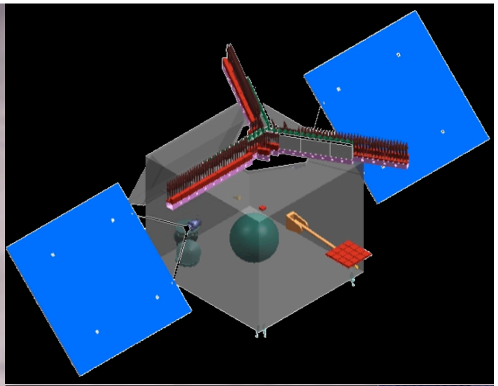
National Aeronautics and Space Administration

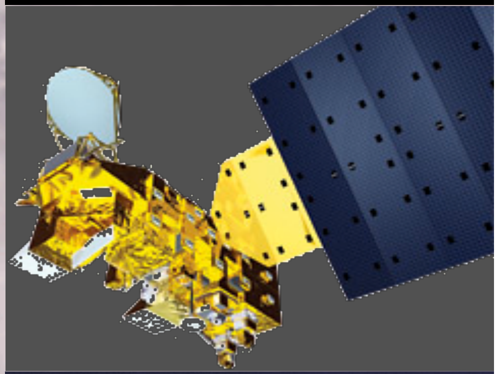
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

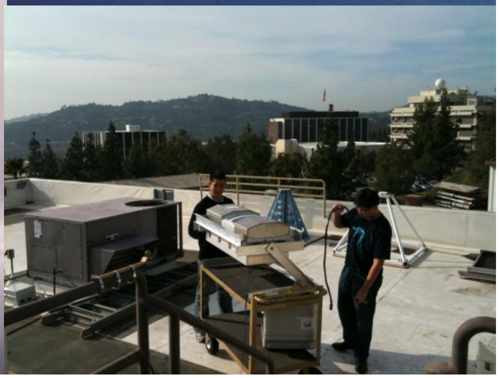
Are microwave sounders *obsolete*?

Bjorn Lambrigtsen
(with contributions from many others)

JPL





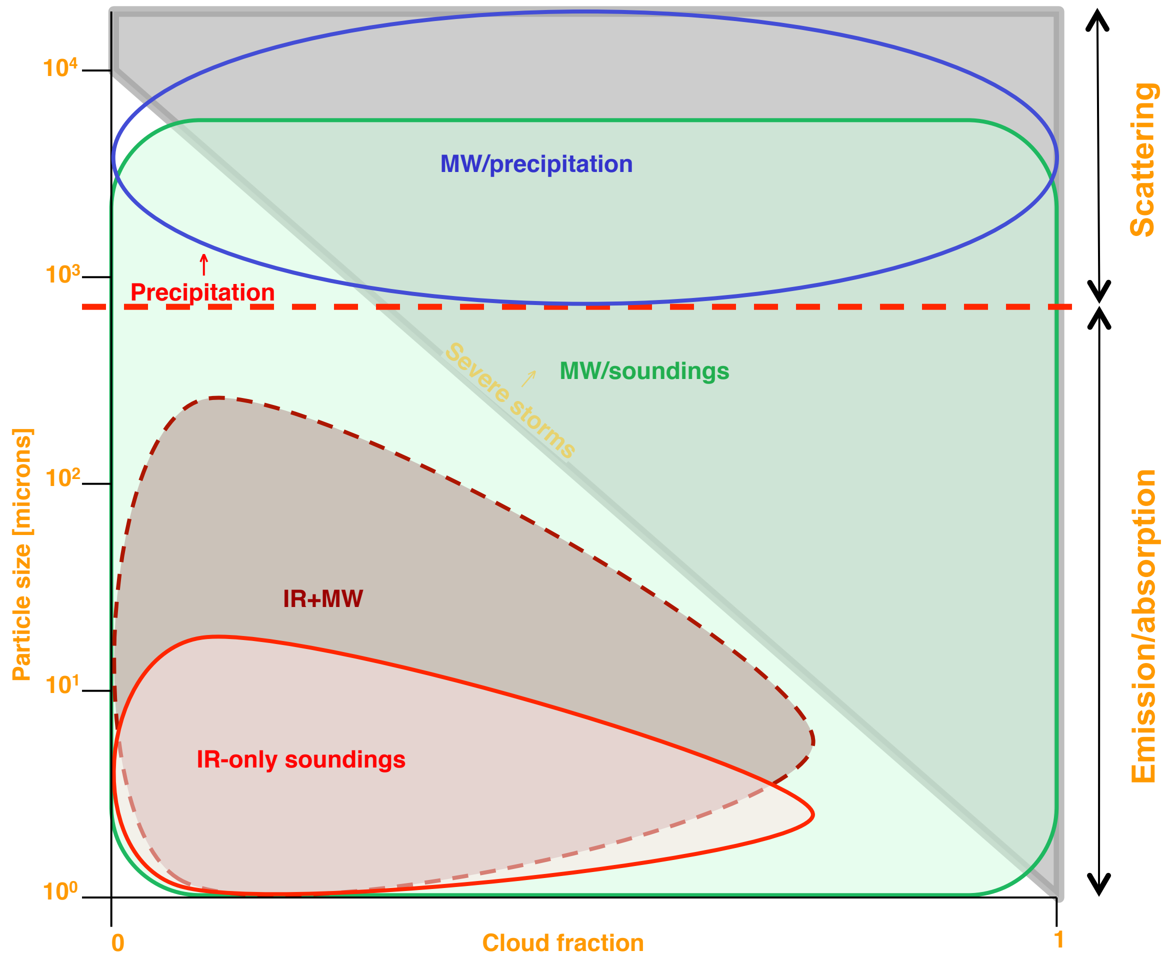


KISS Workshop on Innovative Satellite Observations to Characterize the Cloudy Boundary Layer

Caltech; September 22, 2010

Why we need microwave sounders

MW sounders measure all three phases of water: vapor, liquid (incl. rain), solid (incl. snow)
Ideally suited for the hydrologic cycle



Note: This is a 2-D view of a multidimensional world
Additional dimensions include spatial and temporal scales

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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 canopy
- --MW can see to surface (except in heavy precipitation: switch to convection algorithms)

Summary

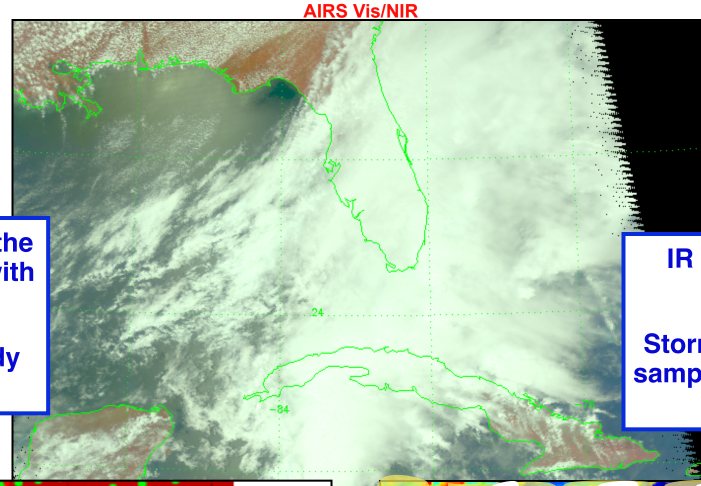
- --IR is best suited for global observations and storm precursor conditions in clear sky
- --MW is best suited for observing in/through storms and precursor conditions in clouds

Example

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

(May 16, 2006)

AIRS Vis/NIR

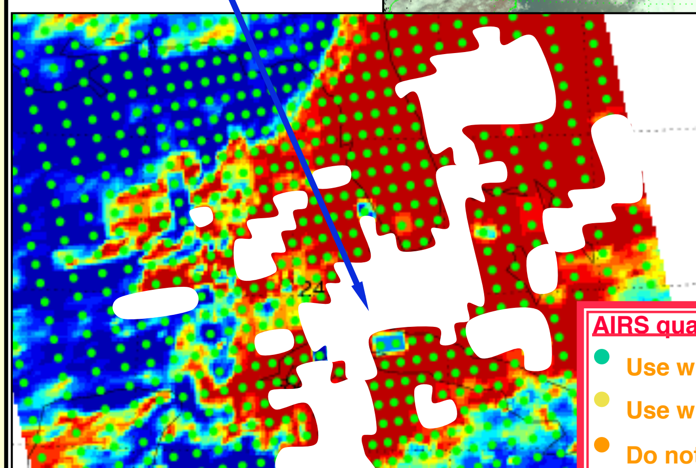


MW soundings fail only in the presence of precipitation with current algorithms

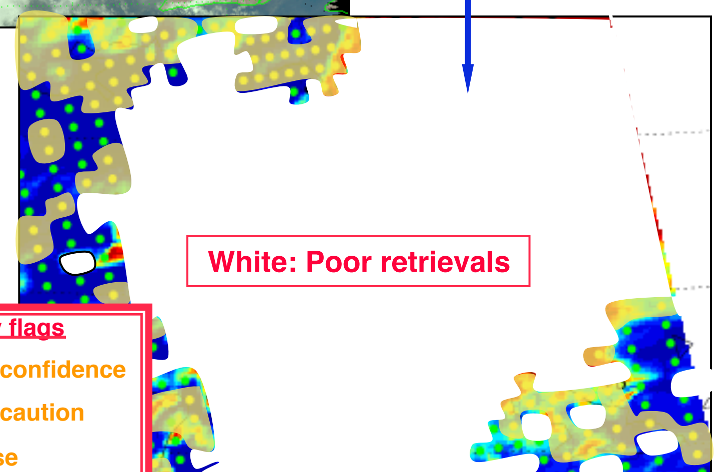
New algorithms will remedy that

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

AIRS quality flags

- Use with confidence
- Use with caution
- Do not use

Color background: cloud fraction

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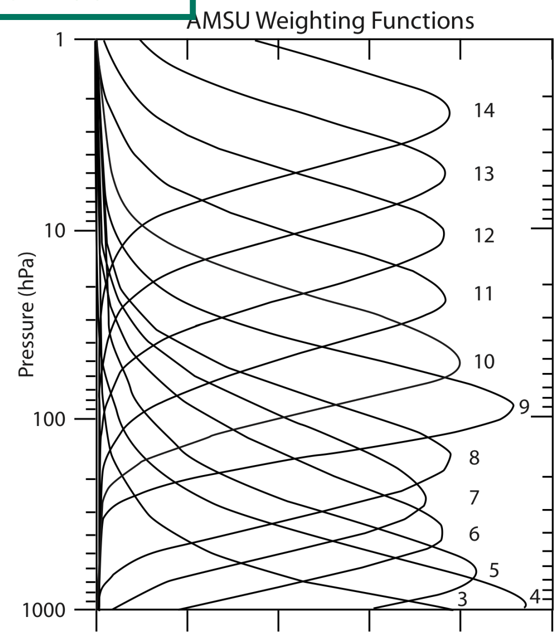
Satellite MWS state of the art: AMSU

AMSU-A (temperature sounder); spatial res ~ 50 km

Ch #	Cen.freq. [MHz]	B-width [MHz]	Meas. NEDT [K]	Pol
1	23800	1x270	0.17	V
2	31400	1x180	0.25	V
3	50300	1x160	0.25	V
4	52800	1x380	0.14	V
5	53596±115	2x170	0.19	H
6	54400	1x380	0.17	H
7	54940	1x380	0.14	V
8	55500	1x310	0.16	H
9	57290.344 [f_0]	1x310	0.16	H
10	f_0±217	2x 77	0.22	H
11	f_0±322.4±48	4x 35	0.24	H
12	f_0±322.4±22	4x 16	0.36	H
13	f_0±322.4±10	4x 8	0.50	H
14	f_0±322.4±4.5	4x 3	0.81	H
15	89000	1x2000	0.12	V



AMSUs are flying on multiple satellites:
- NASA/Aqua
- NOAA-15
- NOAA-16
- NOAA-17
- NOAA-18
- NOAA-19
- Metop-A

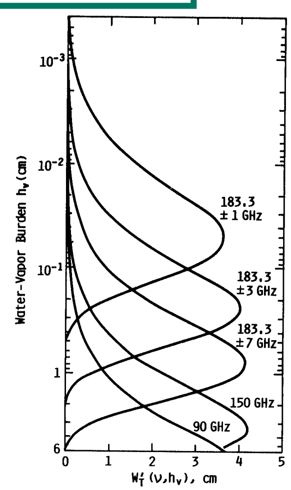
Producing > 2 million soundings per day!

ATMS coming soon
- NASA/NPP
- JPSS

ATMS ≈ AMSU, except
- 2x humidity channels
- 30 km res T-sounding

AMSU-B (humidity sounder); spatial res ~ 15 km

Ch #	Cen.freq. [MHz]	B-width [MHz]	Meas. NEDT [K]	Pol
	89000	1x4000	N/A	V
	150000	1x4000	0.68	V
	183310±1000	2x 500	0.57	—
	183310±3000	2x1000	0.39	—
	183310±7000	2x2000	0.30	V



Other products:
- Cloud liquid water (~ 1 piece of info ≈ LWC or nominal profile
- Precipitation (height resolved)

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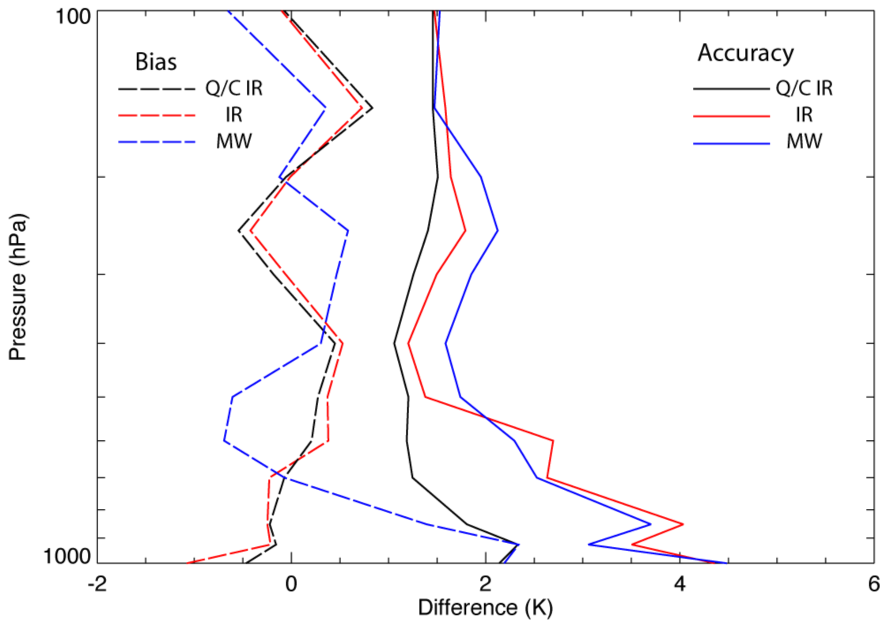
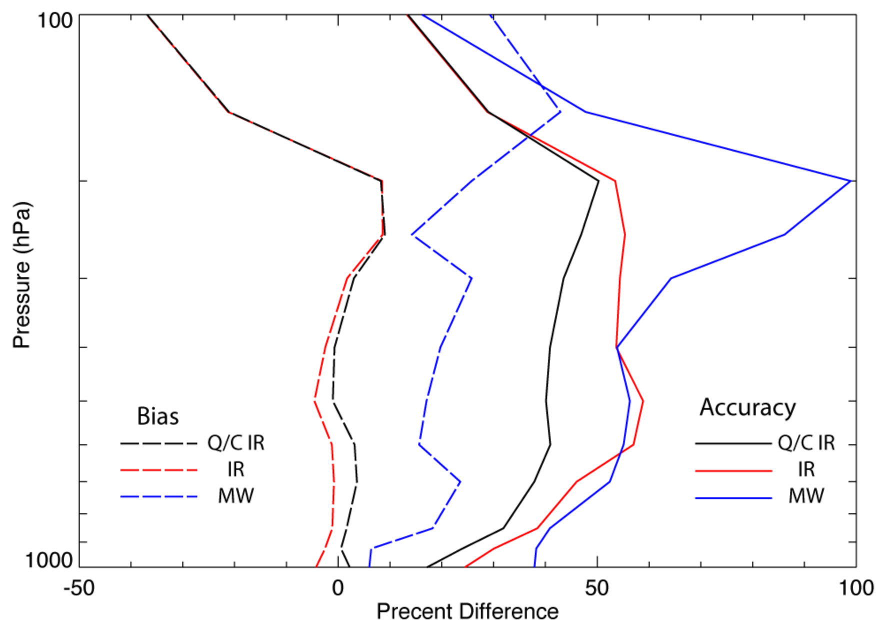
Sounding accuracy: IR vs. MW

Global statistics, one day



🡐 Temperature retrievals

Water vapor retrievals ➔



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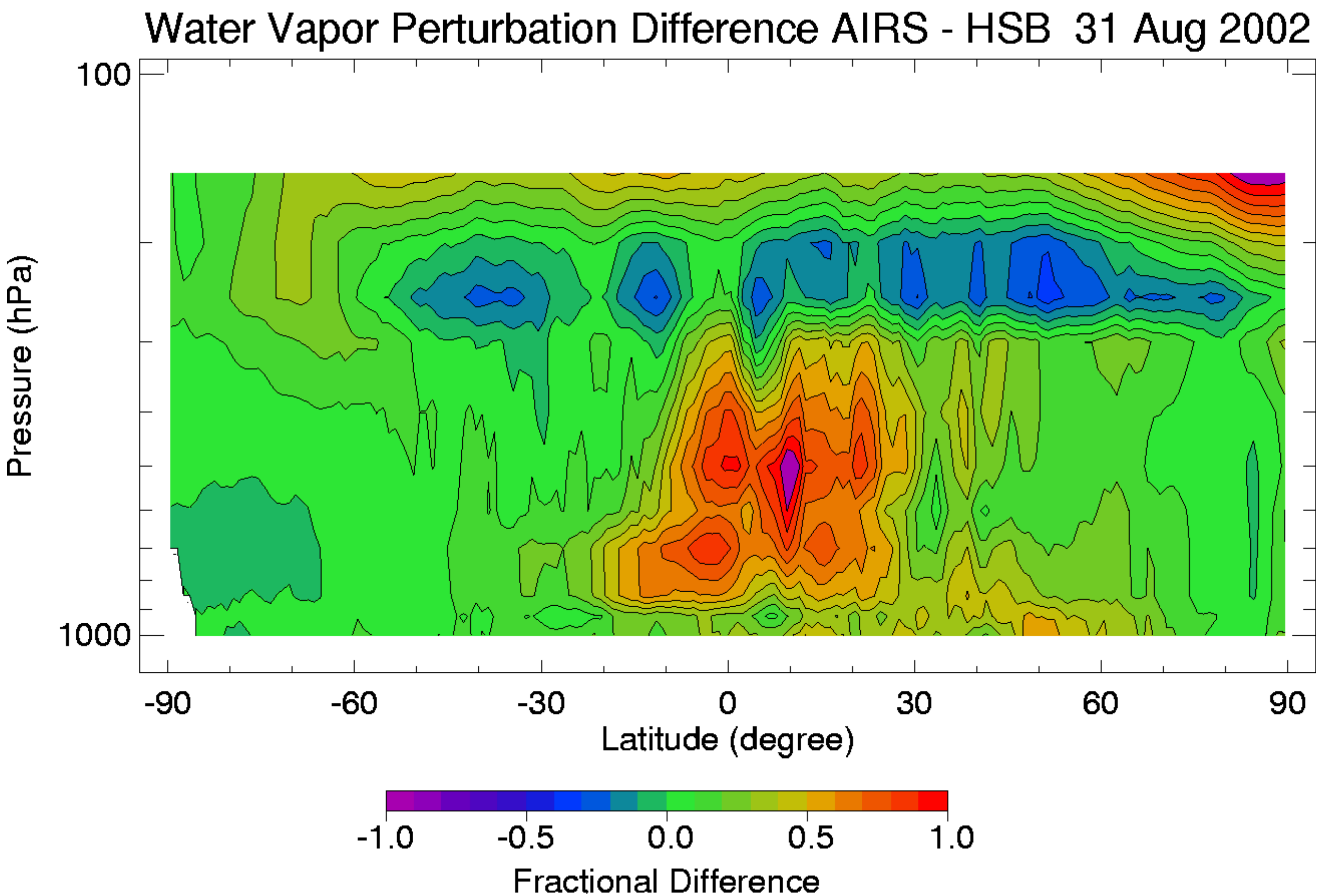
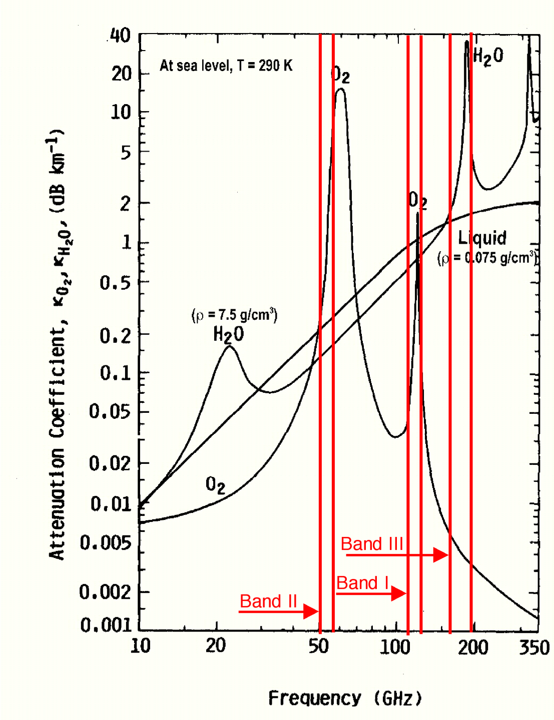
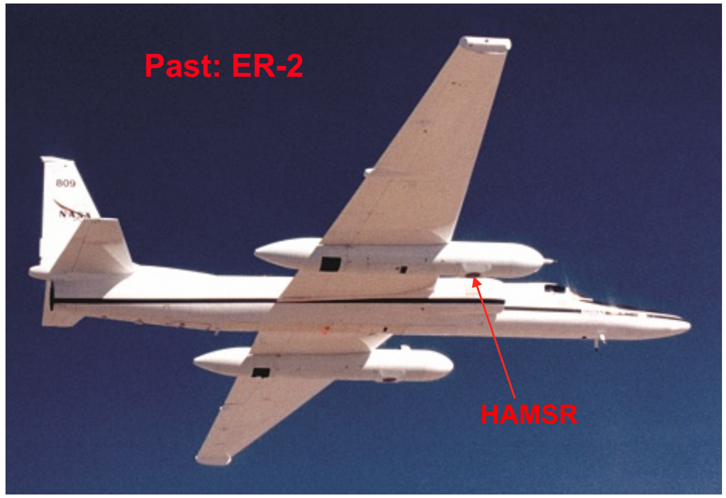
Regime sampling: IR vs. MW

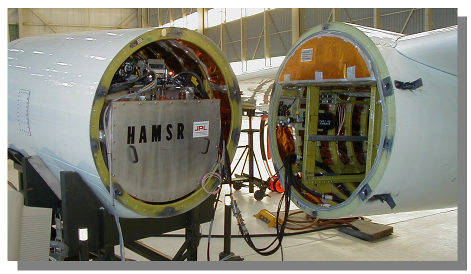


Aircraft MWS state of the art: HAMSR

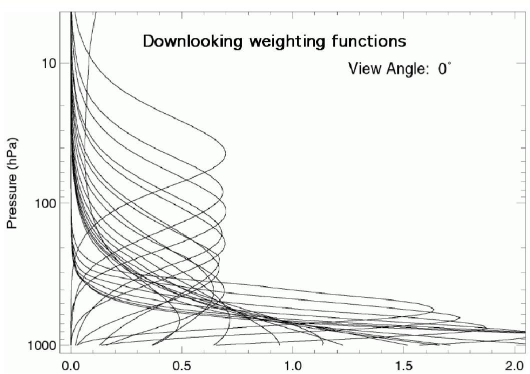
The High Altitude MMIC Sounding Radiometer
HAMSR

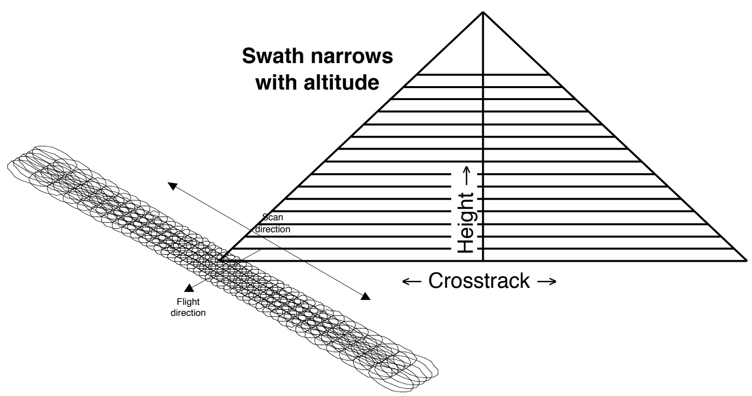






Chan #	Center freq. [GHz]	Offset [GHz]	Bandwidth [MHz]	Wt-func. Peak [mb or mm]
I-1	118.75	-5.500	1500	Sfc/[30 mm]
I-2	“	-3.500	1000	Surface
I-3	“	-2.550	500	Surface
I-4	“	-2.050	500	1000 mb
I-5	“	-1.600	400	750 mb
I-6	“	-1.200	400	400 mb
I-7	“	±0.800	2x400	250 mb
I-8	“	±0.450	2x300	150 mb
I-9	“	±0.235	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 56.67	0	270 330	90 mb
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]





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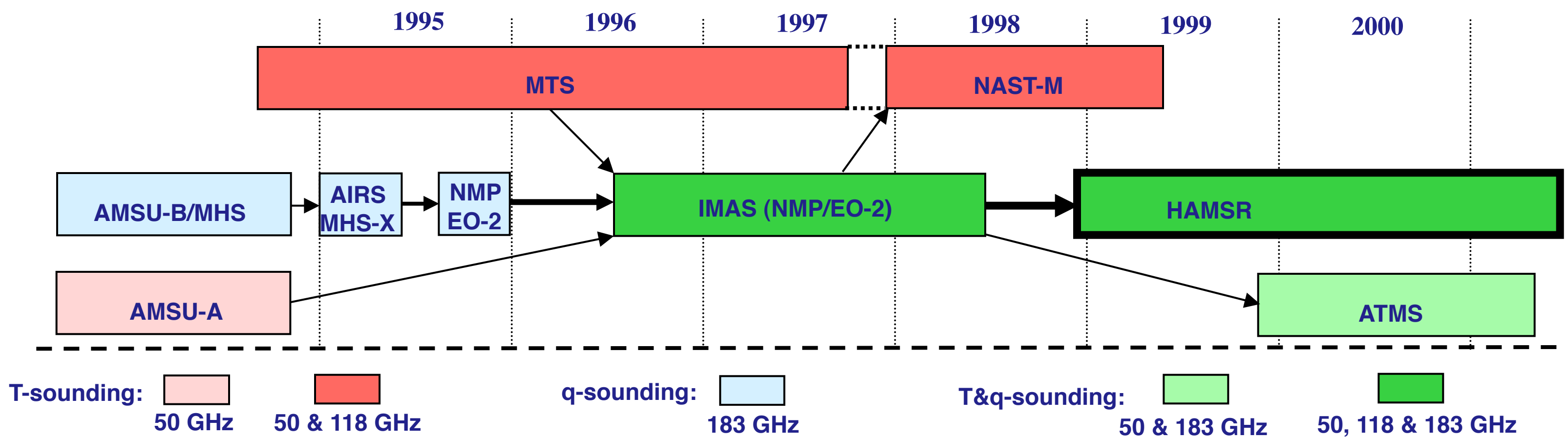
Context and Pedigree of HAMSR



- **HAMSR carries the IMAS development effort to maturity**
  - Dual-band T-sounding + q-sounding in single package
  - New MMIC receiver technology; Small instrument
- **ATMS is also based on IMAS**
  - Single-band T-sounding + q-sounding
- **NAST-M implements IMAS T-sounding**
  - Dual-band T-sounding — No q-sounding

HAMSR Microwave Sounder on Global Hawk

New receiver technology

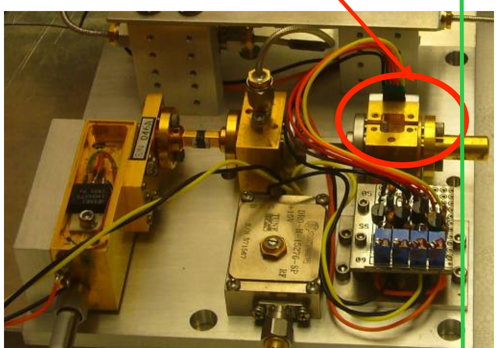
- 183 GHz receiver upgraded with LNA developed under ESTO/ACT
- Noise reduced by an order of magnitude
- Defines new state-of-the art

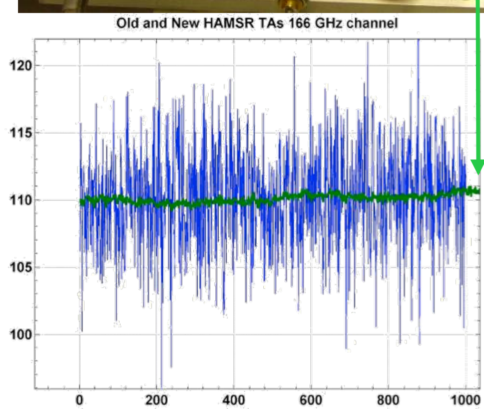
Multiple platforms

- ER-2 (CAMEX-4, TCSP)
- DC-8 (NAMMA)
- *Global Hawk (GRIP, 2010)*

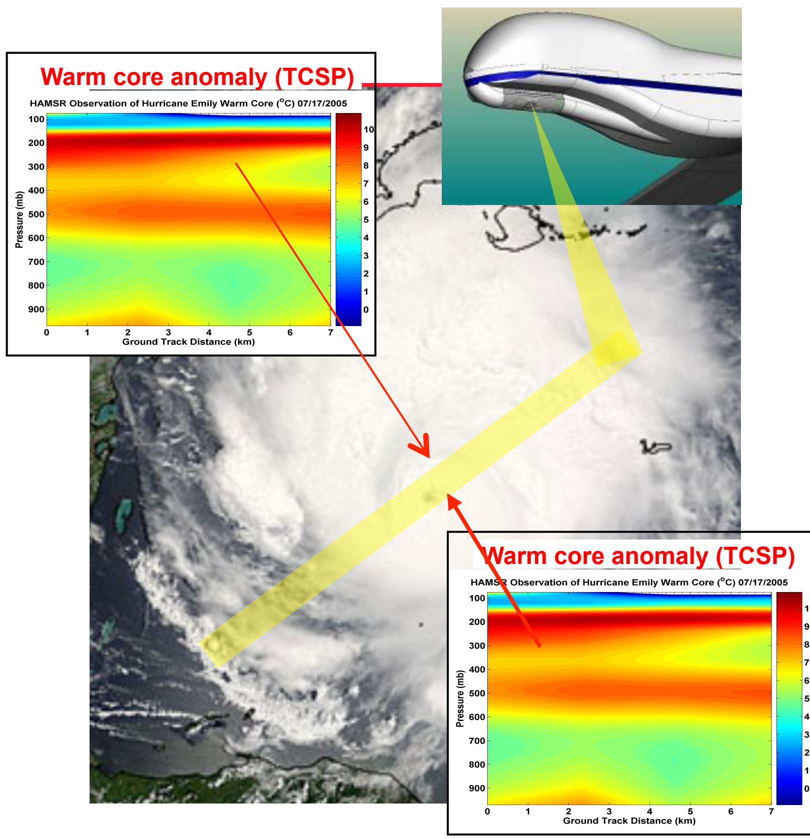
Convective structure

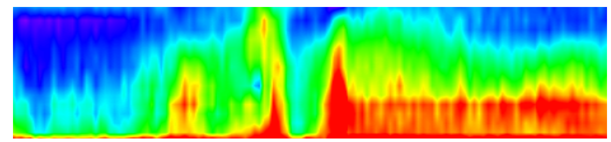
- Radar-like reflectivity
- 1 km vert.res/40 km swath
- Conv.intens., precip(z), ice (z)

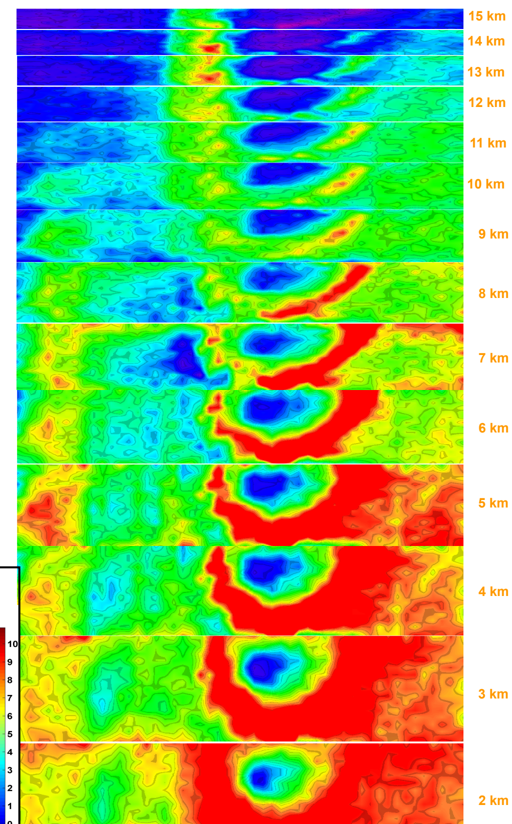




Noise reduced from 2 K to 0.2 K



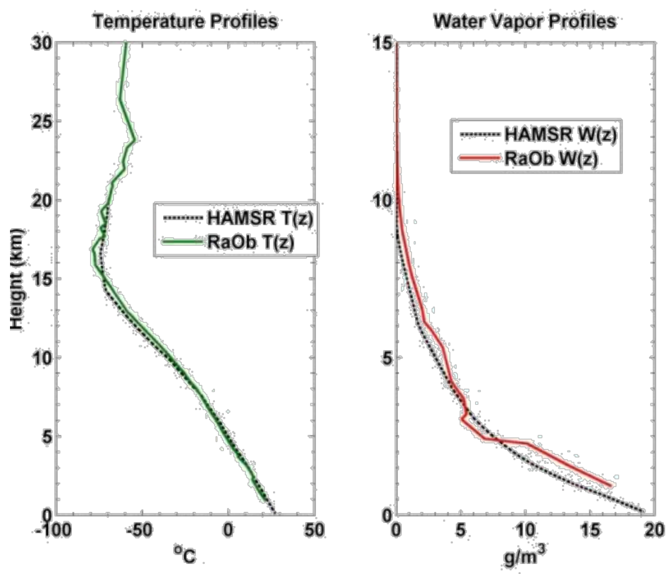




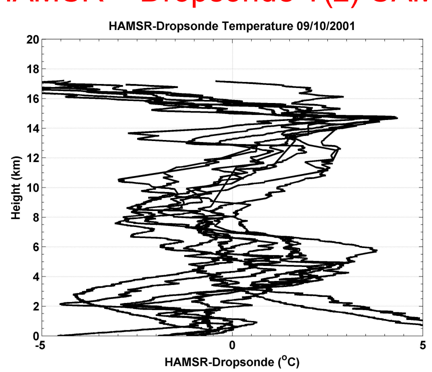
3D reflectivity, Hurricane Emily (2005)

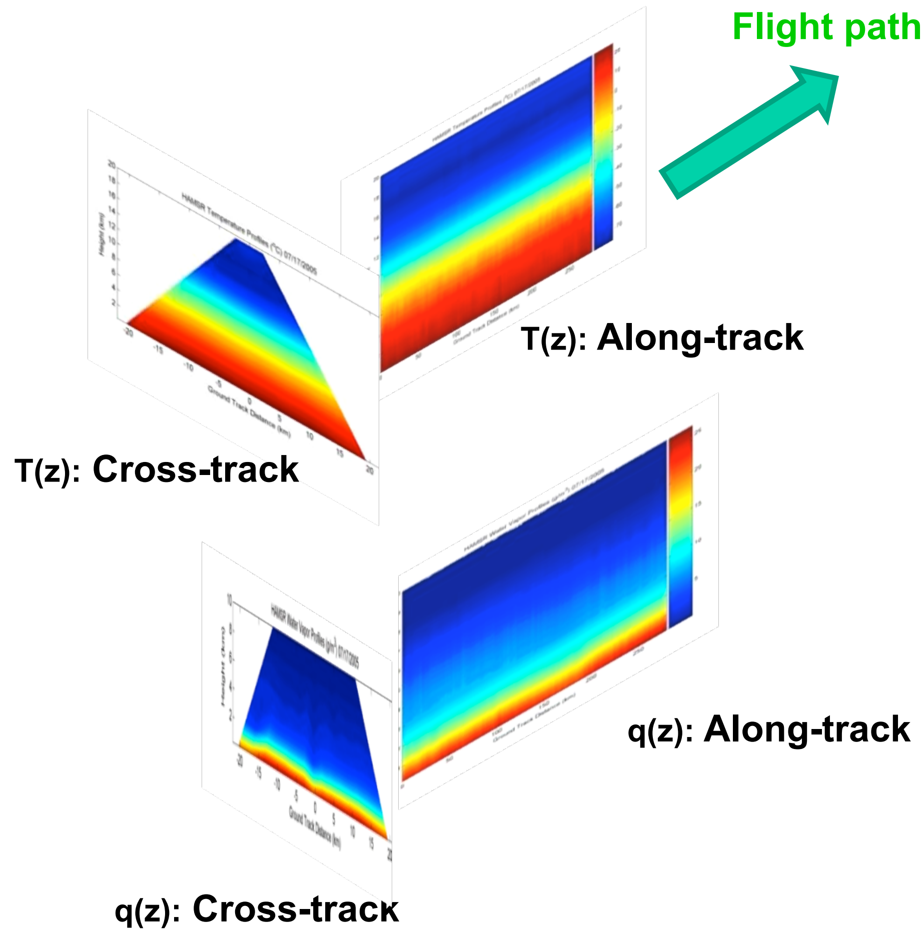
HAMSR sounding accuracy

- **Retrieval of 3-D atmospheric temperature, water vapor and cloud liquid water profiles using optimal estimation inversion approach**
- **Good agreement with dropsonde observations**



HAMSR – Dropsonde T(z) CAMEX-4





Note: Third band (118 GHz) also makes it possible to retrieve L(z)

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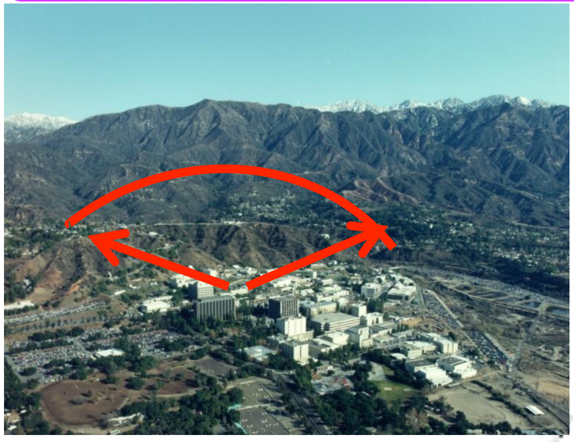
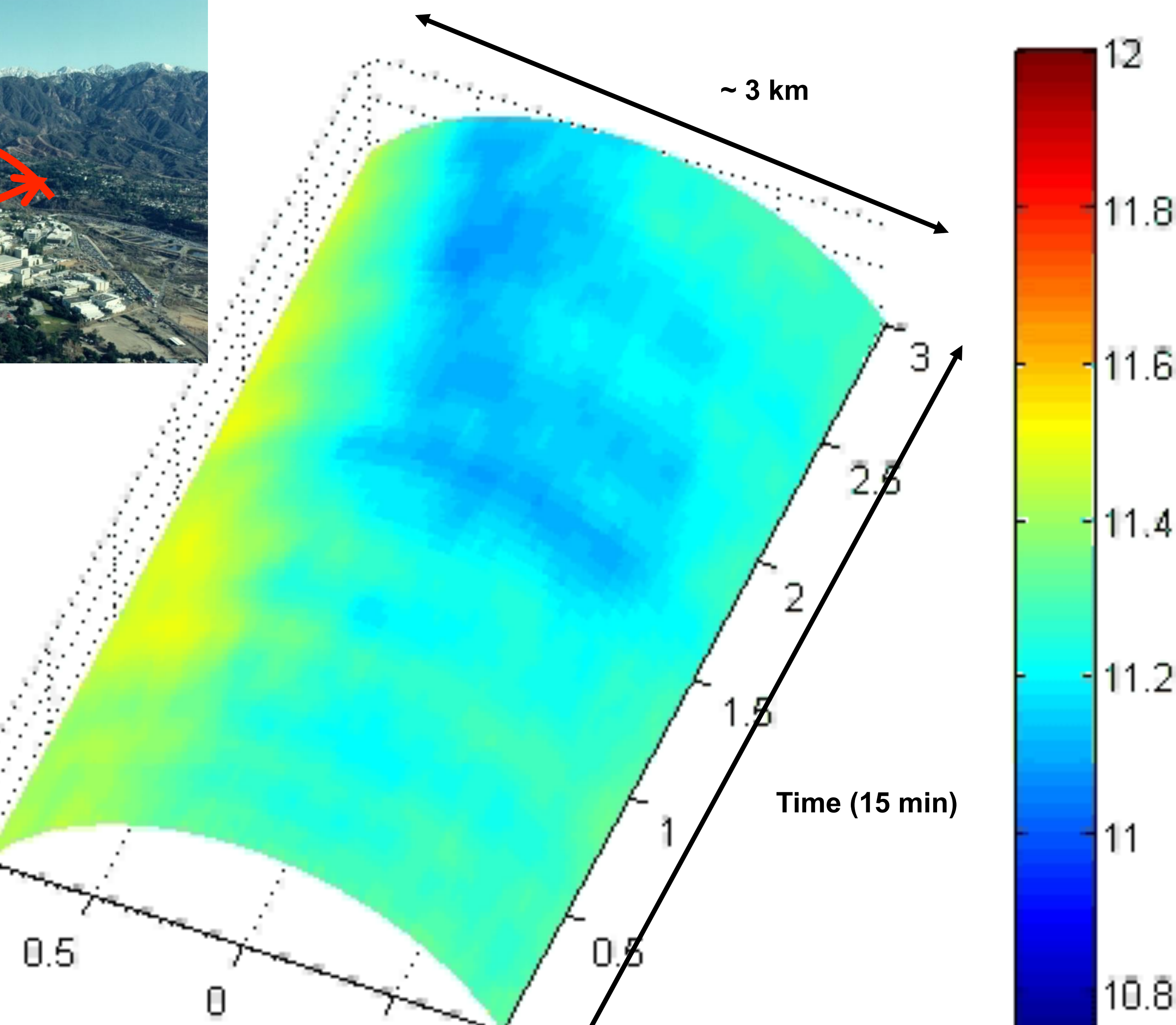
Boundary layer sounding with HAMSR





- 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

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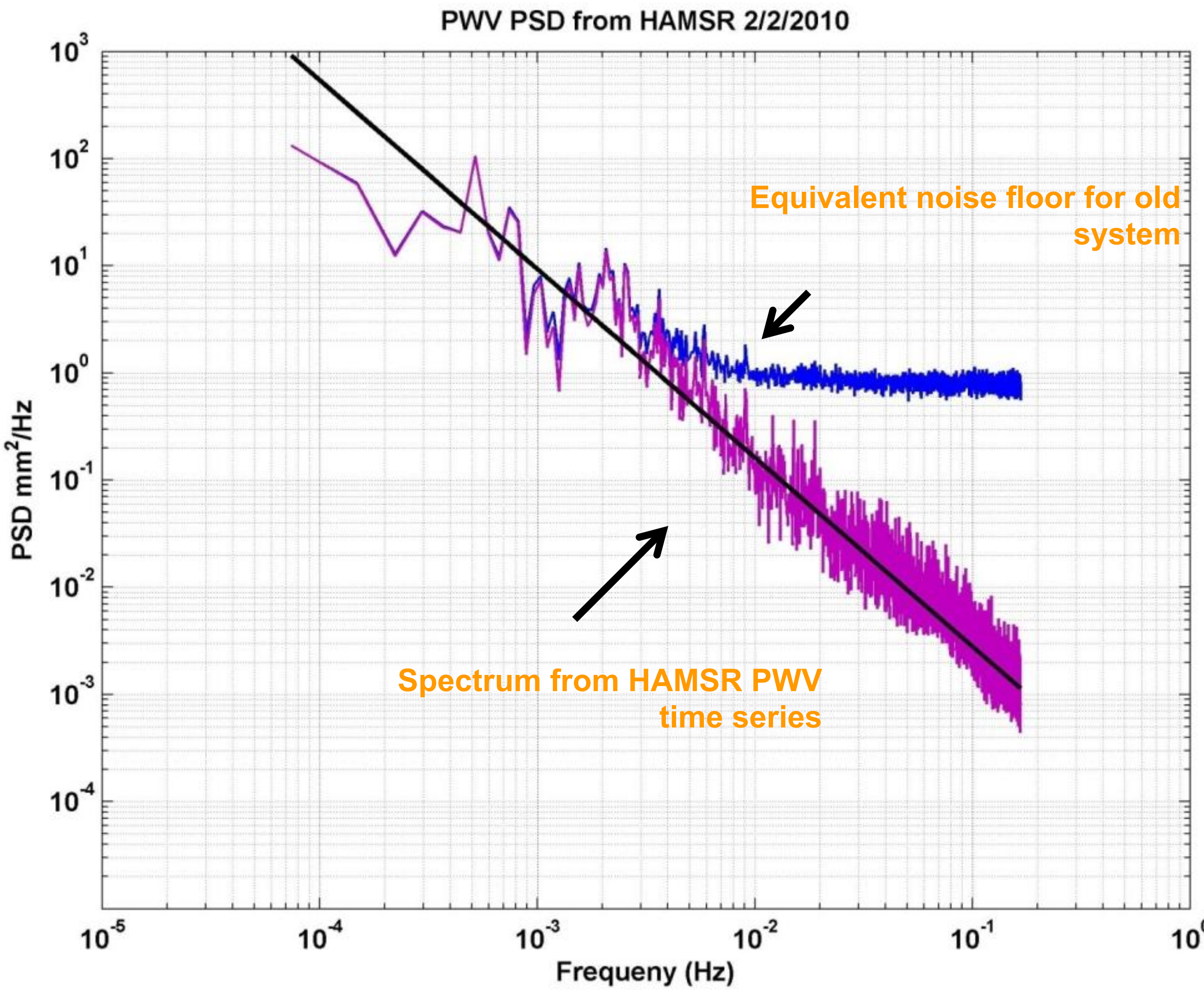
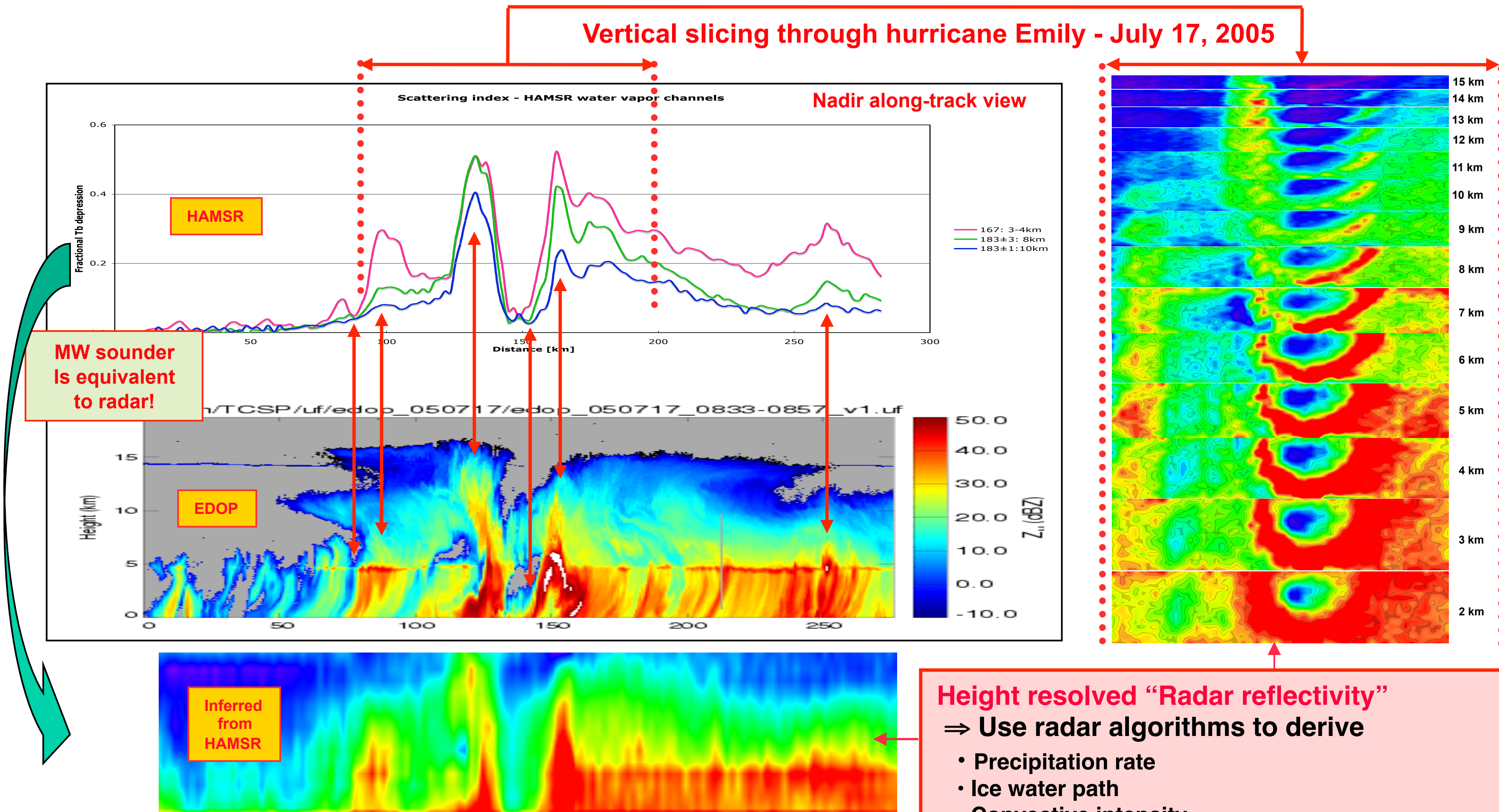
HAMSR TPW spectrum reveals fine structure

- **In upward looking mode, low noise floor enables measurement of variability on seconds to minutes time scales**



A new application: Scattering profiling

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

Height resolved "Radar reflectivity"
⇒ Use radar algorithms to derive
- Precipitation rate
- Ice water path
- Convective intensity
- Vertical structure

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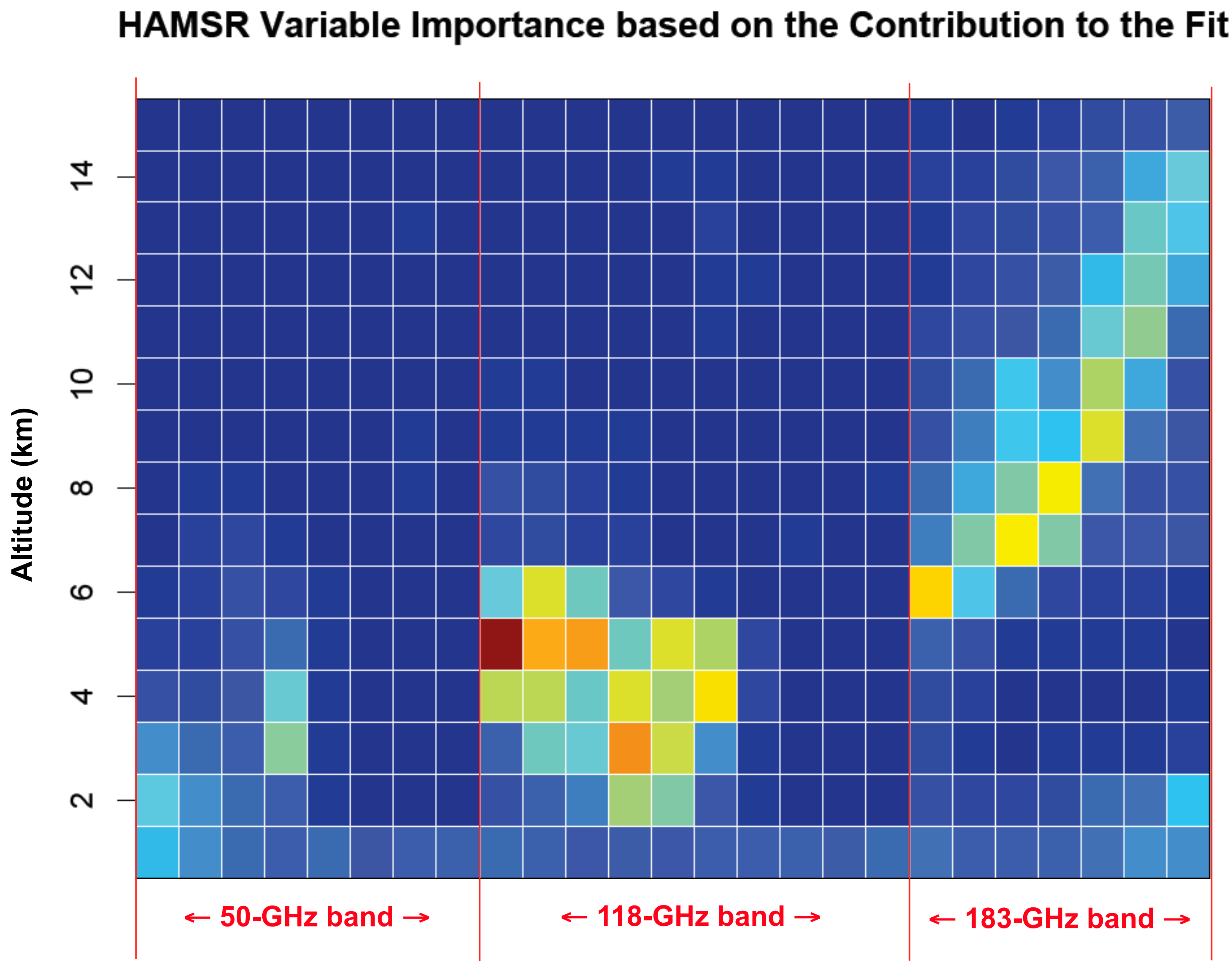
All cannels contribute information



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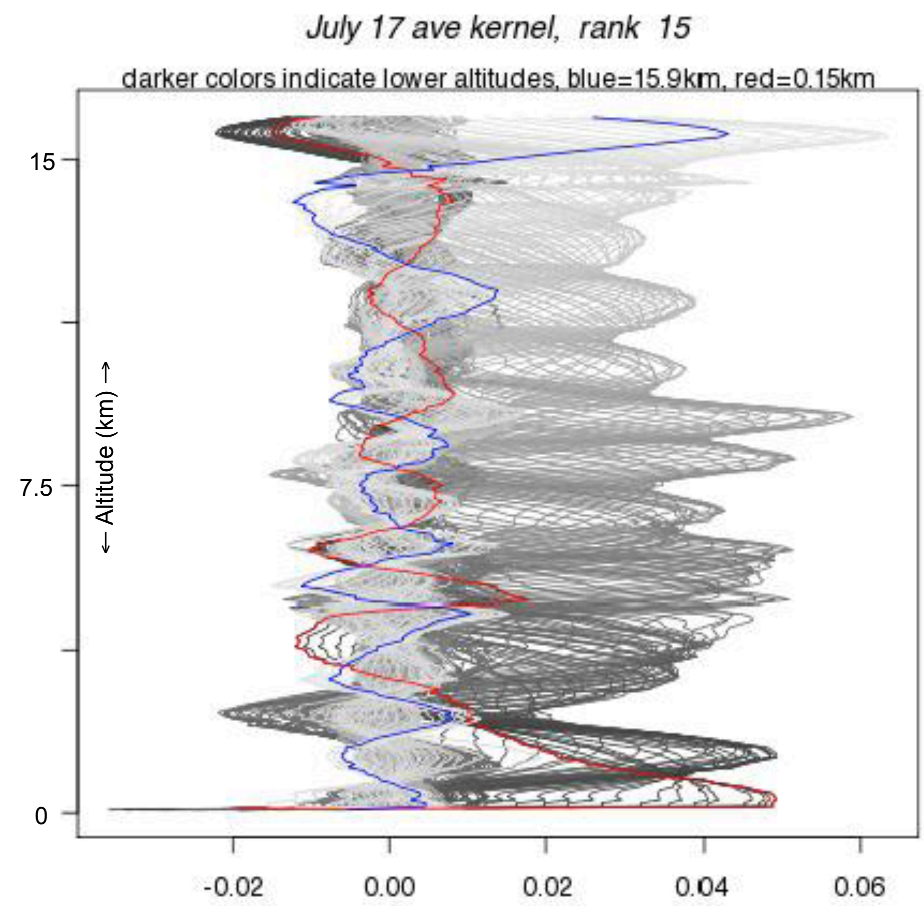
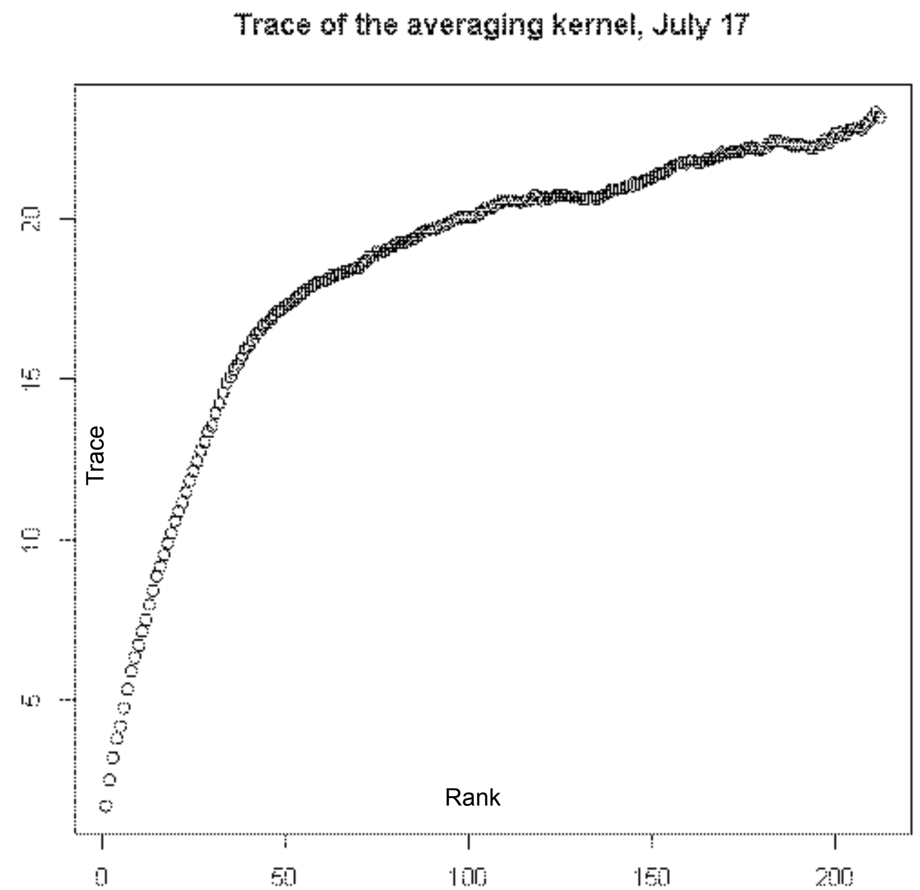
Averaging kernels

Single flight - July 17 (Emily)





~ 15-16 degrees of freedom of information; true vertical resolution ~ 1.5 km

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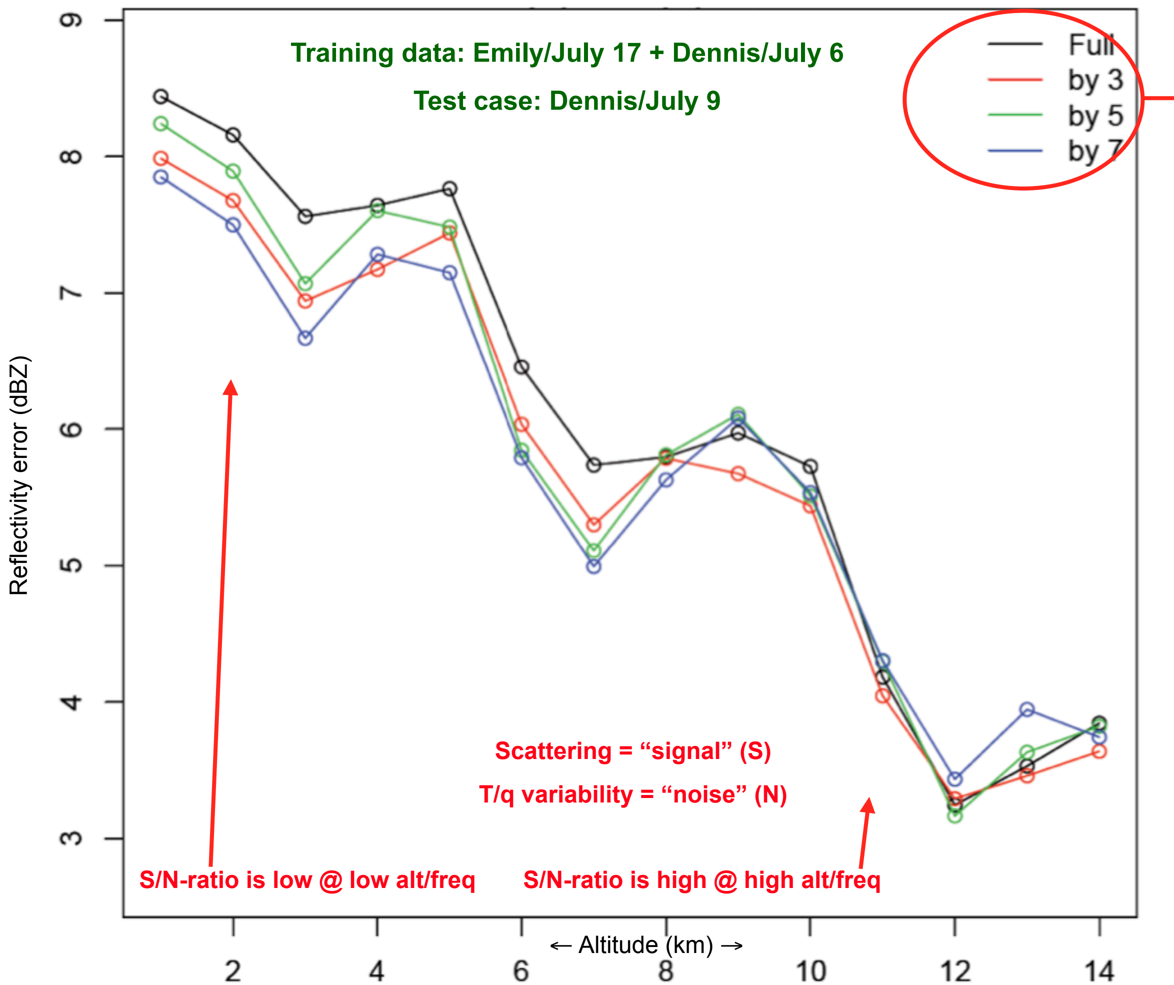
Retrieval accuracy

Several empirical models investigated:

Linear regression, Random forest, Projection pursuit regression, Perceptron neural network, RBF neural network

The winner: Random forest



Results differ little if training data are averaged to simulate coarser spatial resolution

This means the empirical model derived from aircraft data can be applied to satellite data

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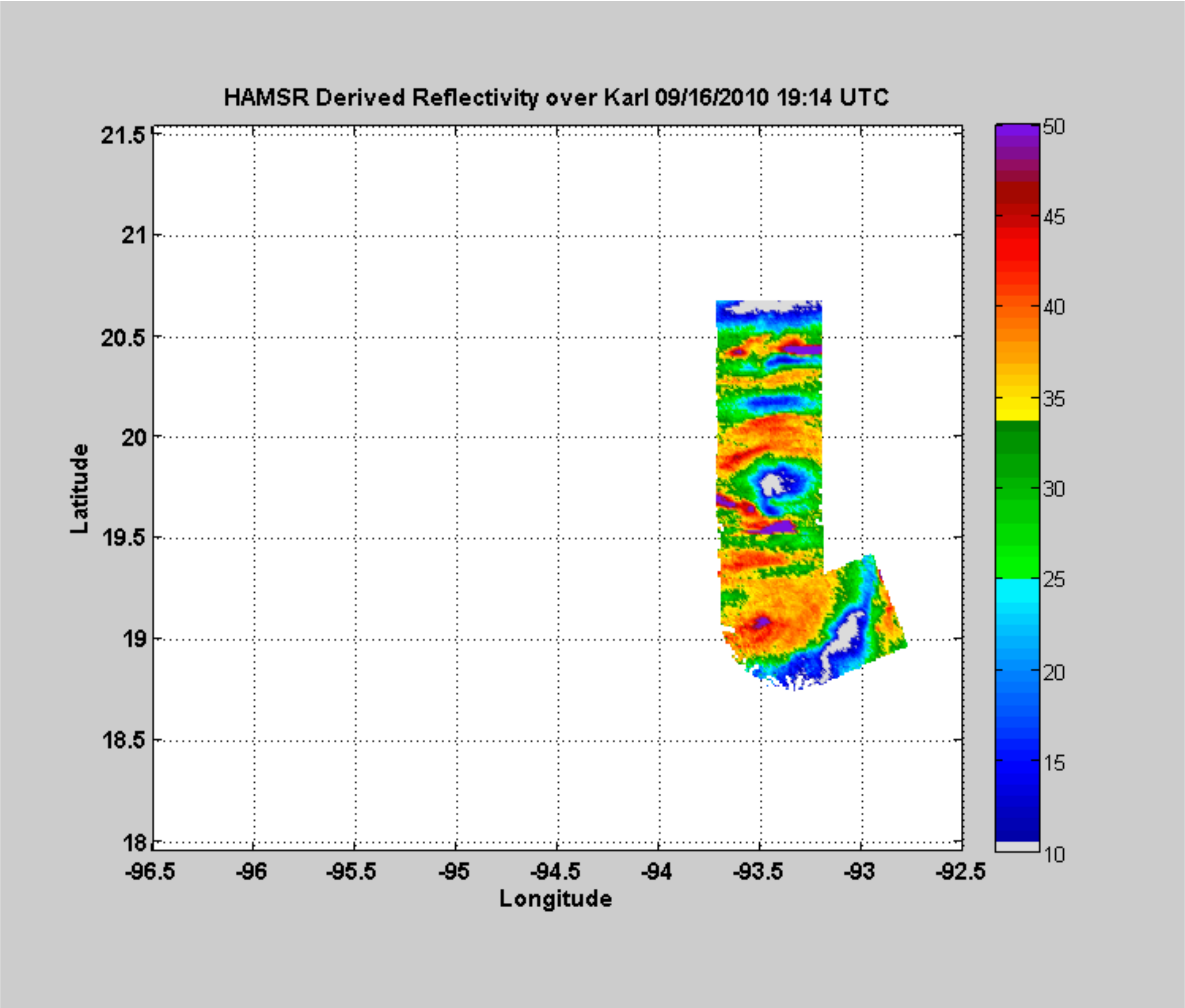
Hurricane Karl, September 16, 2010



Reflectivity derived from HAMSR flying on Global Hawk UAV

20 consecutive passes over eye

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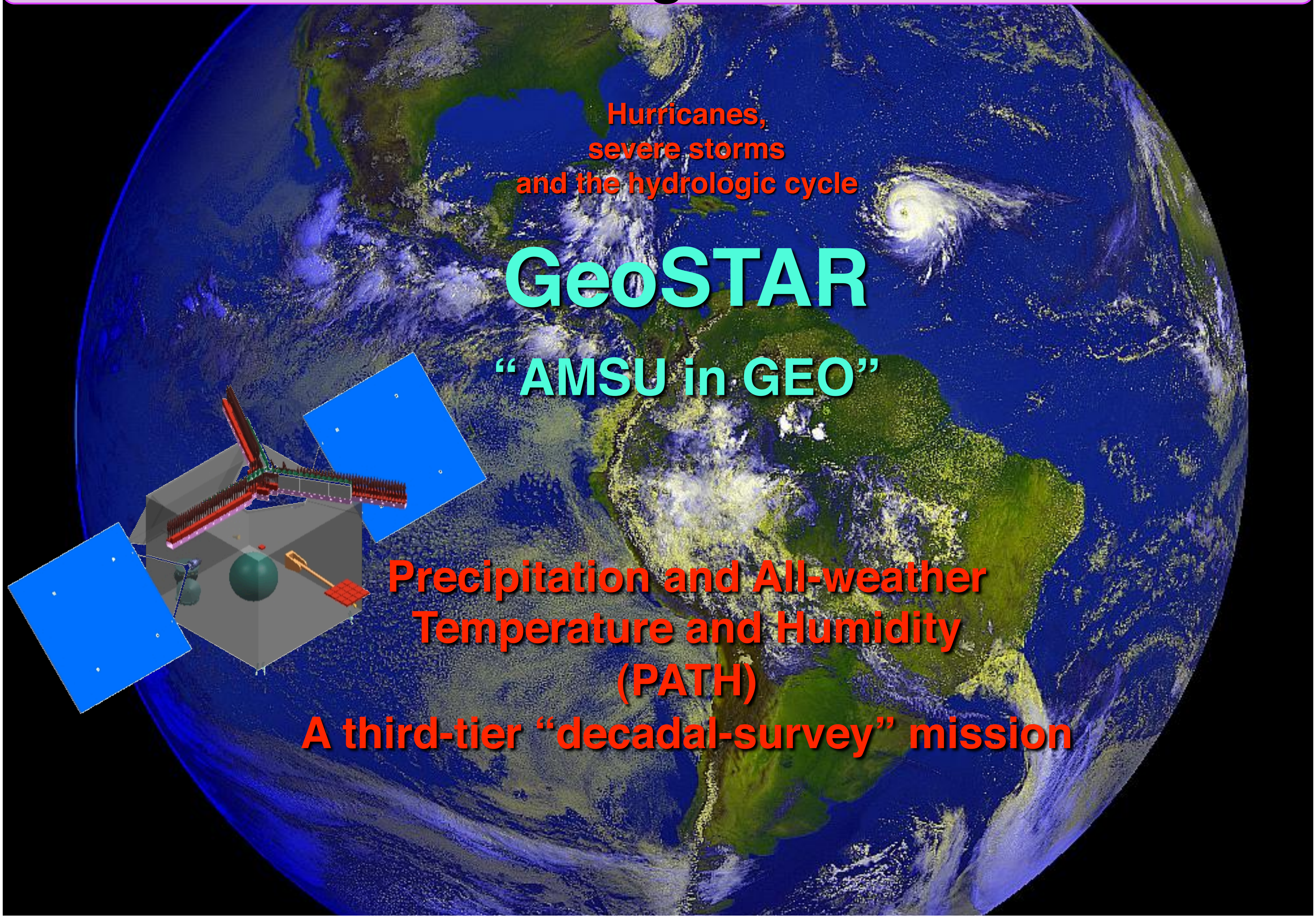
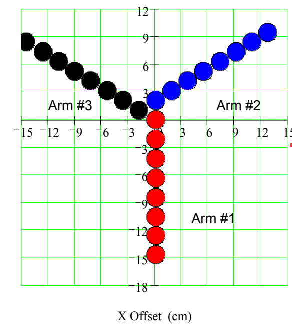
GEO MWS coming soon: GeoSTAR

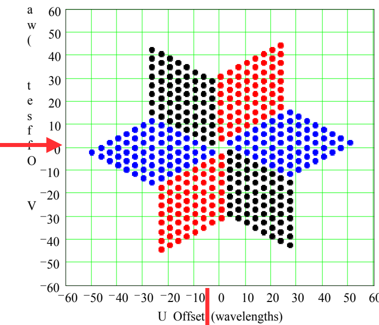


GeoSTAR overview

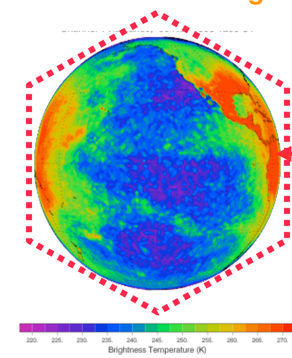
- **Problem: How to develop a microwave sounder for geostationary orbit?**
  - Need: Time-continuous all-weather observations of the atmosphere
  - Challenge: Achieve adequate spatial resolution from 37,000 km
- **Solution: Aperture-synthesis concept**
  - Can make a very large aperture w/out large parabolic dish antenna
  - Sparse array employed to synthesize large aperture
  - Spatial interferometry -> Fourier transform of Tb field
  - Inverse Fourier transform on ground -> Tb field
  - Bonus: No moving parts, simultaneous 2-D "synoptic" imaging
- **Design: Sparse array - GeoSTAR**
  - Optimal: Y-configuration; 3 "sticks"; 100-200 elements each
  - Each element = I/Q receiver, ~4λ wide (6 mm @ 183 GHz!)
  - Example: 100/arm $\Rightarrow$ Pixel = 50 km at nadir $\approx$ LEO sounders
  - One "Y"-array per sounding band, interleaved
- **Proof of concept**
  - Ground-based prototype under NASA/ESTO/IIP, 2003-2006
  - Performance is excellent & as predicted => Proof of concept
- **Risk reduction for space mission**
  - Further technology development under IIP, 2008-2010
  - Mission design studies
- **"PATH" decadal-survey mission**
  - Precipitation and All-weather Temperature and Humidity
  - Ready to start implementation ~2012
- **"GeoSTAR-pathfinder"**
  - GeoSTAR-lite
  - Mission of opportunity
  - Launch ~2016-18

Receiver array & resulting uv samples

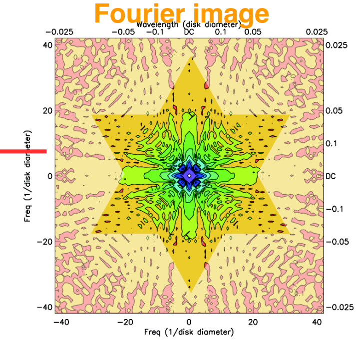


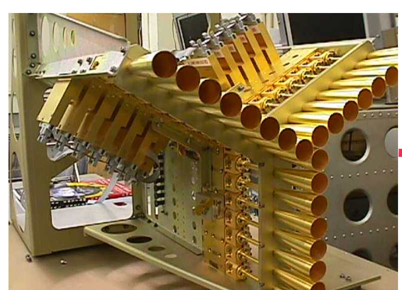


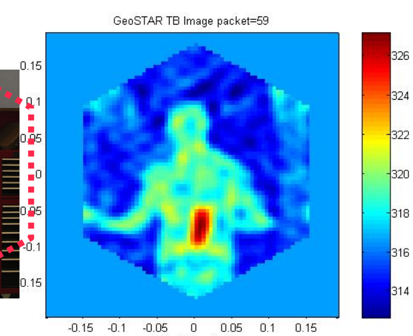
Radiometric image



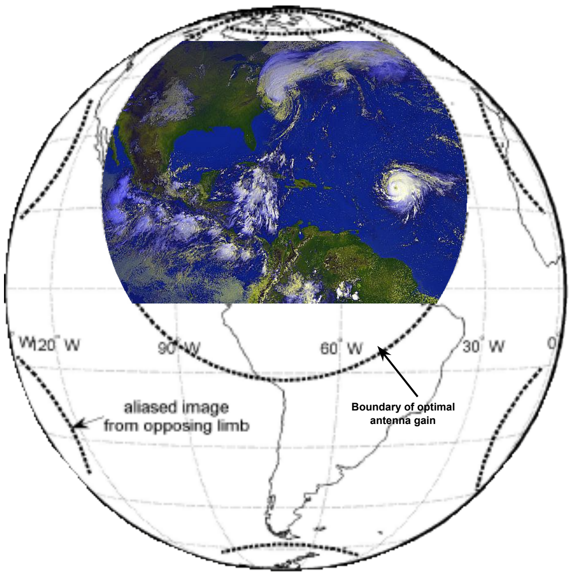
Fourier image







GeoSTAR/PATH applications



Hurricanes - Severe storms - Moisture flow - Hydrologic cycle - Climate

Weather forecasting -Improve regional forecasts; severe storms

- All-weather soundings, including cloudy and stormy scenes
- Full hemispheric soundings @<50/25 km every ~ 15-30 minutes (continuous)
- "Synoptic" rapid-update soundings => Forecast error detection; 4DVAR applications

Severe-storm diagnostics -Quintessential hurricane sensor

- Scattering signal from convection easily measurable
- Measure *location*, *intensity* & vertical *structure* (incl. *shear*) of deep convection
- Detect *intensification/weakening* in real time, 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 current capabilities

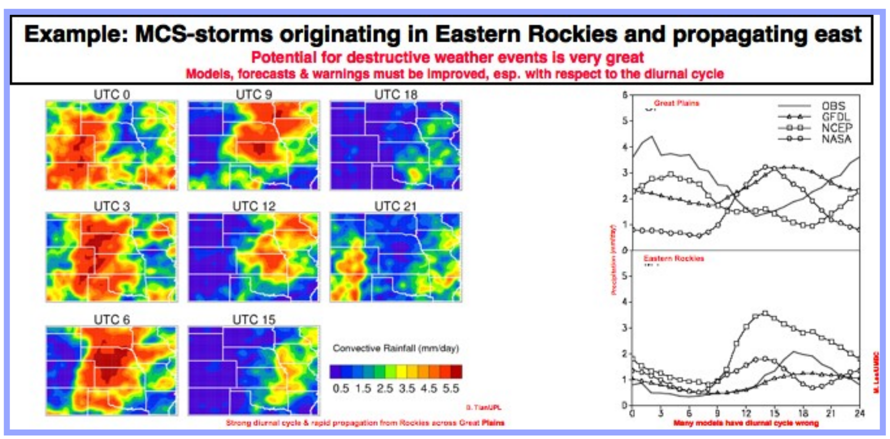
- Full hemisphere @ ≤ 25 km every 15 minutes (continuous) - both can be improved
- Directly measure storm and diurnal *total rainfall*: predict flooding events
- Measure *snowfall*, light rain, intense convective precipitation

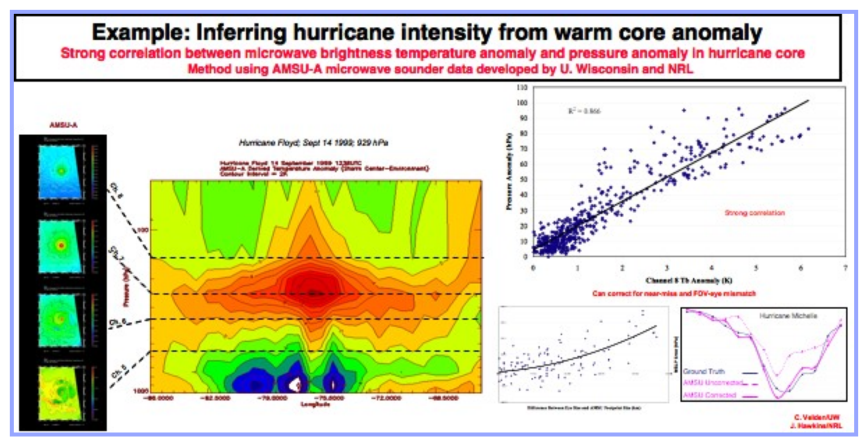
Tropospheric wind profiling -NWP, transport applications

- 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

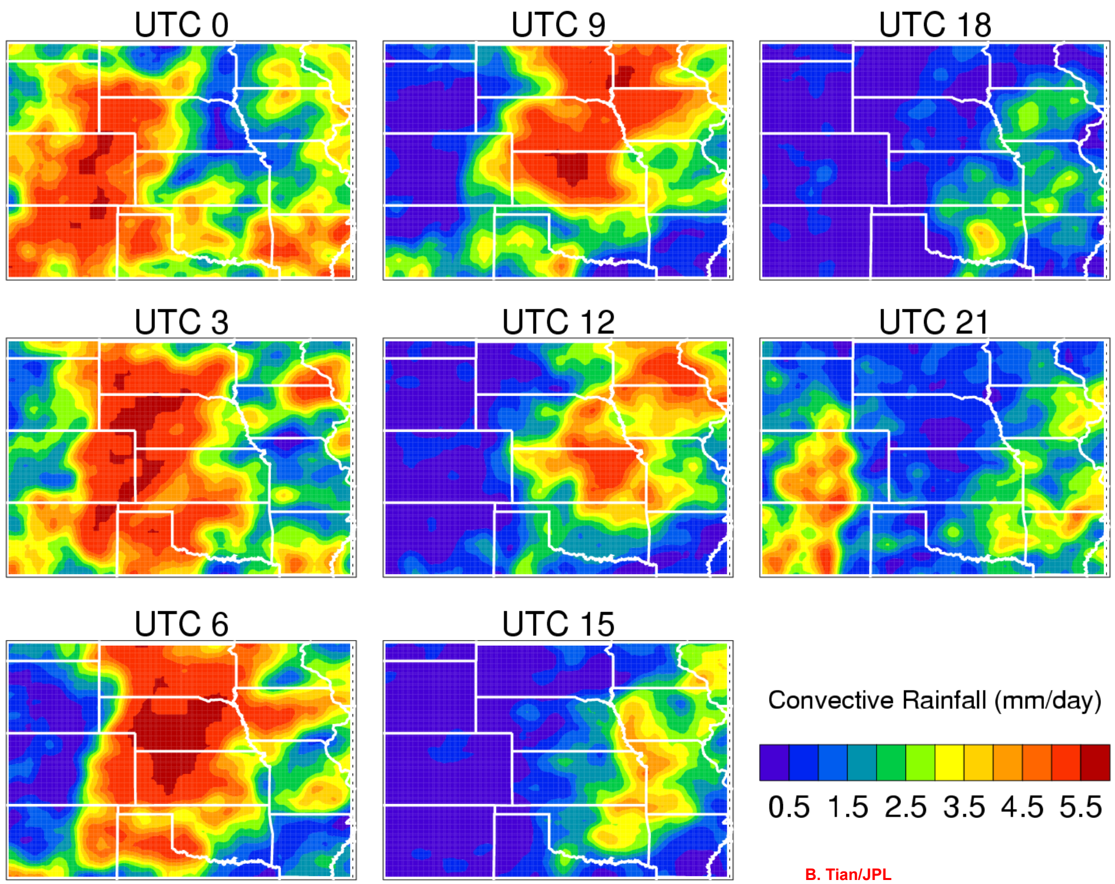
- Stable & continuous MW observations => Long term trends in T & q and storm stats
- Fully resolved diurnal cycle: water vapor, clouds, convection
- ENSO observer: Continuous observations from "warm pool" to Pacific coast under all conditions
- "Science continuity": PATH ≈ AMSU (currently operating LEO sounders)



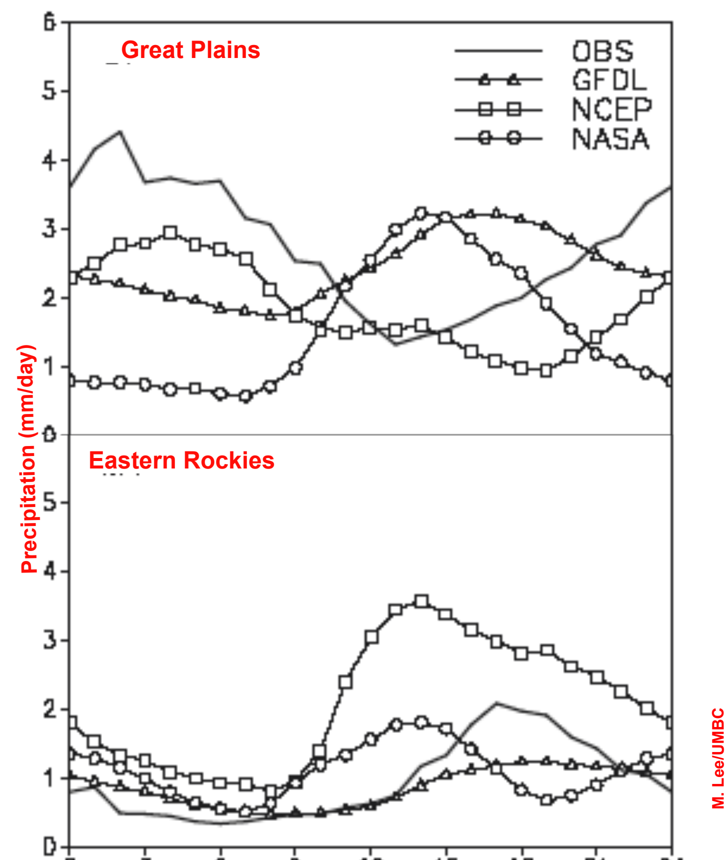


Diurnal cycle: Problem with models

In Sounding Science Workshop held in May 2009 accurate modeling of the diurnal cycle was identified as an issue



Strong diurnal cycle & rapid propagation from Rockies across Great Plains



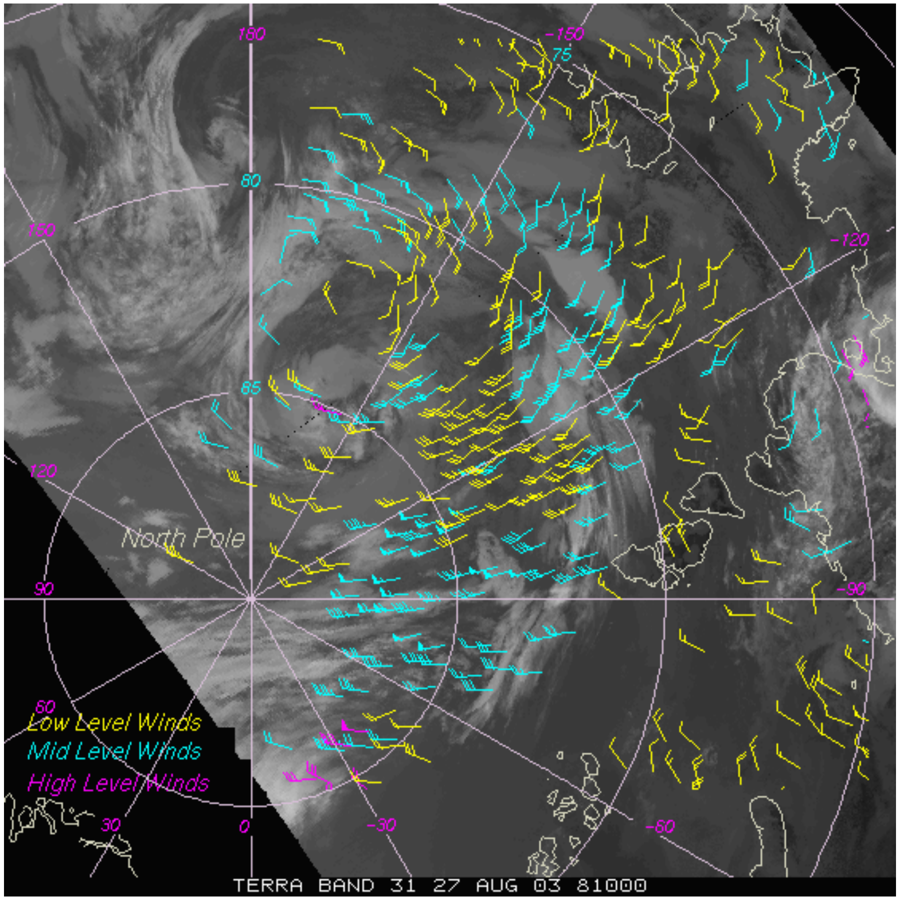
Many models have diurnal cycle wrong

Key application: 3-D tropospheric wind

Tropospheric wind vector profiles

– Derived from moisture feature tracking
– Key parameter for improved numerical weather prediction
– *Tropospheric* wind (esp. at 500 mb) will have more impact on forecast accuracy than *surface* wind (Bob Atlas)

- **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**
- **GeoSTAR capabilities**
  - **Clear *and* cloudy**
    - **Including below clouds**
  - **Continuous: no time gaps**
  - **Applicable algorithms available**
    - **UW (Velden et al.)**

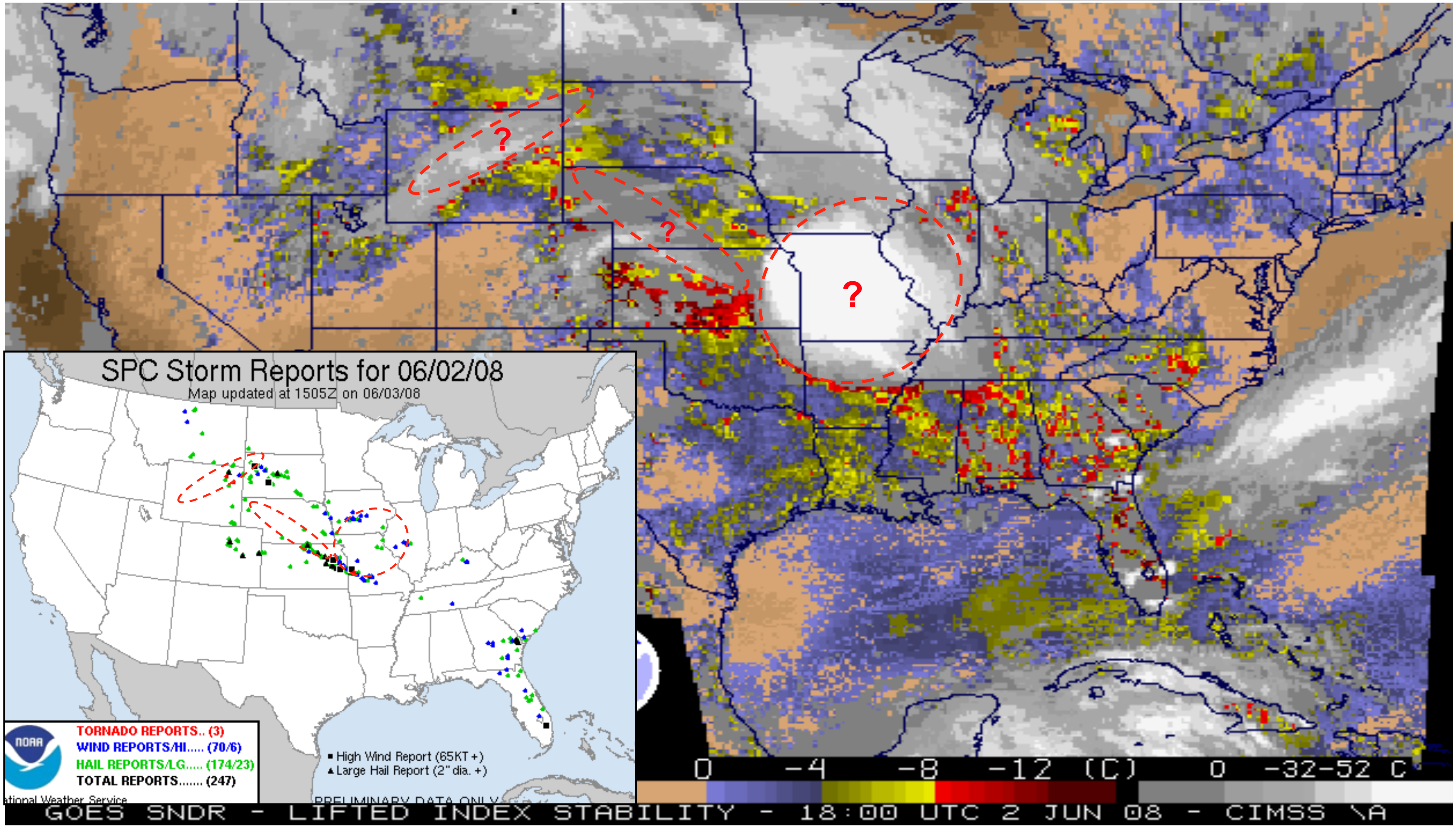


Example wind vectors from MODIS

Lambrigtsen

Storms: What's going on below the clouds?

Current capabilities: Poorly observed; infrequently sampled; poorly modeled
PATH capabilities: *All* conditions, observations *in* storms; every 15 minutes



Let's not forget about storms – They are important to boundary layer dynamics

Lambrigtsen

Some thoughts

- Need to assess continuous vs. regime-sampling observational needs
- Need to consider spatial *and* temporal scales
- HAMSR demonstrates some valuable lessons:
  - Adding 118-GHz band adds enough info to enable full L(z) sounding
  - Just as in IR, there is more info.content in MW soundings than currently exploited
  - Upward-sounding example demonstrates that there is very high spatial variability in WV
    - *Can probably only be observed from ground or air*
  - Ability to resolve sub-mm water vapor features enabled by high radiometric sensitivity
    - *Enabled by new receiver technology*

Lines of pursuit

- **Hyperspectral MW sounders => 100's of channels**
  - Increased information content
    - *=> increased vertical resolution*
    - *=> higher accuracy*
    - *=> solve for more independent parameters*
  - Can be done with moderate development
  - Will be demo'd with GeoSTAR (LO tunable to any frequency)
  - Could be demo'd with HAMSR
    - *FPGA/ASIC auto-correlator spectrometer for HAMSR: ~ $1M*
- **Large-aperture satellite sounders => 1-5 km spatial resolution**
  - Aperture synthesis (suitable for GEO/MEO, could be adapted for LEO)
  - Focal plane arrays (suitable for LEO)
- **Combined active-passive methods**
  - Is a "sounding radar" feasible?
- **Solve surface problem**
  - On-line/off-line spectral sampling near weak lines
  - Combine imagers & sounders to solve for surface emissivity
    - *SSM/IS is an example, but conical scanners are problematic*
- **Algorithm development**
  - Data fusion: low-res MW + high-res "other
  - Optimal estimation: error & information characterization