National Aeronautics and
Space Administration

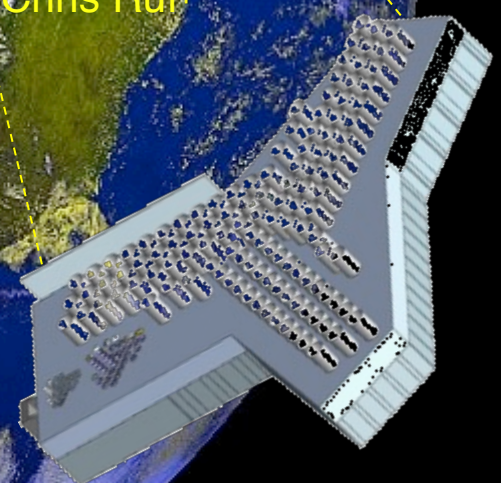
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Enabling the NASA Decadal-Survey "PATH" mission concept

Bjorn Lambrigtsen

Todd Gaier, Pekka Kangaslahti, Boon Lim, Alan Tanner, Chris Ruf†

*Jet Propulsion Laboratory
California Institute of Technology
† University of Michigan



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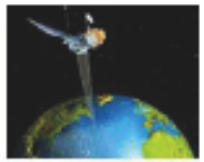
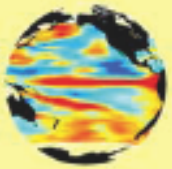
Decadal survey: PATH mission concept

Decadal Survey Mission	Mission Description	Orbit	Instruments	Rough Cost Estimate
Timeframe 2010 – 2013, Missions listed by cost				
CLARREO (NASA portion)	Solar radiation: spectrally resolved forcing and response of the climate system	LEO, Precessing	Absolute, spectrally-resolved interferometer	$200 M
SMAP	Soil moisture and freeze/thaw for weather and water cycle processes	LEO, SSO	L-band radar L-band radiometer	$300 M
ICESat-II	Ice sheet height changes for climate change diagnosis	LEO, Non-SSO	Laser altimeter	$300 M
DESDynI	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	LEO, SSO	L-band InSAR. Laser altimeter	$700 M
Timeframe: 2013 – 2016, Missions listed by cost				
HyspIRI	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	LEO, SSO	Hyperspectral spectrometer	$300 M
ASCENDS	Day/night, all-latitude, all-season CO_2 column integrals for climate emissions	LEO, SSO	Multifrequency laser	$400 M
SWOT	Ocean, lake, and river water levels for ocean and inland water dynamics	LEO, SSO	Ka-band wide swath radar C-band radar	$450 M
GEO-CAPE	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	GEO	High and low spatial resolution hyperspectral imagers	$550 M
ACE	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	LEO, SSO	Backscatter lidar Multiangle polarimeter Doppler radar	$800 M
Timeframe: 2016 -2020, Missions listed by cost				
LIST	Land surface topography for landslide hazards and water runoff	LEO, SSO	Laser altimeter	$300 M
PATH	High frequency, all-weather temperature and humidity soundings for weather forecasting and SST[a]	GEO	MW array spectrometer	$450 M
GRACE-II	High temporal resolution gravity fields for tracking large-scale water movement	LEO, SSO	Microwave or laser ranging system	$450 M
SCLP	Snow accumulation for fresh water availability	LEO, SSO	Ku and X-band radars K and Ka-band radiometers	$500 M
GACM	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	LEO, SSO	UV spectrometer IR spectrometer Microwave limb sounder	$600 M
3D-Winds (Demo)	Tropospheric winds for weather forecasting and pollution transport	LEO, SSO	Doppler lidar	$650 M

Precipitation and All-weather Temperature and Humidity (PATH)
Launch: 2016-2020
Mission Size: Medium





Sea surface temperature

Temperature and humidity profiles

Constraints on models for boundary layer, cloud, and precipitation processes

More accurate, longer-term weather forecasts

Improved storm track and intensification prediction and evacuation planning

Determination of geographic distribution and magnitude of storm surge and rain accumulation

PATH	High frequency, all-weather temperature and humidity soundings for weather forecasting and SST[a]	GEO	MW array spectrometer **= GeoSTAR**	$450 M

Summary of the PATH mission concept

Scientific Objectives

- Enable major science advances: ENSO, monsoons, flow of tropical moisture into U.S.
- Improve model representation of cloud formation, evolution and precipitation
- Use time-continuous all-weather observations to impose new constraints on models
- Mitigate requirements on models in forecasts by enabling frequent re-initialization with observations

Needs

- Early identification and reliable forecasting of track and intensity of tropical cyclones
- Geographical distribution and magnitude of rain accumulation totals during/after landfall
- Required observations:
  - 3D atmospheric temperature and water vapor
  - SST
  - Precipitation
  - All-weather conditions (clear and cloudy)
  - Temporal refresh every 15–30 minutes

Mission and Payload

- MEO or GEO - GEO preferred in near term ← or CubeSat constellation?
- Requires 50 or 118 GHz + 183 GHz
- GEO requires microwave array spectrometer

Current storm sensors: Inadeqate

For storm science we need *frequent* observations of
temperature, water vapor, cloud liquid water/ice water, wind, rain/snow/hail, microphysics

None of the current observing systems are adequate:

- LEO satellites do not have adequate revisit times
- IR GOES cannot penetrate clouds
- None observes thermodynamics, wind and rain at the same time

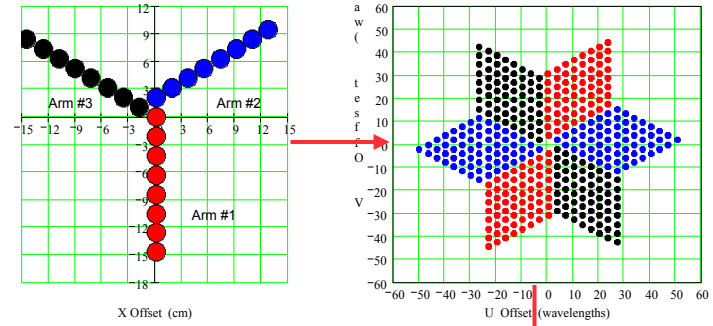
Sensor system	Continuous	Targeted obs.	All-weather	TCs & MCSs	Coverage	Temp, humid.	Precipitation	Wind
Ground radar (NEXRAD)	+		+		+		+	O
GEO imagers (GOES)	+	O		+	+		O	+
LEO MW-sounders (AMSU)			+	+	O	+	+	
LEO MW-imagers (SSM/I)			+	+	O		+	O
LEO IR-sounders (AIRS)				+	O	+	X	
LEO radar (TRMM/GPM)			+	+	O		+	

+ = *capable*, O = *partially capable*, blank = *incapable*

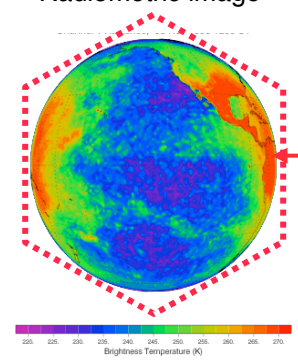
The GeoSTAR/PATH concept

- **Aperture-synthesis concept**
  - Sparse array employed to synthesize large aperture
  - Cross-correlations -> Fourier transform of Tb field
  - Inverse Fourier transform on ground -> Tb field
- **Array**
  - Optimal Y-configuration: 3 sticks; N elements
  - Each element is one I/Q receiver, 3.5λ wide (2.1 cm @ 50 GHz; 6 mm @ 183 GHz!)
  - Example: N = 100 ⇒ Pixel = 0.09° ⇒ 50 km at nadir (nominal)
  - One "Y" per band, interleaved
- **Other subsystems**
  - A/D converter; Radiometric power measurements
  - Cross-correlator - massively parallel multipliers
  - On-board phase calibration
  - Controller: accumulator -> low D/L bandwidth

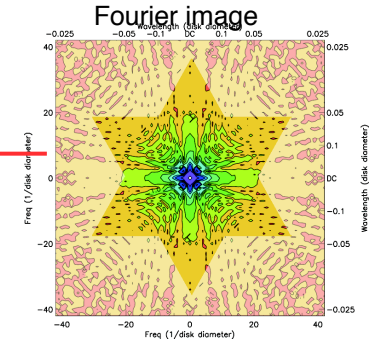
Receiver array & resulting uv samples



Radiometric image

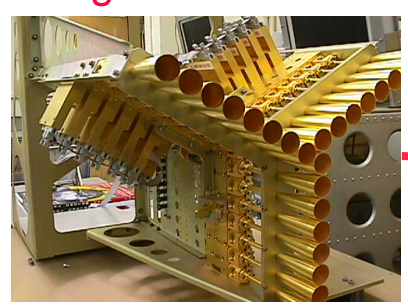


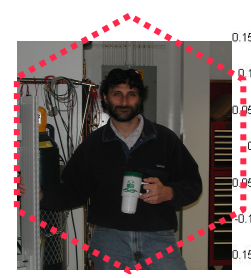
Fourier image

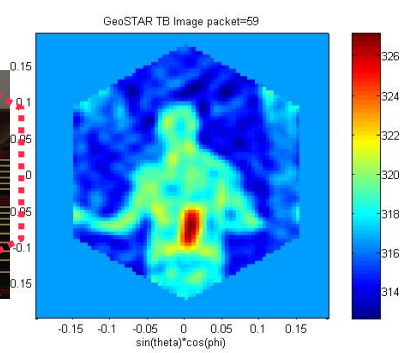


This is the only viable "array spectrometer" design and is what the NRC had in mind

Proof-of-concept prototype developed at JPL



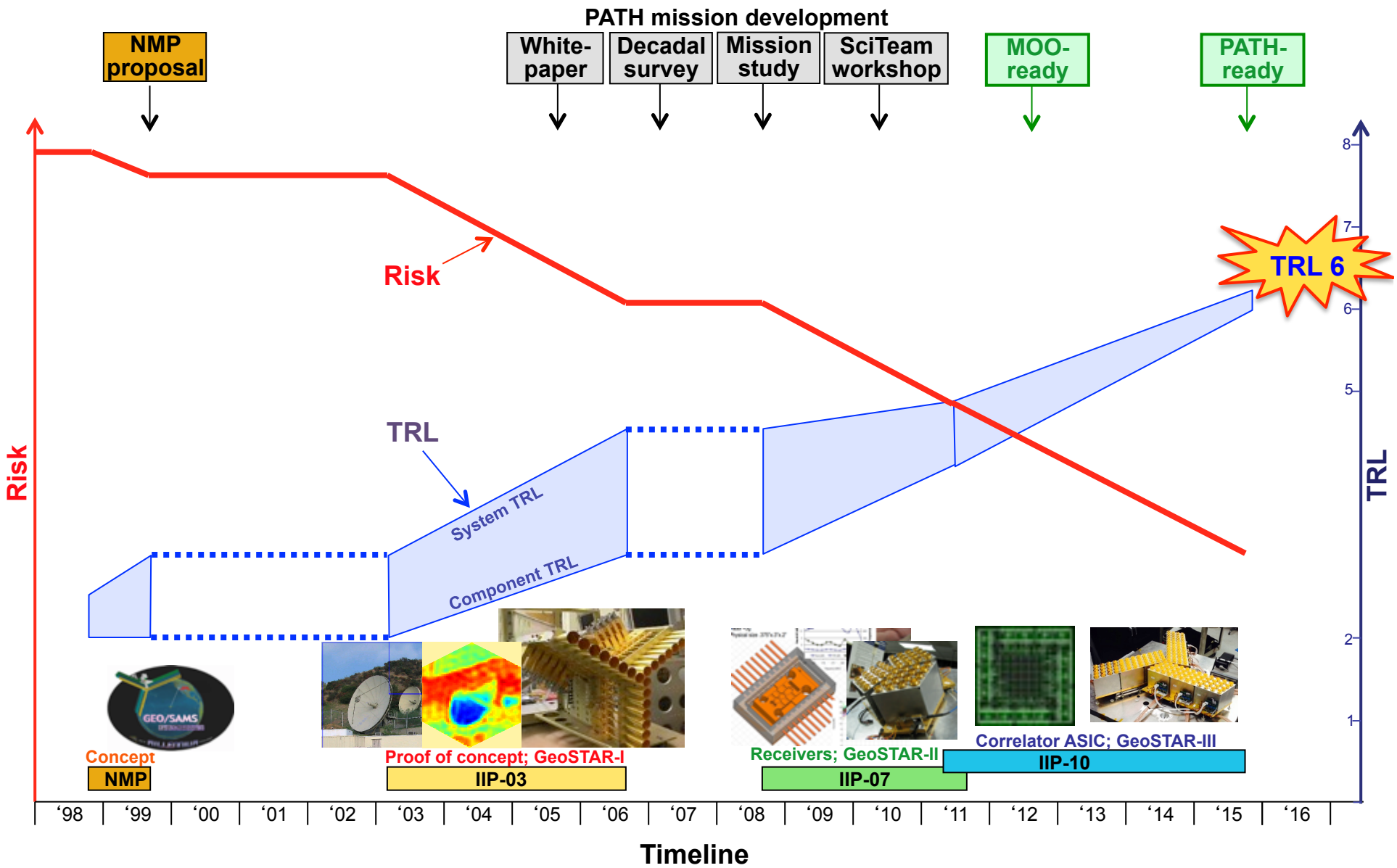




GeoSTAR development

- Concept development
  - NMP/EO-3 proposal (1998-1999)
  - NRC white paper (2005)
  - NRC Decadal Survey (2007)
- ESTO technology development
  1. IIP-03 (2003-2006): Proof-of-concept prototype
  2. ACT-05 (2006-2008): MIMRAM receivers
  3. IIP-07 (2008-2011): Key technology
  4. IIP-10 (2011-2015): Risk reduction
- Space implementation
  - *Venture mission (2020?)*
  - *PATH mission (~202X?)*

Timeline


PATH mission development
NMP proposal
White-paper
Decadal survey
Mission study
SciTeam workshop
MOO-ready
PATH-ready
Risk
TRL
System TRL
Component TRL
TRL 6
Concept
NMP
Proof of concept; GeoSTAR-I
IIP-03
Receivers; GeoSTAR-II
IIP-07
Correlator ASIC; GeoSTAR-III
IIP-10
'98
'99
'00
'01
'02
'03
'04
'05
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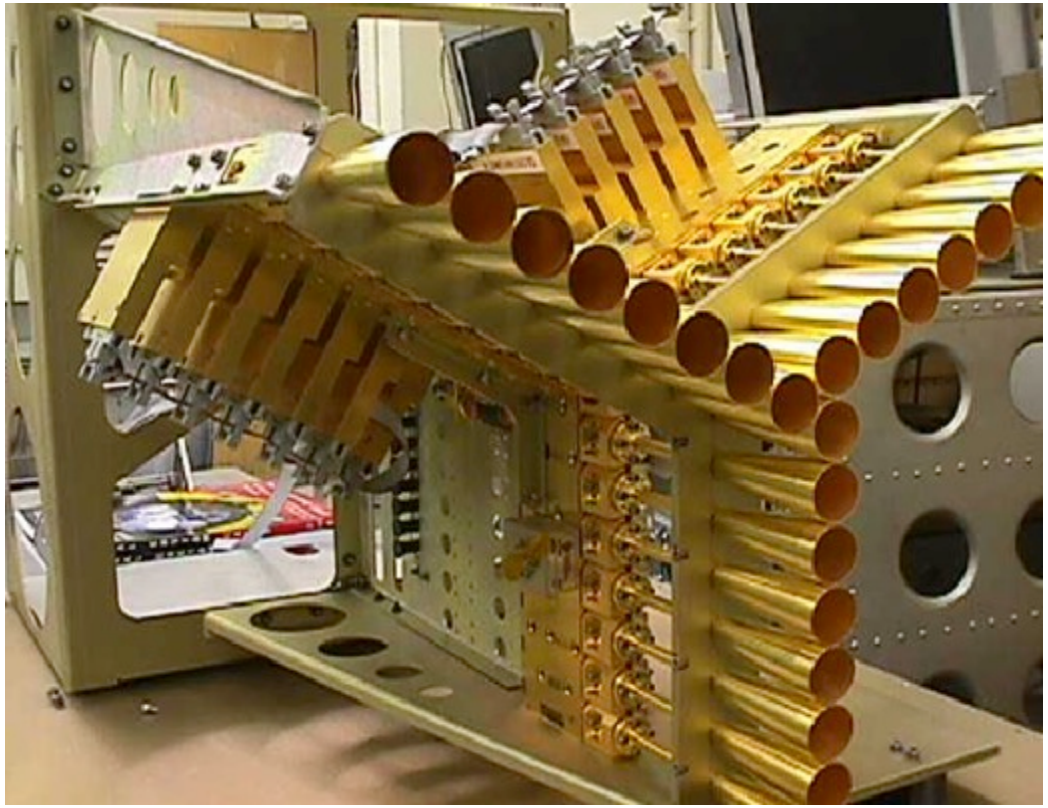
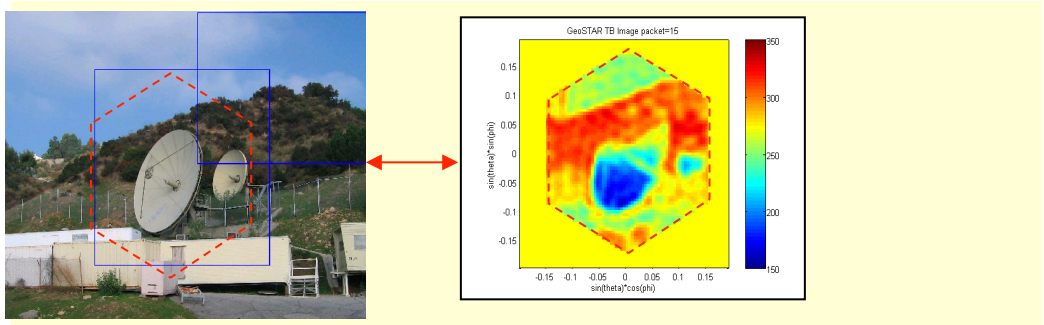
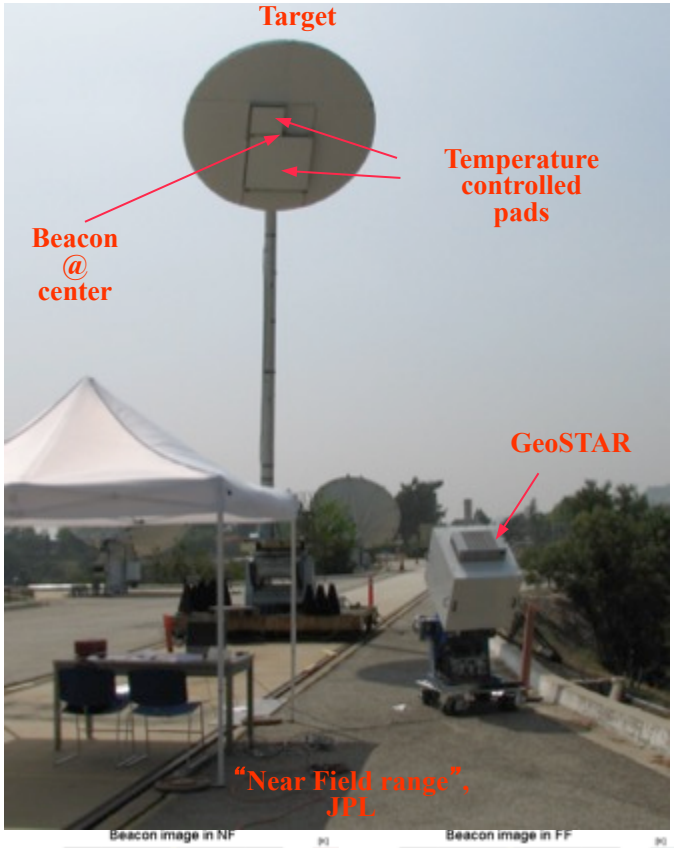
'15
'16
Timeline

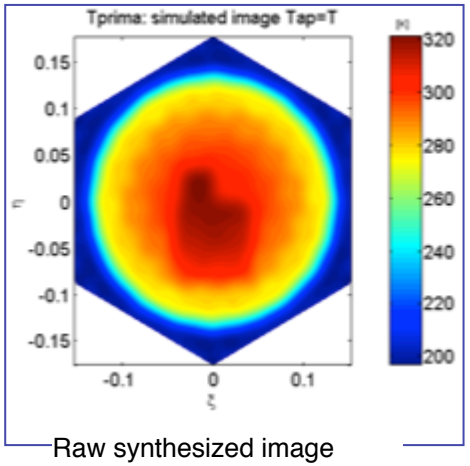
IIP-03: Proof of concept



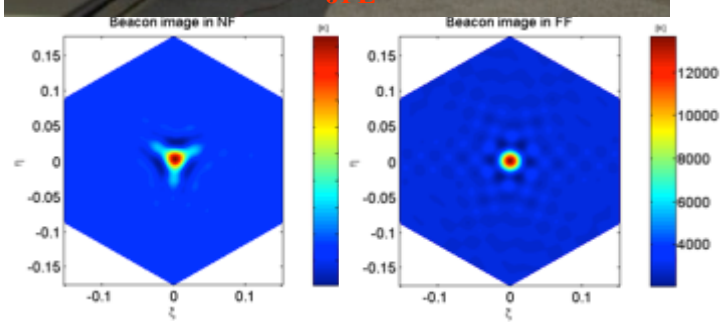


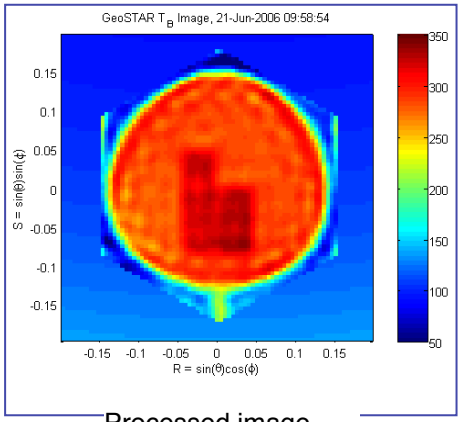
JPL R&TD: Calibration





Raw synthesized image

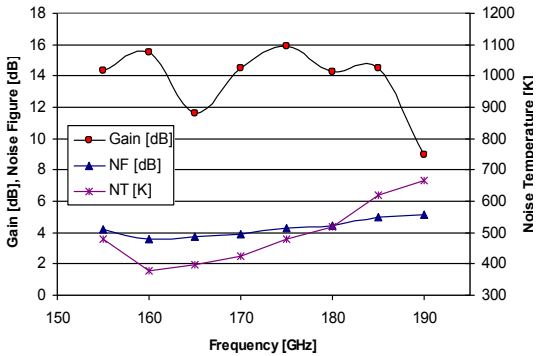


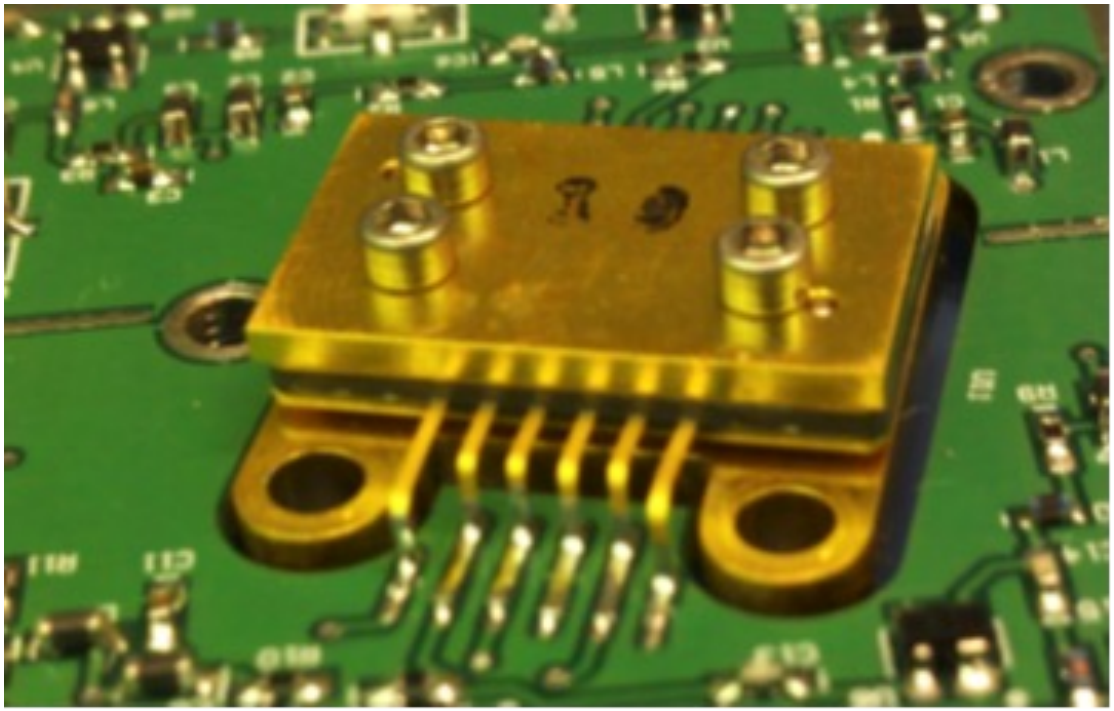


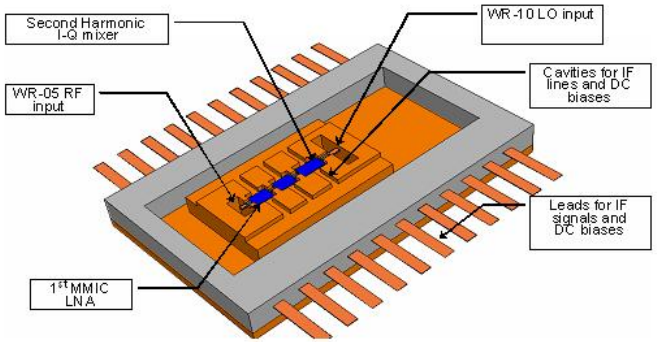
Processed image

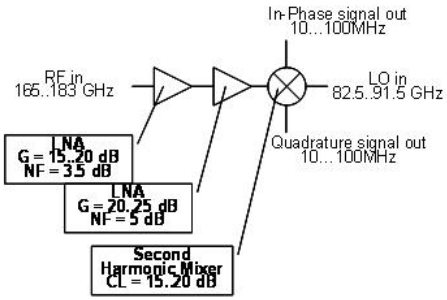
MIMRAM receivers (ACT-05)

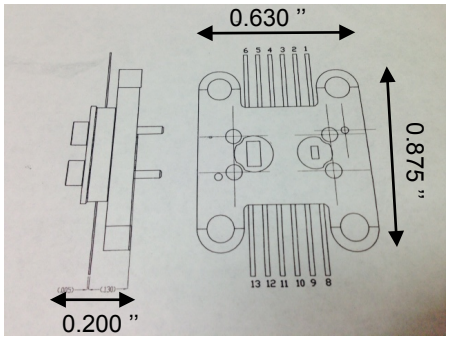
Miniaturization: 25 mW, 3 g per receiver









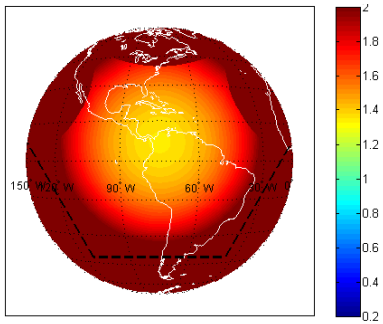


Complete LNA + mixer receiver; broadband, up to 190 GHz

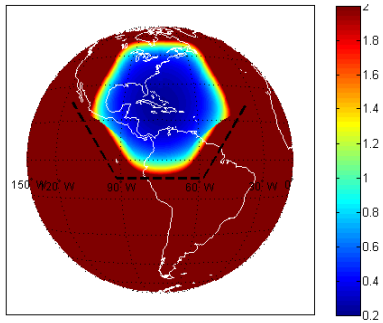
GeoSTAR-II: 183 GHz (IIP-07)

Multi-row antenna design

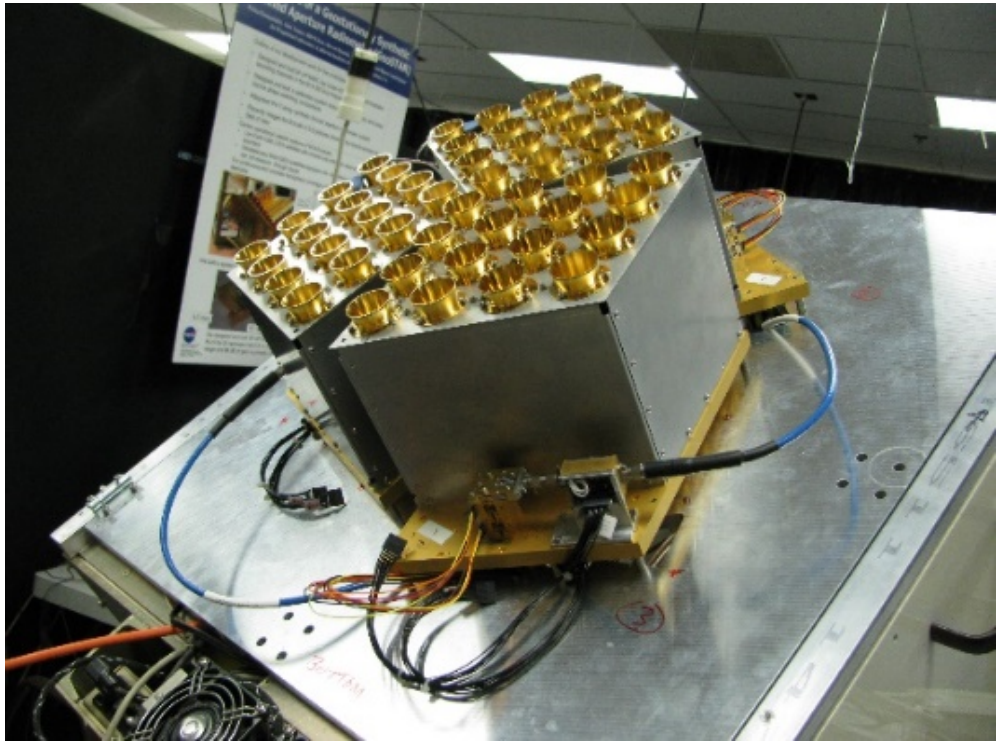
Improved antenna efficiency

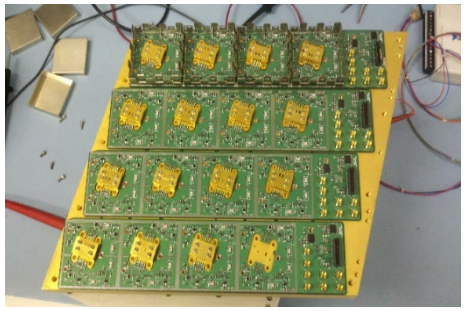


GeoSTAR-I



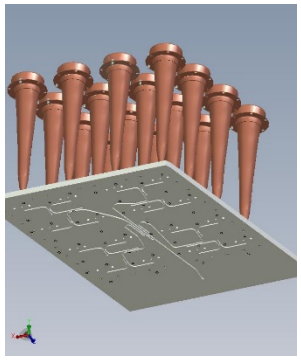
GeoSTAR-II





MIMRAM receiver arrays

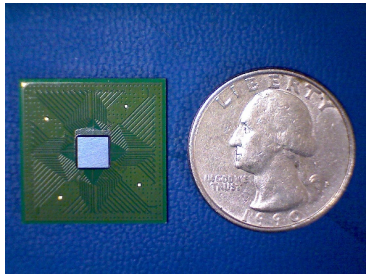
"Tile" assemblies

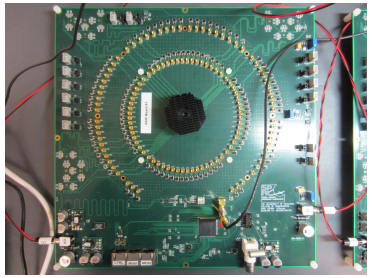


GeoSTAR-III: Correlator (IIP-10)

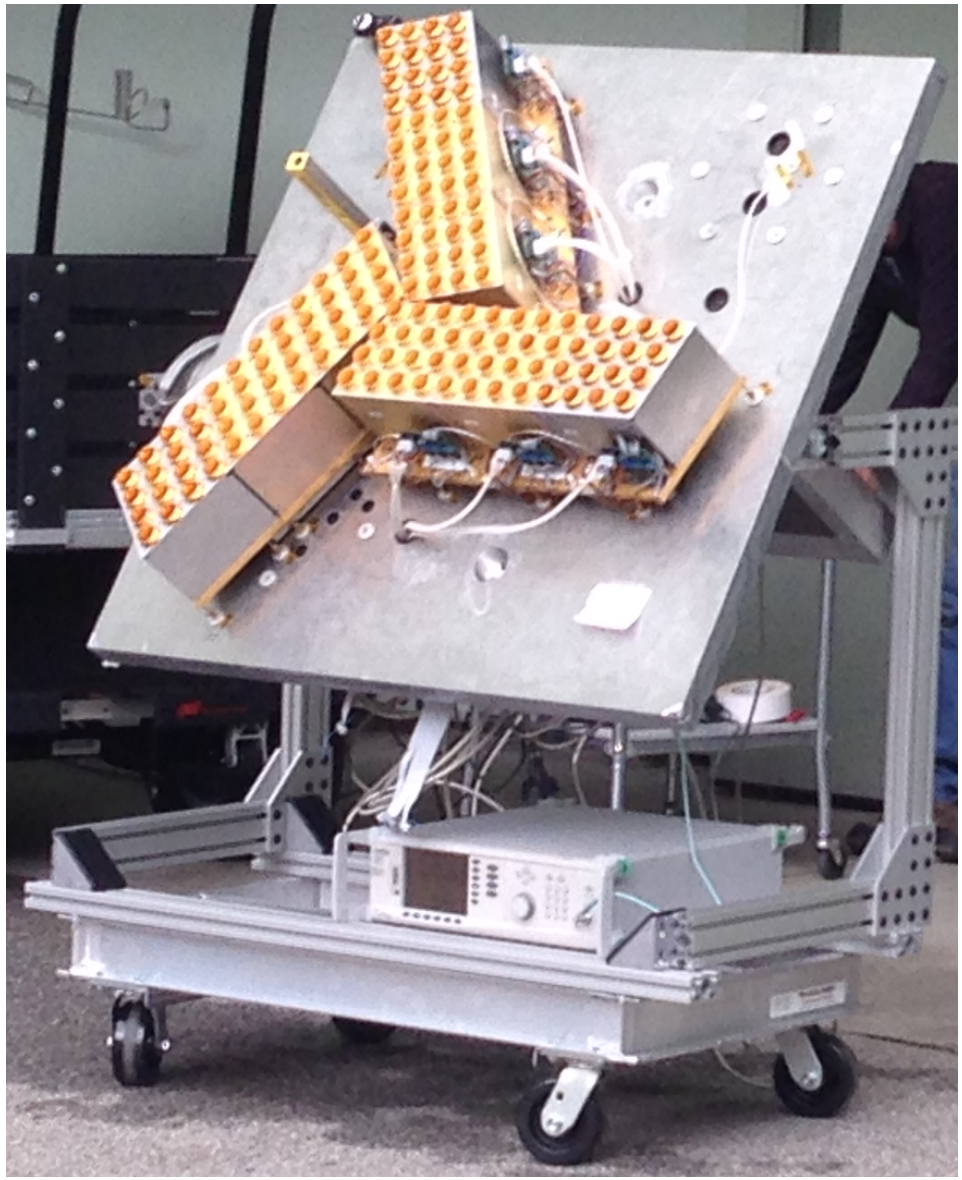
Complete high-gain 183-GHz STAR

ASIC-based correlator





2-bit ADC + digital correlator
128 analog in @ 500 MHz
64x64 = 4096 correlators
98% efficiency @ -15dBM in
Clock speed up to 1.5 GHz
Up to 6.1×10^{12} 2-bit mult/sec
1.44 Watts @ 1 GHz



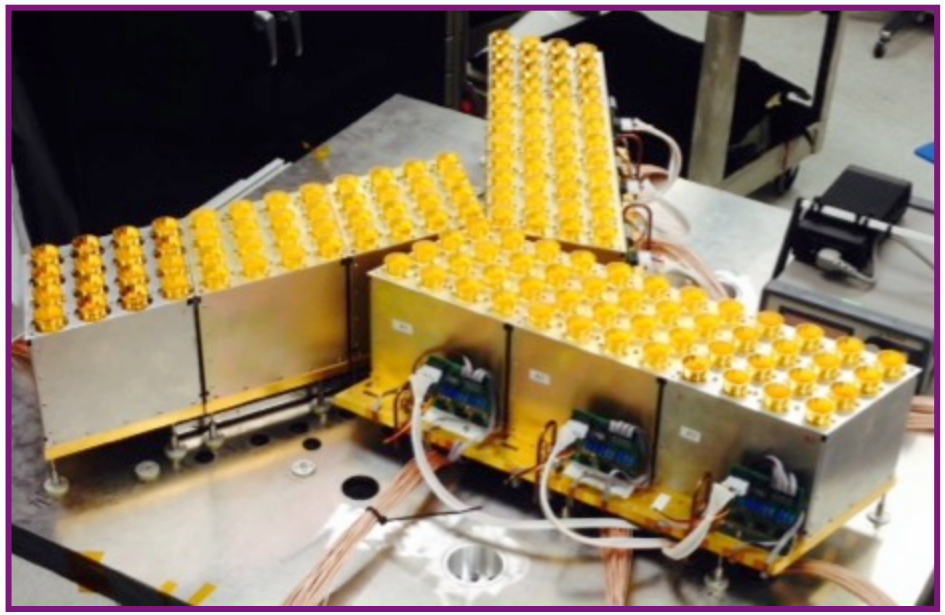
Key technologies tested to TRL 6

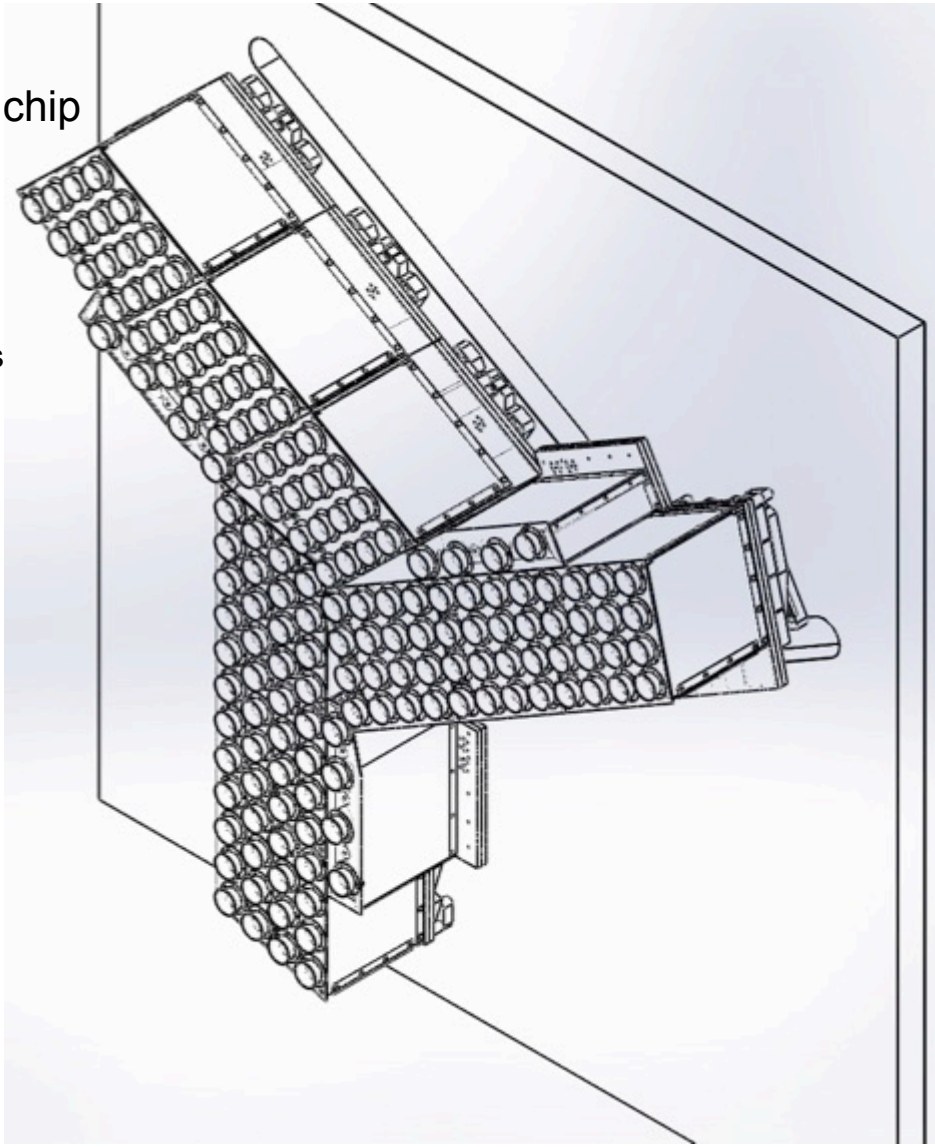
All other elements are engineering developments

Ready for space implementation!

System performance testing: Objectives

- Further testing of correlator ASIC
  - Complete full correlator board hosting new chip
  - Full functional testing of new chip
- System testing
  - Assemble small 183-GHz antenna array
    - Using miniature ultra-low-power MIMRAM receivers
  - Integrate full system with correlator
  - Characterize system performance
  - Imaging demonstration

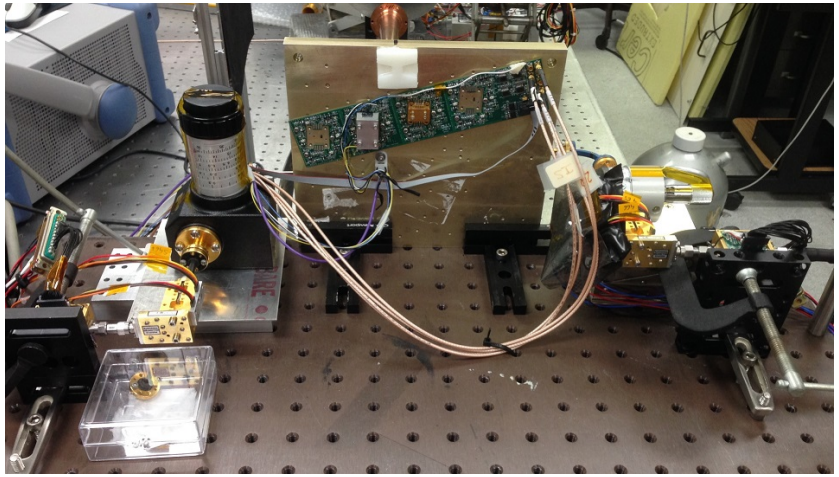


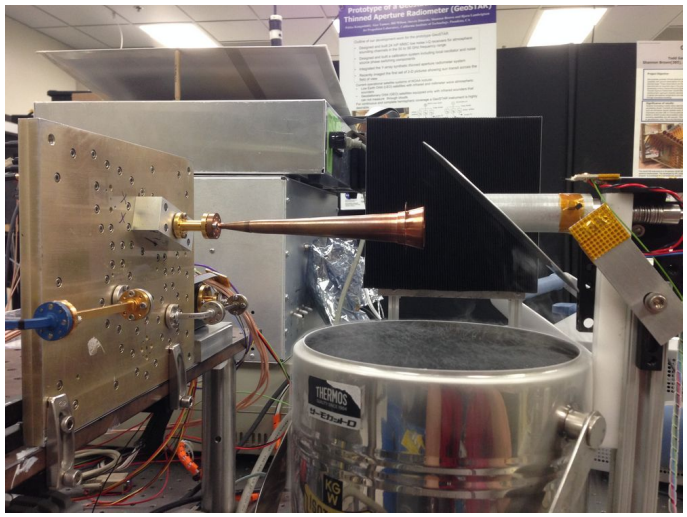


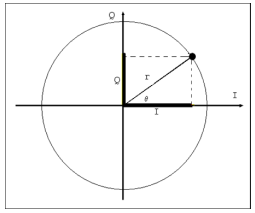
Integration, Assembly, Testing

Receivers

Receivers are mass produced on assembly line
Large number of MIMRAMs to test (144 units)
Automated process in single measurement setup





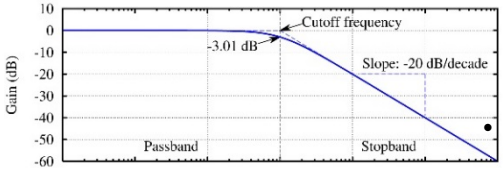


Phase

- Vector voltmeter
- Vector analyzer

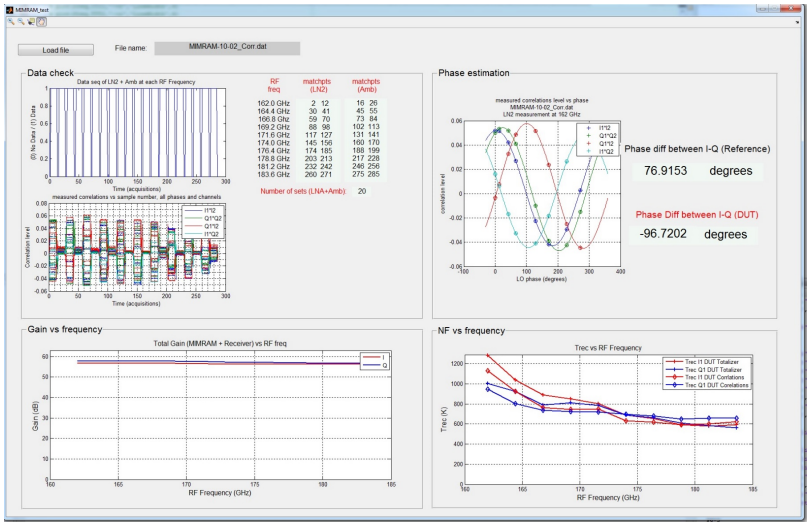
NF

- Noise Figure analyzer
- Power meter (Y factor)



Gain

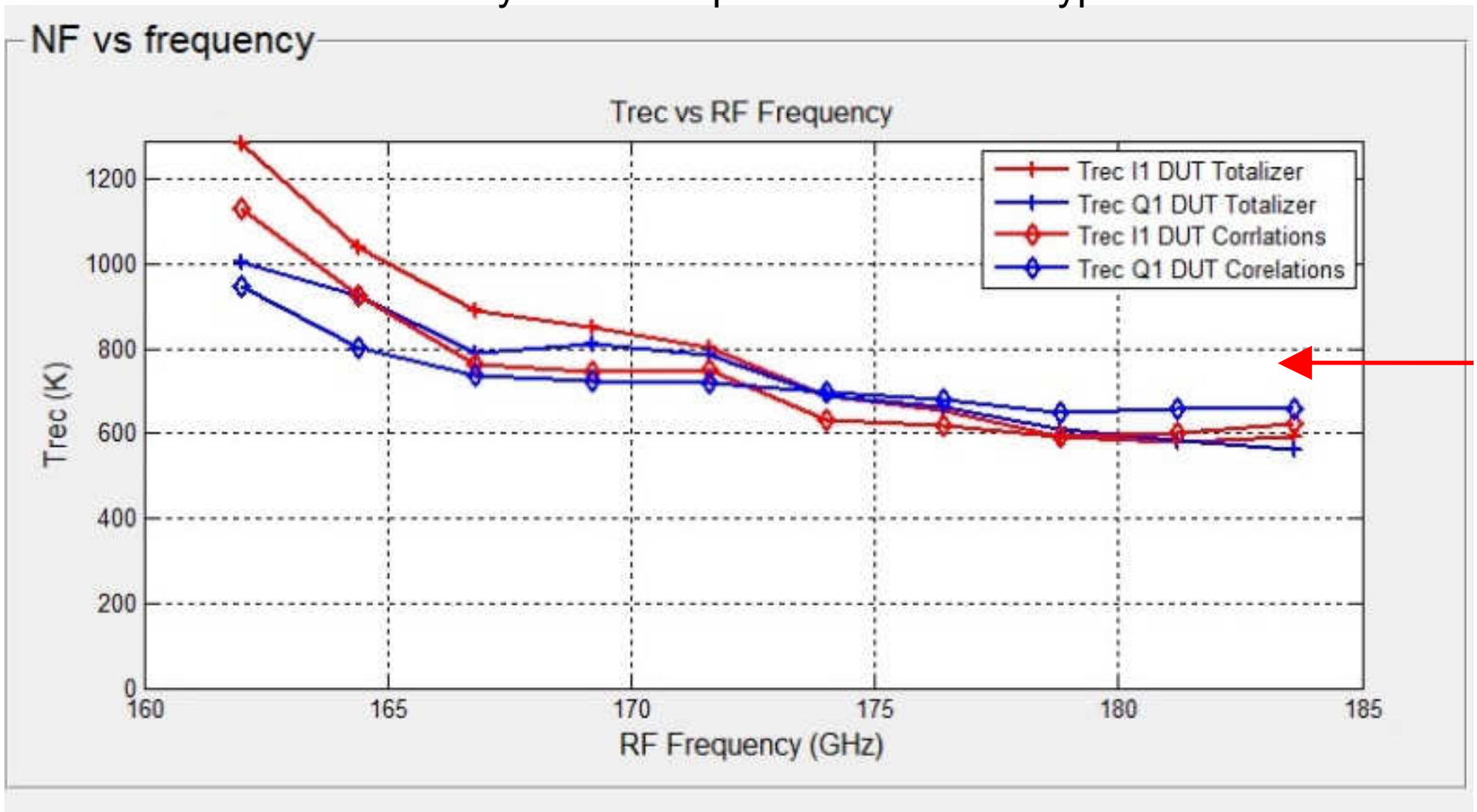
Spectral Analyzer
- Power meter



Analysis software

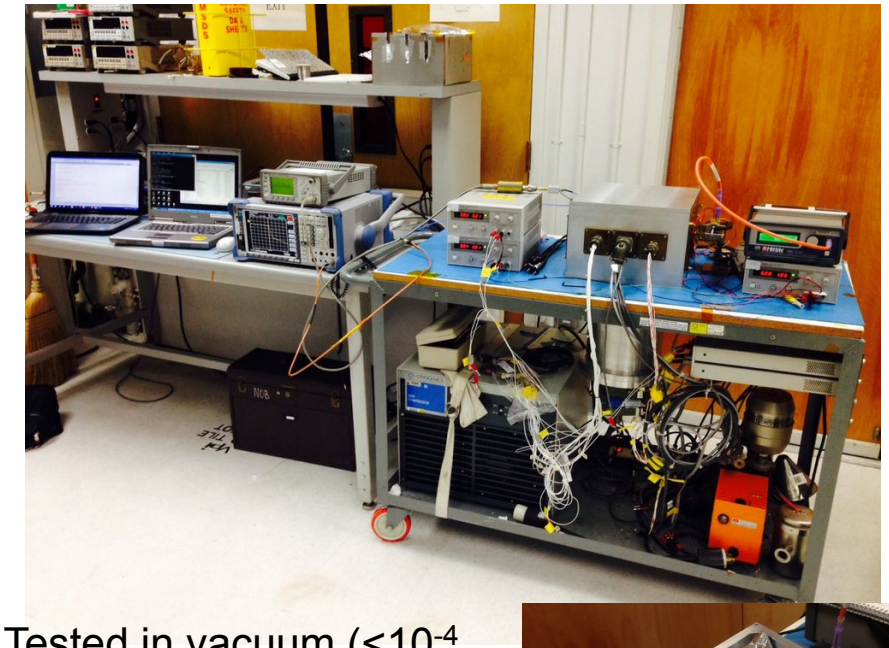
135 Receivers Populated

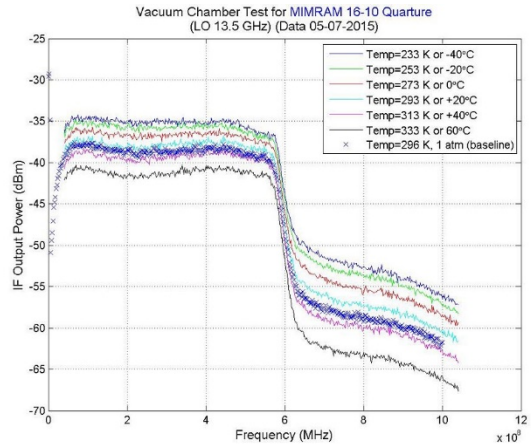
FPGA-based system level performance for a typical receiver.



Thermal-Vacuum tests

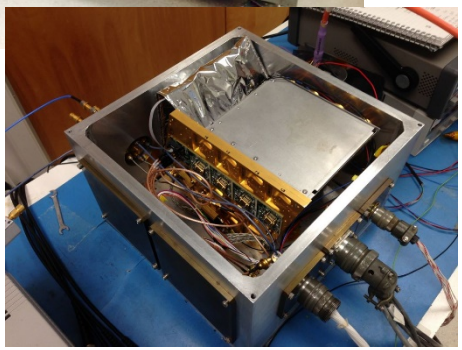
Thermal Vacuum test: IF board + MIMRAMs

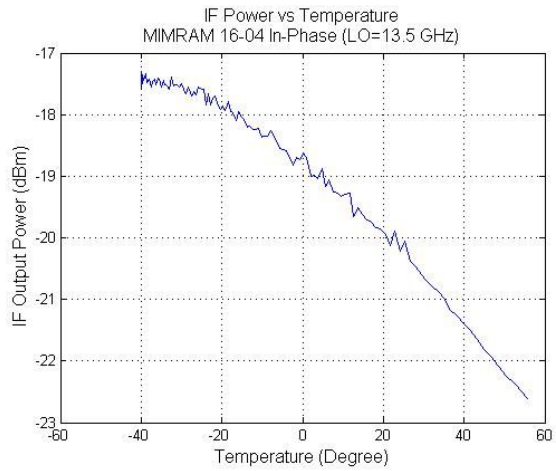




Tested in vacuum (<10^{-4} torr) over AFT± 10° C

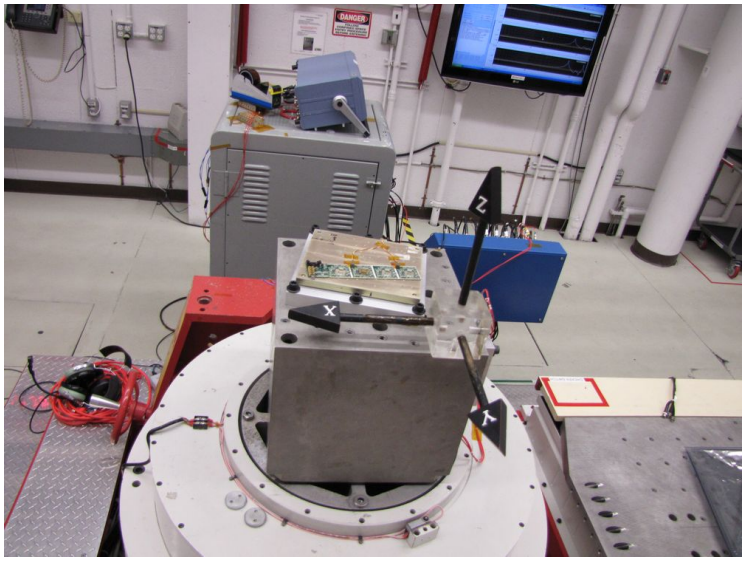
4 IFs monitored, one continuously





Vibration tests

Vibration test: IF board + MIMRAM



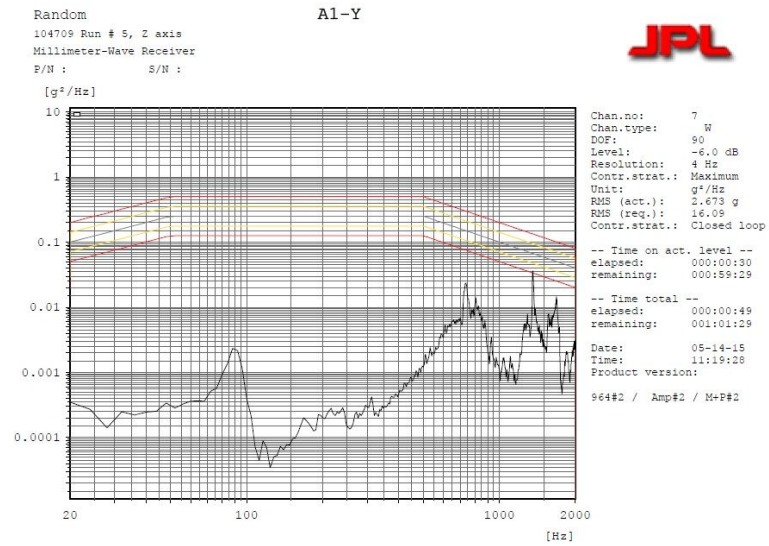
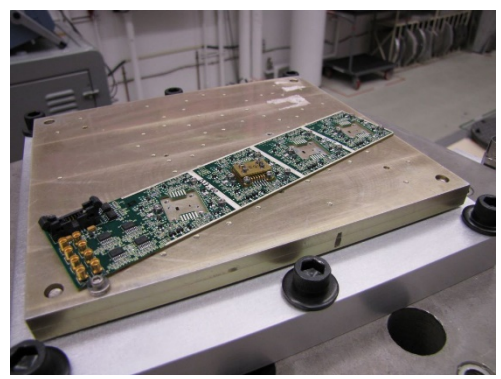
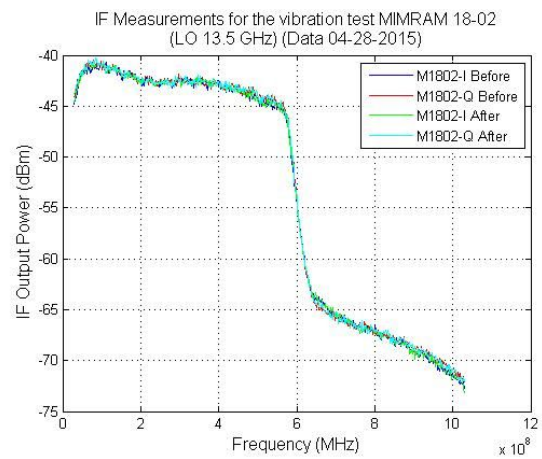


Table 5.2 - GEO Random Vibration Environment

Frequency (Hz)	Level
20	0.4 g^2/Hz
20 – 50	+3 dB /octave
50 – 500	1.0 g^2/Hz
500 – 2000	-4 dB /octave
2000	0.16 g^2/Hz
Overall G_{rms}	32.1

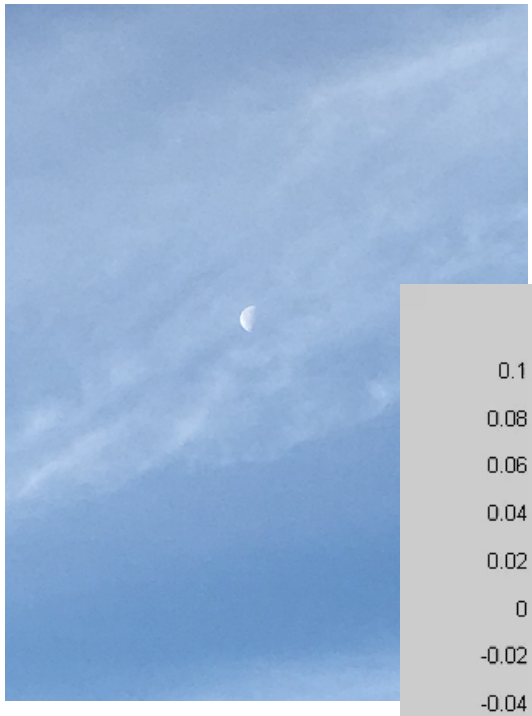
Test duration: 120 seconds

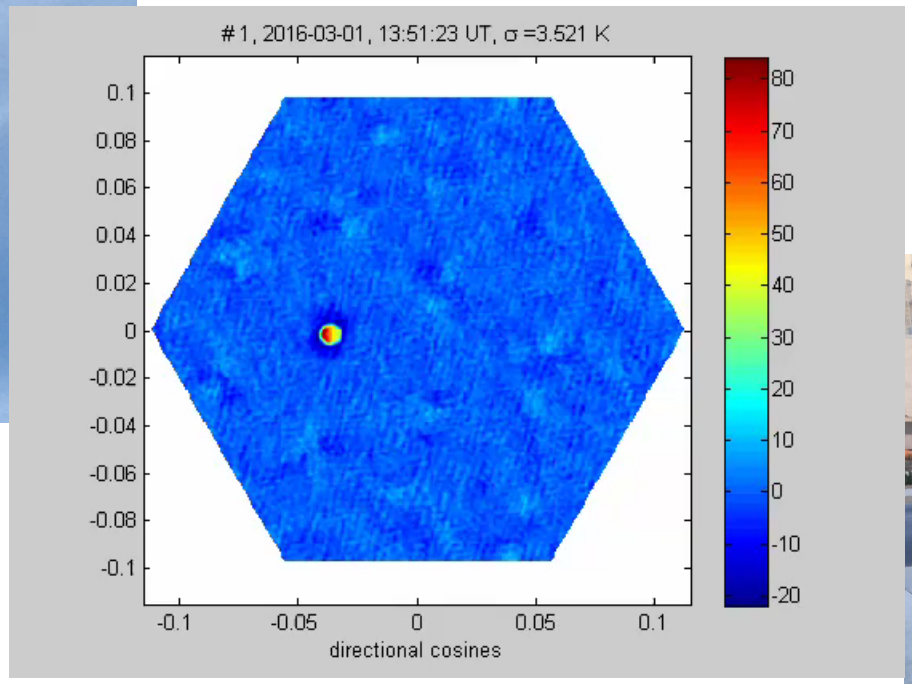




Imaging test: Moon

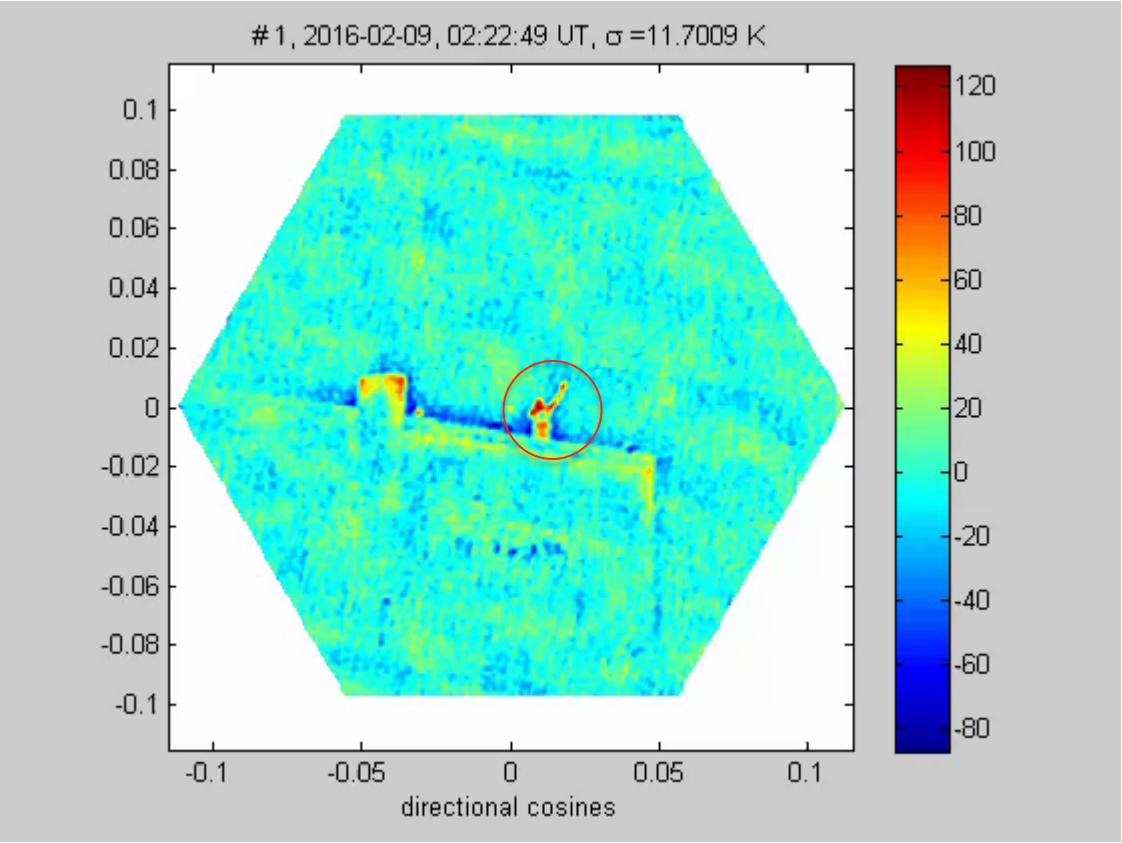
Third quarter moon, March 1 2016





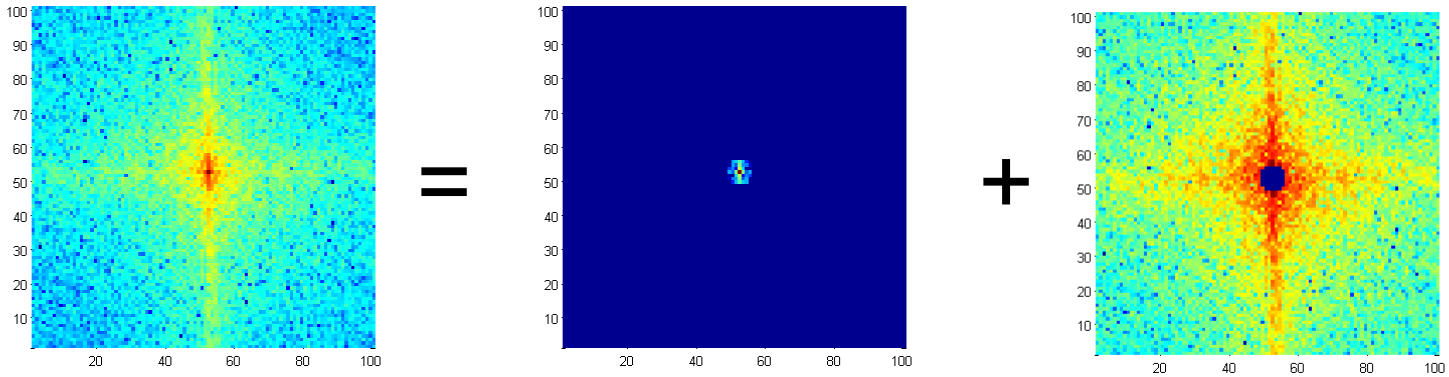
Imaging test: Ground scene

Man on top of a building

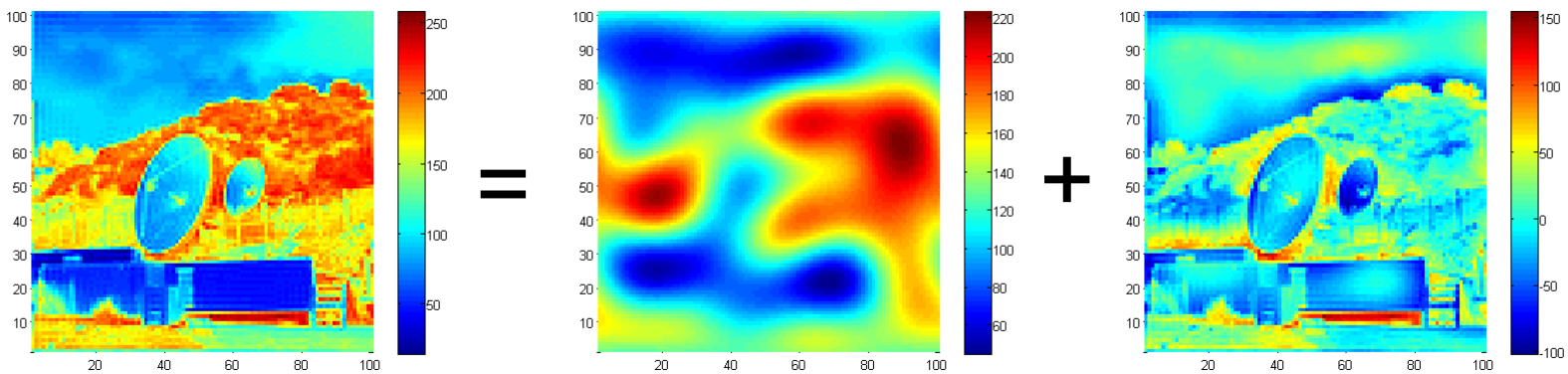


Spatial scales: HGA vs. LGA

Need LGA (GeoSTAR-I) *and* HGA (GeoSTAR-III) for complete image



Full visibility function | Short baselines | Long baselines



Full image

Low gain array (LGA)
Large spatial scales

High gain array (HGA)
Short spatial scales

What could we do with GeoSTAR?

TIME TESTED MEASUREMENTS AND DATA PRODUCTS USING MATURE ALGORITHMS

GeoSTAR would make similar measurements from GEO as AMSU currently does from LEO, but every 15 minutes vs. 2 times per day

High-intensity events can be sampled in 5 minutes or less

GeoSTAR would uniquely provide measurement of
Temperature/moisture/clouds; Wind; Precipitation
simultaneously, continuously and in 3 dimensions

Parameter	Horizontal	Vertical	Temporal	Precision	Accuracy	Thermodyn.	Bulk microphys.	Dynamics
Brightness temperatures	25 - 50 km	N/A	5-20 min.	0.5-1.5 K	0.5 K			
Temperature	25 - 50 km	2-3 km	5-20 min	1.5 K	0.5 K	√		
Water vapor				25%	10%	√		
Wind vector (u,v)				2 m/s	1 m/s			√
Reflectivity				4 dBZ	2 dBZ		√	
Rain rate		N/A		3 mm/hr	50%	√	√	
LWP				25%	10%	√		
IWP				25%	20%	√	√	

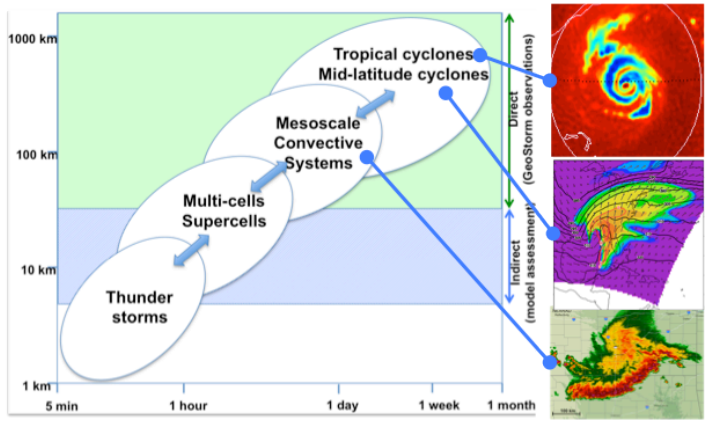
Precision & accuracy reflect performance of MIRS (except for reflectivity)

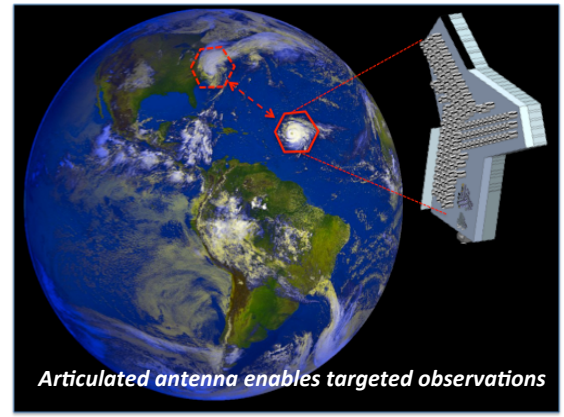
"GeoStorm": A pre-PATH mission concept

A GEOSTATIONARY MICROWAVE SOUNDER MISSION FOCUSED ON THE EVOLUTION OF SEVERE STORMS

Improve our understanding of sudden and unpredicted change in intensification and motion of destructive storms:

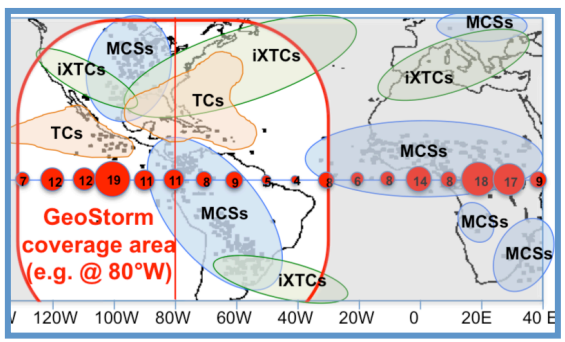
- ***hurricanes***
- ***severe thunderstorms and mesoscale convective systems***
- ***mid-latitude cyclones and winter storms***





Low cost as a hosted payload

Many hosting opportunities in GEO:



There are more than 80 GEO comm-sats that provides a view of the Americas, being replaced at a rate of 5-6 per year

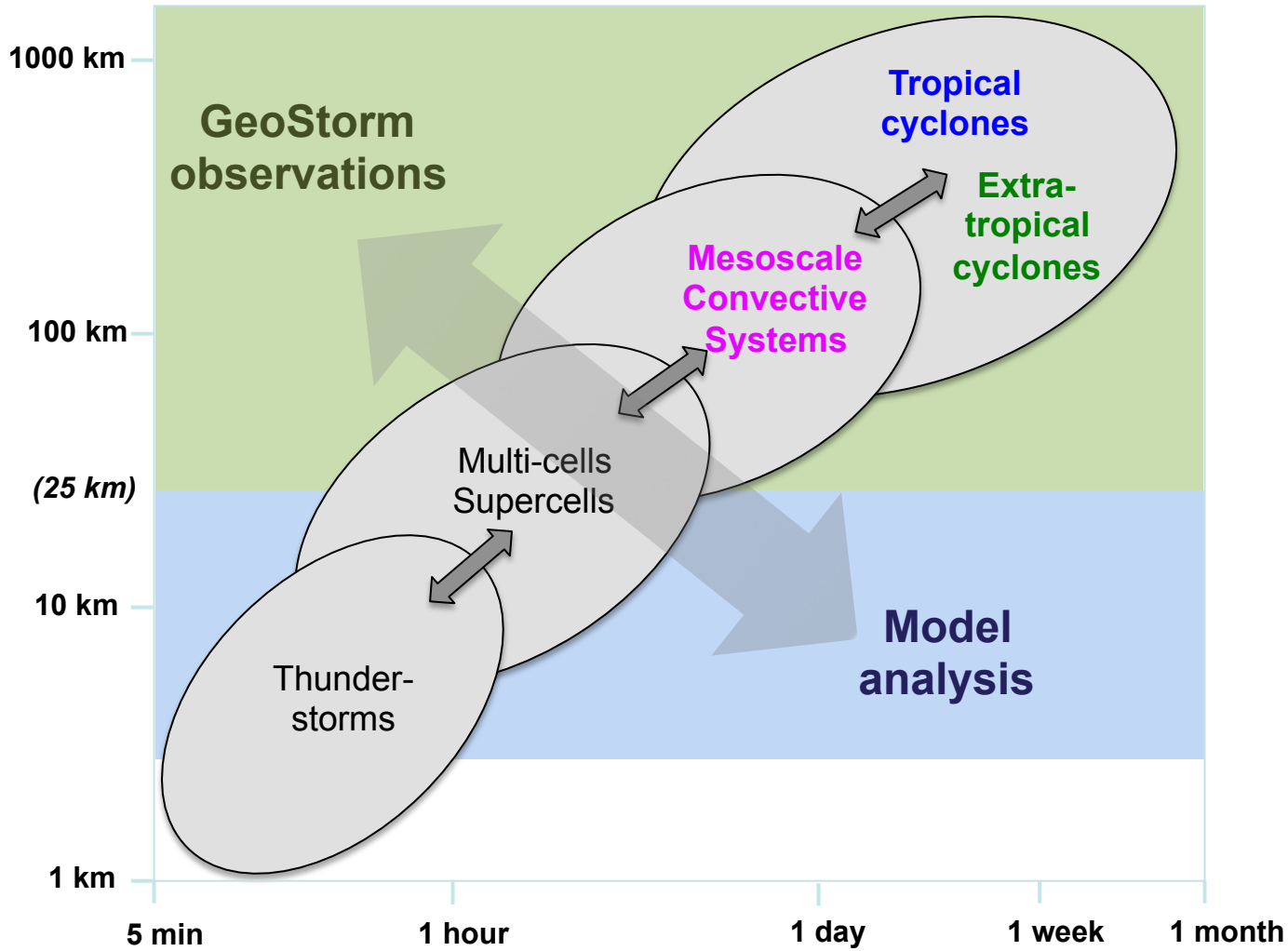
GeoStorm Highlights	
Targeted observations	Life cycle storm tracking
Time-continuous	Capture dynamic processes; diurnal cycle fully resolved
Multiple simultaneous key parameters	Temperature, humidity, precipitation, wind
All-weather	Cloud/rain-penetrating
3-D observations	1000 km dia x 15 km vert. (volume); 25 km dia x 3 km vert. (resolution)
Wide coverage	All storms visible from GEO

GeoStorm covers a substantial subset of the PATH science objectives at a greatly reduced cost (~ $100M vs. ~ $500M), using all key PATH technologies and flying as a hosted payload.

Wide range of space-time scales

GeoStorm would cover temporal scales from 15 minutes to weeks, spatial scales from 25 km to 1000 km

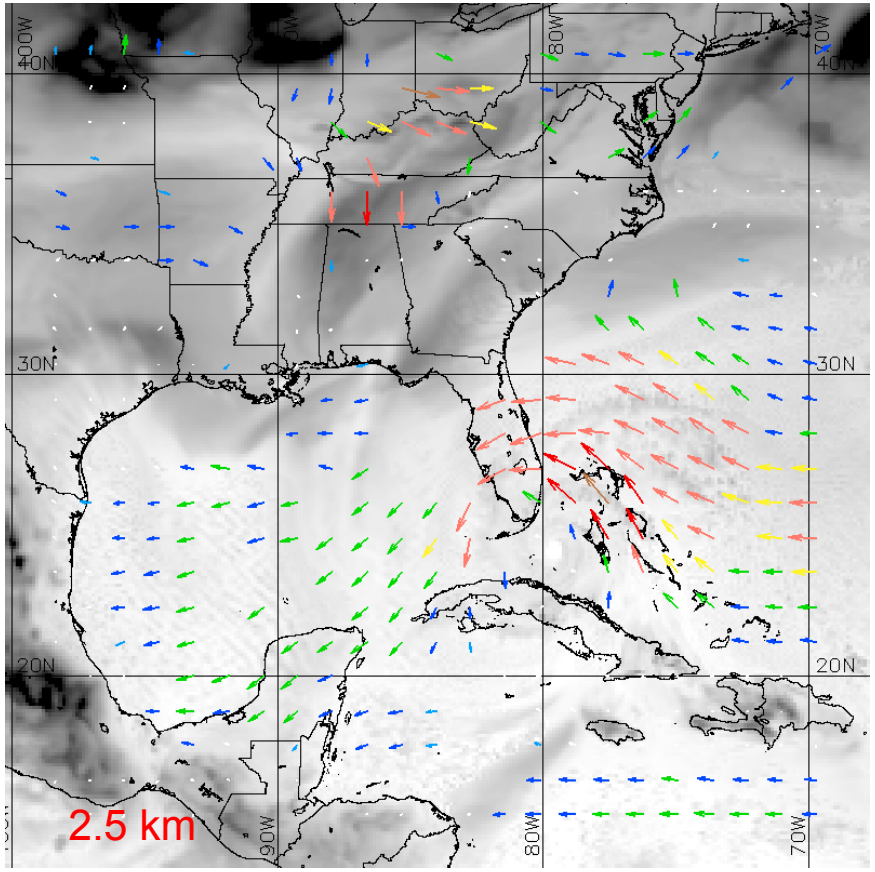
This enables new investigations of multi-scale interactions, such as storm-scale with environment

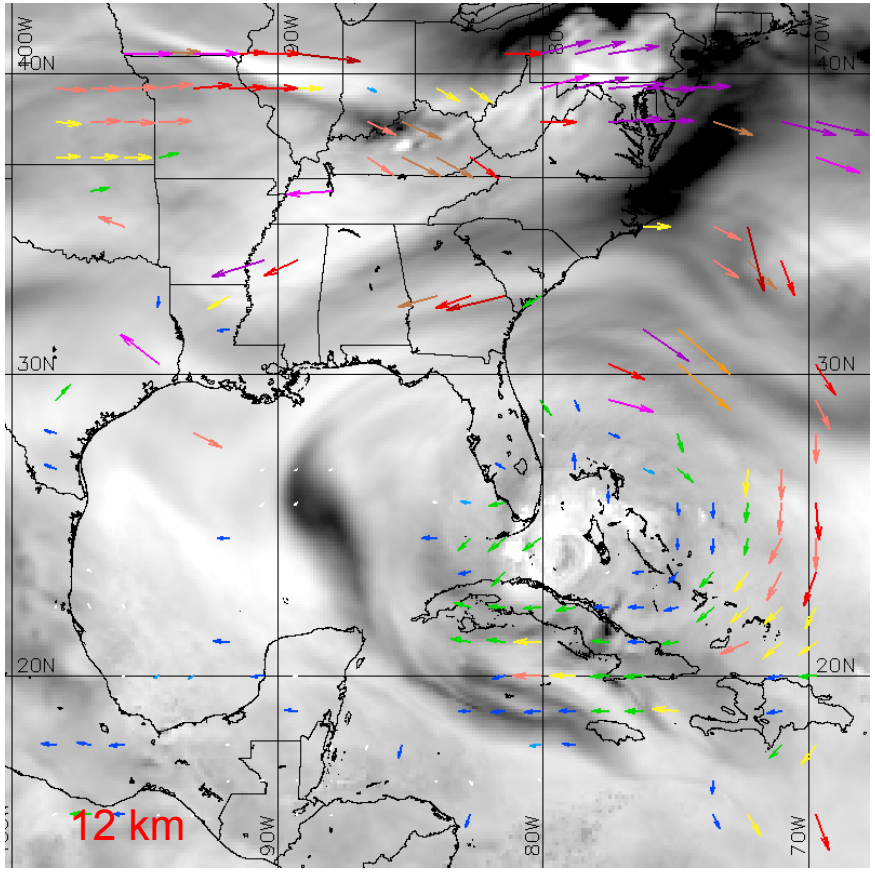


PATH and GeoStorm concepts do wind

Height-registered wind vectors will be derived from water vapor features (AMVs)
Based on method developed at U. Wisconsin (Velden et al.)
GeoStorm will provide u,v wind maps @ 25 km x 3 km resolution in 3-D every 15 minutes!

WRF simulation of Rita (2005)





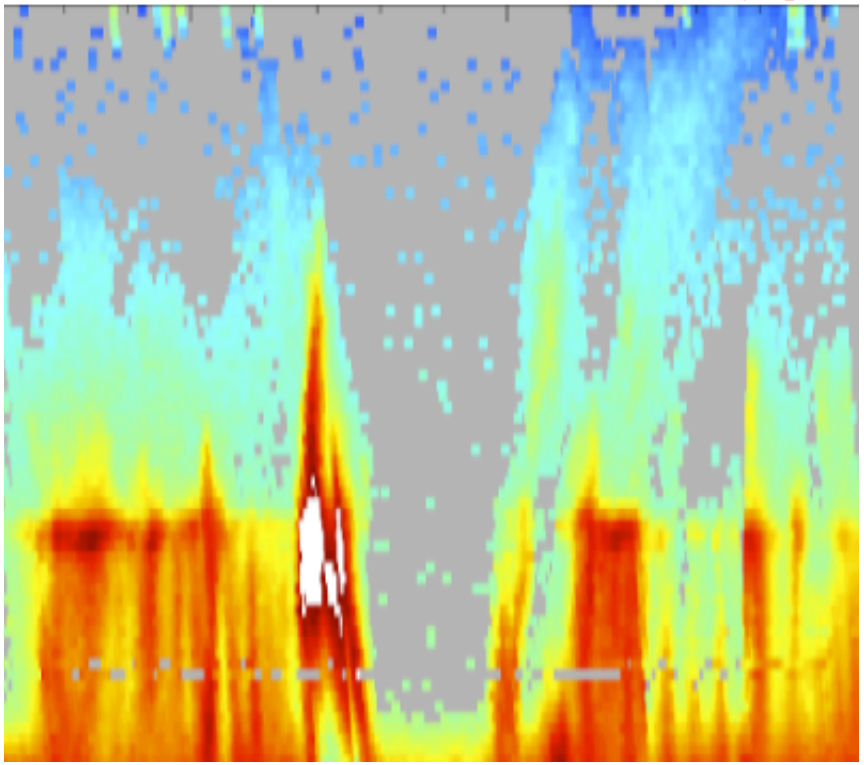
Credit: S. Hristova-Veleva & J. Turk, JPL

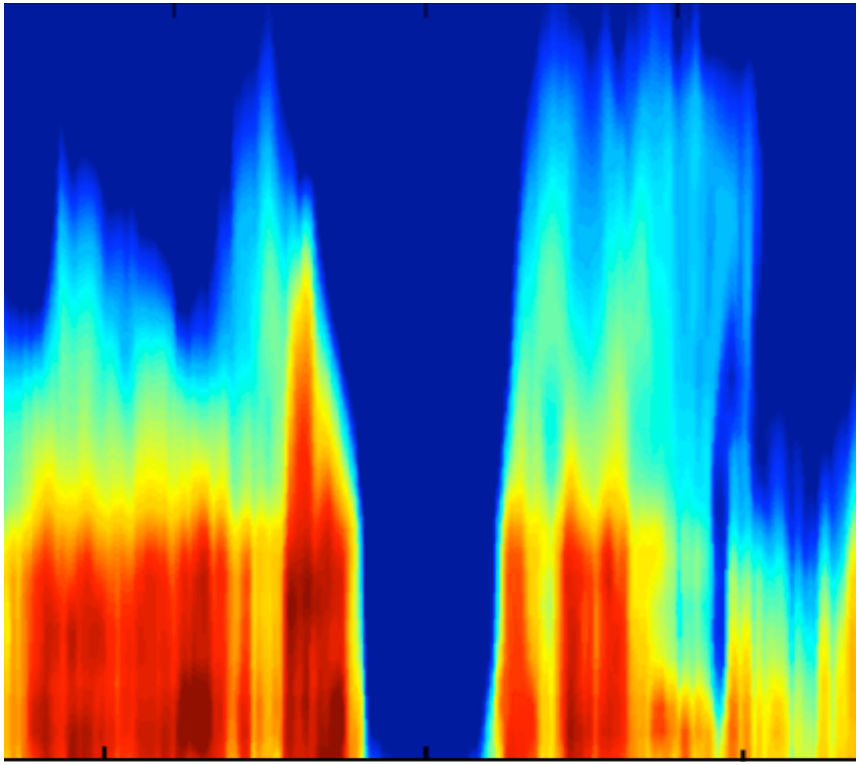
Poor man's radar

An algorithm has been developed to produce reflectivity profiles from MW sounder data

Images below show real radar (left) vs. MW product (right) from an aircraft campaign
Our product has less vertical resolution (1-2 km) and less sensitivity (~ 4 dBZ) than the radar, but all major features are accurately reproduced.

GRIP: H. Karl, eye pass #16 (0644 UTC 9/17 2012)





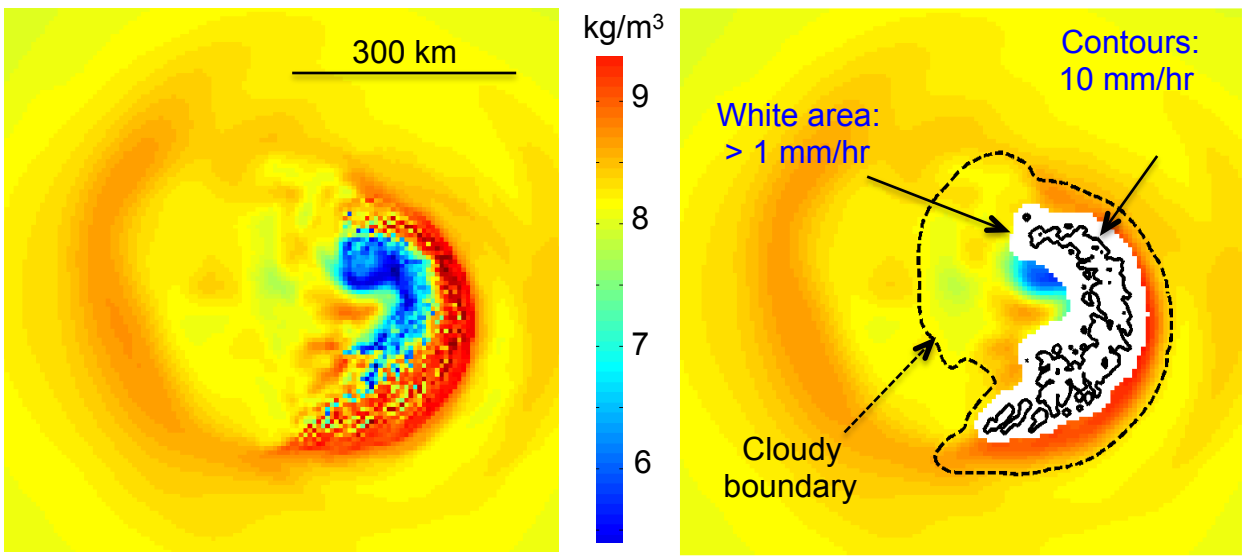
HIWRAP (radar) ⟷ **HAMSR (MW sounder)**

Note: No space-time mismatch since both sensors are on same aircraft

Penetrates clouds and precipitation

Example MCS simulation shows GeoStorm will penetrate inner regions
Colored areas shows where GeoStorm obtains full measurement – Up to 1 mm/hr
White area: Can still get water vapor profiles above 700 mb – Up to 3 mm/hr
Inside solid contour: Can still get temperature profiles – Up to 10 mm/hr
(IR & VIS sensors cannot penetrate inside cloudy boundary)

Therefore, we can (for example) investigate Convective Momentum Transport



Model (6 km res.) GeoStorm (25 km res.)

New state of the art in storm sensors

For storm science we need *frequent* observations of
temperature, water vapor, cloud liquid water/ice water, wind, rain/snow/hail, microphysics

GeoStorm measures up well against current observing systems

Sensor system	Continuous	Targeted obs.	All-weather	TCs & MCSs	Coverage	Temp, humid.	Precipitation	Wind
Ground radar (NEXRAD)	+		+		+		+	O
GEO imagers (GOES)	+	O		+	+		O	+
LEO MW-sounders (AMSU)			+	+	O	+	+	
LEO MW-imagers (SSM/I)			+	+	O		+	O
LEO IR-sounders (AIRS)				+	O	+	X	
LEO radar (TRMM/GPM)			+	+	O		+	
GeoStorm	+	+	+	+	+	+	+	+

+ = *capable*, O = *partially capable*, blank = *incapable*

Summary

- STAR concept demonstrated in IIP-03
  - Developed a functional 50-GHz STAR demonstrator
- Key technologies developed in IIP-07
  - Developed miniature low-power 183-GHz MMIC receivers
  - Developed new alias-rejecting antenna array design
- Ready for PATH mission concept after IIP-10
  - Full-size 64x64 correlator ASIC is a success!
  - All key technologies are now at TRL 6
  - Can start PATH mission development any time

- We have advanced the technology from Tier-3 level to Tier-1 level – a major achievement