The Science and Technology of Terahertz Applications

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Abstract: It has long been known that the terahertz (aka submillimeter) offers many opportunities for unique and powerful applications. Some of these have come to fruition, have made substantial impact on many scientific fields, and have evolved to attract support for three billion-dollar instruments.

This talk will focus on how the science of terahertz applications impacts the choice of technological approach. We will show how source brightness is often more important than source power and also consider the importance of frequency agility, spectral purity, and accuracy. We will also discuss noise and distinguish between applications for which small amounts of power need to be detected and those for which the detection of small changes in relatively large amounts of power are necessary. Fundamental limits for both will be developed.

Although two legacy applications, chemical sensors and imaging, have been considered for a number of decades, there are as yet no 'public' implementations of either, or for that matter of other applications. However, we will show paths that are both powerful and cost effective for both. We will pay particular attention to the relation between demonstrations that depend upon either special geometries and scenarios in imaging or highly favorable choices of target molecules for gas sensors. We will show that many orders of magnitude are at stake. For imaging, we will show recent work that eliminates coherent speckle in active imaging. We will also show a packaged terahertz sensor that can automatically quantify large mixtures of complex gases and compare it with other terahertz and infrared systems.

SICAST
Shenzhen, China
November 21 - 25, 2011

Areas of Submillimeter (a.k.a. THz) Interest and Activity of the OSU Microwave Laboratory

- **Molecular Spectroscopy**
- **Astrophysics**
- **Chemical Remote and Point Sensors**
- **Analytical Chemistry**
- **Atmospheric Propagation**
- **Imaging**
- **Plasma Processing of Semiconductor Wafers**
- **Systems and Technology**

Acknowledgements

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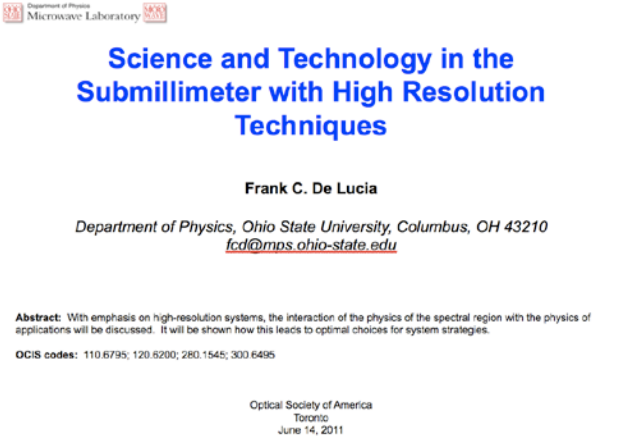
Chris Ball

The Three Cultures*

THz/Optical

Optical Society of America,
“THz Spectroscopy and Imaging Applications”
Toronto, June 14, 2011

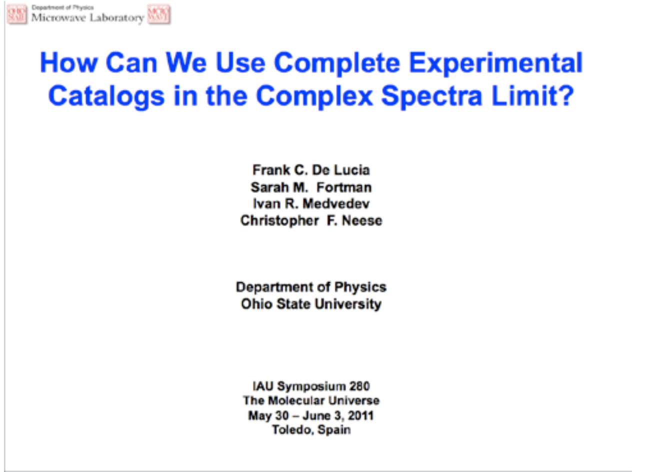


Millimeter/Electronic (Engineering)

IEEE International Microwave Show 2011
“Workshop on MM-Wave and Terahertz Systems”
Baltimore, MD, June 6, 2011

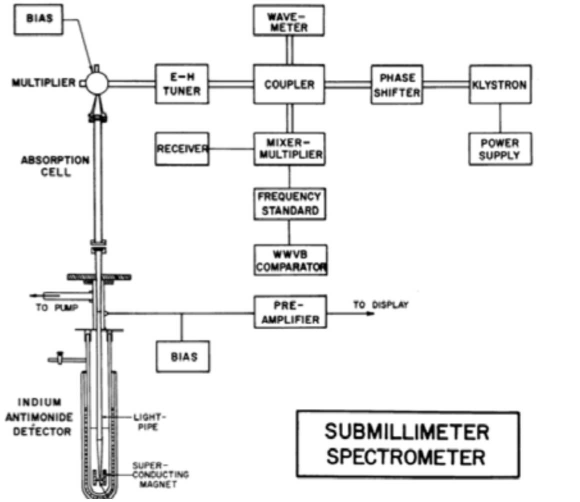
Submillimeter/Electronic (Scientific)

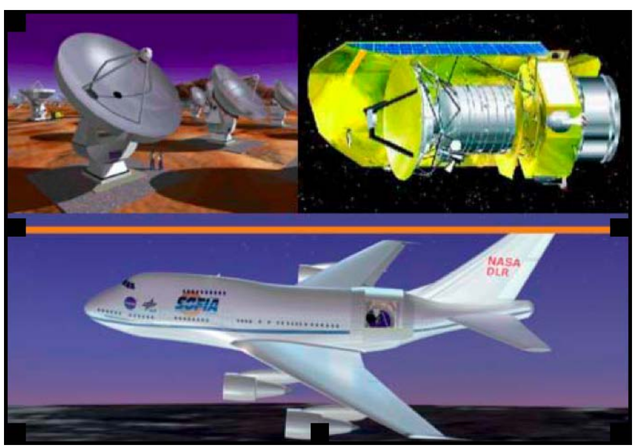
International Astronomical Union,
“The Molecular Universe”
Toledo Spain, June 2, 2011

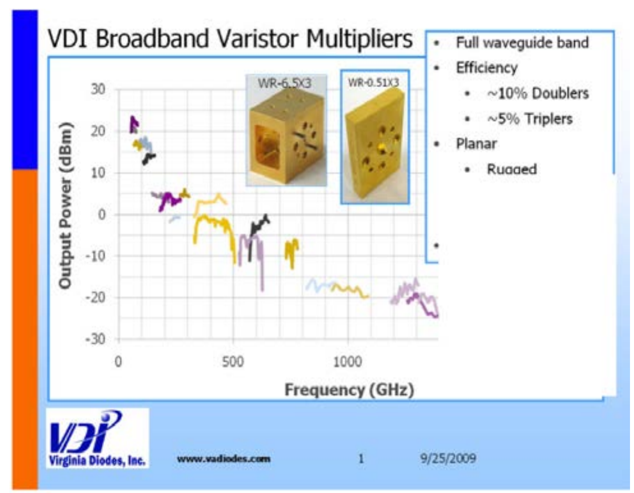


With apologies to C. P. Snow, “The Two Cultures”

The THz (SMM) has Come a Long Way (Incrementally)

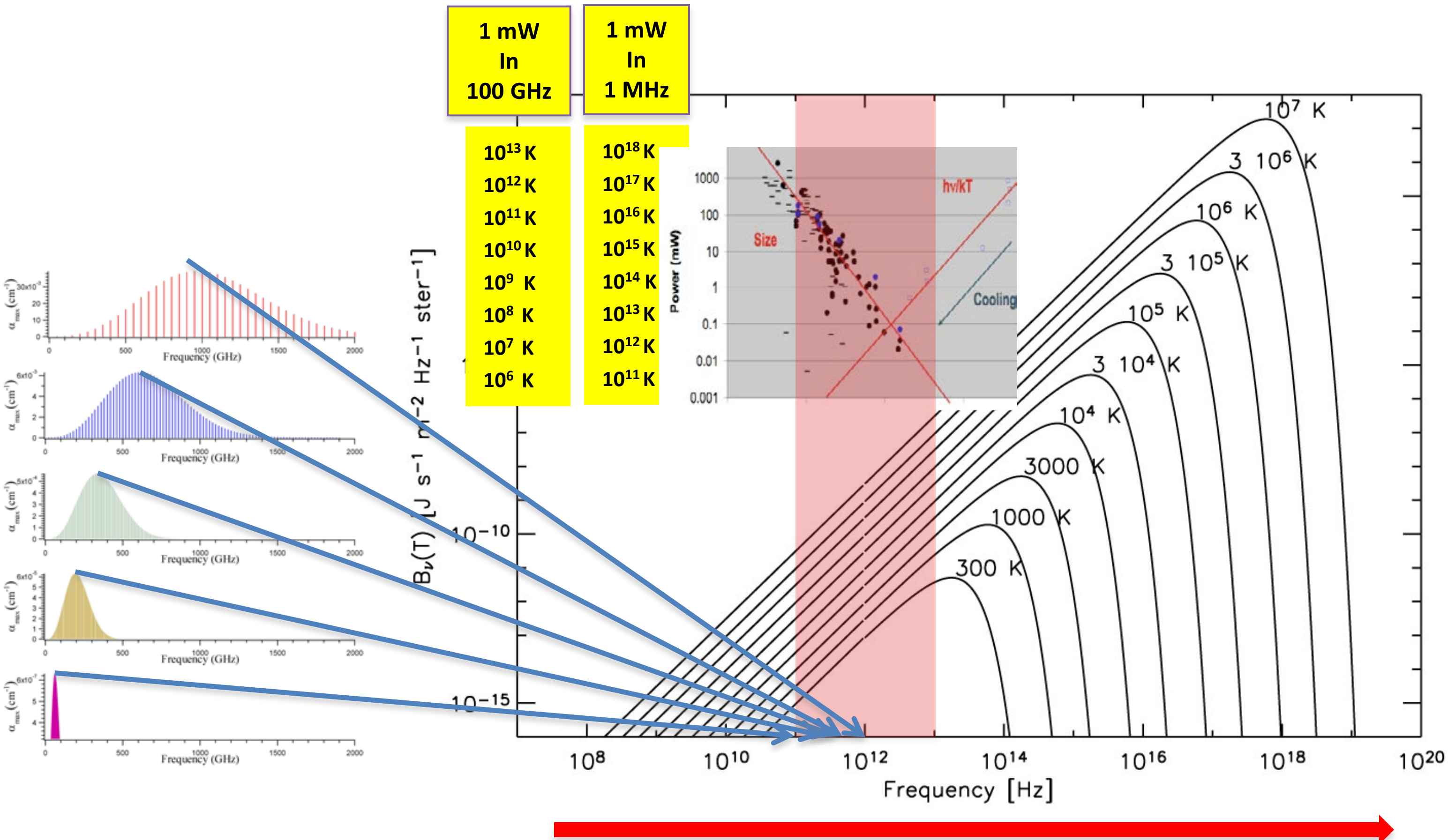






The Physics

Radiation and Interactions: Orders of Magnitude



The SMM/THz – broadly defined

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

Bandwidth matters: Spectral Brightness and Figures of Merit

Spectral distribution as function of molecular size at 300 K

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

SMM and small static samples are favorable combination

What is the Physics? – Numbers Matter

Brightness Temperatures (W/Hz):

1 mW in 1 MHz corresponds to 10^{14} K
1 mW in 100 Hz corresponds to 10^{18} K

Bandwidth

SMM Detectors:

1.5 K InSb bolometer: NEP ~10^{-12} $W/Hz^{1/2}$
1.5 K Si bolometer: ~10^{-13} $W/Hz^{1/2}$
0.3 K Si bolometer: ~10^{-15} $W/Hz^{1/2}$
Heterodyne *with* T_N = 3000 K
$b = B = 10^6$ Hz: $P_N = 5 \times 10^{-14}$ W
b = 10^6 Hz, B = 1 Hz: $P_N = 5 \times 10^{-17}$ W

Very Large Ratios

SMM Sources:

10^{-12} W Solid state sources at high frequency
10^{-3} W Nominal for many classes of sources
10^{2} W Tubes at 1 mm; More with pulsed?

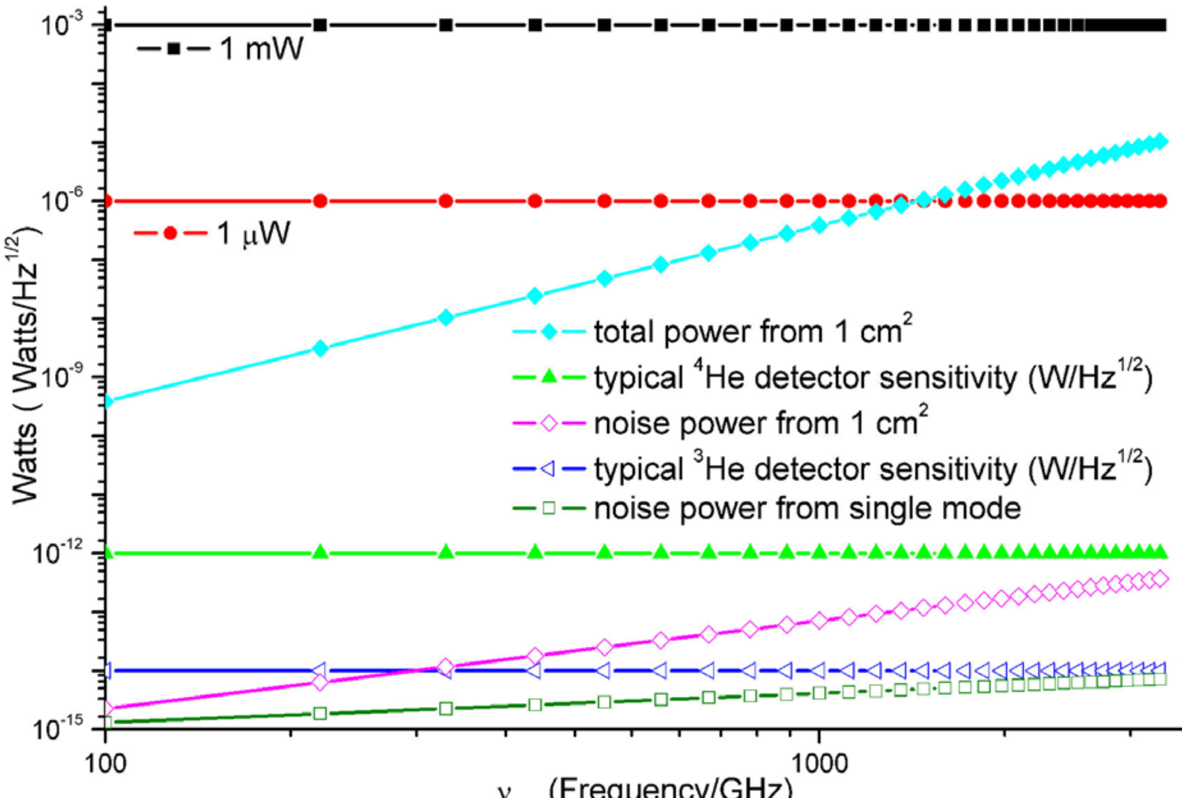
Number of Spatial Modes in Hemisphere, 1 m Antenna, λ = 1 mm

At 100 m: ~ 10^5
At 1000 m: ~10^7

=> Power from Vacuum Electronics

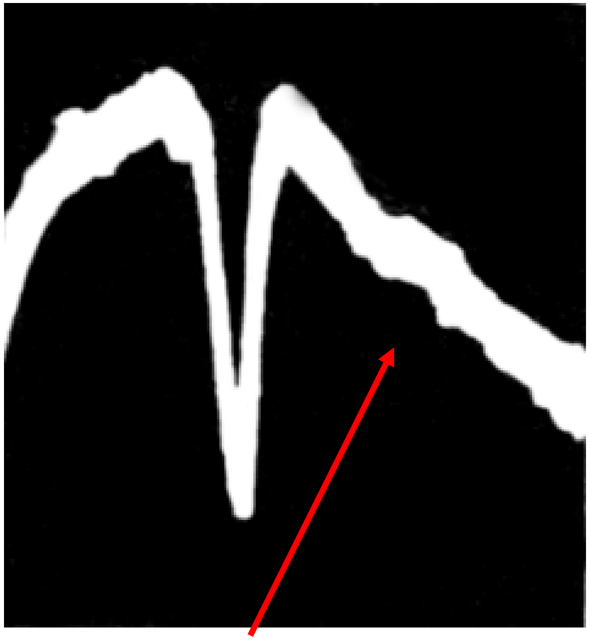
Department of Physics
Microwave Laboratory

The THz is *VERY* Quiet even for CW Systems in Harsh Environments



10^{10} Misconception

Experiment: SiO *vapor* at ~1700 K



***All* noise from 1.6 K detector systemm**

Noise, detectors, and submillimeter–terahertz system performance in nonambient environments

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System Numbers

For a receiver noise temperature T_N = 3000 K and $b = B = 10^6$ Hz, $P_N = 5 \times 10^{-14}$ W.

$$\frac{P_c}{P_N} \sim 10^{10}$$

If we have a carrier power of P_c = 1 mW, we must also consider the noise associated with the adding of the blackbody noise *voltage* with the carrier. For this case

$$P_n' \approx \sqrt{kT\Delta\nu P_c} = \sqrt{(5\times10^{-14})(10^{-3})} \approx 10^{-8} W$$

Five Orders of Magnitude

This is about five orders of magnitude above the receiver noise.

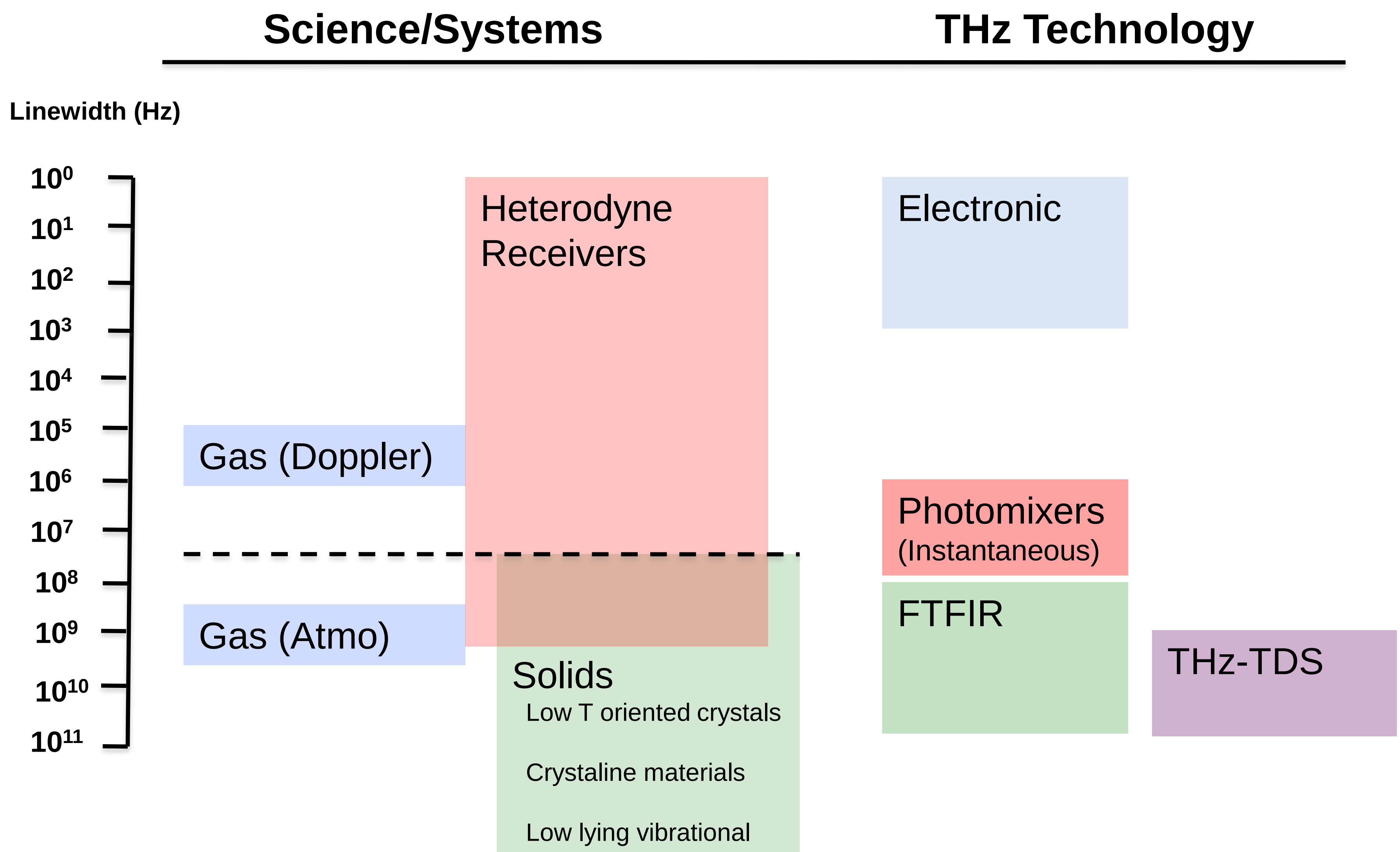
The system S/N is then

$$S/N = \frac{P_c}{P_N'} \sim \frac{10^{-3} W}{10^{-8} W} \sim 10^5$$

This is the impact of the so called ‘Townes Noise’.

Impact is only large when we are looking to detect a small change in a large P_c

Why 2/3 Cultures? Logarithmic Linewidths



Consequences of the Physics

Optimum pressure is ~ 10^{-5} atmospheres (Doppler) and sample is static

- => very small sample requirements
- => small sampling volumes for large preconcentration gains (1 liter STP - 10^5 gain)
- => vacuum requirement greater than in IR/Op
- => atmospheric clutter limit ~1 ppt (aided by spectroscopic specifics as well)

Electronic sources are

- => essentially delta functions, even in Doppler limit
- => frequency agility to optimize photon use

Small Power provides very high brightness

- => path to very small and inexpensive technology

Spectral density strong function of molecular size

- => large molecule limit with static ambient samples

Clear Paths to Legacy Applications

Chemical Sensors

Imaging

These are enabled by combination of technology advances and mass market (wireless) cost savings

Point Sensors

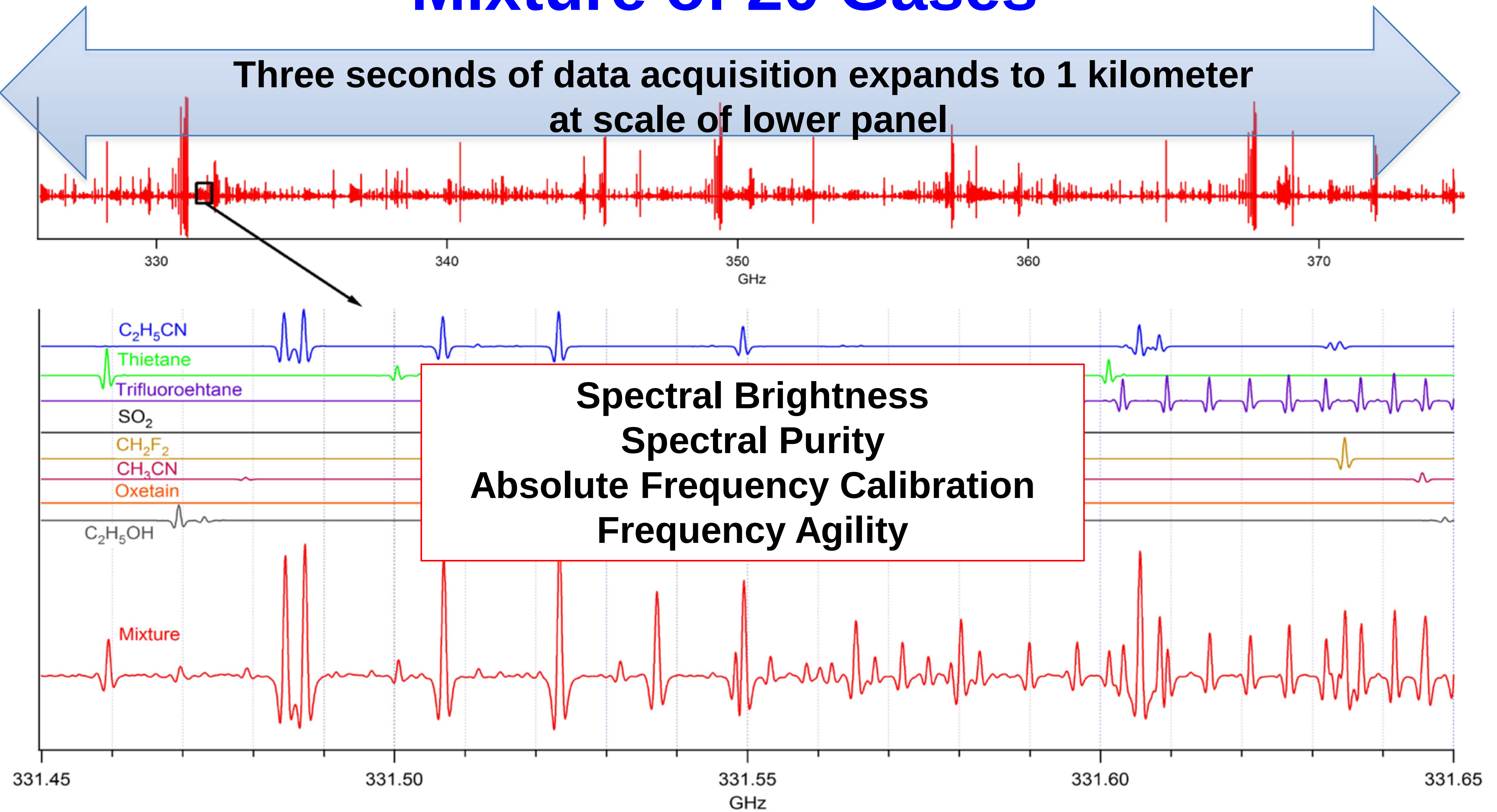
Sensor and Analysis Trade Space

- **Very complicated for spectroscopic sensors**
- **First: Show particular optimization**
- **Second: Consider trades from this locus**

- **Trades**

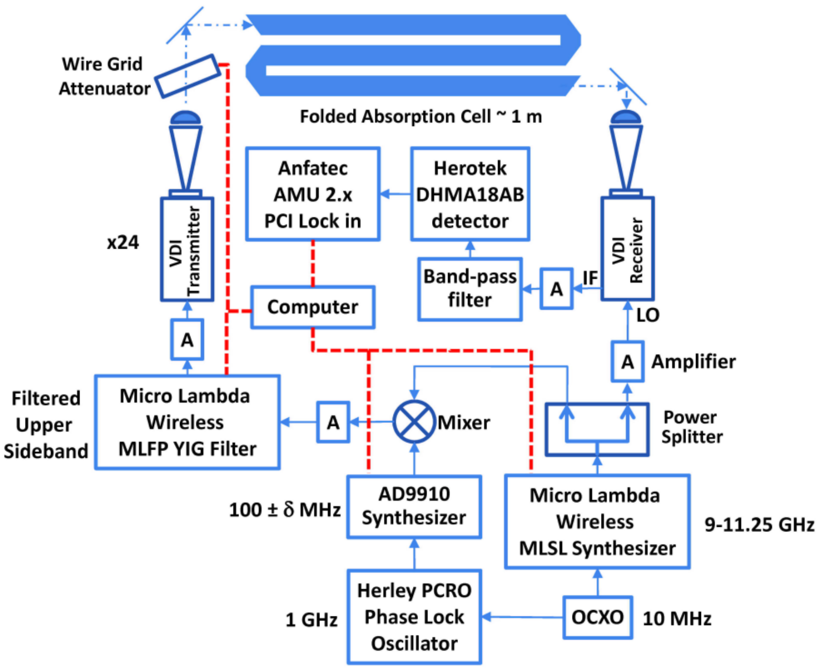
- **Speed**
- **Sensitivity**
- **Specificity**
- **Generality**
- **Size – Cost**
  (not always a ‘trade’ in SMM – rapid, predictable path)

For Comparison: Vacuum Electronics Spectrum of a Mixture of 20 Gases



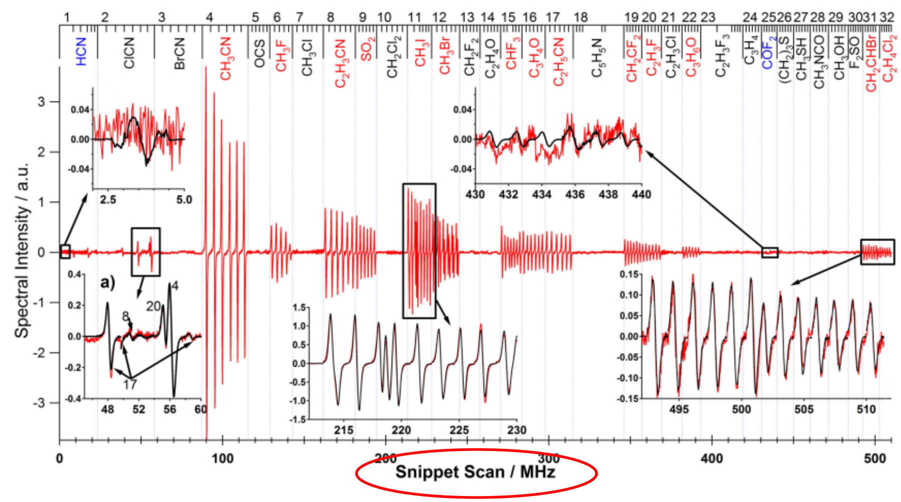
An Implementation as a Point in Trade Space

Goals:
1 Cubic Foot Box
$<10^{-4}$ PFA on >30 gas mixture
<100 ppt on one gas



Synthesized snippets to optimize photon use

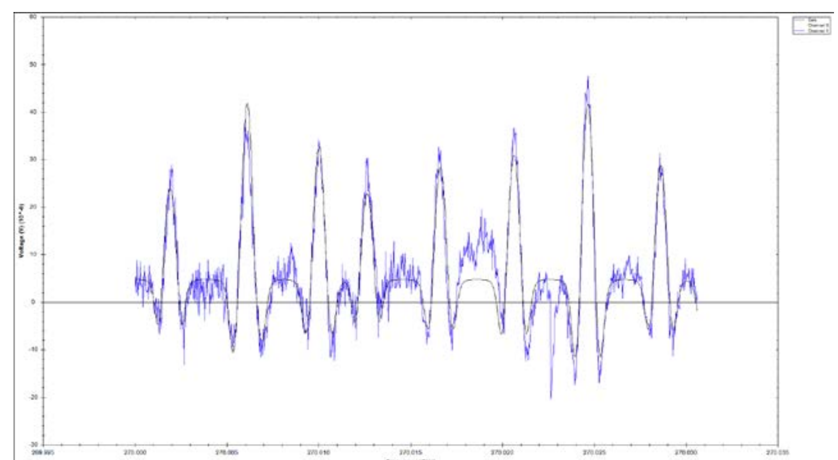
'absolute' specificity on mixture of 32



	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

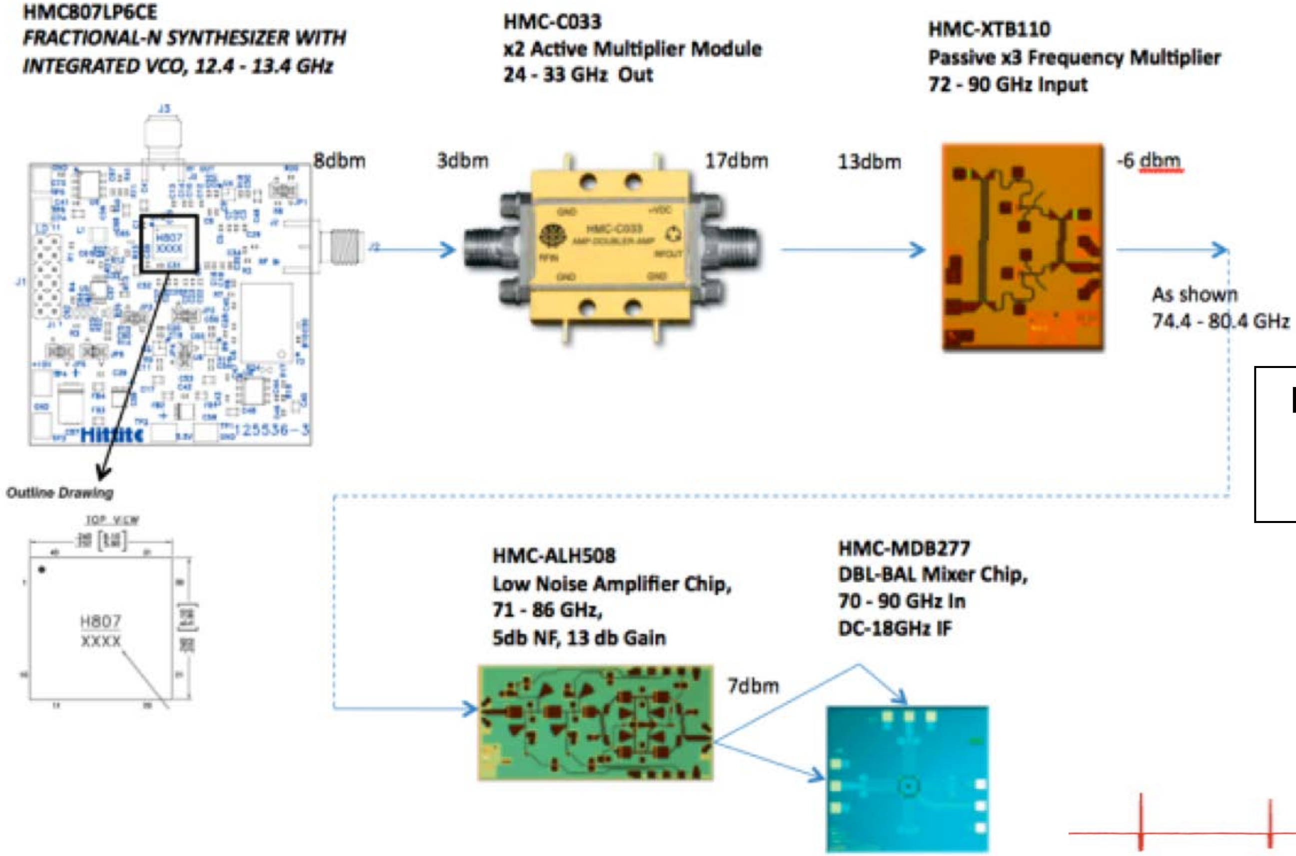


Advances in Electronic Technology

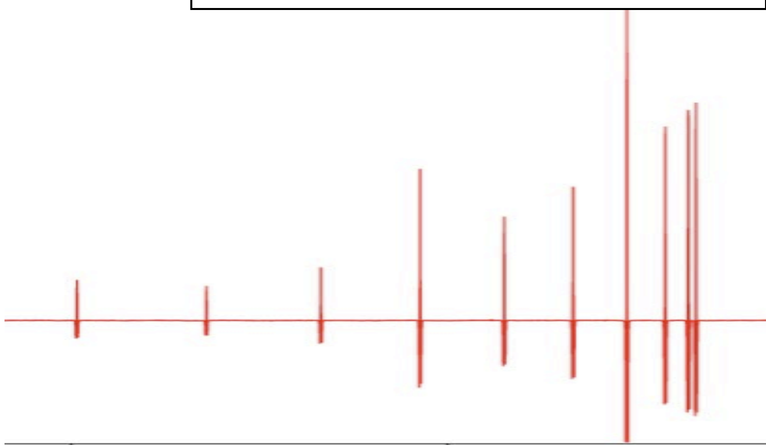
Size and Cost Drivers from the Wireless Communications Industry

Because the brightness of low power, high spectral purity sources is very high the 'physics' to support low cost, small size, and low power is very favorable

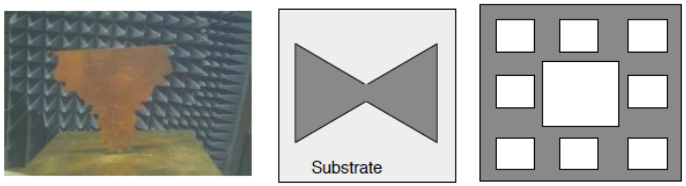
Broad Line of Chip Level IC Through 100 GHz Commercially Available in Large Quantity



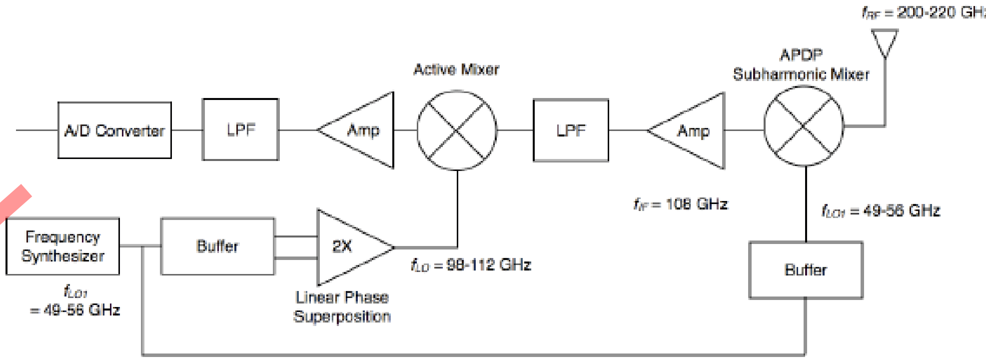
Experimental demonstration at 600 GHz of spectral purity of chip level synthesizer



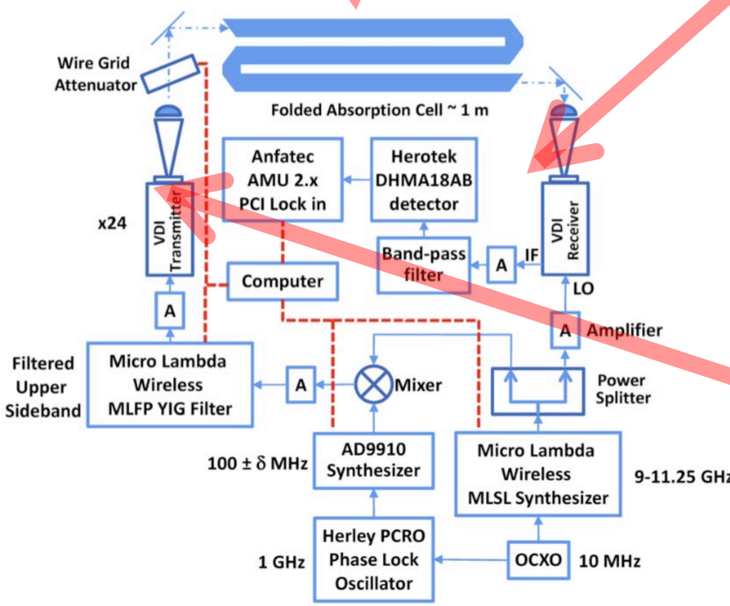
CMOS Integration for 240 GHz*

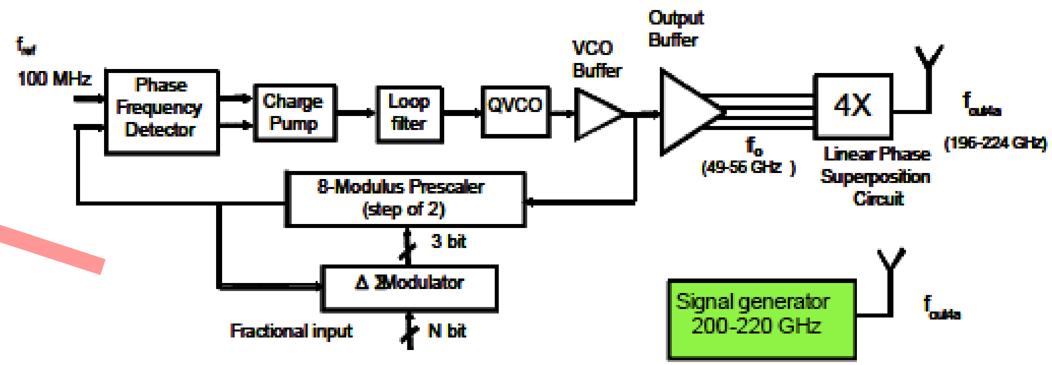


Antennas: Rashaunda Henderson (UT-D)



Receiver: Bhaskar Banerjee (UT-D)





Transmitter: Kenneth O (UT-D)

*Sponsored by the Semiconductor Research Corporation

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

•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

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

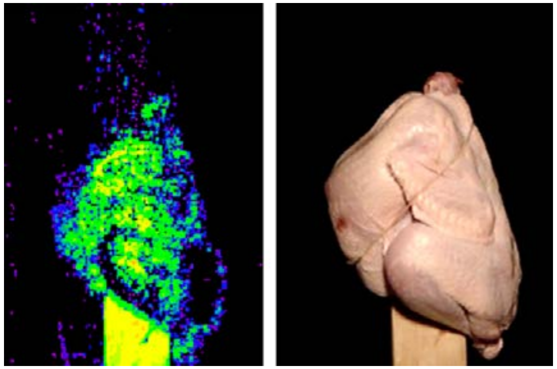
Imaging

Elimination of requirements for

1. Outdoor sky illumination
2. 'Special' orientations
3. Speckle in active illumination

Cold Sky Illumination at 94 GHz

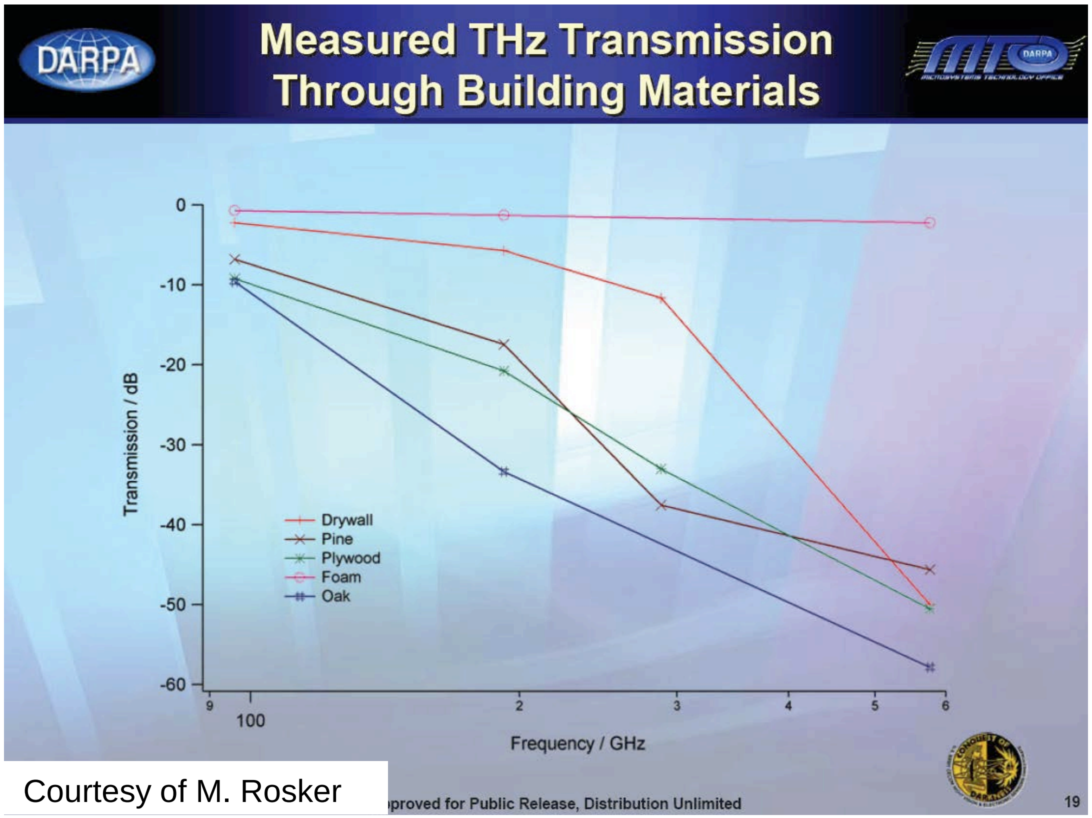
Active image of turkey showing speckle



Indoor Passive Image at 700 GHz (0.3 K bolometer)

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

The Columbus Dispatch
dispatch.com



Courtesy of M. Rosker

No, unless you live in a foam (or straw?) house!

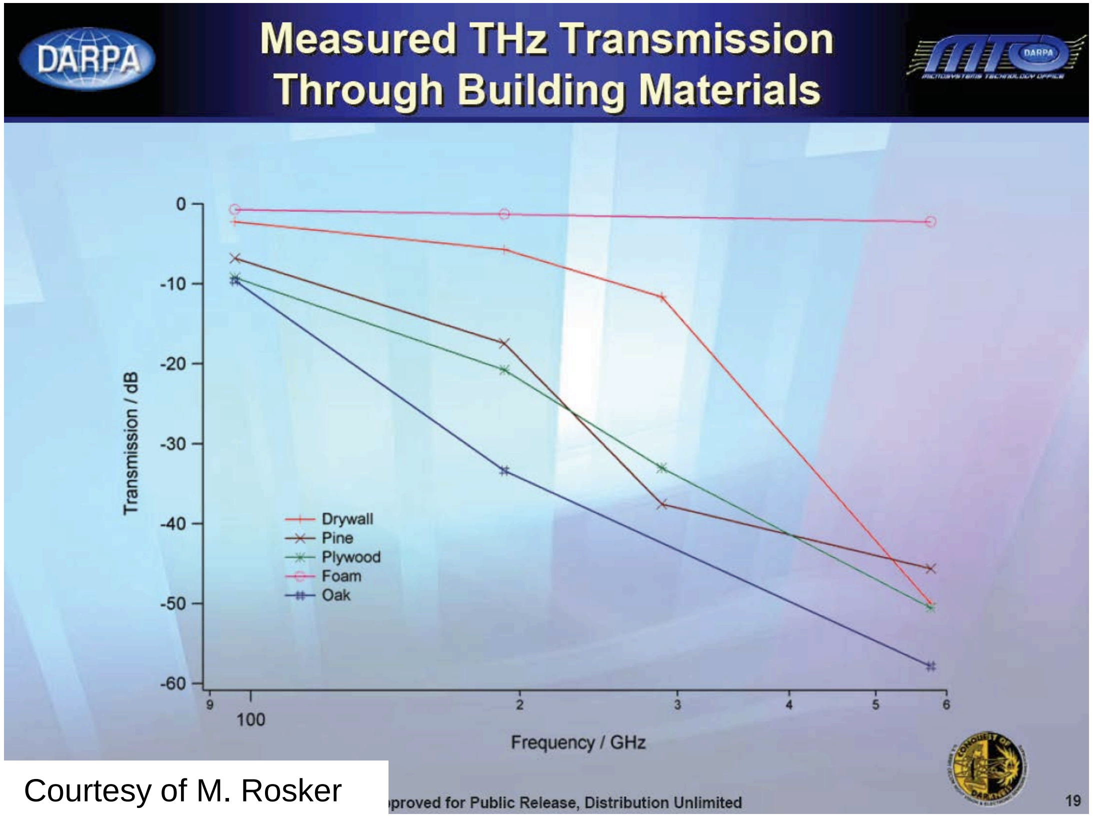
Will THz photons 'see through walls'?

Local (Physics Dept) Measurements)

Local Publicity

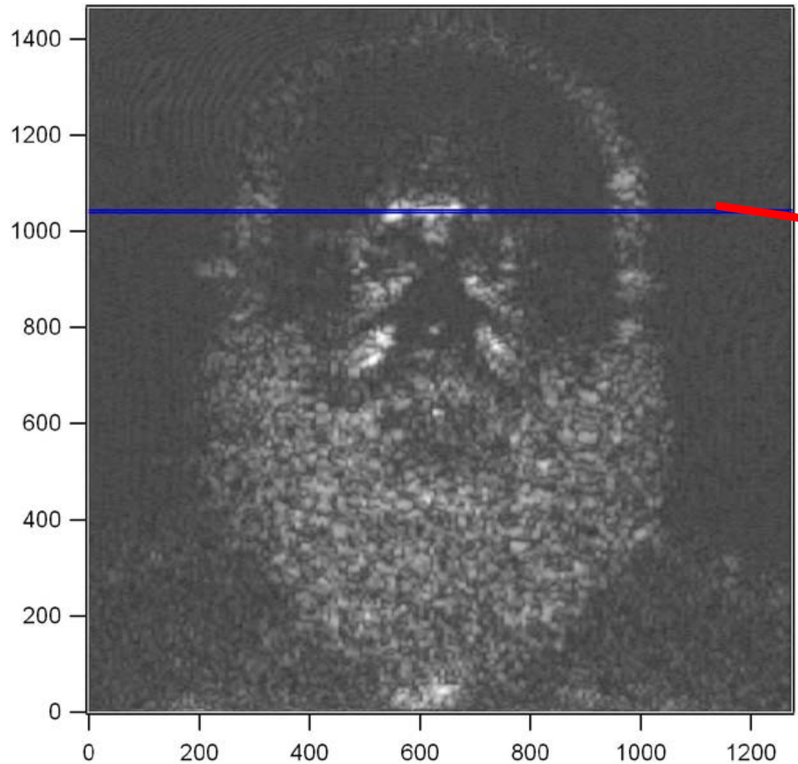
"they can pass through fabric, paper, cardboard, wood, masonry, and ceramics," Columbus Dispatch

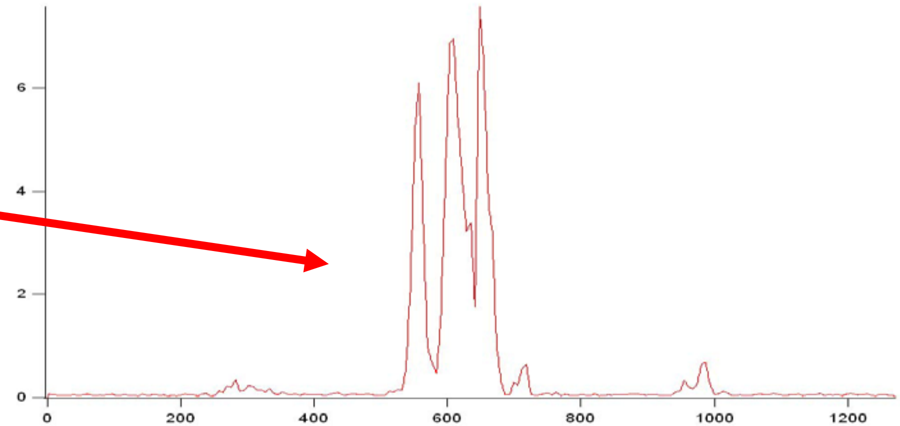
"in security and defense – where the ability to "see thru walls to identify bad guys will save lives," OTF



Courtesy of M. Rosker

Active vs. Passive Images





Active Image

Skin is close to specular - Hair really lights up

At least 40 db of dynamic range across this target

Speckle noise ~ 50%

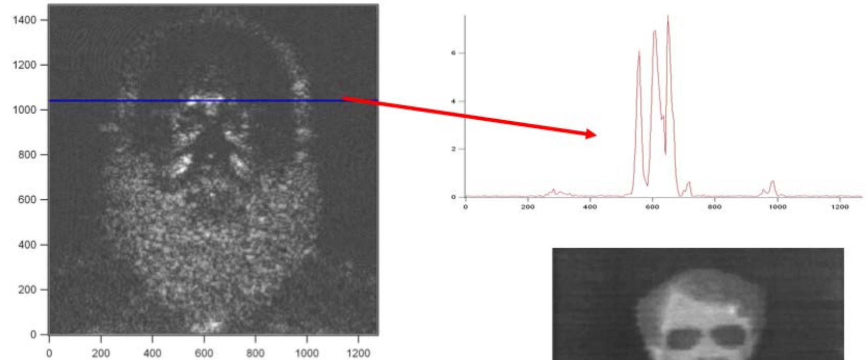
Thermal Image: $\Delta T/T = 0.1$

The Goal: Active Imaging without Speckle or Special Target Angles

Our initial goal was to develop and demonstrate an imaging strategy that would simultaneously have the high signal-to-noise of the active image on the left (image from the TIFT program) *and* the quality (no special angles and no speckle) of the passive image on the right (from Microwave Lab work in the 1980's).

We proposed to do so by using the high power of vacuum electronics to fill many modes of a scenario and to mix and modulate these modes on a time scale short in comparison to the pixel dwell time. In other words, we wanted to use vacuum electronic technology to make a really hot and incoherent blackbody. Since we want to be able to do so over a tactically useful range, the high power of vacuum electronics is especially critical.

Active vs. Passive Images



Active Image

Skin is close to specular - Hair really lights up

At least 40 db of dynamic range across this target

Speckle noise ~ 50%

Thermal Image: $\Delta T \sim 0.1$ K

Modes and Angles: Active and Passive Imaging in the THz

For a single mode, 100 Hz bandwidth, 300 K, the thermal power/noise is ~4 x 10^{-19} W

1 mW in 100 Hz corresponds to a noise temperature of ~10^{18} K
A reasonable receiver noise temperature is 3000 K

For diffuse target, the number of return modes is

N_{AD} = (spot size/wavelength)^2 ~ 100 (our system in portrait mode)
For a specular target, the number of return modes is 1

Floodlight limit: If an illuminator of power P_I is used to flood light (i.e. fill all modes) of an object whose scale is *l, in a 100 Hz bandwidth* the temperature/mode is

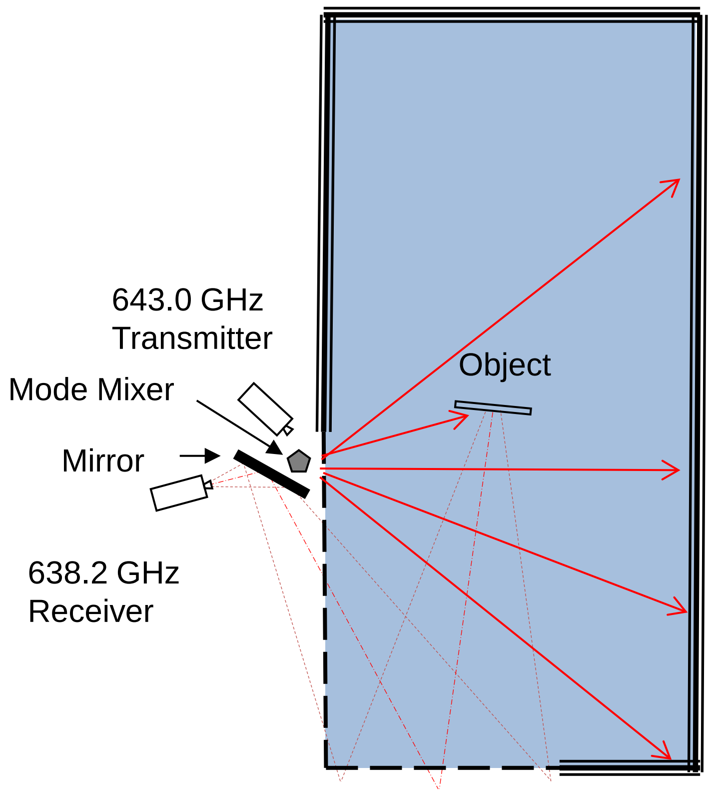
$$T_I = \left(\frac{P_I}{k\Delta\nu}\right)\left(\frac{\lambda}{l}\right)^2$$

With *l = 1* m, λ = 0.5 mm T_I ~2 x 10^{11} K

Random illumination limit: A practical way to get spotlight illumination would be to illuminate the whole room or 'urban canyon' assume a 10% reflection, and let the target come into equilibrium with the room. If we let *l* = 100 m, then

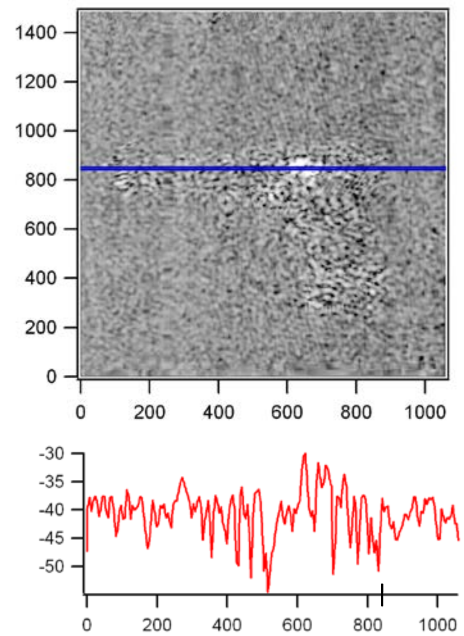
T_I ~2.5 x 10^6 *K.*

Phase Incoherent Multimode Imaging for 'hot' images with speckle minimization

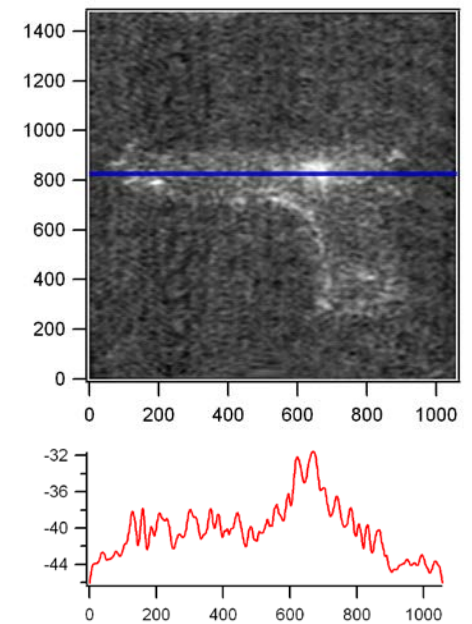


Diameter = 30 cm
Focal Length = 50 cm

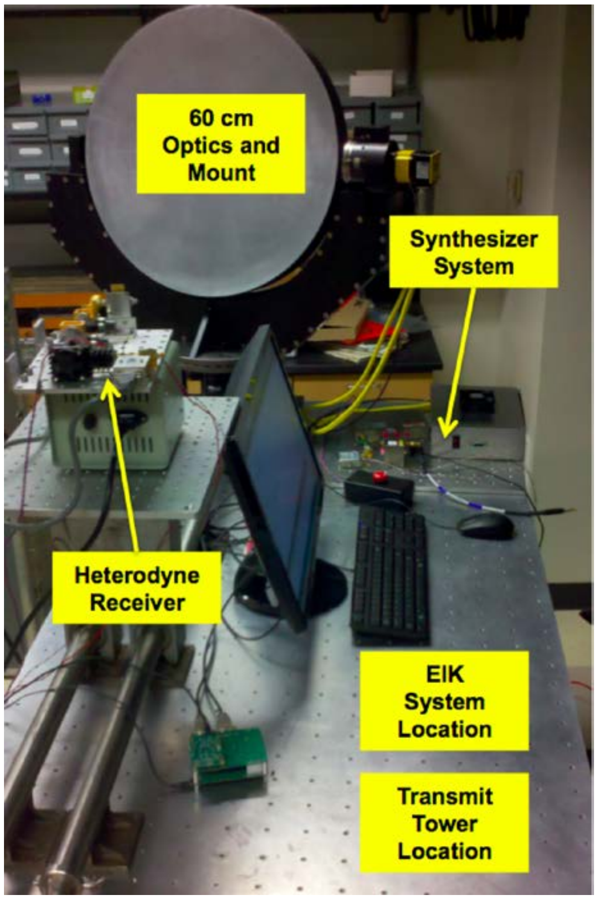
Without Mode Mixing

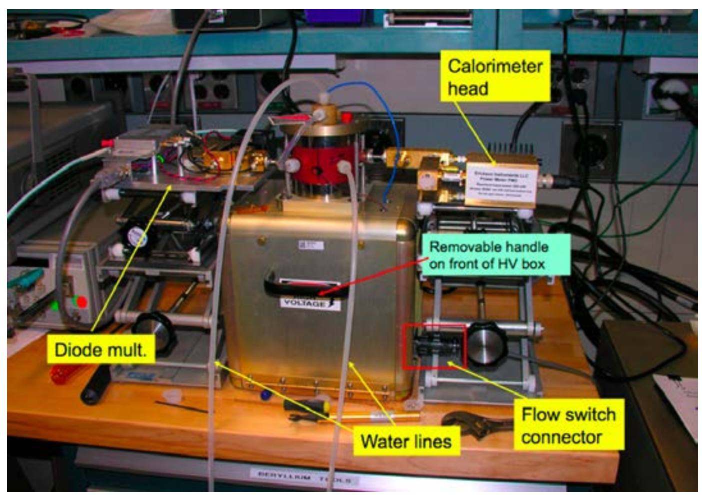


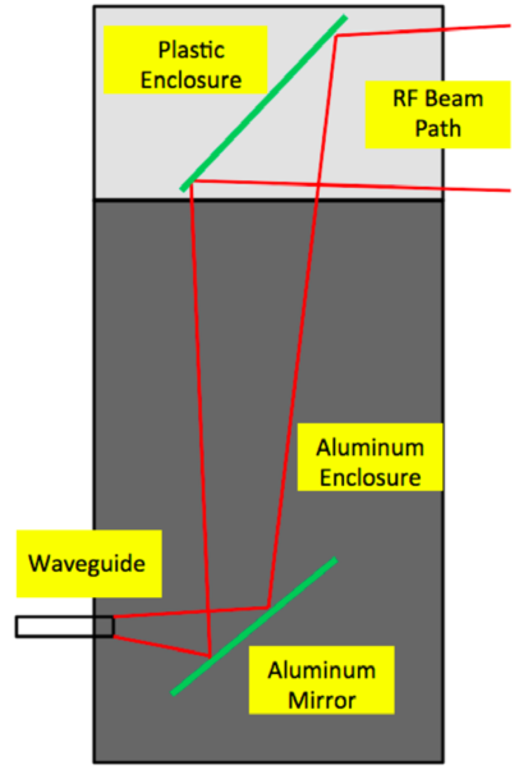
With Mode Mixing



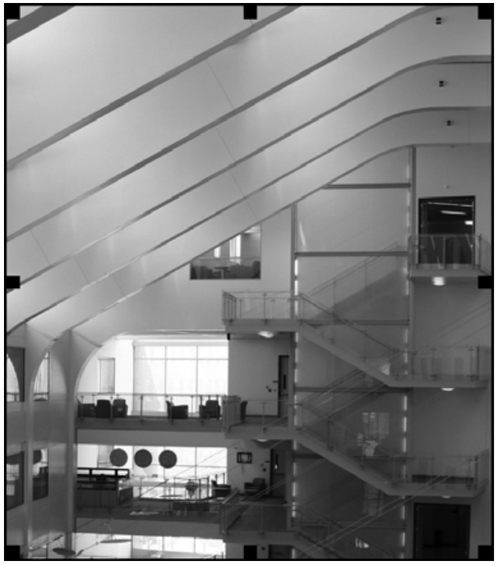
The OSU/NRL Modulated Mode Mixing System







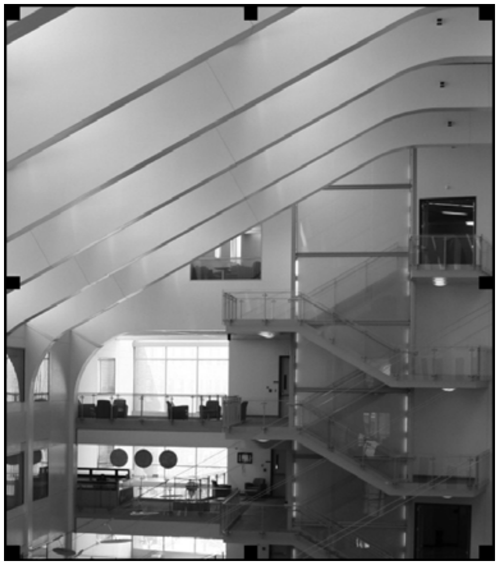
Active Illumination with mode modulation to eliminate speckle and coherent effects in actively illuminated images



Without Mode Modulation

With Mode Modulation

Modulated Mode Mixing with NRL EIK Source at 220 GHz



Optical Image

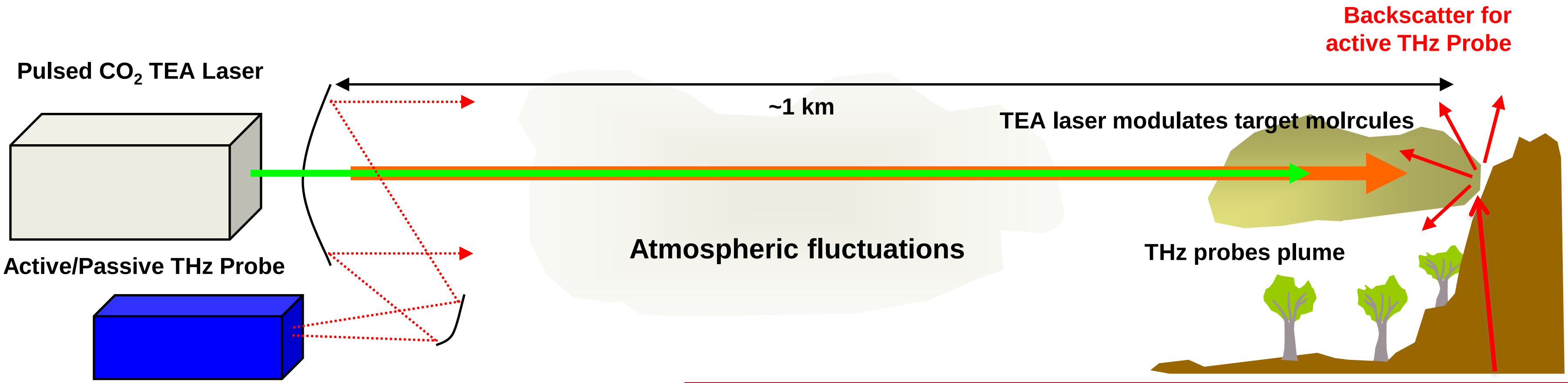
Multimode illumination without mode-mixing modulation

Multimode illumination with mode-mixing modulation

If there were a 4th image with the usual single mode illumination, it would be dominated by a few glints from specular reflections

Remote Chemical Sensing at Atmospheric Pressure

A New Approach:
Double Resonance Modulation for Remote Sensing



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

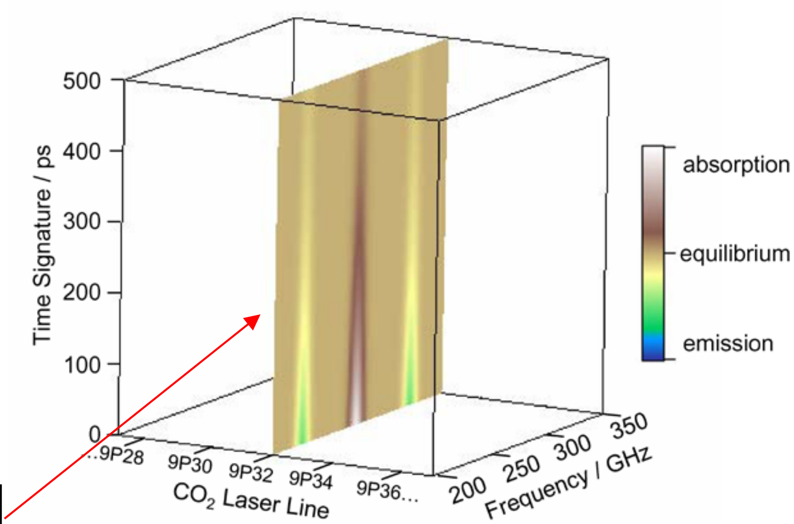
Problem # 1: Specificity
- Dimension 1: Choose IR pump frequency
- Dimension 2: Monitor the SMM/THz probe frequencies
- Dimension 3: Match pump pulse to relaxation of atmosphere (~100 ps)

=> 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

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**