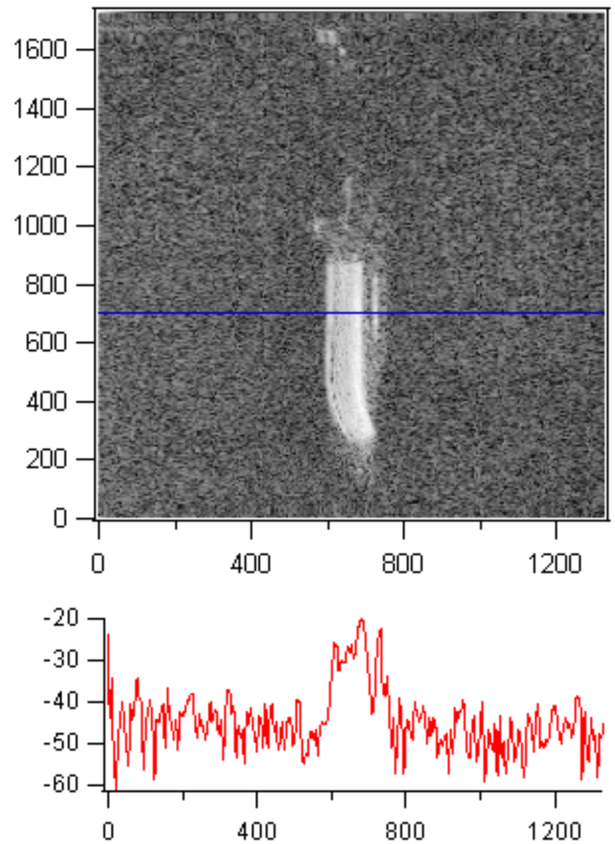
$$T_o = 10^{18} K \left(\frac{\lambda}{l}\right)^2 R_w R_o \sim 2.5 \times 10^5 K$$

More power: larger volumes, less cooperative reflections, more Doppler bandwidth, shorter integration times

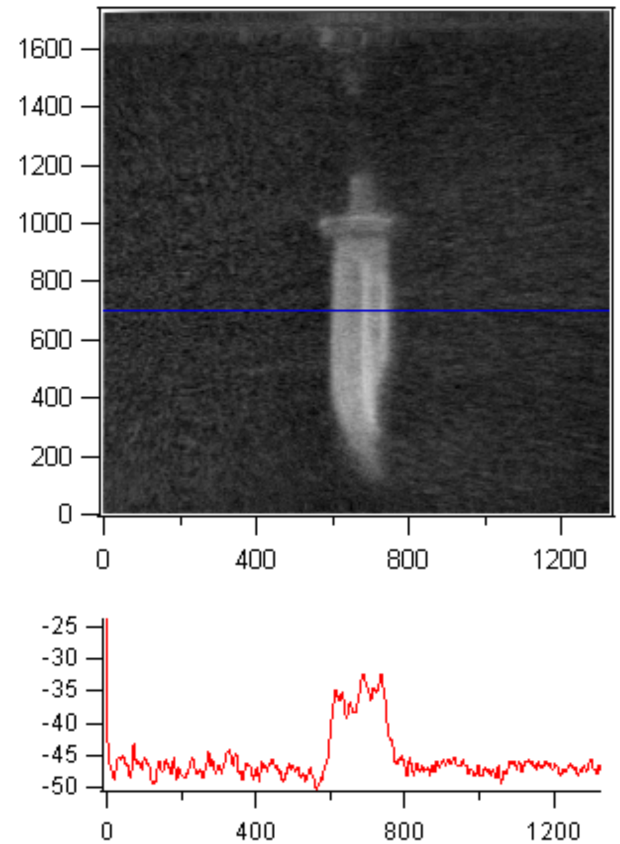


maging at mm-wave and beyond.

Brown robe, Log images



1 image at 0 degrees



41 images averaged from -20 to +20 degrees

The power of vacuum electronic sources has the potential to make very hot 'passive' (multimode) images using natural reflections

Goal: The SMM equivalent of turning the lights on in this room!

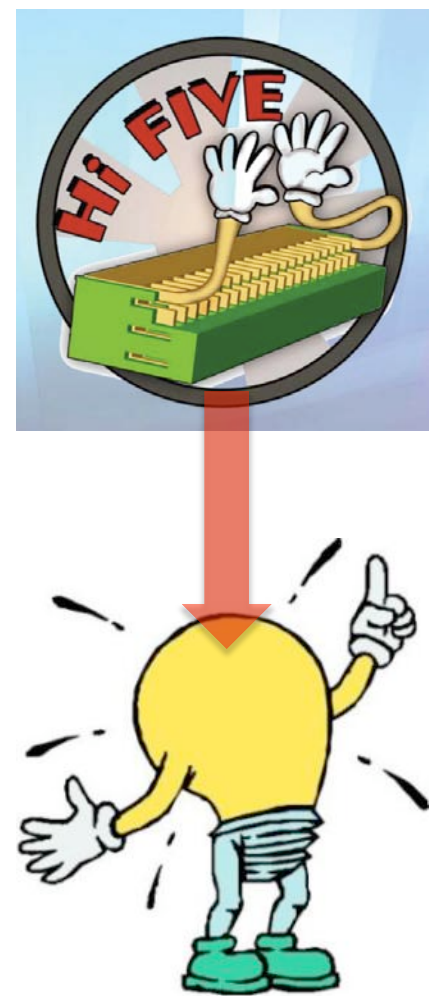
A 220 GHz Lightbulb

A 'black body' optical source, for which you can control:

- Frequency agility and selectivity
- Timing/pulse sequence
- Relative phase of modes
- Brightness
  - Broadband (50 W in 50 GHz => 10^{14} K)
  - Narrowband (50 W in 50 Hz => 10^{23} K)

Provides:

- Multiplex and multimode opportunities
- Spectroscopic/texture imaging
- Minimization of coherent effects in active imaging



Imaging Summary

1. In passive imaging, the thermal emission from the target and the reflected 'passive' thermal illumination are both multimode.

   a. No special angles for strong specular reflections

   b. A relatively low contrast: $\Delta T/T$ - but no speckle modulation

   c. Off axis(bistatic) thermal illumination improves this contrast (true for active as well)

2. in active imaging, there are many possible illumination strategies

   a. Monostatic systems results in glints from corners and normal surfaces which are many orders of magnitude stronger than returns from non-normal or scattering surfaces - signatures?

   b. Logarithmic processing recovers this range of data and can provide images with significantly enhance recognition

   c. 'All' mode illumination closely resembles passive imaging IF the coherence among the illumination modes is destroyed

3. Obscurations: Active systems can have very large *system S/N.* However, the clutter associated with covering obscurations can limit a system long before the system S/N

   a. Much of this clutter is coherent, and multimode approaches can significantly reduce/eliminate it

   b. Recognition strategies based on the strong glints rather than images

4. Range: Because spot size is a function of range, the definition of normal is a strong function of range (i.e. active illumination will be a complex function or range, not just a diffraction degradation)

Models which describe and compare system approaches must reflect these target and range effects as a function of illumination strategy

Summary

- Incremental advances over 40 years have brought us to the threshold of a THz revolution
  - Technology
  - Science and phenomenology
- Recent advances in technology will both
  - Provide a step function in capability
  - Enable the mass market
- We should be grateful to the optical THz community for bringing the THz spectral region to broader attention
  - (but we have to be careful not to be tarred by some of their claims)
- Microwave electronics approaches are *very* competitive
- Applications (from 'one-off' to 'public')
  - Submillimeter Astronomy (>$$10^9$) instruments
  - Atmospheric remote sensing
  - Laboratory science (both basic and to support applications)
  - Radar (providing mass market to drive technology)
  - Communications (providing mass market to drive technology)
  - Imaging (through obstruction)
  - Gas sensors (point and remote)
  - Analytical chemistry
  - Process diagnostics and control