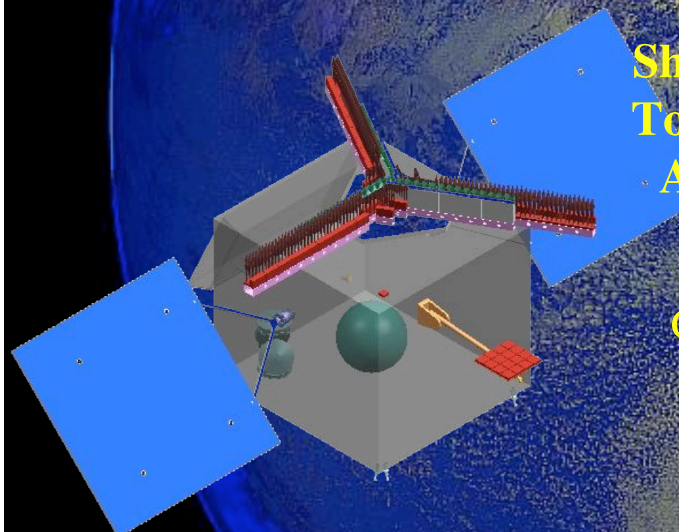
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Developing the GeoSTAR Science Mission ("PATH")



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IGARSS 2007

Barcelona, Spain; July 23-27, 2007

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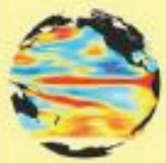
NRC Decadal Survey

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

Summary of Decadal Survey on "PATH"

- **Needs**
  - Early ID & reliable forecasting of track & intensity of tropical cyclones
  - Geographical distribution & magnitude of rain accum. totals during/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 & precipitation
  - Use time-continuous all-weather observations to impose new constraints on models
  - Mitigate req's on models by enabling frequent re-initialization by observations
  - Enable major sci. advances re. ENSO, monsoons, flow of tropical moisture to U.S.
- **Mission and Payload**
  - MEO or GEO; Part of all-weather sensor suite on future GOES
  - Require 50 or 118 GHz + 183 GHz
  - Microwave array spectrometer

GeoSTAR Highlights

- **Time-continuous microwave sounding from GEO**
  - Tropospheric temperature & water vapor sounding @ 50/183 GHz with ≤ 50/25 km resolution
    - Functionally equivalent to AMSU
    - Stand-alone all-weather temperature & water vapor/liquid soundings
    - Rain mapping; convective intensity
    - Tropospheric wind profiles (only feasible from GEO)
  - Primary focus on hurricanes: Observation and forecasting of intensity
    - Significant synergy with GPM & scatterometer: PATH adds tropo.winds & fills in spatio-temporal gaps
    - PATH addresses significant hurricane issues: now-casting, improved intensity observations/forecasts
    - Urgent societal need for PATH mission in view of possible increased tropical cyclone activity
  - Greatly-improved boundary layer, cloud and precipitation process modeling
    - Major science advances in the understanding of El Niño, monsoons and tropical moisture flow
  - Ready for implementation phase now
    - Technology & prototype development has advanced TRL more rapidly than anticipated
    - Ground-based prototype: Excellent performance; breakthrough development
- **Ground-based proof-of-concept prototype has been developed**
    - ***Excellent performance => Breakthrough development***
- **Recent mission study**
    - Prototype design meets measurement requirements & is ready for flight development
    - Mission development can begin ahead of the 2010 NRC recommended start date

Why GEO Microwave Sounder?

- **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
- **MW sounders 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

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

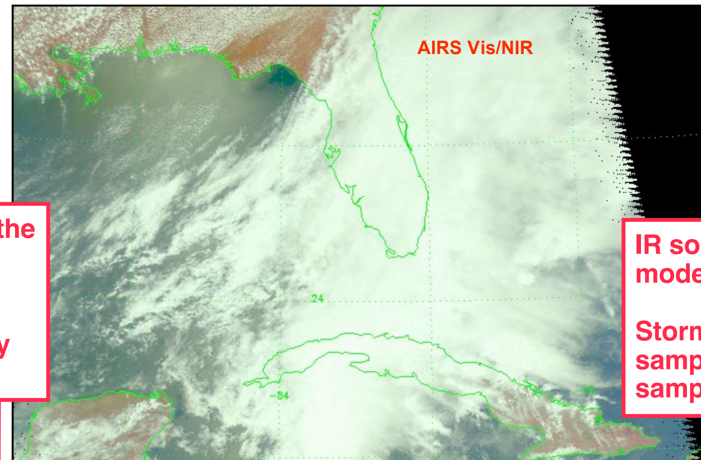
--IR is best suited for global observations and storm precursor conditions in clear sky

--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)

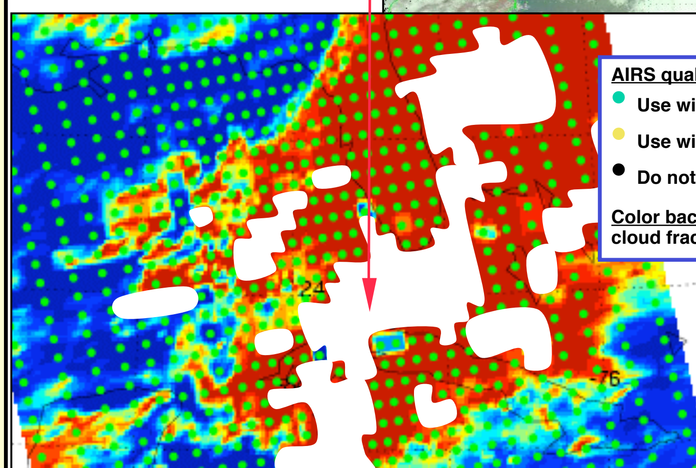


MW soundings fail only in the presence of precipitation with current algorithms

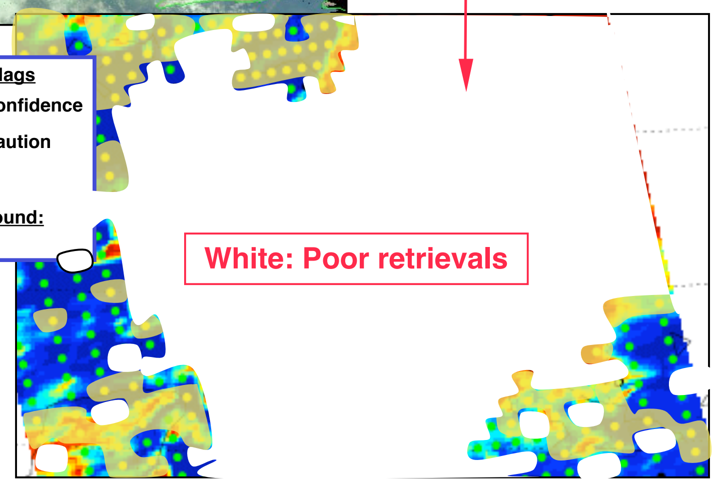
New algorithms will remedy that

IR soundings fail with even moderate cloud cover

Storm/cloud cases are not well sampled - i.e. there is significant sampling bias



AIRS MW-only retrievals



White: Poor retrievals

AIRS IR+MW cloud-cleared retrievals

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

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 convective bursts
  - Detect intensification/weakening in NRT, frequently sampled (~ 10 minutes)
  - Measure all three phases of water: vapor, liquid, ice
- **Rain** **-Complement GPM**
  - Full hemisphere @ ≤ 25 km every 20 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 (per Weng and per Staelin)
- **Tropospheric wind profiling** **-NWP, transport applications**
  - Surface to 300 mb; very high temp.res.; *in & below clouds*
  - Major forecast impact expected
- **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

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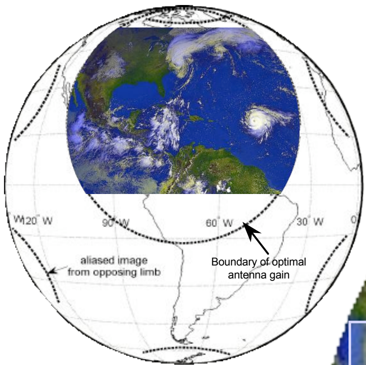
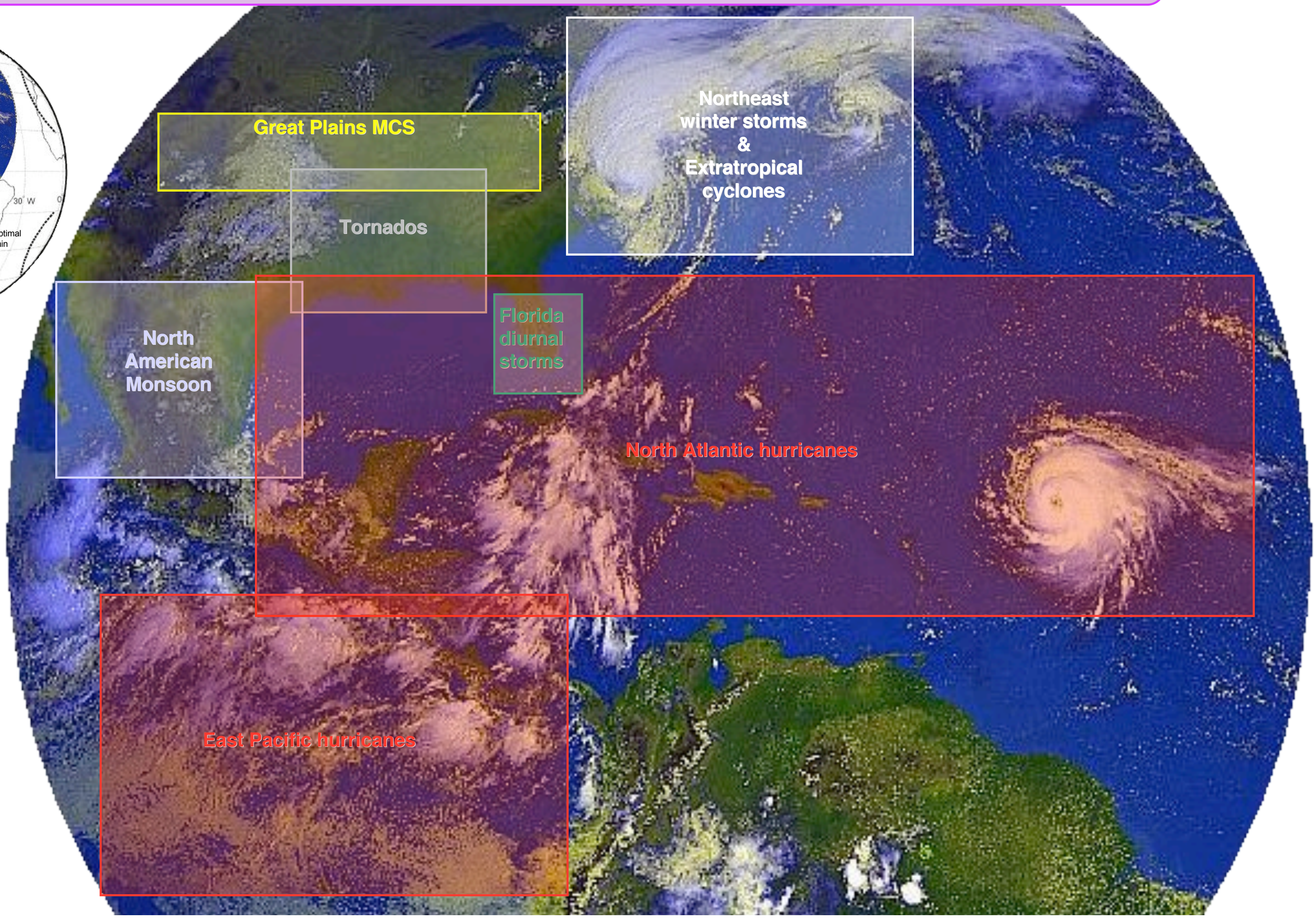
Science Focus Topics





Hurricanes

Observations with
Microwave Sounders

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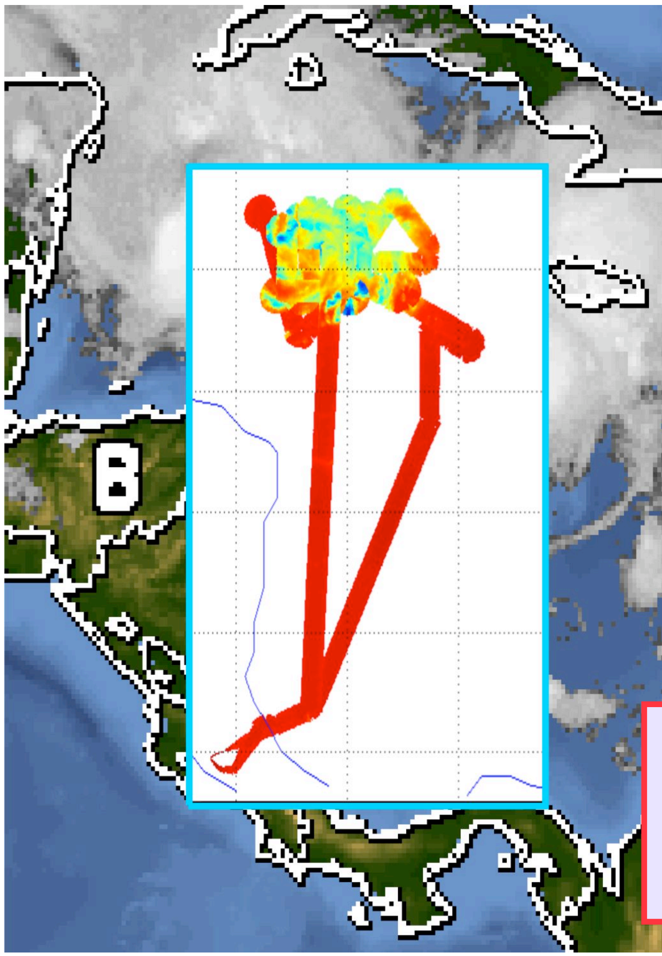
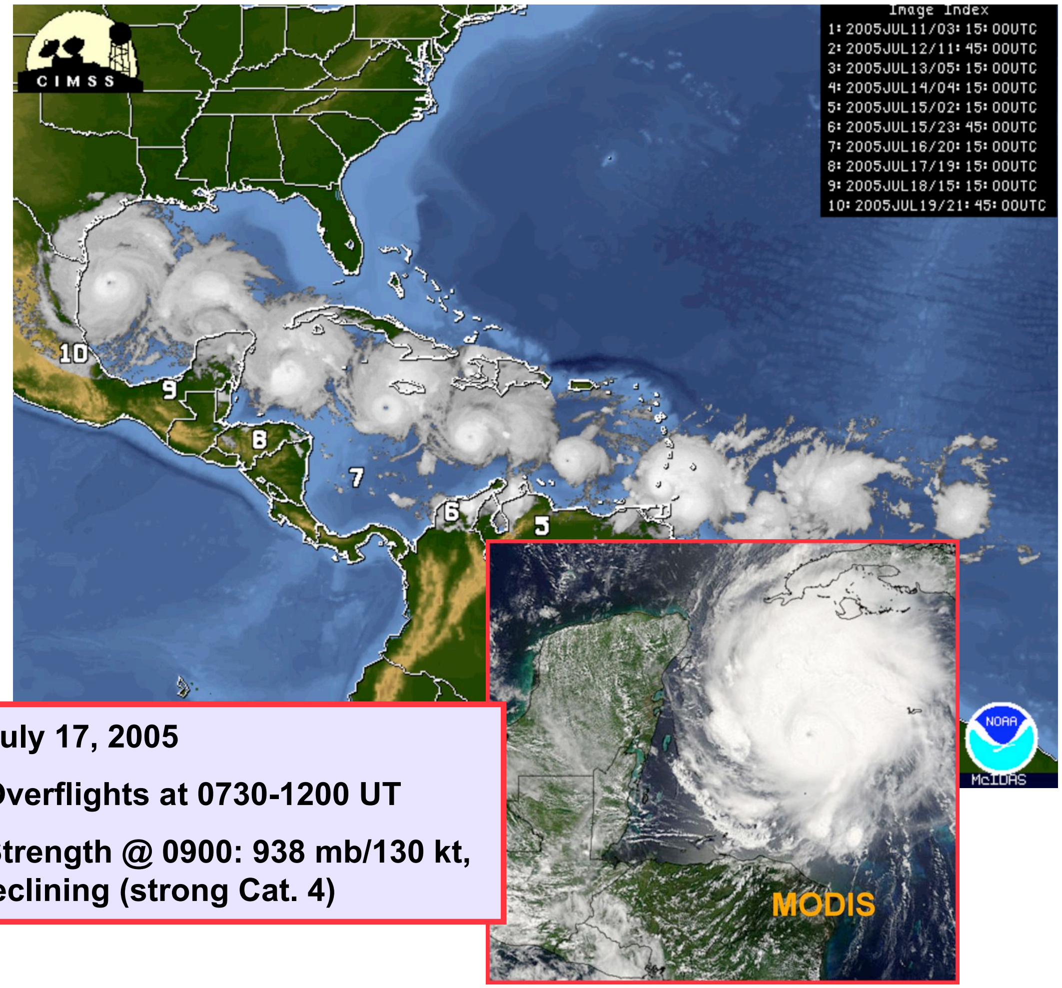
TCSP Example: Hurricane Emily

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

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

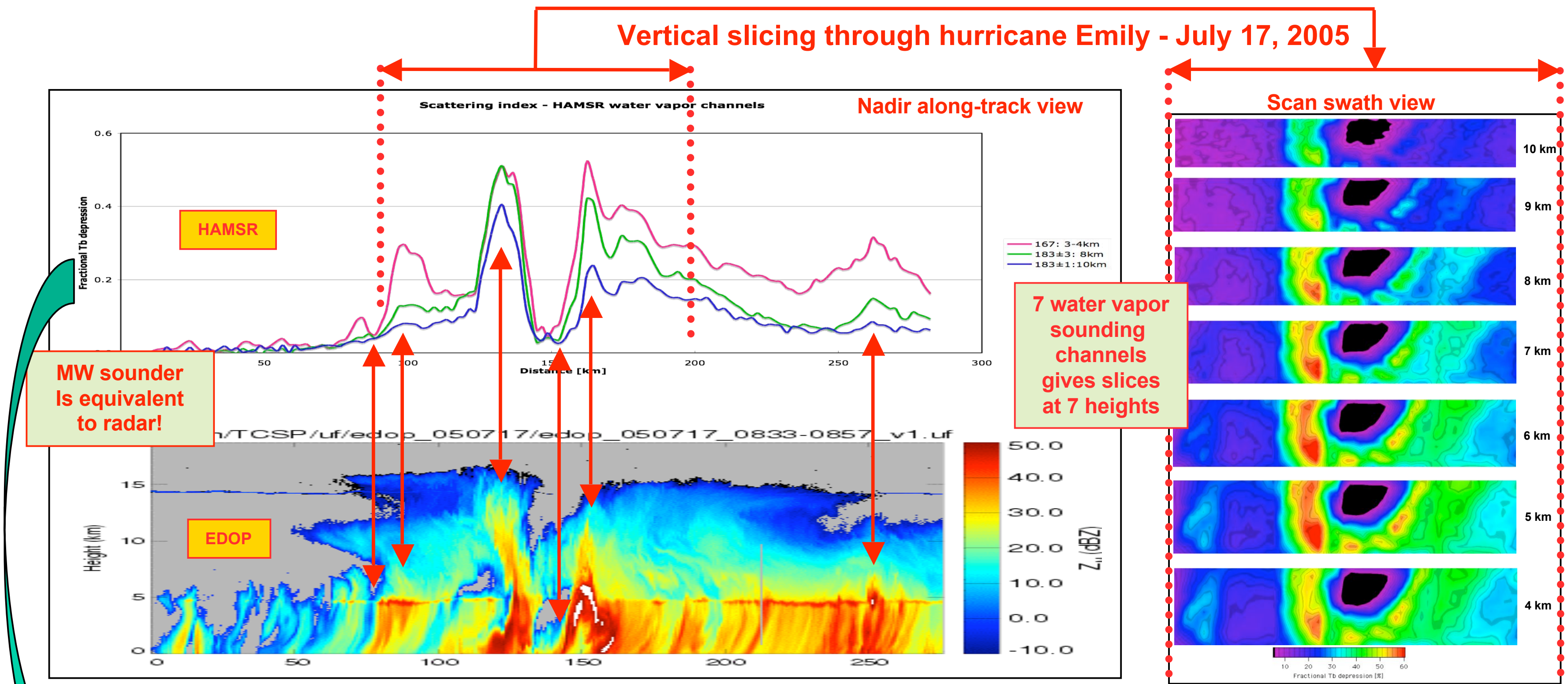


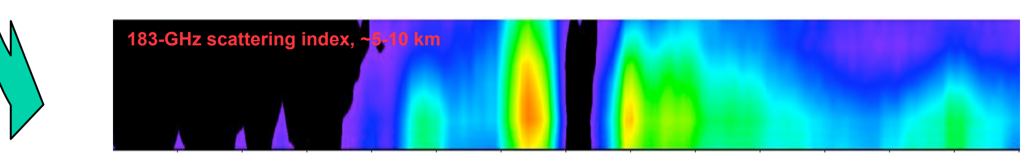


- **July 17, 2005**
- **Overflights at 0730-1200 UT**
- **Strength @ 0900: 938 mb/130 kt, declining (strong Cat. 4)**

Radar Emulation with MW Sounders

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





<u>"Radar reflectivity" - partially height resolved</u>
- Convective rain
- Ice water path
- Convective intensity

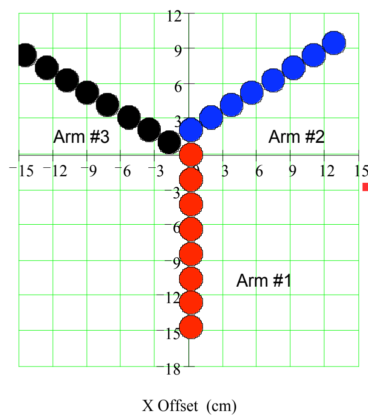
Methodology under development

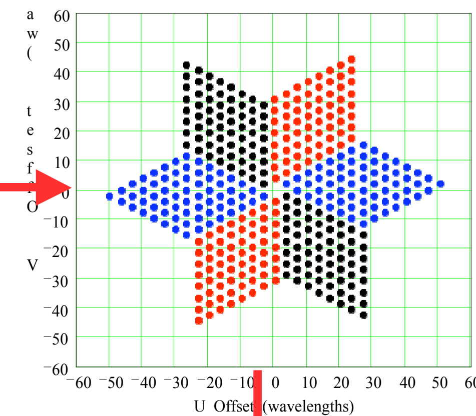
Instrument Concept

GeoSTAR System Concept

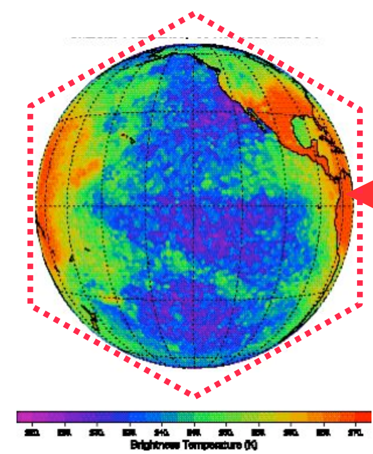
- **Concept**
  - Sparse array employed to synthesize large aperture
  - Cross-correlations -> Fourier transform of Tb field
  - Inverse Fourier transform on ground -> Tb field
- **Array**
  - Optimal Y-configuration: 3 sticks; N elements
  - Each element is one I/Q receiver, 3.5l wide (2.1 cm @ 50 GHz; 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

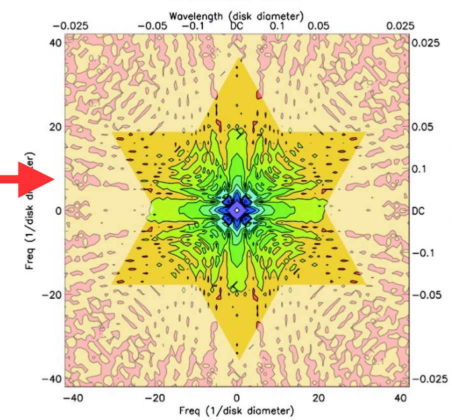
Receiver array & resulting uv samples





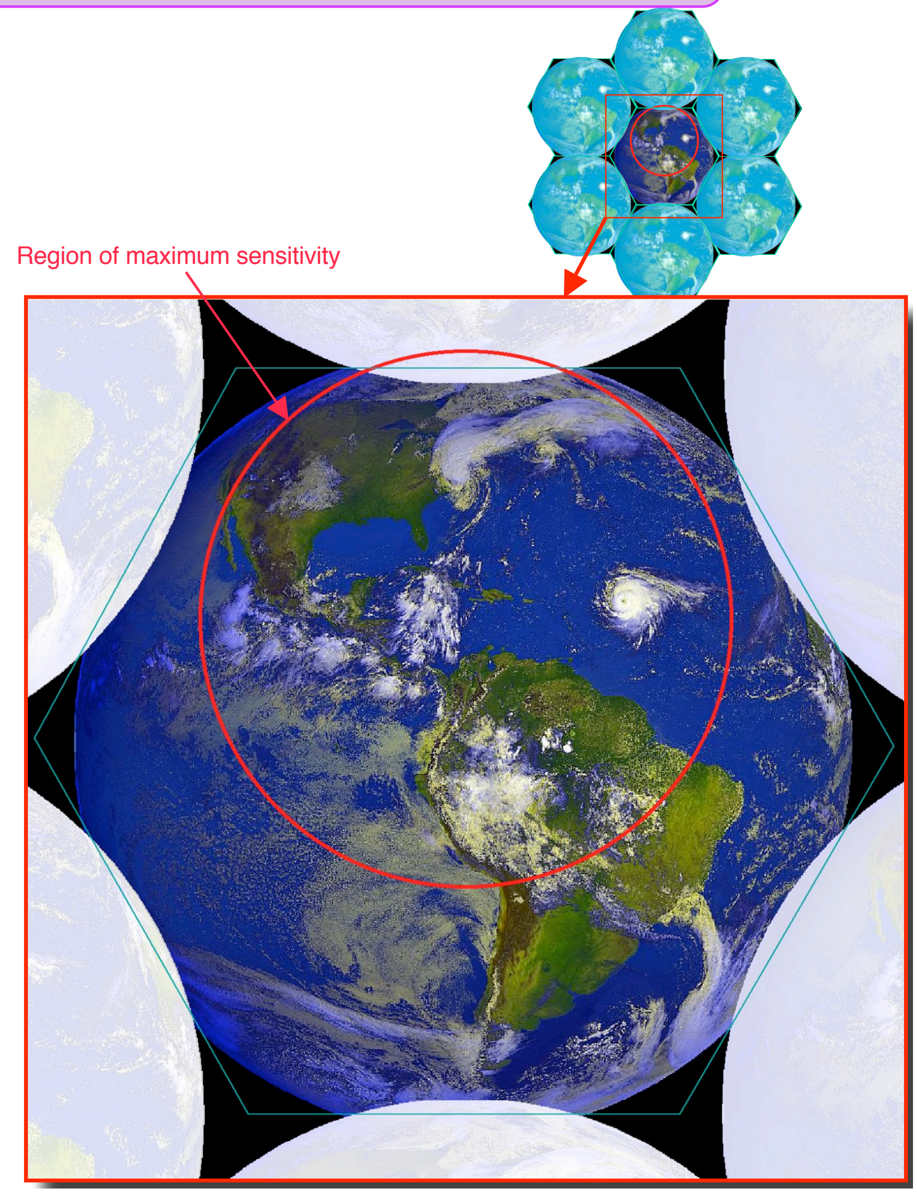
Example: AMSU-A ch. 1





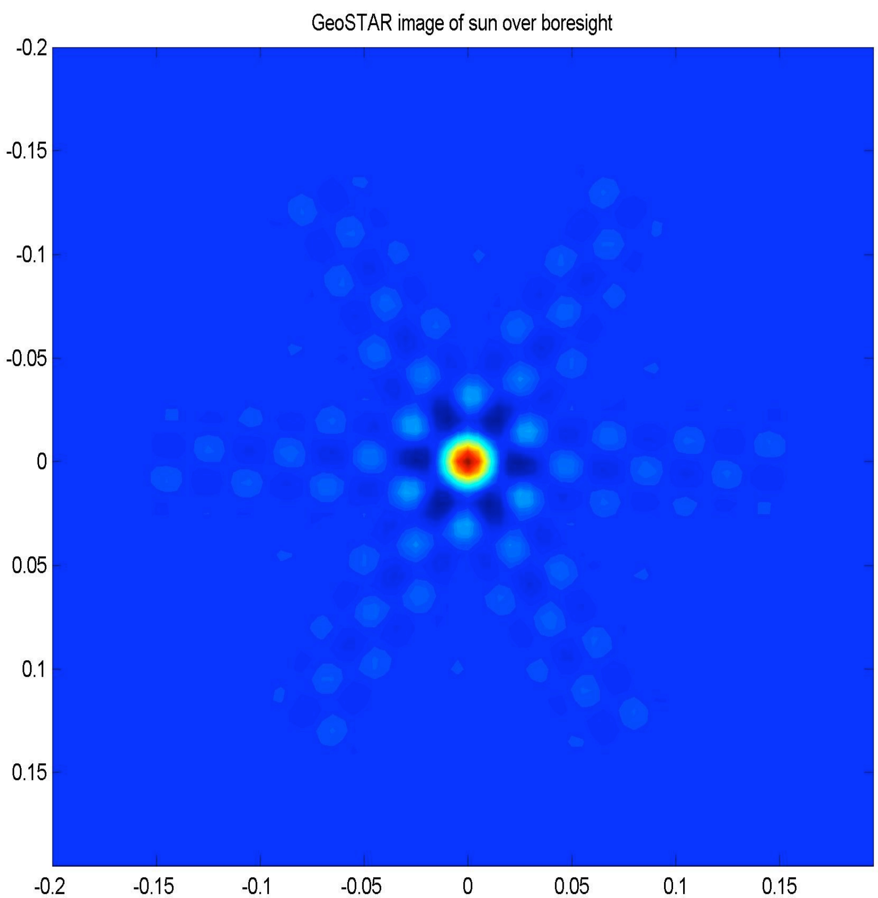
GeoSTAR Spatial Coverage

- **Fourier imaging features**
  - Basic imaging area is a hexagon
  - Periodic nature of Fourier series creates infinite series of secondary imaging hexagons
  - Sources in secondary areas are aliased into primary area
- **Basic PATH configuration**
  - 4-wavelength element spacing for optimal performance
  - Edges of Earth then extend into secondary hexagons
  - Those areas are therefore alias contaminated
  - This is not a problem: unimportant areas
  - Earth’s limb visible in 6 sectors
    - Use this for calibration
- **Region Of Interest**
  - Maximum performance near center of antenna patterns
  - Pitch instrument ~3° N for focus in Caribbean
  - ROI is largely free of alias

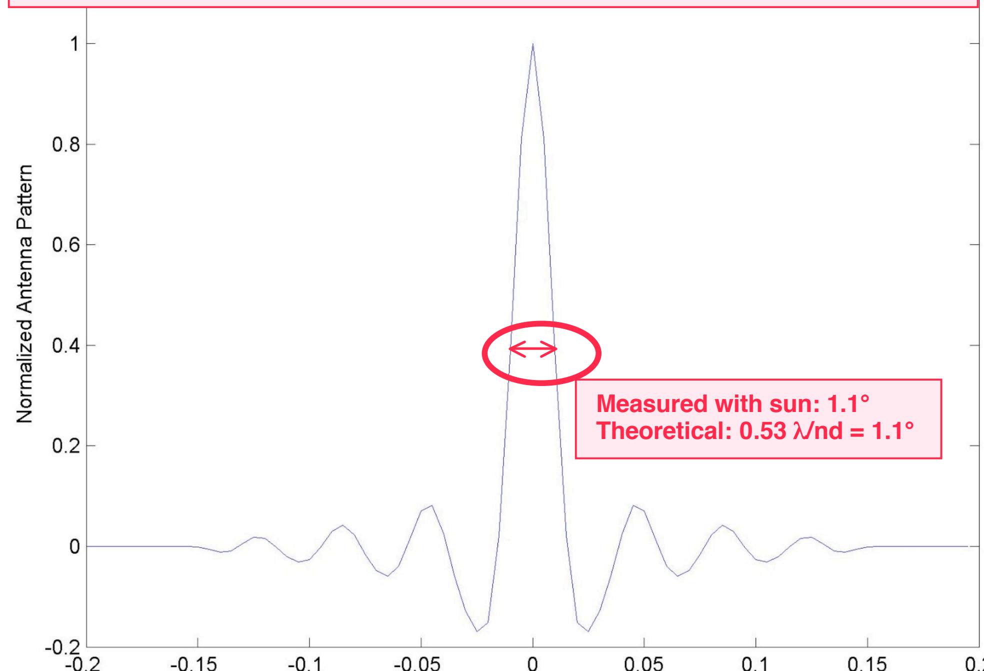


GeoSTAR Spatial Resolution

PSF measured with sun as quasi point source



- **Notice that sinc goes both positive AND negative**
- **This makes it possible to remove sidelobes through simple linear image processing - not possible with real-aperture systems**
- **Many options exist to optimize spatial resolution vs. beam efficiency, including “super-resolution”**



This is a nearly pure “sinc” function - in amplitude space
Performance is almost identical to theoretical prediction!
Note that RA systems have PSF ~ (sinc)^2 - positive everywhere

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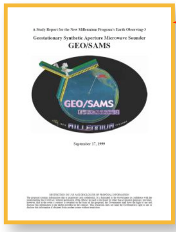
GeoSTAR Development History

1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007

NMP/EO-3 Phase-A

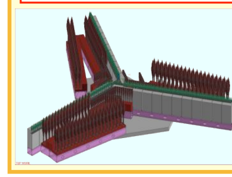


NOAA Study

NOAA Mission Study

PATH Mission Study

Design innovations



IPP: MMIC development

ACT: Signal distribution

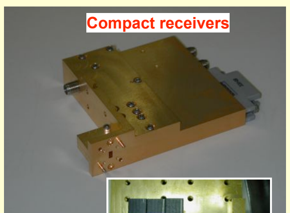
IIP: GeoSTAR ptototype

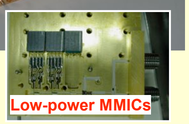
ACT: 183-GHz MMIC development

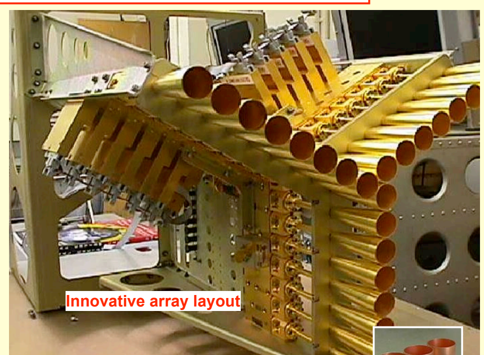
JPL R&TD: MMIC development

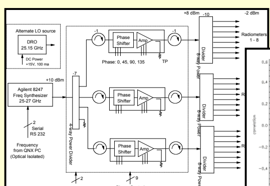
JPL R&TD: GeoSTAR calibration

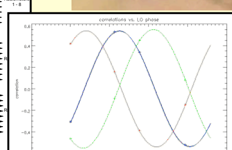
All required technology elements developed & tested


Compact receivers


Low-power MMICs

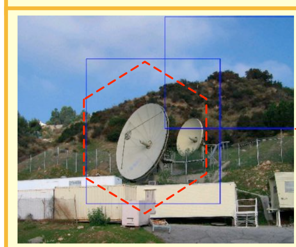

Innovative array layout

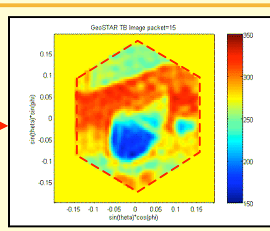



LO phase switching system: Ultrastable operation


Correlator:
- Efficient
- Redundant
- OK for ASICs

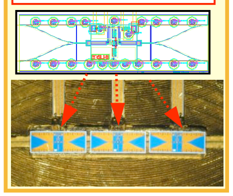

Feedhorns: Low mutual coupling

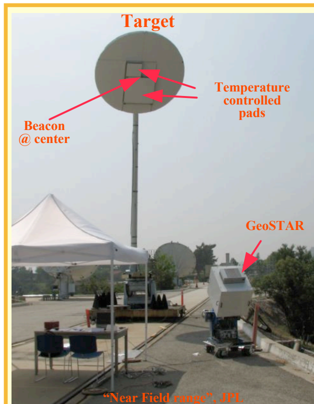


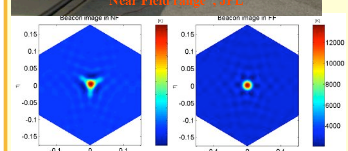


First images at 50 GHz by aperture synthesis

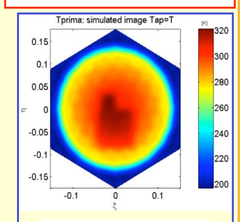
MMICs embedded in waveguides



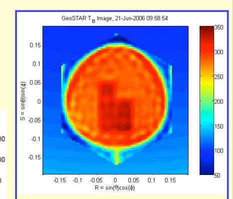




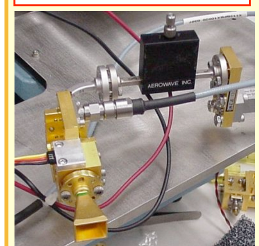
Absolute calibration

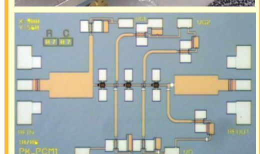


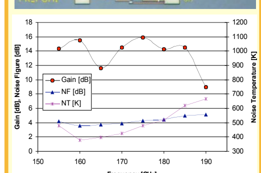
Raw synthesized image


Processed image

Breakthrough MMIC performance



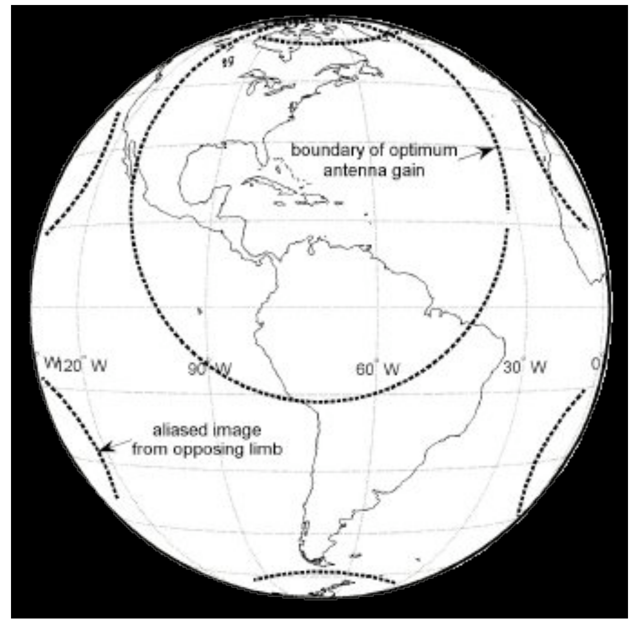




Mission Development

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
  - 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
- **Note: Primary mission objective is NOT precipitation!**
  - Focus is on high-value soundings in cloudy/unstable conditions
  - Bonus: Synergy with GPM, scatterometer, GOES-R (ABI, GLM)

Measurement Specifications

Channel	Frequency (GHz)	Wt-func. peak	Int. time (minutes)	Duty cycle (%)
Band 1	**50-57**		**10 (6 ch)**	
1-1	50.3	Surface/100 mm	2	100
1-2	52.8	1000 mb	2	100
1-3	53.7	750 mb	2	100
1-4	54.4	400 mb	2	100
1-5	*54.9*	*250 mb*	*2*	*70*
1-6	*55.5*	*150 mb*	*2*	*30*
Band 2	**167-183**		**20 (4 ch)**	
2-1	167	10 mm	5	100
2-2	176.31	4 mm	5	100
2-3	180.31	1 mm	5	100
2-4	182.31	0.3 mm	5	100
Optional third T-sounding band (to be studied later)				
Band 3	**113-118**		**TBD**	**TBD**
3-1	TBD	TBD	TBD	TBD
3-2	TBD	TBD	TBD	TBD
…	…	…	…	…

Data Products

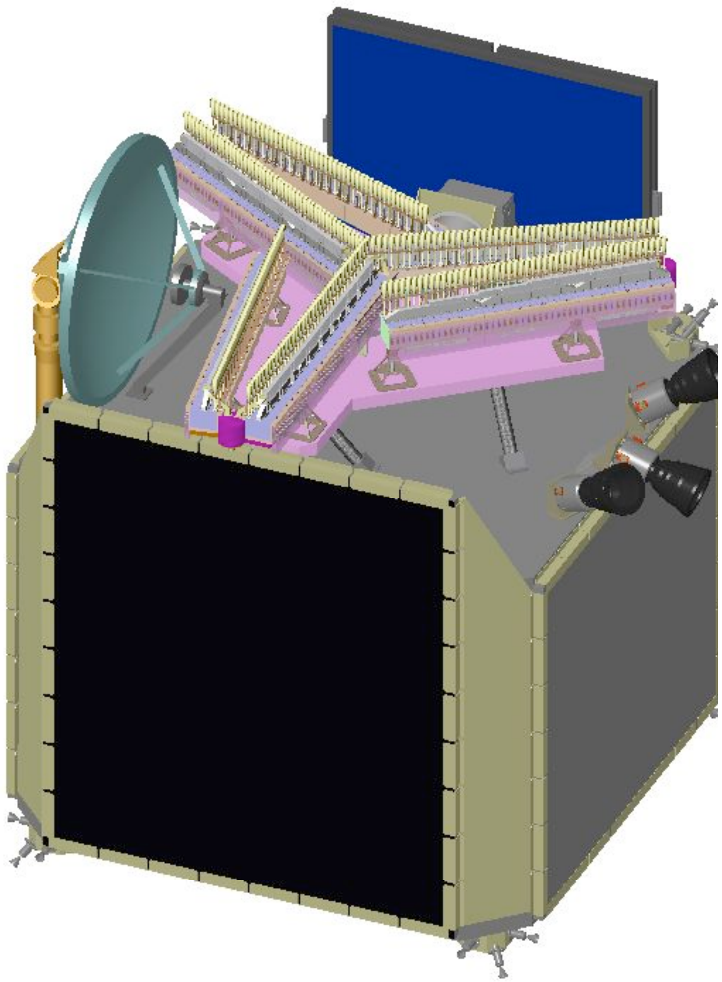
Mature products :

Parameter	Horizontal	Vertical	Temporal	Accuracy
Tb (50 GHz)	50 km	(6 channels)	3 min per ch.	< 1 K
Tb (183 GHz)	25 km	(4 channels)	5 min per ch.	< 1 K
Temperature	50 km	2 km	20 min	1.5 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

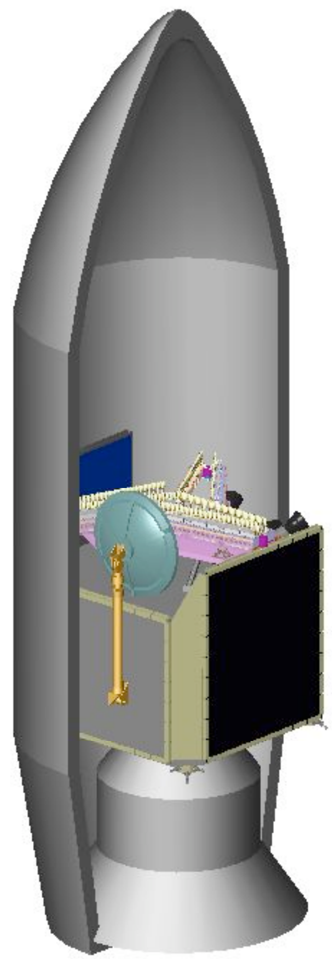
Evolving experimental products:

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

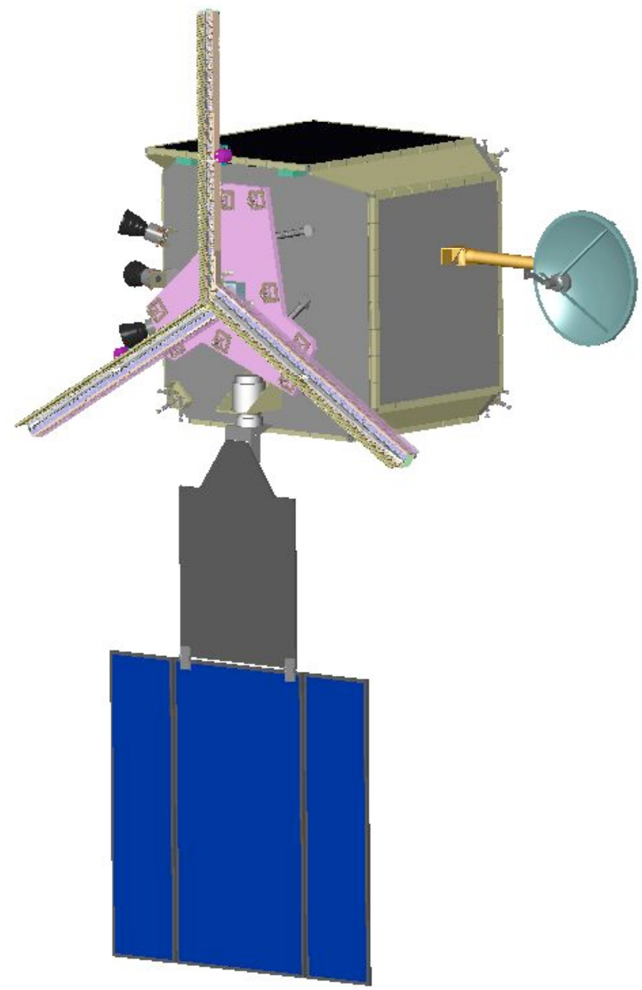
Platform Accommodation Example



Array arms folded for launch



Stowed in Delta fairing



Deployed on-orbit

Ball Aerospace

Roadmap

- **Prototype: 2003-2006**
  - Fully functional system completed - now being tested & characterized
- **Continuing *engineering* development: 2005-2008**
  - Develop 183-GHz compact/lightweight multiple-receiver modules
  - Develop efficient radiometer assembly & testing approach
    - Reduce cost per receiver
  - 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): ~2008-2014**
  - Start formulation phase in 2008-2009
  - Ready for launch in 2014-16
- **Demonstration mission: ~2014-2016 or later**
  - Joint NASA/NOAA mission?
    - Part of operational GOES or standalone PATH research mission
  - 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
- **Must build community consensus**
  - Focus on science mission & advocacy
  - End real-aperture vs. synthetic-aperture "debate" now


NASA
National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
GEOSTAR A NEW
HURRICANE
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FOR
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SEE THIS IN
MICROWAVE!
This work was carried out at the
Jet Propulsion Laboratory,
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under a contract with the
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