Harnessing the Upper Portion of the Electromagnetic Spectrum for the Internet of Things

Bill Deal

Outline

- Introduction and Motivation
- High Frequency Technology Overview
- Existing Applications at Short Millimeter Wave and Submillimeter Wave
- Communications at Short Millimeter Wave and Submillimeter Wave
- Conclusion

Introduction

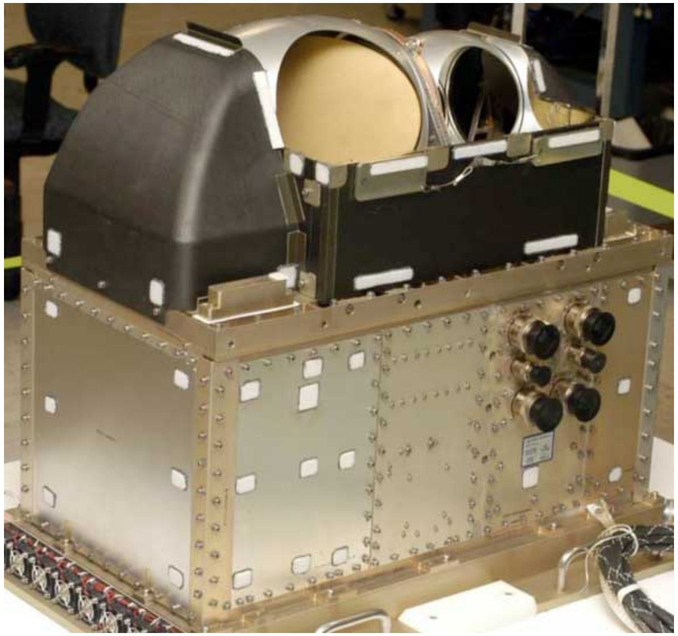
- The Internet of Things will need higher bandwidth and better connectivity
- Improvements in space technologies will be needed help to build a better backbone
  - High data-rate LEO-LEO Crosslinks
  - LEO-Aircraft Links
  - Air-to-Air Links
- Leveraging the upper portion of the millimeter wave spectrum may enable this

"First Demonstration of Amplification at 1 THz Using 25-nm InP High Electron Mobility Transistor Process" (IEEE EDL, 2015)

Introduction

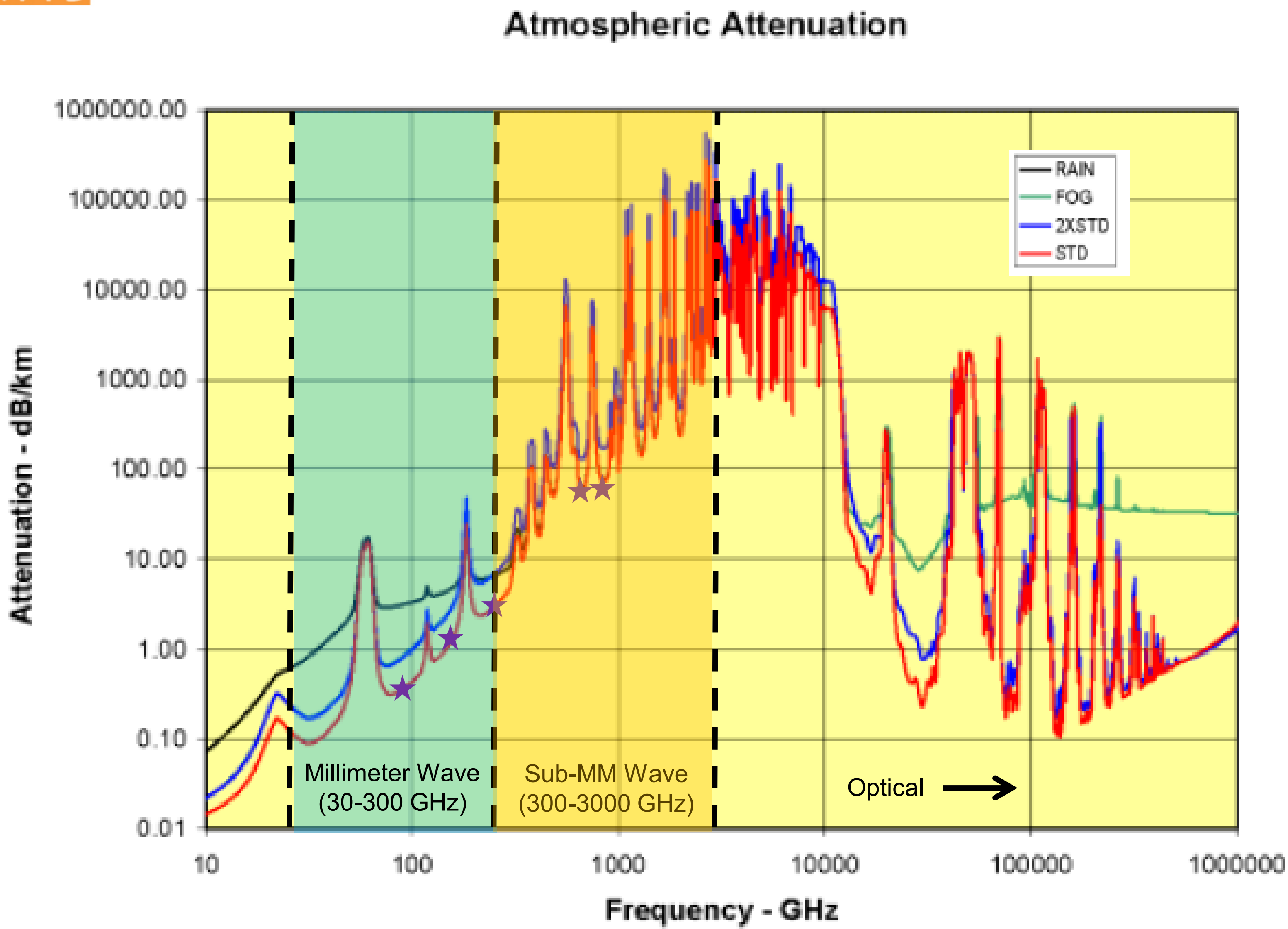
- Military / Science applications tend to pull technology
- Millimeter wave systems have existed in space for many years
- Today will be talking about technologies operating above 100 GHz, and technology "pulls"

mm-wave satcom



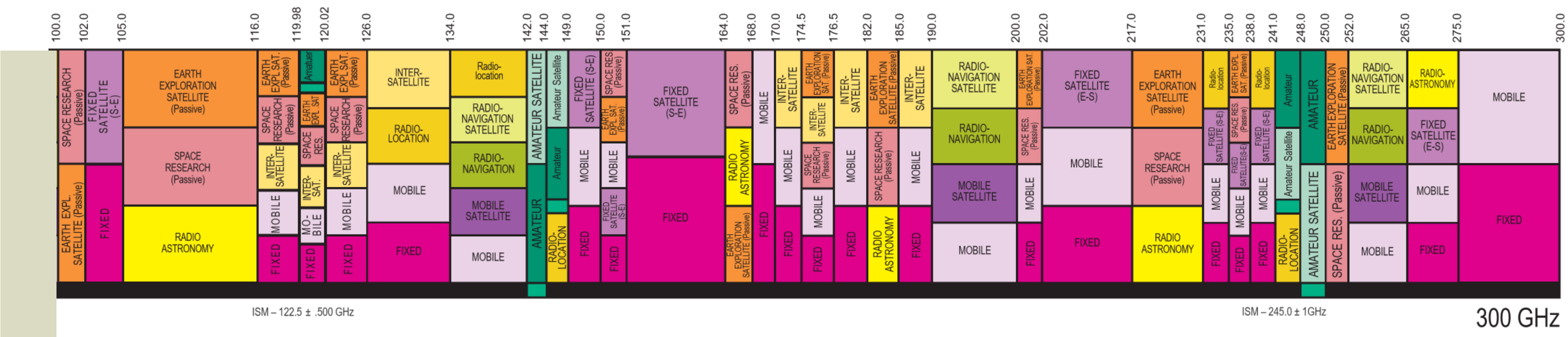
NOAA Advanced Technology Microwave Sounder 23-183 GHz

High Frequency Bands



Introduction

- Millimeter Wave Ranges from 30 – 300 GHz
- We usually think of the lower portion, but-----
- **The FCC has frequency allocations from 100 - 300 GHz!**



100 – 300 GHz Portion of FCC Allocation Chart

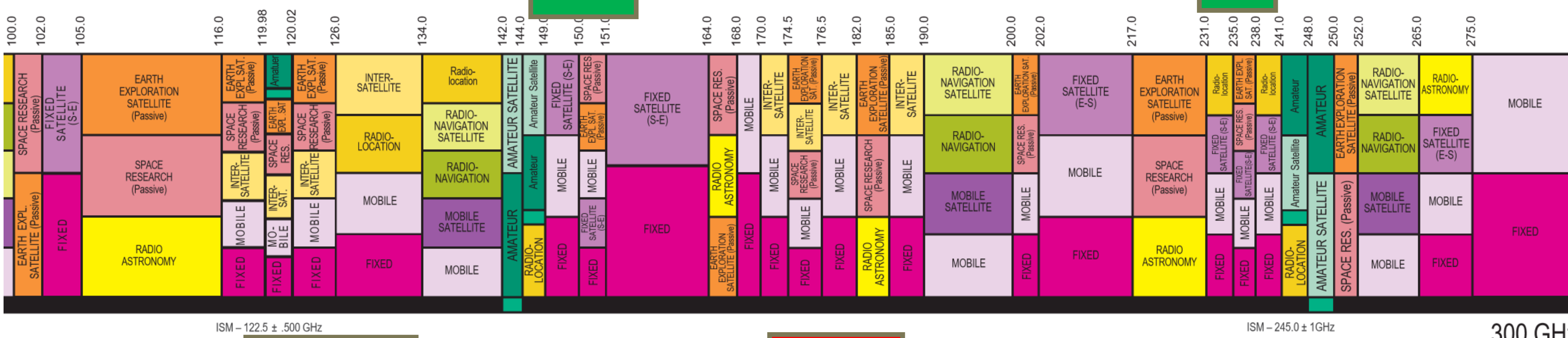
What Does this Mean for the IoT?

- Ground Based Point-to-Point Feasible
- *Maybe* Point-to-Multipoint with Si Phased Arrays and III-V Front-Ends

Atmospheric Windows

140 GHz

235 GHz



118 GHz

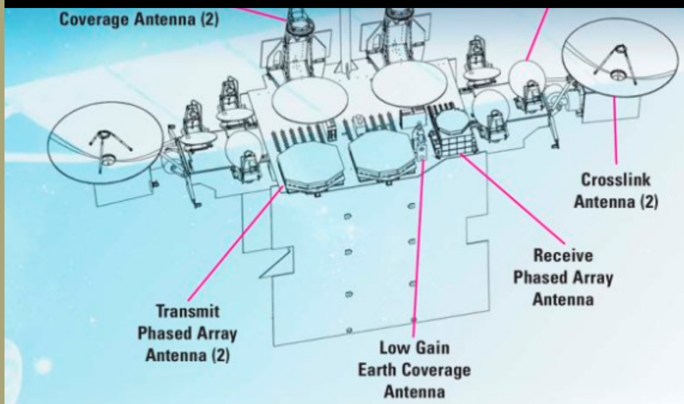
183 GHz

- LEO-to-LEO Crosslinks Possible
- High Data Rate Space to Upper Atmosphere may be possible

Absorption Lines

Out of the Atmosphere

MM-WAVE Crosslink

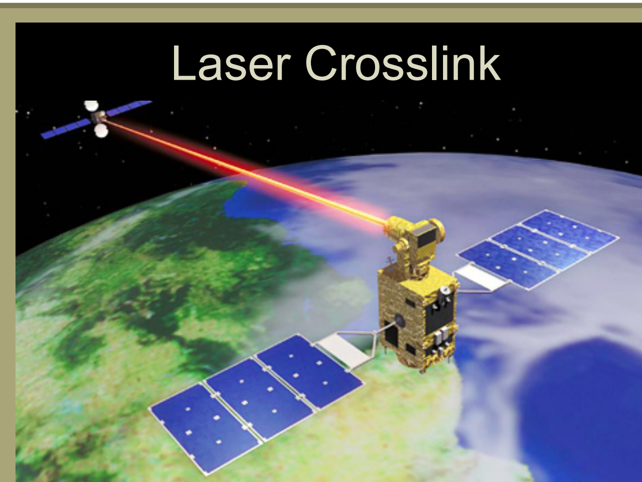


<u>MM-Wave Crosslink Benefit</u>:
- Robust, mature microwaves
- Well-understood pointing-and-tracking
- RF Comm infrastructure (backend, mod schemes)

<u>Disadvantage:</u>
- Large Aperture (6 ft for Satcom)
- Limited Bandwidth

<u>Laser Crosslink Benefit</u>:
- Smaller Aperture (wavelength)
- High instantaneous Bandwidth

<u>Disadvantage:</u>
- Maturity
- Modulation schemes
- Pointing-and-tracking



Wavelength Comparison for Leo-to-Leo Crosslink

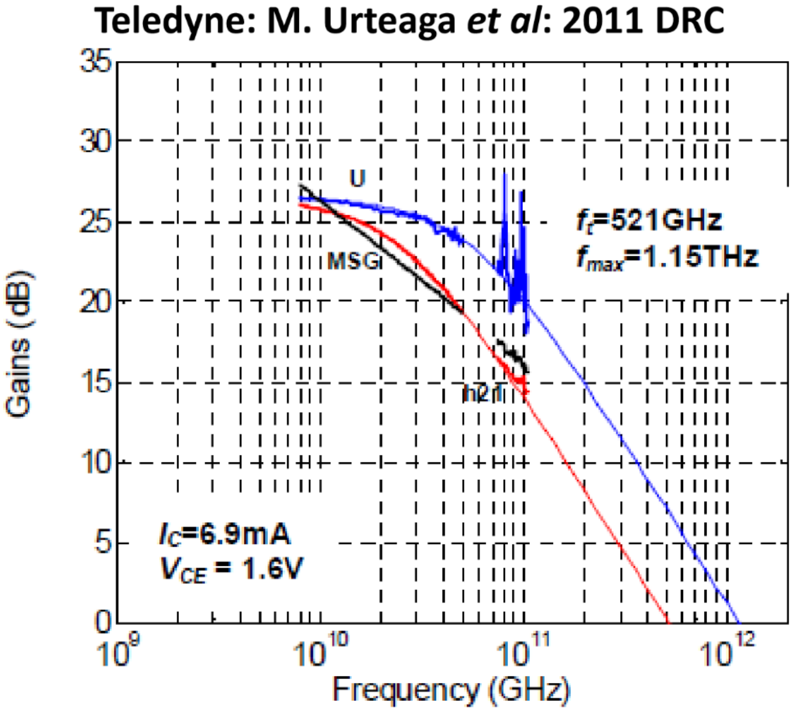
Metric	60-GHz	G-Band	Optical
Bandwidth	Moderate	High	Very High
Size Weight Power	Large Antenna Highest Highest	Moderate Antenna Medium Lowest w/ TWT	Small Aperture Lowest Medium
Pointing and Tracking	Easiest	Moderate	This is the hard part
Cost Now	Lowest, but large apertures make payload large (payload and launch costs)	High, but small apertures will fit on small satellite	Most components are cheap, but pointing and tracking makes it expensive
Cost at Volume	Hard to get around aperture and payload size	Similar technology and manufacturing as microwave	Should be cheap if pointing-and-tracking can be addressed
Maturity	High	Low, ground based demos	Moderate

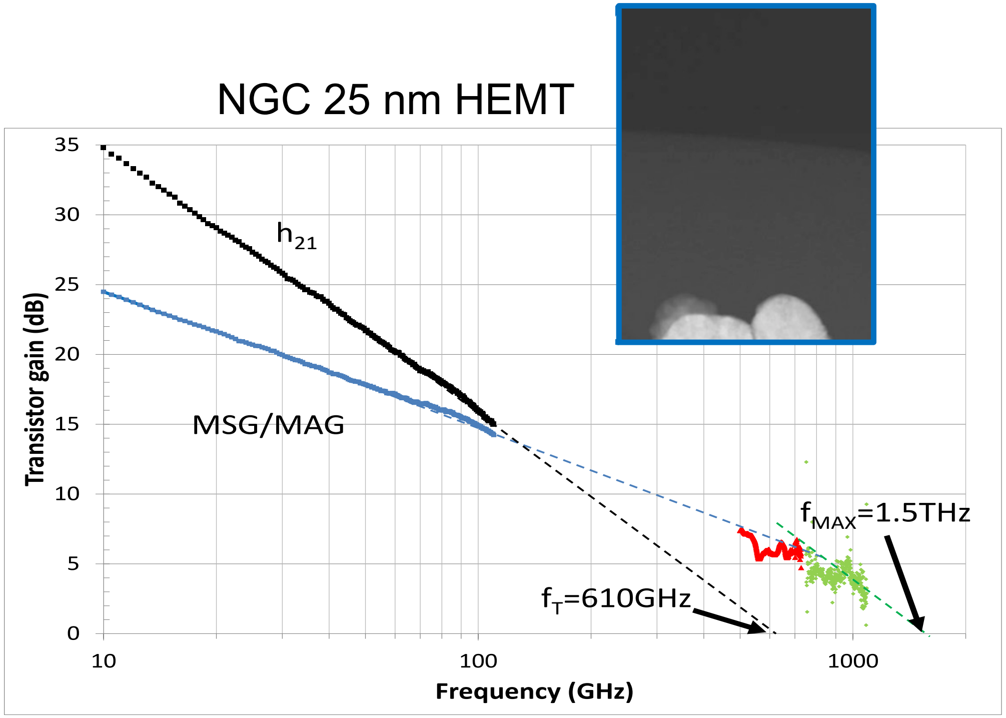
High Frequency Application Matrix

	Description	Application Maturity	Frequencies of Interest	Customer Base
Radioastronomy	Radio-telescopes look deep into space	• Mature • Cryogenic SIS receivers		Science
Atmospheric Sensing	Monitor weather patterns from space	• Well-established • GaAs Schottky receivers • LNA based below 118 GHz	• 118 GHz, O2 • 183 GHz, H2O • 325 GHz, H2O • 380 GHz, H20 • 425 GHz, O2 • 474 GHz, H20 • 488 GHz, H20 • 556 GHz, H20 • 620 GHz, H20	Civil/DoD/Science
Imaging/Security	• Use SMMW to "image" concealed weapons • Better resolution, and stand-off imaging	• Successful demonstrations have been performed in industry/academia	• 140 GHz • 235 GHz • 340 GHz • 670 GHz	Civil/DoD
Point-to-Point Communications	• Take advantage of large instantaneous bandwidth for broadband point-to-point link	• Successful demonstrations at 140, 220, 340 GHz	• 140 GHz • 235 GHz • 340 GHz • 670 GHz	Civil/DoD/ Commercial
Wireless Communications	• THz WiFi would enable massive instantaneous bandwidth	• Initial Demonstrations	• 140 GHz • 235 GHz • 340 GHz • 670 GHz	Commercial/ Consumer
Chemical Spectroscopy	• Use SMMW "signatures" to detect explosives or biological weapons	• Demonstrations	• Depends on the chemical sample "Smearing" of signature is hurdle	Civil/DoD
Medical	• Use THz radiation to treat medical conditions	• Demonstrated on tissue samples	• 670 GHz	Commercial

InP Terahertz Transistors

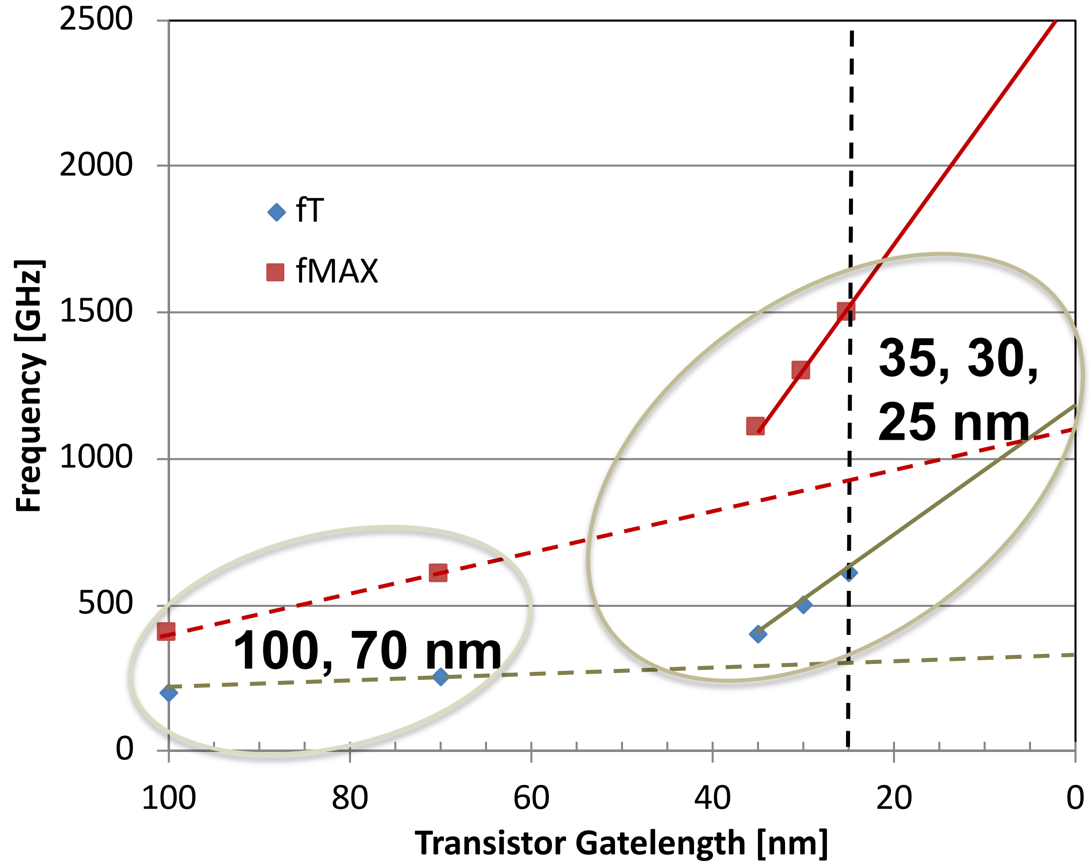
- Both InP HBT and HEMT have pushed past 1 THz fMAX





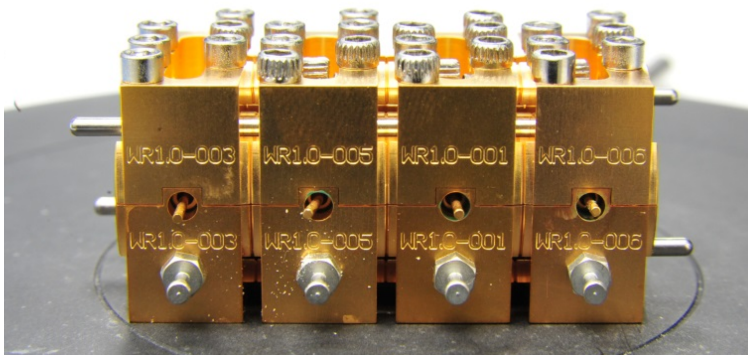
THz InP HEMT Scaling

- Transistor speed improvements come from:
  - Gate scaling
  - Channel design
  - Device design
- Significant benefits come from channel and device design
- Device continues to scale nicely
- Upward f_{MAX} limit not yet reached.

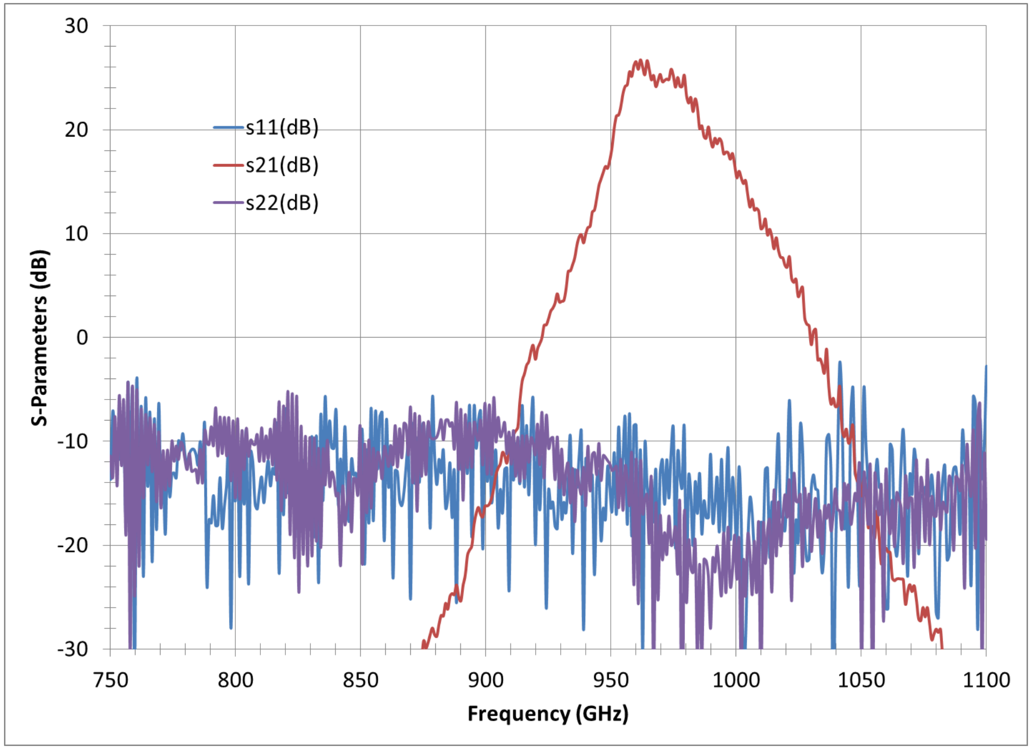


Cascaded 1 THz Amplifiers

- Cascaded four amplifiers together
- Measured 16 dB gain @ THz
- Measured 25 dB gain @976 GHz

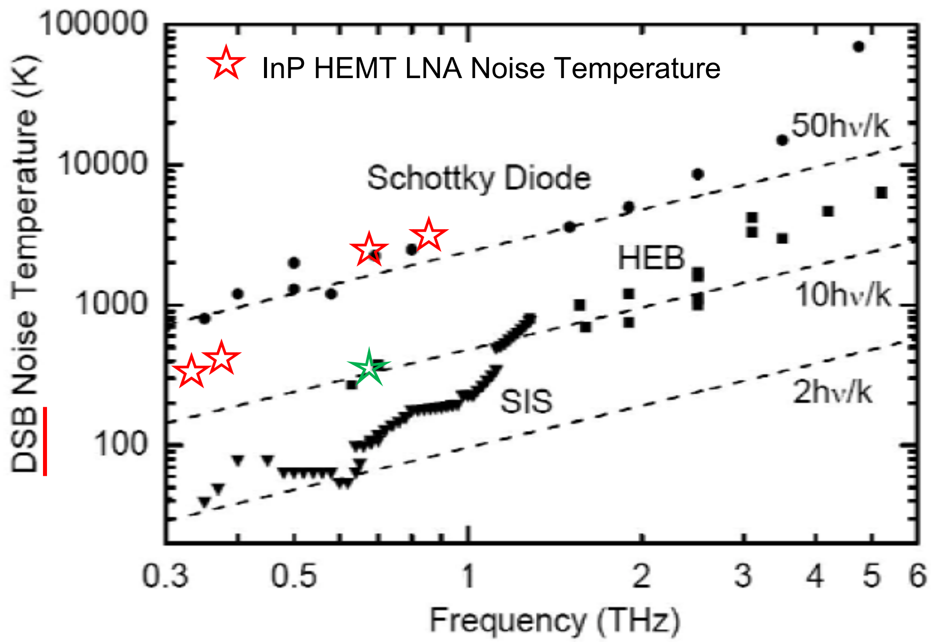


Measured S-parameters



LNA Benchmarks

Mixer DSB Noise Performance



Q: How Do InP HEMT LNA-based Front Ends Compare to Mixer-based Front Ends?

- **InP HEMT LNA sensitivity approaches that of DSB mixers.**
- **InP HEMT LNA is superior to that of mixers operated in SSB mode.**
- **This extends to cryogenic operation.**

SOA

	Ambient Temperature [K]	Noise Figure [dB]	Noise Temperature [K]
HEMT	270 25	9.6 3.8	2355 400
GaAs Schottky	270	9.4 DSB (12.4 SSB*)	2236 DSB (4750 SSB*)
HEB	Cryo	2.7 DSB (5.7 SSB*)	250 DSB (788 SSB*)
SIS	4	1.3 DSB (4.3 SSB*)	100 DSB (491 SSB*)

SOA

	Ambient Temperature [K]	Noise Figure [dB]	Noise Temperature [K]
HEMT	270	12	3361
GaAs Schottky	270	9.8 DSB (12.8 SSB*)	DSB 2500 (5236 SSB*)

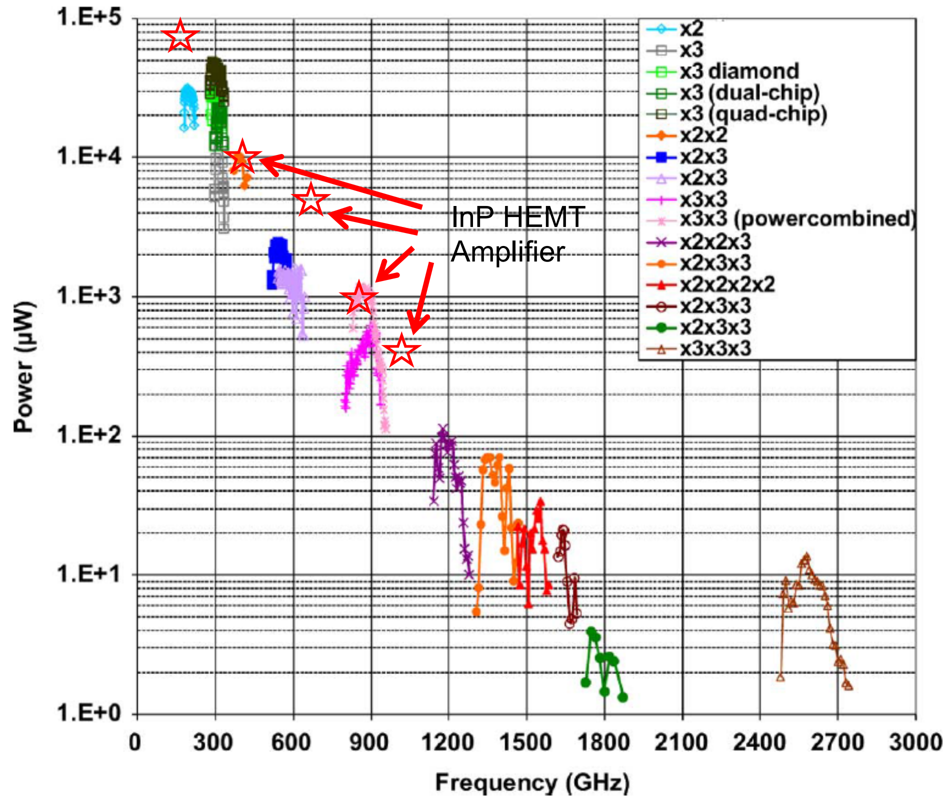
*Performance estimated from plot. SSB is calculated from DSB by adding 3 dB

How Good are THz PA's?

Q: How Do InP HEMT PA's Compare to SOA?

- InP HEMT PA Output Power is higher than GaAs Schottky Multiplier output at room temperature.
- Multiplier results includes power combining
- DC efficiency is also significantly improved with power amplification

Room Temperature Multiplier Performance



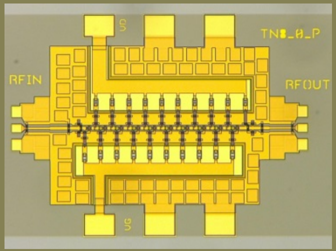
Technology Overview

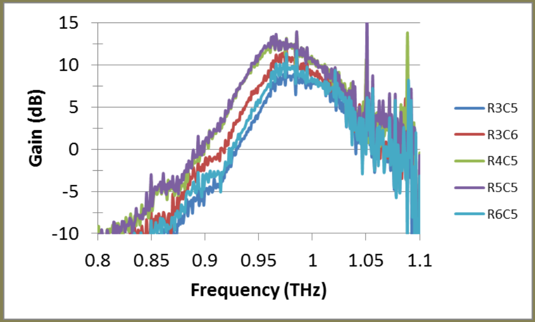
Amplifiers demonstrated to 1 THz

25 nm InP HEMT

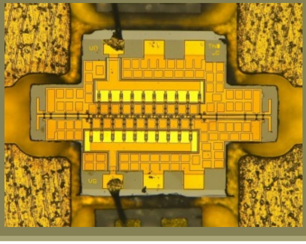
1.5 THz fMAX

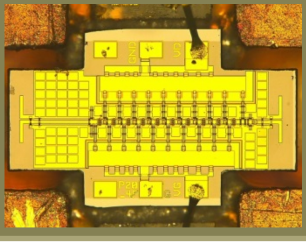
0.7 THz fT

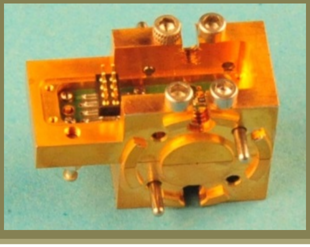




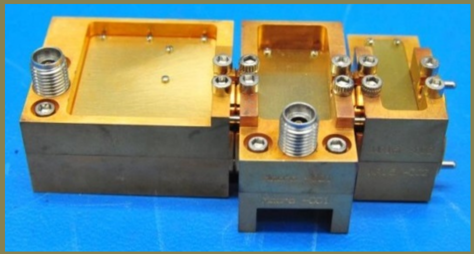
InP Integrated Circuits are Progressing Rapidly





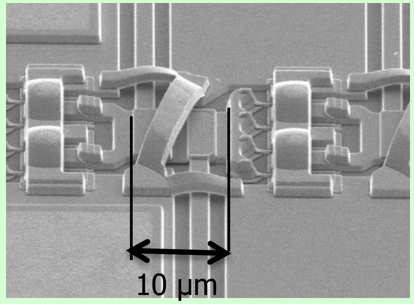


Receivers and Transmitters Demonstrated to 850 GHz

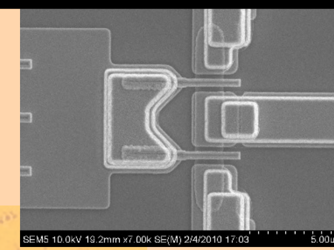


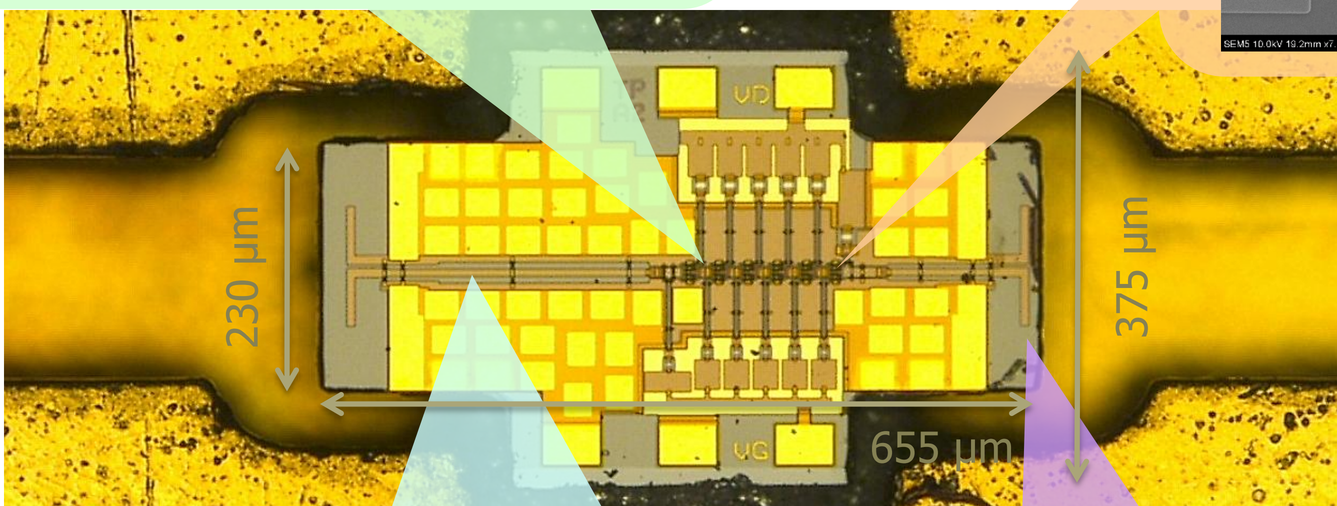
Packaging Approach

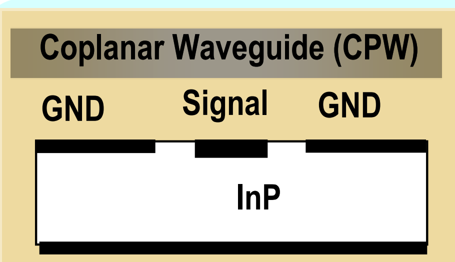
Passive TMIC Technology:
High compaction.
HEMT to HEMT spacing of 10 µm.

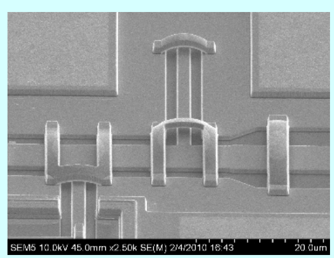


- Transistor Technology:
- 25 nm InP HEMT

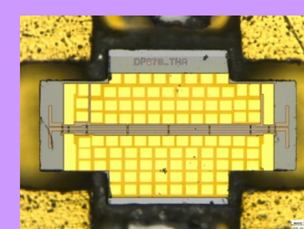








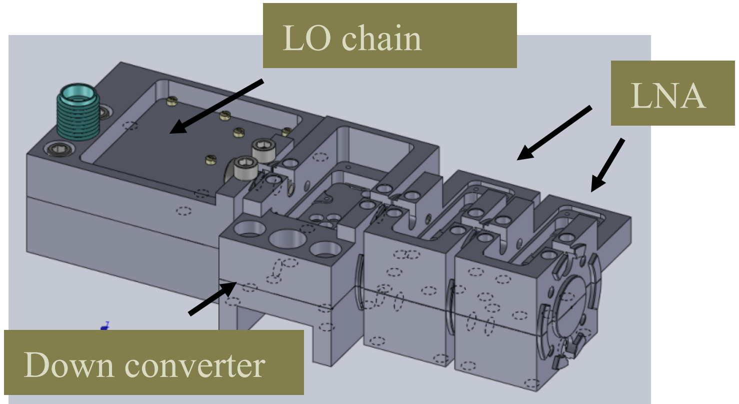
•Integration Challenges:
•Need wide chip for circuit, but narrow for transition
•Cross-shaped chip



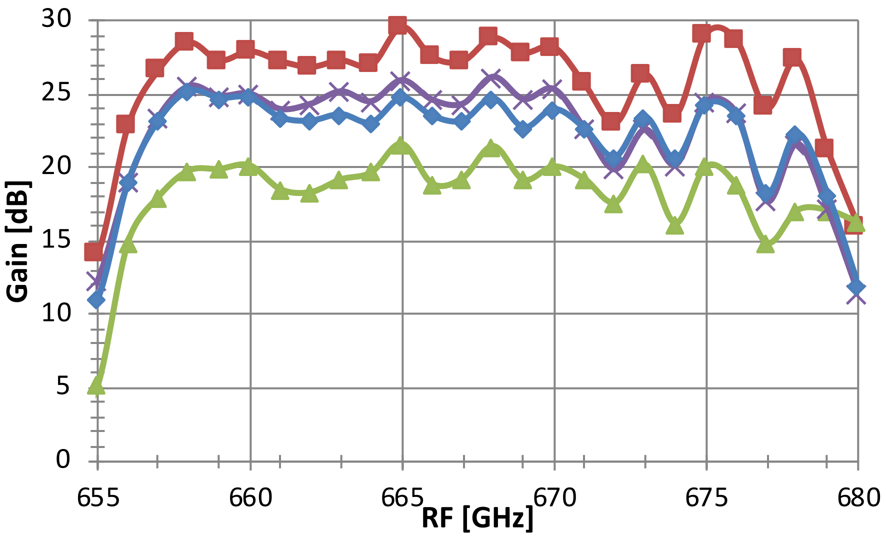
Approved for Public Release; Distribution Unlimited. DISTAR 28851; NGAS Case 17-2377

670 GHz Receiver Data

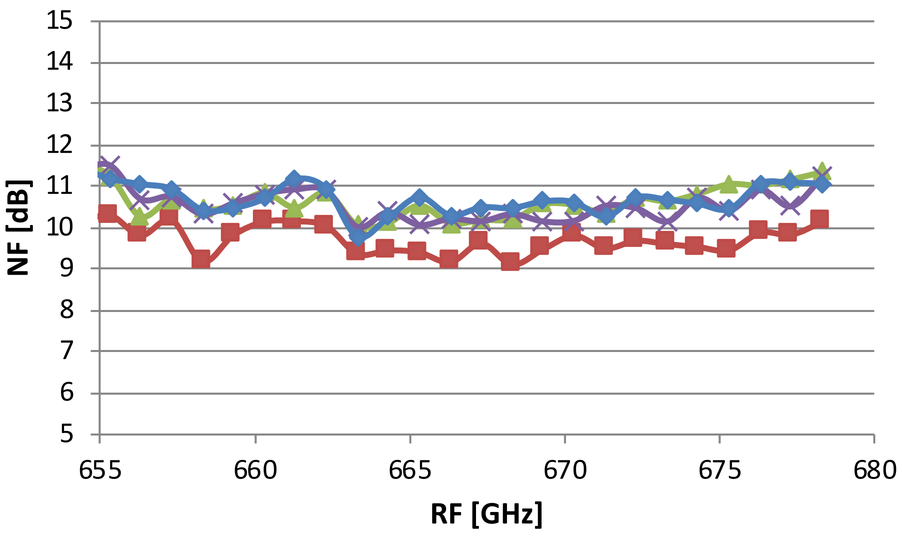
- ~25 dB Gain and 10 dB NF
- Bandwidth ~ 20 GHz
- Limited by IF mixer bandwidth



Measured Gain

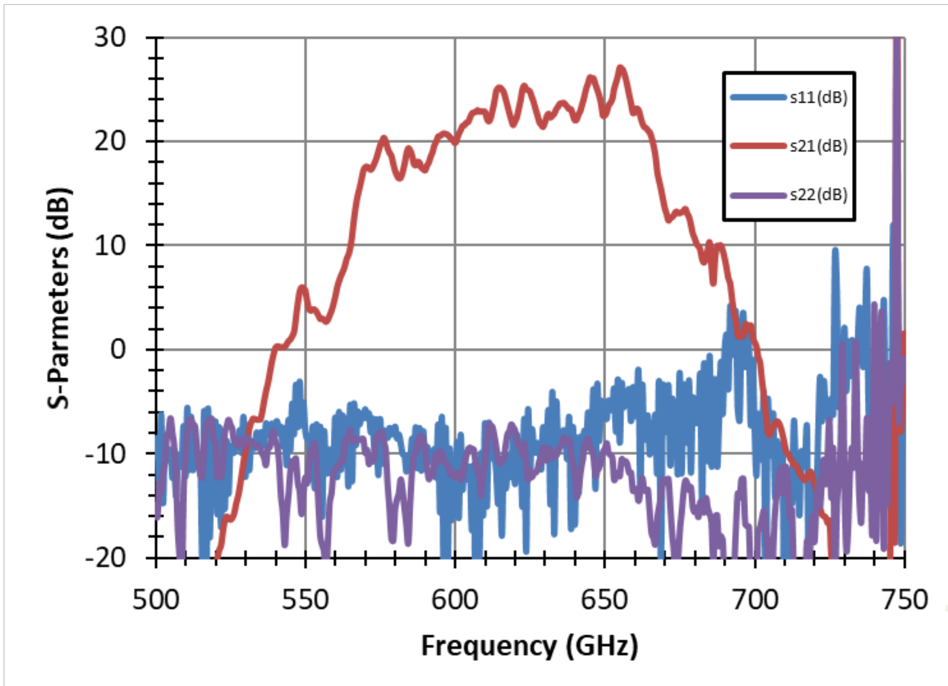


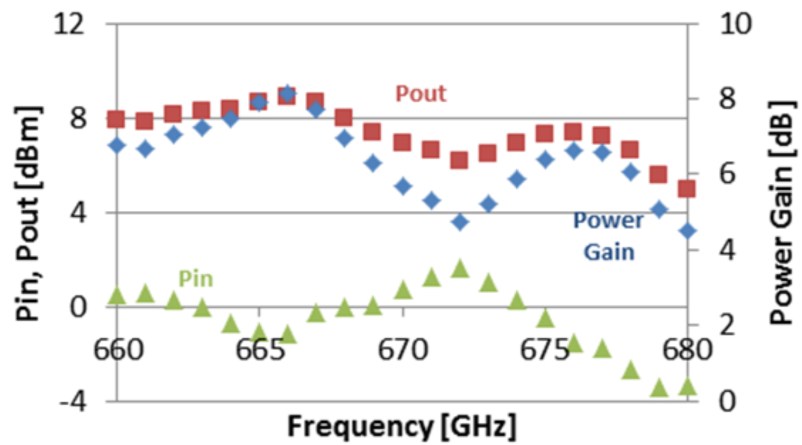
Measured Noise Figure

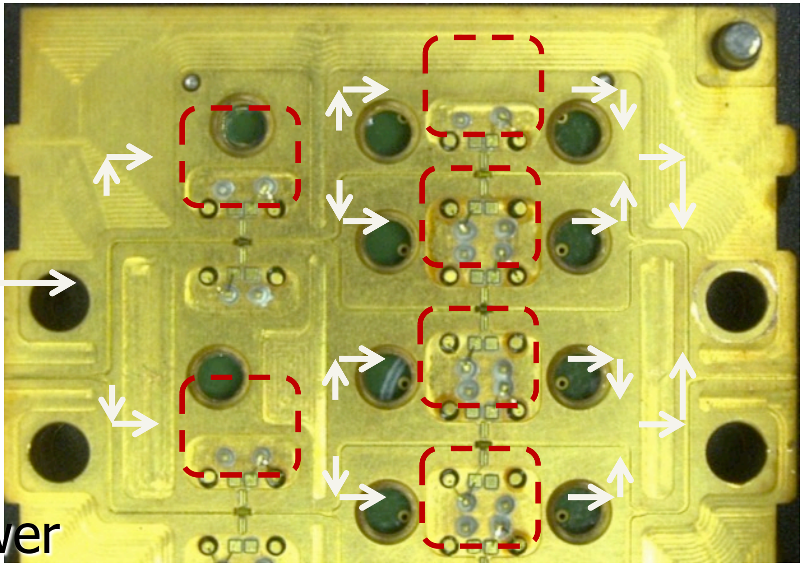


Combined Power Amplifier Results

Measured S-Parameters







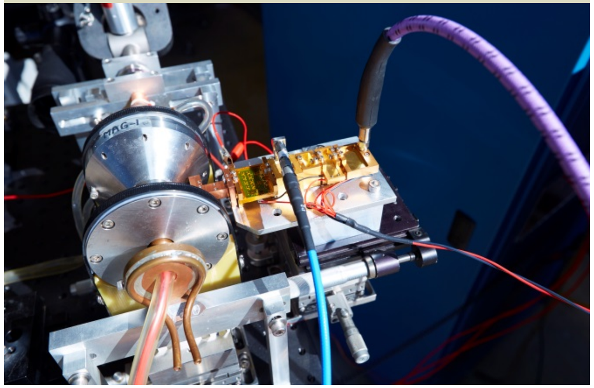
- Combined 6 PA TMICs (2 driving 4)
- Meets requirement of 6 dBm (4 mW)
- 8.9 dBm (7.8 mW) maximum output power

7.8 mW Peak Power at 665 GHz with InP HEMT

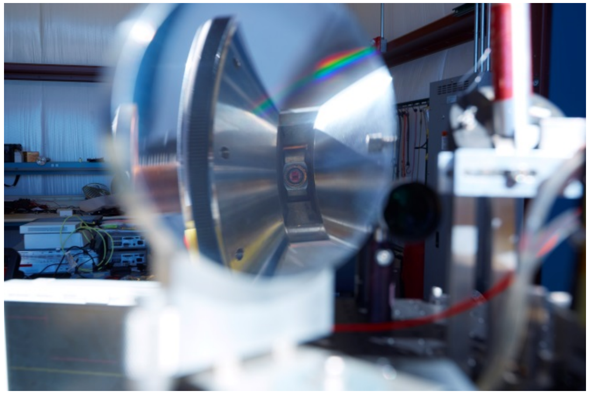
TWT (NGC, Rolling Meadows)

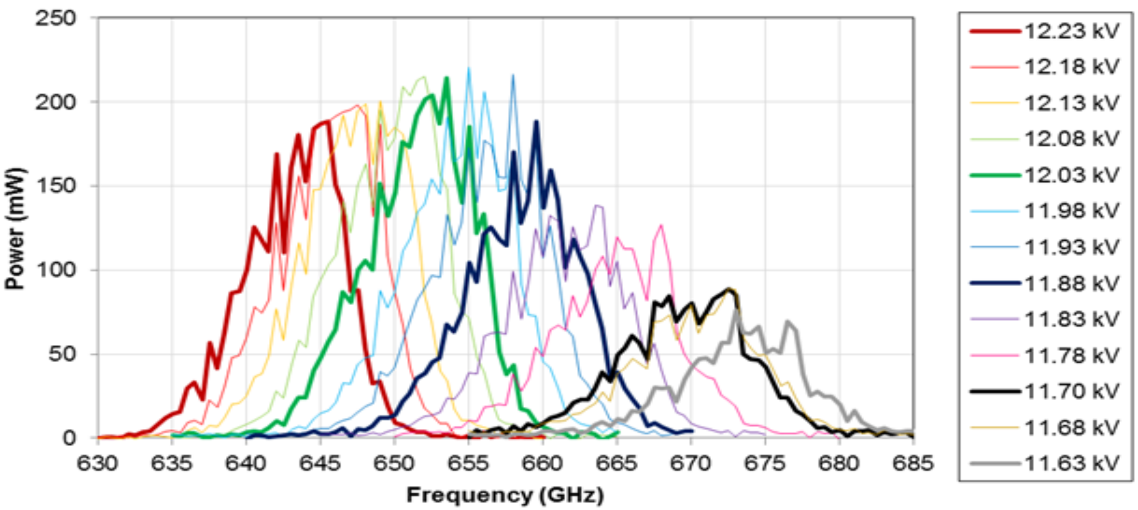
- Peak power of 200 mW
- >100 mW available at demo frequency (666 GHz)
- Tuneable with voltage
- Integrated with frequency converter (exciter and SSPA) and 10 cm reflector

TWT with exciter

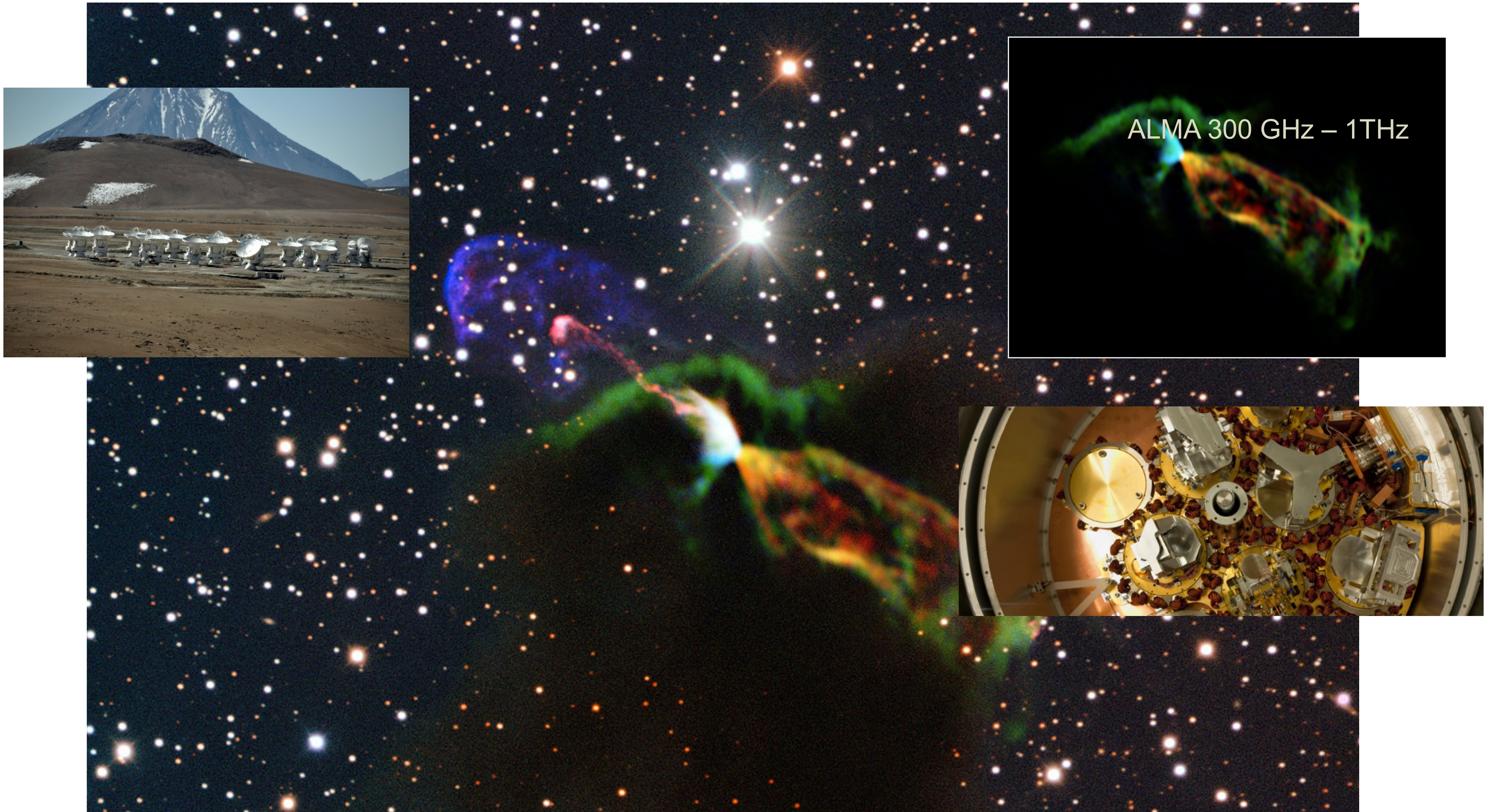


Reflector and Window





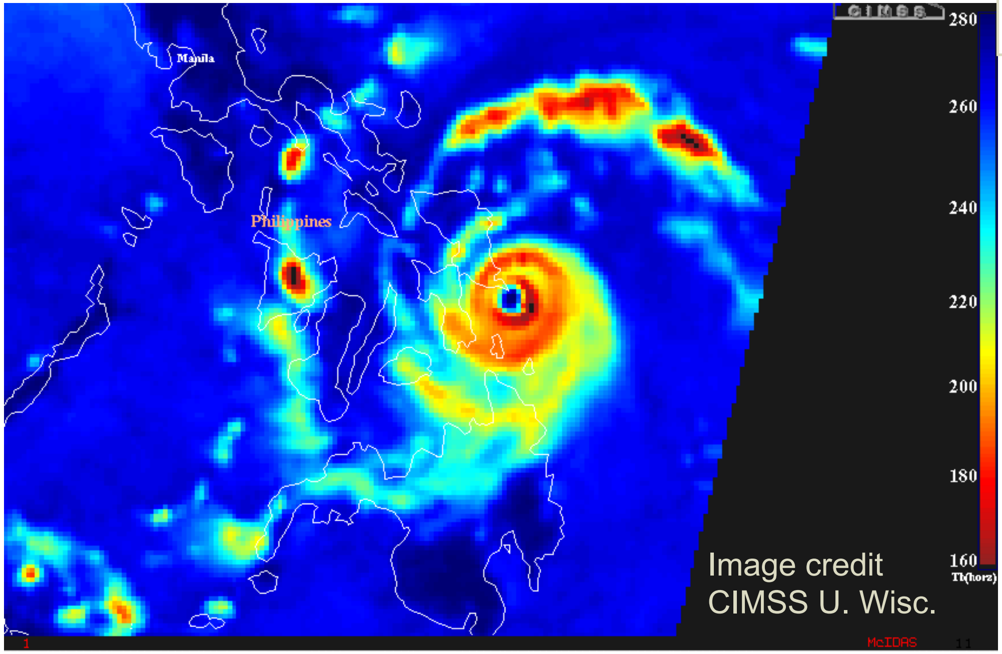
"Traditional" Applications: Radioastronomy



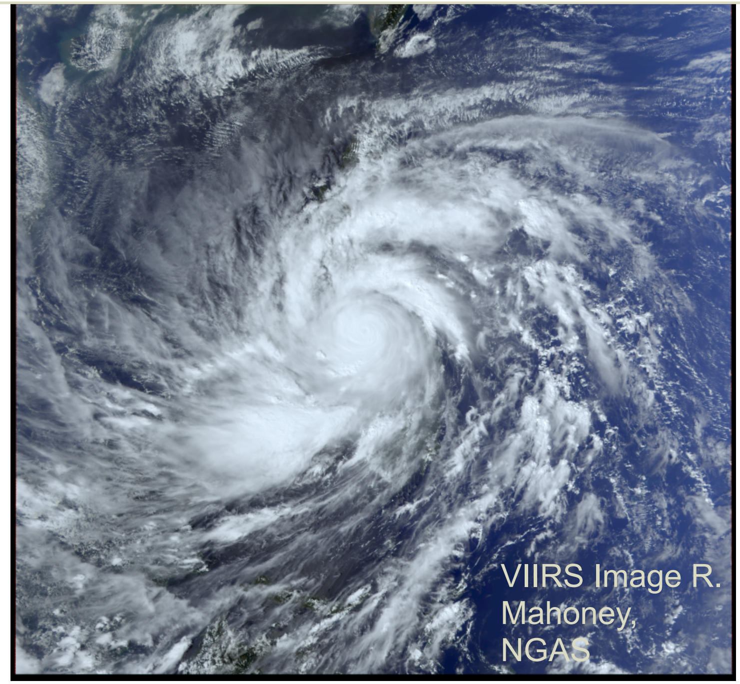
Astronomers using ALMA have obtained close-up view of material streaming away from a newborn star by looking at the glow coming from carbon monoxide molecules in an object called Herbig-Haro 46/47

“Traditional” Applications: Weather Forecasting and Earth Science

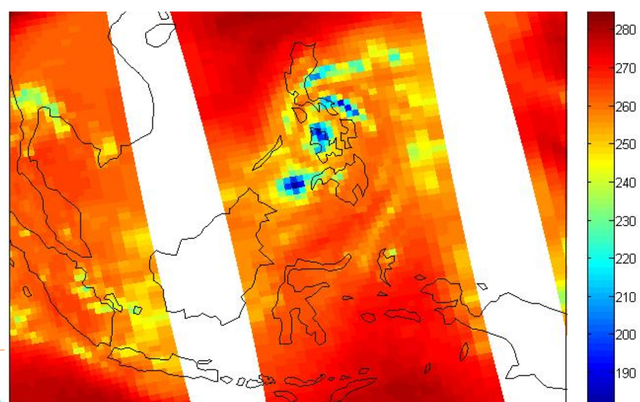
SSMIS, 85 GHz Brightness Temperature Channel Sensitive to Temperature

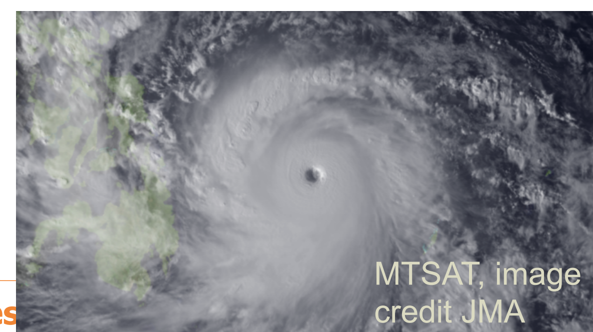


Microwave sensor measures the warm eye (region of subsidence), eye walls and rain bands in the hurricane cold core



ATMS, 183 GHz Brightness Temperature Channel Sensitive to Moisture



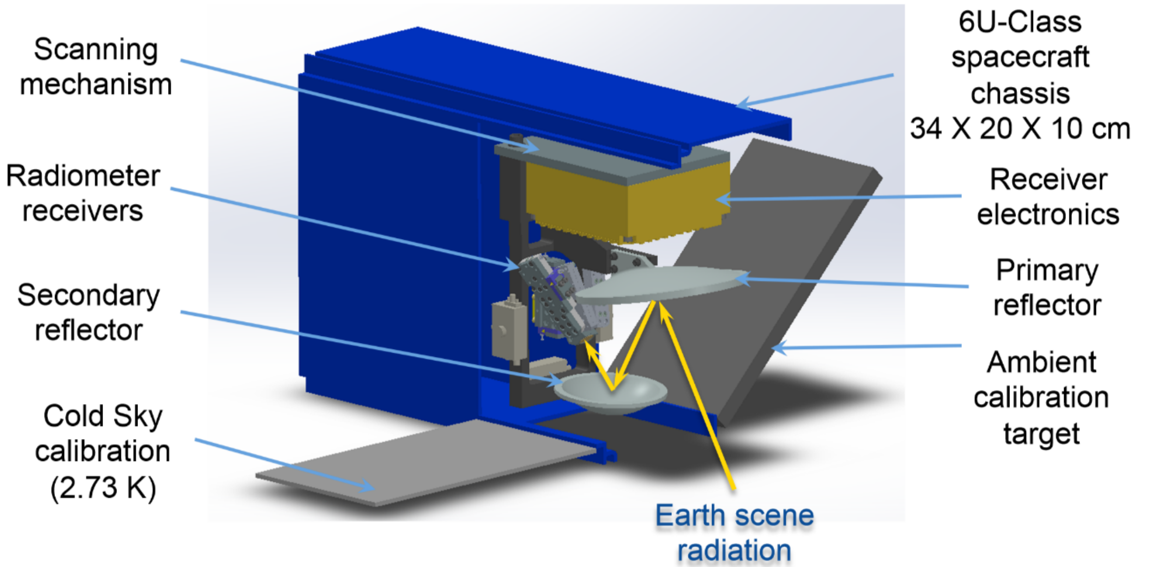


TWICE

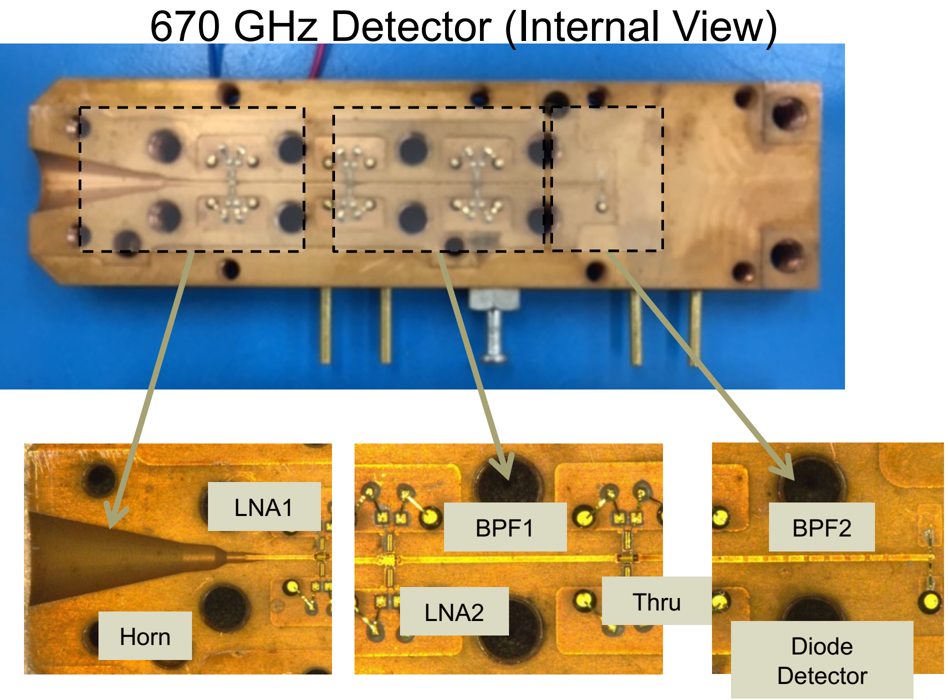
- "TWICE" is funded by NASA ESTO
  - CSU (Steve Reising, PI)
  - JPL and Northrop
- Multi-band radiometer in 6U CubeSat payload

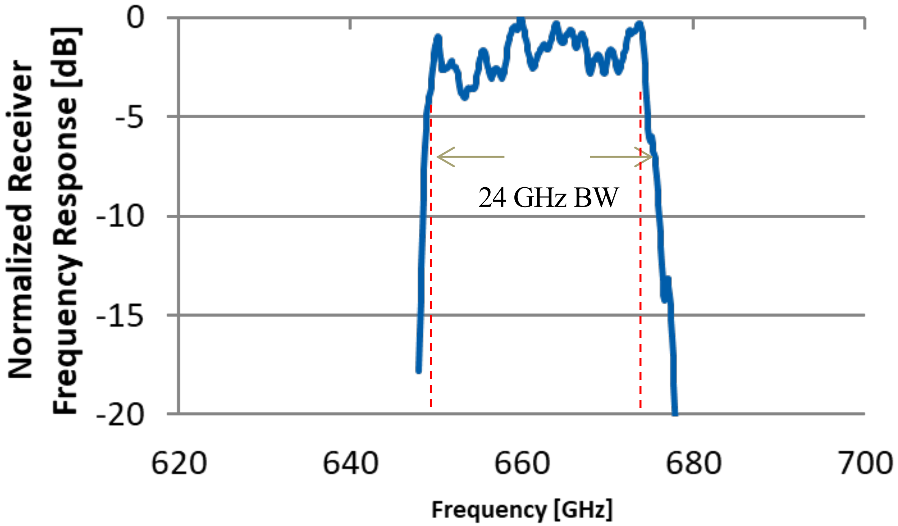
Subsystem	Mass (kg)	Power (W)
118-183 GHz Sounder	0.55	4.53
240 GHz & 310 GHz Radiometers	0.1	0.35
380 GHz Sounder	0.3	2.31
670 GHz Radiometers (H&V)	0.09	0.54
Back-end Board	0.13	0.73
Power Regulation Board	0.13	3.00
Optics	0.40	-
Calibration Target/Reflector	0.71	-
Scanning Motor	0.33	1.00
Totals	**2.74**	**12.46**

- Three frequency bands in one Gregorian quasi-optical subsystem
- Conical scanning with 9.5-cm primary reflector
- Cold sky and ambient target calibration each scan (60 rpm)



TWICE 670 GHz Receiver





- Small receiver with ~220 mW DC Power Consumption
- 11.7 dB noise figure
- Direct detection
- Chopped to mitigate 1/f noise

THz Communications

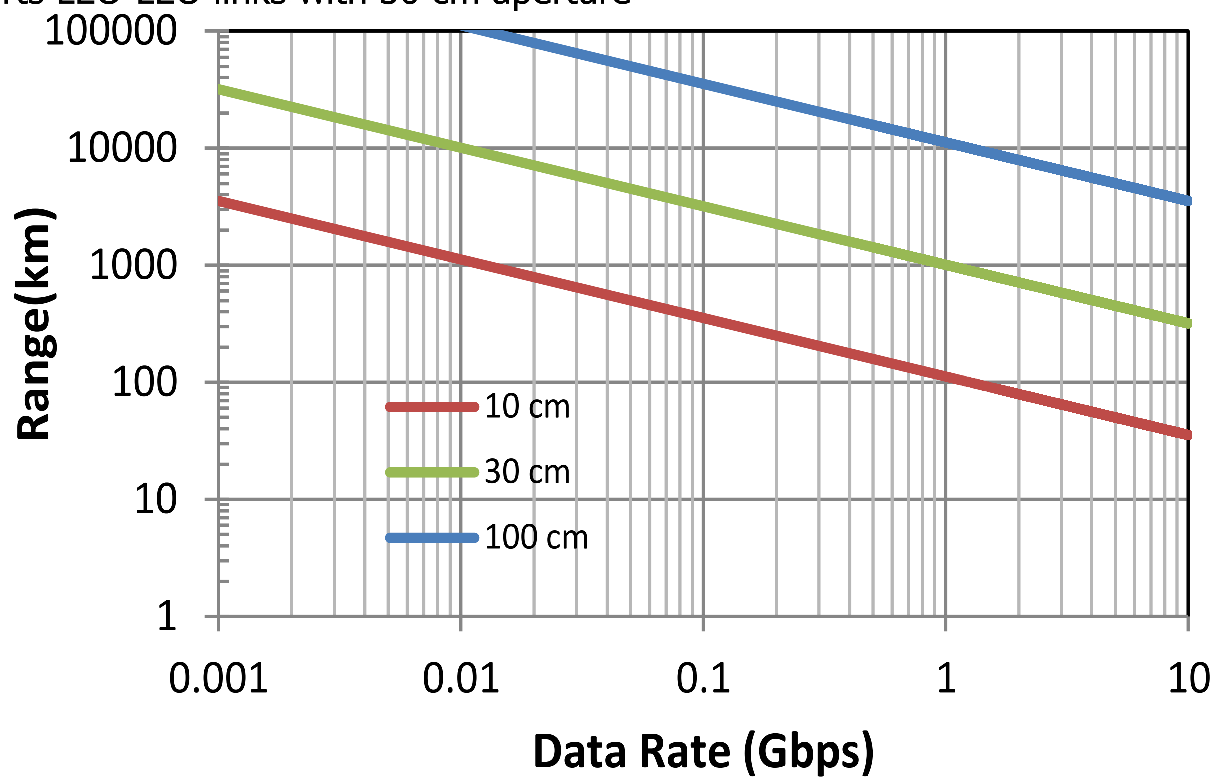
- 60 GHz is typical RF crosslink frequency (oxygen)
- Could scale to 190 GHz (water)
- But, how far could we go?
- Could we scale by 10x?

$\frac{P_{rec}}{P_{tran}} = G_{tran} * Grec * (\lambda/4\pi r)^2$	Friis Transmission Formula
$G \propto \left(\frac{d}{\lambda}\right)^2$	Small Wavelength
T_{rec} ~1/f	Sensitivity Degrades
P_{trans} ~(1/f)^3	Power Drops Quickly

What would it take to do a 670 GHz Link?

Link Calculations

- Terahertz high data rate communications now proven at short range in atmosphere
- Satellite crosslinks may be ideal application for this technology
  - Low probability of intercept
  - Supports high level modulation rates
  - Supports LEO-LEO links with 30 cm aperture

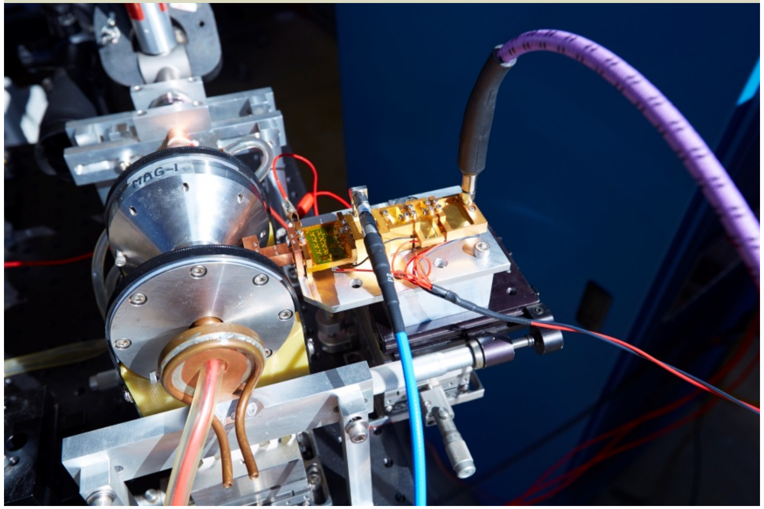


THz Data Link Overview

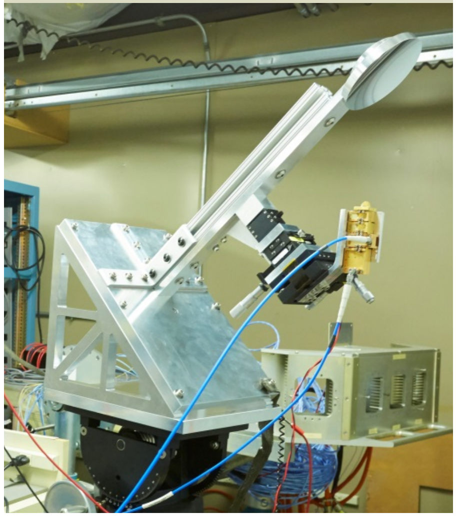
- Demo took place in Rolling Meadows, Illinois
- Week of March 33rd 2017
- Two Demos:
  - "Short Range": 250 M
  - "Long Range": 600 M

100 G Modulator

THz Electronics TX (with TWT)



RX with Reflector



Ground Based Link Projections

Parameter		Unit	Notes
Transmit Frequency	666	GHz	
Modulation & Coding	16-APSK r=7/8		
Data Rate	25	Gb/s	
Net Transmit Power	20	dBm	
Backoff	-1.8	dB	
Losses	-1	dB	
Net Transmit Gain	55.9	dBi	
Aperture Diameter	10.00	cm	
Pointing Loss	-0.5	dB	
EIRP	**75.6**	**dBmi**	
Path Loss	-144.5	dB	
Range	600.0	m	Long range test
Atm Loss	-5.8	dB	15% humidity
Total Channel Losses	-150	dB	
RSSI	**-74.6**	**dBmi**	
Net Receive Gain	54.9	dBi	
Aperture Diameter	10.00	cm	
Pointing Loss	-0.5	dB	
Circuit Loss	-1	dB	
Received Signal Power	-20.2	dBm	
Noise Temperature	3238.3	K	
LNA NF	10.5	dB	
Earth+Sky Contribution	191.0	K	
LNA+Backend Rx	2975.7	K	
Net G/T	**19.8**	**dB/K**	
Available Eb/No	**41.3**	**dB**	
Net Req'd Eb/No	**11.4**	**dB**	
Ideal Reqd Avg Eb/No	6.4	dB	
Implementation Loss	-5	dB	
Link Margin	**30.0**	dB	

- **Original link budget booked -61 dB/km for gaseous atmospheric losses based on ITU reference standard atmosphere**
- **Weather measurements taken during testing predicted a loss of -9.6 dB/km due to favorably low humidity**
  - **22% during demo, 15% during long range testing**

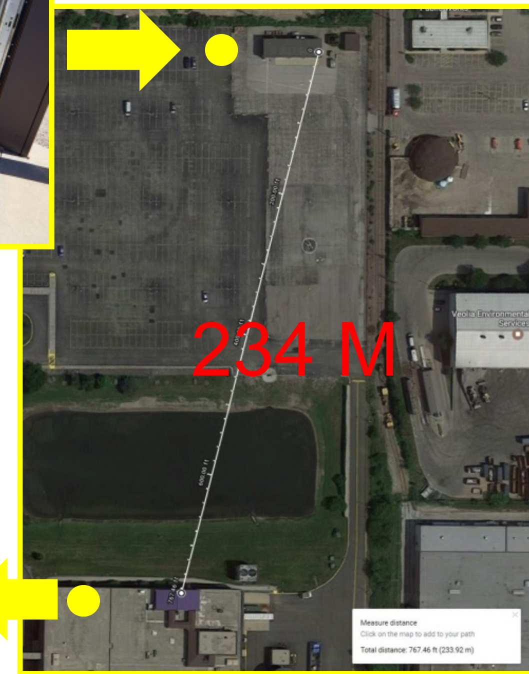
Weather Station

Demo Overview (Short range)

Link Details:

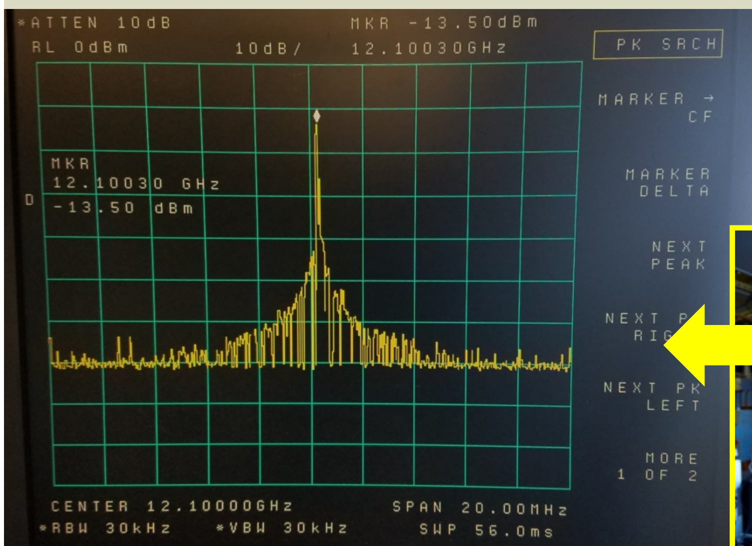
- **234 M Range**
- **Receiver initially saturated**
- **Rotated receive horn by 90 degrees to receive Cross-Polarization and reduce receive power**

TX



RX

CW Mode Receiver Output*

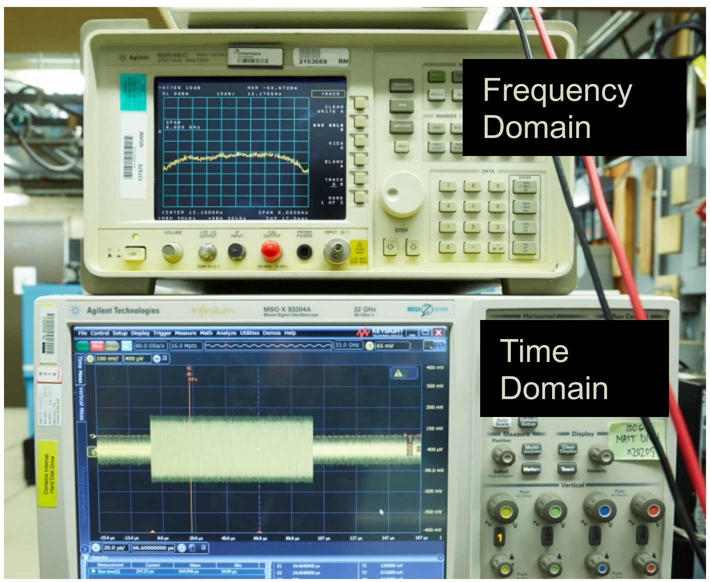


*Note that TWT is operated in pulsed mode

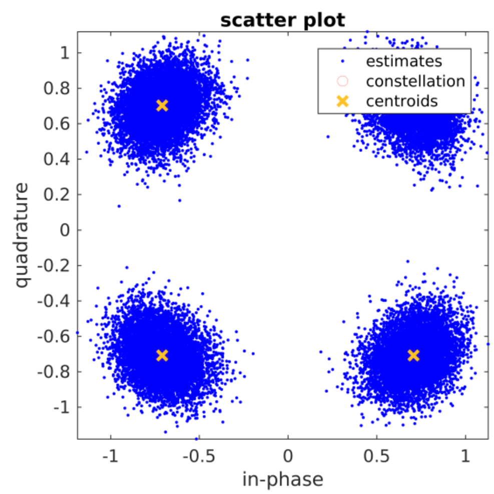
Results (Short Range)

- Successfully received and demodulated QPSK and 16-APSK

Received Waveform

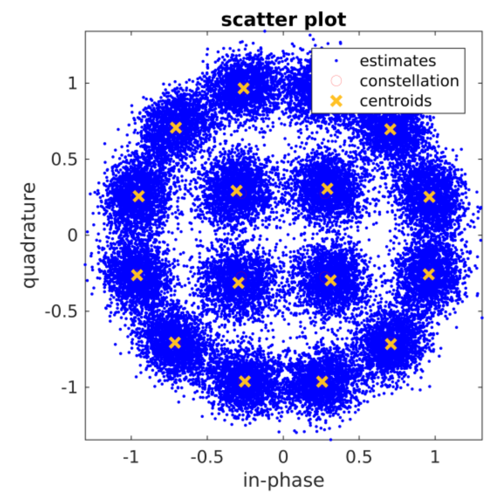


QPSK



EVM: 17.6%

16-APSK



EVM: 19.1%

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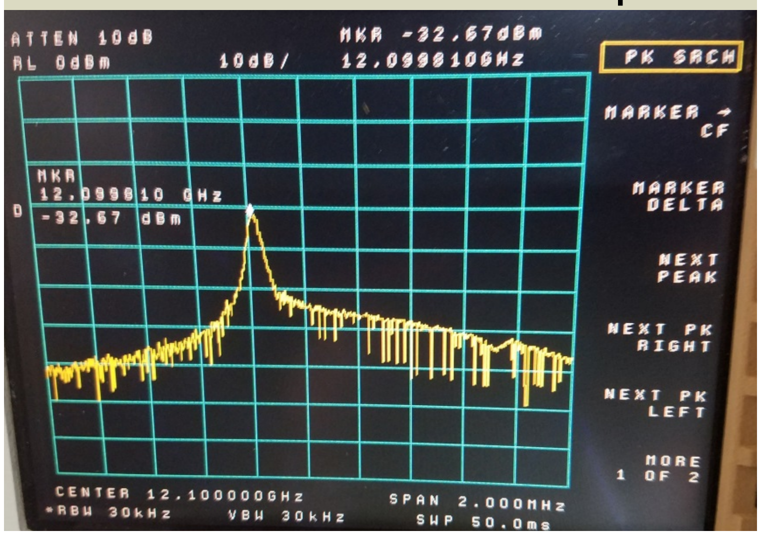
Long Range Results

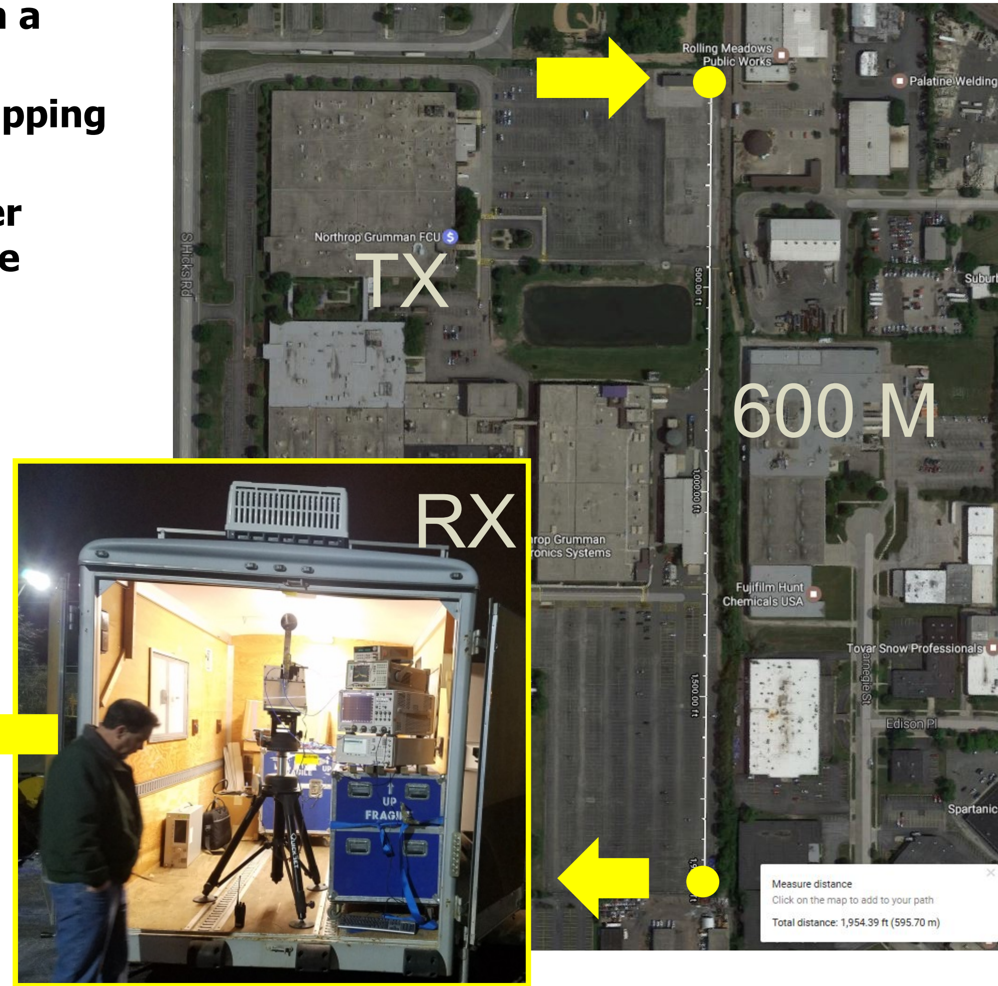
Link Details:

- **600 M Range**
- **Receive and Transmit each deployed in a trailer**
- **Received power ~ 20 dB lower after flipping polarization of horn to Co-Polarization**
- **Note transmit mixer was swapped after power outage due to component failure**

CW Mode Receiver Output*



*Note that TWT is operated in pulsed mode



Conclusion

- Technology capable of operating above 100 GHz has improved significantly over last 20 years
- InP technology could be useful for the backbone of the Internet of Things
  - Gbps class Leo-Leo crosslink
  - Air-to-Air crosslinks
  - Air-to-space crosslink
- Other (demonstrated) backbone applications include high data rate point-to-point in the 100-300 GHz range