National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

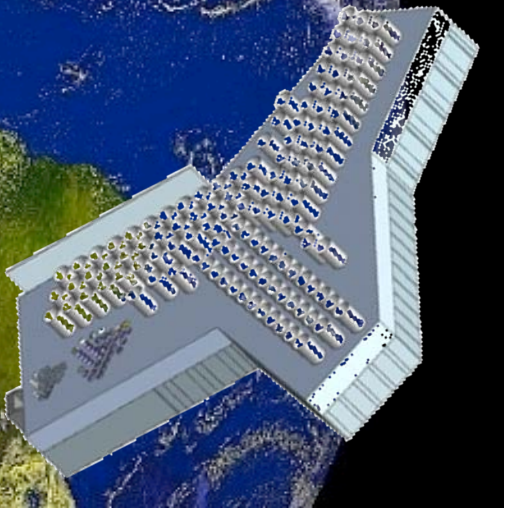
Is a Geostationary Microwave Sounder now feasible?

Bjorn Lambrigtsen
and many others

Jet Propulsion Laboratory
California Institute of Technology

ITSC-23
Virtual conference; June 24-30, 2021

lambrigtsen@jpl.nasa.gov



Q: Why do we need a GEO MW sensor?

A: Bad weather!

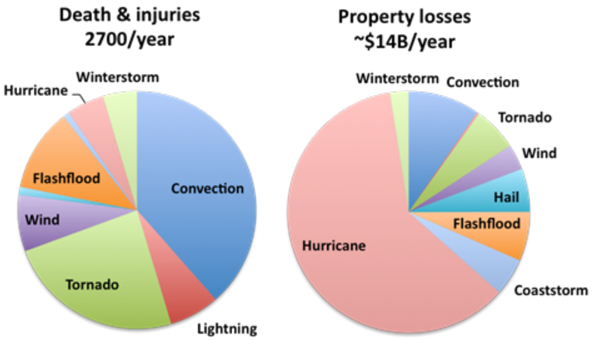
None of our current observing systems are adequate storm sensors:

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

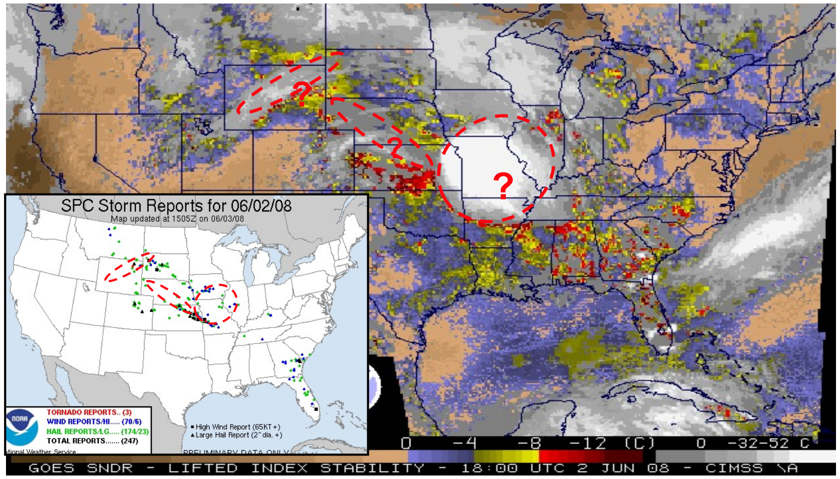
Sensor system	**Continuous**	**All-weather**	**Full coverage**	**Thermodyn.**	**Precipitation**	**Hor. wind**	**Vert. wind**	**Microphysics**
Ground radar (NEXRAD)	✓	✓	–	X	✓	–	–	✓
GEO imagers (GOES-16)	✓	X	✓	X	X	–	X	X
LEO MW-sounders (ATMS)	X	✓	–	✓	✓	X	X	–
LEO MW-imagers (SSM/I)	X	✓	–	X	✓	–	X	–
LEO IR-sounders (AIRS, CrIS, IASI)	X	X	–	✓	X	X	X	X
LEO radar (GPM)	X	✓	–	X	✓	X	X	✓
GeoSTAR	✓	✓	✓	✓	✓	✓	X	–

GEO/MW capabilities:

***All* conditions, incl. *in* storms; 3D soundings every ≤15 minutes**



Severe storms cause tremendous damage (U.S. storm losses 1998-2010 avg.)



What's going on below those clouds?

NOAA study of GeoSTAR (Fall 2020)

Geostationary Orbit Concept Exploration
Broad Agency Announcement

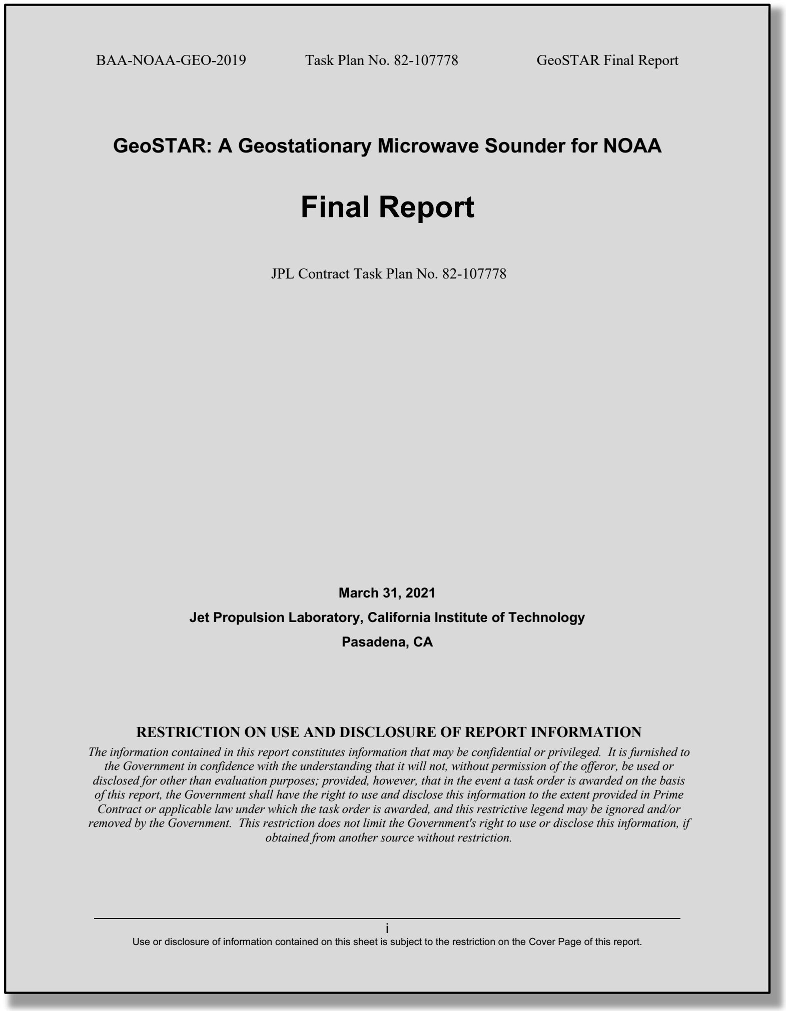
BAA-NOAA-GEO-2019

October 3, 2019

Office of Systems Architecture and Advanced Planning (OSAAP)
National Environmental Satellite, Data, and Information Service (NESDIS)
National Oceanic and Atmospheric Administration (NOAA)
Department of Commerce (DOC)

Aug-Dec, 2020: JPL conducts a study of concept for a GEO microwave sounder

Study team:
P. Kangaslahti
O. Montes
N. Niamsuwan
D. Posselt
J. Roman
M. Schreier
A. Tanner
L. Wu
I. Yanovsky



BAA-NOAA-GEO-2019 Task Plan No. 82-107778 GeoSTAR Final Report

GeoSTAR: A Geostationary Microwave Sounder for NOAA

Final Report

JPL Contract Task Plan No. 82-107778

March 31, 2021
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA

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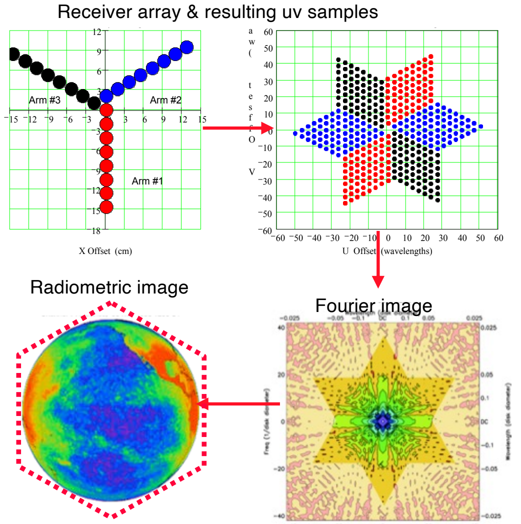
Mature instrument concept

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

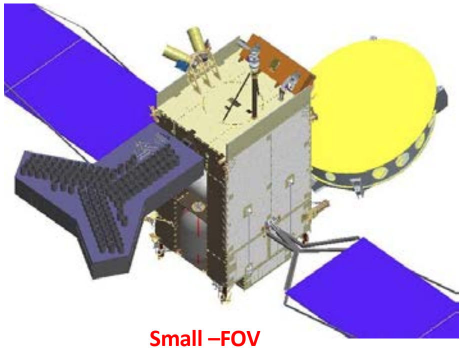
- Optimal Y-configuration: 3 sticks; N elements
- Each element is one I/Q receiver, 3.5λ wide (2.1 cm @ 50 GHz; 6 mm @ 183 GHz!)
- Example: N = 100 ⇒ Pixel = 0.09° ⇒ 50 km at nadir (nominal)
- Can cover two bands with a single array:
  - T-sounding at 118 GHz
  - q-sounding at 183 GHz



The antenna is the key

- *Antenna size is determined by distance and "spatial resolution"*
- *AMSU antenna is 6" in dia. and gives 40-km resolution from 705 km*
- *GEO orbit is ~36000 km ≈ 50 x 705 km*
- *AMSU-antenna must then be 50 x 6" to give 40-km res. from GEO ≈ 25 ft. Too big!*
- *To get 50-km res. at 50 GHz we need 20 feet. Still can't be done*
- *If we go from 50 GHz to 118 GHz, we still need 8.5 ft*
- *If we want 25 km res at 118 GHz we need a 17-ft antenna*
- *Efficient design could yield ~ 10 ft = 3 m*
- *But a STAR antenna is 30% smaller!*

Fully functional proof-of-concept prototype at TRL 6

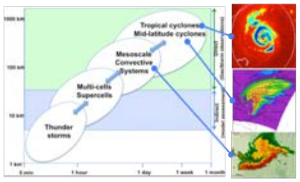


Small –FOV implementation can be flown as a hosted payload

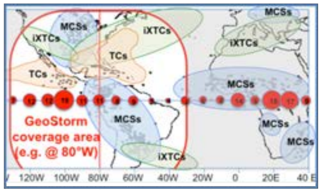
"GEOSTORM" – A GEOSTATIONARY MICROWAVE SOUNDER MISSION FOCUSED ON SEVERE STORMS

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

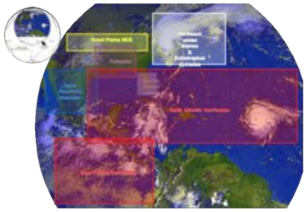
- ***hurricanes***
- ***severe thunderstorms and mesoscale convective systems***
- ***mid-latitude cyclones and winter storms***



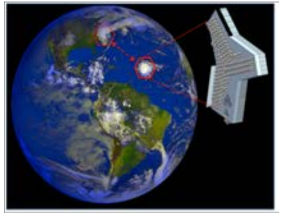
GeoStorm Highlights	
Targeted observations	Life cycle storm tracking
Time-continuous	Capture dynamic processes; diurnal cycle fully resolved
Multiple simultaneous key parameters	Temperature, humidity, precipitation, wind
All-weather	Cloud/rain-penetrating
3-D observations	1000 km dia x 15 km vert. (volume);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



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

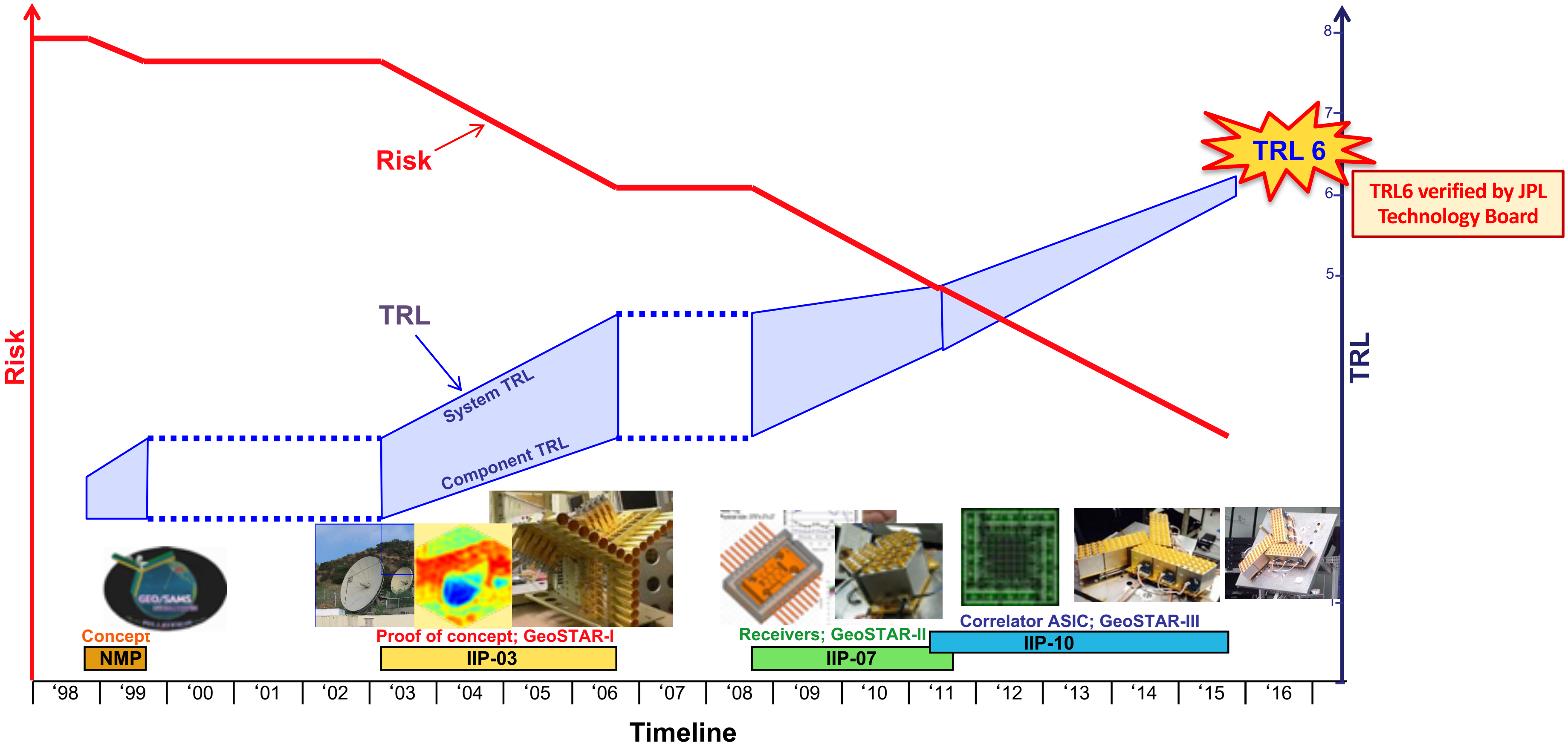


Articulated antenna enables targeted observations



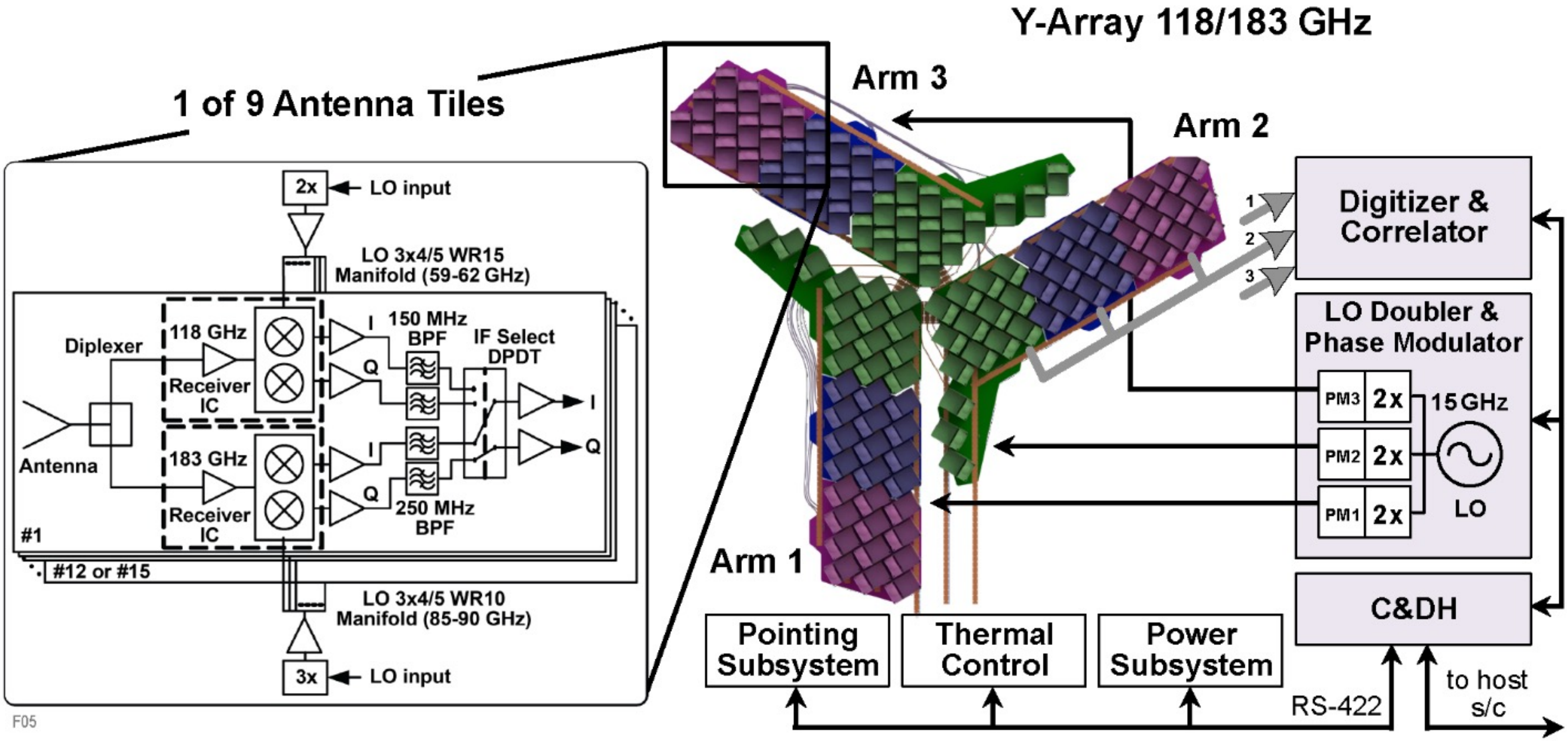
Technology readiness

NASA investments since 1999 → TRL 6: Ready to implement for space



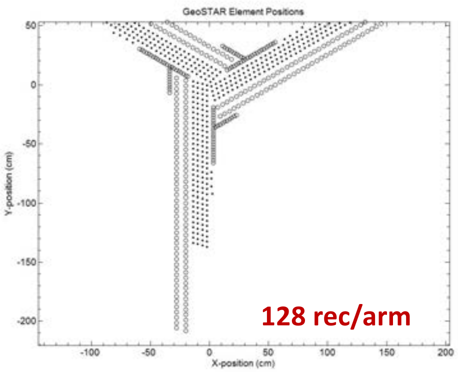
Realizable instrument architecture

Example: Low-cost small-FOV implementation ("GeoStorm")

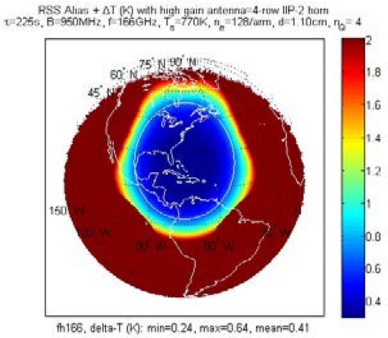


Large trade space

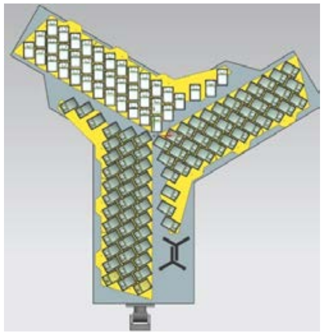
- **Number of receivers per arm determines overall FOV**



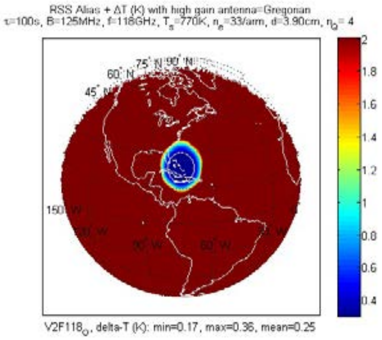
128 rec/arm



5000 km FOV

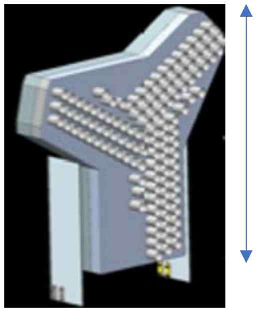


39 rec/arm



1000 km FOV

- **Overall size determines spatial resolution**

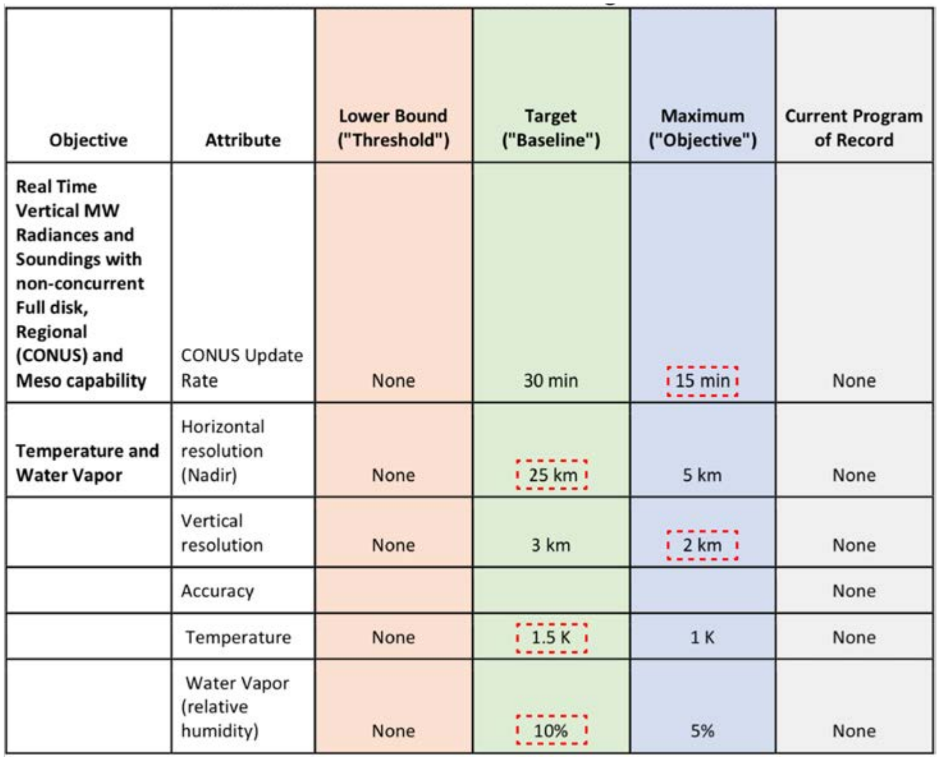


2.5 m → 25 km res
4 m → 15 km res

- **Channel set defined in S/W**
  - Can reconfigure by on-orbit command
  - Legacy channel set for conventional soundings
  - Can approximate "hyperspectral" sounding
- **Temporal resolution trades against sensitivity**
  - 1.5 minutes for full image → NEDT ~ 1 K
  - 15-minute averaging in GDS → NEDT ~ 1/3 K
- **Small-FOV instrument can be hosted on comm-sat**

GeoSTAR performance meets NOAA's requirements

NOAA requirements vs. GeoSTAR performance



Objective	Attribute	Lower Bound ("Threshold")	Target ("Baseline")	Maximum ("Objective")	Current Program of Record
Real Time Vertical MW Radiances and Soundings with non-concurrent Full disk, Regional (CONUS) and Meso capability	CONUS Update Rate	None	30 min	15 min	None
Temperature and Water Vapor	Horizontal resolution (Nadir)	None	25 km	5 km	None
	Vertical resolution	None	3 km	2 km	None
	Accuracy				None
	Temperature	None	1.5 K	1 K	None
	Water Vapor (relative humidity)	None	10%	5%	None

All-sky performance:

Performance in cloudy sky = in clear sky
Retrievals possible in precipitation

← 1.5 minutes possible, far exceeding req's

← 25 km in baseline design, higher-res. design possible

← 1-3 km, depending on environmental conditions

← 1-1.5 K, depending on environmental conditions

← 5-10%, depending on environmental conditions

Excellent instrument performance

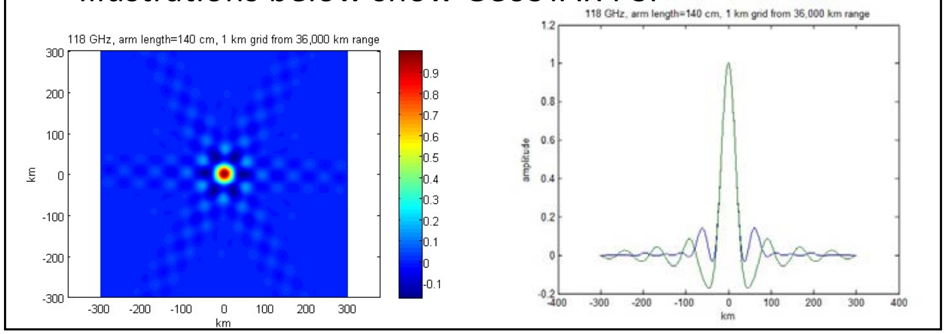
Performance of small-FOV implementation

- Channels are measured sequentially in rapid repeat cycle
  - This is done by driving the LO with with a digitally controlled synthesizer
- Basic 90-second measurement cycle:
  - 6 channels in 118-GHz band (Tsys ~ 695 K): Allocated 11 sec each → NEDT ~ 0.5 K
  - 4 channels in 183-GHz band (Tsys ~ 820 K): Allocated 6 sec each → NEDT ~ 1 K
- Averaging interval of 15 minutes for normal soundings:
  - 118-GHz channels: NEDT ~ 0.15 K
  - 183-GHz channels: NEDT ~ 0.3 K
  - This performance matches or exceeds that of ATMS
- Time allocation between channels can be changed by on-orbit command
- Channel frequencies can be changed by on-orbit command
- Number of channels can be changed by on-orbit command

- Spatial resolution is similar to current LEO sounders:
  - 25 km for 183-GHz channels, used for water vapor sounding
  - 38 km for 118-GHz channels, used for temperature sounding

Excellent spatial characteristics

GeoSTAR is a “truncated” spatial interferometer
It therefore exhibits interferometric sidelobes
These cause image artifacts and must be removed
Illustrations below show GeoSTAR PSF

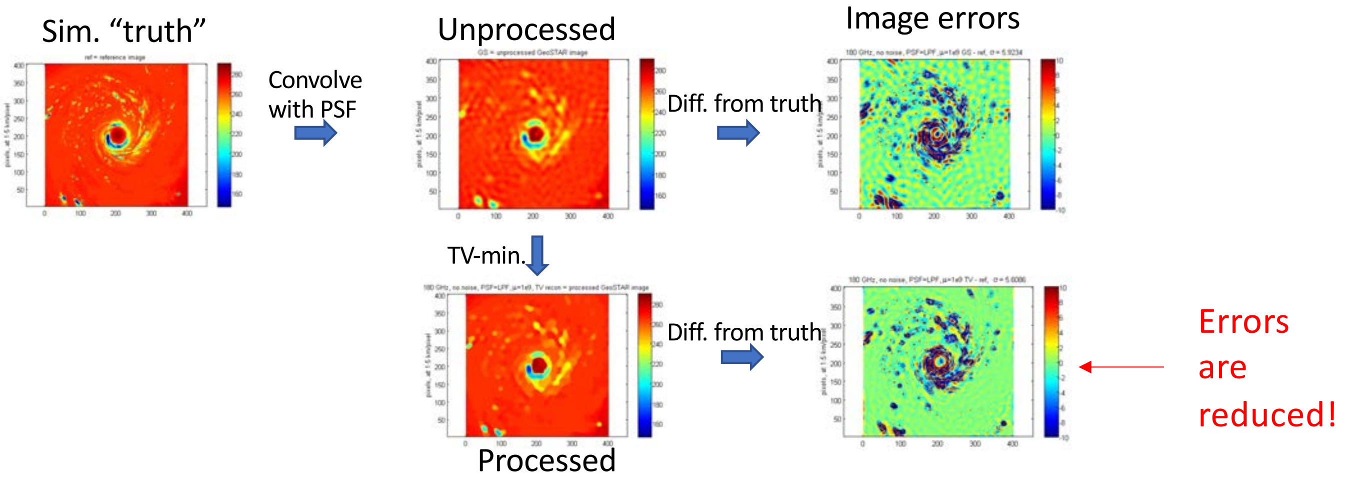


Apodization is conventionally used to suppress sidelobes
But that degrades spatial resolution
We desire is to maximize spatial resolution

Our solution: Image restoration by deconvolution
Our method: Total Variation (TV) minimization
Result: Sidelobes are removed without amplifying noise
Spatial resolution is preserved
Effective beam efficiency is excellent

Evaluated with simulated observations of a hurricane
Sim = WRF @ 1.5 km res.
PSF = GeoSTAR @ 25 km

TV-min results are statistically indistinguishable from applying a 25-km Gaussian
Effective beam efficiency ~ 100%


Sim. “truth”

Convolve with PSF

Unprocessed

Diff. from truth

Image errors

TV-min.

Diff. from truth

Processed

Errors are reduced!

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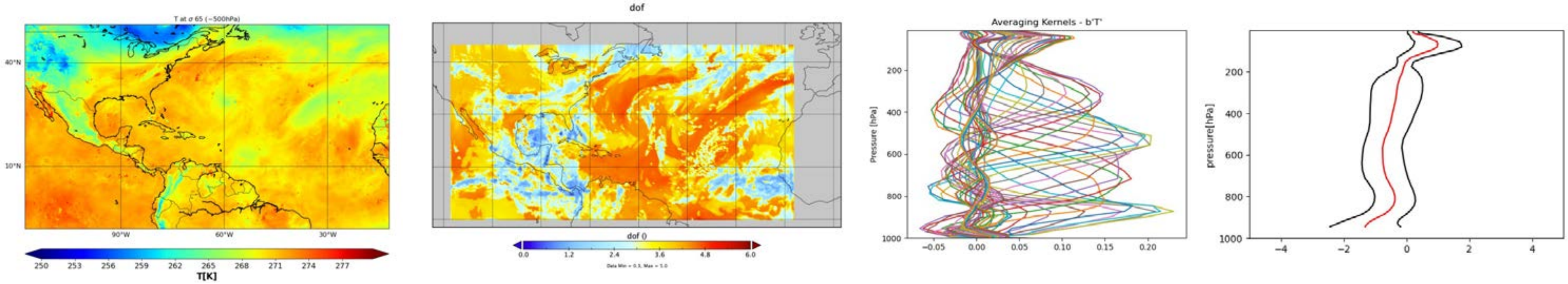
Excellent geophysical performance

With radiometric performance similar to AMSU and ATMS, geophysical retrievals can be derived from GeoSTAR measurements also with similar accuracy and precision

To verify and characterize that performance, we carried out simulation studies using a JPL-developed retrieval system operating on data representing a WRF simulation of Hurricane Harvey (2017)

Example results are for non-precipitating scenes. Retrievals are also done in precipitating scenes

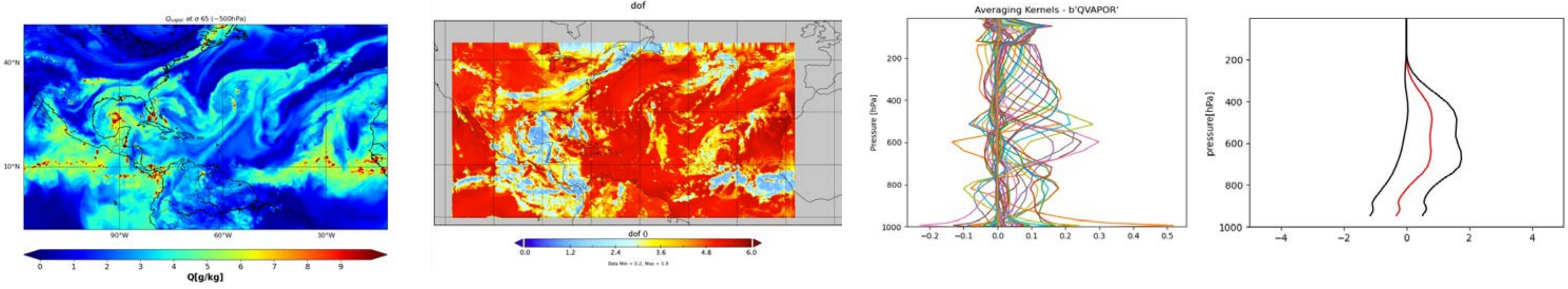
Temperature



Temperature

Value at 500 mb **Degrees of freedom of information** **Averaging kernels** **Retrieval error (rmse)**

Water vapor



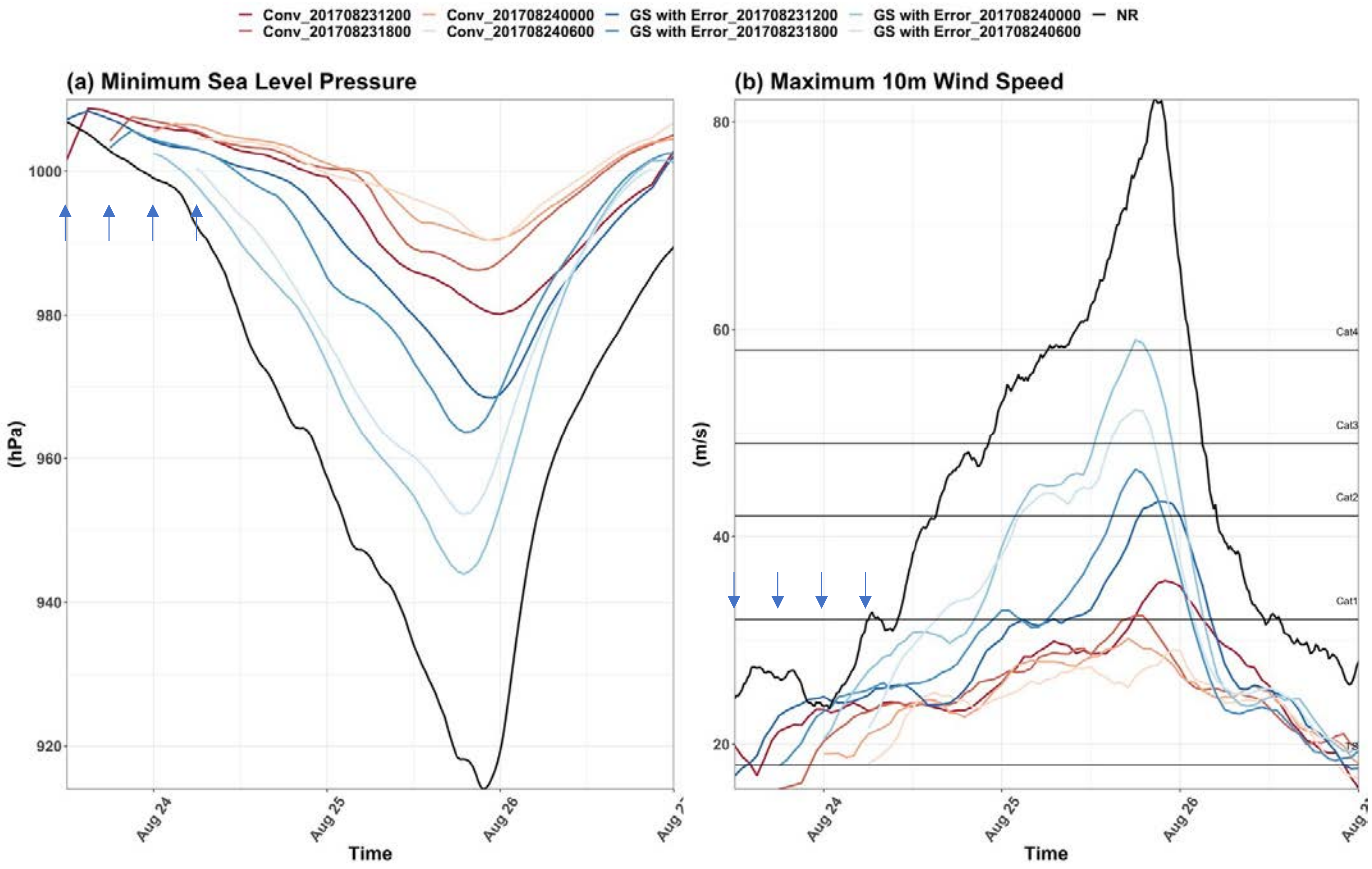
Water vapor

Key application: Numerical weather prediction

Forecast Performance: TC intensity. Example: Sim. of Cat. 5 hurricane

Assimilation of conventional data + all-sky GeoSTAR with realistic errors improves forecast to cat-4

Assimilate All-Sky GeoSTAR Soundings (Pcp < 1 mm/hour)



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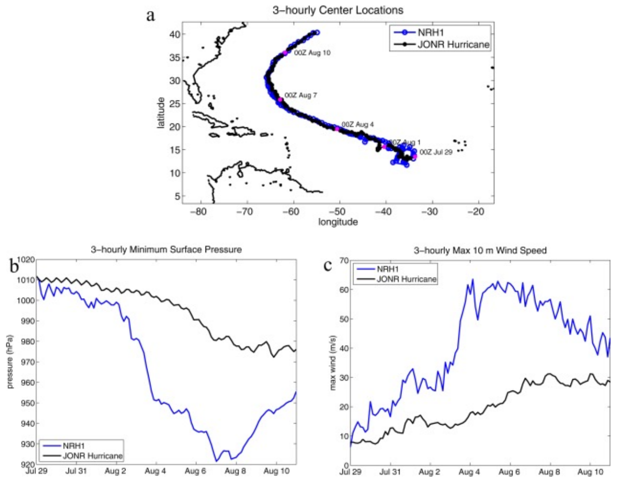
Product highlight: All-weather atmospheric wind

Method based on tracking water vapor

Available at all levels, sfc to 300 mb

Available in & below clouds

OSSE study using NOAA hurricane nature run:

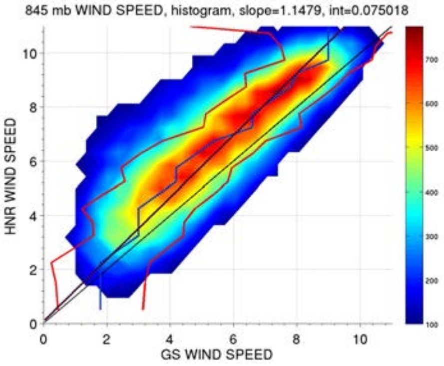


Journal of Advances in Modeling Earth Systems
Volume 5, Issue 2, pages 382-405, 13 JUN 2013 DOI: 10.1002/jame.20031
http://onlinelibrary.wiley.com/doi/10.1002/jame.20031/full#jame20031-fig-0004

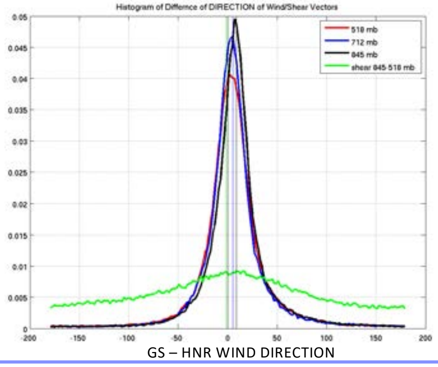
Results with large sample size (> 5000); cases with rain rate < 1 mm/hr only

Pressure level (mb)	Bias		RMS error	
518	-0.8 m/s	2°	1.9 m/s	14°
712	-1.2 m/s	3°	1.6 m/s	11°
845	-1.0 m/s	6°	1.7 m/s	10°

Wind speed: Histogram @ 845 mb

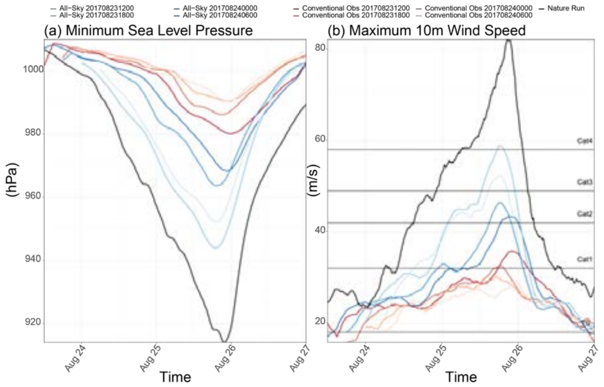


Wind direction: 3 pressure levels

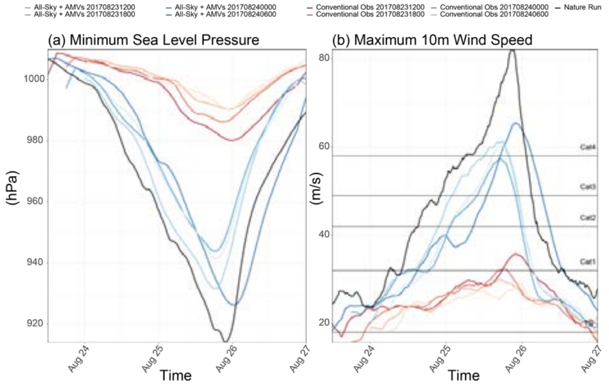


<u>Large forecast impact from assim. wind:</u>

All-sky, no wind



All-sky, with wind

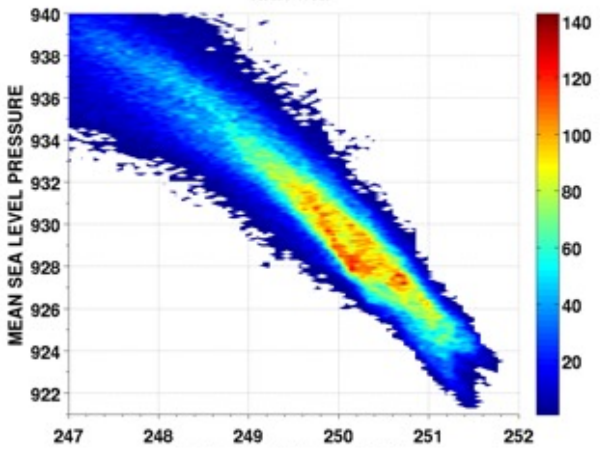


Key application: Hurricane intensity

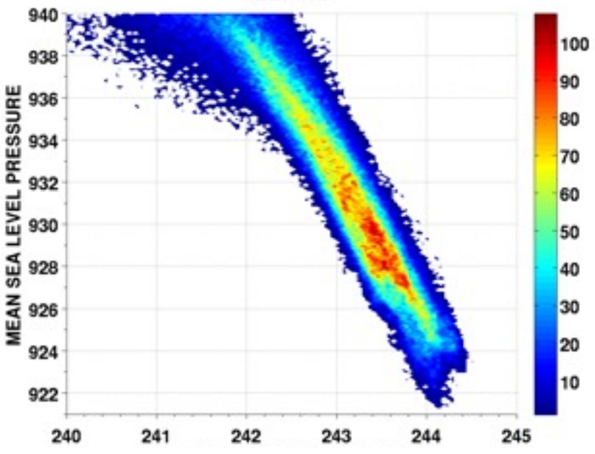
- Method is based on correlation between TC intensity and warm core anomaly as measured by MW channels with peak sensitivity in upper troposphere
- NHC uses algorithm developed by U. Wis./CIMSS using AMSU or ATMS channels.
- Peak sensitivity is found in 54.94-GHz channel, peaking at 250 mb
- Equivalent GeoSTAR channel is 119.95 GHz, also peaking at 250 mb

Below: NOAA nature-run simulations; GeoSTAR (left) vs. AMSU/ATMS (right)

- GeoSTAR channel is more sensitive: 0.25 K/mb vs. 0.14 K/mb for AMSU
- Projected MSLP precision is significantly better than for AMSU/ATMS



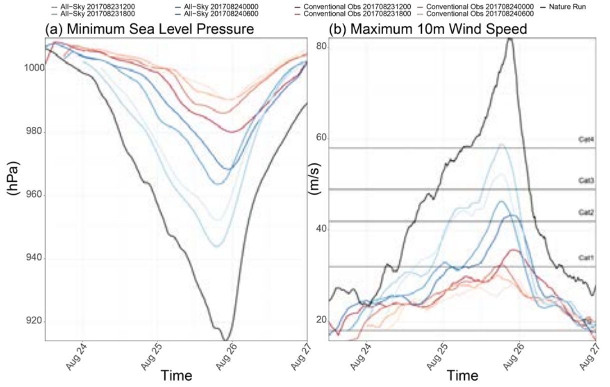
GeoSTAR (119.55 GHz)



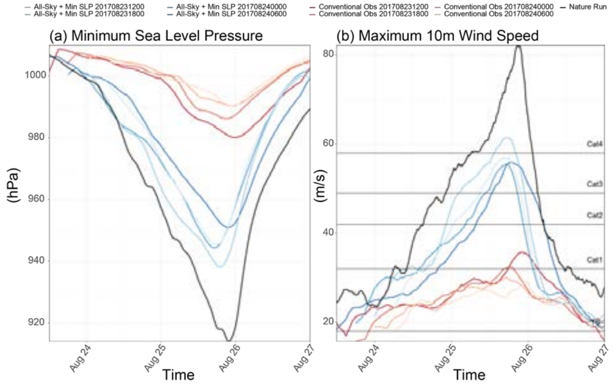
AMSU/ATMS (54.94 GHz)

Some forecast impact from assim. minMSLP:

All-sky, no minMSLP



All-sky, with minMSLP



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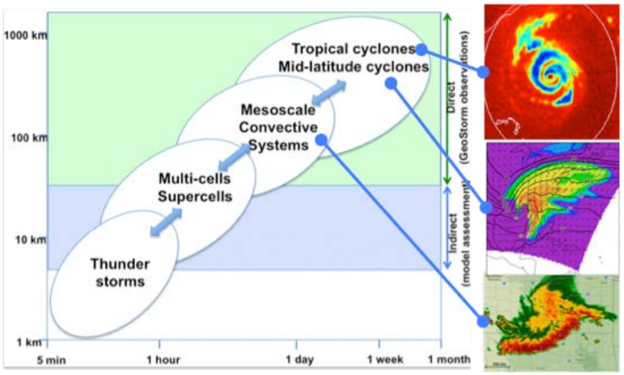
Next? “GeoStorm”: A low-cost GEO/MW mission concept

A GEOSTATIONARY MICROWAVE SOUNDER MISSION TARGETING SEVERE STORMS

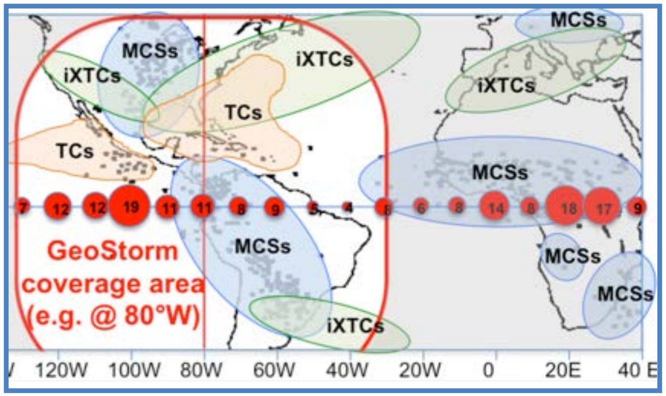
Real-time observations of severe storms, improved forecasting, nowcasting & damage assessment:

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



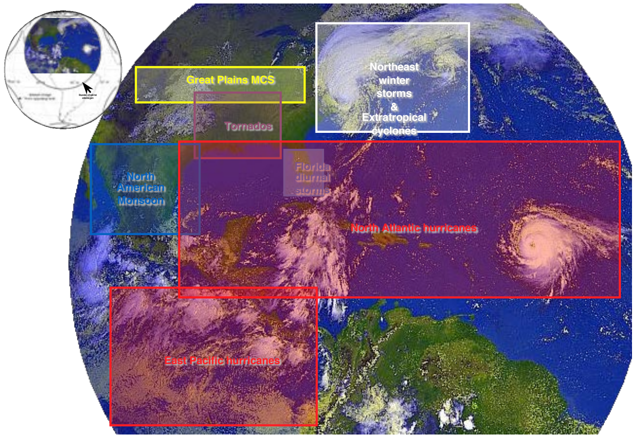
GeoStorm Highlights	
Targeted observations	Life cycle storm tracking
Time-continuous	Capture dynamic processes; diurnal cycle fully resolved
Multiple simultaneous key parameters	Temperature, humidity, precipitation, wind
All-weather	Cloud/rain-penetrating
3-D observations	1000 km dia x 15 km vert. (volume);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

Low cost as a hosted payload

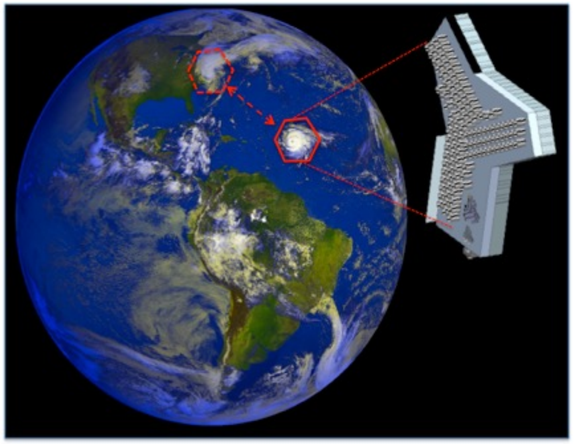


There are more than 80 GEO comm-sats that provides a view of the Americas, being replaced at a rate of 5-6 per year

Real-time in-depth observations of convective storms



Articulated antenna enables targeted observations



This recommended mission implementation, while operator intensive, will meet all of NOAA’s needs and numerous research objectives