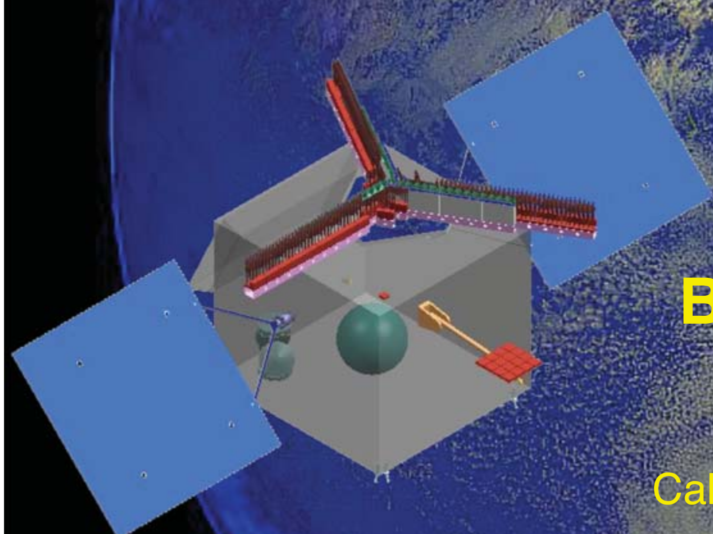
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Will we soon have a

Geostationary Microwave Sounder

and what can we do with it?



Bjorn Lambrigtsen

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62nd IHC

Charleston; March 3-7, 2008

Summary

- **Will we…? Can we…?**

  Yes, if we move quickly to take advantage of the current GOES-R/S opportunity

- **What would it* do?**

  Provide time-continuous microwave sounding from GEO

  - Primary focus on *hurricanes*
    - Addresses significant hurricane issues: now-casting, improved intensity observations/models
    - Urgent societal need for this mission in view of growing U.S. hurricane vulnerability
    - Significant synergy with *GPM* (fills spatio-temporal precip gaps) and *scatterometers* (adds tropo. winds)
  - Greatly-improved boundary layer, cloud and precipitation process *models*
    - Major science advances in the understanding of hydrology cycle, El Niño, monsoons *and hurricanes*

- **Recent mission studies commissioned by NASA and NOAA**
  - Proven instrument concept meets measurement requirements and is ready for flight development
  - Mission development can begin ahead of the 2010 NRC suggested start date
  - Reasonable payload cost/mass/power: $120M/230 kg/260+80 W (*will be reduced*)

- **NASA-NOAA teaming opportunity**
  - Opportunity created by cancellation of GOES-R/HES
  - Urgent action required to use ex-HES slot for GeoSTAR as MOO on GOES-R and/or GOES-S
  - Unique opportunity to greatly enhance hurricane remote sensing at low incremental cost
  - *Strong advocacy required!*
    - User communities must speak up

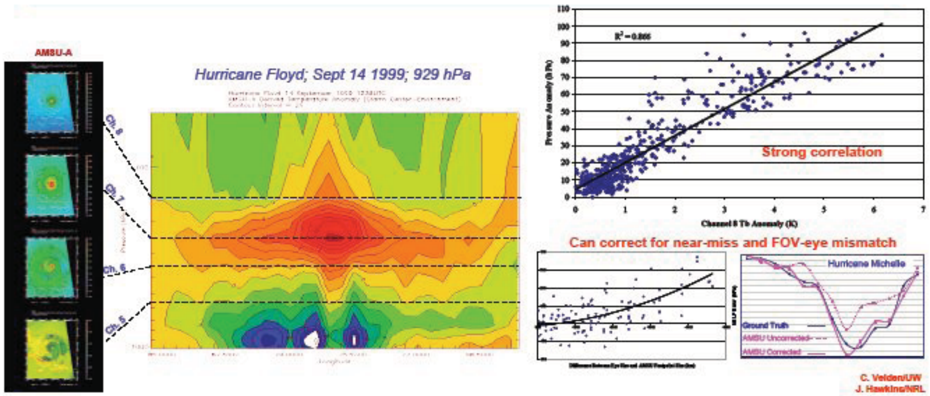
*** GeoSTAR**

GEO/MW Sounder Applications

- **Weather forecasting** -Improve regional forecasts; severe storms
  - All-weather soundings - standalone, but also complements IR soundings
  - Full hemispheric soundings @<50/25 km every ~ 15-30 minutes (continuous)
  - "Synoptic" rapid-update soundings => Forecast error detection; 4DVAR applications
- **Hurricane diagnostics** -Quintessential hurricane sensor
  - Scattering signal from hurricanes/convection easily measurable
  - Measure *location*, *intensity* & vertical *structure* of deep convection
  - Detect *intensification/weakening* in NRT, frequently sampled (< 15 minutes)
  - Measure all three phases of water: vapor, liquid, ice - including rain/snow
  - Use for operational analysis & in research to improve microphysics of models
- **Rain** -Complements GPM
  - Full hemisphere @ ≤ 25 km every 15 minutes (continuous) - both can be improved
  - Directly measure storm and diurnal *total rainfall*: predict flooding events
  - Complements GPM (TRMM): fill space-time gaps through "data fusion" methods
  - Measure *snowfall*, light rain, intense convective precipitation
- **Tropospheric wind profiling** -NWP, transport applications
  - Surface to 300 mb; very high temp.res.; in & below clouds
  - Major forecast impact expected (OSSE planned) - particularly for hurricanes
  - Air quality applications (pollution transport)
- **Climate research** -Hydrology cycle, climate variability
  - Stable & continuous MW observations => Long term trends in T & q and storm stats
  - Fully resolved diurnal cycle: water vapor, clouds, convection
    - "Southwest" monsoon; tropical moisture flow into the US; genesis of severe storms
  - "Science continuity": GeoSTAR channels = AMSU channels

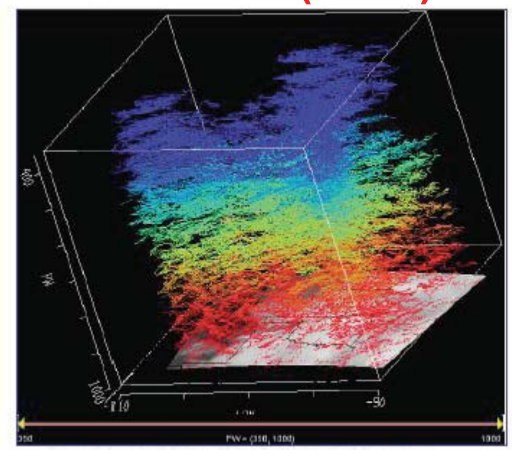
Measurement Highlights

Hurricane intensity (warm core anomaly)



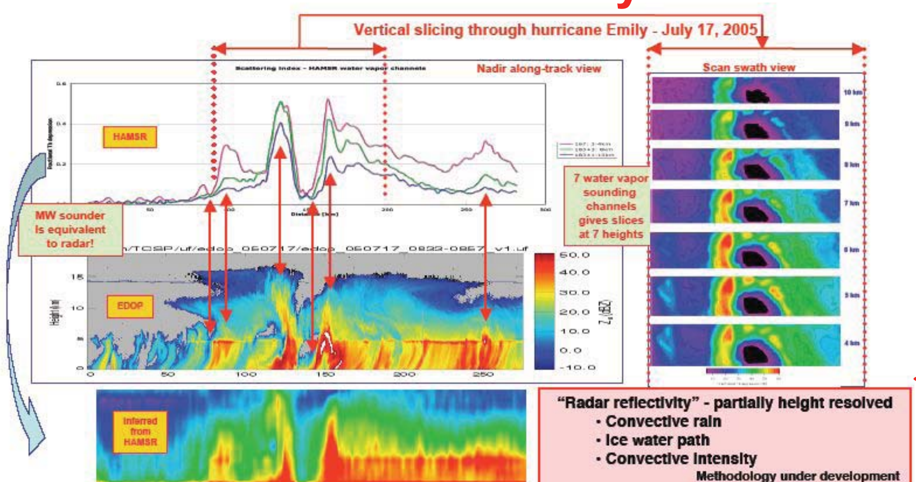
Tropospheric wind vectors (AMV)

- Current capabilities
  - LEO satellites: MODIS
    - Polar regions only
    - Limited-accuracy water vapor profiles
  - GEO satellites: IR sounder
    - Poor sampling: clear only
    - Uncertain height assignment
  - GEO satellites: IR/Vis imager
    - Cloud tracking: cloud tops only
- PATH capabilities
  - Clear AND cloudy
    - Including below clouds
  - Continuous: no time gaps
  - Applicable algorithms available
    - UW (Velden et al.)



Example wind vectors from GIFTS simulations
(3 x 30-minute intervals, 1–2 km vertical resolution, clear only)
C. Velden

"Radar reflectivity"



Correlation between MW-sounder ΔTb and radar reflectivity exceeds 90% at all levels except near surface

Precipitation

⇐ "Radar reflectivity" method most promising for precipitation

All of the above can be used in operational analysis of
intensity, size, location of convective center
in 3 dimensions ⇒ assessment of vertical shear

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A GEO/MW Sounder Is Broadly Justified

NASA	**Strategic Plan (2006)**	***Goal 3A***	*Study Earth from space to advance scientific understanding and meet societal needs*
	Science Plan (2007)	***Science questions***	**Variability:** *How are global precipitation, evaporation, and the cycling of water changing?*
			Response: *What are the effects of clouds and surface hydrologic processes on Earth's climate?*
			Consequences: *How are variations in local weather, precipitation, and water resources related to global climate variation ?*
			Prediction: *How can weather forecast duration and reliability be improved?* *(How will water cycle dynamics change in the future?)*
		Missions	**Weather FA:** *GeoSTAR: Geostationary synthetic aperture microwave radiometer*
	Roadmaps (2005-06)	***Weather FA***	**GEO Microwave sounding**: *Improved short-term forecasts*
NOAA	**Strategic Plan (2005)**	***Climate***	*Describe and understand the state of the climate system through integrated observations, analysis, and data stewardship*
		Weather	*Increase lead time and accuracy for weather and water warnings and forecasts*
			Improve predictability of the onset, duration, and impact of hazardous and severe weather and water events
			Increase development, application, and transition of advanced science and technology to operations and services
	Priorities	***Observations***	**Capable and reliable observation infrastructure**: *Platform investments needed to meet high priority program requirements*
		Forecasts	**Forecast accuracy for high impact weather**: *Accurate short-term hurricane intensity forecasts*
	NESDIS Strategic Plan (2005)	***NOAA Mission Support***	*Provide timely and effective acquisition and delivery of satellite-derived information that supports requirements from the mission goals*
			Provide applied research to ensure the quality, reliability, and accuracy of current and future satellite products and services to support the NOAA mission goals
		Geostationary Satellite Acquisition	*By 2010, through its technology infusion planning activity, NESDIS will have determined the best methods for the following technologies:* ***… Microwave imaging and sounding systems from geostationary orbit***
	GOES-R (2004)	***GPRD P3I requirements***	*(A large number of P3I products requires a microwave sounder)*
	Hurricane Intensity WG (2006)	***Science Advisory Board report***	*Reduce the error in 48-hour intensity forecasts for hurricane-strength storms by at least 10 kt within the next five years, with an emphasis on improved forecasting of rapid intensification and decay, and decay and reintensification cycles*
			Improve hurricane observing systems
NRC	**Decadal Survey (2007)**	***PATH mission***	**Needs**: *Early identification and reliable forecasting of the track and intensity of tropical cyclones* *Geographic distribution and magnitude of storm surge and rain accumulation totals during and after landfall* *Observations: 3D atmospheric temperature & water vapor; SST; precipitation; all-weather conditions (clear and cloudy); temporal refresh every 15-30 minutes*
			Scientific objectives: *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 by enabling frequent re-initialization by observations* *Enable major scientific advances in understanding of El Niño, monsoons, and the flow of tropical moisture to the U.S.*
			Mission & payload: *MEO or GEO; Recommend all-weather sensor suite on future GOES platforms; Require 50 or 118 GHz and 183 GHz; Microwave array spectrometer; Suitable for start in 2010 time frame*

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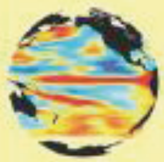
NRC Decadal Survey

NASA is committed to implementing the Decadal-Survey missions, but current funding of SMD/ESD dictates a stretched out schedule

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	$450 M

= GeoSTAR!

Note: The NRC panel put PATH in the 3rd group, reflecting their perception of the maturity of the required technology
Recent developments indicate a higher level of readiness, and it may be feasible to implement PATH earlier than thought

Hurricane Observing Needs (simplified)

- **Why is track forecasting progressing well?**
  - Analogous to global NWP performance (also progressing)
  - Models: Good capture of large-scale dynamics; sub-grid parameterization works OK
  - Observations: Satellites capture synoptic conditions well
  - Result: *Large-scale* forecasts are progressing
- **Why is intensity forecasting stagnant?**
  - *This is the real "storm forecasting" problem*
  - Models: Must capture mesoscale & microscale
    - Sub-grid parameterization is not adequate - must capture real physics at true scale
  - Observations: Storms are not well observed
    - Spotty coverage by both in-situ, aircraft & LEO satellites
    - GEO satellites do not observe microphysics & internal dynamics
  - Result: *Mesoscale/storm* forecasts are not progressing
- **What do we need?**
  - Models: High resolution with correct/complete physics
    - Model runs must be initialized with valid & complete observations
  - Observations: "Storm sensors" with frequent observations
    - Must observe inside & below storm
    - Must capture microphysics and mesoscale dynamics
    - Frequent/continuous observations $\Rightarrow$ GEO satellites, "dwelling" UAS, long-range land stations
  - In short: **Better fidelity, higher resolution, deeper penetration, vertical structure**

Why GEO Microwave Sounders?

- **GEO sounders achieve high temporal resolution**
  - LEO: Global coverage, but poor temporal resolution; high spatial res. is easy
  - GEO: High temporal resolution and coverage, but only hemispheric non-polar coverage; high spatial res. is difficult
  - Requires equivalent measurement capabilities as now in LEO: IR & MW
- **MW sounders measure quantities IR sounders can't**
  - Meteorologically "interesting" scenes
    - Full cloud cover; Severe storms & hurricanes
  - Cloud liquid water distribution
  - Precipitation, convection & microphysics - vertical structure
- **MW sounders also complement IR sounders**
  - Complement primary IR sounder (HES) with matching MW sounder
    - Until now not feasible due to very large aperture required (~ 4-6 m dia. in GEO)
  - Microwave provides cloud/"cloud-clearing" information
    - Requires T-sounding through clouds - to surface under all atmospheric conditions
- **A MW sounder is one of the most desired GEO payloads**
  - High on the list of unmet capabilities

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Why Not Just IR Sounders?

IR vs. MW: Pros & Cons

IR sounders vs. MW sounders

Spatial resolution

- --IR vs. MW: 10-15 km vs. 15-50 km hor.res.; 1-1.5 km vs. ~2 km vert.res.

Basic sounding accuracy

- --IR vs. MW: 1 K vs. 1.5 K for T(z); 15% vs. 20% for q(z); none vs. 40% for L(z)

Scene coverage

- --Cloud free: IR outperforms MW (but IR = MW in coverage)
- --Partly cloudy: IR < MW (IR depends on "cloud clearing", a noise-amplifying process)
- --Fully cloudy, storms: MW far outperforms IR ("cloud clearing" cannot be done)

Hurricanes & severe storms

- --IR can only see cloud tops, often obscured by cirrus shields
- --MW can see to surface (except in heavy precipitation: switch to convection observations)

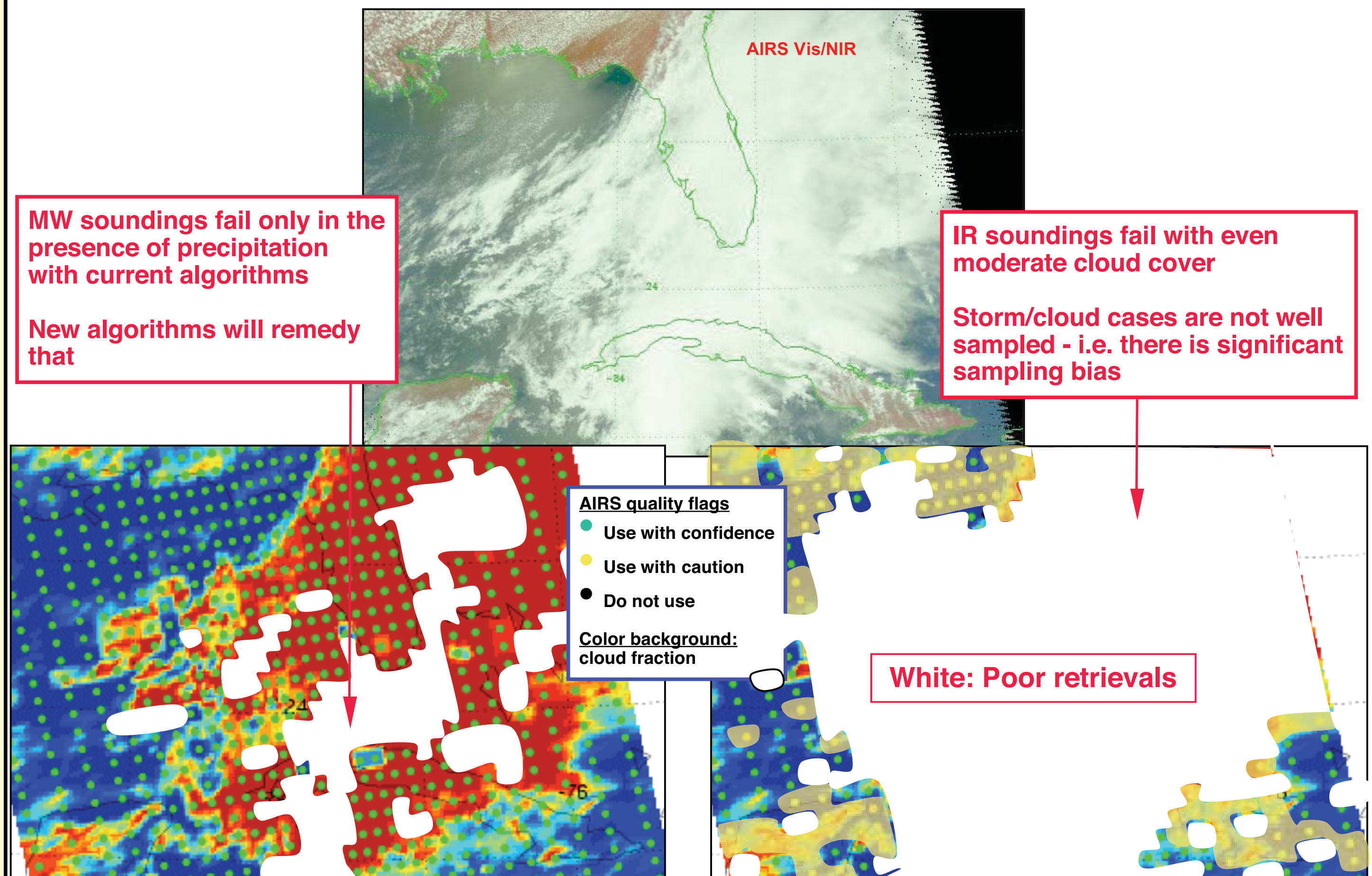
Summary

- --IR is best suited for global observations and storm precursor conditions in clear sky
- --MW is best suited for observing in/through storms and precursor conditions in clouds

Example

Tropical system near Florida observed with the Atmospheric Infrared Sounder (AIRS)

(May 16, 2006)



AIRS MW-only retrievals

AIRS IR+MW cloud-cleared retrievals

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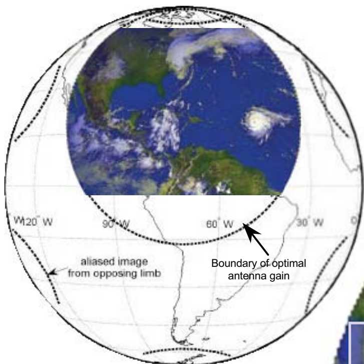
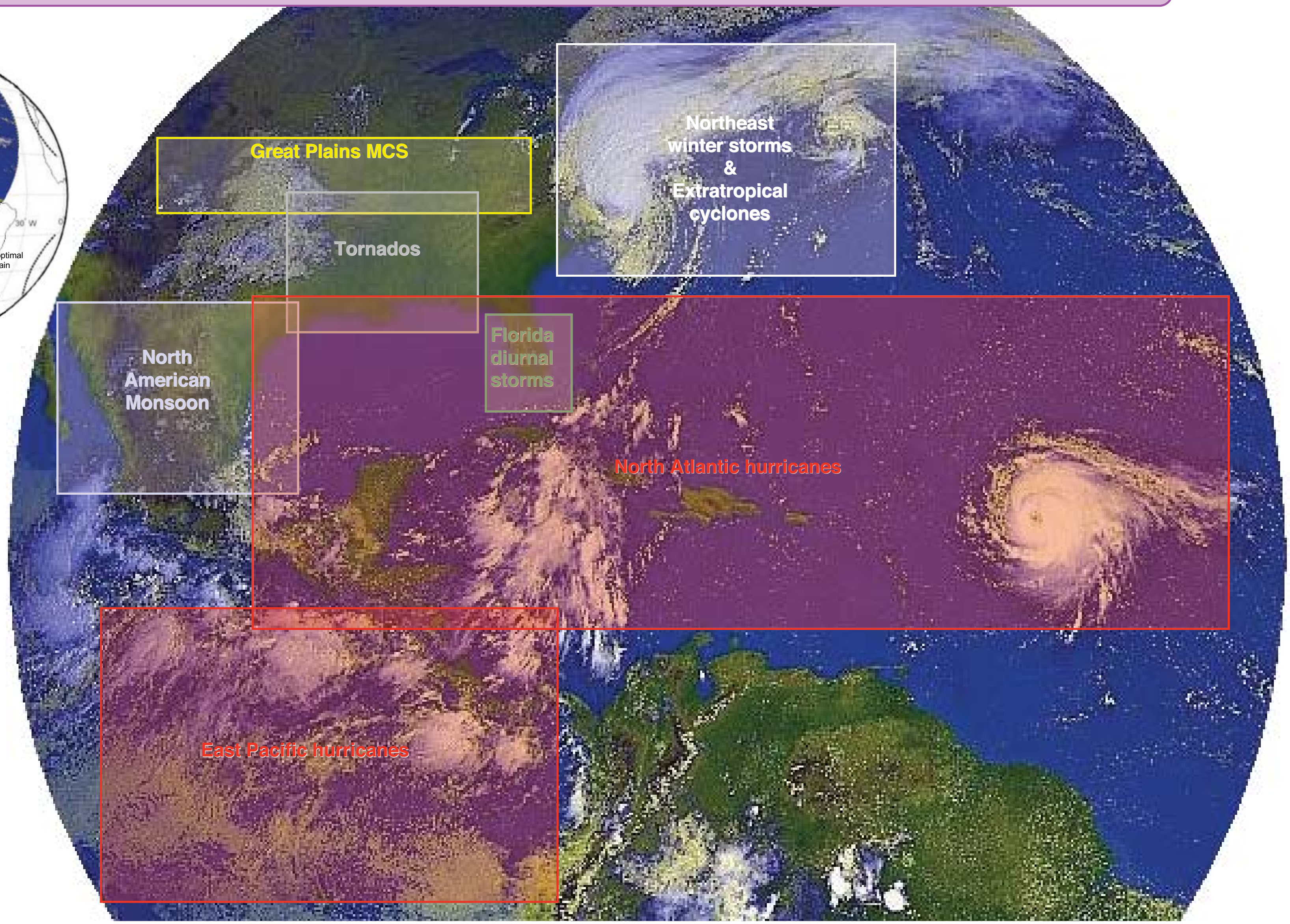
GeoSTAR/PATH Focus Themes

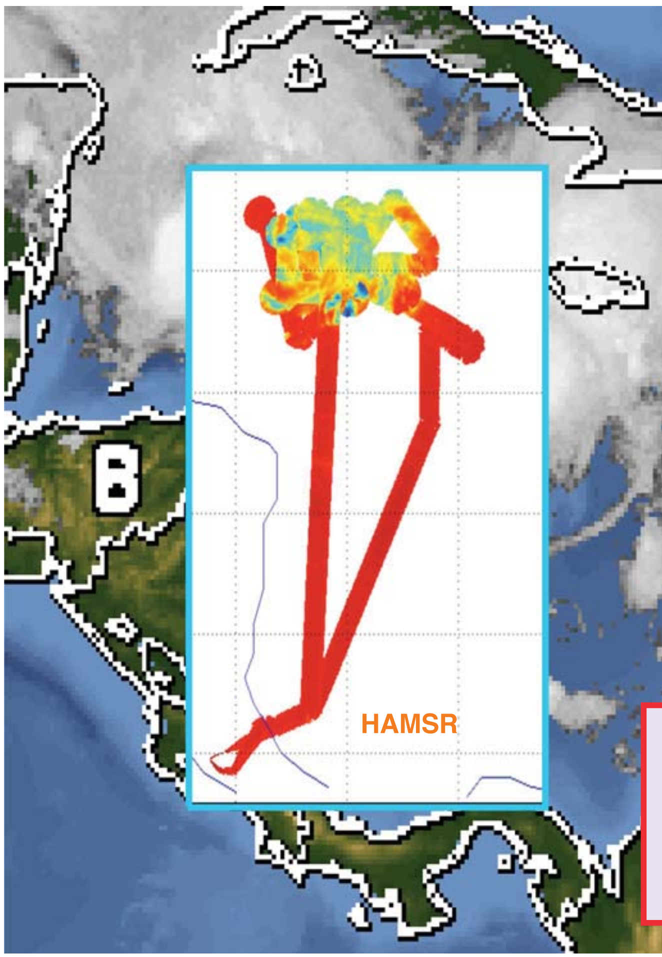


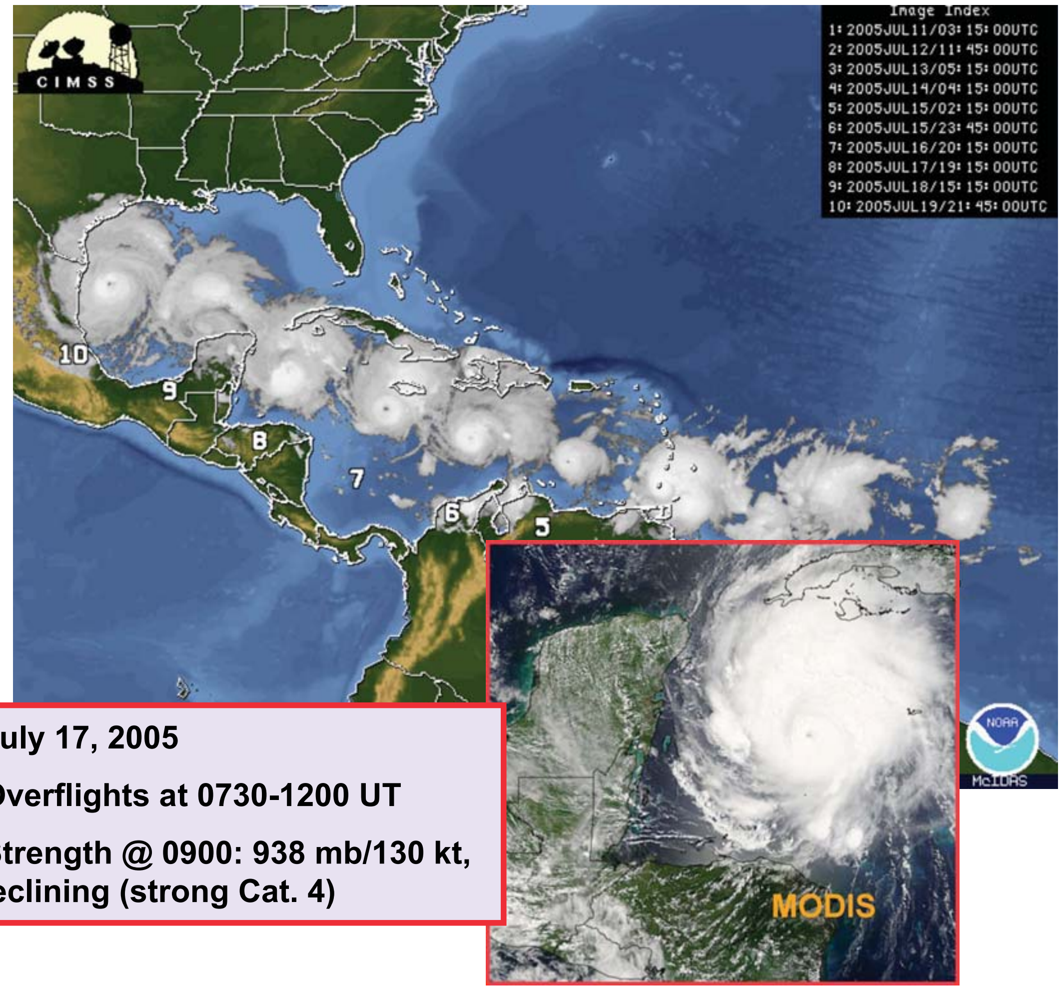


Field campaigns ⇒ New algoritms

TCSP: NASA hurricane field campaign, Costa Rica, July 2005

HAMSR (ATMS prototype built at JPL) flying on ER-2

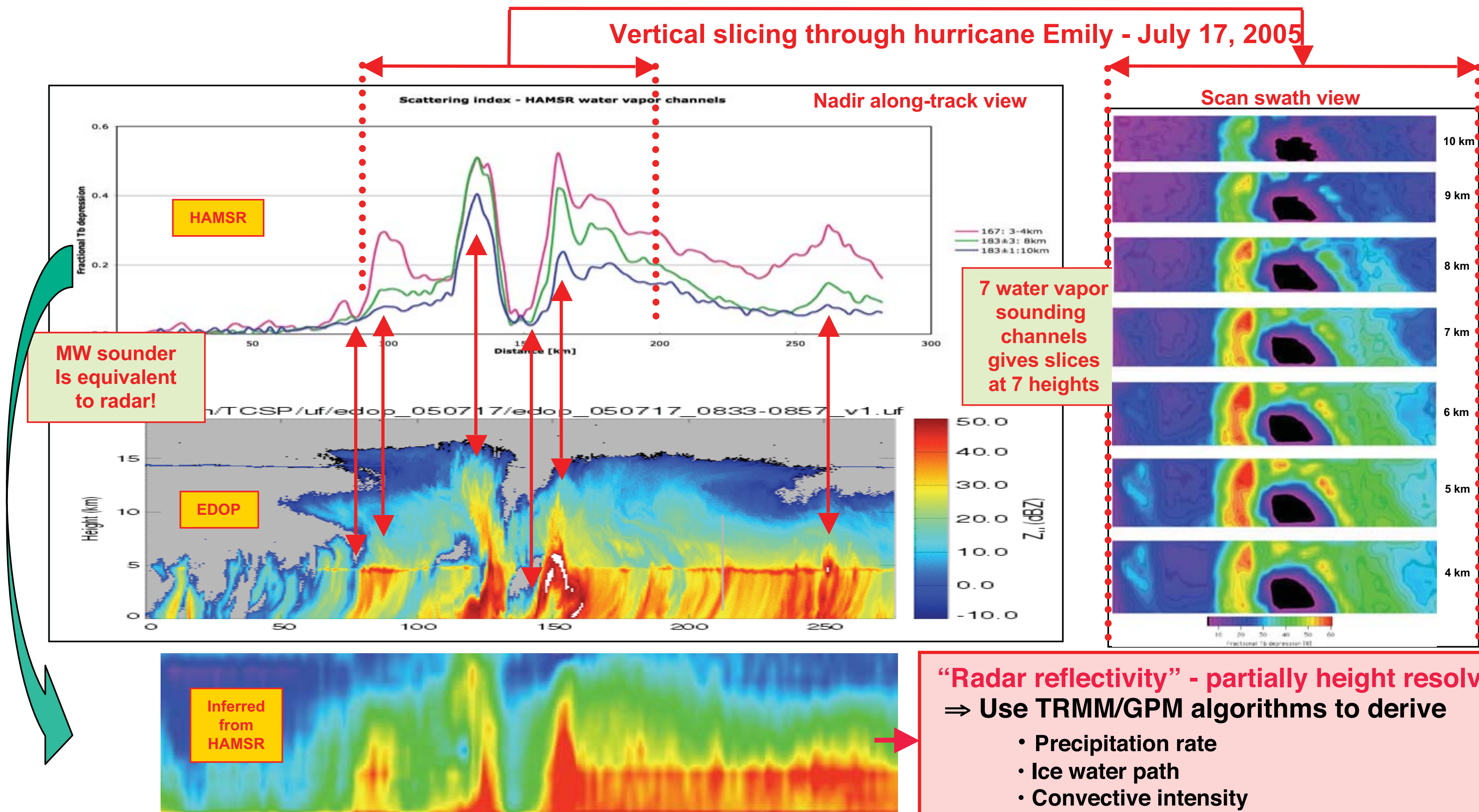




- **July 17, 2005**
- **Overflights at 0730-1200 UT**
- **Strength @ 0900: 938 mb/130 kt, declining (strong Cat. 4)**

New Data Product: “Radar Reflectivity”

Hurricane observations with MW sounder (HAMSR) compared with doppler radar (EDOP)
Observations from NASA TCSP campaign, Costa Rica, 2005



Correlation between MW-sounder ΔTb and radar reflectivity exceeds 90% at all levels except near surface

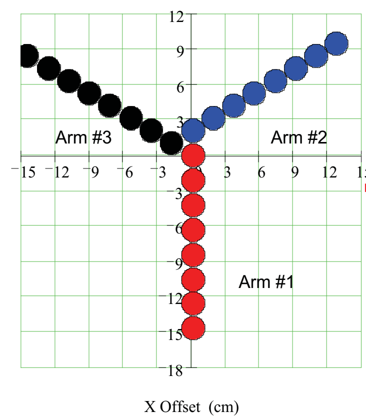
“Radar reflectivity” - partially height resolved
⇒ Use TRMM/GPM algorithms to derive
- Precipitation rate
- Ice water path
- Convective intensity

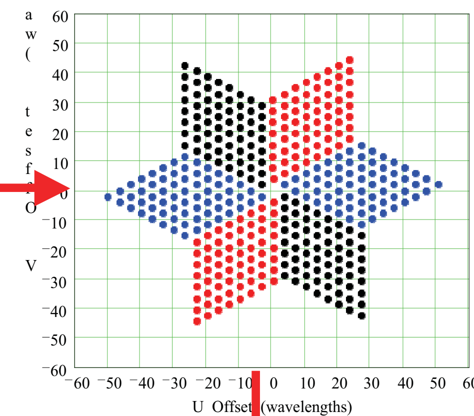
Methodology under development

GeoSTAR System Concept

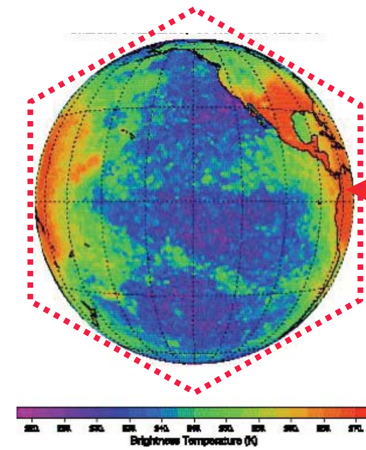
- **Aperture-synthesis concept**
  - Sparse array employed to synthesize large aperture
  - Cross-correlations -> Fourier transform of Tb field
  - Inverse Fourier transform on ground -> Tb field
- **Array**
  - Optimal Y-configuration: 3 sticks; N elements
  - Each element is one I/Q receiver, 3.5l wide (2.1 cm @ 50 GHz; 6 mm @ 183 GHz!)
  - Example: N = 100 Þ Pixel = 0.09° Þ 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

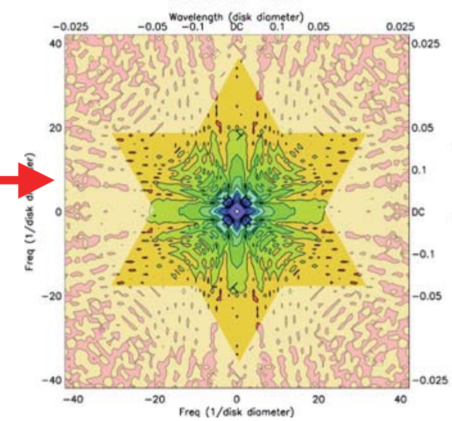
Receiver array & resulting uv samples





Example: AMSU-A ch. 1





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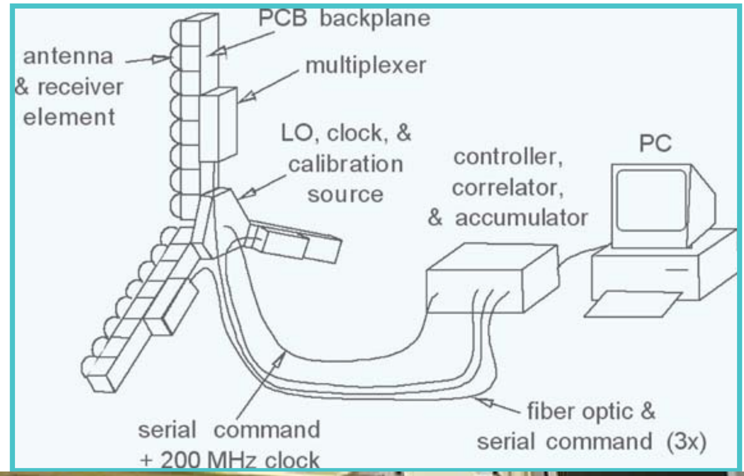
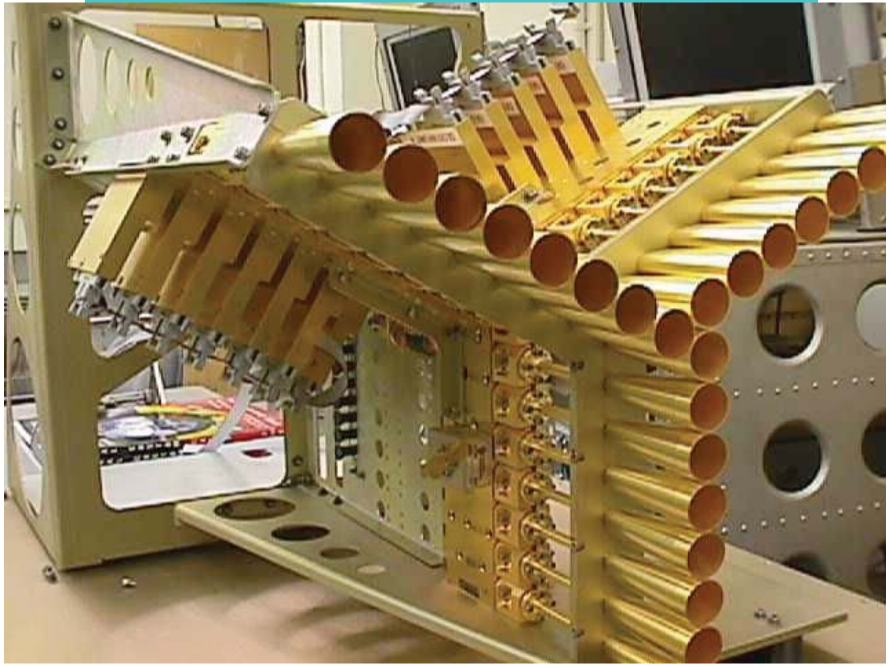
GeoSTAR Prototype Development

- **Objectives**
  - Technology risk reduction
  - Develop system to maturity and test performance
  - Evaluate calibration approach
  - Assess measurement accuracy
- **Small, ground-based**
  - 24 receiving elements - 8 (9) per Y-arm
  - Operating at 50-55 GHz
  - 4 tropospheric AMSU-A channels: 50.3 - 52.8 - 53.71/53.84 - 54.4 GHz
  - Implemented with miniature MMIC receivers
  - Element spacing as for GEO application (3.5 λ)
  - FPGA-based correlator
  - All calibration subsystems implemented





Has been thoroughly tested at JPL

Performance is excellent

Breakthrough development!

Ground-based sounding demonstrated

Observed diurnal cycle of T-inversion at JPL

The Proof Is in the Pudding

November 2005

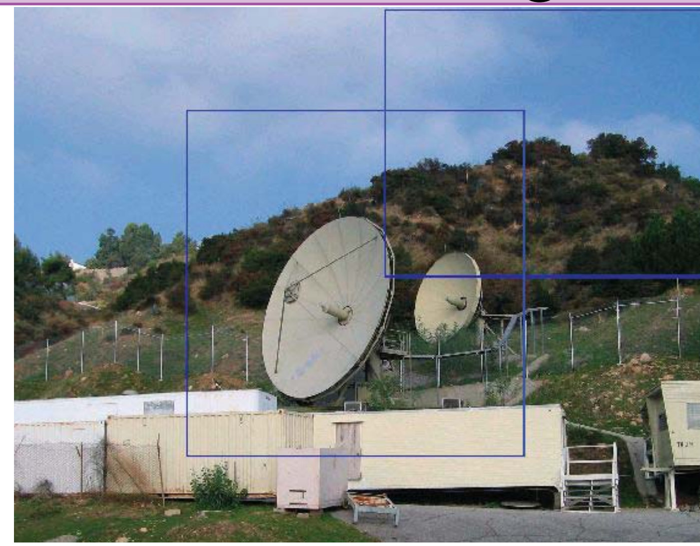
-Images reconstructed from 5-minute interferometric measurement sequences

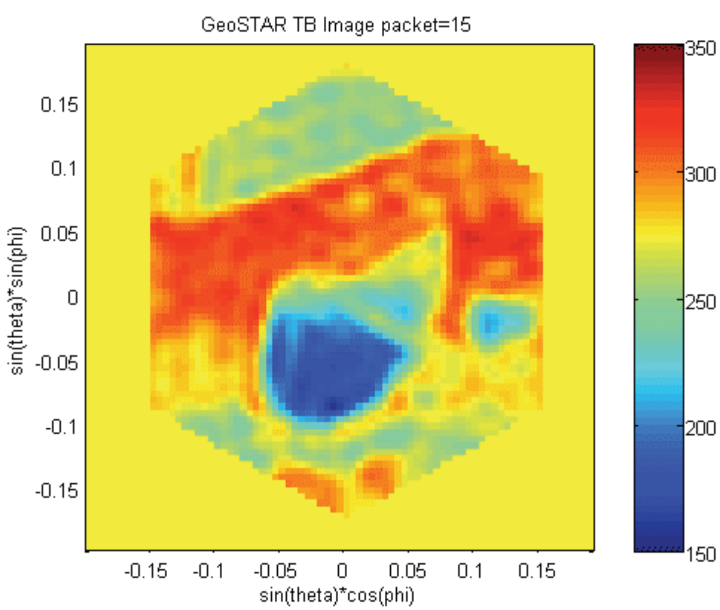
-Hexagonal central imaging area shown

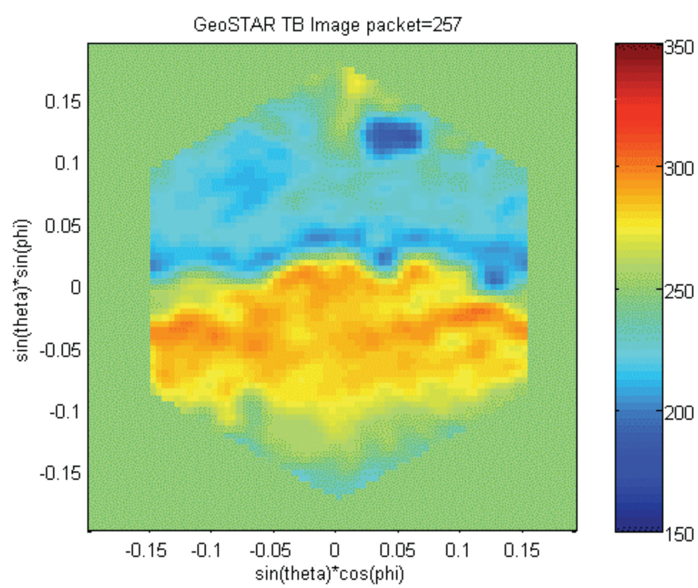
-Aliasing from outside central imaging area can be seen

> **These effects are well understood and can be compensated for, but they will not appear in GEO (background Is 2.7 K)**

This was a first - a major achievement!







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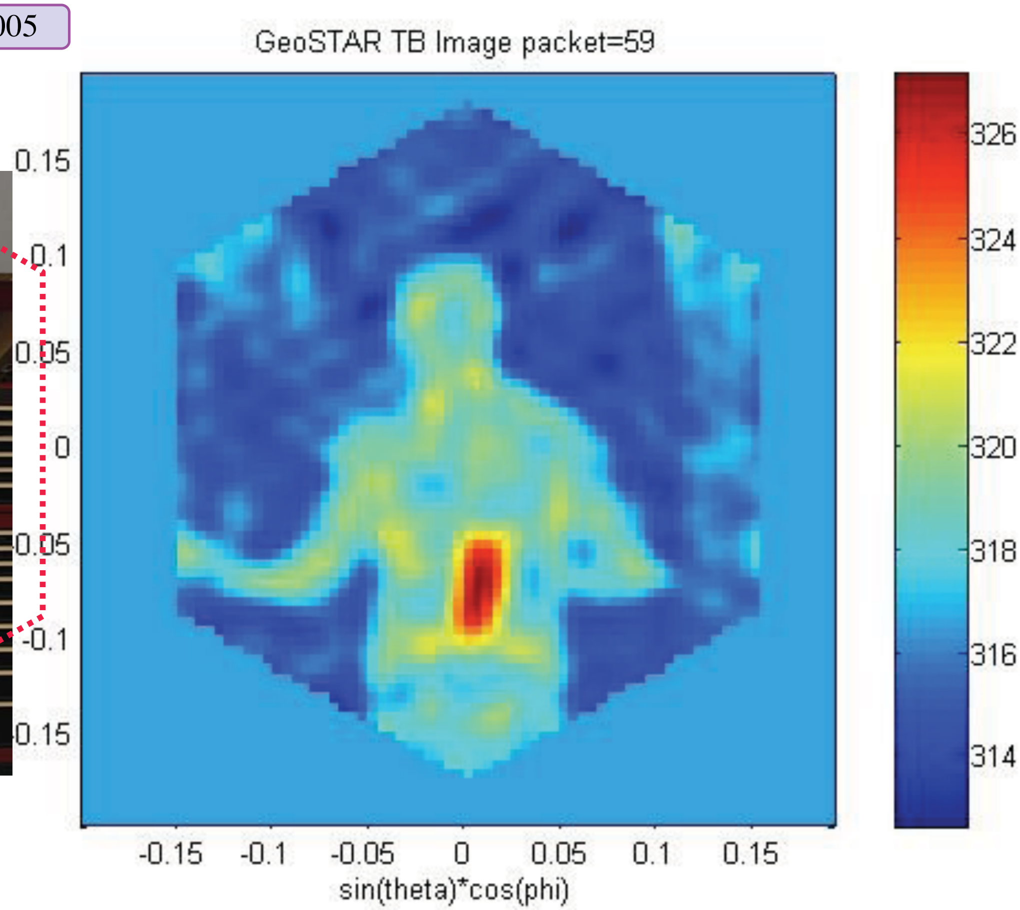
50-GHz Portrait Studio!

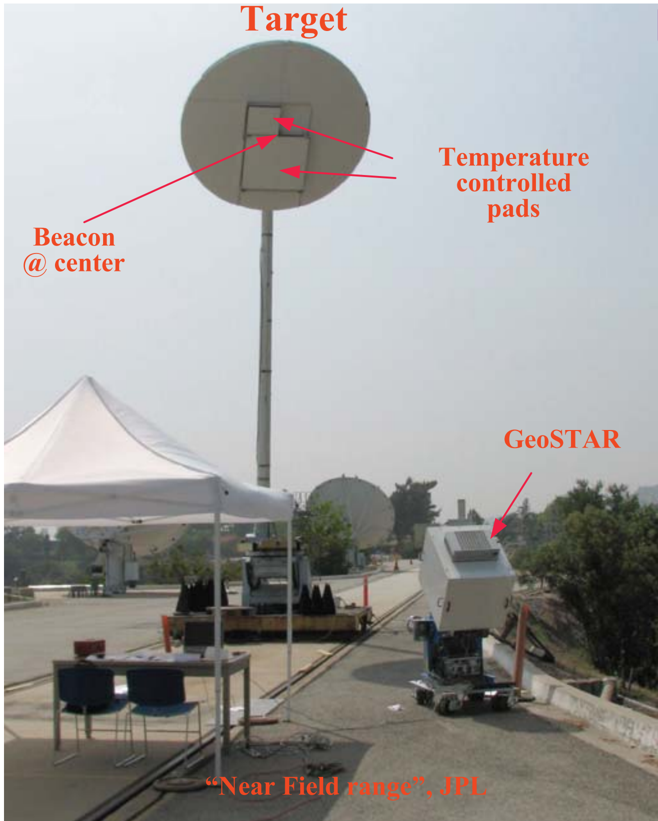
November 2005

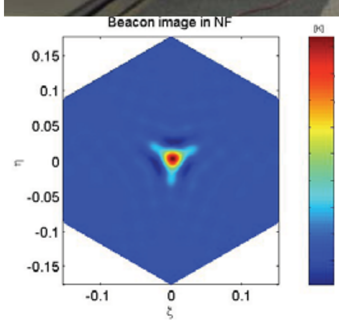


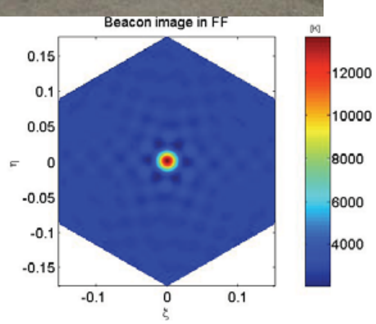
-Developed a method to compensate for distortions when target is in near field
-Enables using near-field targets to measure the performance of the system
-Developed a mocked-up "Earth from GEO" calibration facility using this method

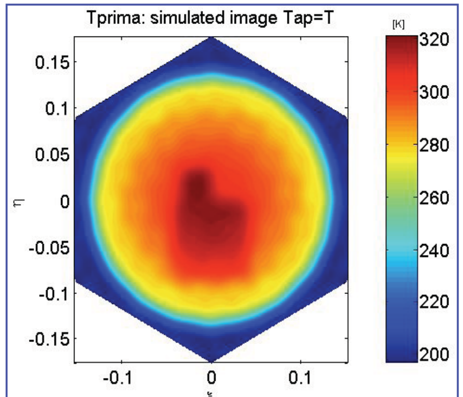
Quantitative-Calibration Facility

June 2006

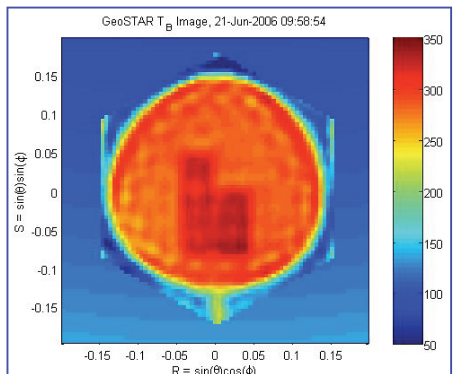






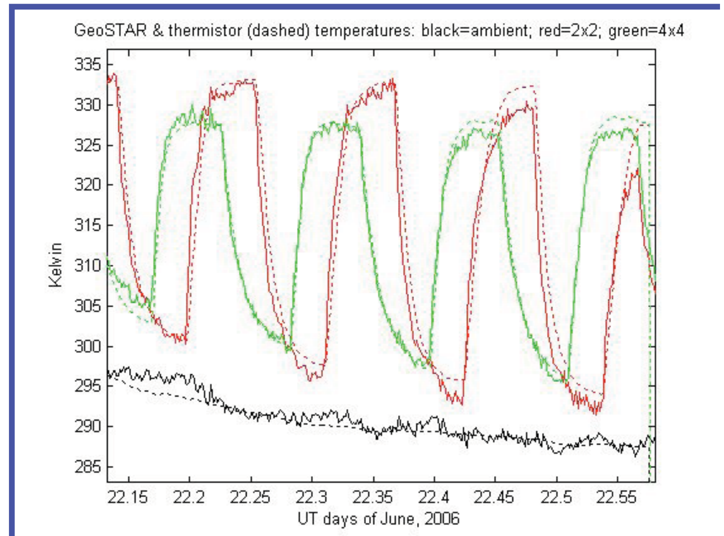


Raw synthesized image



Processed image†

† De-aliased, ant.patt. Corr; Not sidelobe-corrected



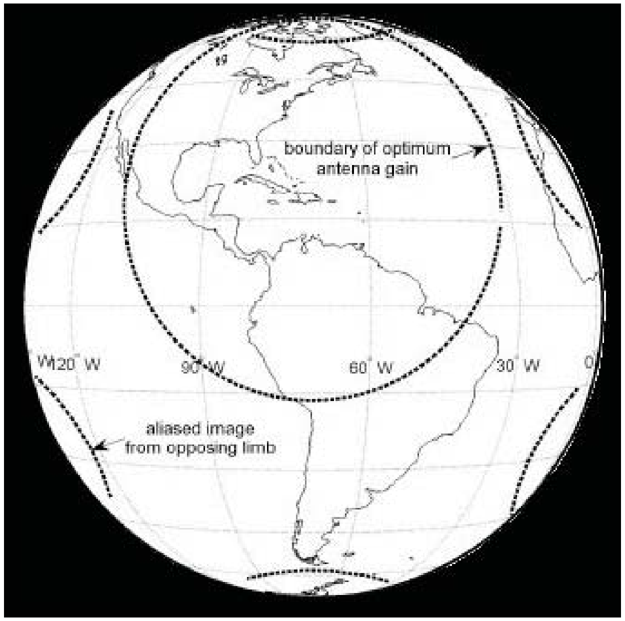
Retrieved vs. measured temperatures

Red: Large pad (4'x4' controlled)
Green: Small pad (2'x2' controlled)
Black: Main target (ambient)

Solid: GeoSTAR retrieval
Dotted: Thermistor average

Notional PATH Mission

- **Objective: Observe US hurricanes & severe storms**
  - Primary: Atlantic hurricanes
  - Secondary: CONUS severe storms; E. Pac. hurricanes
- **ROI focused near E. Carribbean**
  - Center @ 75°W, 20°N (permanently pitch GeoSTAR)
    - Can be pointed in other directions
    - Resolve disc with 60,000 & 240,000 "pixels"
  - 90+ % of visible disc is in alias-free region
    - Can be narrowed down (lower cost => risk mitigation)
  - Highest sensitivity in "circle" of radius 45°
    - Exploring antenna designs to maximize high-sensitivity region



- **Adequate sensitivity with GeoSTAR**
  - ~ 20 minutes "integration time" to reach 1 K for water vapor (183 GHz) in central part of ROI
    - T-band (50 GHz) is twice as sensitive/responsive
    - Exploring designs to improve these numbers
    - Exploring methods to increase temporal resolution
  - Focus is on high-value soundings in cloudy/unstable conditions
  - Bonus: Synergy with GPM, scatterometer, GOES-R (ABI, GLM)

Data Products

Mature products :

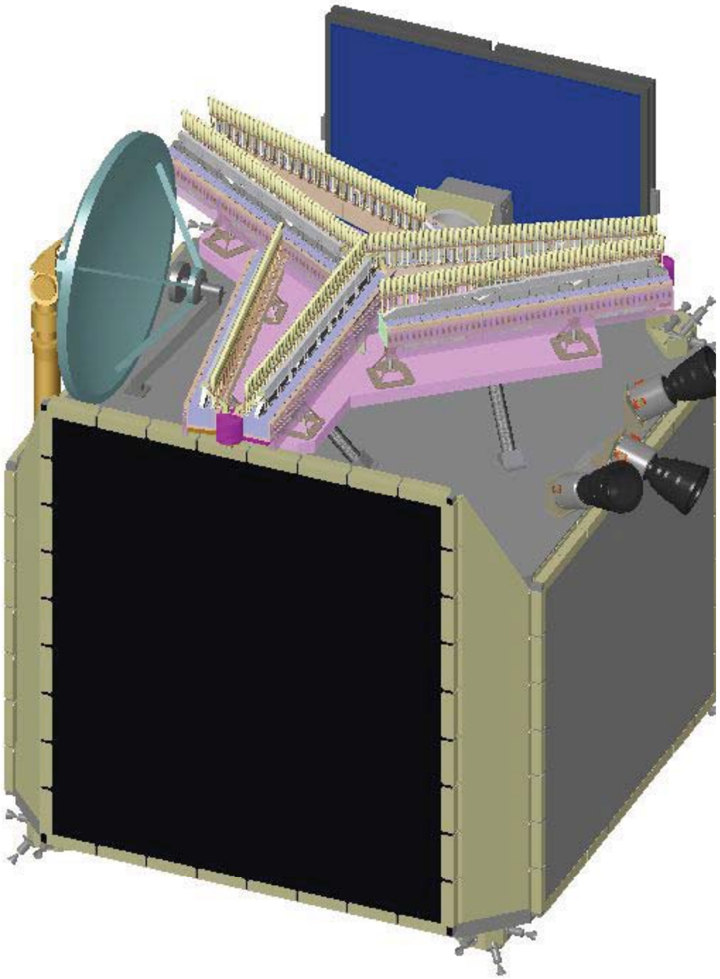
Parameter	Horizontal	Vertical	Temporal	Accuracy
Tb (50 GHz)	50 km	(6 channels)	3 min per ch.	< 1/3 K
Tb (183 GHz)	25 km	(4 channels)	5 min per ch.	< 1/3 K
Temperature	50 km	2 km	20 min	1.5-2 K
Water vapor	25 km	2 km	20 min	25%
Liquid water	25 km	3 km	20 min	40%
Stability index	50 km	N/A	20 min	N/A
TPW	25 km	N/A	20 min	10%
LWC	25 km	N/A	20 min	20%
SST	100 km	N/A	1 hour	< 0.5 K

Evolving experimental products:

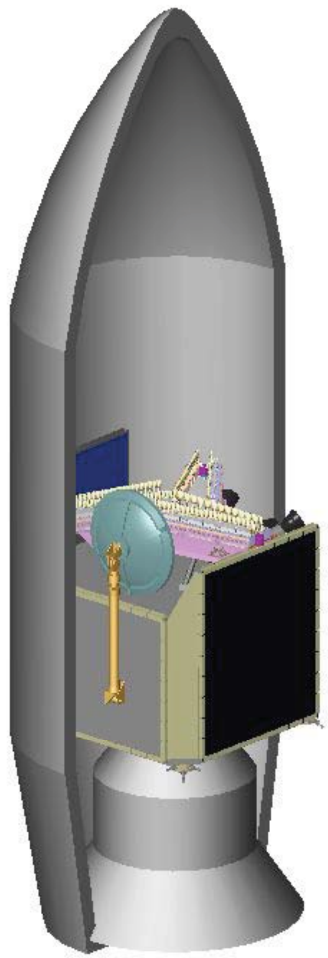
Parameter	Horizontal	Vertical	Temporal	Accuracy
Rain rate	25 km	N/A	20 min	2 mm/hr
Convect. intens.	25 km	N/A	20 min	N/A
IWC	25 km	N/A	20 min	30%
Wind vector	25 km	2 km	30 min	TBD

Platform Accommodation Example

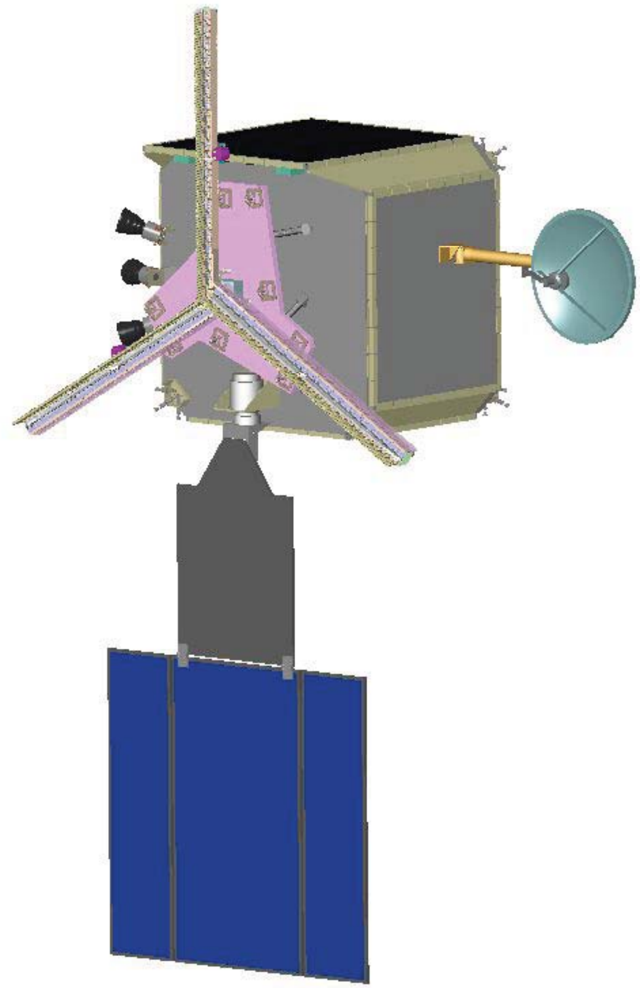
Note: Array arms can be remotely located from central electronics ⇒ Easy accommodation (e.g., GOES-R S/C)



Array arms folded for launch



Stowed in Delta fairing



Deployed on-orbit

Roadmap

- **Prototype: 2003-2006**
  - Fully functional system completed - now tested & characterized
- **Continuing *engineering* development: 2006-2010**
  - Develop 183-GHz low-noise compact/lightweight multiple-receiver modules
  - Develop efficient radiometer assembly & testing approach
  - Migrate correlator design & low-power technology to rad-hard ASICs
- **Science and user assessment**
  - Forecast impact: OSSEs under development
  - Algorithm development; applications
- **Development of space version (PFM): ~2010-2014**
  - Start formulation phase in 2009
  - Ready for integration in 2013-15
- **Joint NASA-NOAA demonstration mission: ~2014-2016**
  - **MOO on GOES-R/S**
  - Transition to quasi-operational mode after 1 year in research mode

Conclusions

- **Prototype development has been a tremendous success**
  - Inherently very stable design; Excellent performance
  - Measurements confirm system models and theory
  - *Breakthrough development!*
- **Technology risk mostly retired**
  - Prototype demos all key technologies
  - Remaining challenges are "engineering risks"
    - Further risk reduction will focus on efficient manufacture of large number of receivers
    - Design & fabrication of correlator ASIC is also an engineering issue, not technology
- **Science potential is tremendous - no other sensor can match this**
  - GeoSTAR is ideally suited for GEO
    - "Synoptic" sensor - continuous 2D imaging/sounding snapshots of Earth disc
  - Soundings *in* hurricanes and severe storms
    - Water vapor, liquid water, ice water, precipitation - all vertically resolved
    - Can derive stability metrics (LI, CAPE, etc.), convective intensity
    - Now-casting: Detect sudden hurricane intensification/weakening
  - Major advances in models: Diurnal cycle of all 3 phases of H_2O fully resolved
- **Urgent need for this mission**
  - But: ***It will happen soon only if the user community demands it***
  - Otherwise — it may take many years before NASA gets to "PATH"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GEOSTAR
HURRICANE
SENSOR
FOR
GEO
COMING SOON:
SEE THIS IN
MICROWAVE!
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NASA/GSFC: Jeff Piepmeier
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