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Space Administration

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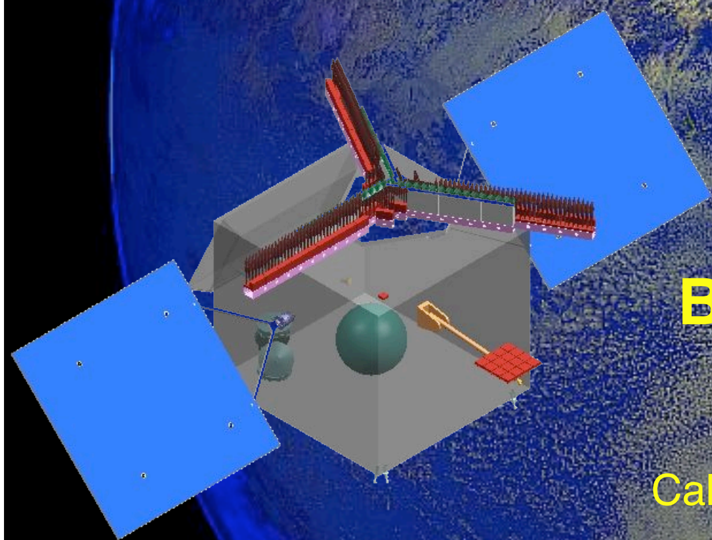
California Institute of Technology
Pasadena, California

Earth Remote Sensing Applications with Microwave Array Spectrometers



Bjorn Lambrigtsen

Jet Propulsion Laboratory
California Institute of Technology

KISS MMIC Workshop

Caltech, Pasadena, July 21-25 2008

Earth Science Applications

Soil moisture; ocean salinity ⇒ Climate

- Aircraft (5-10 km): ~ 180° *ESTAR (1990), 2DSTAR (2004)*
- LEO satellites (700-1000 km): ~ 130° *SMOS (2009)*
- L-band (1.4 GHz, 21 cm)
- Surface emissivity

Hurricane wind speed ⇒ Weather

- Aircraft (5-10 km): ~ 180° *HIRAD (2010)*
- C-band (4-7 GHz, 4-7 cm)
- Surface emissivity (wind-induced foam)

Rain mapping ⇒ Weather

- LEO satellites (400-800 km): 140° *LRR (2006, aircraft)*
- X-band (10.7 GHz, 3 cm)
- Thermal absorption/emission of liquid raindrops

Atmospheric sounding ⇒ Weather

- MEO/GEO satellites (10000-36000 km): 45°/17° *GeoSTAR (2016)*
- V-band & up (50-200 GHz, 1.5-6 mm)
- Thermal absorption/emission of oxygen (temperature), water vapor & liquid

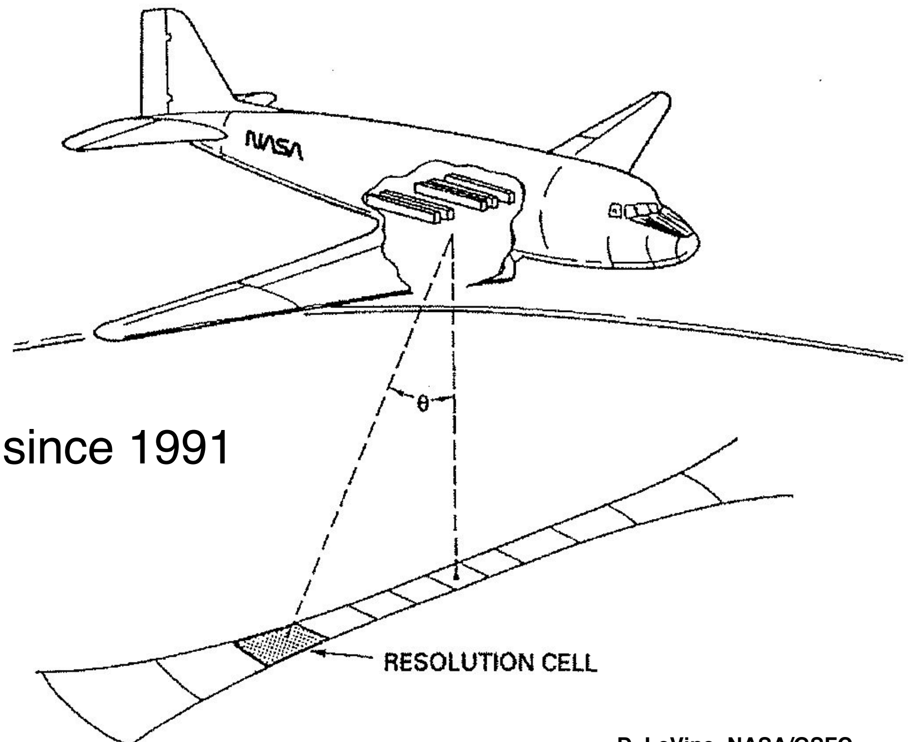
Generally very large sources, Tb ~ 100-300 K; require NEDT ~ 0.1-1 K

Why Array Radiometers?

- **Spatial resolution & coverage!**
  - For applications that require relatively very large apertures
  - Difficult to build, deploy, scan large parabolic reflectors
  - In some cases better NEDT can be attained with array radiometers
- **Array types**
  - Focal-pane arrays: not much used in Earth applications so far
    - Can be used to improve spatial-coverage/integration-time in scanned systems
  - Phased arrays (beam synthesis): not used in Earth applications
    - Earth applications require very high “beam” quality ⇒ Filled array ⇒ Costly
  - STAR arrays (aperture synthesis): dominant in Earth applications
    - Enables large effective aperture using few elements
- **1-D STAR array**
  - Simple; requires few elements & small correlator
  - Can be used if the scene is moving
- **2-D STAR array**
  - Complex; requires large number of elements & very large correlator
  - Must be used if the scene is stationary
  - May be used with moving scene to improve effective NEDT (multiple looks)

First: ESTAR

- 1-D sparse array @ 1.4 GHz
  - 5 slotted-waveguide antennas
    ⇒ 5 fan beams
  - Dual polarization
  - Min. baseline = 0.5 λ
    ⇒ no aliasing in 180° FOV
- Flown in numerous field campaigns since 1991
  - Soil moisture



D. LeVine, NASA/GSFC

Recent 1-D Array: LRR

10.6 GHz, 14 elements

Precipitation (prototype)

C. Ruf, U. Michigan

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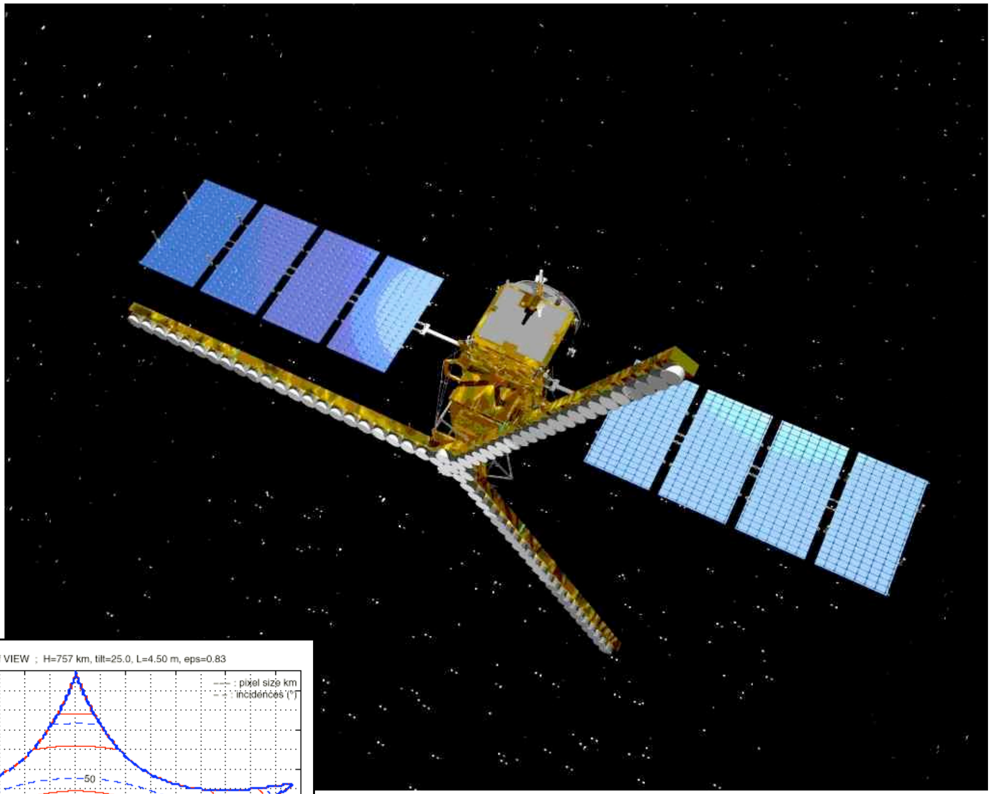
VLA: Model for 2-D STARs

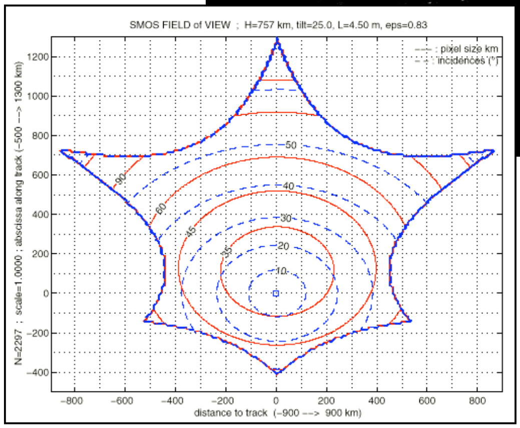
First Y-configuration

http://www.vla.nrao.edu/

Next year: SMOS

- 2-D sparse Y-array @ 1.4 GHz
  - 73 receiver elements
  - 9-meter effective aperture
  - Dual polarization
  - Min. baseline = 0.9 λ
    - ⇒ aliasing limits FOV
      - Scene ≈ 130° ⇔ Δ ≈ 0.65 λ
      - Δ ≈ 0.9 λ ⇒ 80° alias-free
- To be launched by ESA in 2009
  - Soil moisture & ocean salinity
  - Difficult data processing





ESA
http://www.cesbio.ups-tlse.fr/us/indexsmos.html

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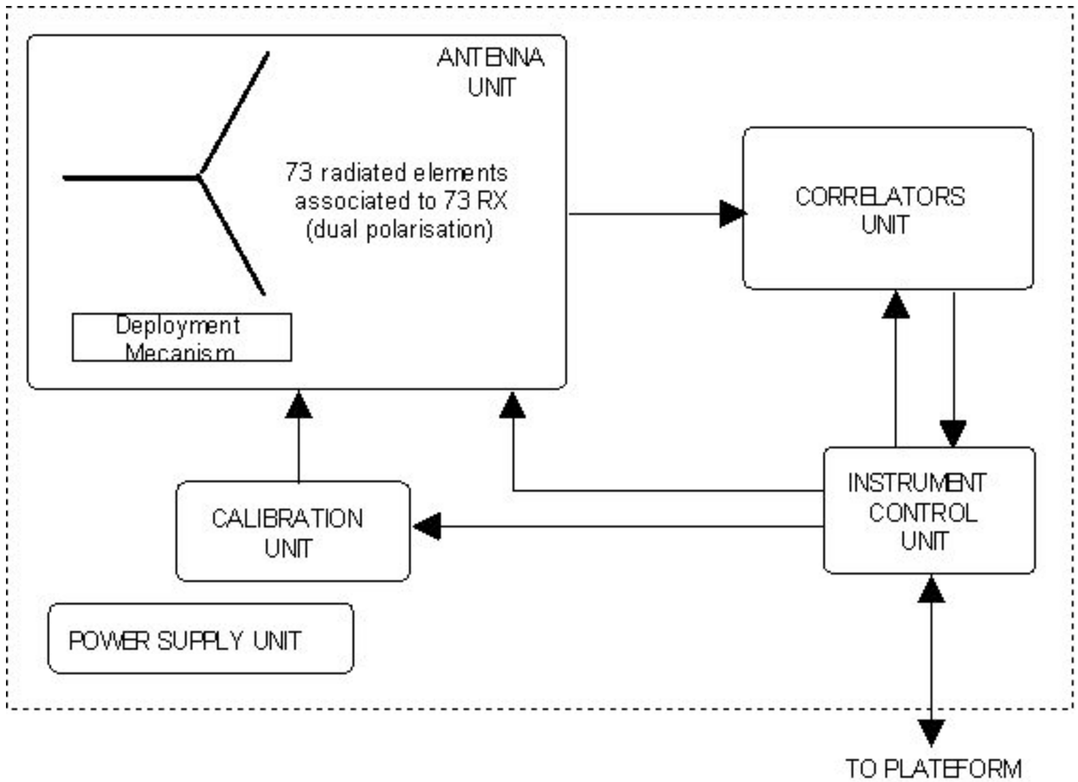
SMOS Architecture



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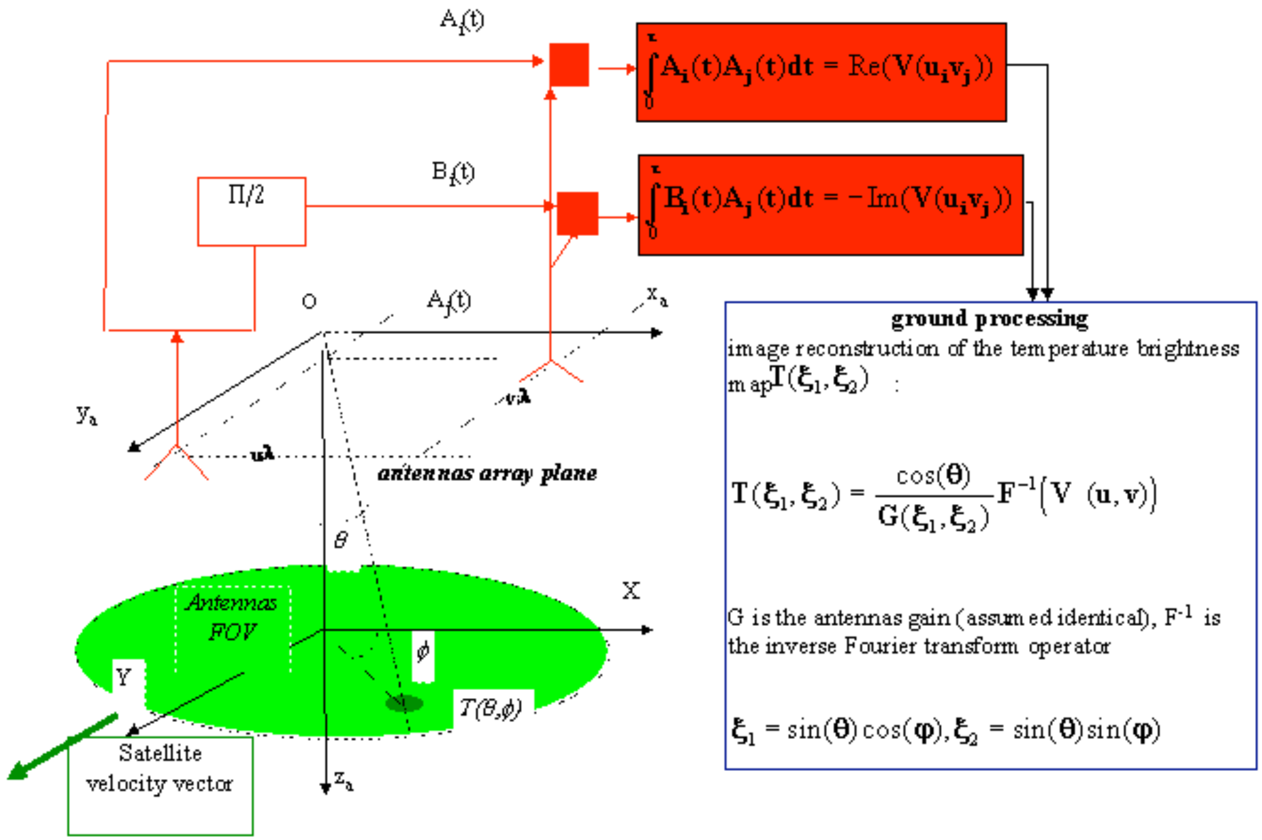
2-D STAR Principle of Operation

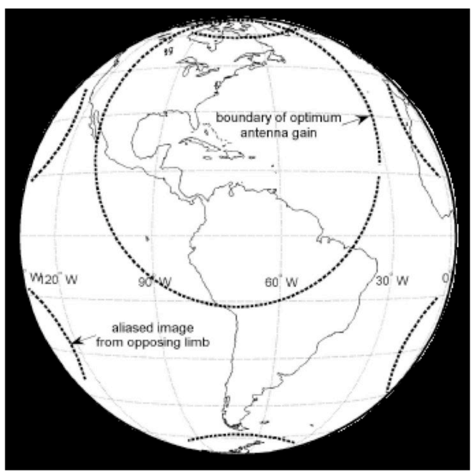


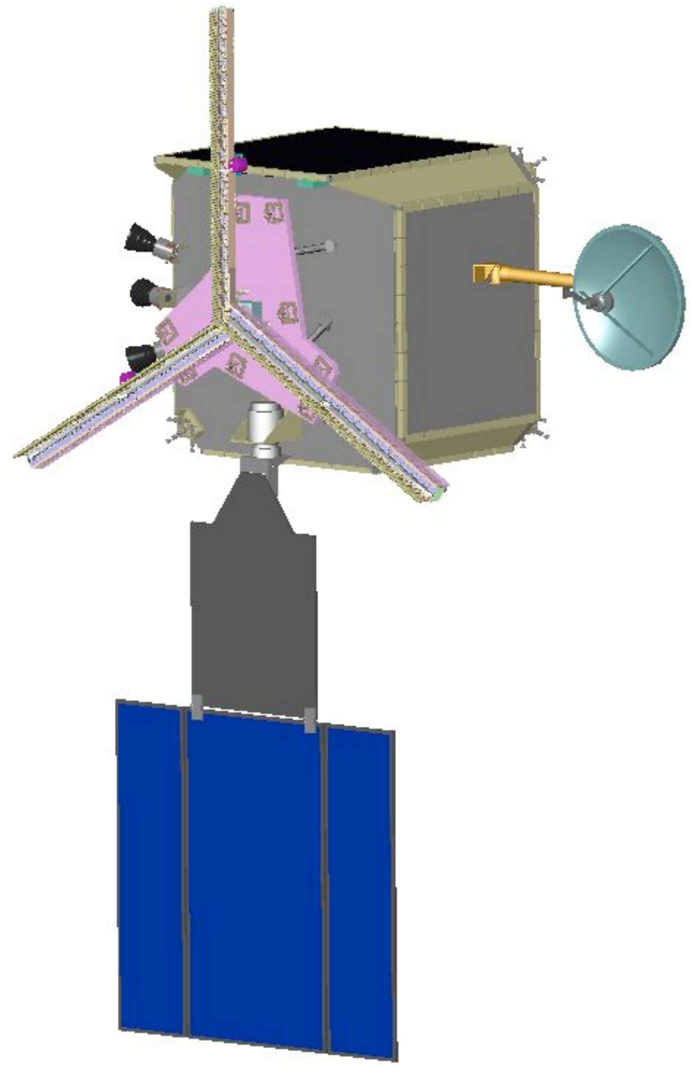
ESA
http://www.cesbio.ups-tlse.fr/us/indexsmos.html

Future: GeoSTAR

- Dual 2-D sparse Y-arrays @ 50 GHz & 183 GHz
  - 300 + 600 receiver elements
  - 4-meter & 2-meter effective apertures
  - Single polarization
  - Min. baseline = 4 λ

    $\Rightarrow$ largely alias-free FOV
- Planned for “PATH” mission
  - Atmospheric T & q sounding from GEO
  - NRC “Decadal Survey” recommendation
  - Possible payload for GOES





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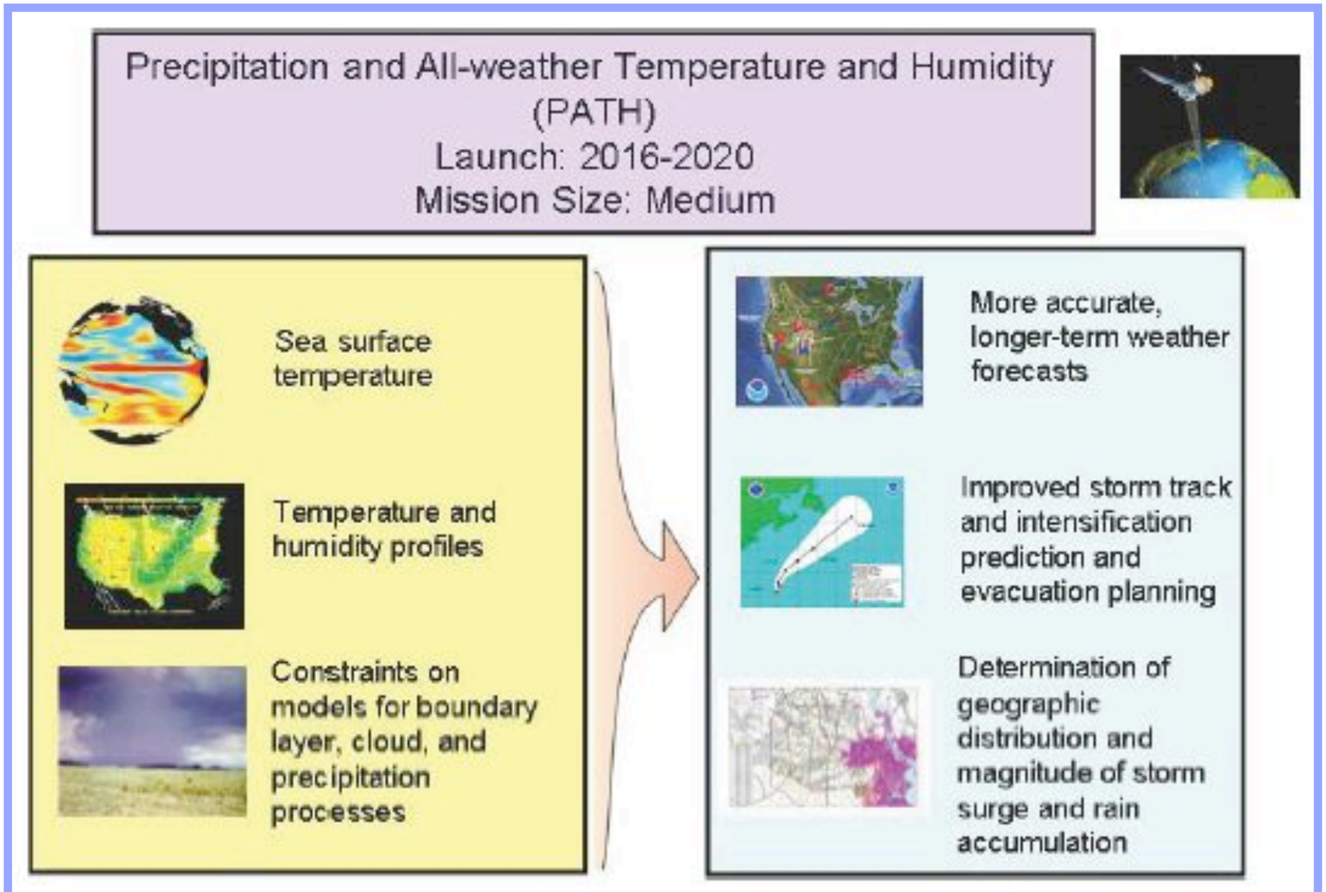
NRC Decadal Survey

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



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

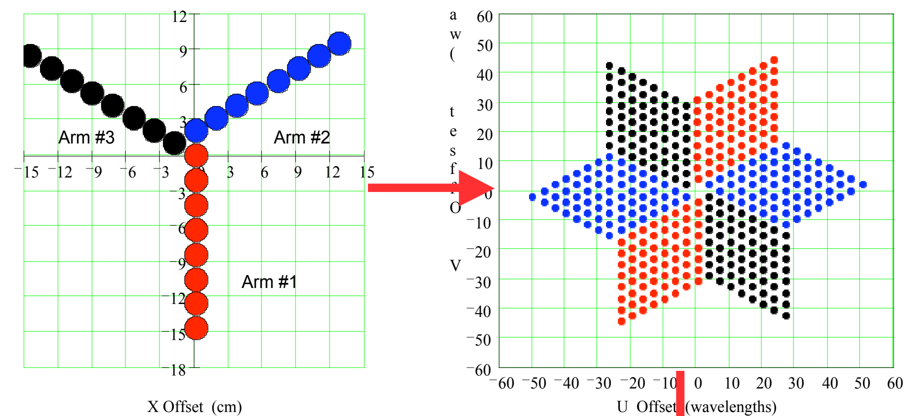
= GeoSTAR!

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

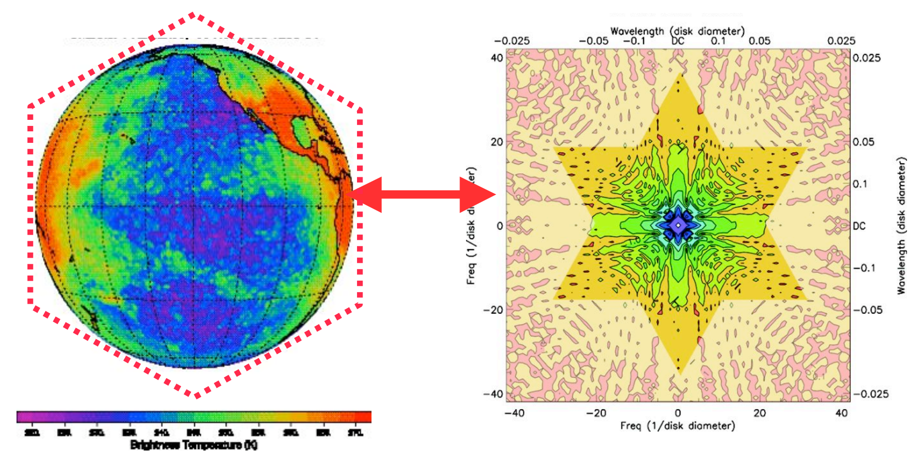
GeoSTAR System Concept

- **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, 3.5λ 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

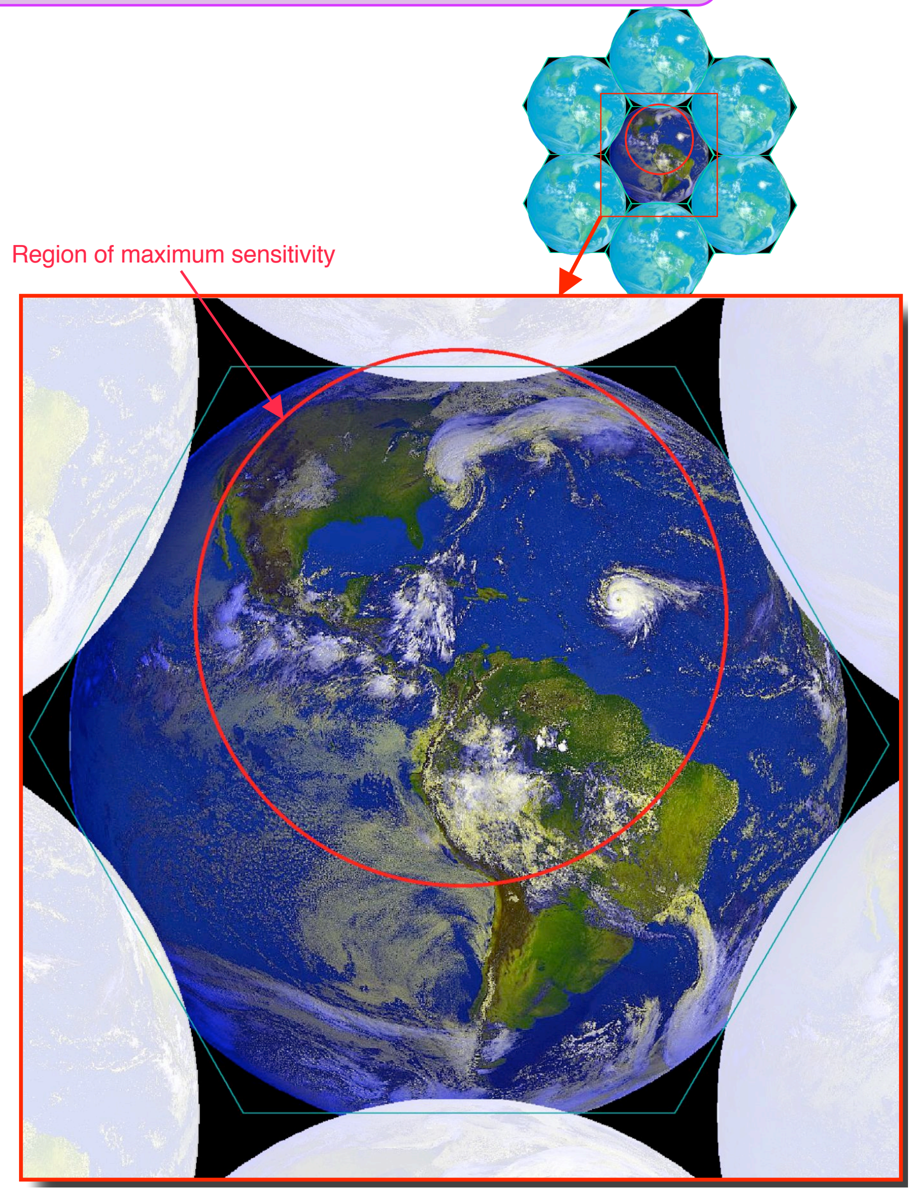


Example: AMSU-A ch. 1



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 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



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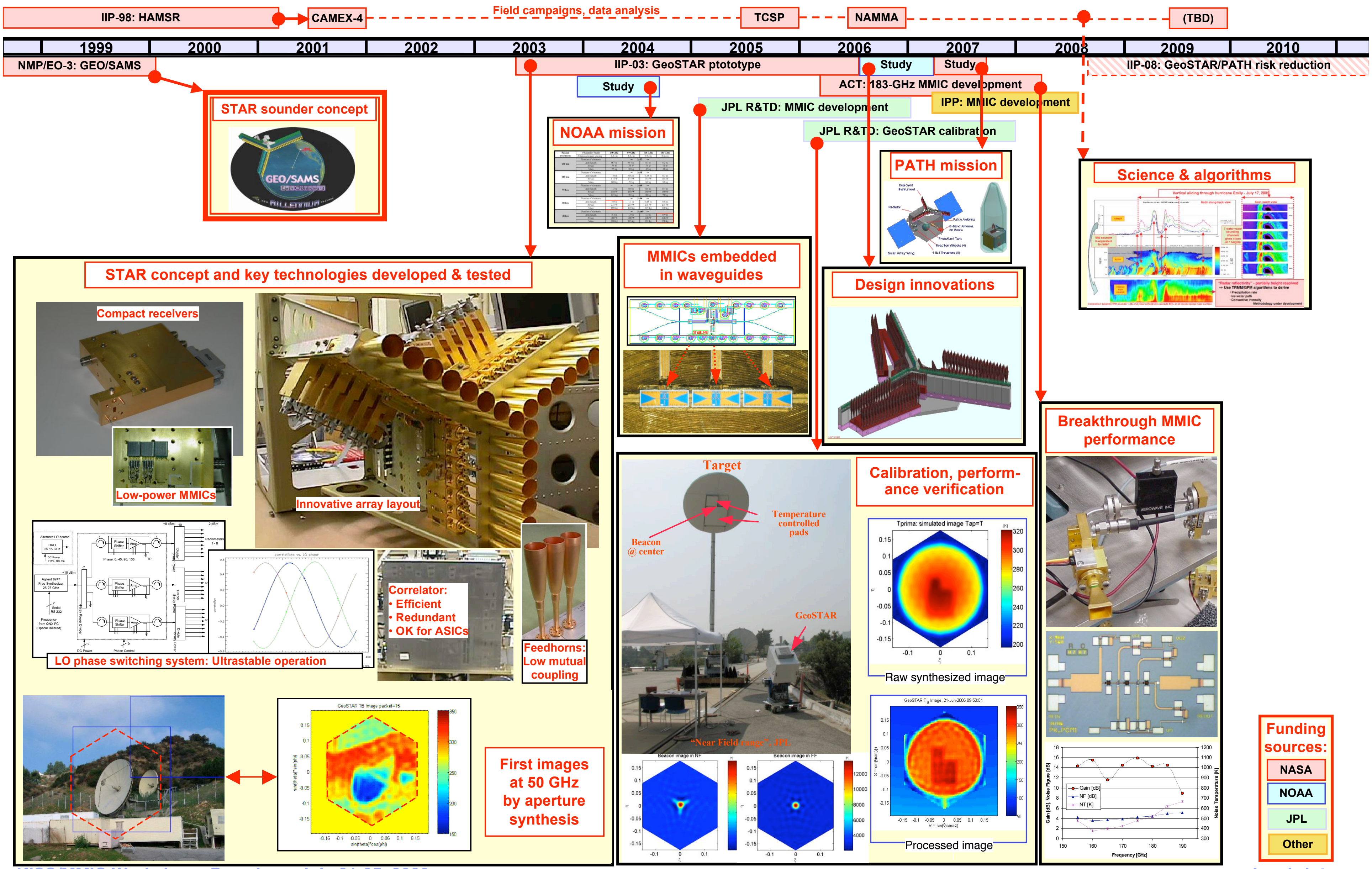
GeoSTAR Development History



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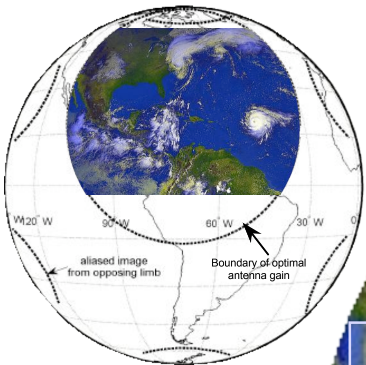
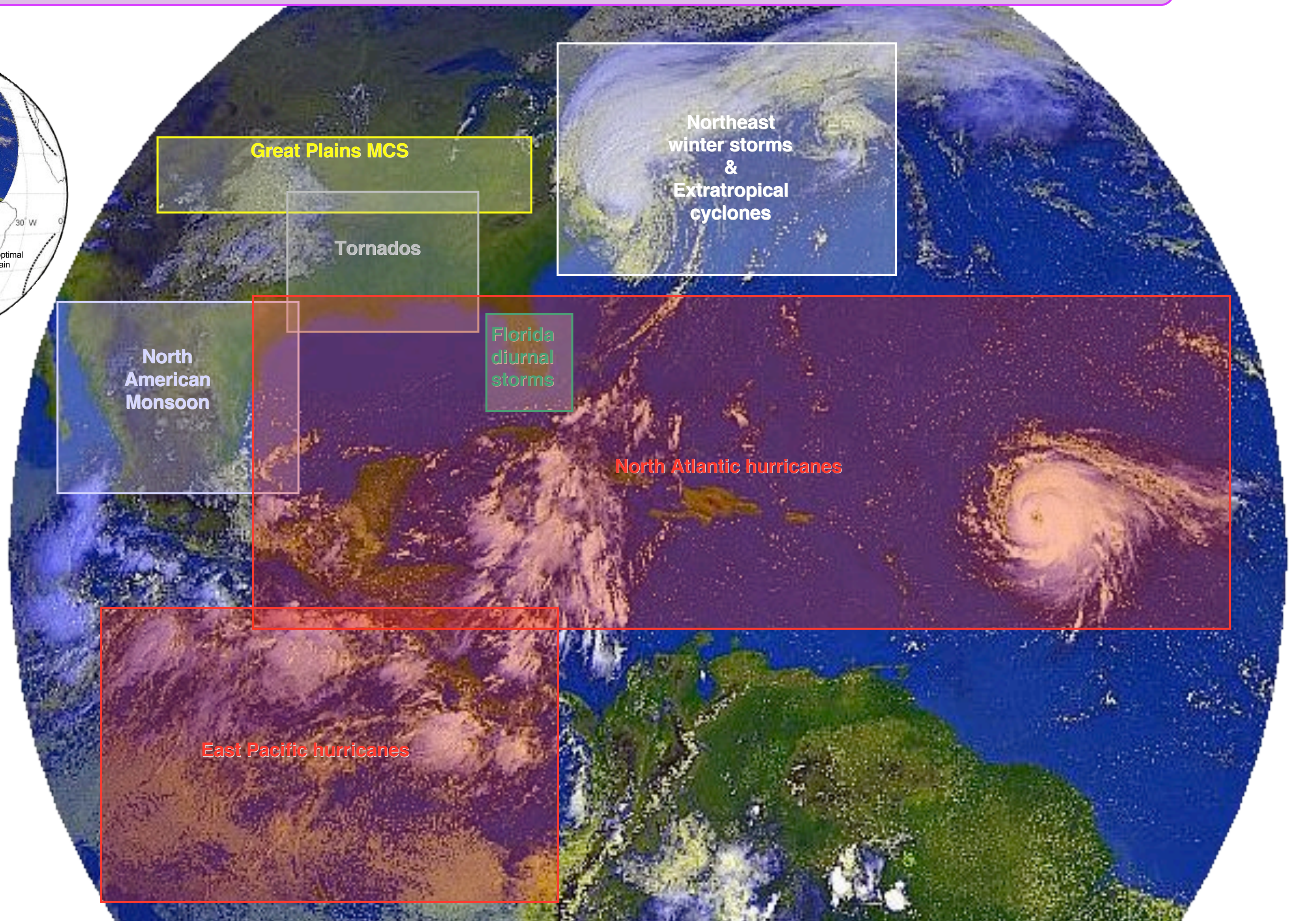
GeoSTAR/PATH Science Themes



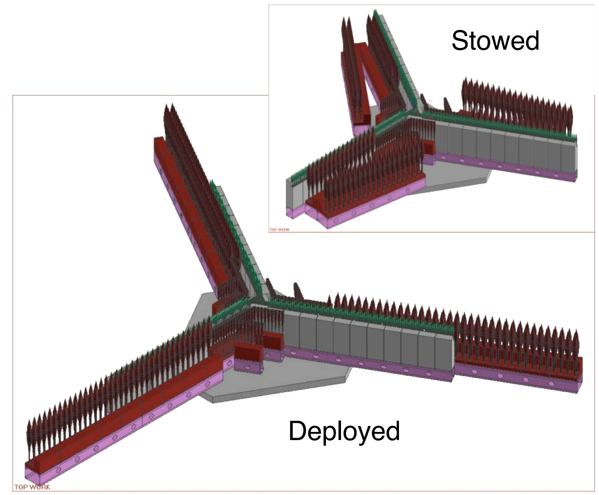


Mission Study: Feasibility of GeoSTAR

Baseline design

Is it possible to develop a GeoSTAR design that meets all key performance requirements?

- Dual band, dual collinear array
  - ~ 300 receivers @ 50 GHz/6 channels ⇒ T-sounding @ 50 km
  - ~ 600 receivers @ 183 GHz/4 channels ⇒ q-sounding @ 25 km
- NEDT < 1 K (baseline reference); high-performance: < 1/3 K
- Δt ~ 15 minutes in central FOV-region



Cost

Is the NRC PATH cost estimate reasonable?

- Mission: ~ $500M (within 15% of NRC estimate)
- Payload: < $150M

Power

Is it possible to run ~ 900 receivers & 600,000+ correlators with reasonable power?

- Receivers: ~ 150 mW each ⇒ less than 140 W total
- Correlators: < 10 μW per 1-bit cell (90 nm ASIC @ 100 MHz) ⇒ ~ 5 W total
  - High-performance option: 1.5 bits, 0.5-1 GHz, 65 nm ⇒ NEDT < 1/3 K @ < 50 W
- Total: ~ 250 W (+ 0-90 W solar heat load compensation)

Mass

Is total payload mass reasonable?

- Receivers: ~ 100 mg each ⇒ less than 90 kg
- Total: ~ 230 kg

CONCLUSION: GeoSTAR/PATH *is* a feasible medium-class mission

Technology Challenges

- **Stressing requirements**
  - Spatial resolution ⇒ Large number of receivers; very large number of digital processors
  - Temporal response ⇒ High radiometric sensitivity; parallel processing
  - Radiometric sensitivity ⇒ Sensitive receivers; fast "processing"
  - Limited resources ⇒ Reduce mass, power, complexity, cost
- **RF front-end (MMIC receivers)**
  - Low noise, reduced size, mass, *power*
  - Suitable for mass production, integration & testing
    - Array element matching
  - Large-scale module integration
    - Multiple-receiver modules integrated with apertures & structure
- **Digital back-end**
  - Digitizers & correlators
    - Large-scale chip integration (rad-hard ASICs)
  - Low power, high bandwidth
- **Other drivers**
  - Signal distribution & cabling
  - Power distribution (low-loss low-voltage DC-DC)