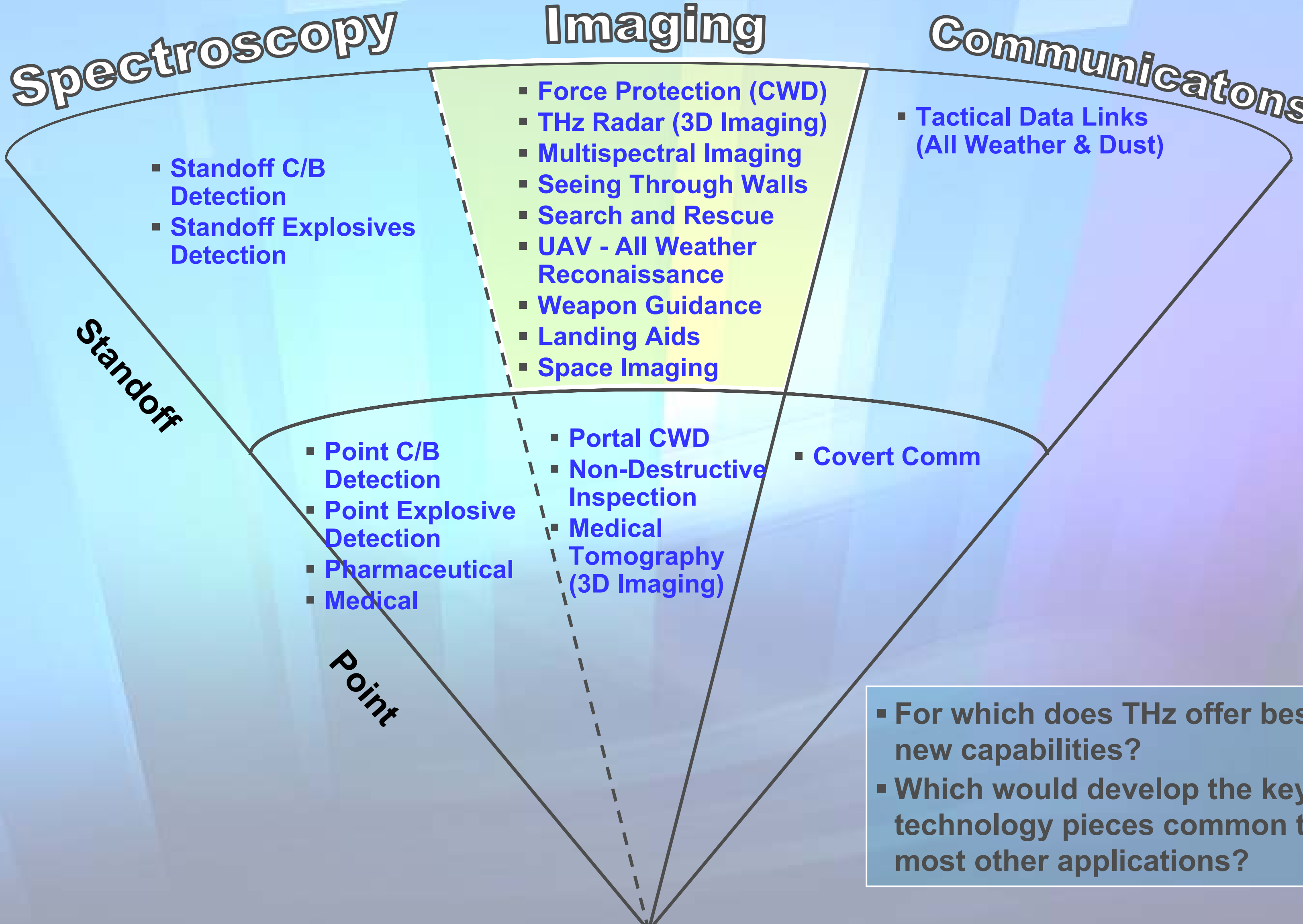
Progress Towards a THz Imager

Mark Rosker, Program Manager, DARPA / MTO

IMS2007 Workshop WFE
"Terahertz Device Characterization and Security Applications"

8 June 2007

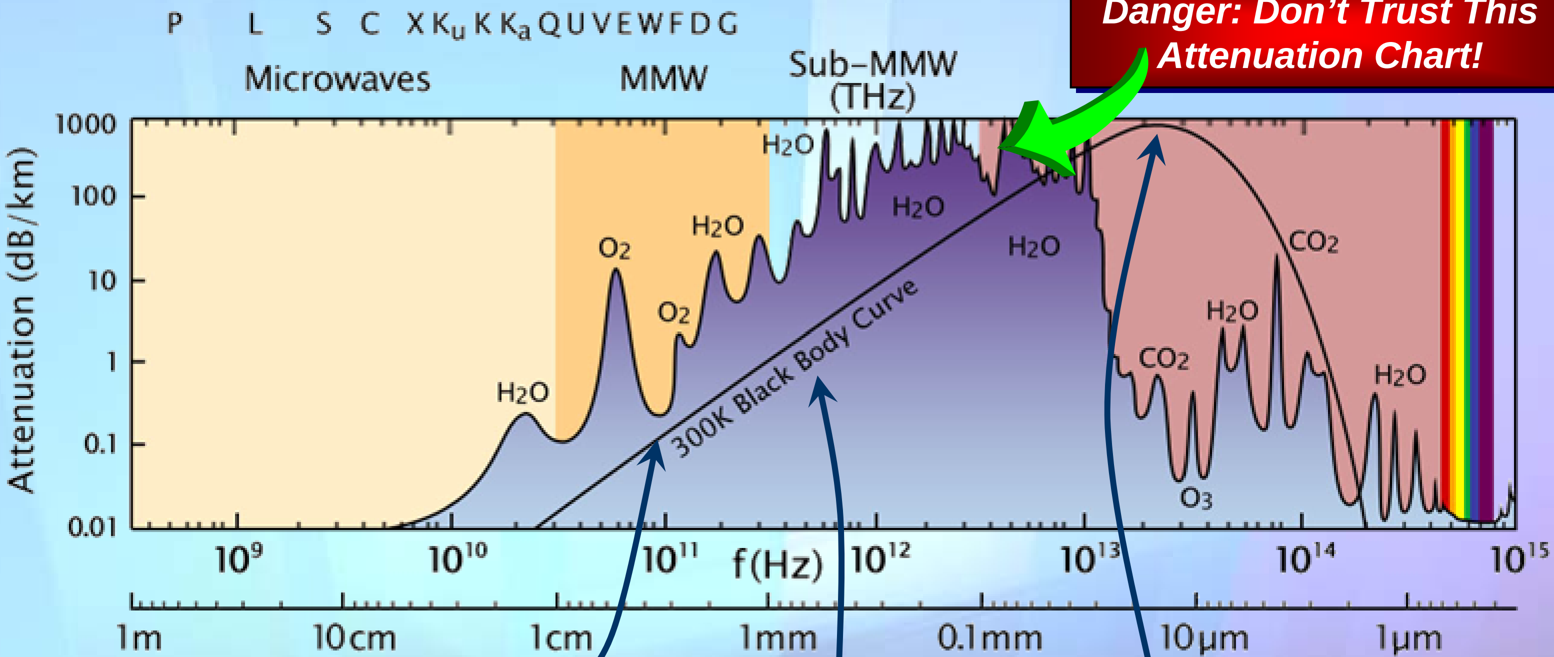
THz Applications

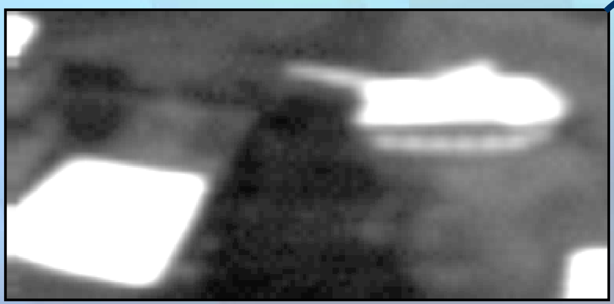


- For which does THz offer best new capabilities?
- Which would develop the key technology pieces common to most other applications?

Remote Imaging Across the Spectrum

Danger: Don't Trust This Attenuation Chart!





MMW

THz

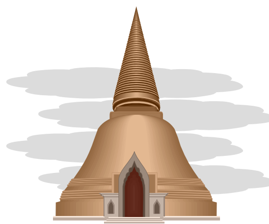
IR

THz *Remote* Imaging
or
Just How Far Can You Go?

A THz Atlas: The 6 B's

Increasing THz Absorption

Bangkok



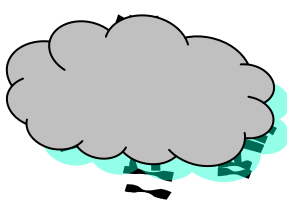
T = 35C
RH = 90%

Basra

T = 43C
RH = 30%

Dust:
10m visibility

Berkeley



T = 20C
RH = 60%

Fog:
100m visibility

Bellingham

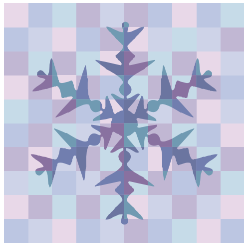
T = 22C
RH = 50%

Rain:
4mm/hr

Boulder

T = 20C
RH = 44%

Buffalo

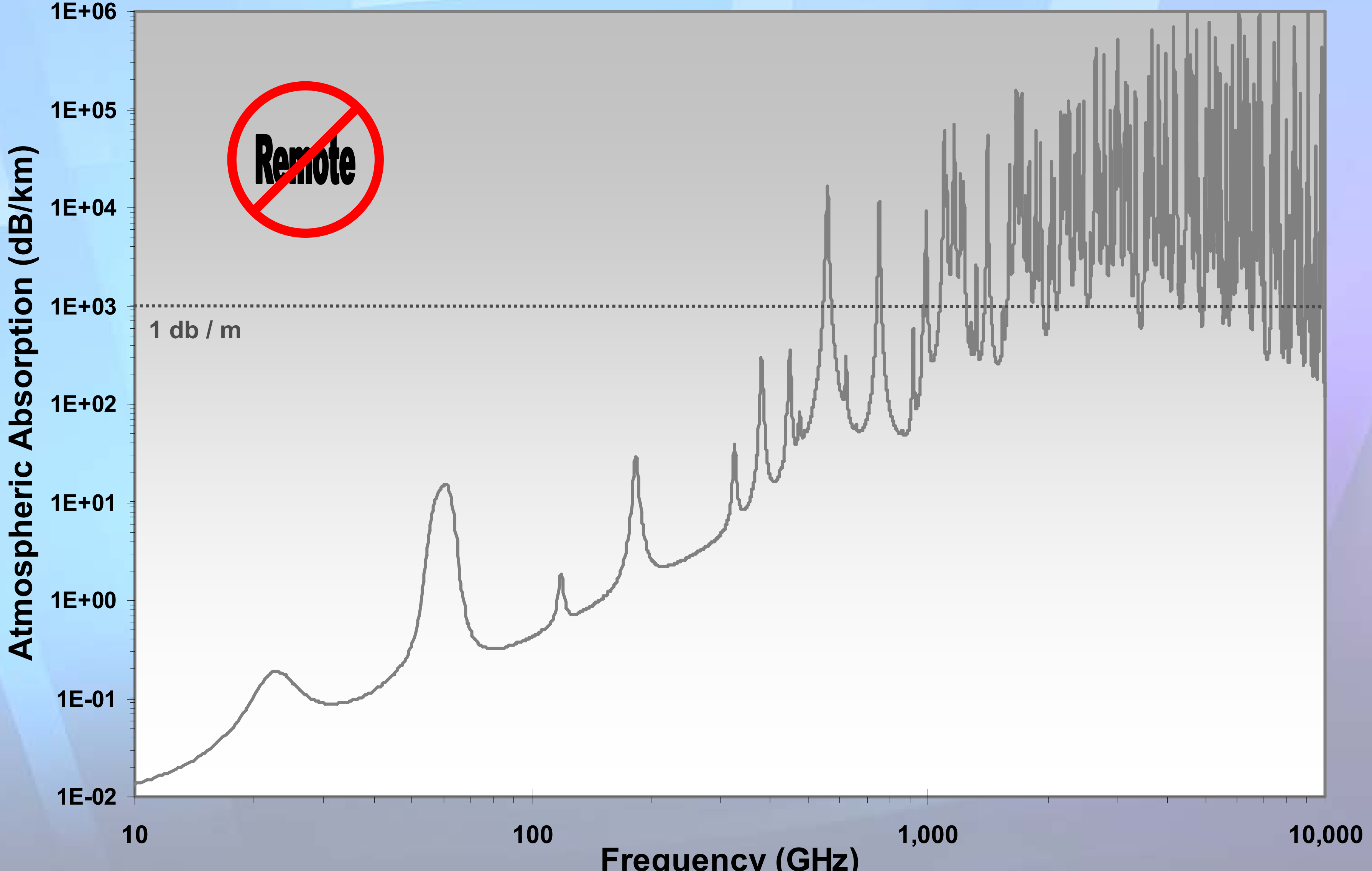


T = –10C
RH = 30%

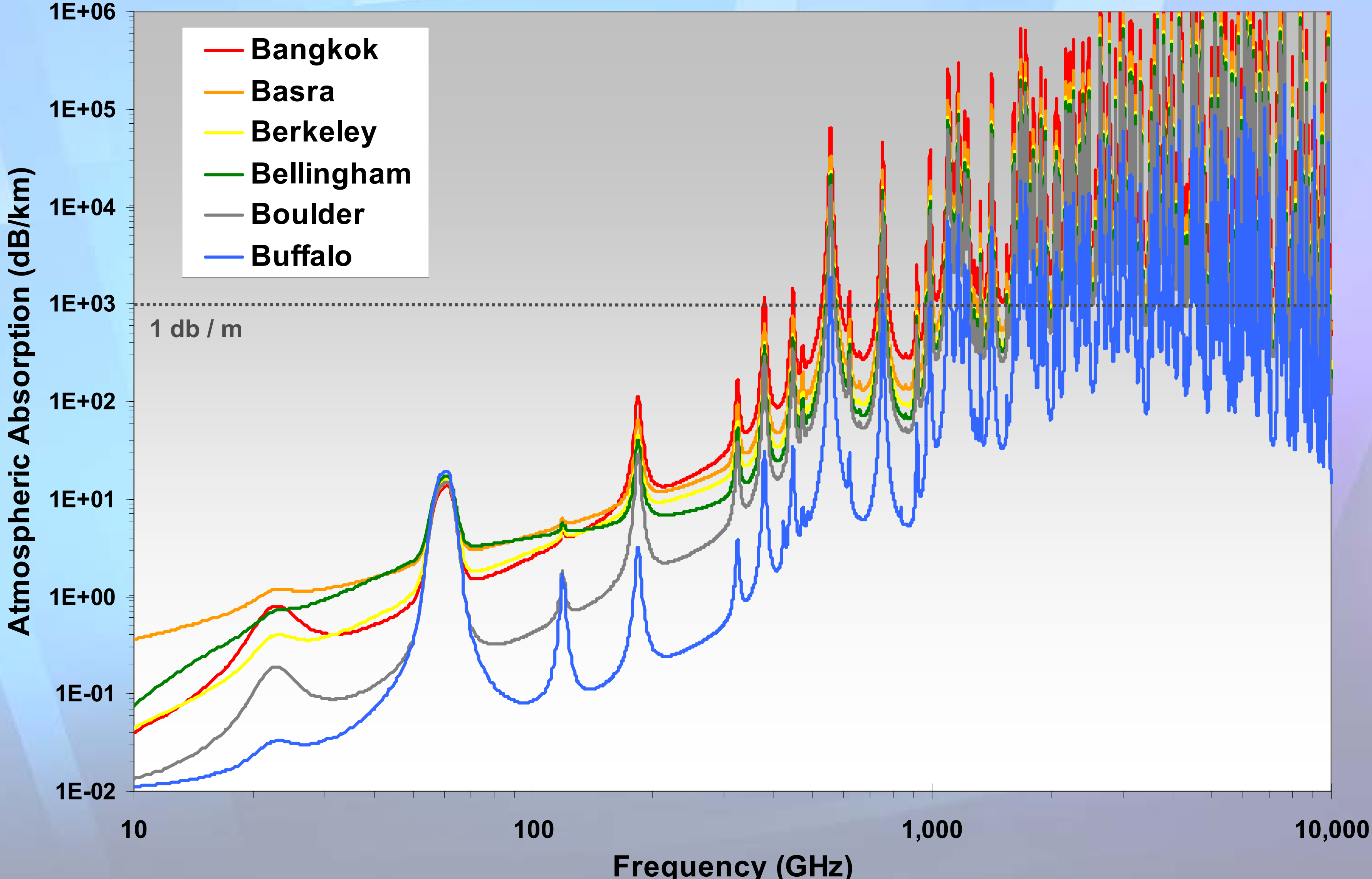
Snow

Decreasing THz Absorption

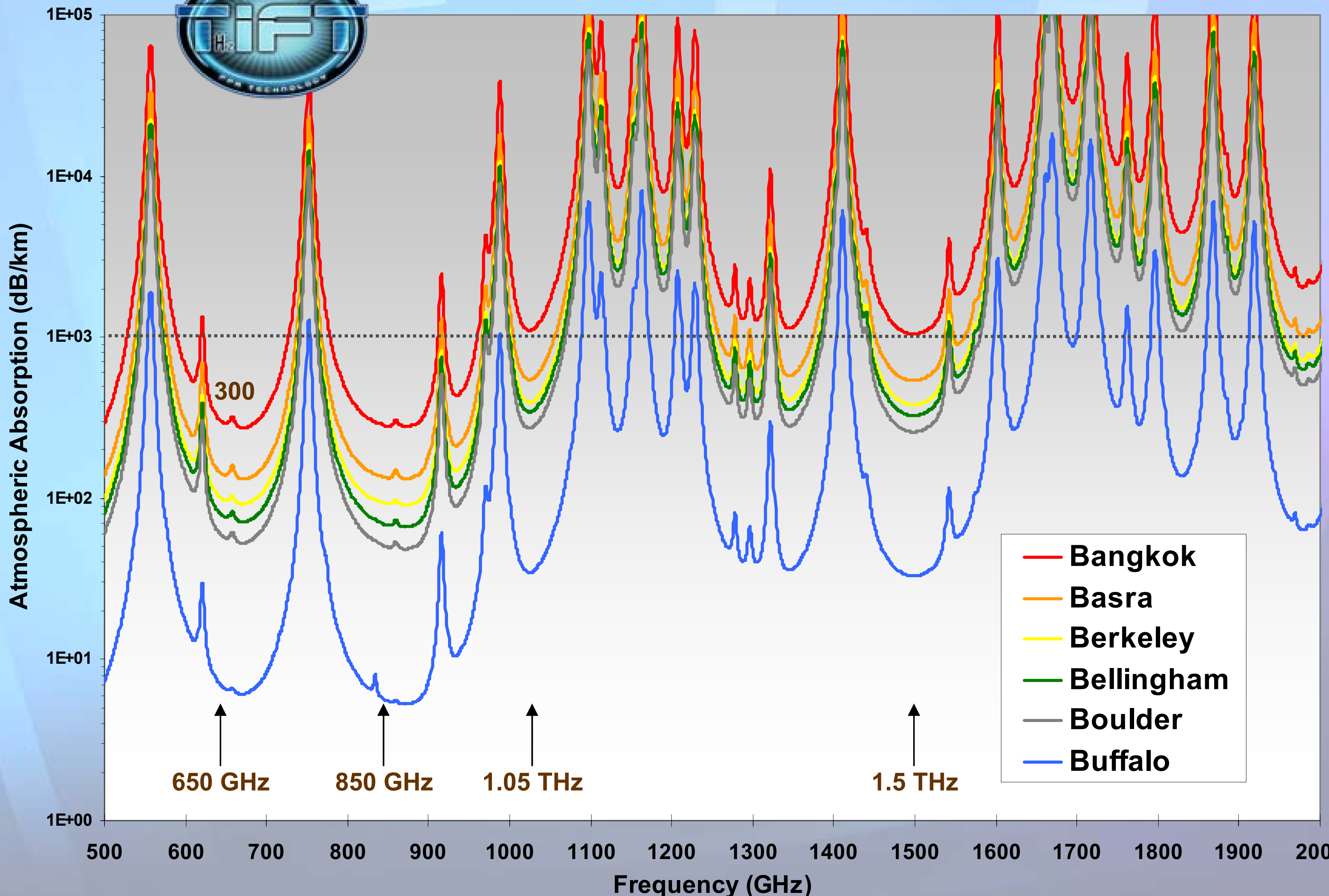
Compiled Atmospheric Models



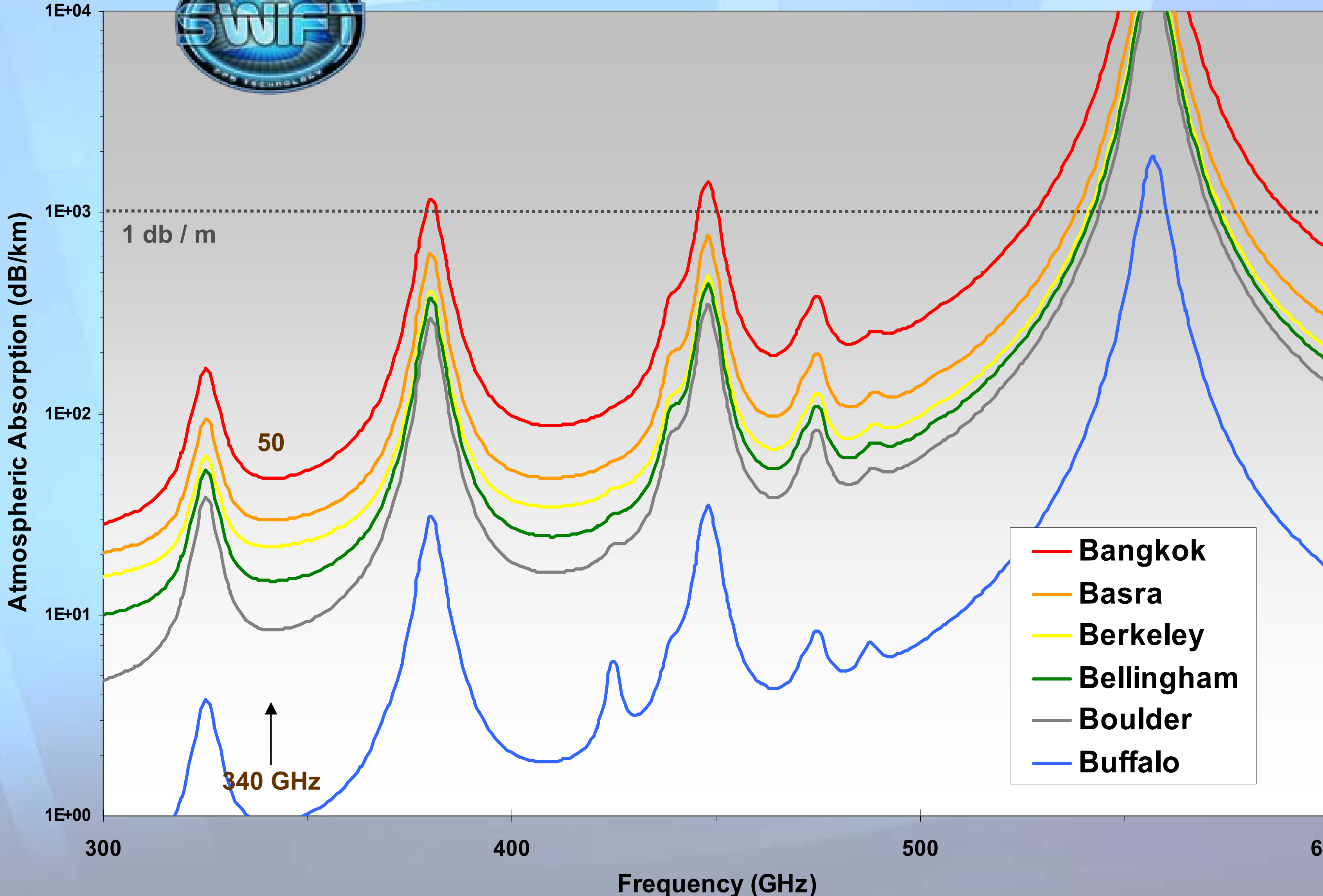
Compiled Atmospheric Models



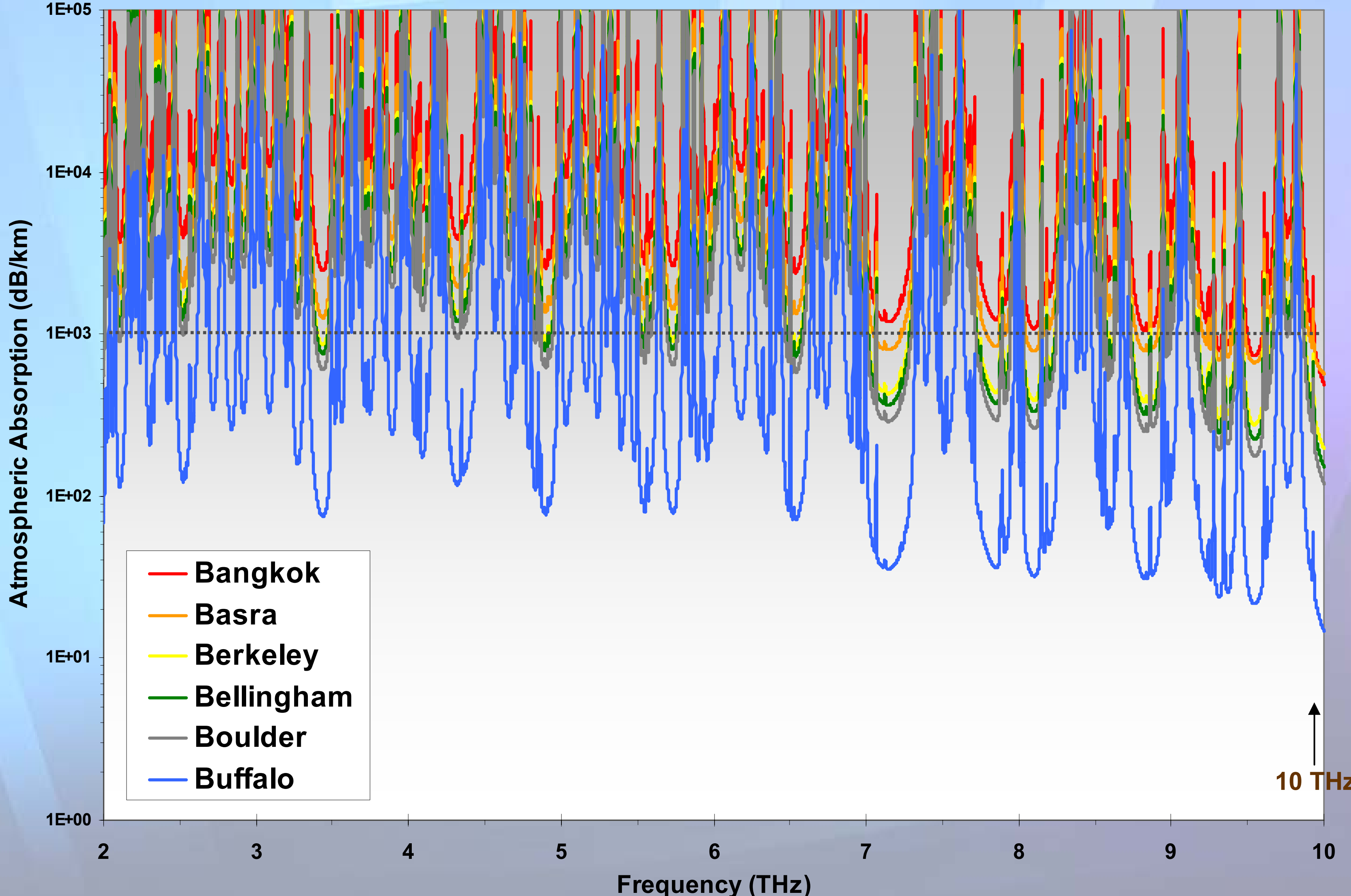
Compiled Atmospheric Models



Compiled Atmospheric Models



Compiled Atmospheric Models



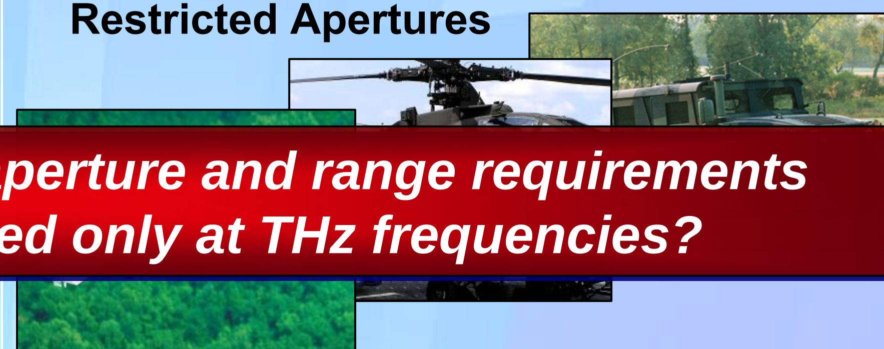
Approved for Public Release, Distribution Unlimited

THz Imaging

THz Imaging: Why Bother?

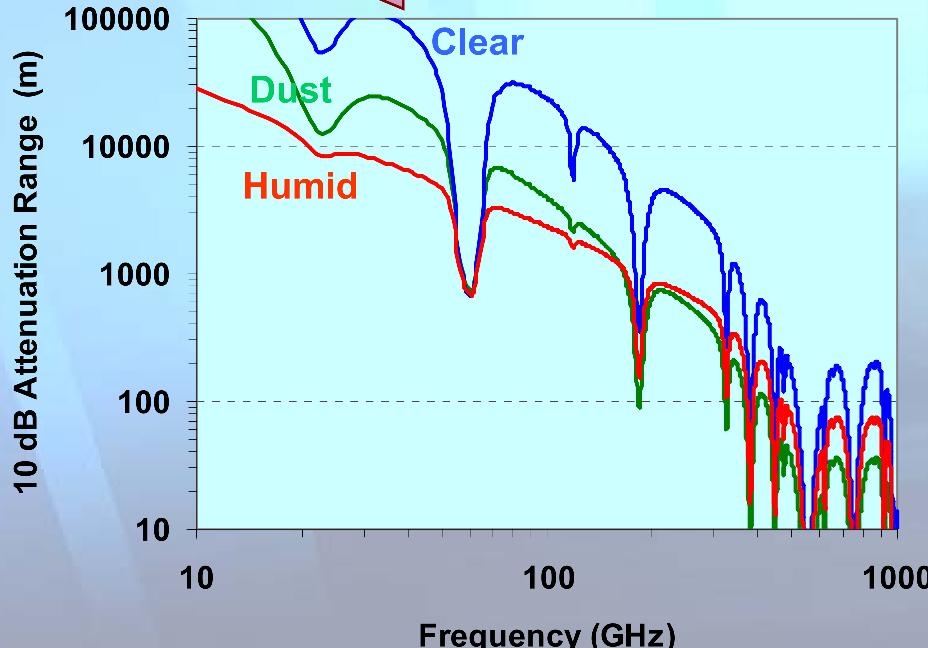
“IR-Blind” Environments

Restricted Apertures

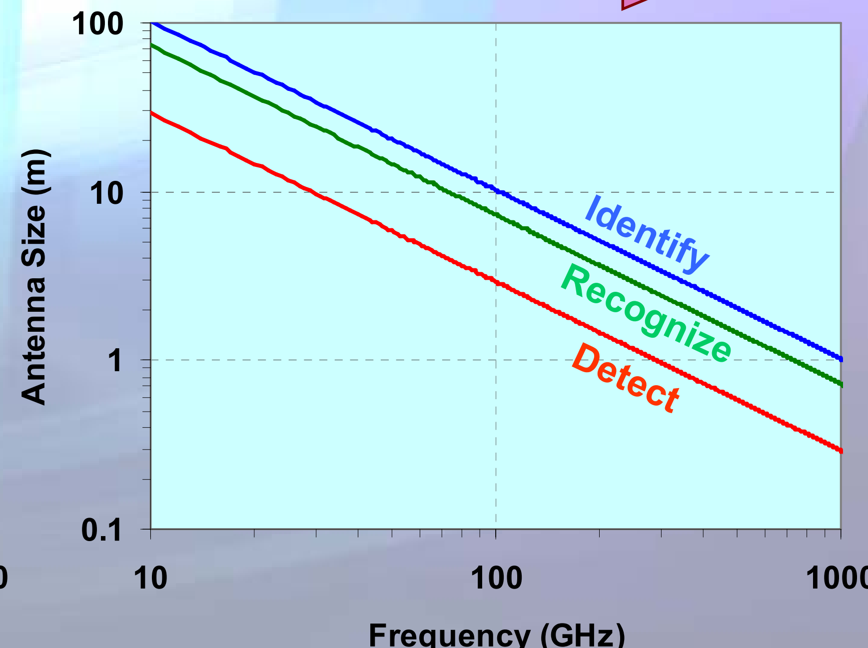


Are there applications for which aperture and range requirements can be simultaneously satisfied only at THz frequencies?

Greater range



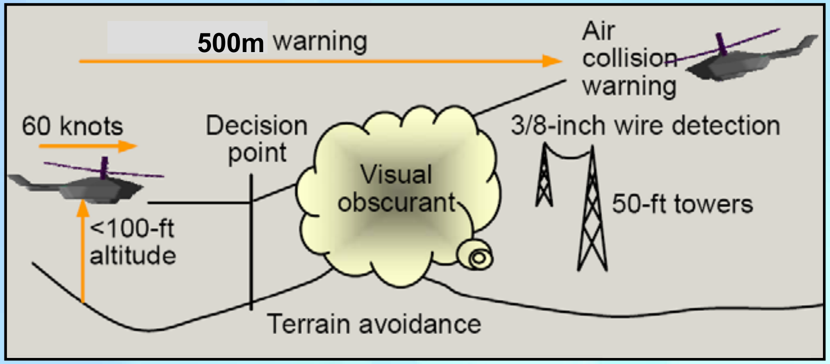
Smaller aperture

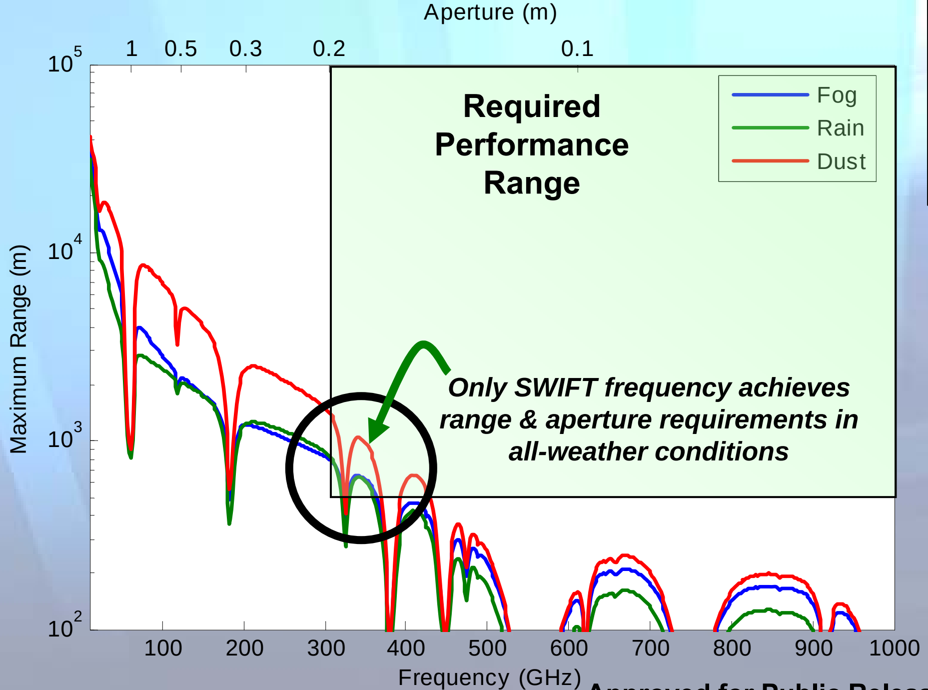


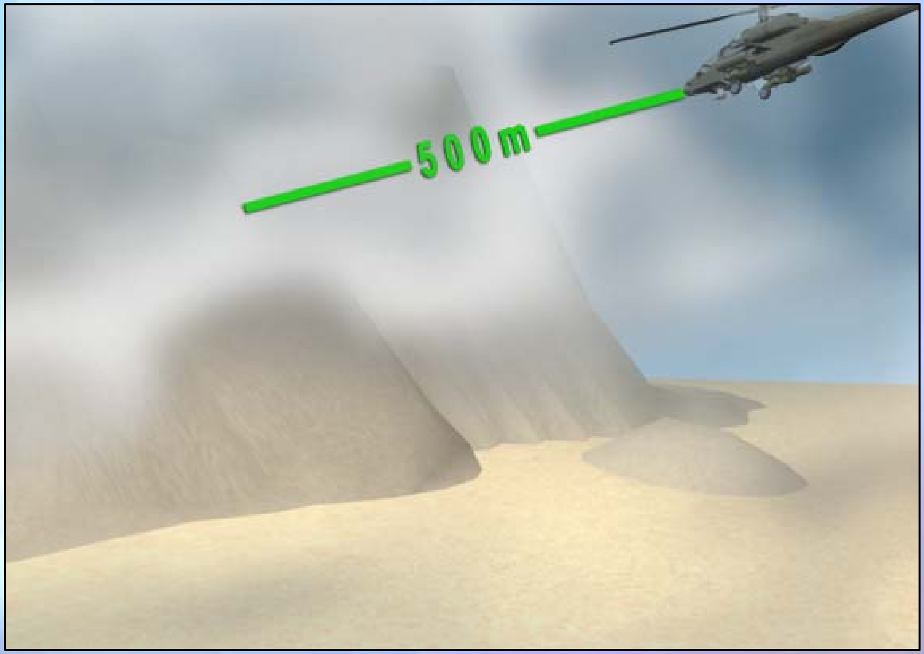
(7.5cm object at 30 meter range)

Aircraft Terrain Avoidance

- **Image terrain and other potential obstacles through all-weather conditions**





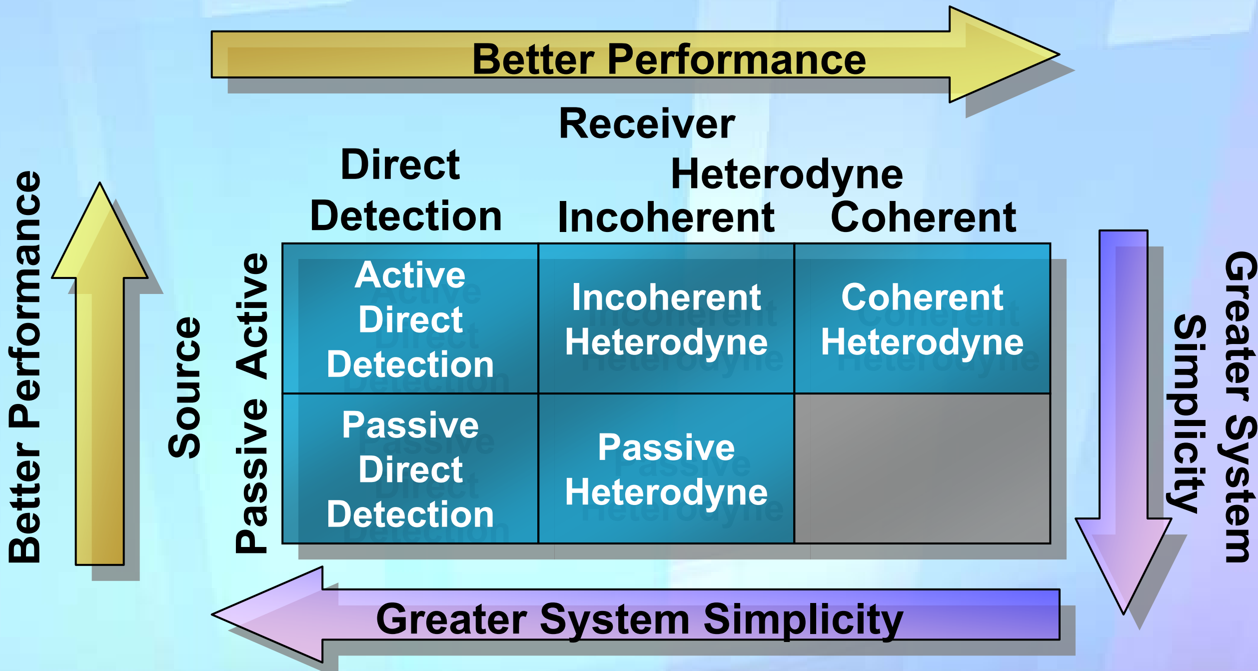


Notional Requirements

- Aperture < platform radome (~0.2m)
- Range up to at least 0.5km
- Resolution = 2m at range
- Good image quality (SNR ≥ 8)
- Frame rate (30 Hz) set by pilot reaction time

Architecting a THz Imaging System

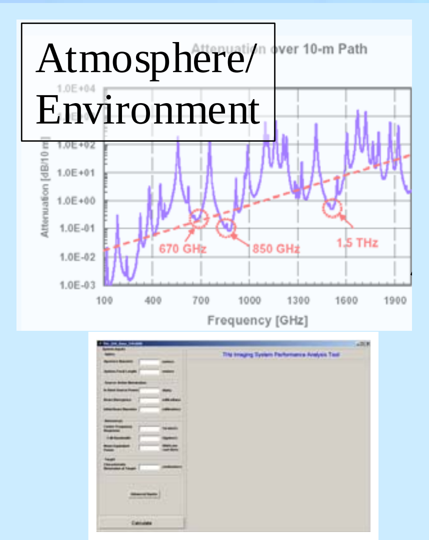
Which System Architecture(s) Can Provide Adequate THz Imaging Performance?

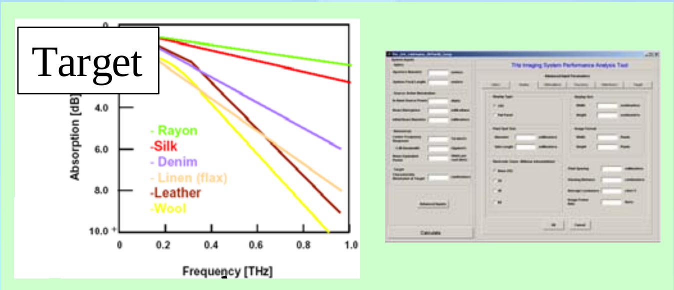


Other important system architectural considerations include:

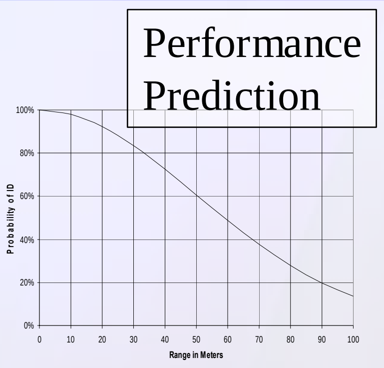
- Scanning vs. staring array
- Pulsed vs. CW source
- Flood vs. line illumination

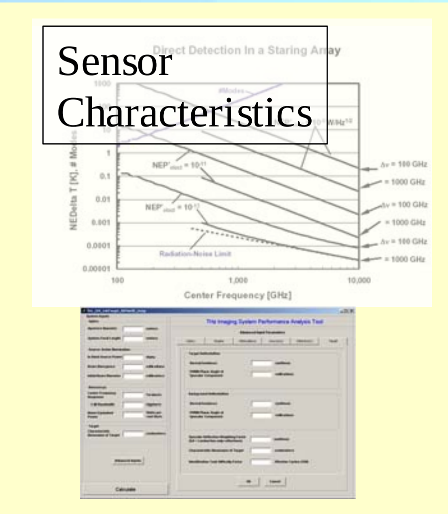
Parametric Model of Various THz System Architectures





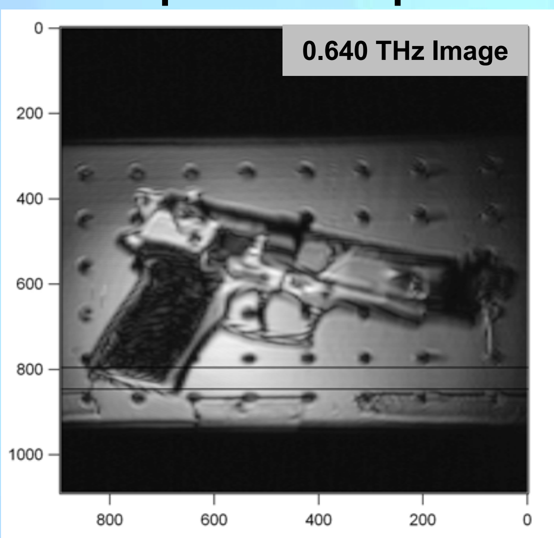
- Model based on NVESD IR system model
- THz phenomenology measured in TIFT Phase I
  - Atmospheric absorption
  - Materials transmission
  - Spectral reflectance
- Task difficulty follows NVESD IR image analytic techniques
  - THz model calibrated with sample of THz images and trained image analysts





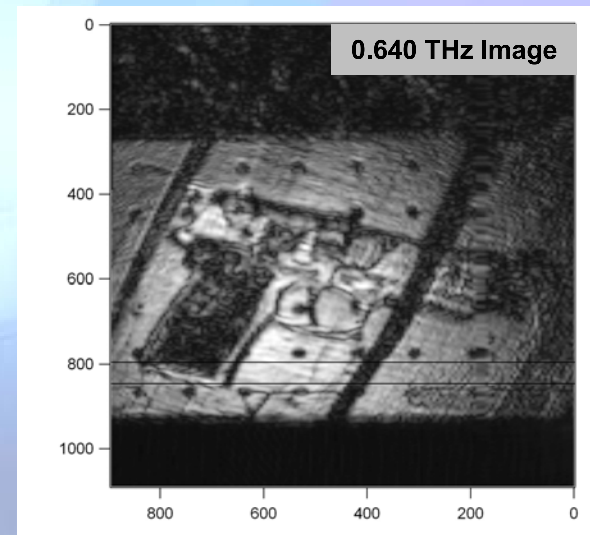
Measured THz Transmission Through Clothing

Metallic Cap Gun on Optical Table

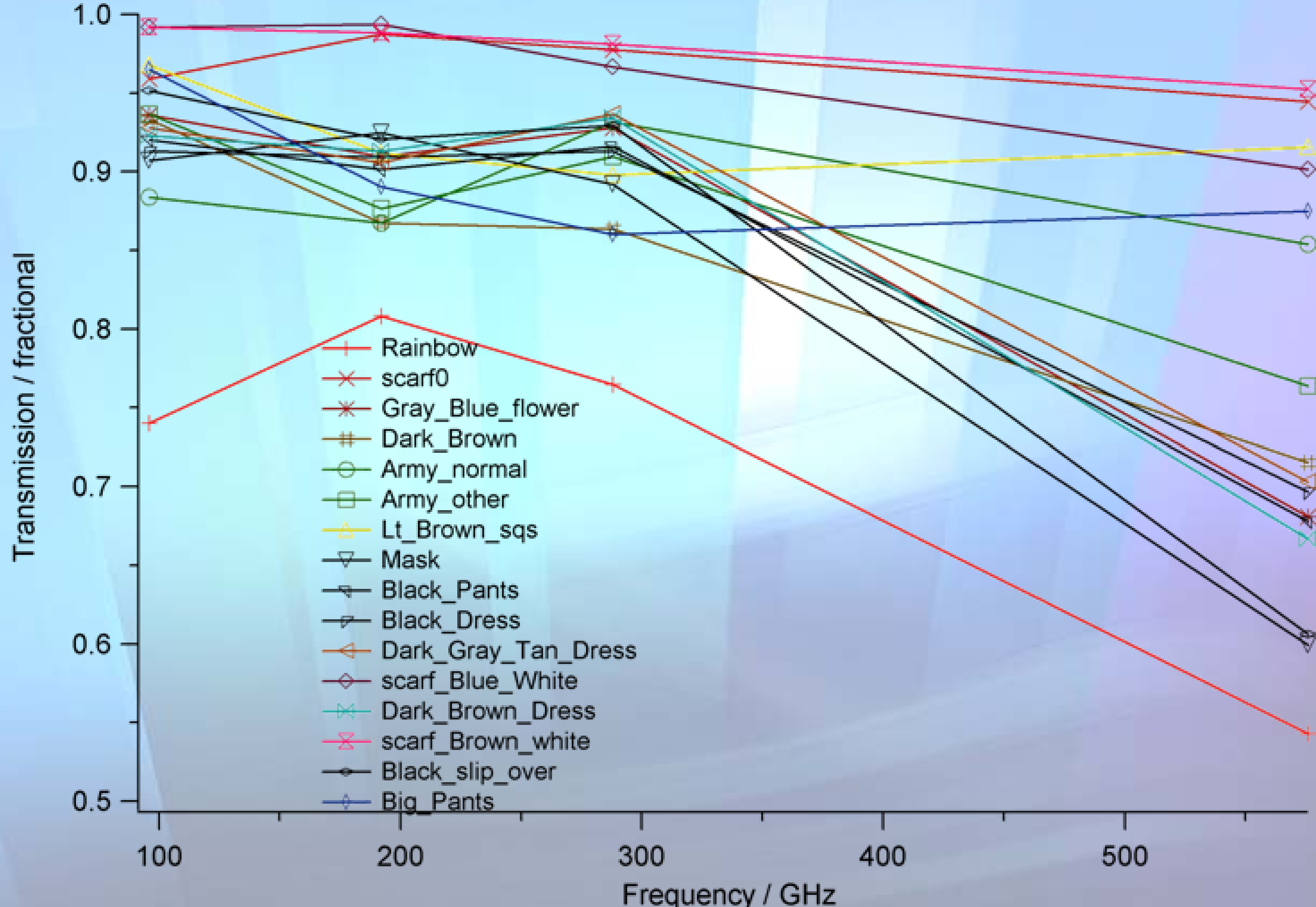


Thick Robe

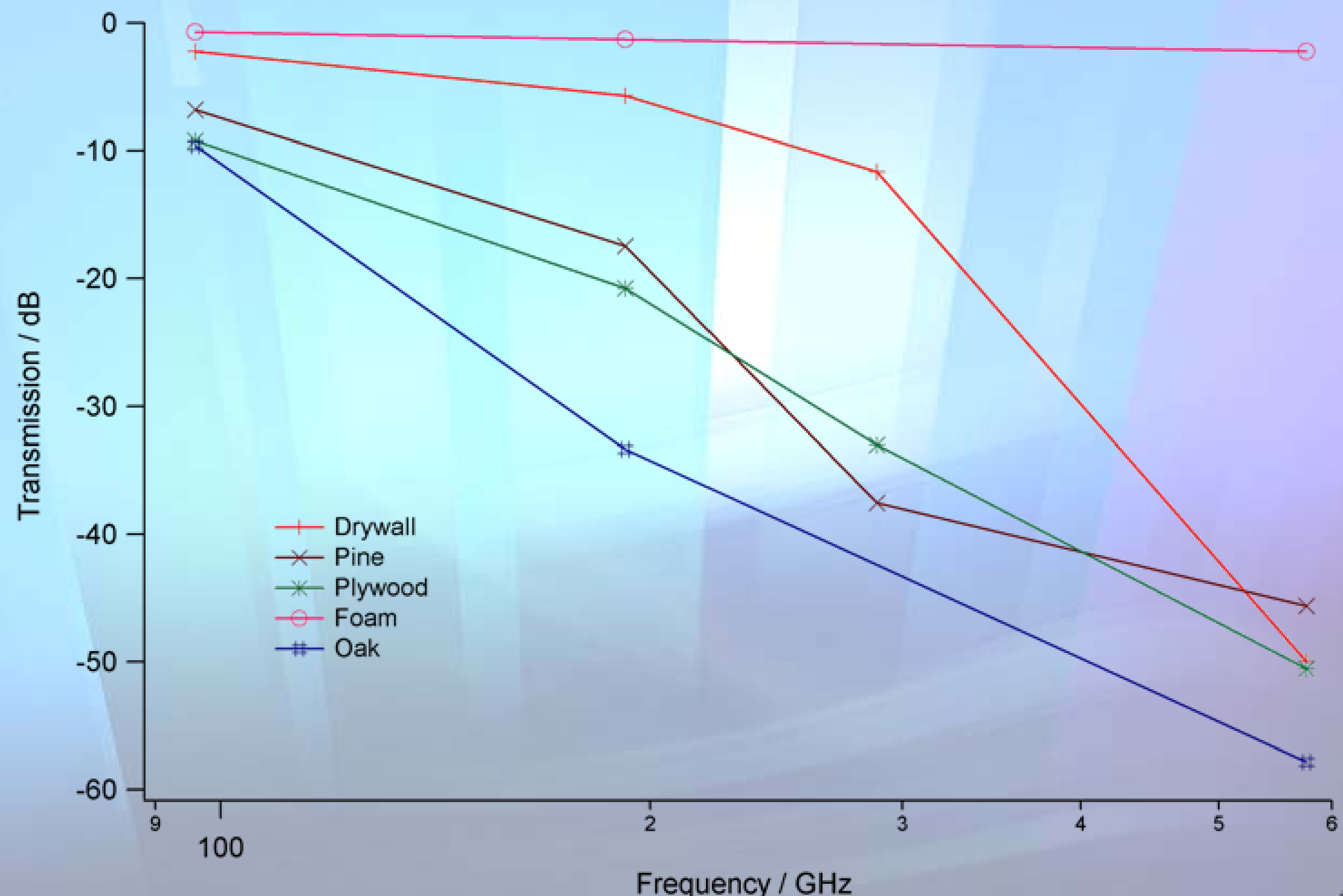
Gun Under Thick Robe



Measured THz Transmission Through Clothing



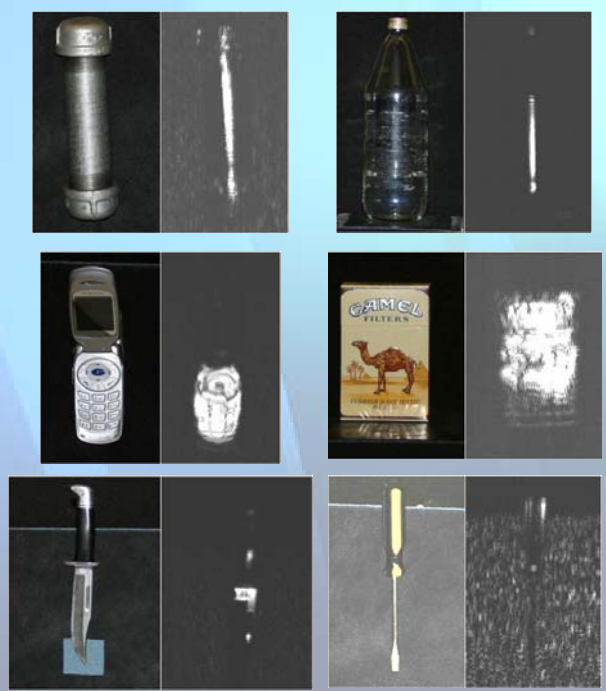
Measured THz Transmission Through Building Materials



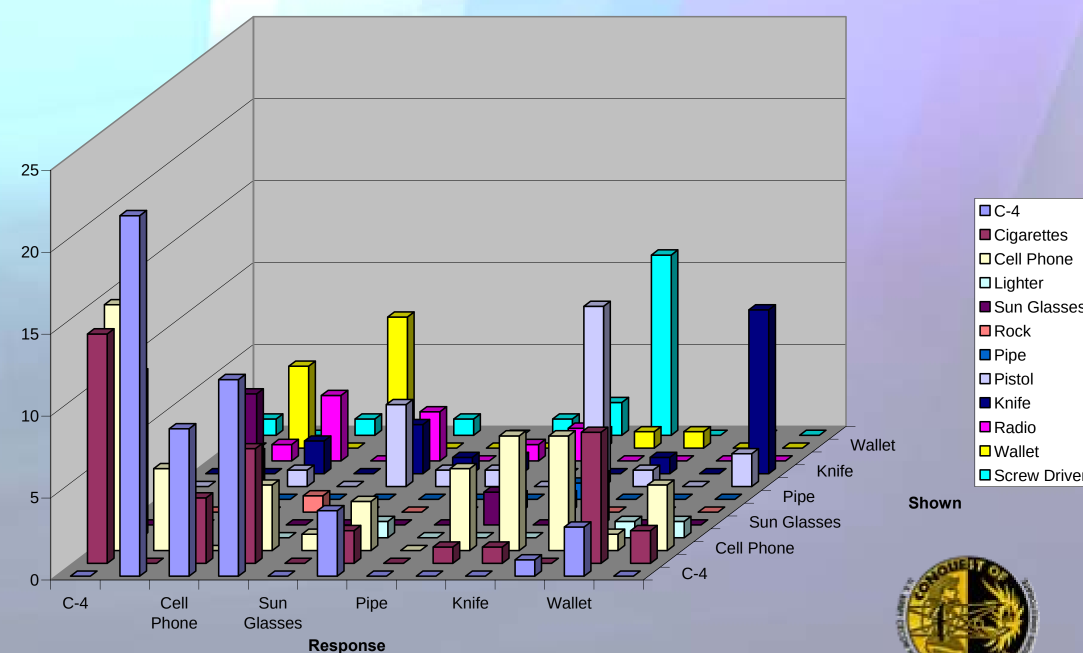
Extension of Standard NVESD Perception Model to THz

Item	Identifier
PVC Pipe Bomb	PVC
Rock	RCK
Lighter	LIT
Cell Phone	CEL
Water Bottle (glass)	WBL
Knife	KNF
Sunglasses	SNG
Pack of Cigarettes	CIG
Newspaper (folded)	NEW
Purse (small)	PRS
Wallet	WLT
Pistol	PIS
Mug/Cup	MUG
Radio (communication)	RAD
Screw Driver	SCR

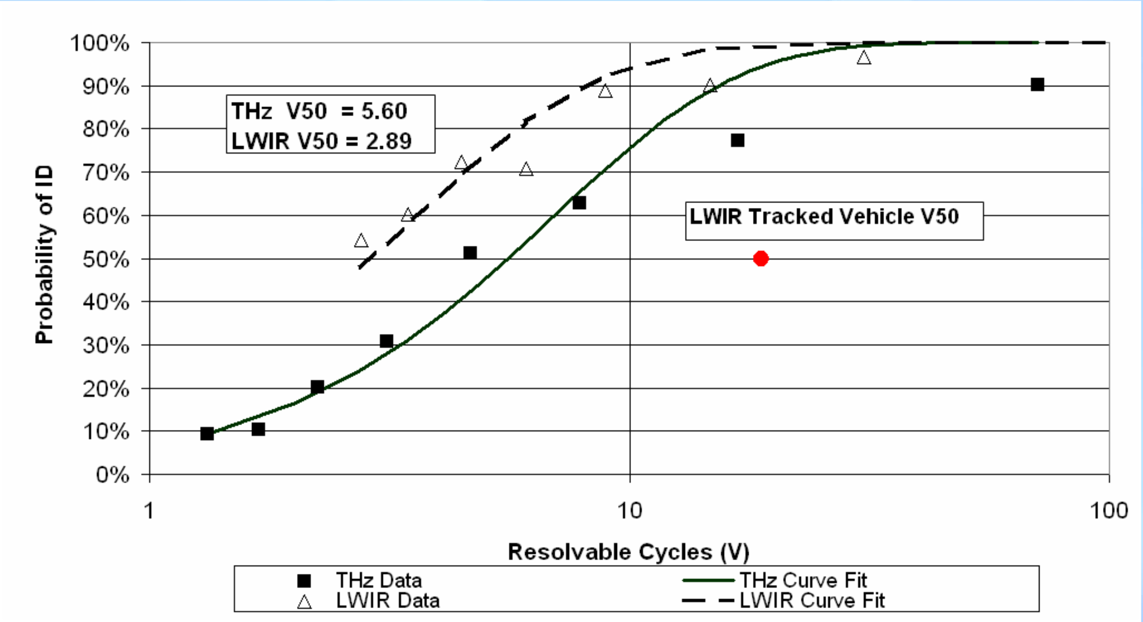
- IR image analysts trained to interpret THz imagery
- Library of THz images (see left) presented to analysts with varying amounts of gaussian blur applied
- Task difficulty determined by level of blur at which 50% of analysts made correct identification of objects
- THz task difficulty not worse than task difficulty for IR imagery
- Confusion matrix (see below) shows few systematic misidentifications among objects in image library



Confusion Matrix



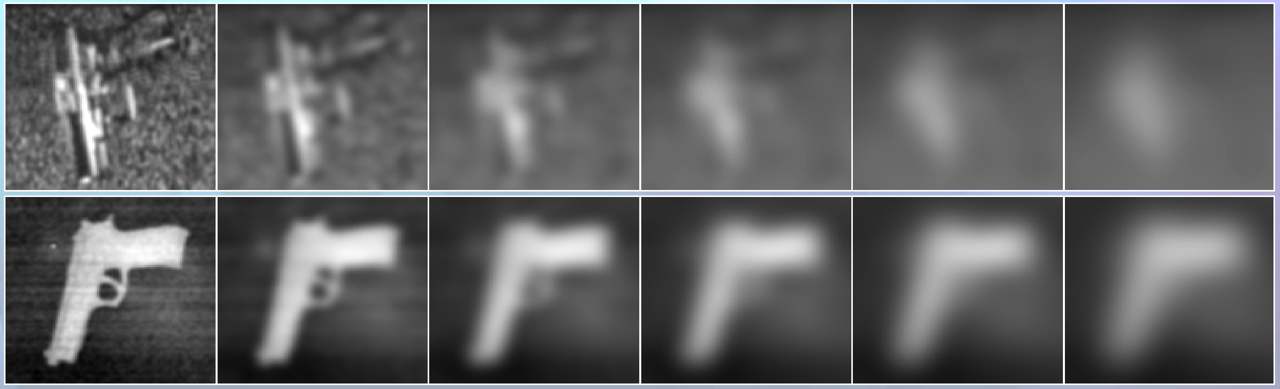
Task Difficulty for THz Weapon Identification



Metal Pipe Bomb	Pack of Cigarettes
Lighter	Screwdriver
Sunglasses	Rock
Pistol	Knife
Cell Phone	Commun-ications Radio
Wallet	Block of Explosive (Plumber's Putty)

THz

LWIR

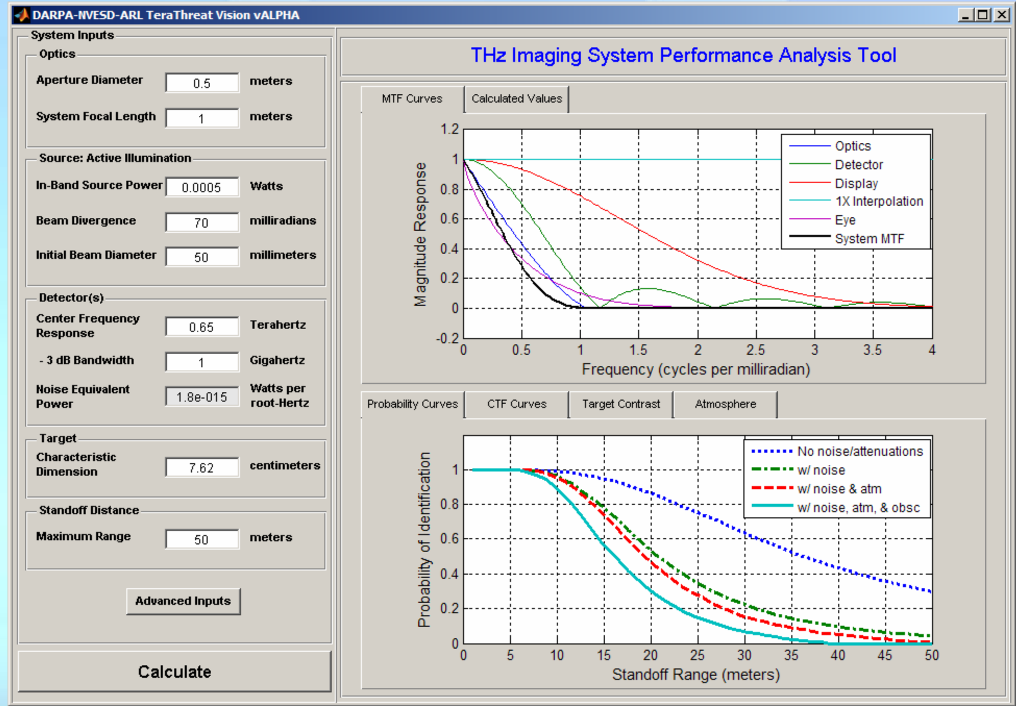


THz weapon ID more difficult than LWIR weapon ID. Easier than LWIR tracked vehicle ID.

THz Imaging System Model

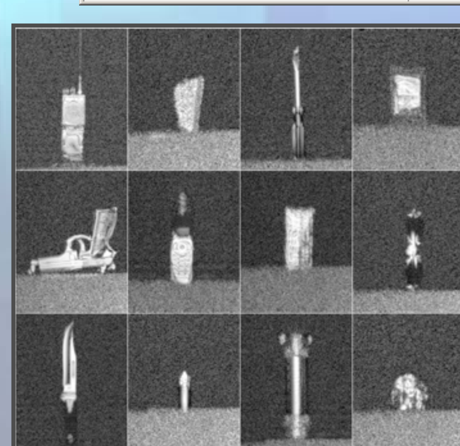
The model accounts for:

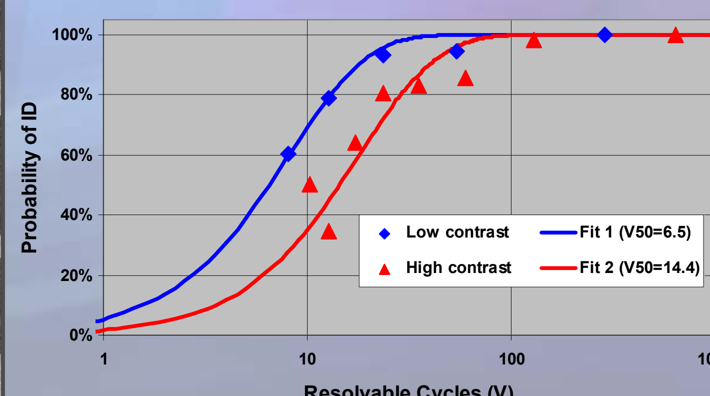
- Focal plane array (FPA) and single-detector scanned systems
- Active target illumination & passive self emission
- Target obscurants, e.g., clothing material, in the propagation path (attenuation)
- Atmospheric effects: constant & band-integrated attenuation
- Target reflectivity/emissivity characteristics: target orientation
- Display characteristics
- Heterodyne & direct-detection-based systems



Model Outputs

- System MTF curves
- Eye & CTF curves
- Target contrast curves
- Atmospheric attenuation curves
- Probability of ID curves
  - With no noise or attenuation(s)
  - With noise
  - With noise & atmospheric attenuation
  - With noise, atm., & obsc. attenuation

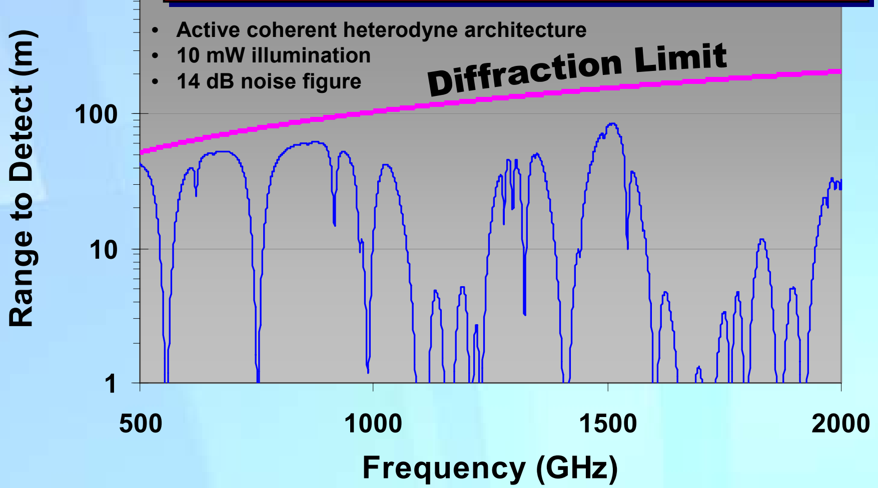


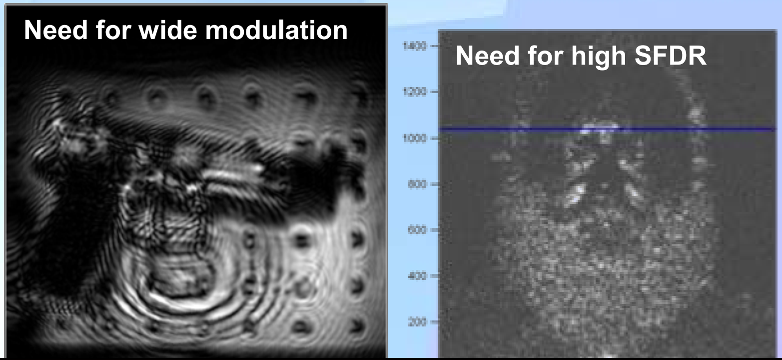


Approved for Public Release, Distribution Unlimited

Lessons Learned from TIFT Phase Ia (>557GHz)

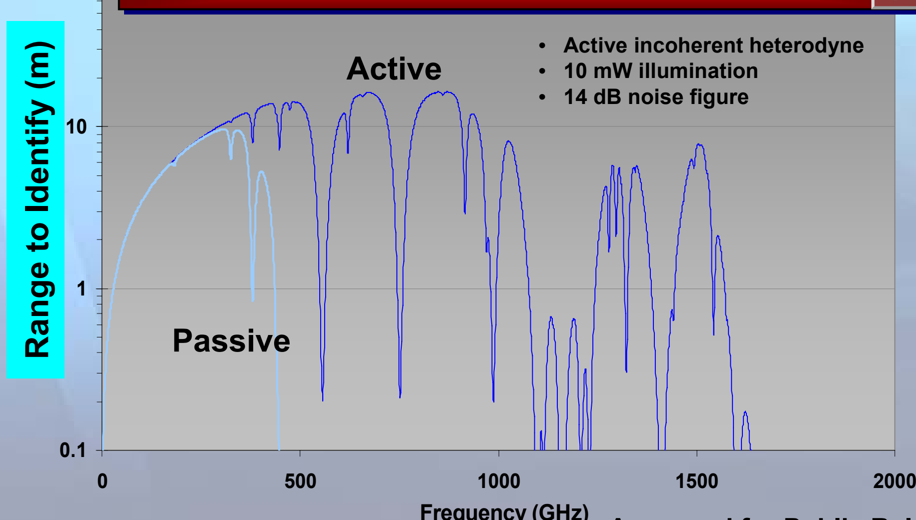
Near-diffraction limit, video-rate THz imaging <u>is</u> achievable



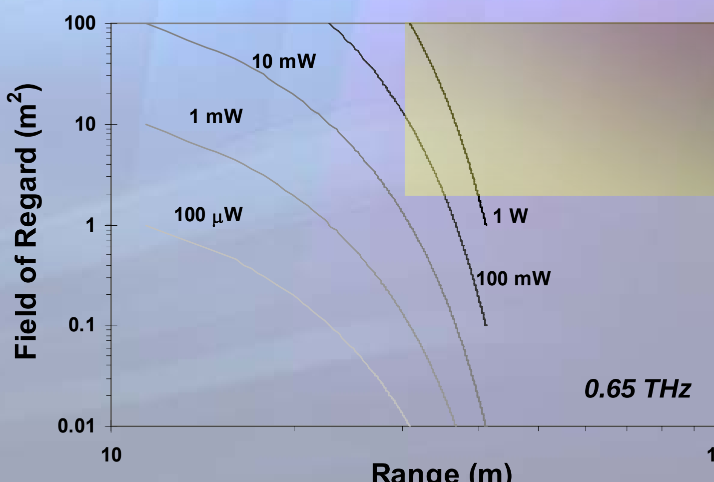


Transmit / receive must satisfy challenging new bandwidth and dynamic range requirements

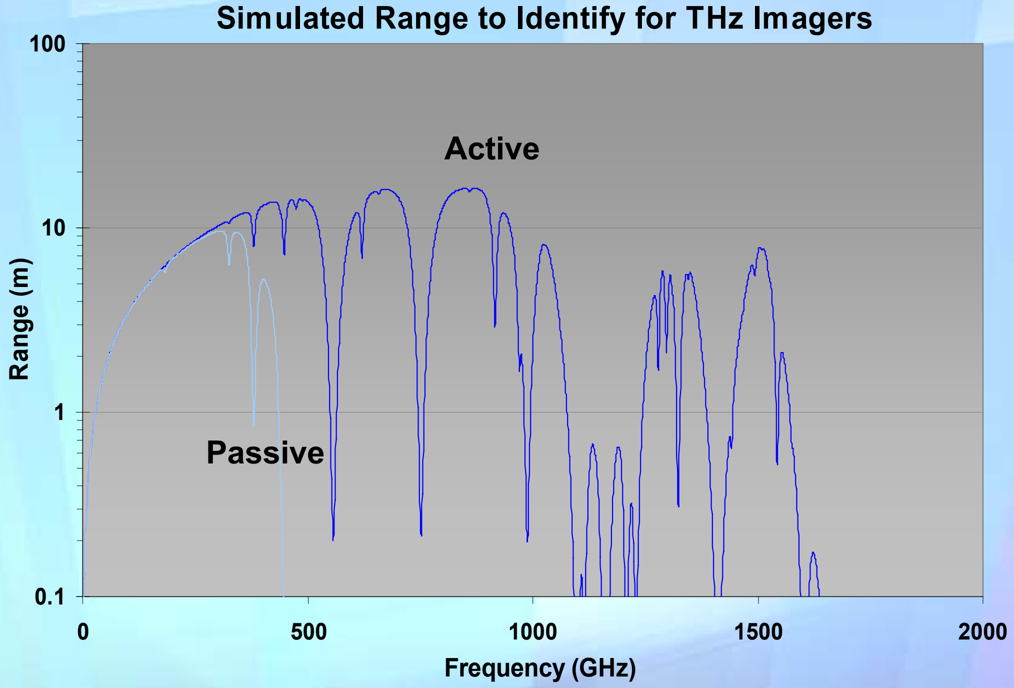
Passive is not a viable for THz imaging



Total illumination power requirements set by field of regard, not by range



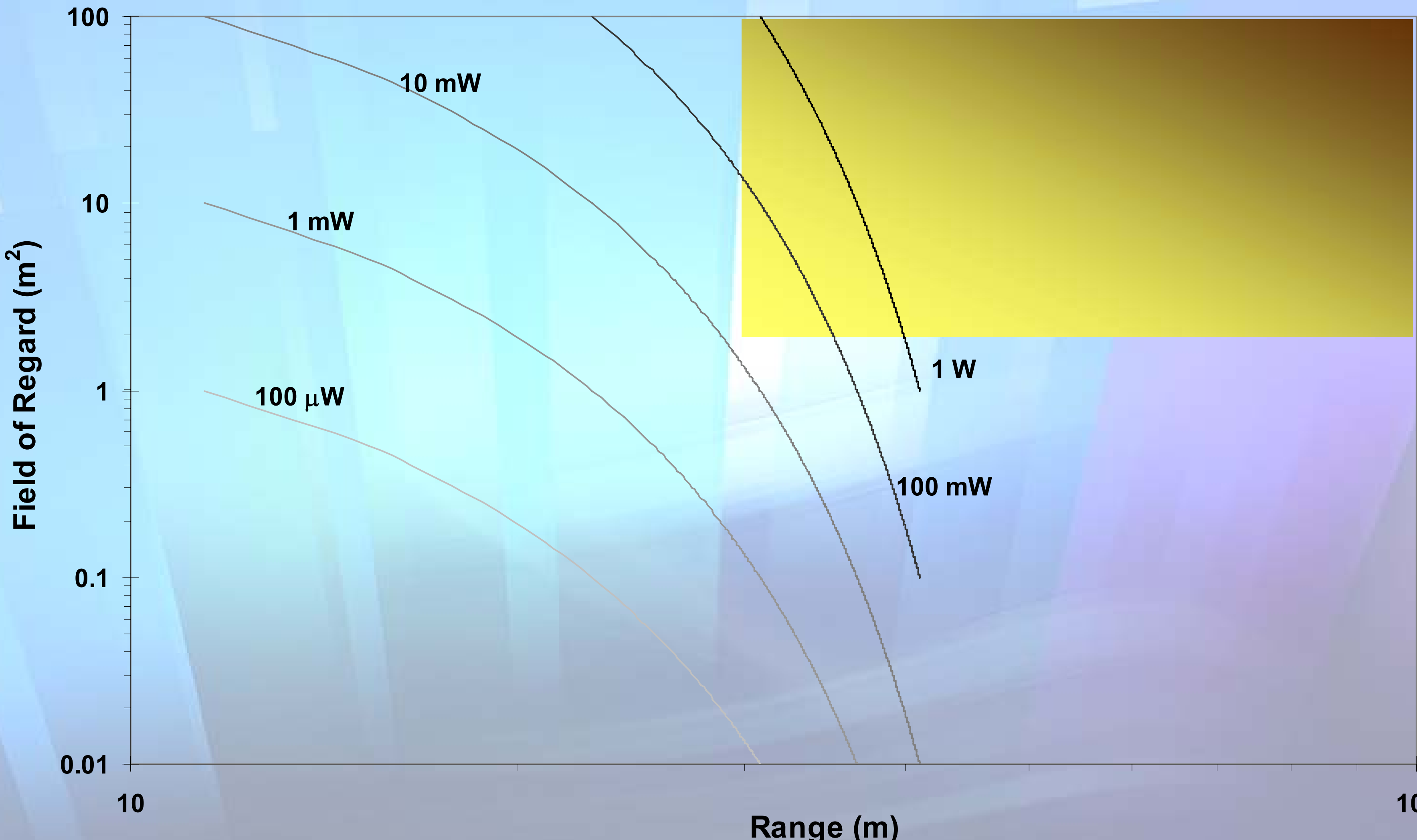
Need Active Imaging



Broadband passive

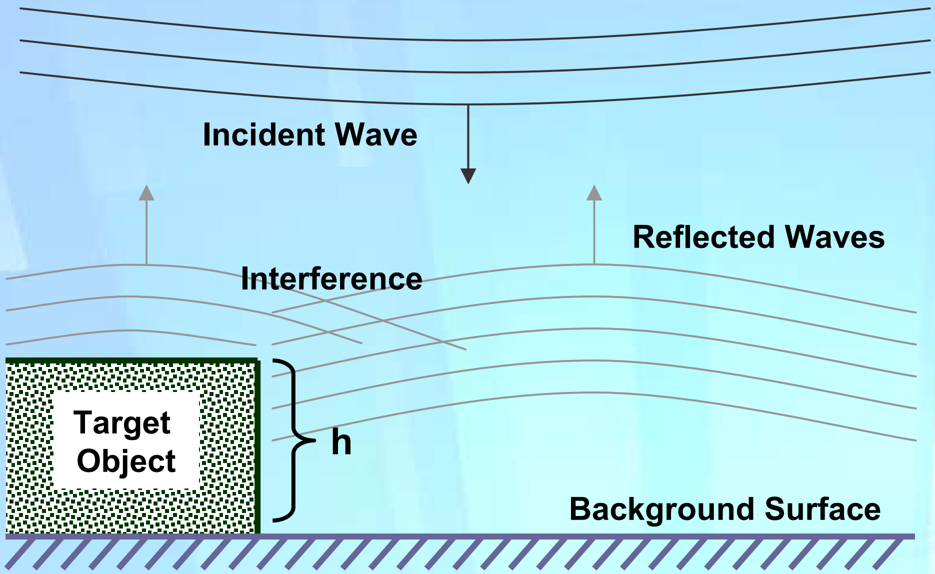
Heterodyne active @ 640 GHz

Power Requirements Driven by Field of Regard, Not Range

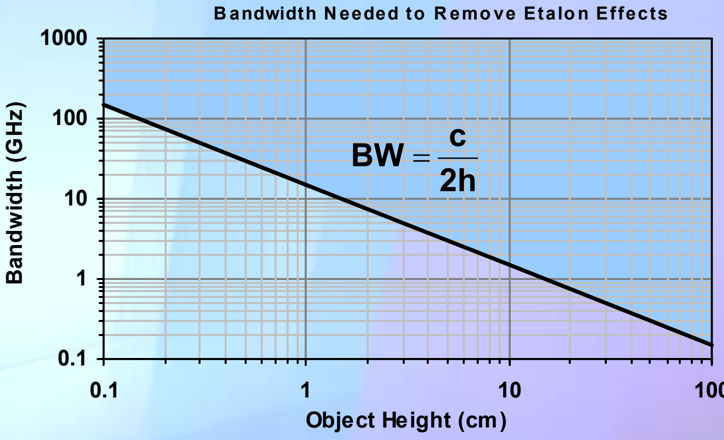


Active direct detection, line illuminated

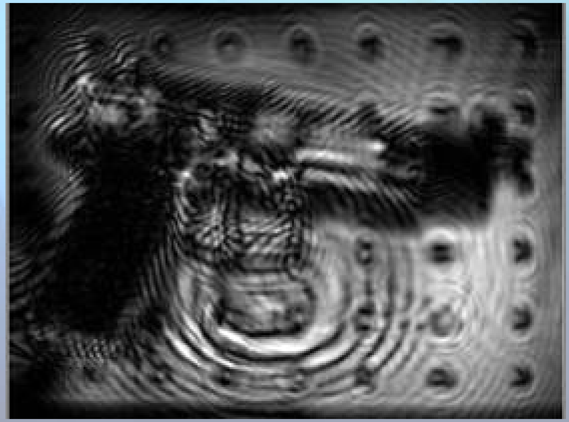
Interference Effects Can Be Eliminated With 15 GHz Source Bandwidth



Bandwidth required to remove interference from waves reflecting from surfaces at a difference in distance of h away from the imager:



Narrowband



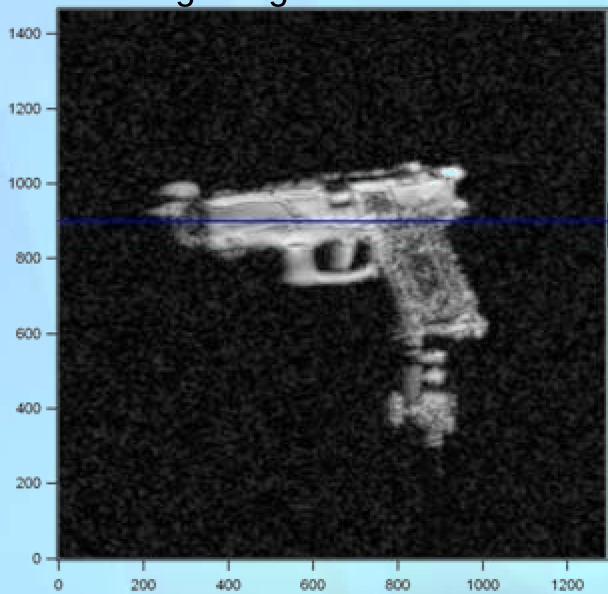
650 MHz Bandwidth

Visible Image (no interference)

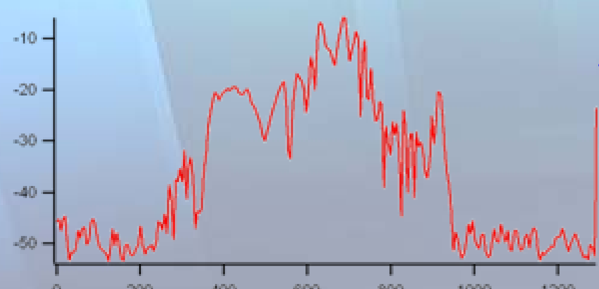
Large Dynamic Range Needed to Separate Signal from Backgrounds

Typical THz Signal Object

Image of gun at 650 GHz

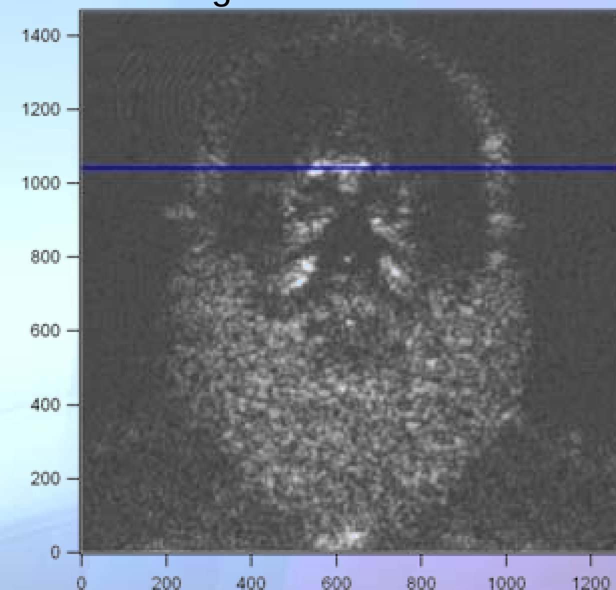


Detector response (dB)

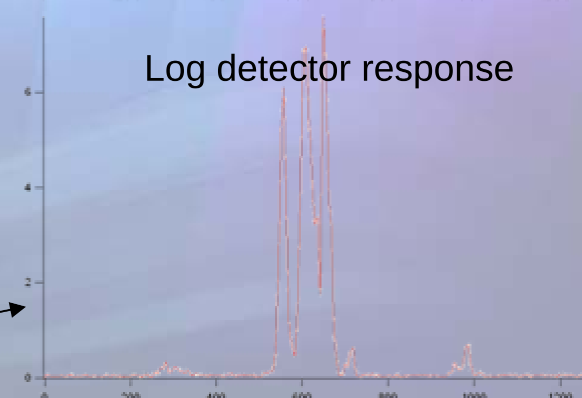


Typical THz Background Texture

Image of face at 650 GHz

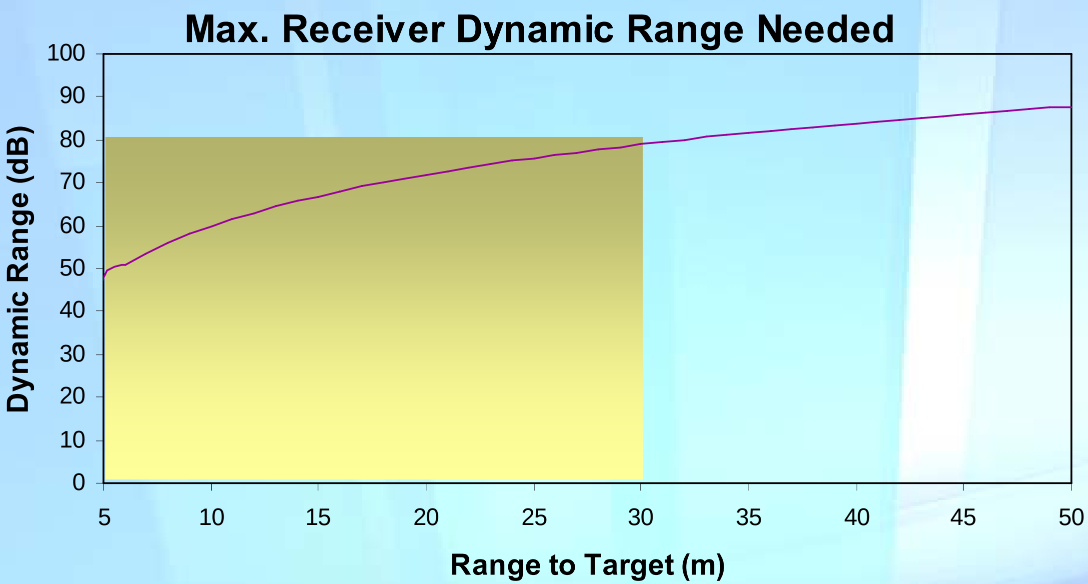


Log detector response



Similar scales

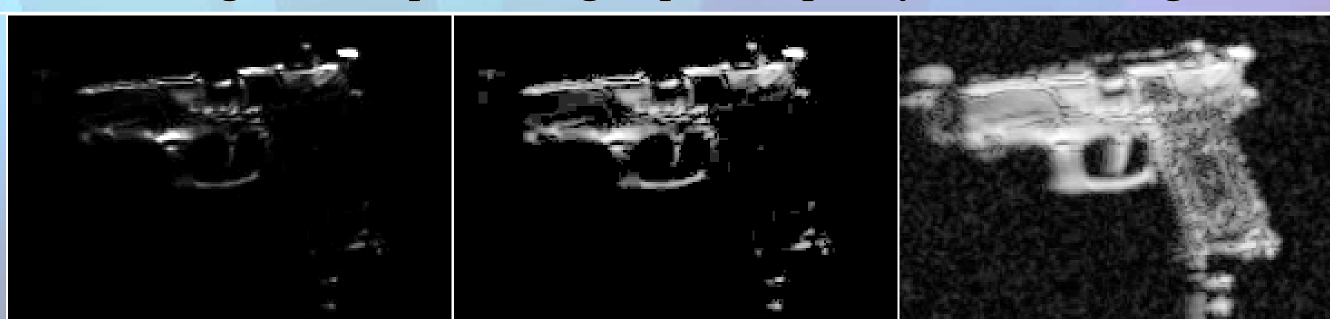
Receiver Needs 80 dB of Dynamic Range



Assumptions:

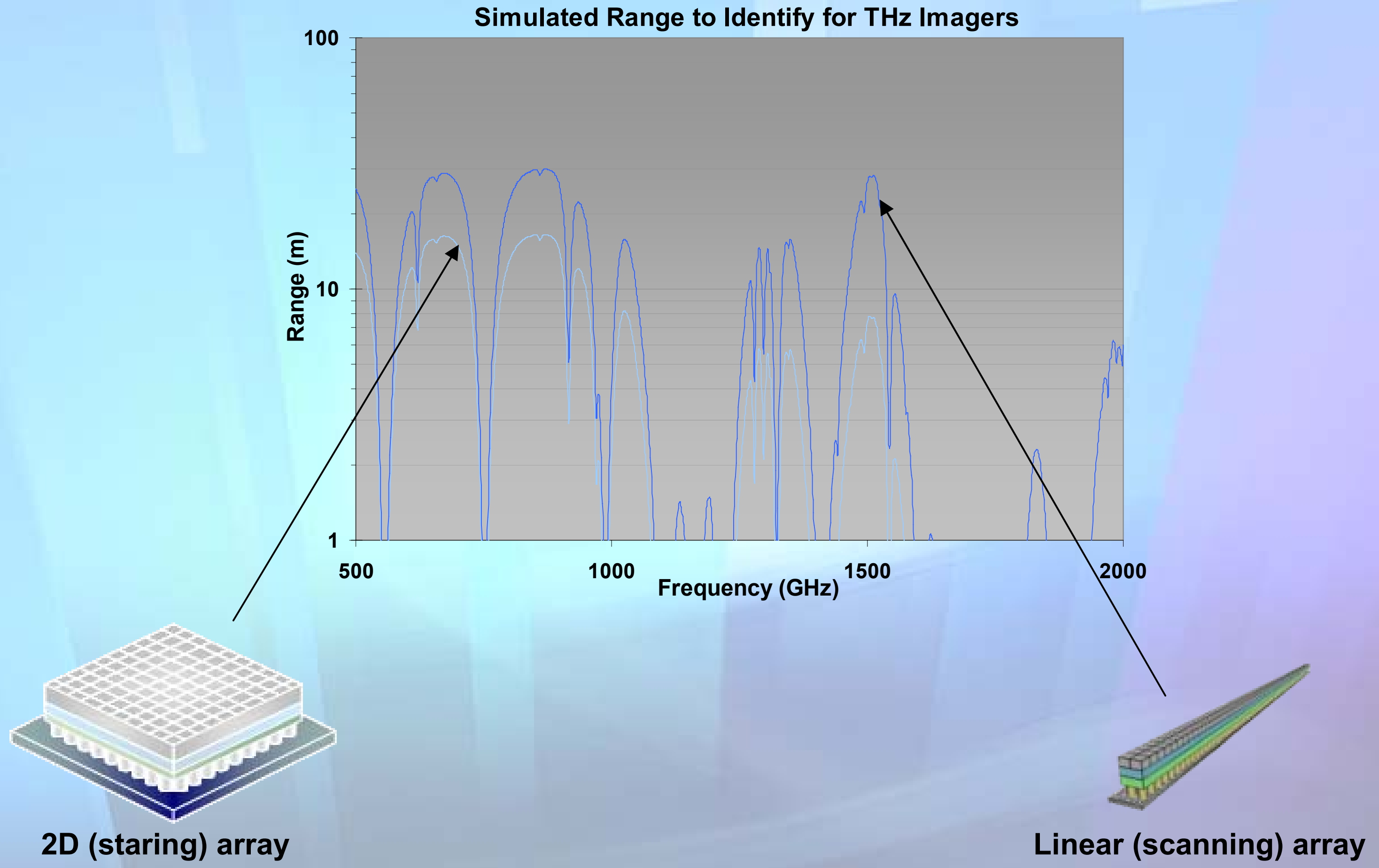
- RCS range (max:min) : 40 dB
- Minimum acceptable SNR: 6:1
- Minimum range to target: 5 m

Logarithmic processing improves quality of active images



Linear processing | Log post process | Log IF process

Scanning Arrays May Provide Better Performance Than Staring Arrays



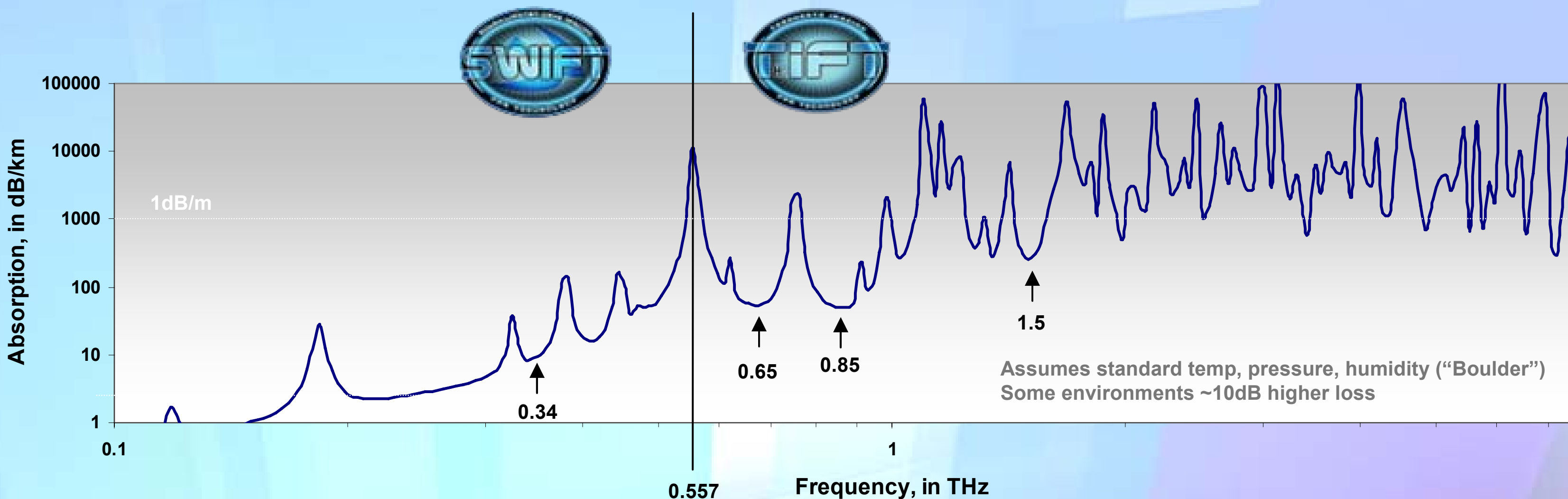
Line scanning systems reduce electro-mechanical requirements and allow for array calibration/stabilization

Approved for Public Release, Distribution Unlimited

DARPA THz Imaging Programs

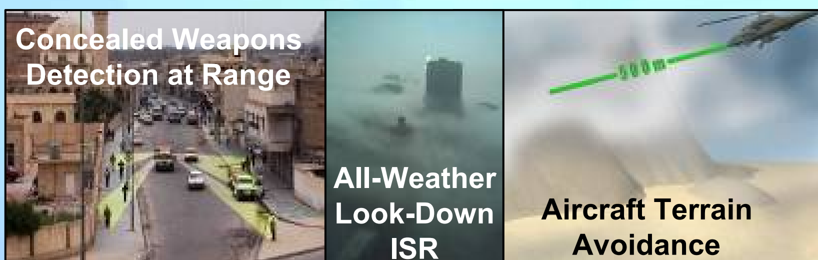
MTO's THz Programs

Phenomenology



Applications

Ranges up to 1 km

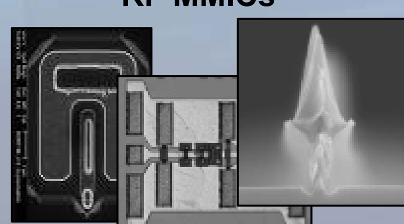


Ranges < 100m

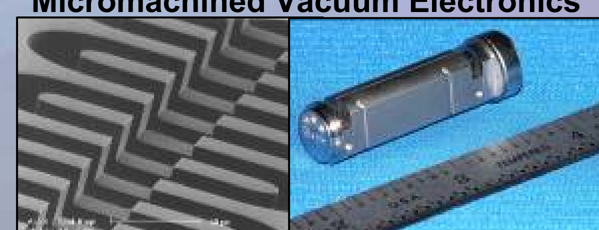
Technologies

Electronic Upconversion

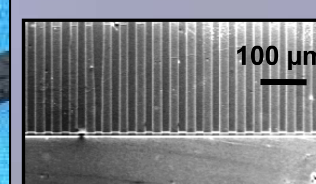
RF MMICs



Micromachined Vacuum Electronics



Photonic Downconversion

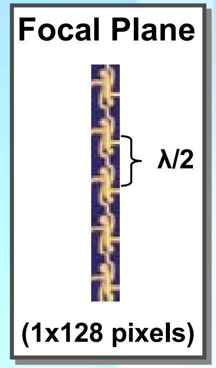


Sub-millimeter Wave Imaging Focal-plane Technology (SWIFT)

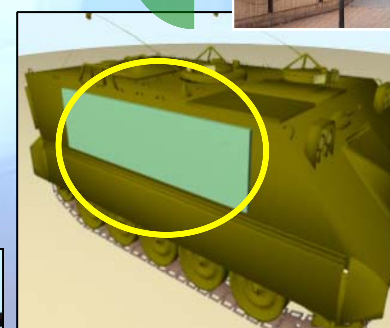
SWIFT Objective and Impact

Goal
- Demonstrate high-performance transmit/receive sub-aperture to enable diffraction-limited and video-rate sub-MMW (340 GHz) imaging

Impact
- Push the limits of RF electronics
- Enable imaging in environments where no other sensor can function

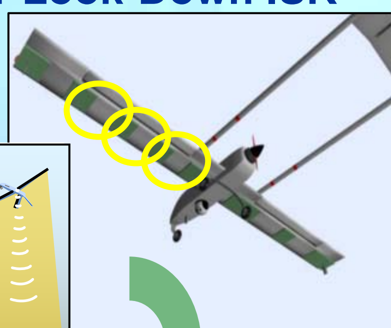


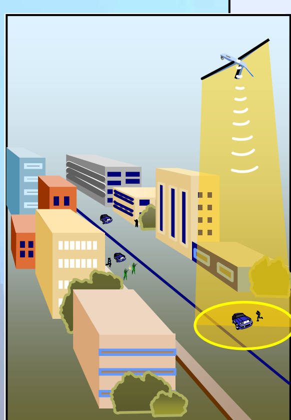
Concealed Weapons Detection at Range



Range ~ 100m

All-Weather Look-Down ISR





Scan angles > 60°

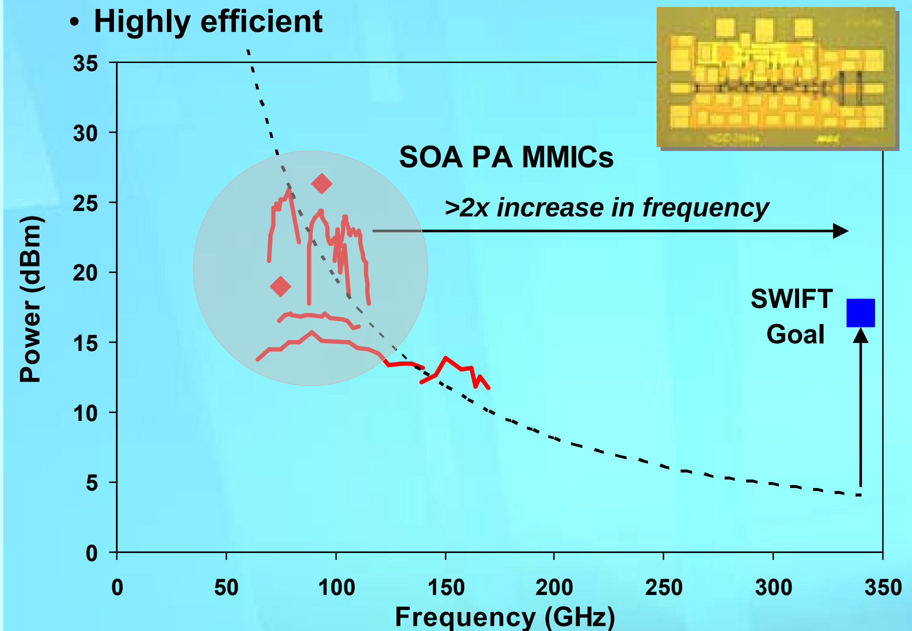
All-Weather Terrain Avoidance

Radome-limited aperture

SWIFT Technical Challenges

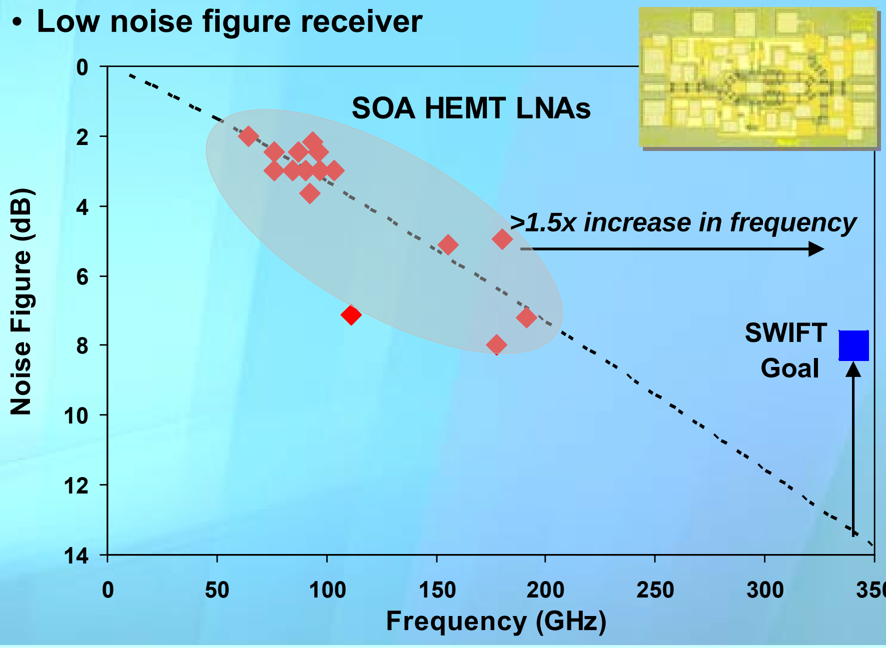
Sub-MMW Sources

- Ultrafast power amplifier MMICs
- Highly efficient



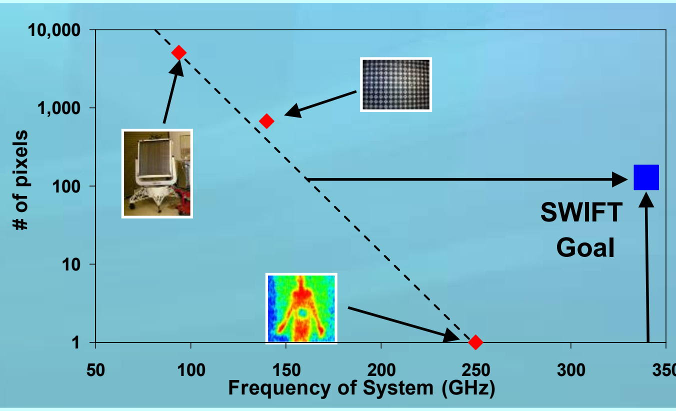
Sub-MMW Receivers

- Ultrafast LNA MMICs and mixers
- Low noise figure receiver



Imaging Array Architecture

- Minimization of LO power
- Low loss interconnects



SWIFT Program Metrics

Metric*	Unit	Today	Phase I		Phase II
			Mid-term MMIC Demo	MMIC GNG	Sub-Aperture GNG
PA P_{out}	mW	None**	5	50	
PA PAE	%	None	2.5	5	
RF bandwidth	%	None	≥ 5	≥ 5	
Receiver NF	dB	None**	12	8	
Phase noise ‡	dBc/Hz	None	-38	-38	
Transmit power	mW	N/A			1000
Sub-array receiver NF	dB	N/A			8
Level of integration	pixels	N/A			128
Frame rate	Hz	N/A			30
Receiver LO power	mW	N/A			< 500

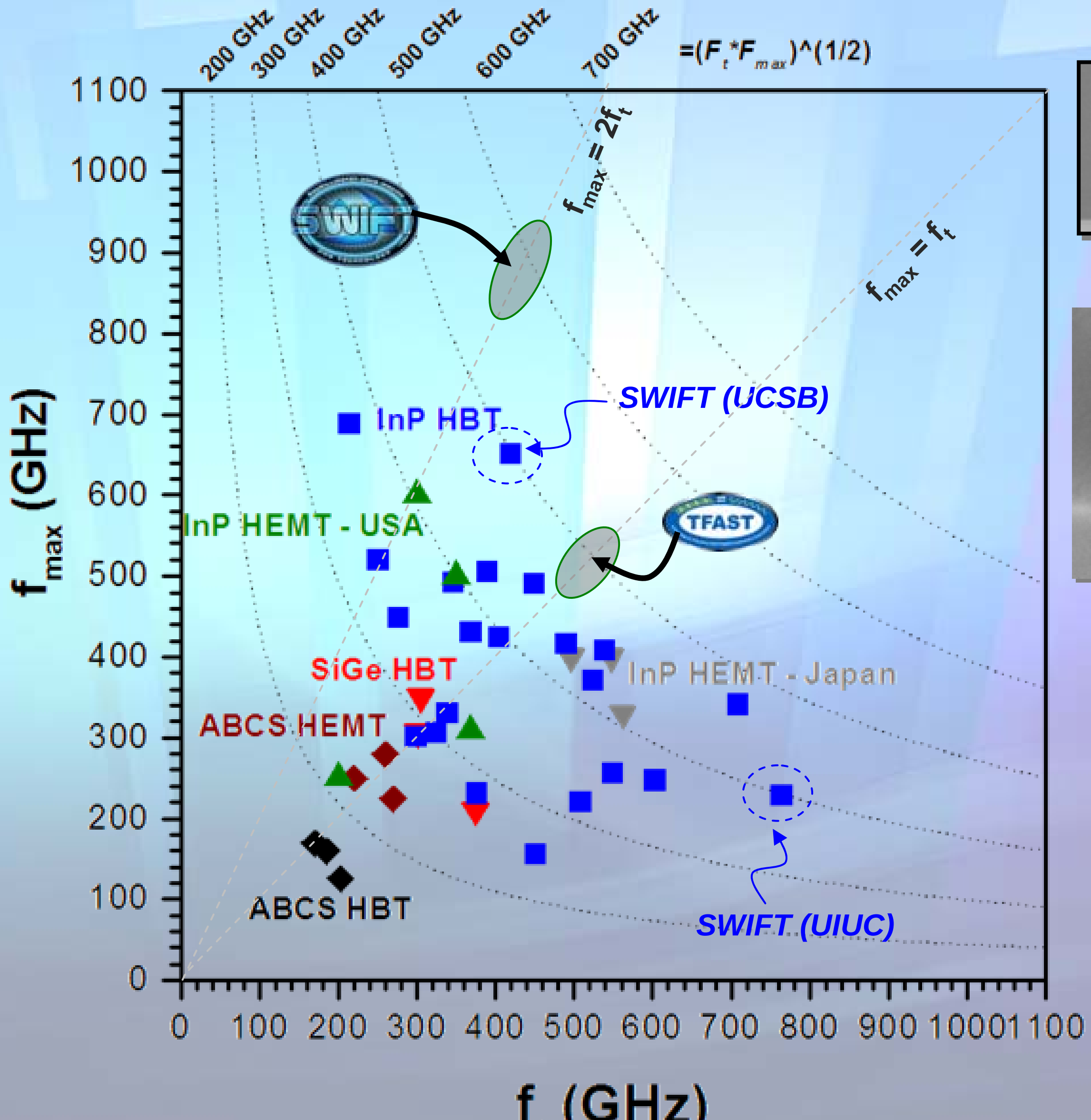
* At 340GHz

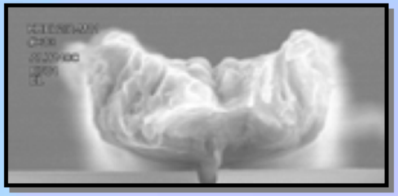
** Best reported value for hybrid PA power/LNA NF at 340 GHz are 0.1 mW and 12 dB, respectively

† Azimuthal (height) x cross-track (width)

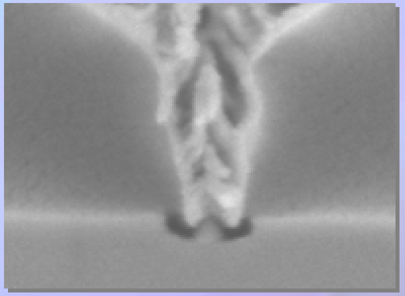
‡ Value to be measured at f_c = 340GHz at offset frequency of 100Hz

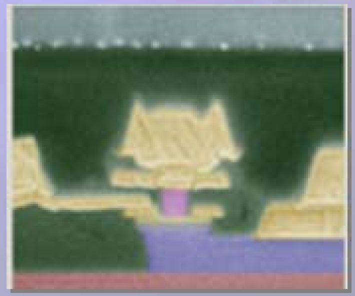
Towards a THz Transistor





InP HEMT





InP HBT

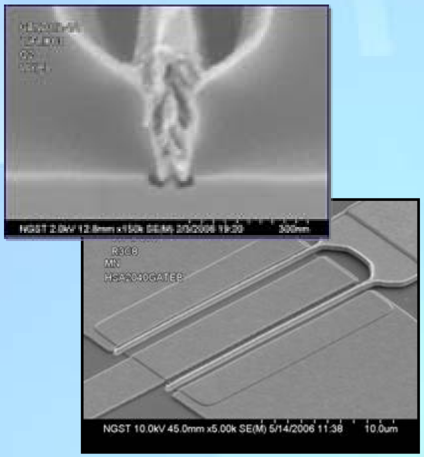
SWIFT Accomplishments

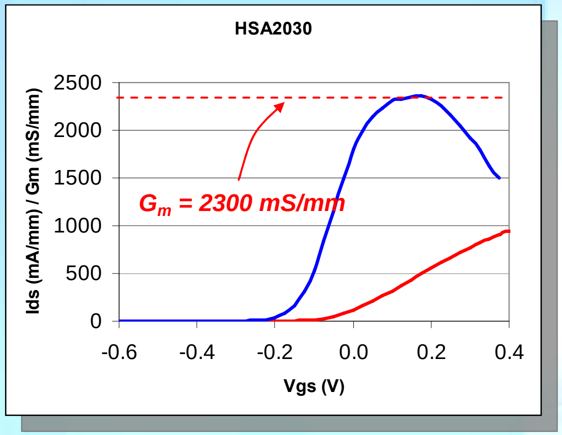
World's Fastest MMICs

35nm InP HEMT Devices

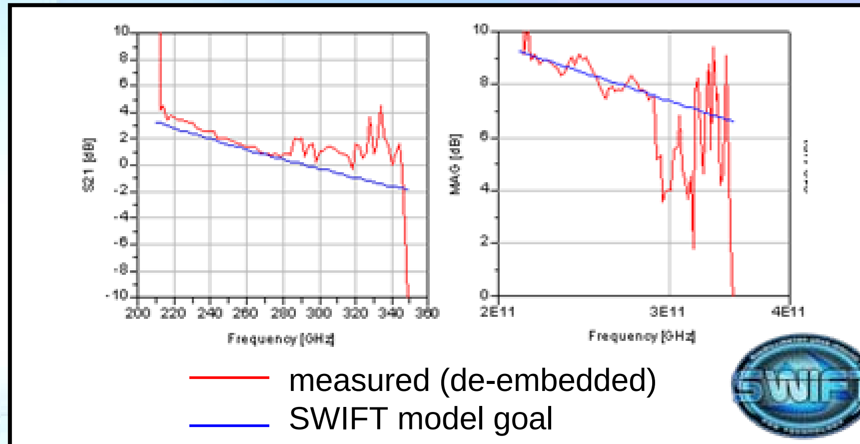
NORTHROP GRUMMAN

35nm gate of InP HEMT with record Gm = 2300mS/mm



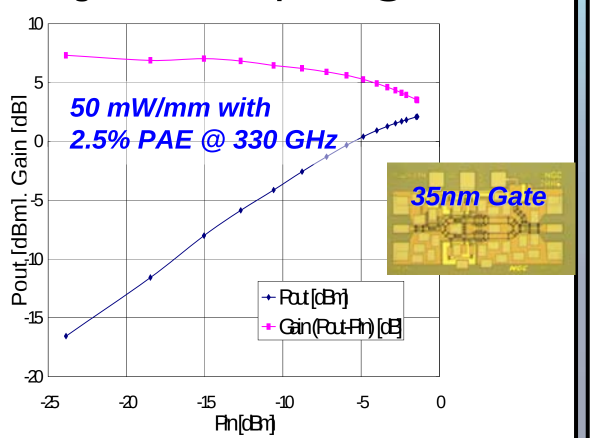


MAG@340 GHz > 6 dB for both model & measured results

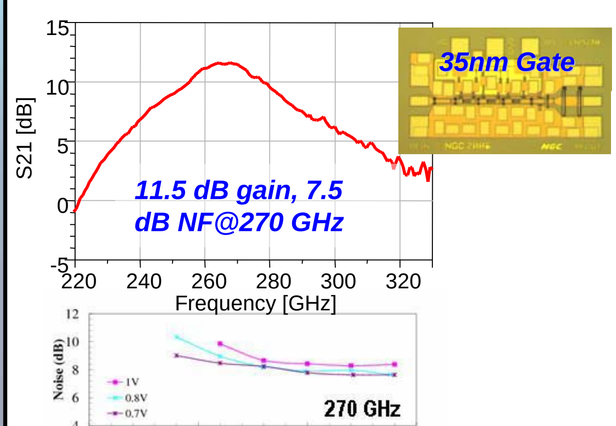


World Record Sub-MMW MMICs ("s-MMIC")

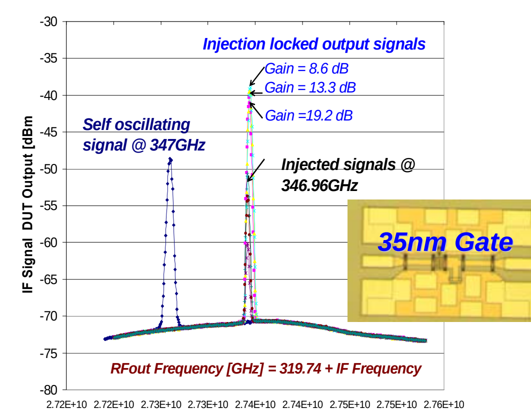
3-stage Power Amplifier @ 330 GHz



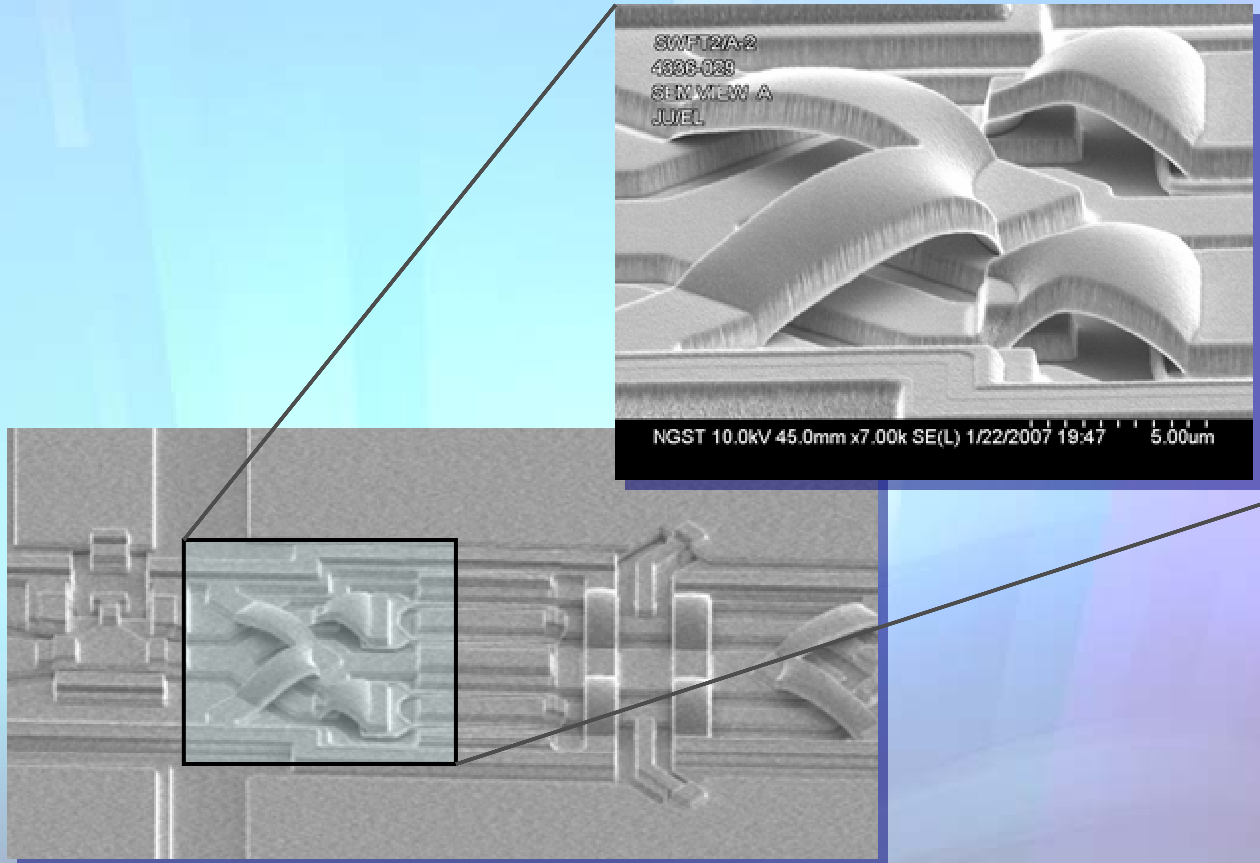
3-stage Low Noise Amplifier @270 GHz



First s-MMIC: a 347GHz HEMT VCO



What Does an s-MMIC Look Like?

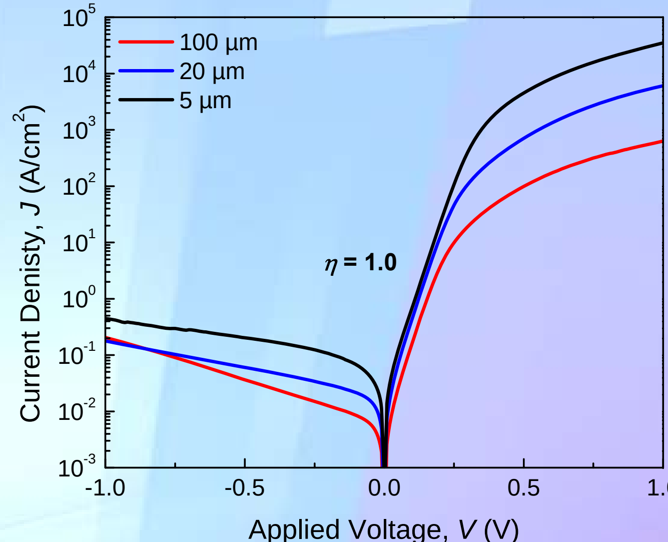


Compact.

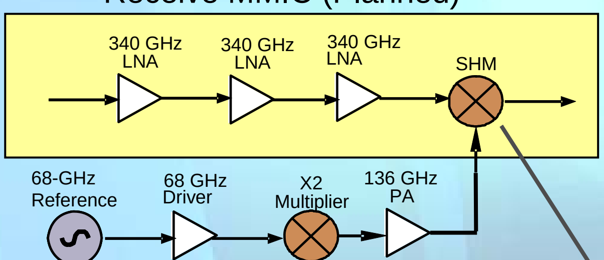
THz Sb-Based Diodes for Sub-Harmonic Mixers

InGaSb/InAlAsSb PN Diodes

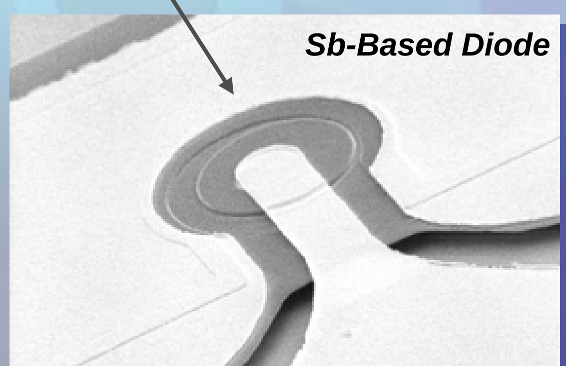
- **Excellent ideality factor, η = 1.0**
- **Relatively low reverse-bias leakage at low voltage**
- **Extracted series resistance of 1 Ω for a 5 µm diameter diode**
- **Cut-off frequency from *S*-parameter extracted *RC* is 1.5 - 9 THz (best fit results in 6.5 THz)**

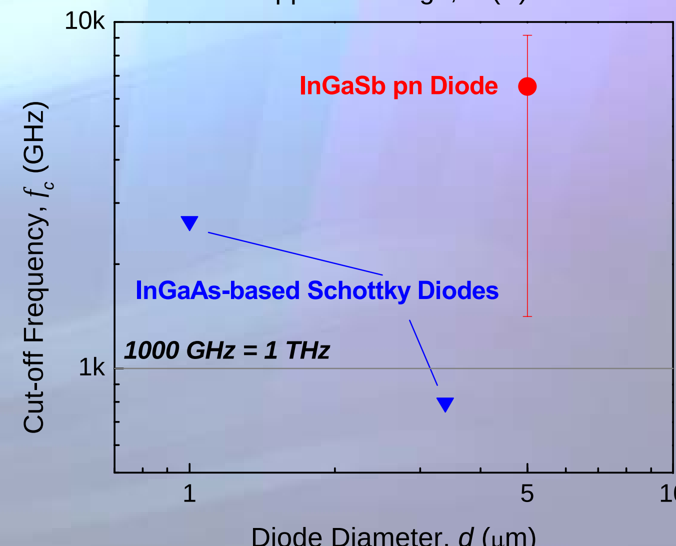


Receive MMIC (Planned)



Performance
- 7-dB NF
- 5% BW



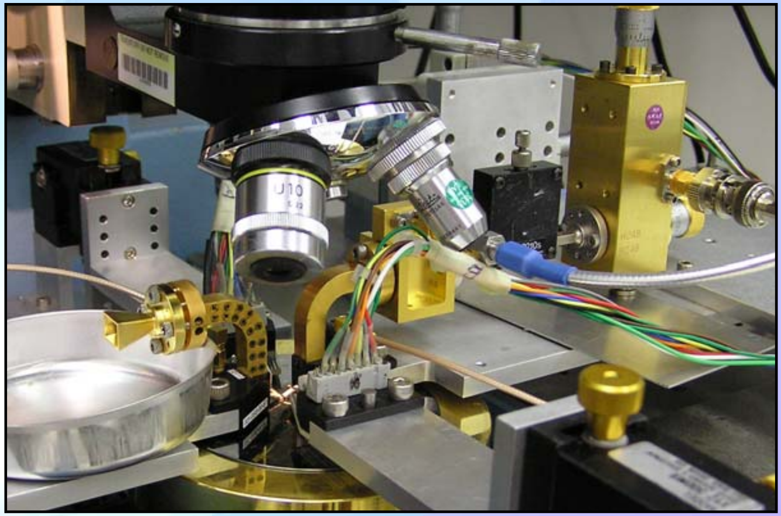


NORTHROP GRUMMAN

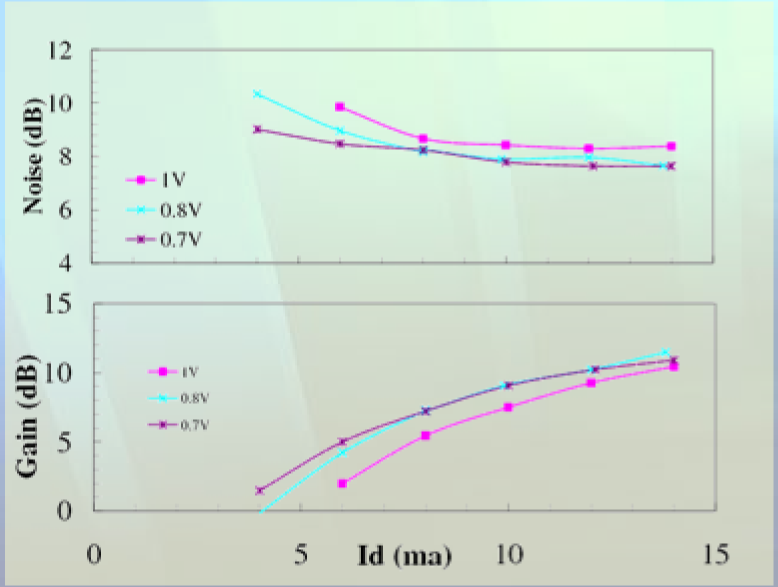
Sub-MMW Metrology: Another DARPA-Hard Challenge

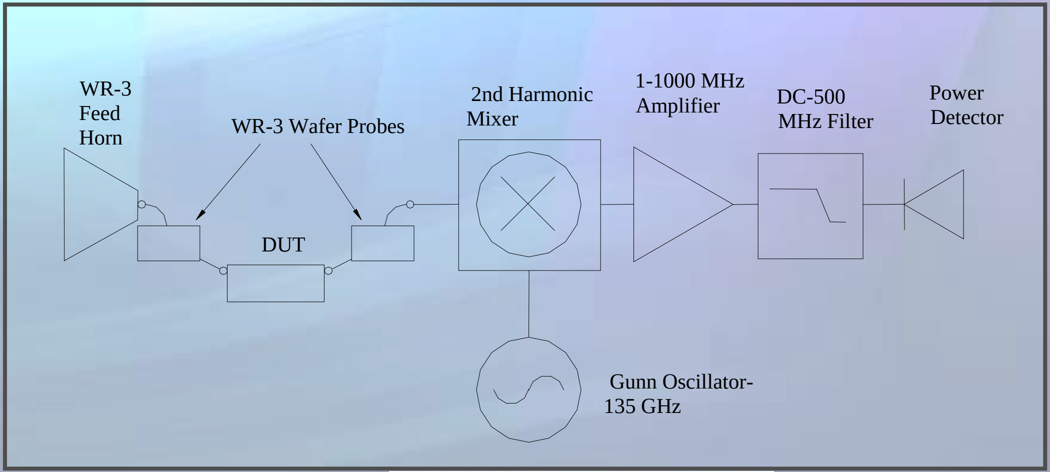
Things that don't exist at 340 GHz…

- Isolators
  - Impedance control for power and noise measurements
- Rotary vane attenuators
  - Calibrated loss
- Low loss couplers
  - In-situ power calibrations
- Low loss probes
  - De-embedding noise measurements
- Power amplifiers
  - Input power margin in power measurement
- Impedance tuners
  - Noise/load pull measurement



330 GHz Noise Figure Test Set

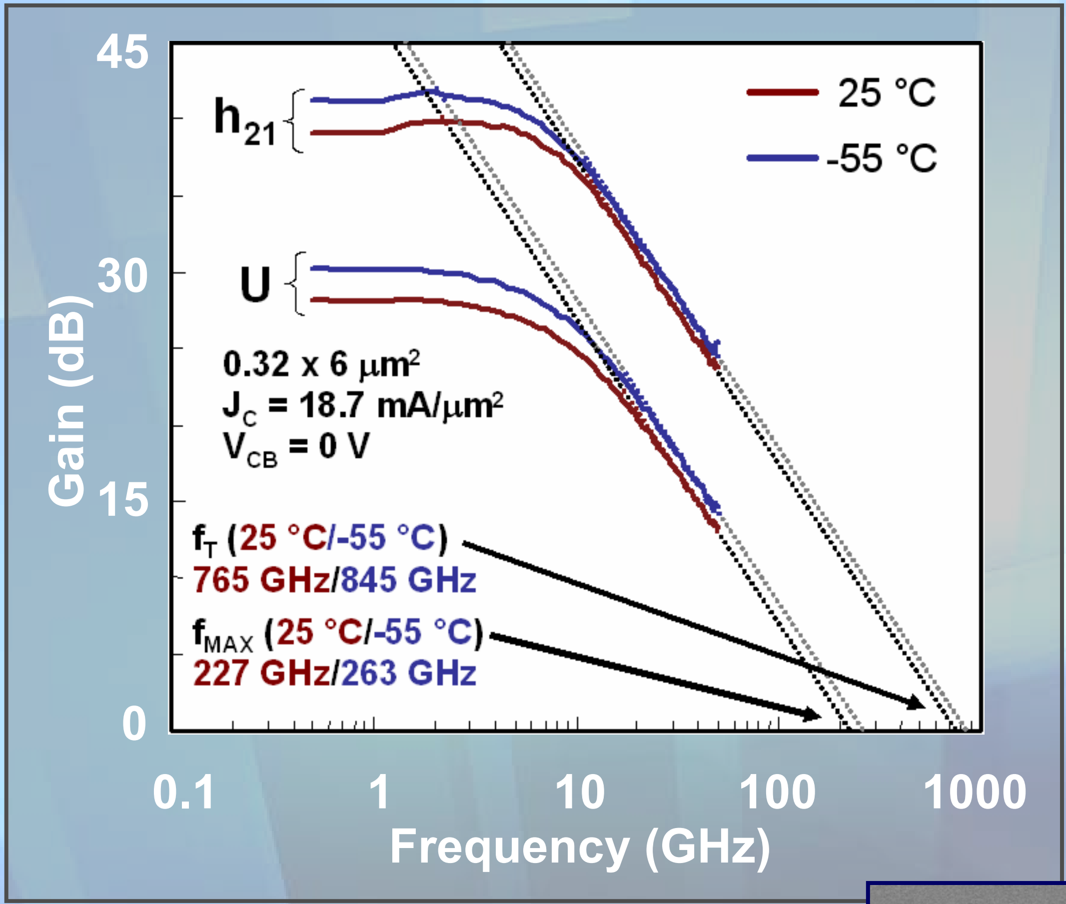


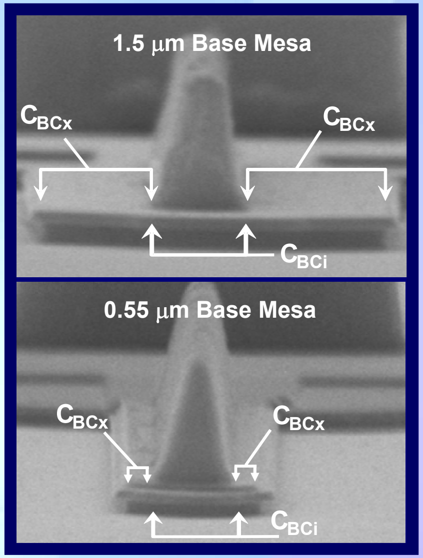


NORTHROP GRUMMAN

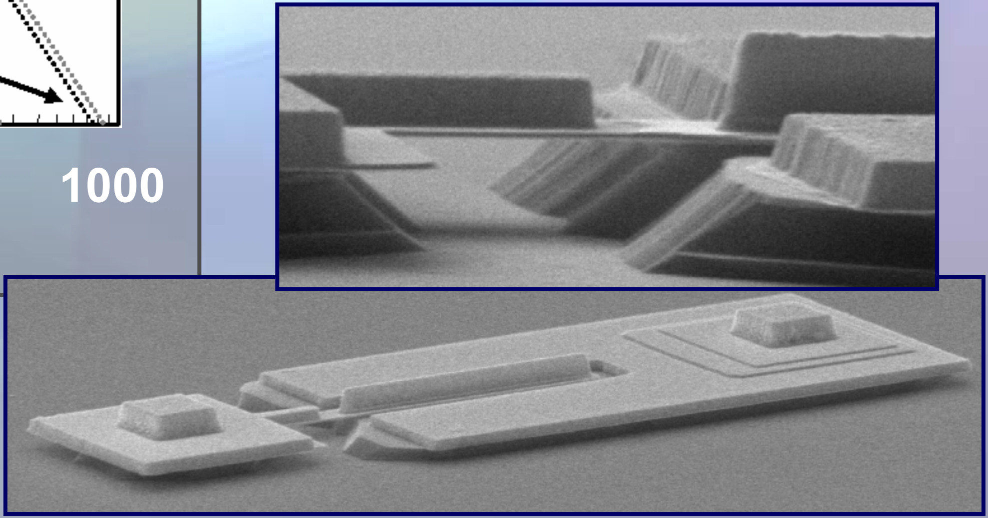
JPL

World's Fastest Transistor





Reduce base contact junction area



µ-bridge Base Contact

Vertical Scaling
From 180 GHz to 765 GHz

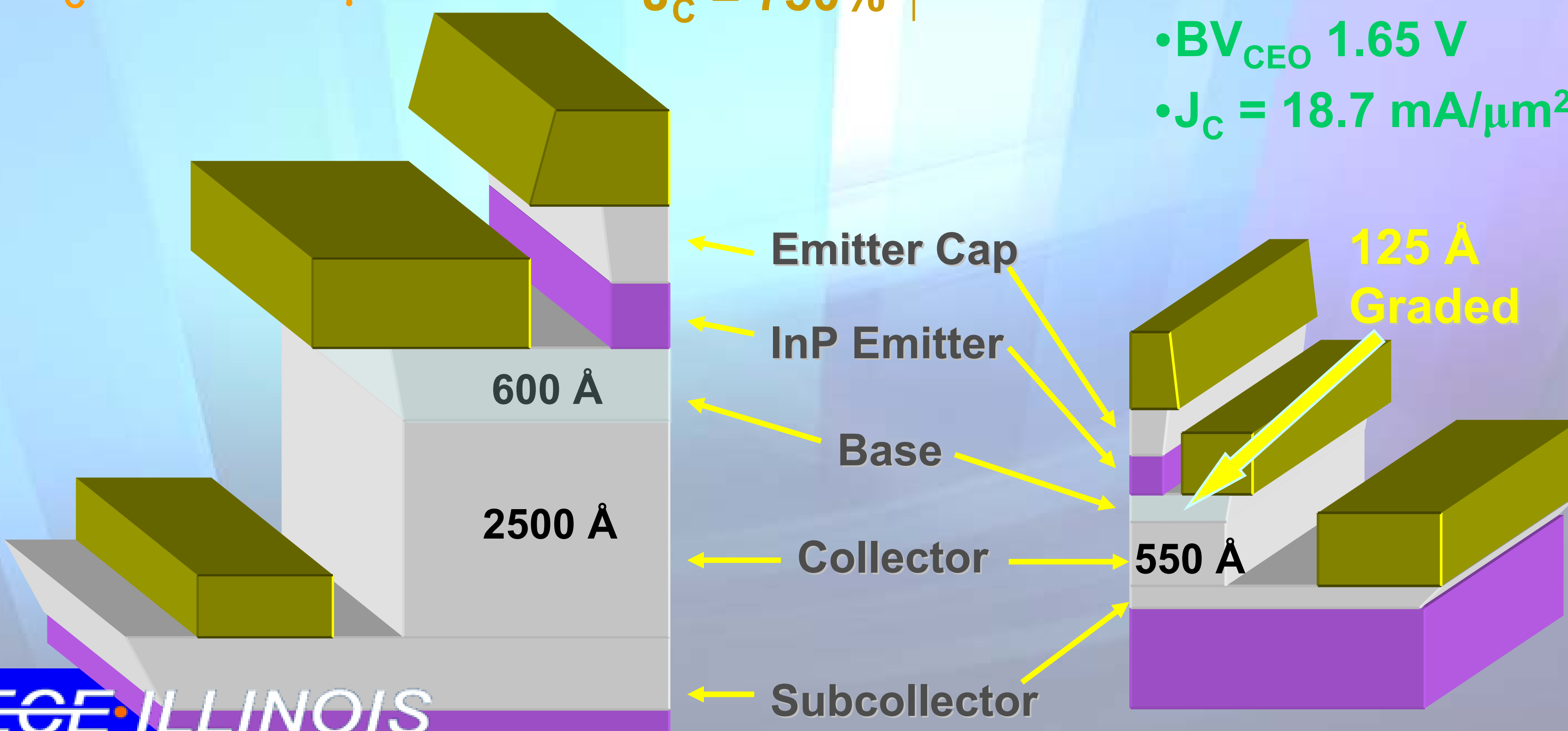
Early results:

- f_t = 180 GHz
  f_{max} = 340 GHz
- BV_{CEO} 5.1 V
- J_C = 2.50 mA/μm^2

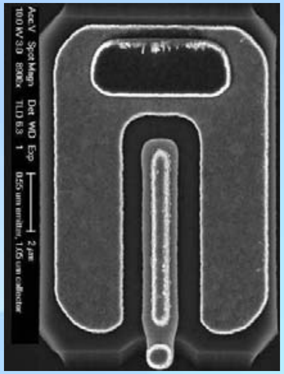
τ_B = 90% ↓
τ_C = 80% ↓
C_{BC} = 400% ↑
J_C = 750% ↑

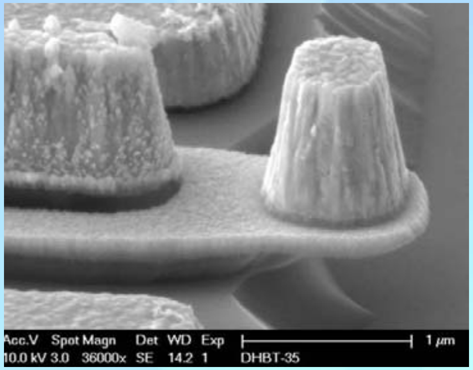
Current results:

- f_t = 765 GHz
  f_{max} = 227 GHz
- BV_{CEO} 1.65 V
- J_C = 18.7 mA/μm^2

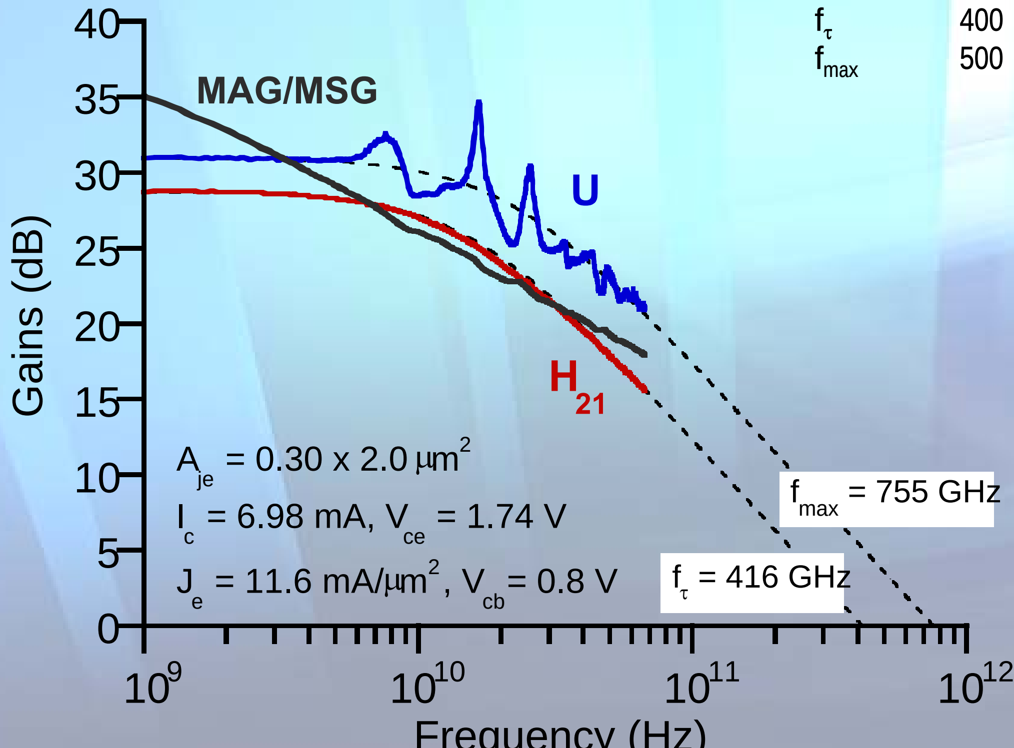


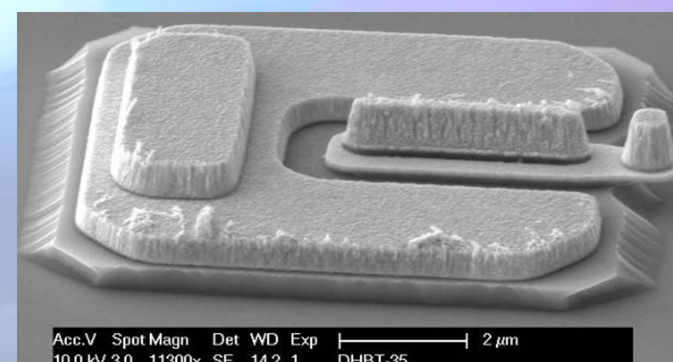
250 nm InP HBT Scaling





emitter	500	250	125	63	nm width
	16	9	4	2.5	$\Omega \cdot \mu m^2$ contact ρ
base	300	150	75	70	nm width,
	20	10	5	5	$\Omega \cdot \mu m^2$ contact ρ
collector	150	100	75	53	nm thick,
	5	10	20	35	$mA/\mu m^2$ current density
	5	3.5	3	2.5	V,breakdown
f_τ	400	500	700	1000	GHz
f_{max}	500	700	1000	1500	GHz

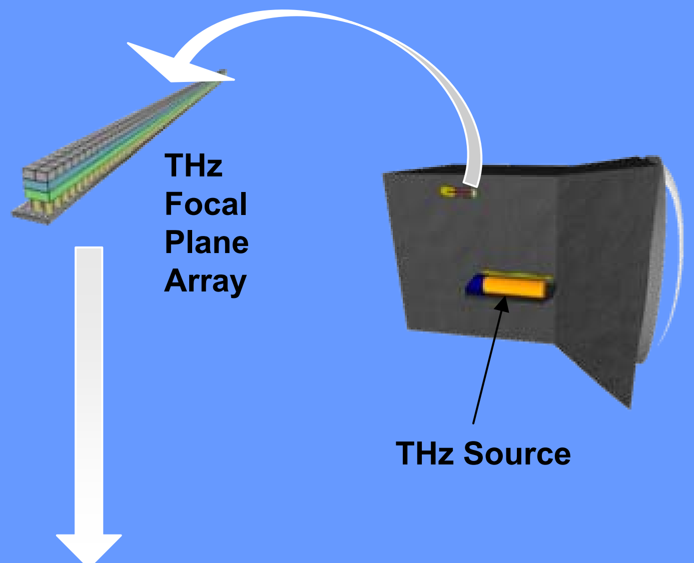




UCSB

Terahertz Imaging Focal-plane Technology (TIFT)

Terahertz Imaging Focal-Plane Technology (TIFT)



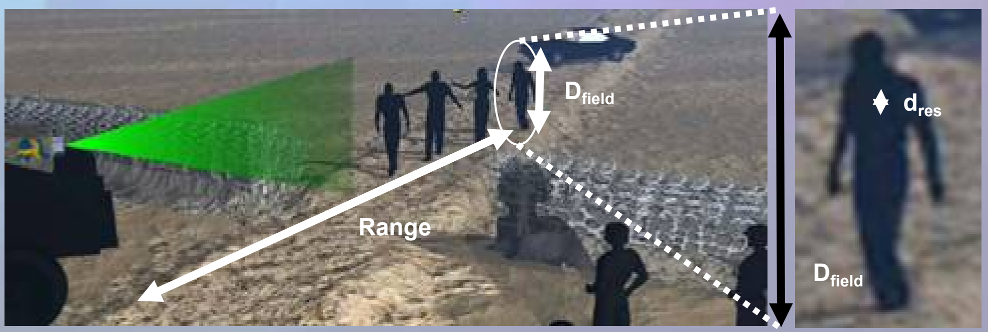
THz Sources and THz Receivers

Program Objective:

- Achieve revolutionary advances in THz transmit and receive technology
- Develop building blocks to enable compact THz (>557 GHz) sensor arrays for diffraction-limited, video-rate imaging

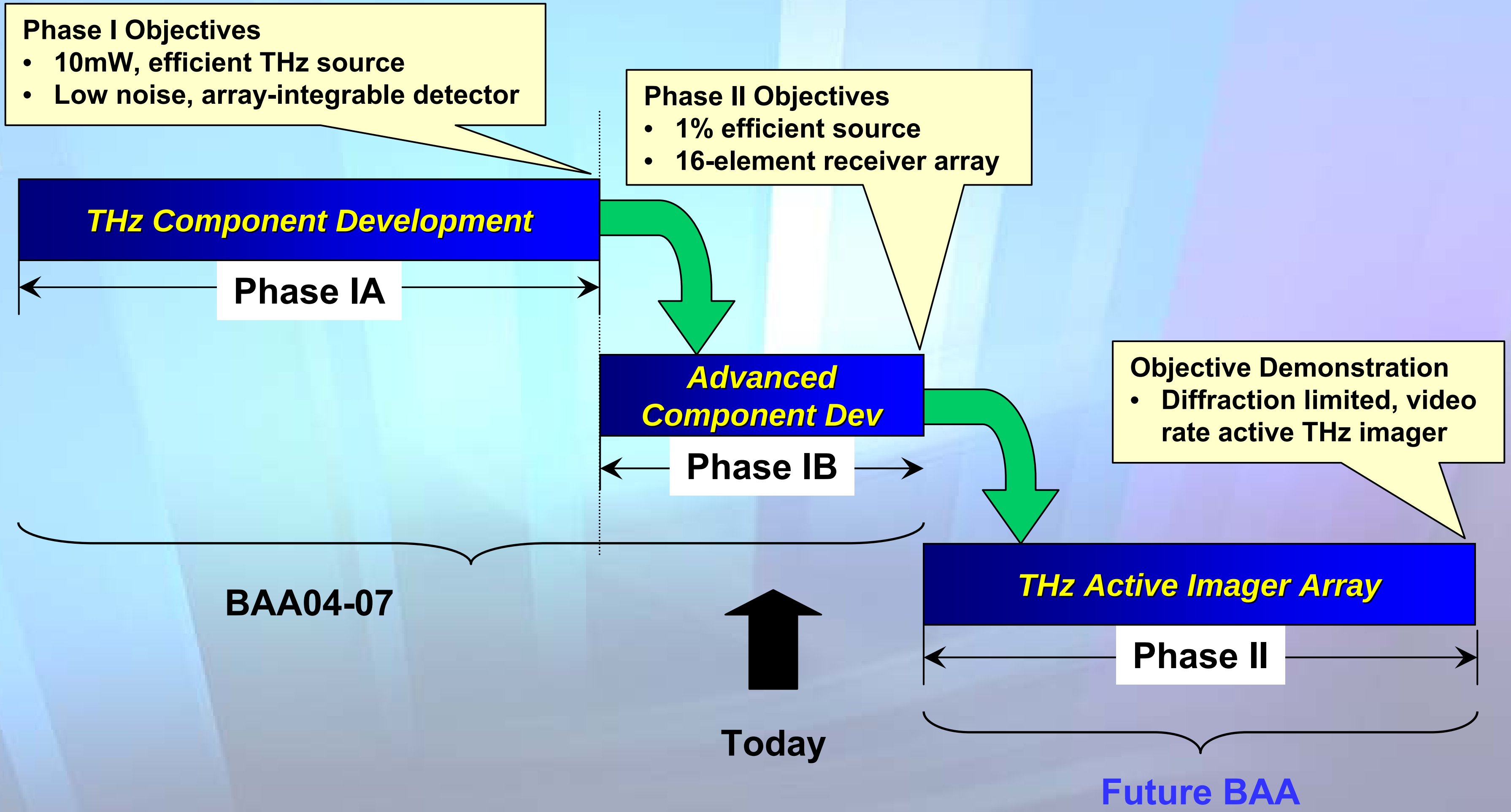
DoD Benefits

- Spectral dominance: will enable exploitation of currently inaccessible region of EM spectrum
- Will develop key components needed for THz systems (sensing, secure communications, and spectroscopy)
- Concealed weapons detection (CWD)



Concealed Weapons Detection at Moderate Range

TIFT Program Plan

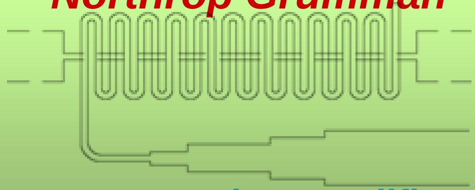


Key Technical Challenges for Phase IB

Sources
- **Increase available sub-MMW power by 100X (10 – 100 mW)**
- **Achieve 20X increase in efficiency (1%)**

Micromachined Vacuum Electronics

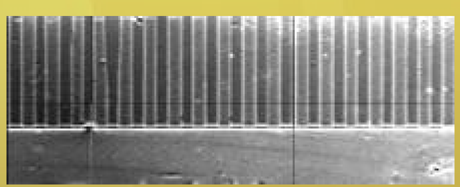
Northrop Grumman



Regenerative Amplifier

Photonic Downconversion

Stanford

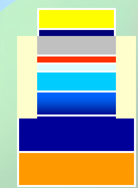


Cascaded OPO

Detectors
- **Implement an array-integrable approach achieving at least 100X improvement in NEP' ($1x10^{-12}$ W/√Hz)**
- **16 element array**

Direct Detectors

UC Santa Barbara

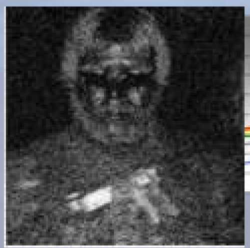


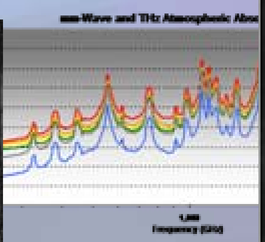
ErAs Diodes

Phenomenology
- **Define FPA requirements for TIFT imaging through IR-blind conditions**

THz transmission through materials/Atmosphere

NVESD



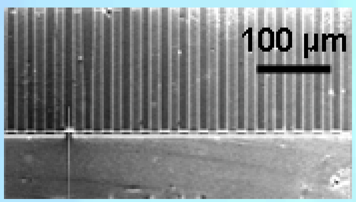


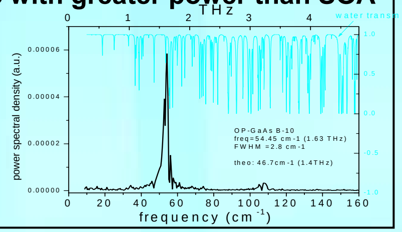
Phase I Program Accomplishments

THz Source Technology

World's first THz micromachined vacuum electronics source

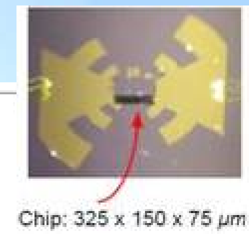
Tunable downconversion source with greater power than SOA

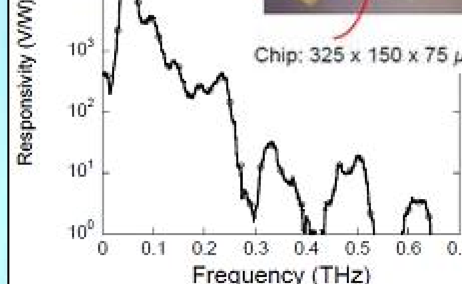




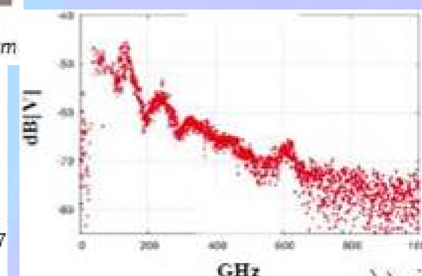
THz Detector Technology

World's most sensitive THz direct detection receiver



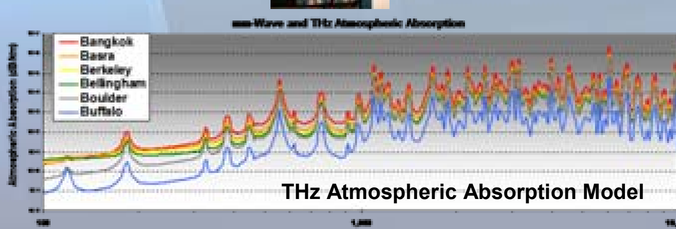


4.5 pW/√Hz at 640 GHz



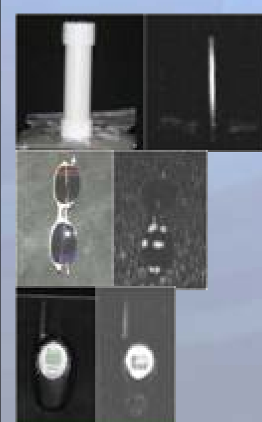
THz Phenomenology

Measured THz transmission through clothing and building materials

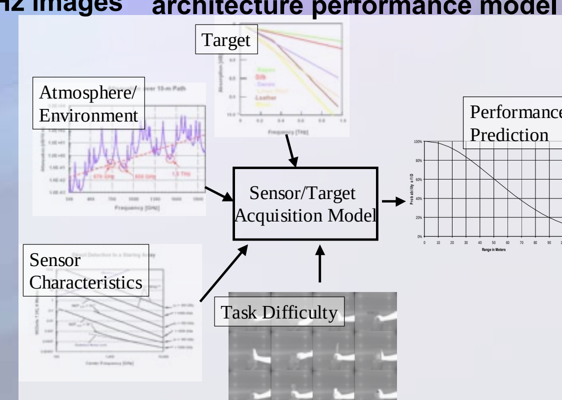


THz System Model

Extended NVESD IR perception model to THz using THz images



Constructed THz imager architecture performance model

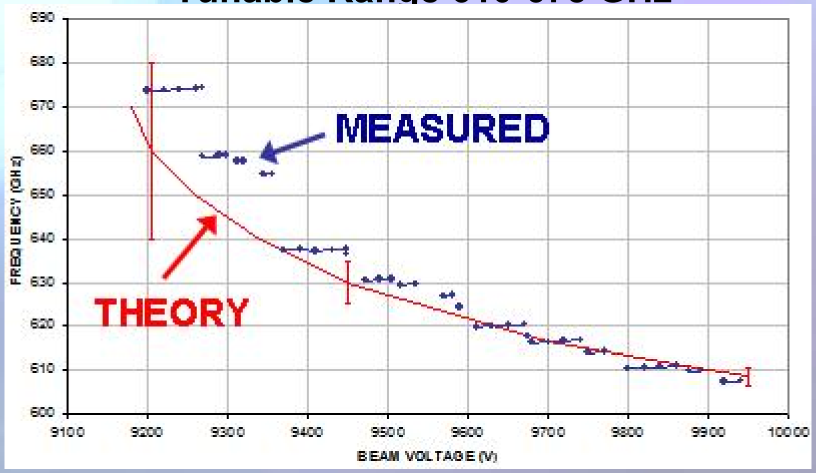


World's First THz Micromachined Source

SOA 0.65 THz 1 mW Source [(1)]

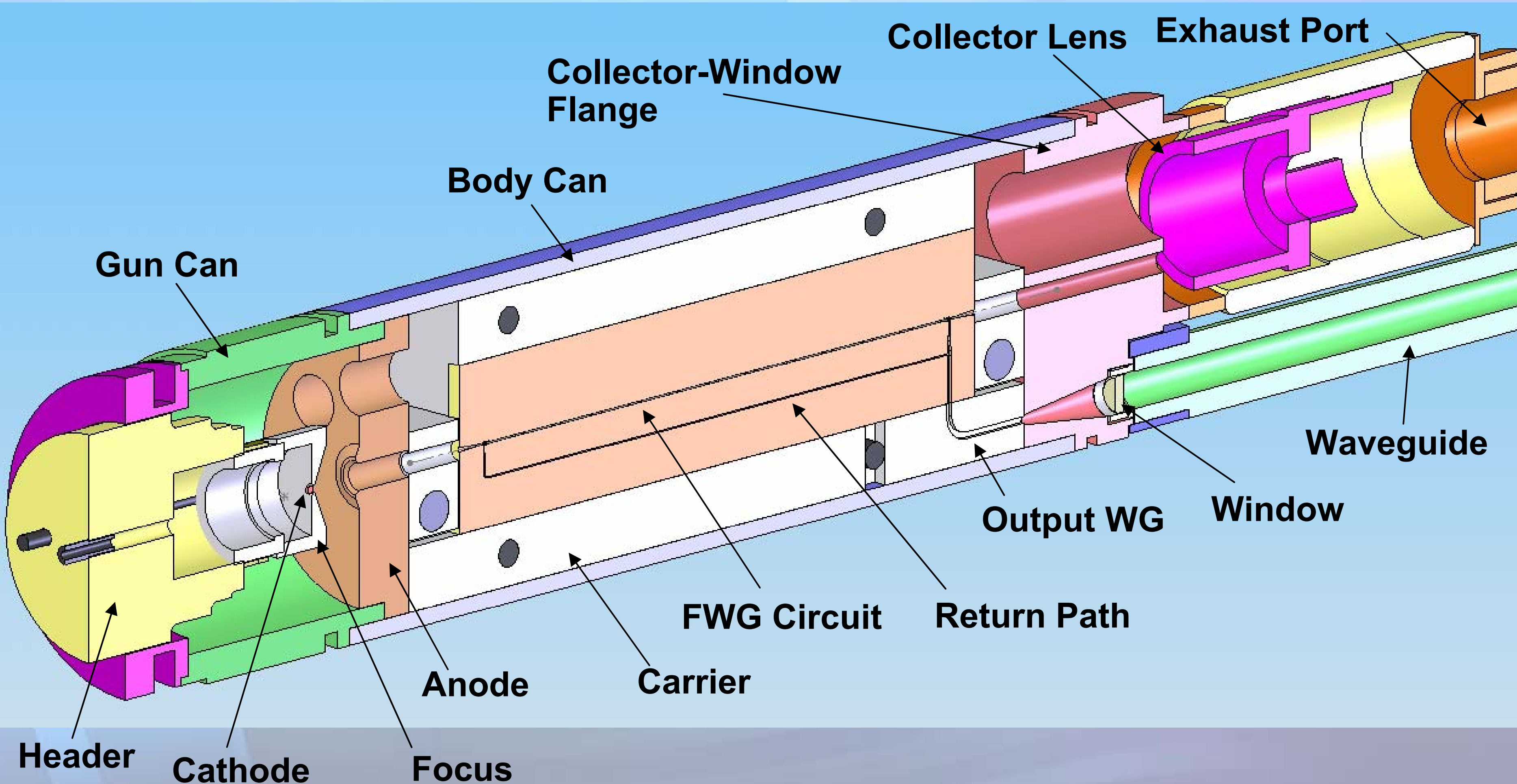
TIFT 0.65 THz 16 mW Source

Tunable Range 610-675 GHz

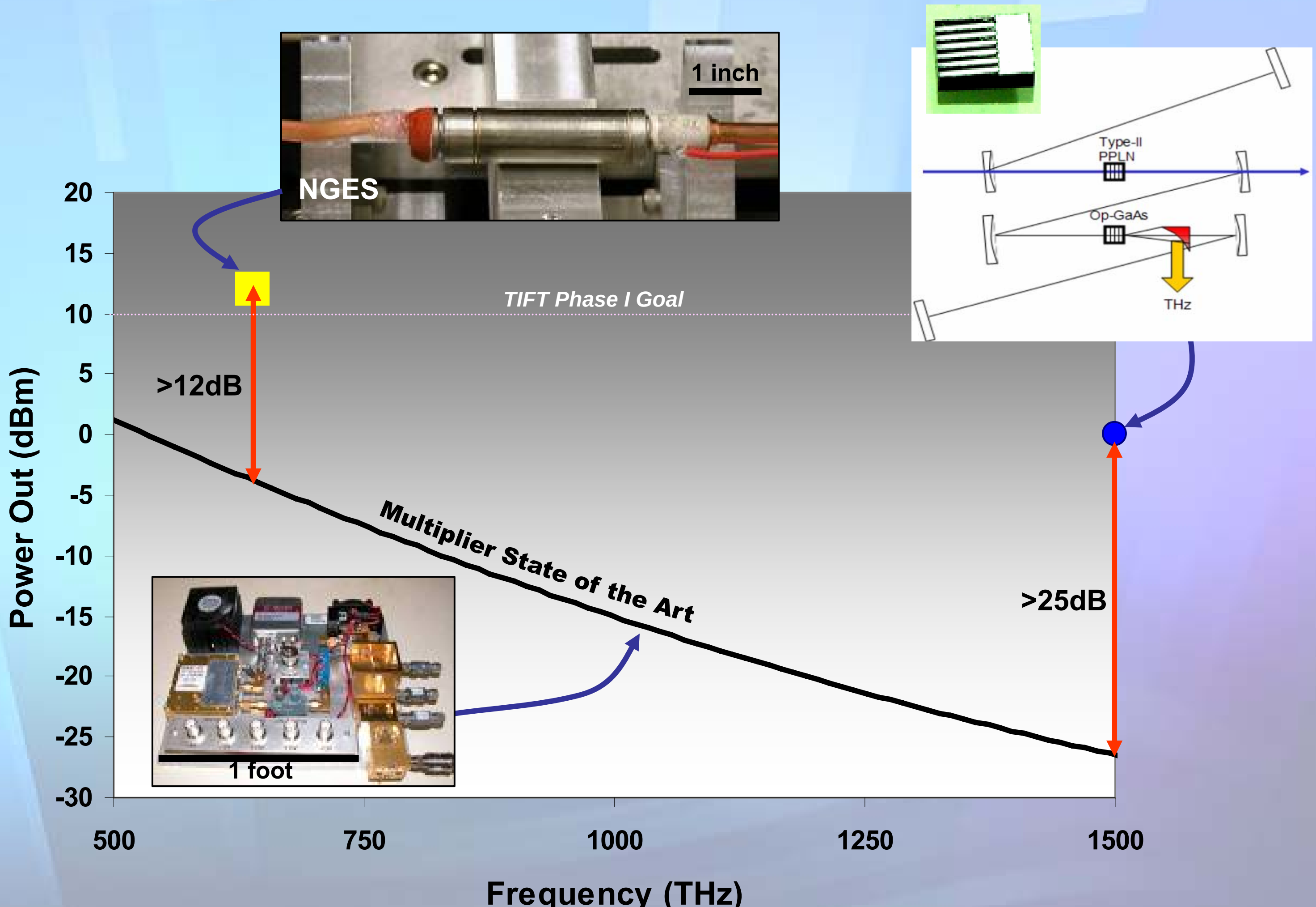


(1) Virginia Diodes, Inc.

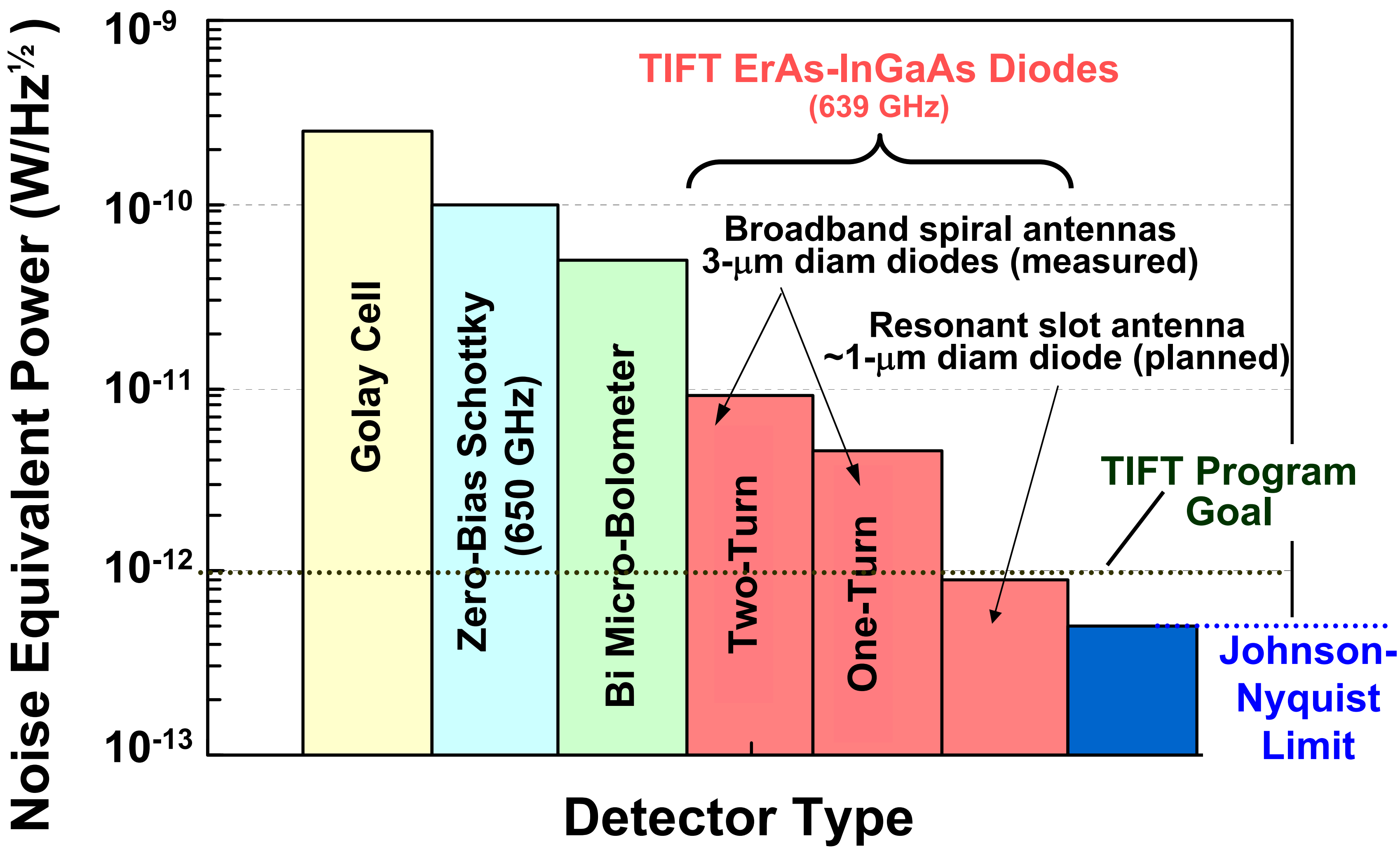
THz Micromachined Source



Phase I TIFT Power Goal Achieved



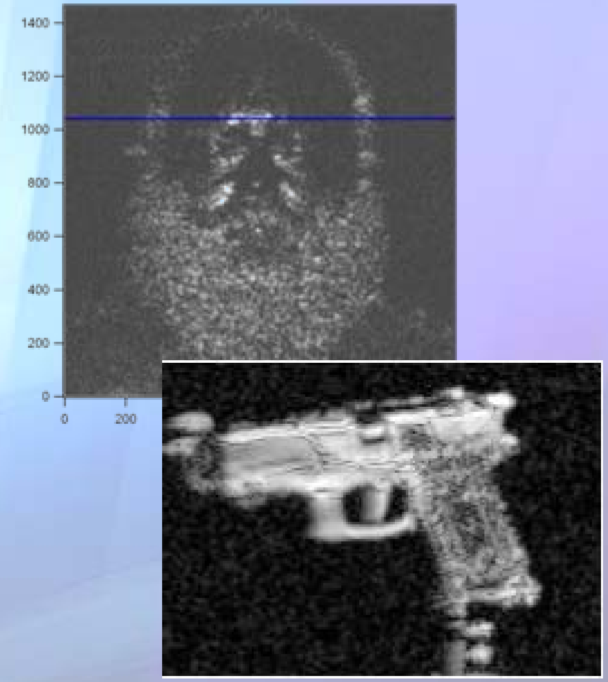
>600 GHz, 300K Direct Detectors



UCSB
ROCKWELL SCIENTIFIC

Summary

- THz is a tough neighborhood to live in
- THz imaging has significant promise for certain IR-blind environments
  - Aperture vs. range
- Component technologies are critical
  - Sources
  - Receivers
  - Integration
  - Architectures
- DARPA is actively supporting research in THz electronics



THz and Sub-MMW imaging may be the only possible solution to IR-blind imaging for many missions