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Pasadena, California

Using Microwave Sounders to Probe the PBL

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The PBL sounding challenge

Prevailing cloudiness

- IR sounders can only sample the "clear air" outside the clouds
  - Cloud-cleared: Soundings from *clear sky* in partly cloudy regions
  - No idea what T & q is *inside/below* the clouds ← But see below
  - However: IR sounders have high V-res & precision
- Therefore: Need MW sounders
  - Look through clouds & precip: Get soundings *inside and below* clouds & precip
  - Large thermal contrast w/surface => High sensitivity to near-surface atmosphere
- Combined IR+MW: Best of both worlds
  - Est. q in/below clouds? → q(clouds) ≈ q(MW) – q(IR)

Vertical resolution of MW sounders

- More channels needed → Hyperspectral
- Need to keep hyperspectral noise limited

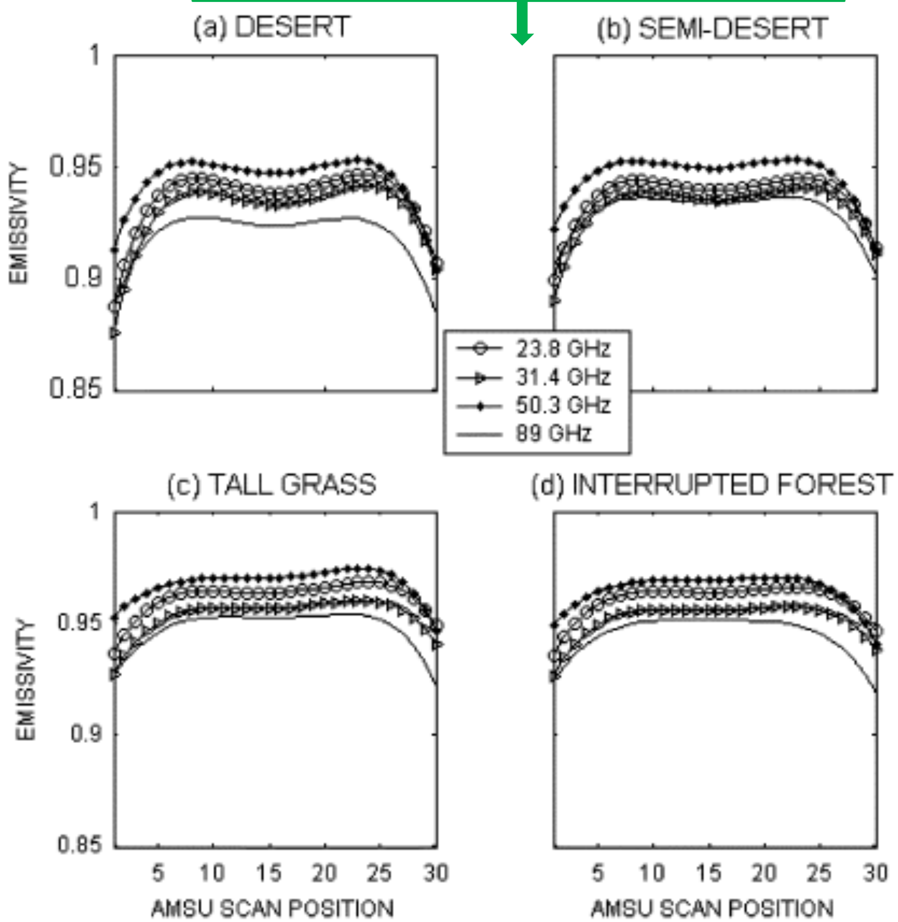
Surface emissivity issues

- Wide range of values: Need good "first guess", solve for it
- Best: Polarimetric (measure both H and V polarization)
  - Conical scanner?

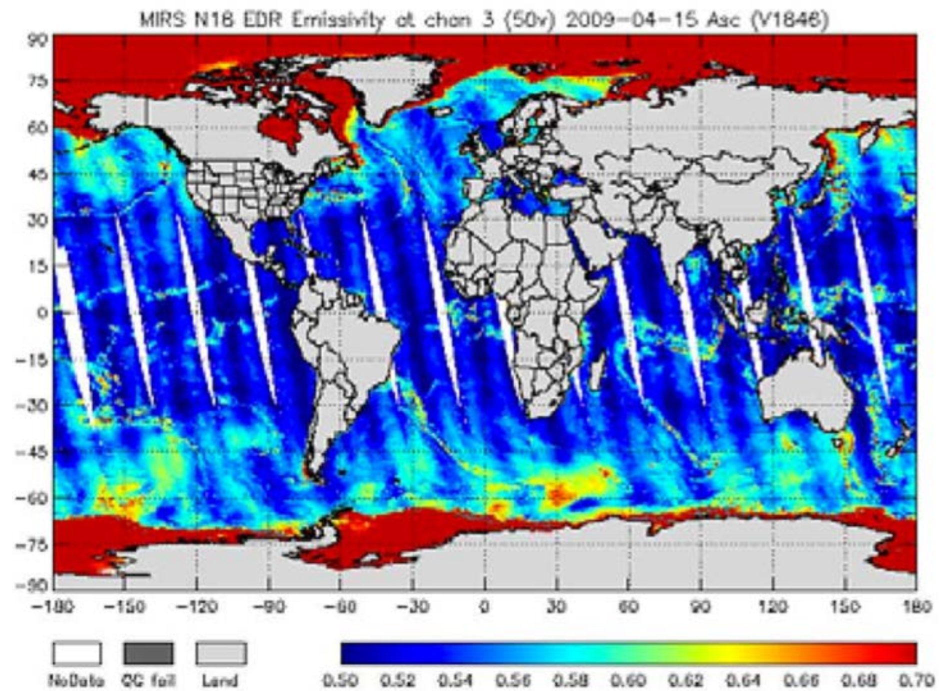
Wide range of emissivities

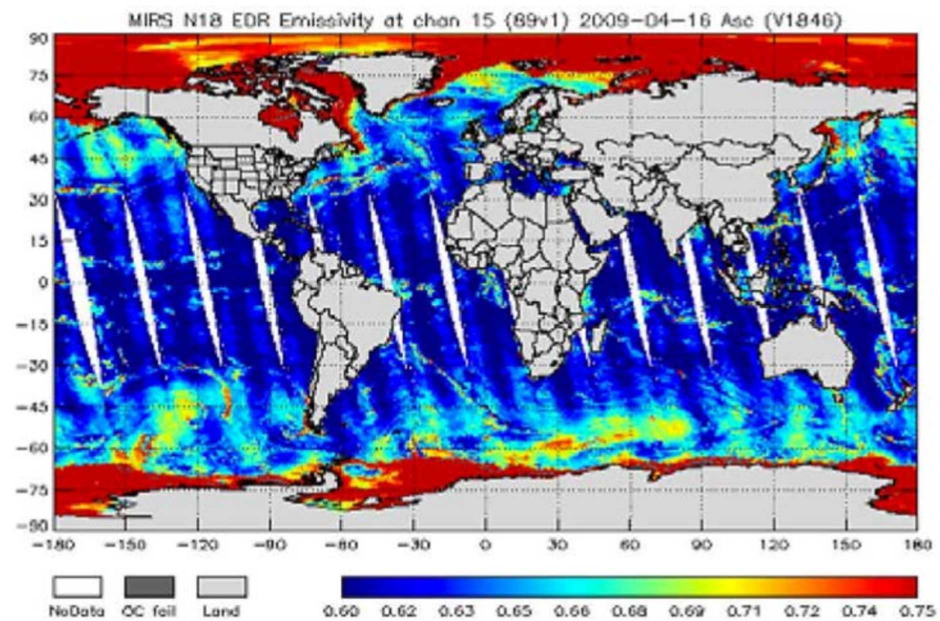
Ocean: Low (~ 0.5 & up)
Sensitive to surface wind
Snow & ice: High, but < land

Land: Relatively narrow range
(but $\Delta\varepsilon$ ~ 0.05 ←→ 10-15 K)



Karbou TGRS 2005

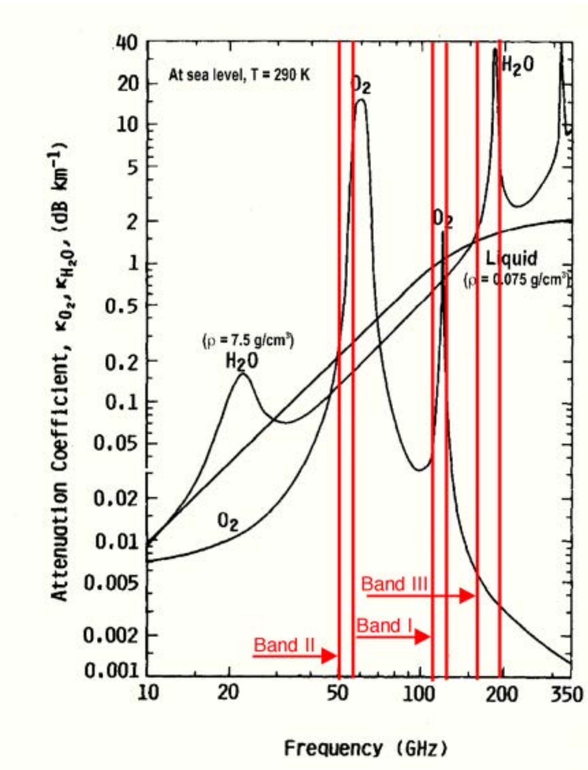


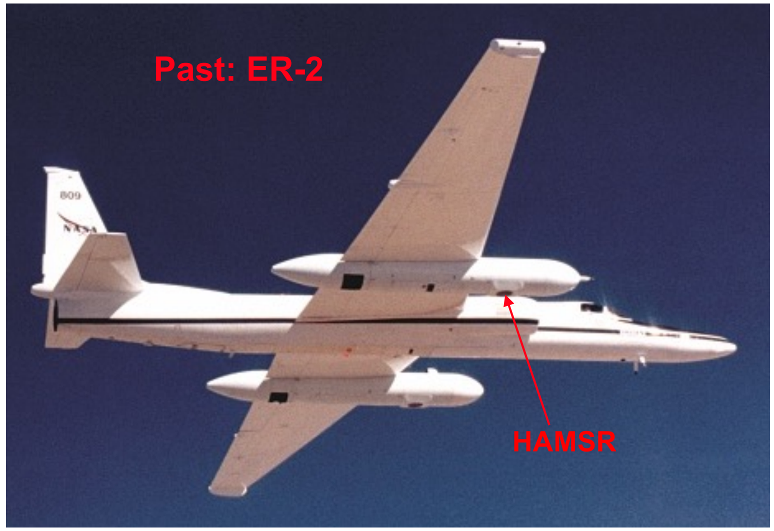


Kongoli TGRS 2011

Microwave sounders at JPL: HAMSR

Bjorn Lambrigtsen PI

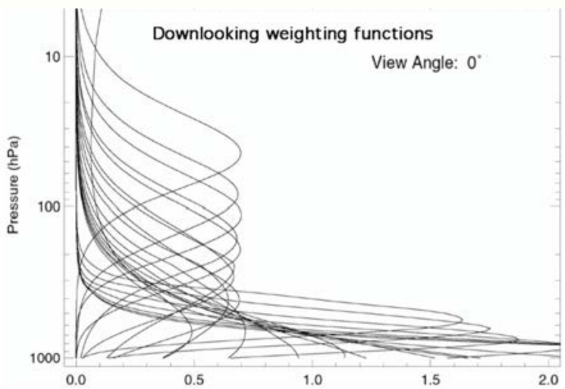


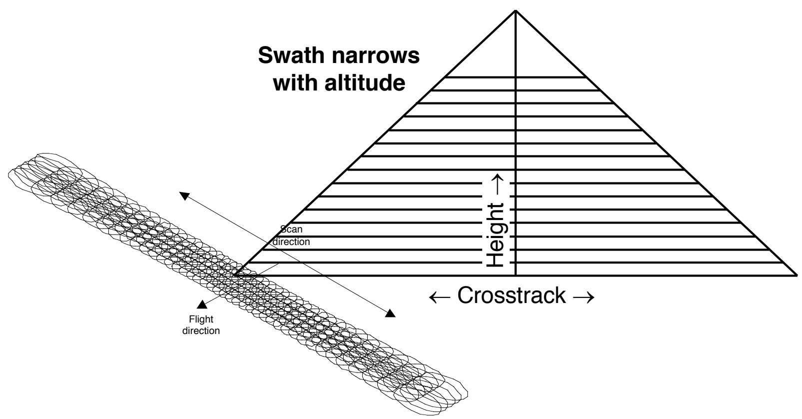


AMSU-equivalent channels circled in red

Chan #	Center freq. [GHz]	Offset [GHz]	Bandwidth [MHz]	Wt-func. Peak [mb or mm]
I-1	118.75	-5.500	1500	Sfc/[30 mm]
I-2	"	-3.500	1000	Surface
I-3	"	-2.550	500	Surface
I-4	"	-2.050	500	1000 mb
I-5	"	-1.600	400	750 mb
I-6	"	-1.200	400	400 mb
I-7	"	±0.800	2x400	250 mb
I-8	"	±0.450	2x300	150 mb
I-9	"	±0.235	2x130	80 mb
I-10	"	±0.120	2x100	40 mb
II-1	50.30	0	180	Sfc/[100 mm]
II-2	51.76	0	400	Surface
II-3	52.80	0	400	1000 mb
II-4	53.596	±0.115	2x170	750 mb
II-5	54.40	0	400	400 mb
II-6	54.94	0	400	250 mb
II-7	55.50	0	330	150 mb
II-8	56.02	0	270	90 mb
	56.67		330	
III-1	183.31	-17.0	4000	[11 mm]
III-2	"	±10.0	2x3000	[6.8 mm]
III-3	"	±7.0	2x2000	[4.2 mm]
III-4	"	±4.5	2x2000	[2.4 mm]
III-5	"	±3.0	2x1000	[1.2 mm]
III-6	"	±1.8	2x1000	[0.6 mm]
III-7	"	±1.0	2x500	[0.3 mm]

2x # of AMSU channels ➔ ~ 2x vertical resolution

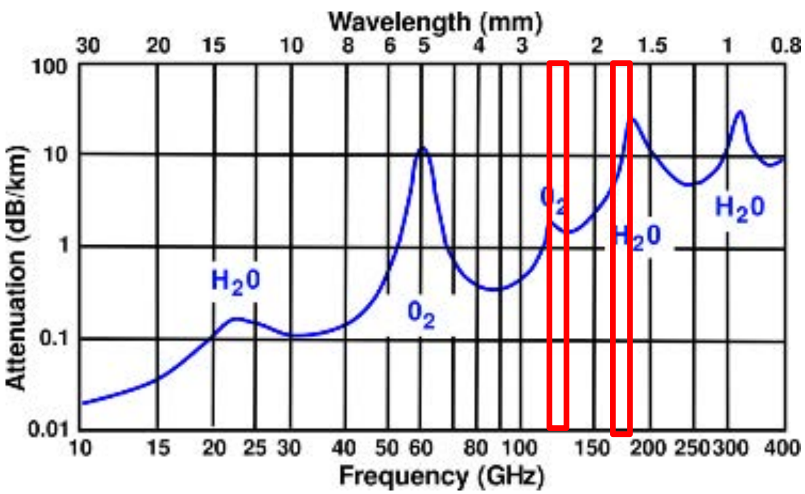




Microwave sounders at JPL: MASC

Sharmila Padmanabhan PI

2 Spectral bands



Direct measurements:

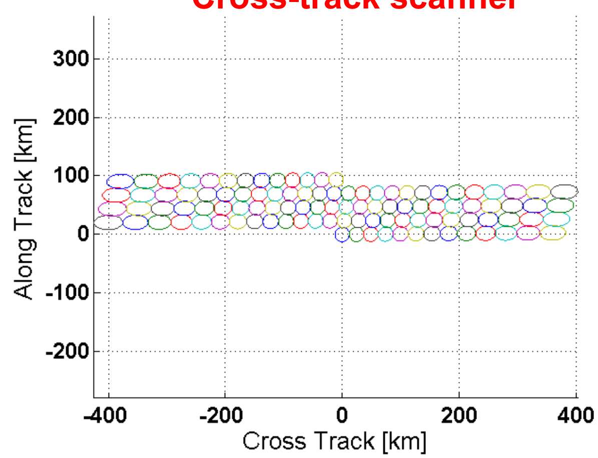
- **Brightness temperatures**
  - **8 channels**
  - **~ 0.5 K NEDT @ 5ms**

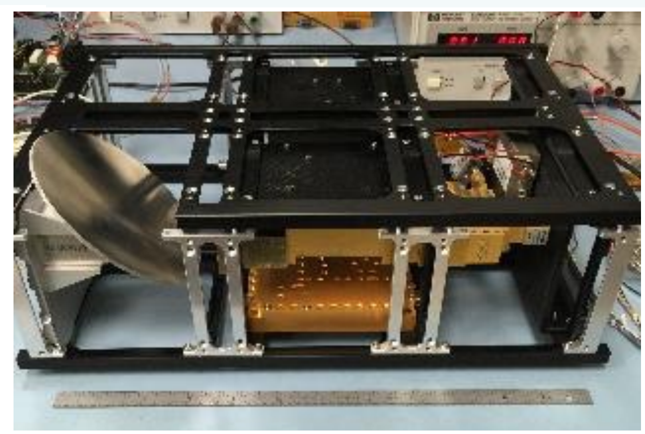
Derived vertical profiles:

- **Temperature profiles (118 GHz)**
- **Water vapor profiles (183 GHz)**

	118 GHz	183 GHz
System noise temperature	< 600 K	< 800 K
Minimum # of channels	4	4
Minimum spectral resolution	350 MHz	350 MHz
If Channels	+1, +2, +7 and +8 GHz	-1, -2, -7 and -8 GHz
Minimum Spatial resolution	24 km at nadir (orbit:400 km)	13 km at nadir (orbit:400 km)
Minimum Beam efficiency	>90%	>90%
Mass	5 kg	
Power	W	
Volume	3U	
Data Rate	10 kbps	

Cross-track scanner

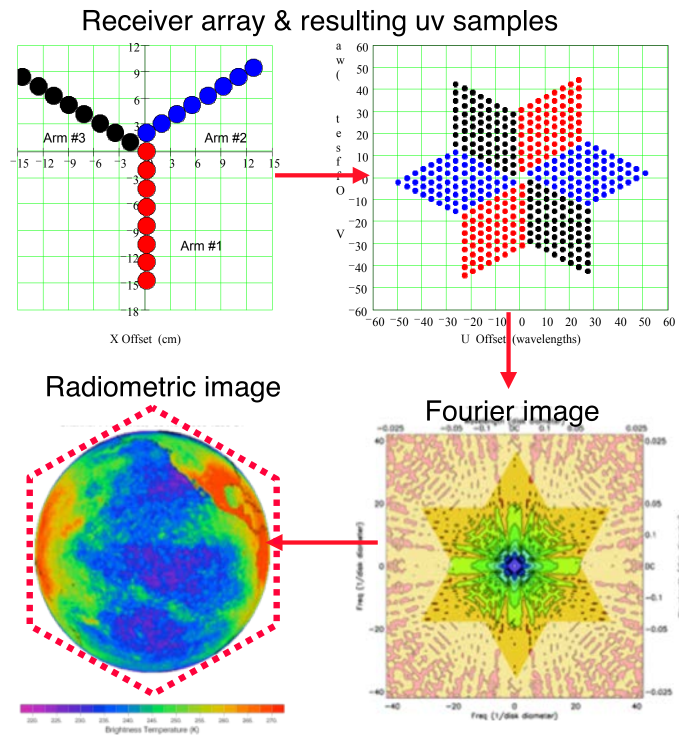




Microwave sounders at JPL: GeoSTAR

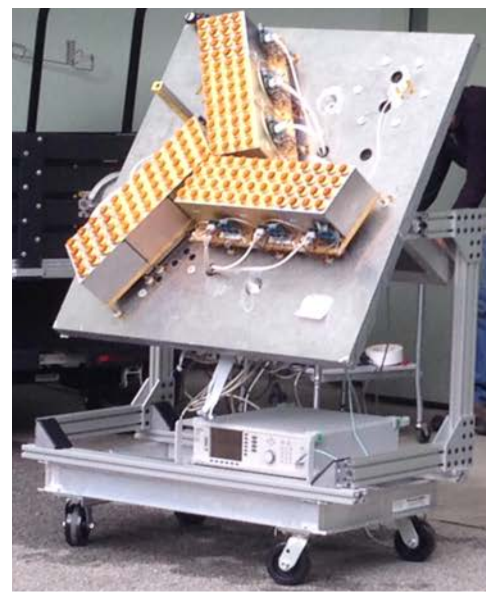
Bjorn Lambrigtsen PI

- **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 $\Rightarrow$ Pixel = 0.09° $\Rightarrow$ 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



This is the only viable "array spectrometer" design and is what the NRC had in mind in the 2007 "decadal survey"

Proof-of-concept prototype developed at JPL



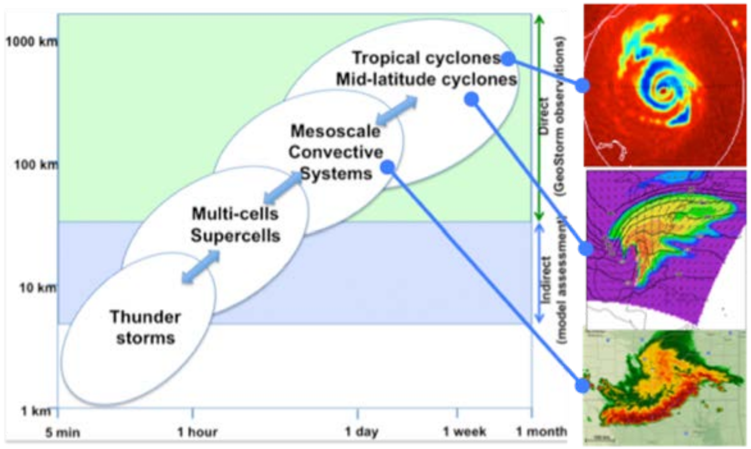
GeoStorm: A low-cost GEO/MW mission concept

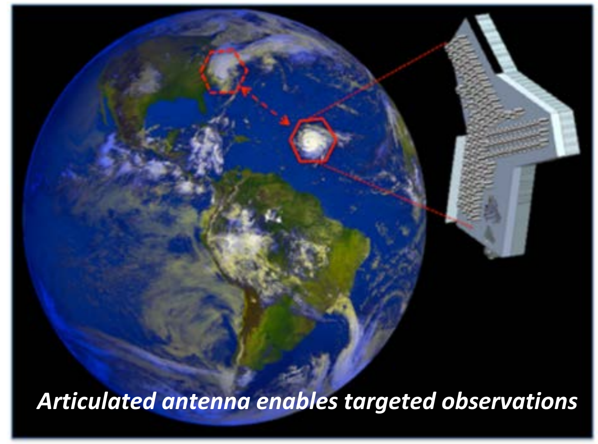
Pre-Decisional Information -- For Planning and Discussion Purposes Only

GEOSTORM: 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:

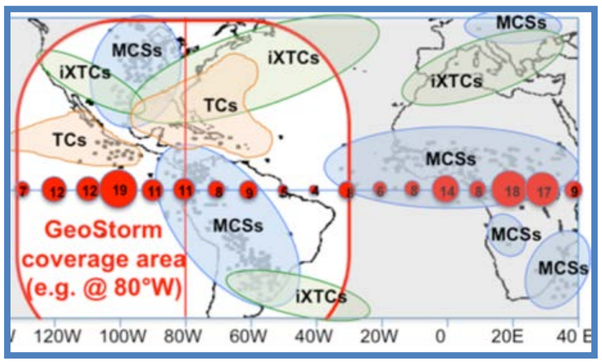
- ***hurricanes***
- ***severe thunderstorms and mesoscale convective systems***
- ***mid-latitude cyclones and winter storms***





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" implements a small version of GeoSTAR and requires articulation to cover the Earth disc
A full-size version of GeoSTAR will cover the entire Earth disc without articulation
Hosting on a commsat minimizes mission cost

Ground based: State of the art

Developed by Westwater in the 1980's

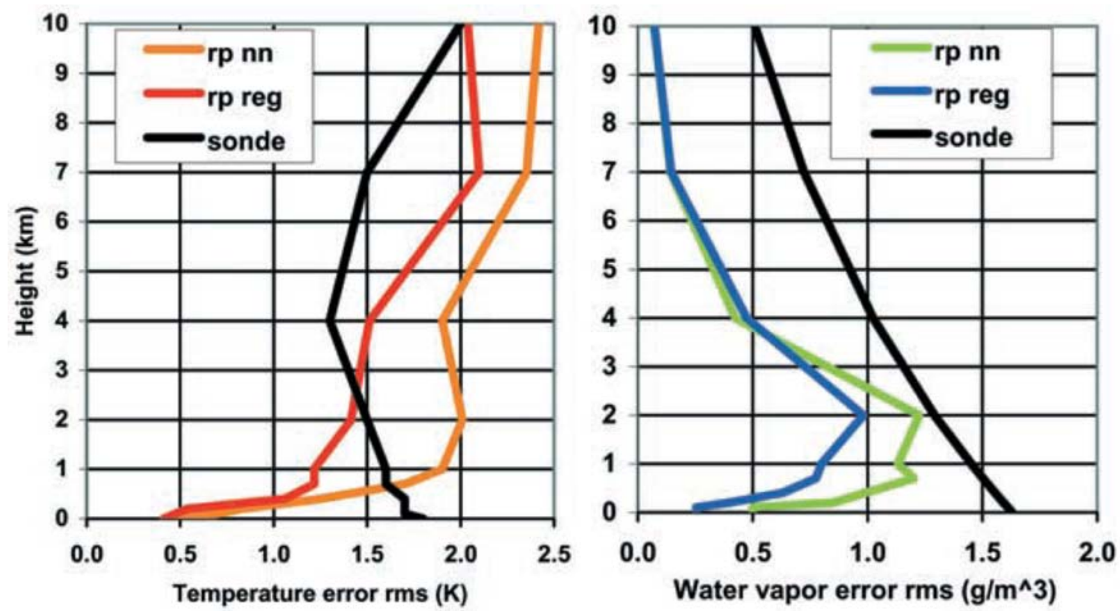
- Used to complement raobs in Colorado
- Fair vertical resolution of T(z), modest for q(z)

State of the art: Radiometrics Microwave Radiometer Profiler (MWRP)

- 12-channel T & q sounder
- Rugged construction, autonomous operation
- Fair vertical resolution

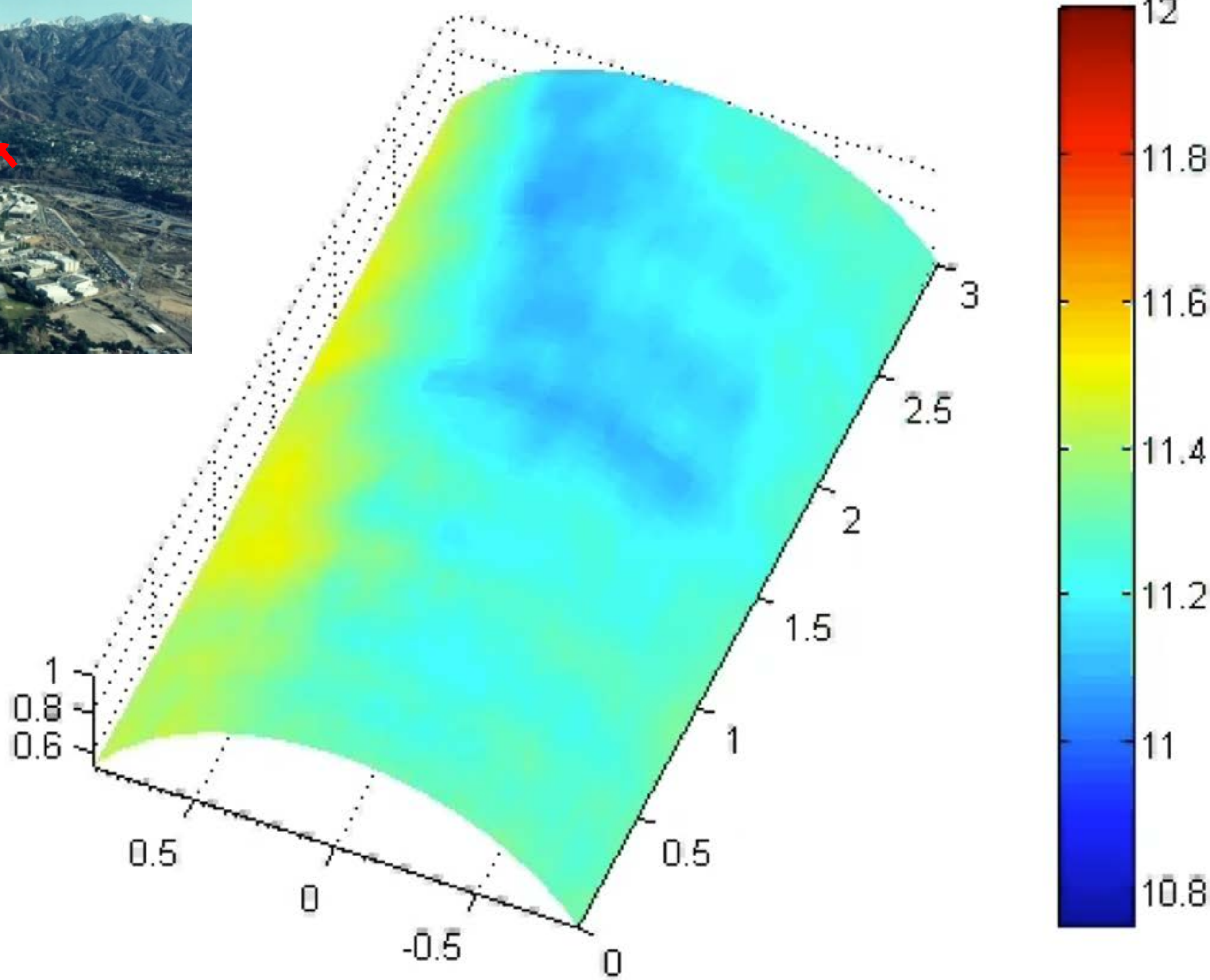
Limitations

- Uses 22-30 GHz for q-sounding → only modest vertical resolution & sensitivity



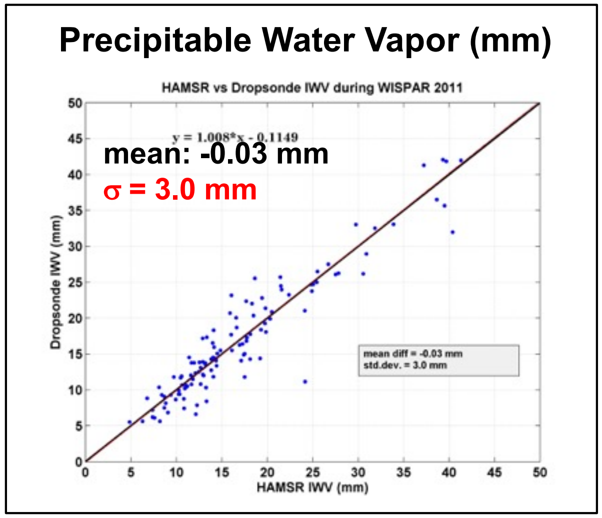
Ground based: HAMSR observations

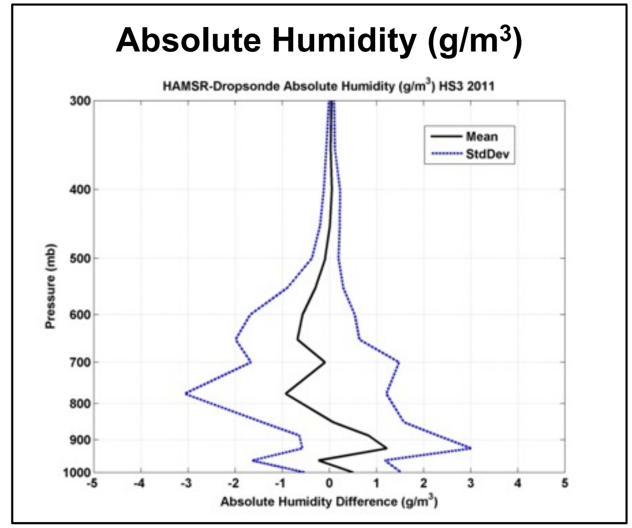
- HAMSR operated in upward looking scan mode at JPL 2/2/2010
- Retrieved PWV time series along scan arc reveals small scale structure: 0.3 mm resolution

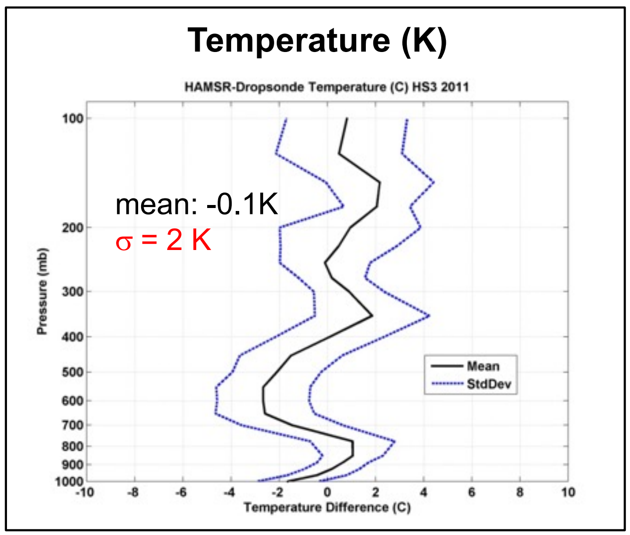


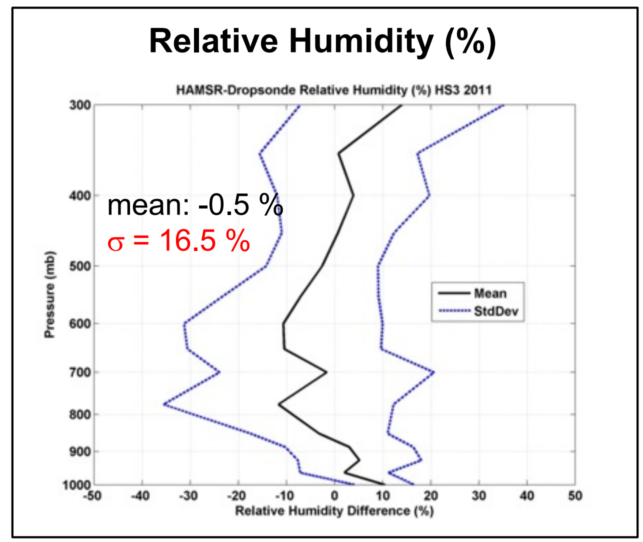
HAMSR retrieval accuracy (from above)

- **50 dropsonde comparisons during HS3 over a wide variety of atmospheric conditions**
- **Dropsonde profiles smoothed vertically to match HAMSR vertical resolution**









HAMSR: Vertical resolution ~ 1-2 km; horizontal resolution ~ 1 km

Satellites (ATMS): Vertical resolution ~ 2-3 km; horizontal resolution ~ 15-25 km

Future: Nadir MW sounders optimized for PBL

From the ground

- Optimize spectrometer to produce evenly spaced weighting functions
- Moderate engineering effort

From the air (HAMSR) or space (MASC)

- Hyperspectral sounding: 100's or 1000's of channels
- Moderate technology development
- Moderate engineering effort

Hyperspectral: What is possible?

- We think ¼ km vertical resolution is feasible

Spatial resolution

- Current MW satellite sounders: ~ 15 km
- We think ~ 5 km is feasible, maybe even better

But: Temporal resolution, sampling & coverage is a big problem

→ *Next slide…*

GeoSTAR: Notable & useful features

Flexible measurement frequency

- Basic cycle = 1 minute
- Accumulation period = 5 min to 20 min (typically 15 min)
- Can accumulate over unlimited intervals
- Independent measurements: Measurement cycles are not correlated with each other

Flexible radiometric sensitivity (NEDT) vs. "integration time"

- NEDT $\sim 1/\sqrt{\tau}$
- For q: about 2 K in 1 minute ("GeoStorm" implementation – later slide)
- → 0.9 K in 5 minutes; 0.5 K in 15 minutes; 0.25 K in 1 hour
- "Integration time" = "averaging interval" in ground processing ← S/W selectable!

Flexible channel set

- Basic "AMSU" sequence: 6 T-channels + 4 q-channels in rapid succession
- Can command subset on-orbit: e.g., only 4 q-channels → reduce NEDT by x1.6

Hyperspectral mode of operation

- Spectrometer is fully programmable and can be reconfigured in < 1 second
- LO operates from frequency synthesizer → can create arbitrary channel set
  - achieve closely spaced channels
  - achieve wide channel set over time

GeoSTAR and the PBL problem

Full temporal resolution

- Can capture rapid processes
  - Trade temporal resolution vs. NEDT: 1 minute @ 2 K to 1 hour @ 0.25 K
- Fully resolve the diurnal cycle
- Fully resolve complete life cycles of processes & phenomena
  - Maintain calibration & continuity for weeks

Enhanced vertical resolution

- Can synthesize hyperspectral characteristics
  - Especially for slowly evolving processes: Synthesize very high resolution & maintain low noise
  - We can create a sequence of channels with very closely spaced wt-functions
  - Effective noise can can be reduced without limit → deconvolution without undue noise amplification
  - Can use other “image processing” techniques to increase effective vertical resolution

Solve the emissivity problem by staring

- Effective where emissivity is changing very slowly
  - Separate emissivity term from atmospheric term: Generate first-guess maps
  - This will work well because angle of incidence (polarization) is constant
- Separate out any diurnal term
- Separate out any impulse term (precipitation event)

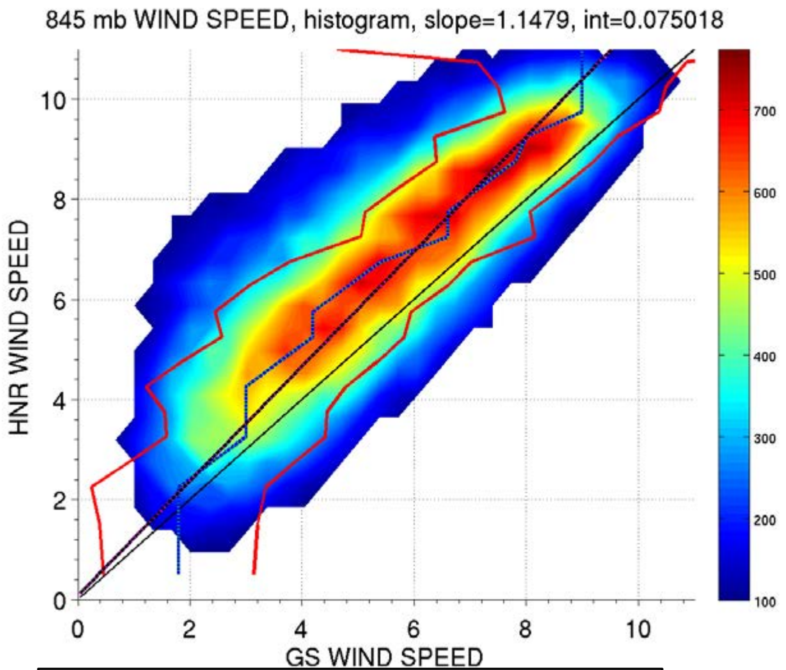
GeoSTAR does wind!

- Water vapor feature tracking (AMV wind)
- Under all weather conditions (clouds, rain)
- OSSE: Δ(speed) < $\pm$2 m/s; Δ(dir) < 15°

GeoSTAR wind OSSE

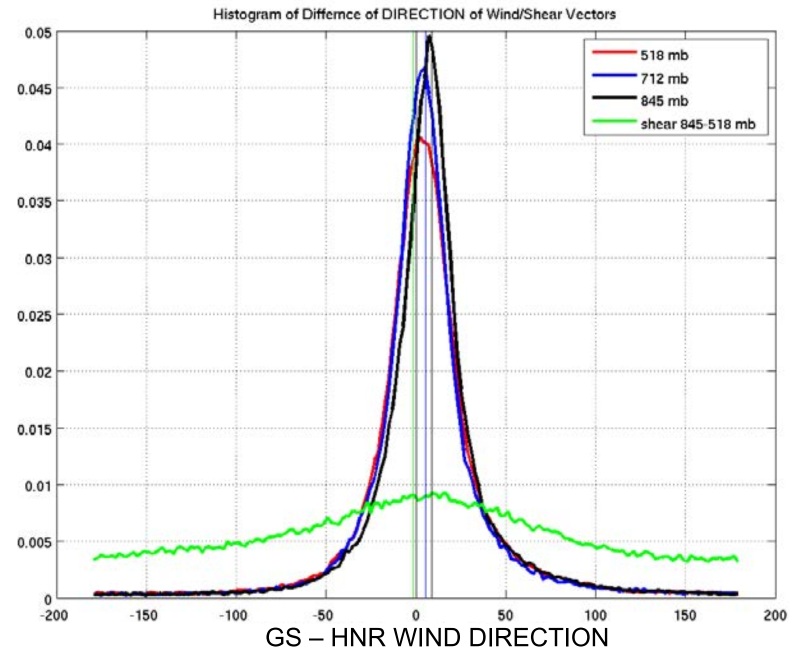
Based on large sample size (> 5000); cases with rain rate < 1 mm/hr

Wind speed: Histogram @ 845 mb



Red lines indicate 1-sigma levels
Black line: Best fit, nearly linear
Precision (rms) = 1.7 m/s; bias = -1 m/s

Wind direction: 3 pressure levels



Direction at 3 pressure levels
Also showing wind shear
Precision (rms) < 15°; bias < 6°

Precision < ± 2 m/s - This meets WMO requirements for wind

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°

Lambrigtsen JSTARS 2018

Summary

We probably need a full complement of sensors

- Radar: High vertical resolution of hydrometeor profiles, convective structure
- Lidar: High vertical resolution of moisture (but only in non-cloudy scenes)
- GPSRO: High vertical resolution of q(z) (but needs T from other source)
- IR sounders: Moderate vertical resolution of thermodynamics (clear only)
- MW sounders: Moderate vertical resolution of thermodynamics (all-weather)

From all vantage points

- From the ground: Resolve small-scale structure in local ROI
- From the ocean (buoys etc.): Measure remote-area MBL with high vertical resolution
- From the air: Measure regional PBL (ROI/process-focused)
- From space (LEO): Measure global PBL (moderate resolution)
- From space (GEO): Measure mesoscale PBL (high resolution & coverage)

Coordinated effort

- All observing systems operating in tandem → fill individual capability gaps

MW sounders: Important component of a PBL observing system!

A geostationary MW sounder can provide key PBL observables