CET
Center for Environmental Technology

Application of a CubeSat-Based Passive Microwave Constellation to Operational Meteorology

Professor Albin J. Gasiewski

NOAA-CU Center for Environmental Technology
Department of Electrical and Computer Engineering
University of Colorado, Boulder, CO, USA

Thanks to: Brian Sanders (CU CoSGC)
Dave Gallaher (CU NSIDC)
Orbital Micro Systems (OMS)
and many CU students (Kun Zhang, Lavanya Periasamy, Glenda Alvarenga, Brenden Hogan)

Topics

- PATH mission: Persistent High Resolution Microwave Imaging and Sounding
  - Geostationary concepts (GEM, GeoSTAR,)
  - LEO Cubesat fleet concept
- Prospects for microwave radiance assimilation over clouds by “precipitation locking”
- PolarCube LEO CubeSat demonstration mission
  - Low-cost fleet-scalable concept
  - Student designed and built

NRC Decadal Survey & PATH

- NRC = U.S. National Research Council, which conducted a decadal survey of Earth satellite missions in 2006-07:

  Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future (2007)*

- PATH = Precipitation, Atmospheric Temperature and Humidity mission
  - One of ten approved new Earth science missions to be conducted by NASA
  - Tier 3 mission to be launched 2016-2020 (~$450M)

- Based on implementation of an "Array Spectrometer"

*** http://www.nap.edu/catalog.php?record_id=11281**

PATH Capabilities

- All-weather AMSU-class temperature and humidity sounding at ~15-30 minute intervals over a large fraction (up to ~25%) of Earth's surface
  - Mesoscale weather forecasting
- Imaging of precipitation and convective thermodynamics beneath cloud tops and at time scales relevant for precipitation
  - Quantitative precipitation forecasting (QPF)
  - Hurricane intensification
  - Global water and energy cycling
- Cross-calibration and temporal interpolation of low-earth orbiting sensors (GMI, JPSS, …)

GEM Spatial Resolution

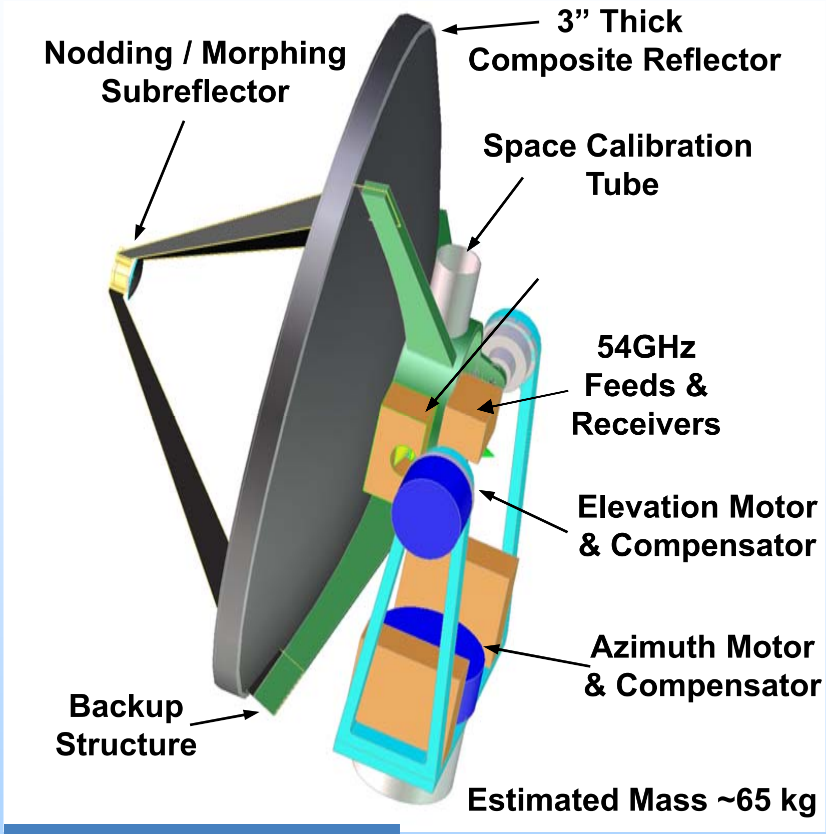
Frequency (GHz)		Aperture size (m) 0.1	0.25	0.5	1	1.5	2	4.4	8	15	30	Tolerance (mm)
6.8	W	19611.0	7844.4	3922.2	1961.1	1307.4	980.5	445.7	245.1	130.7	65.4	1.764
10.7	W	12463.1	4985.2	2492.6	1246.3	830.9	623.2	283.3	155.8	83.1	41.5	1.121
18.7	W	7131.3	2852.5	1426.3	713.1	475.4	356.6	162.1	89.1	47.5	23.8	0.641
37.0	W	3604.2	1441.7	720.8	360.4	240.3	180.2	81.9	45.1	24.0	12.0	0.324
56.0	O2	2381.3	952.5	476.3	238.1	158.8	119.1	54.1	29.8	15.9	7.9	0.214
89.0	W	1498.4	599.3	299.7	149.8	99.9	74.9	34.1	18.7	10.0	5.0	0.135
118.8	O2	1123.0	449.2	224.6	112.3	74.9	56.1	25.5	14.0	7.5	3.7	0.101
166.0	W	803.3	321.3	160.7	80.3	53.6	40.2	18.3	10.0	5.4	2.7	0.072
183.3	H2O	727.5	291.0	145.5	72.8	48.5	36.4	16.5	9.1	4.9	2.4	0.065
220.0	W	606.2	242.5	121.2	60.6	40.4	30.3	13.8	7.6	4.0	2.0	0.055
325.1	H2O	410.2	164.1	82.0	41.0	27.3	20.5	9.3	5.1	2.7	1.4	0.037
340.0	W	392.2	156.9	78.4	39.2	26.1	19.6	8.9	4.9	2.6	1.3	0.035
380.2	H2O	350.7	140.3	70.1	35.1	23.4	17.5	8.0	4.4	2.3	1.2	0.032
424.8	O2	313.9	125.6	62.8	31.4	20.9	15.7	7.1	3.9	2.1	1.0	0.028
448.0	H2O	297.7	119.1	59.5	29.8	19.8	14.9	6.8	3.7	2.0	1.0	0.027
556.9	H2O	239.5	95.8	47.9	23.9	16.0	12.0	5.4	3.0	1.6	0.8	0.022
620.0	H2O	215.1	86.0	43.0	21.5	14.3	10.8	4.9	2.7	1.4	0.7	0.019
752.0	H2O	177.3	70.9	35.5	17.7	11.8	8.9	4.0	2.2	1.2	0.6	0.016
916.2	H2O	145.6	58.2	29.1	14.6	9.7	7.3	3.3	1.8	1.0	0.5	0.013
987.9	H2O	135.0	54.0	27.0	13.5	9.0	6.7	3.1	1.7	0.9	0.4	0.012

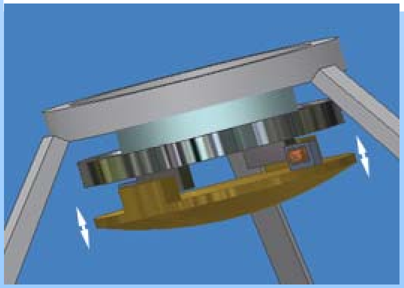
- 3-dB best resolution degrades by ~1.3x to ~21 km at 50^{o} latitude.
- Oversampling by ~2x above Nyquist expected to recover ~30-40% of this lost resolution for high SNR cases.

GEM Concept Summary

GEosynchronous Microwave (GEM) Sensor*

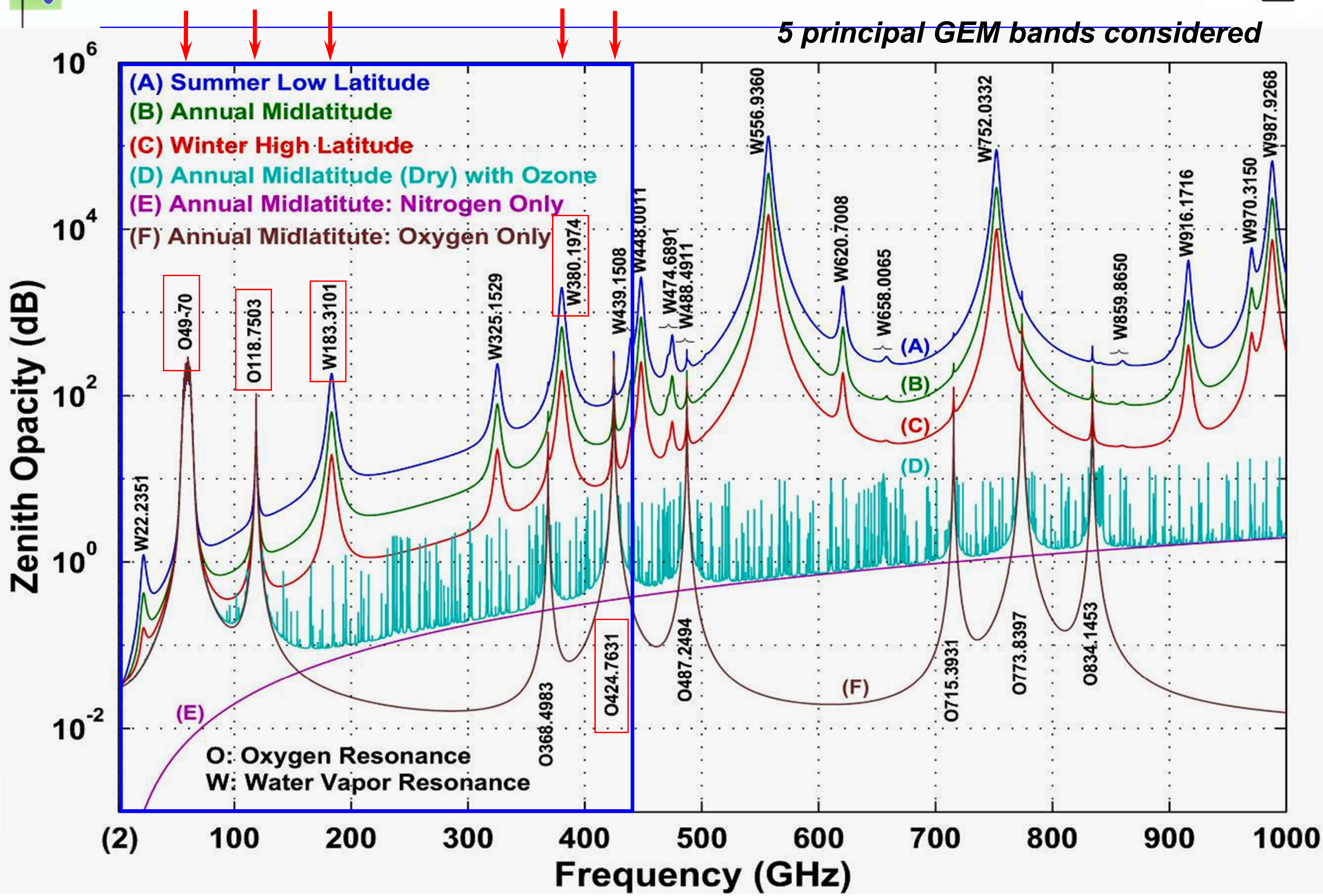
- Baseline system using 54, 118, 183, 380, and 424 GHz with ~2 m diameter Cassegrain antenna.
- ~16 km subsatellite resolution (~12 km using oversampling) above 2-5 km altitude at highest frequency channels.
- The 380 and 424 GHz channels selected to map precipitation through most optically opaque clouds at sub-hourly intervals. (Gasiewski, *TGARS*, 1992)
- Temperature and humidity sounding channels penetrate clouds sufficiently to drive NWP models with ~hourly data.
- Estimated 2010 costs: ~US$50M non-recurring plus ~US$45M/unit.





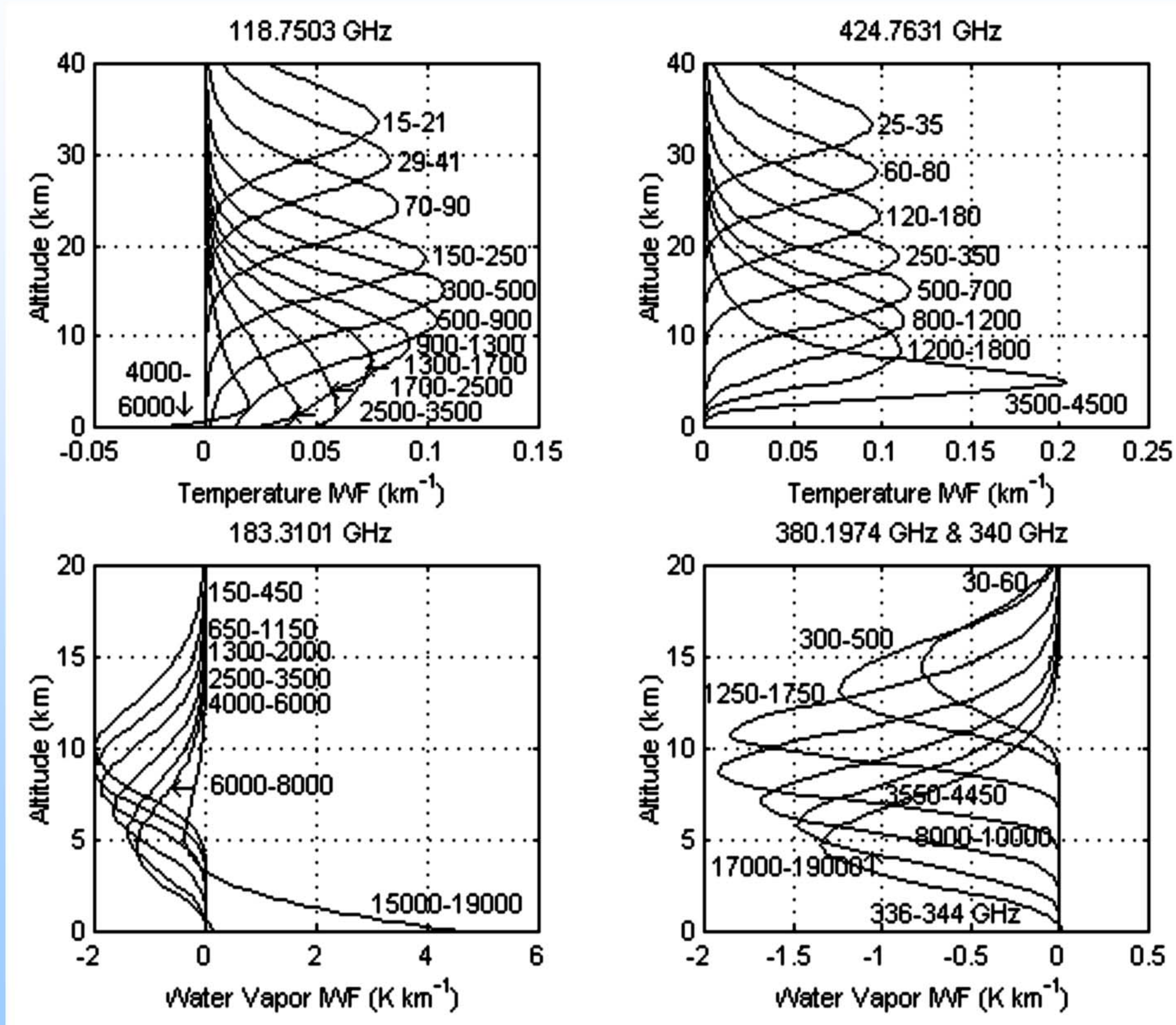
** Geosynchronous Microwave Sounder Working Group, Chair: D.H. Staelin (MIT)*

GEM Geo-Microwave Bands



GEM Vertical Response

- Clear Air -



Clear-air incemental weighting functions

O_2
118.750 GHz
424.763 GHz

H_2O
183.310 GHz
380.197/340

Klein & Gasiewski, *JGR-ATM*, July 2000

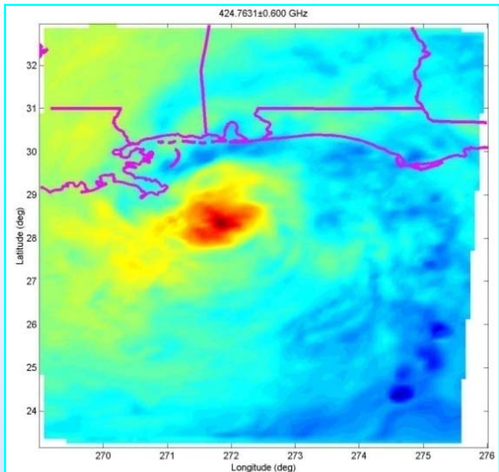
CET GEM Simulated SMMW Imagery

Spectral Response

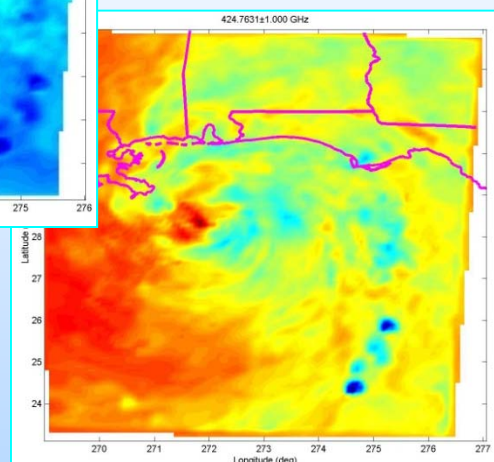
Hurricane Opal 1995

Opaque

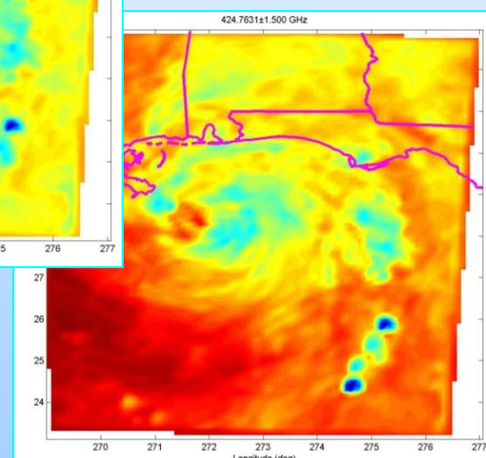
Transparent



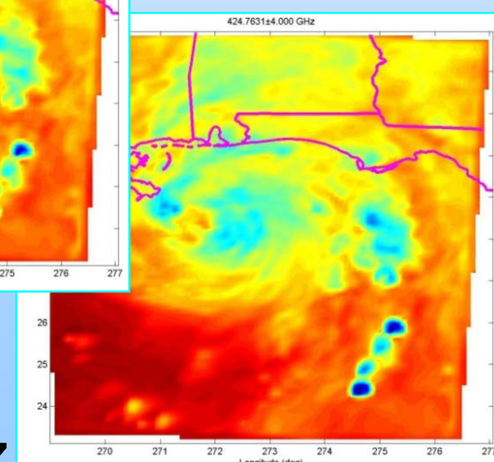
+/-0.6 GHz



+/-1.0 GHz



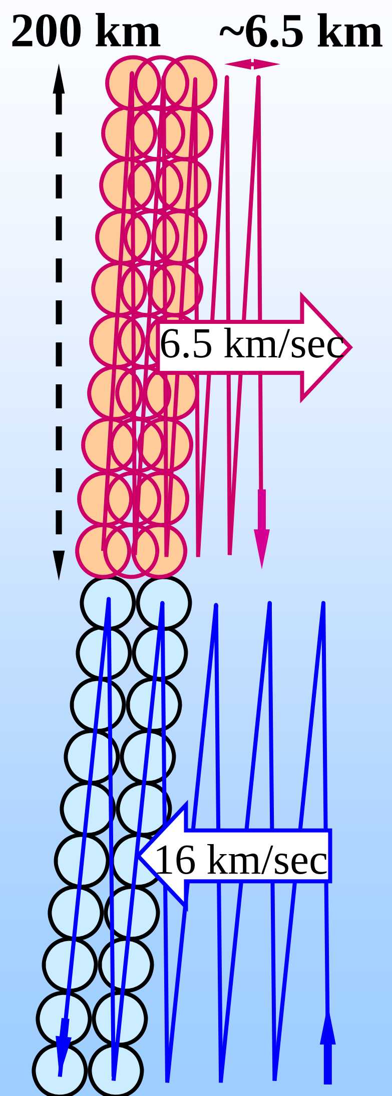
+/-1.5 GHz



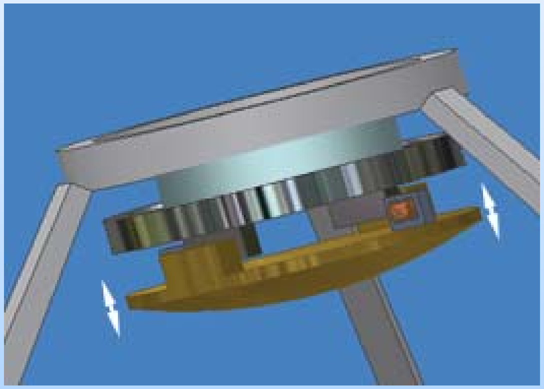
424.763+/-4.0 GHz

MM5/MRT
Reisner 5-phase

GEM/GOMAS Micro-Scan Concept

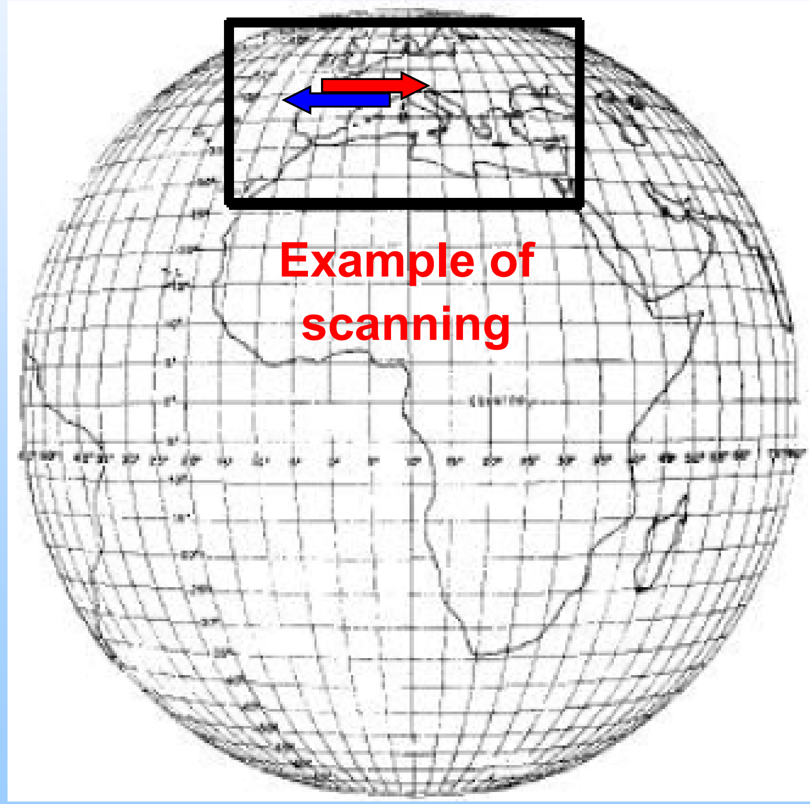


Nodding subreflector scans ~200-km swath, 1 second per scan with 0.1 sec retrace, ~6.5 km swath spacing for Nyquist sampling



200-km swaths are assembled into regional precipitation maps; antenna slews between regions in ~20 seconds

Nodding subreflector and slow steady scanning has minimal momentum impact; primarily images rainy areas



GEM Sensitivity & Scan Times

- **Regional** (1500 x 1500 km^2) : ~15 minutes

Band (GHz)	3-dB IFOV (km, SSP)	Deconvolved Resolution (km, SSP)	ΔT_{RMS} (K)	ΔT_{RMS} Required (K,SNR=100)	Probing Height (km)
50-56	138.6	~104	0.03-0.07 ✓	0.1-0.6	Surf
118.705	60.2	~45	0.03-0.6 ~	0.1-0.6	Surf
183.310	41.9	~31	0.04-0.15 ✓	0.3-0.6	Surf
380.153	20.5	~16	0.2-2.1 *	0.3-0.5	~2.5
424.763	16.4	~12	0.5-5.3 *	0.4-0.6	~4

Assumptions:

- Midlatitude (30°-60° annual averaged atmosphere)
- Nyquist sampling at 424 beamwidth
- Averaging of beams to fundamental deconvolved resolution for each band

* Further reductions in ΔT_{RMS} achievable via additional spatial averaging.

- **CONUS imaging time (3000 x 5000 km^2) : 90 minutes**

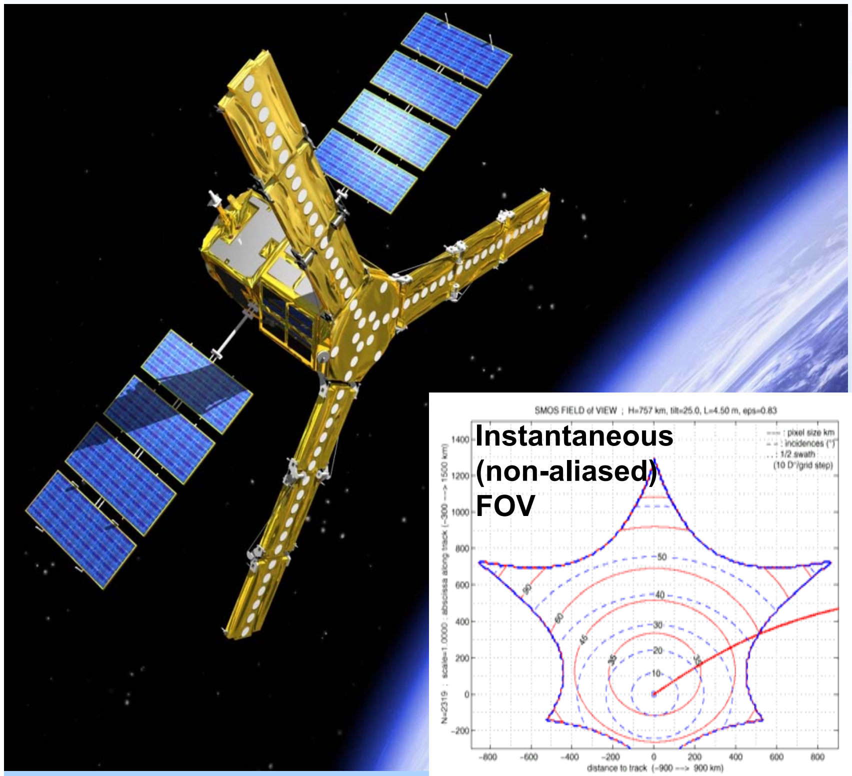
Downlink rate ~45 kb/sec at ~17 msec sample period

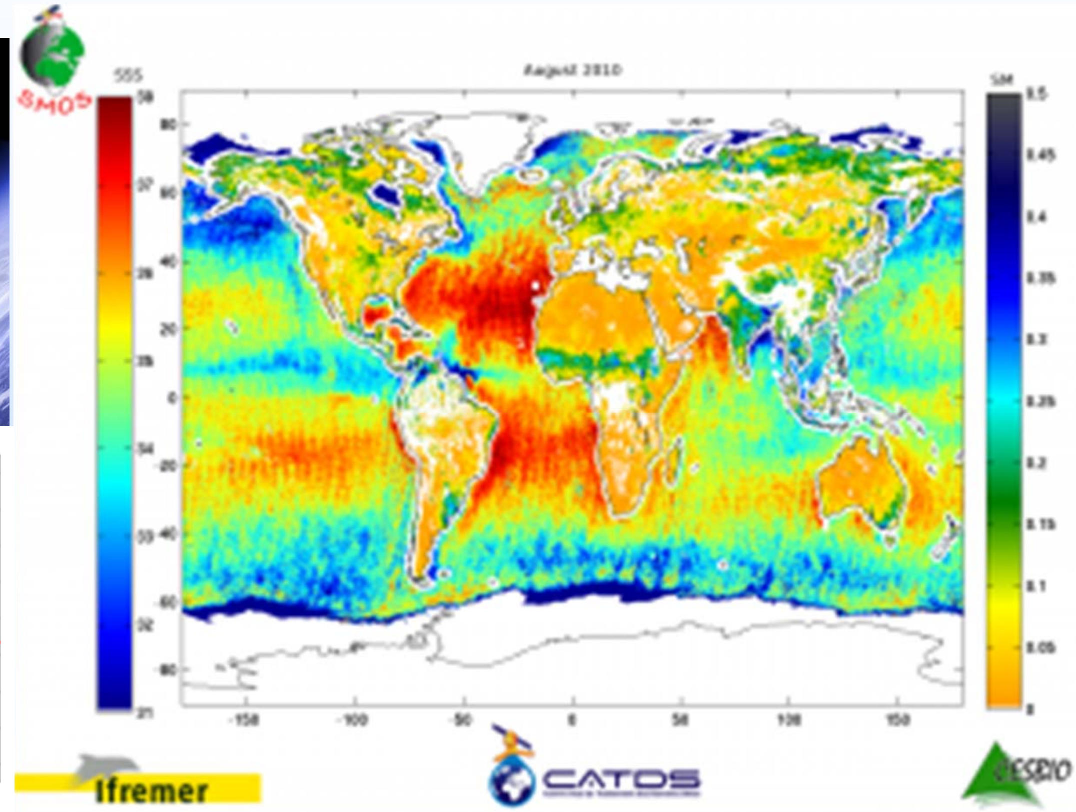
Interferometric Imaging

Principle: Measure the complex field corelation function $\overline{\overline{R}}_{E_a}(\rho_x, \rho_y, 0)$ in an aperture plane, then apply a 2-D spatial Fourier transform to obtain the angular distribution of radiation intensity. Practical issues include:

- **Sampling (density, range, angular sensitivity)**
- **Integration noise and bandwidth (fringe washing)**
- **Absolute calibration (magnitude and phase)**
- **Data corelation techniques**

SMOS – Soil Moisture and Ocean Salinity
ESA Project: L-band, Polar low-Earth orbit, Launched November 2009

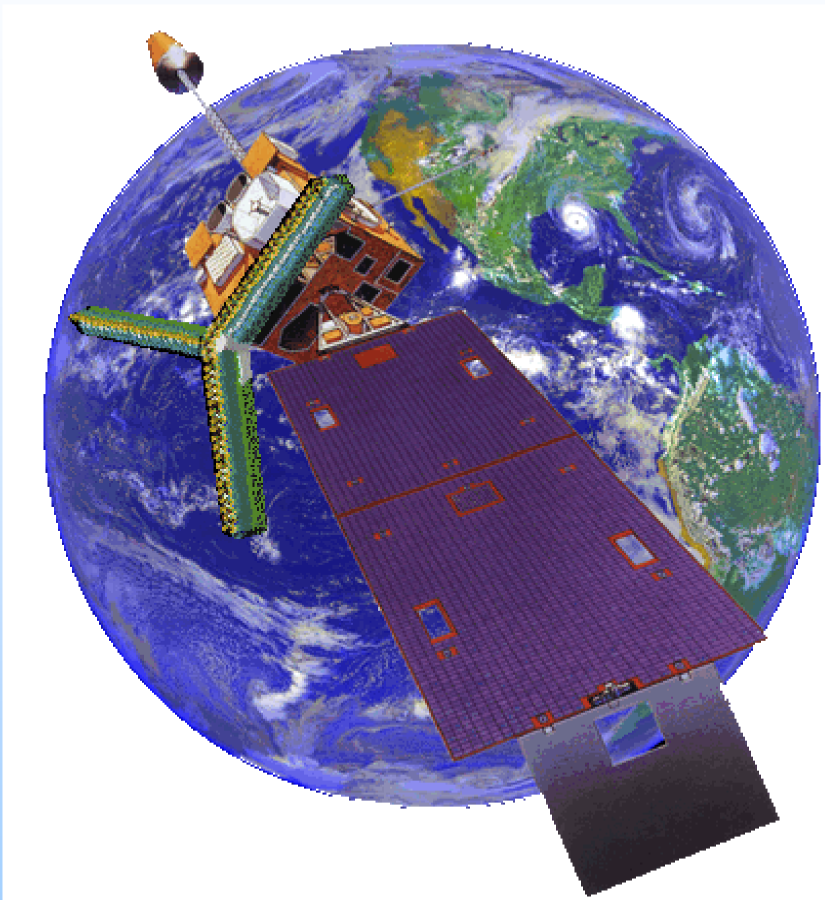


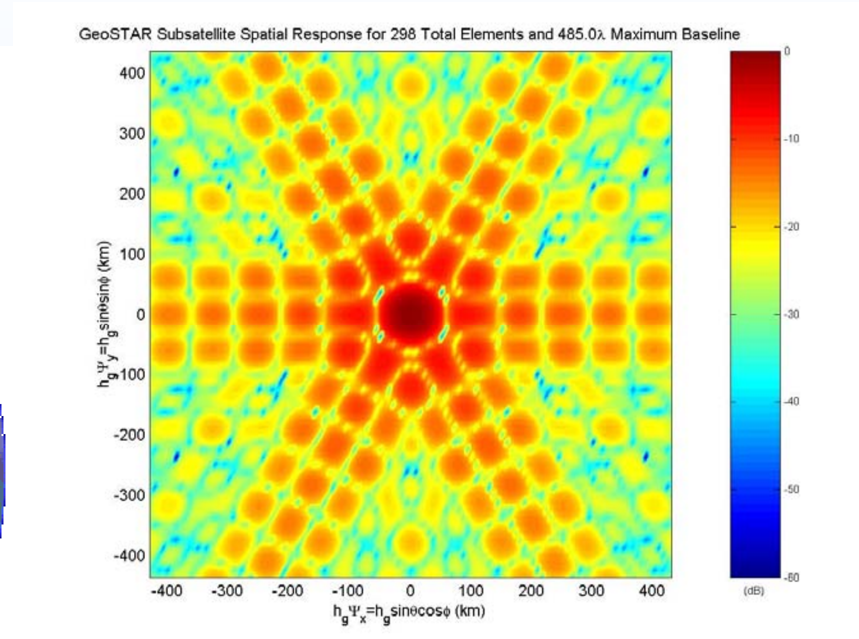


L-band: 1400-1427 MHz
69 total elements in Y-array (21 elements per arm X three arms)
6.75-m maximum baseline
Dual polarimetric (T_x,T_y)
Surface resolution: ~50 km at 775 km altitude

GeoSTAR Concept

2-D Geostationary Sounder/Imager





GeoSTAR spatial response pattern for 298 elements with 2.8λ spacing

- **~50/25 km spatial resolution (55/183 GHz)**
- **~60% disk image every one hour**
- **No moving parts or momentum transfer**
- **~2.5m maximum baseline**
- **NASA/JPL concept (B. Lambrigtsen, PI)**

Y-Array of ~hundreds (*N*) of receiver elements and ~tens to hundreds of thousand (N^2) one-bit corelators in AMSU A/B bands of 50-56 and 183 GHz.

GeoSTAR Aperture Synthesis Issues

- **Receiver power, weight, reliability, and cost**

  Approximately 1000 receivers and antennas are required in the 50-120 and 50-190 GHz bands for ~18 km resolution for precipitation, impacting power, weight, reliability, and cost.

- **Correlator complexity and power**

  1000 receivers in a Y-array would require ~500,000 digital corelators per band that measure magnitude and phase. Additional bands and channels have large to moderate cost.

- **Suitability to observational needs for rapidly evolving weather**

  Is full-disk imaging desirable over "random access" imaging using a scanned filled aperture system?

Sampling Requirements for NWP Precipitation Locking

What sampling rate and density is needed? The sampling requirements for all-weather microwave assimilation using near-term NWP models (especially regional models) are well satisfied by either of the following

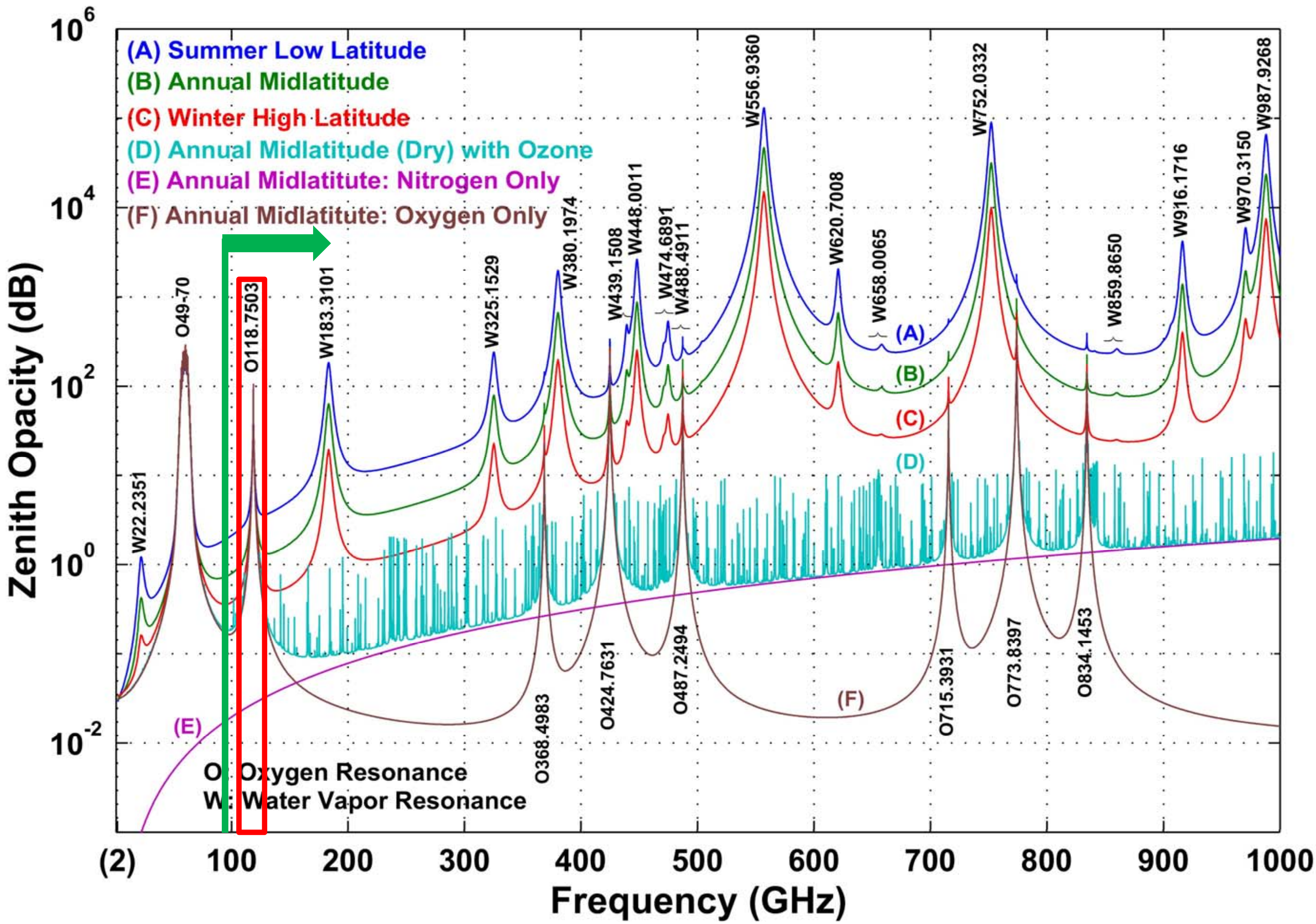
- **Large-aperture geosynchronous microwave imaging sounder**

  But each observing only a portion of the Earth's disk, and at operational costs of several hundred US$M.

- **A fleet of low cost microwave imaging sounders**

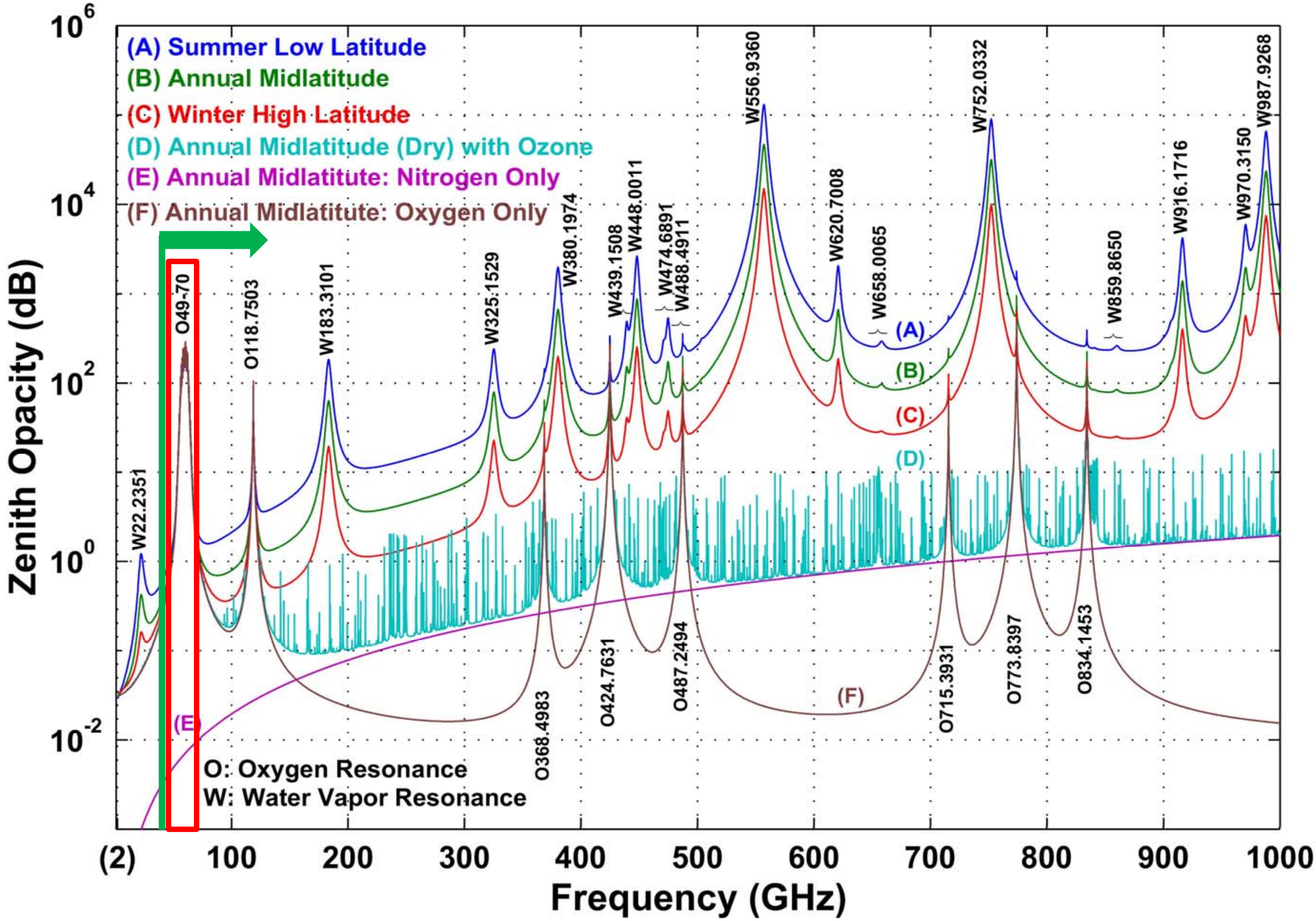
  30-40 ~6U CubeSats in random orbits, each with ~2 year on-orbit lifetime for global coverage, low system risk, regular technology infusion, and economy of scale.

  The fleet concept poses significant but surmountable communications and data assimilation challenges.



<17 km surface resolution from ~420-450 km LEO altitude using **3U or 6U** CubeSats w/ solid focusing element

Klein & Gasiewski, 2000



<18 km surface resolution from ~420-450 km LEO altitude using **12U** CubeSats w/ solid focusing element

Klein & Gasiewski, 2000

LEO Fleet Concept

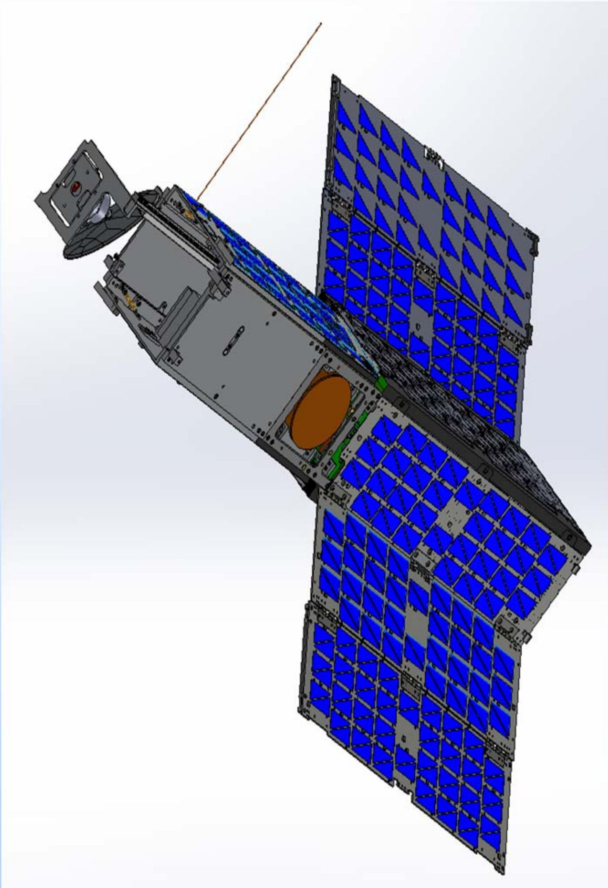
- Microwave imaging/sounding from ~425-550 km altitude can provide ~15 km (or better) spatial resolution using 3-U CubeSats envelope for all frequencies above ~90 GHz, and for lower frequencies using 6-U or 12-U envelopes.

- Fleet concept requires ~48 units in staggered orbital planes for GEO-equivalent temporal resolution

- Low altitudes and random orbit access promotes lifetimes to less than 2 years and requires 4D-Var assimilation

- Economy of scale and simplicity of launch provide competitive cost model with regular technology infusion

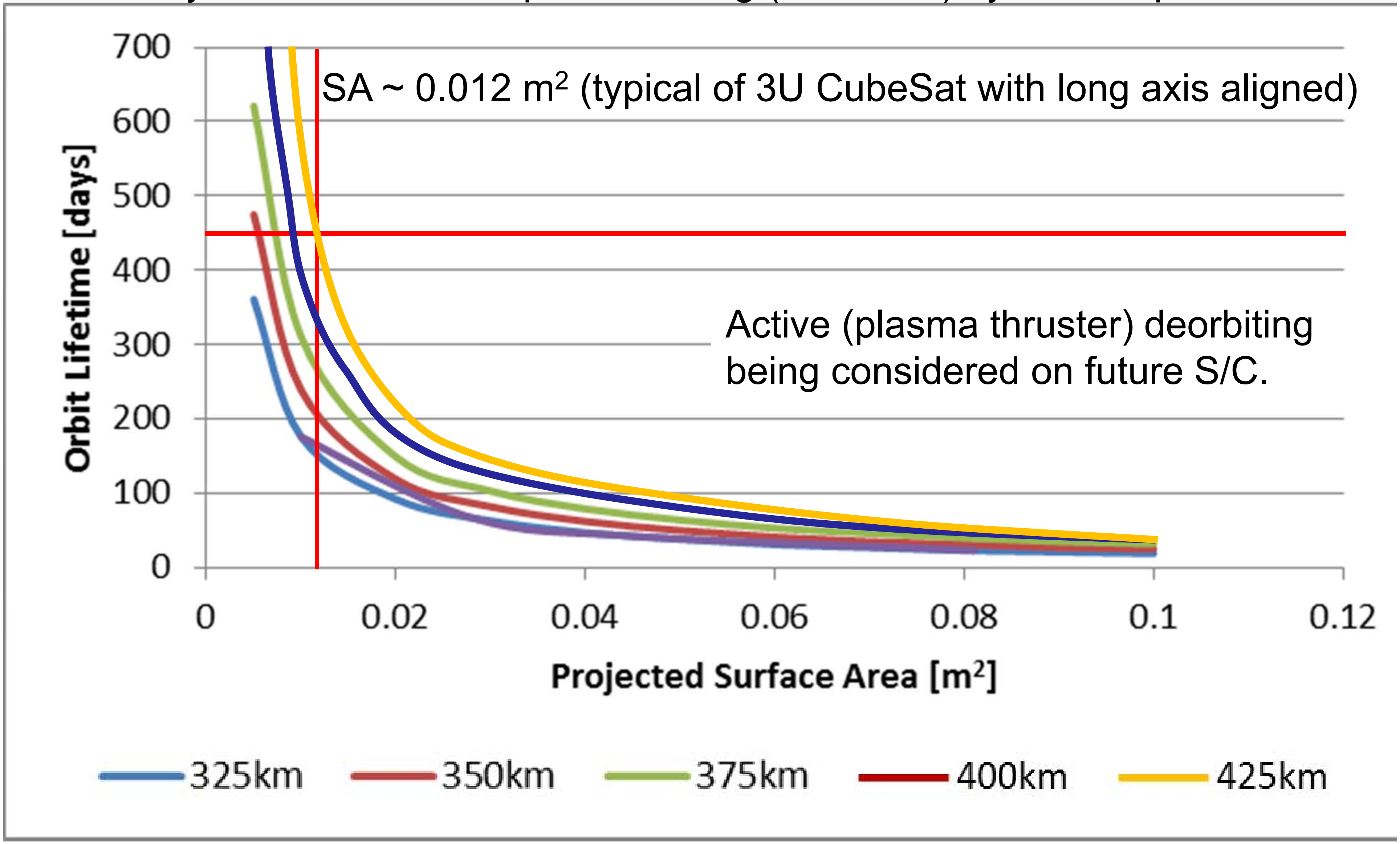
- Challenges include power management and low latency communications



CU MiniRad 118-GHz 8-channel CubeSat imager/Sounder on CU PolarCube All-STAR 3-U bus

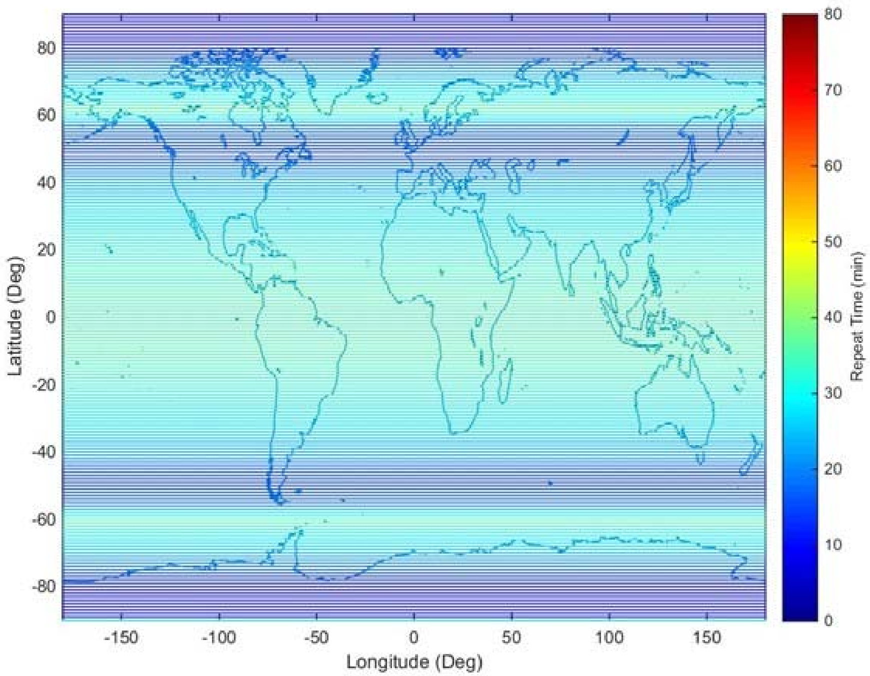
Orbit Lifetime, Replenishment, and Deorbiting

Expected orbital lifetime at ~425 km for a 4.5 kg 3U PolarCube S/C is ~1.5 years. Controlled rapid deorbiting (~1 month) by attitude pitch.



LEO CubeSat Fleet : 36x Revisit Times

2 year average on-orbit lifetime (3U)



Orbit Plane	Inclination (deg)
GPS	55.0
ISS	51.6
A-Train	98.14
Iridium	86.4

Simulation Number	Planes	Satellites per Plane	GPS	ISS	A-Train	Global Star	Iridium
1	8	3	1	3	1	0	3
2	10	3	2	3	1	0	4
3	12	3	2	4	2	0	4
4	14	3	2	5	2	0	5
5	16	3	2	6	3	0	5

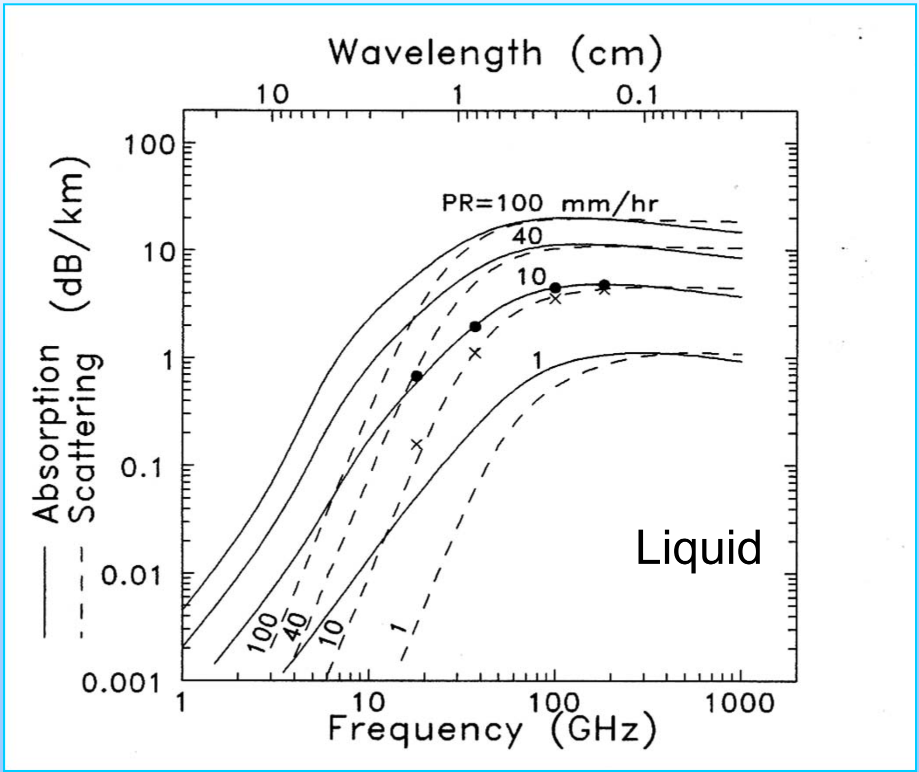
~15-30 minute revisit time achievable using a modest “random” 36-satellite constellation array

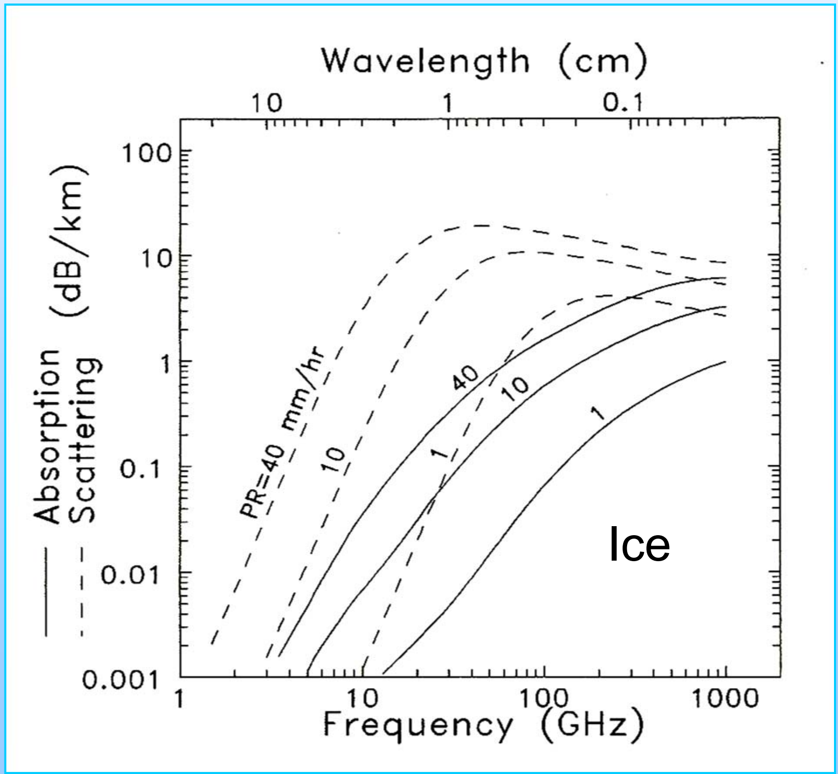
Prospects for microwave radiance assimilation over clouds by "precipitation locking"

PATH Constellation Study

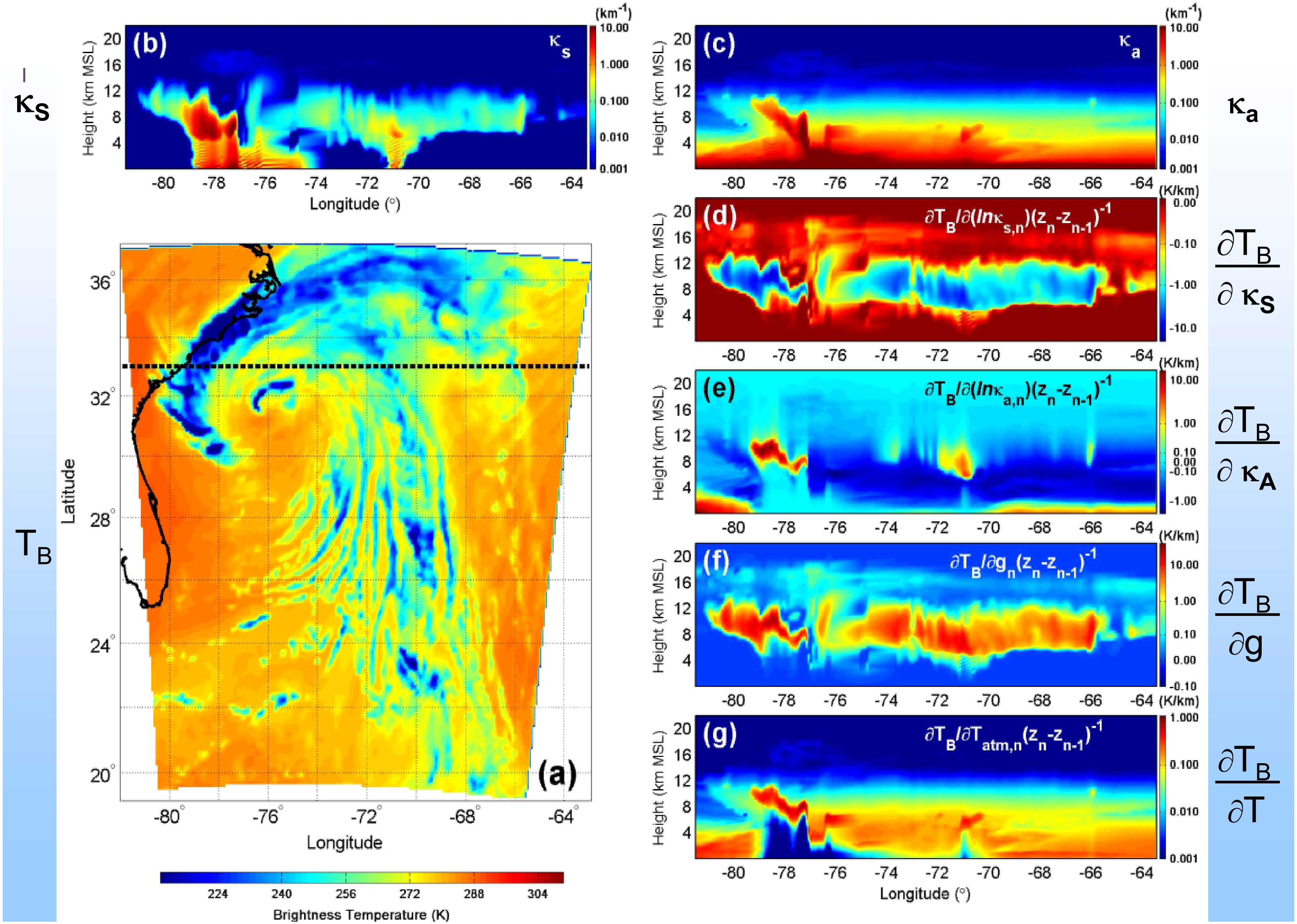
Effects of Hydrometeors on Microwave Signatures

Scattering and absorption by hydrometeors needs to be considered in all-weather microwave radiance assimilation both to extend soundings into cloudy regions and "lock" NWP models to raincell occurrence.





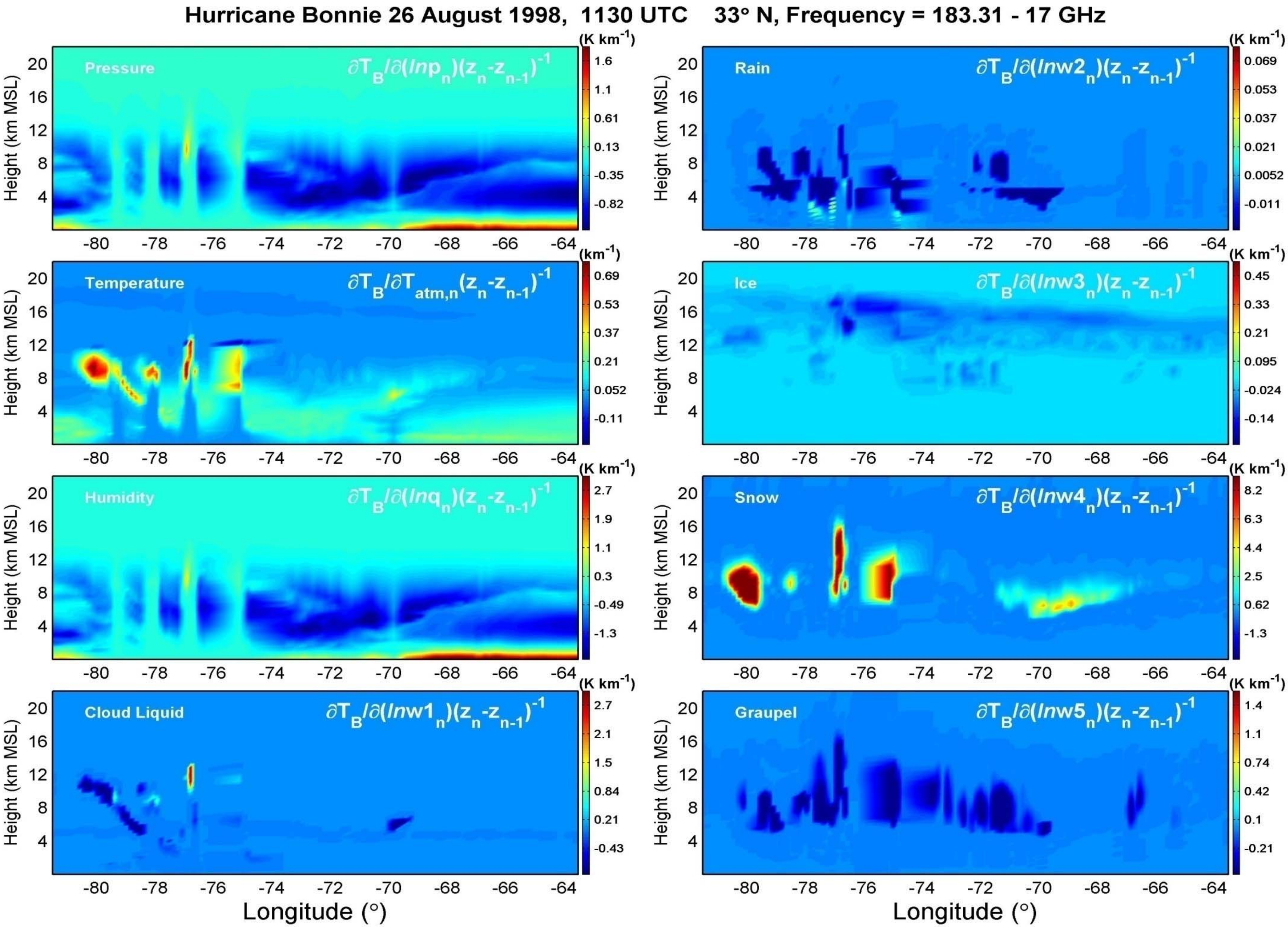
MM5/DO Hurricane Bonnie 183.3101 - 17GHz 26 August 1998 00:15 UTC



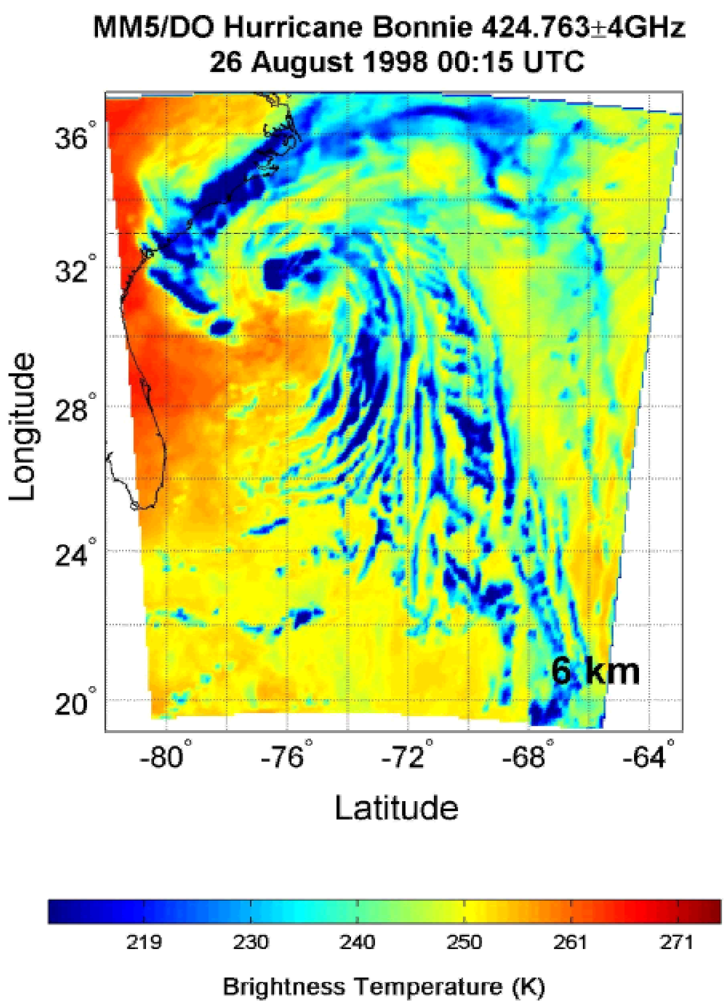
Jacobian Components

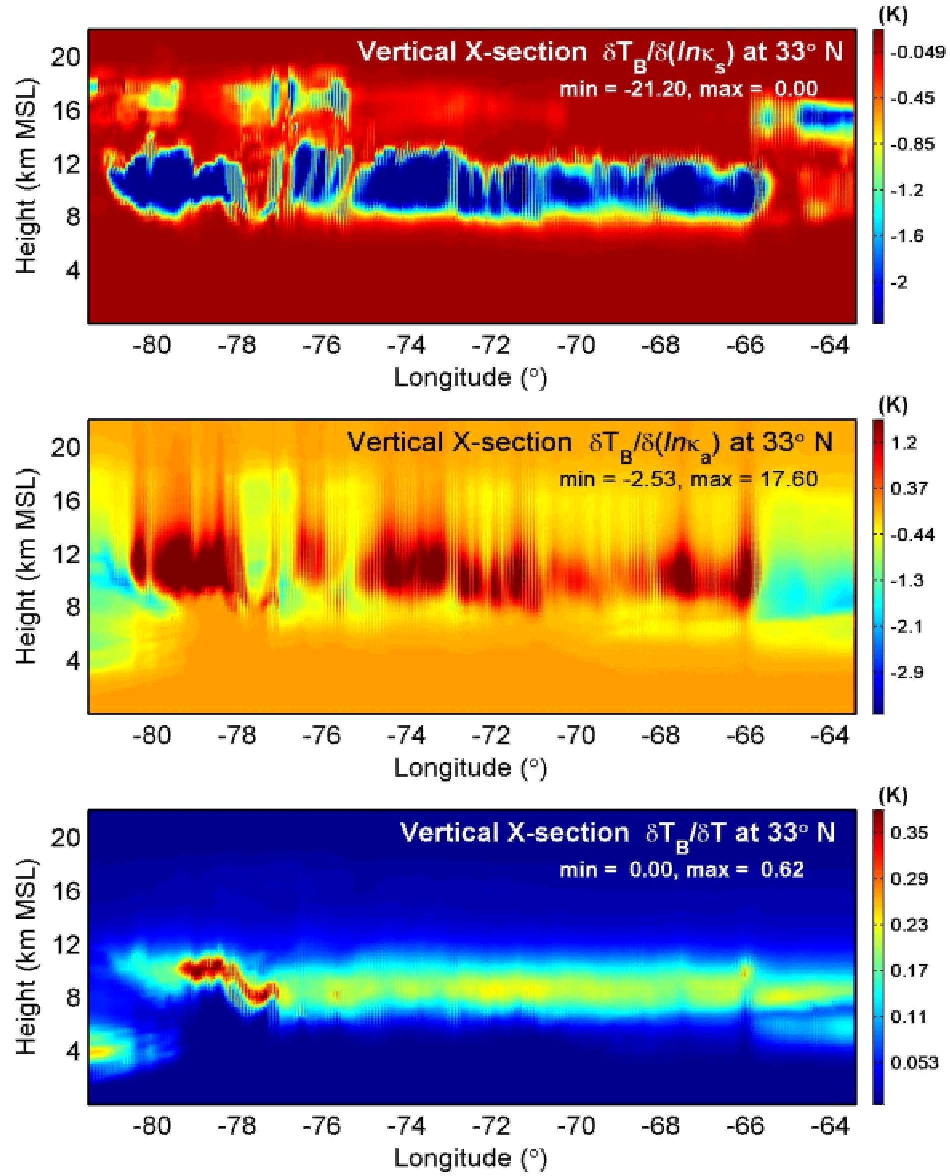
$$H = H_I \, H_R \, H_G$$

H	=	Total Jacobian
H_I	=	Instrument Jacobian
H_R	=	Radiation Jacobian
H_G	=	Geophysical Jacobian

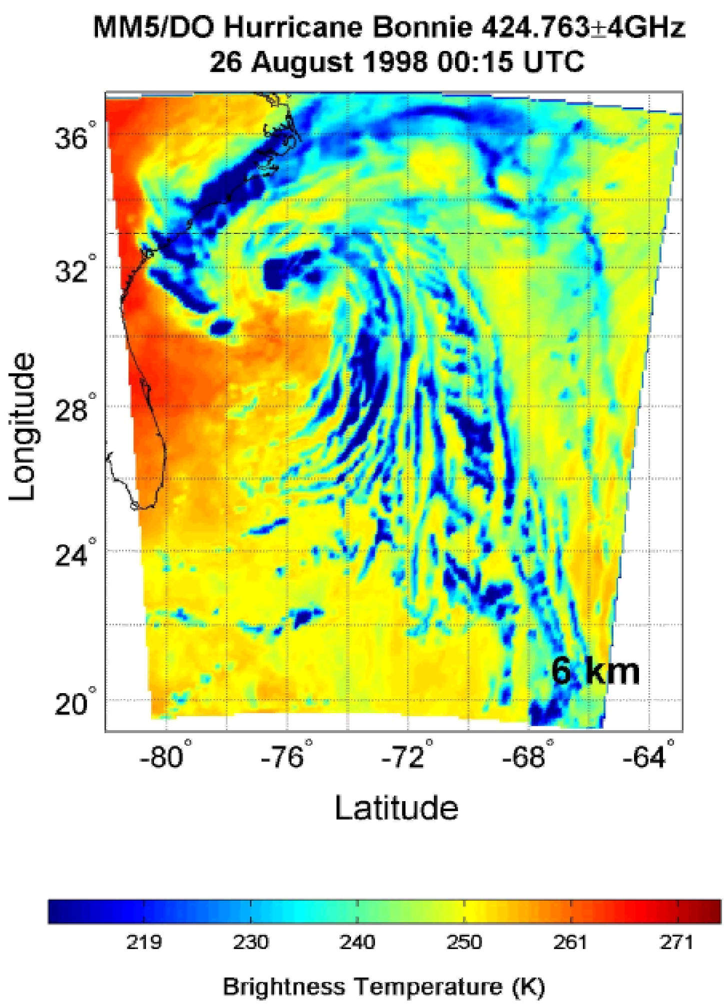

Hurricane Bonnie 26 August 1998, 1130 UTC 33° N, Frequency = 183.31 - 17 GHz
Pressure
$\partial T_B/\partial(\ln p_n)(z_n-z_{n-1})^{-1}$
Rain
$\partial T_B/\partial(\ln w2_n)(z_n-z_{n-1})^{-1}$
Temperature
$\partial T_B/\partial T_{atm,n}(z_n-z_{n-1})^{-1}$
Ice
$\partial T_B/\partial(\ln w3_n)(z_n-z_{n-1})^{-1}$
Humidity
$\partial T_B/\partial(\ln q_n)(z_n-z_{n-1})^{-1}$
Snow
$\partial T_B/\partial(\ln w4_n)(z_n-z_{n-1})^{-1}$
Cloud Liquid
$\partial T_B/\partial(\ln w1_n)(z_n-z_{n-1})^{-1}$
Graupel
$\partial T_B/\partial(\ln w5_n)(z_n-z_{n-1})^{-1}$
(K km^{-1}) 1.6 1.1 0.61 0.13 -0.35 -0.82
(K km^{-1}) 0.069 0.053 0.037 0.021 0.0052 -0.011
(km^{-1}) 0.69 0.53 0.37 0.21 0.052 -0.11
(K km^{-1}) 0.45 0.33 0.21 0.095 -0.024 -0.14
(K km^{-1}) 2.7 1.9 1.1 0.3 -0.49 -1.3
(K km^{-1}) 8.2 6.3 4.4 2.5 0.62 -1.3
(K km^{-1}) 2.7 2.1 1.5 0.84 0.21 -0.43
(K km^{-1}) 1.4 1.1 0.74 0.42 0.1 -0.21
Height (km MSL)
4 8 12 16 20
-80 -78 -76 -74 -72 -70 -68 -66 -64
Longitude (°)

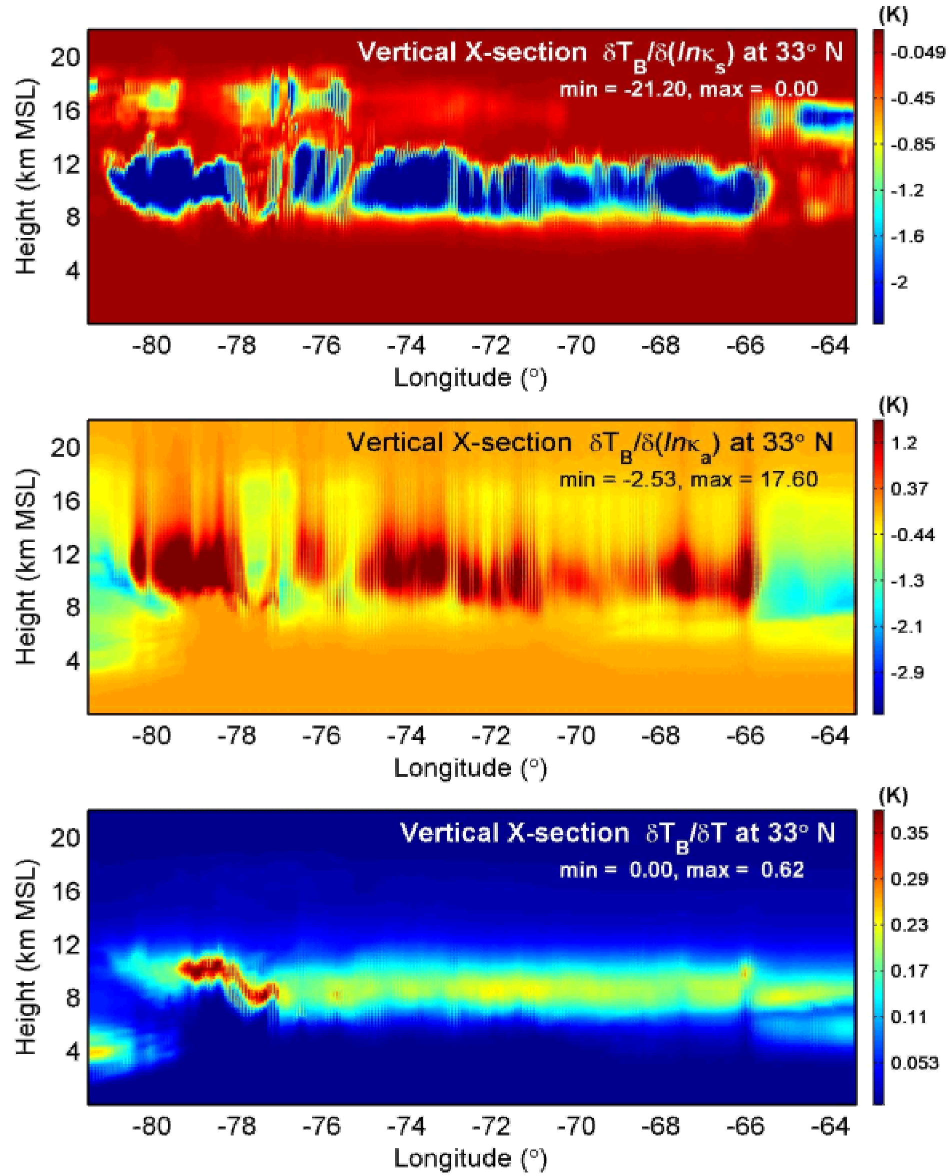
424+/-4 GHz - 15 min time steps





424+/-4 GHz – 3 hour time steps

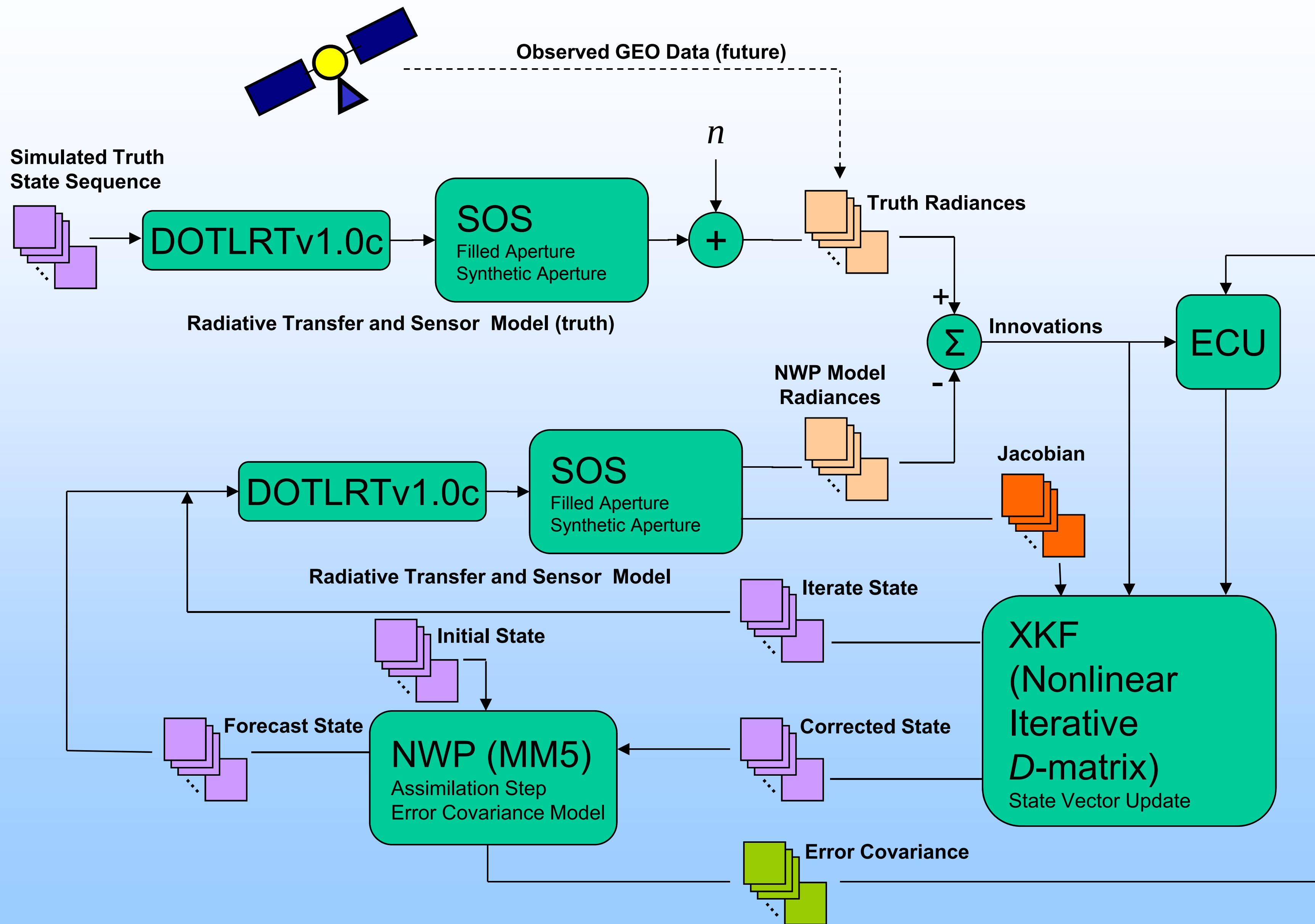




NWP Precipitation "Locking"
(or, "hydrometric tracking")

- Stable linear NWP model updates can be achieved provided that the cloud and precipitation state does not decorrelate between satellite observations.
- To realize "locking" of an NWP model onto precipitation, observations are needed at time and space scales of order ~5-15 km and ~15 minutes.
- Locking is analogous to phase-locked loop in electrical engineering wherein linear phase differencing is achieved only when oscillator and signal remain within same phase cycle.

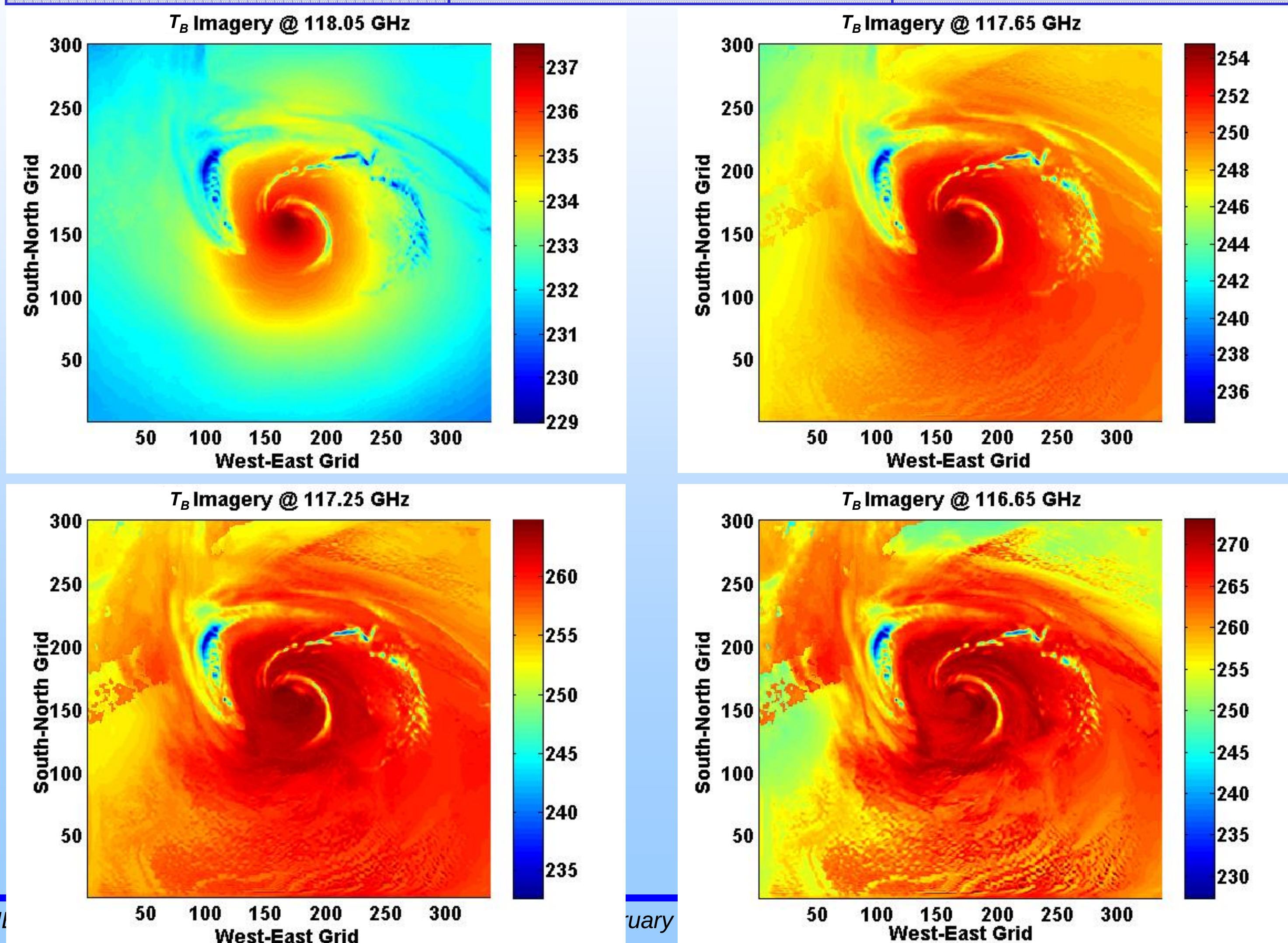
Hydrometric Tracking Simulator



Gasiewski and Weber

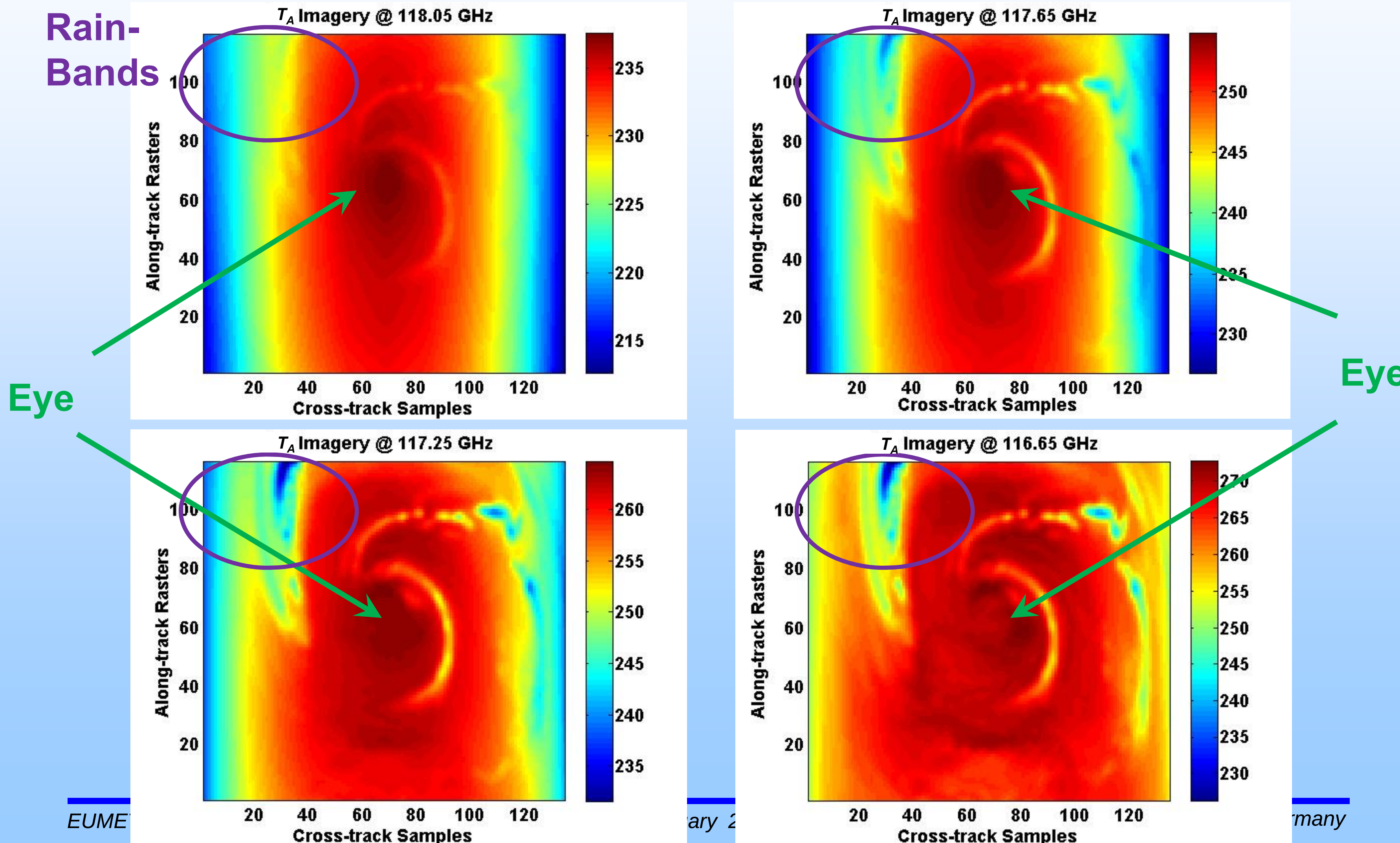
Brightness Temperature (T_B) at a Fixed Time

$\theta_{zenith} = 0^\circ$	Vertical Polarization	2012-10-29 01:15:00



Antenna Temperature (T_A) at a Fixed Time

Imaging Effects: Resolution, Distortion, and Limb Darkening		
Local inc. angle varying	Quasi-Vert. Polarization	2012-10-29 01:15:00



Extended Kalman Filter (XKF)

Corrector:

$$\widehat{x}_i = \widehat{x}_{i|i-1} + \overline{\overline{K}}_i \left(\overline{y}_i - \overline{W}\left(\widehat{x}_{i|i-1} \right) \right)$$

Predictor:

$$\widehat{x}_{i+1|i=} = \overline{A}\left(\widehat{x}_i \right)$$

Kalman gain (*D*-matrix):

$$\overline{\overline{K}}_i = \overline{\overline{R}}_{e_{i|i-1}e_{i|i-1}} \overline{\overline{H}}_i^t \left(\overline{\overline{H}}_i \overline{\overline{R}}_{e_{i|i-1}e_{i|i-1}} \overline{\overline{H}}_i^t + \overline{\overline{R}}_{n_{y_i}n_{y_i}} \right)^{-1}$$

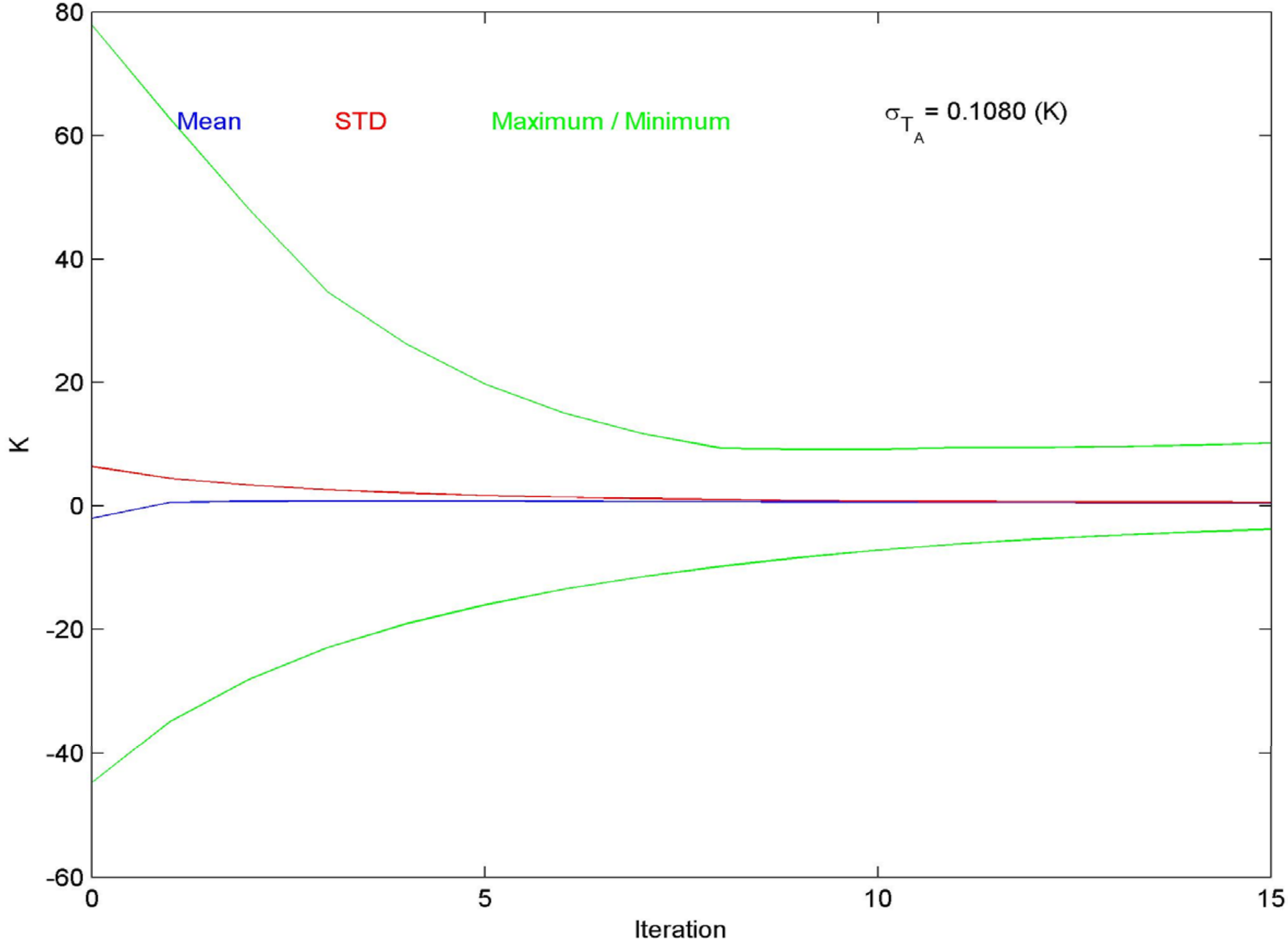
Error covariance update:

$$\begin{aligned} \overline{\overline{R}}_{e_{i+1|i}e_{i+1|i}} = \; & \overline{\overline{L}}_i \overline{\overline{R}}_{e_{i|i-1}e_{i|i-1}}^t \overline{\overline{L}}_i^t + \overline{\overline{B}}_i \overline{\overline{R}}_{n_{x_i}n_{x_i}} \overline{\overline{B}}_i^t - \\ & \overline{\overline{L}}_i \overline{\overline{K}}_i \left(\overline{\overline{H}}_i \overline{\overline{R}}_{e_{i|i-1}e_{i|i-1}} \overline{\overline{H}}_i^t + \overline{\overline{R}}_{n_{y_i}n_{y_i}} \right) \overline{\overline{K}}_i^t \overline{\overline{L}}_i^t \end{aligned}$$

Initial conditions: $\widehat{x}_{0|-1} = \widehat{x}(0)$ $\quad$ $\overline{\overline{R}}_{e_{0|-1}e_{0|-1}} = \overline{\overline{R}}_{xx}^o$

Innovation Trends – 166.3 GHz

Full-Frame Error Covariance



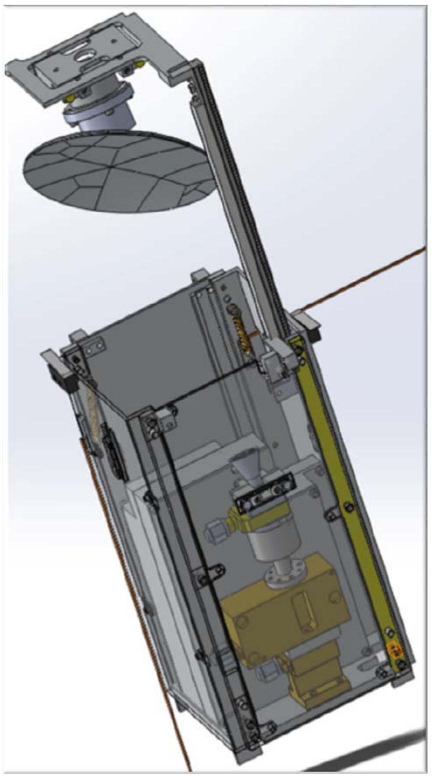
National Snow and Ice Data Center

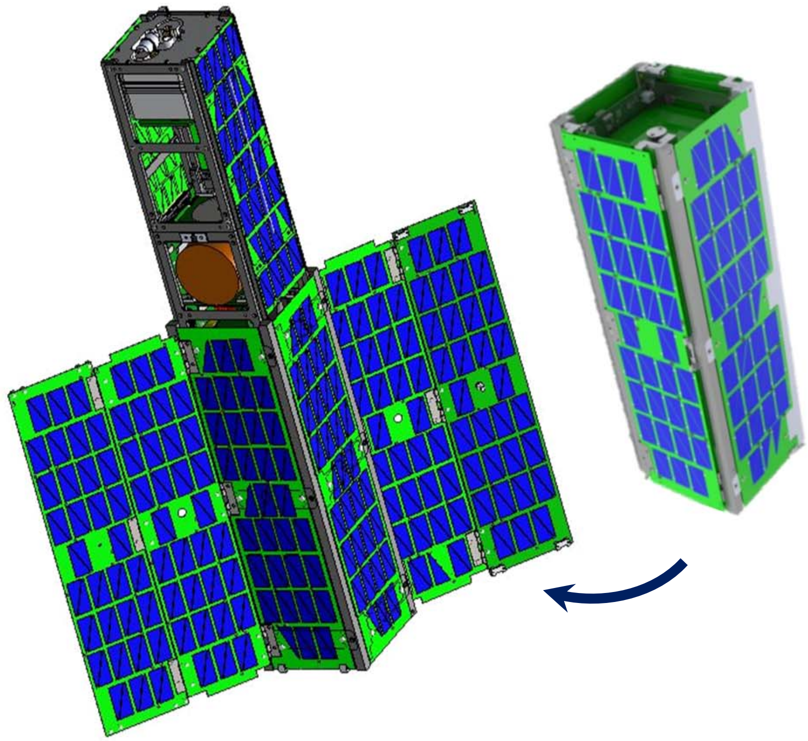
Supporting Cryospheric Research Since 1976

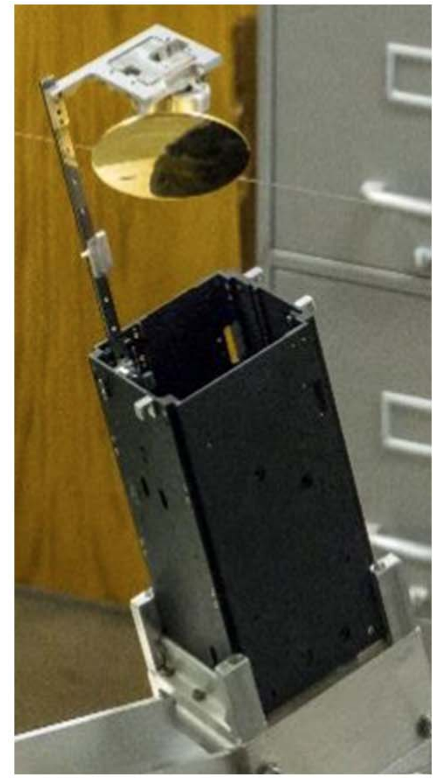
COSGC

CET Center for Environmental Technology

CU PolarCube Project







Air Force Research Laboratory

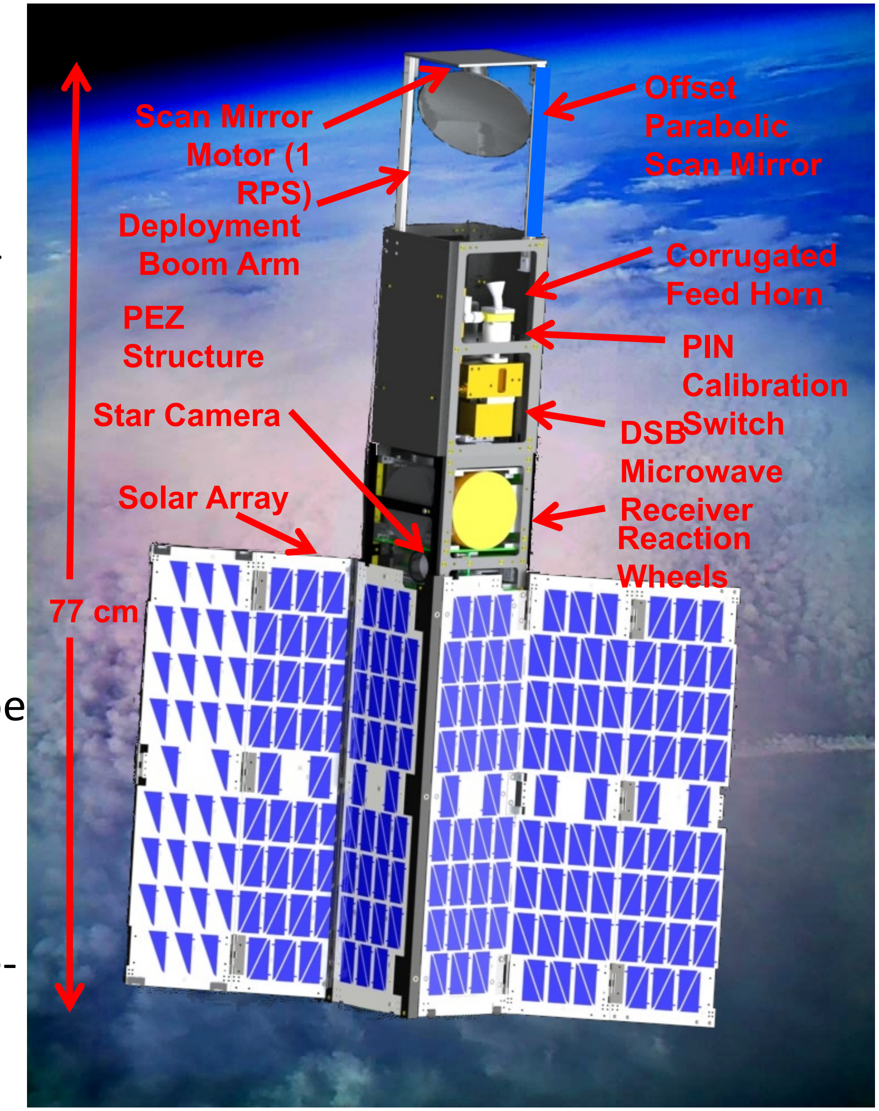
PolarCube

Orbital Micro Systems

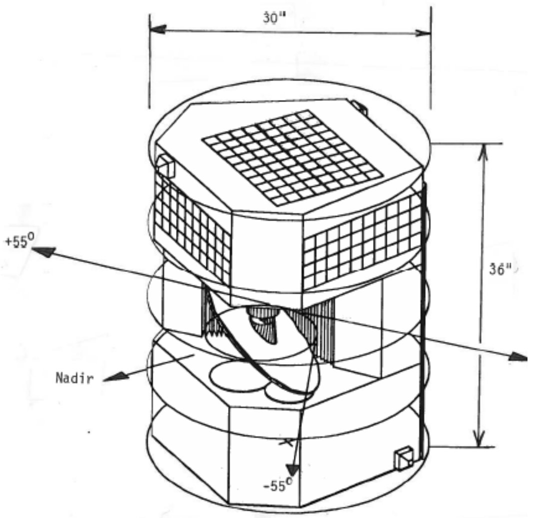
NASA

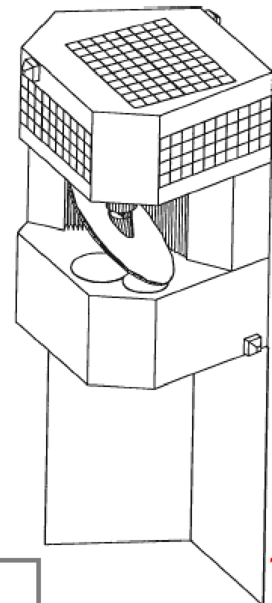
PolarCube 118 GHz Imager/Sounder

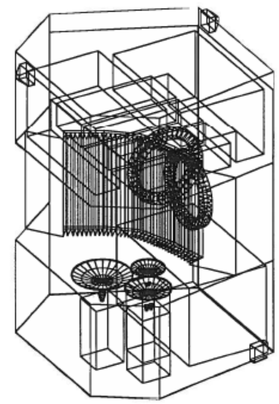
- PolarCube is a 3U CubeSat satellite based on an existing bus design (CU ALL-STAR).
- **Payload** consists of a passive 8-channel 118.753-GHz scanning microwave O_2 temperature sounder with suborbital aircraft flight heritage with 2.3° 3-dB beamwidth.
- Low cost to build/launch: < $1M. Designed to operate for 12-18 months in low Earth orbit ~425 km. Launch: NASA ELaNa in early 2017, USAF UNP program and NASA funding.
- One of the first passive microwave sensors on a small satellite.
- Demonstrator of similar inexpensive satellites to be deployed in fleets for global weather forecasting and climate science in response to NRC's Decadal Survey vision as a global **PATH** sensor system.
- **Science Product:** Demonstrate coincident atmospheric temperature profiling and sea ice/ice-free ocean detection and mapping, along with mesoscale weather imaging.



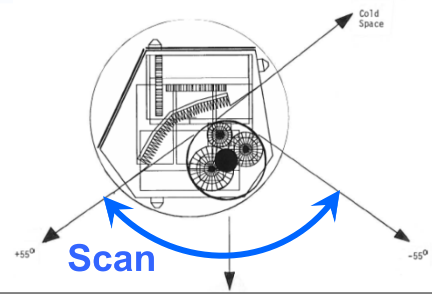
High Resolution Submillimeter-Millimeter-wave Imaging Radiometer HSMIR (July, 1994)*

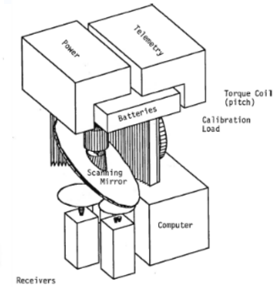


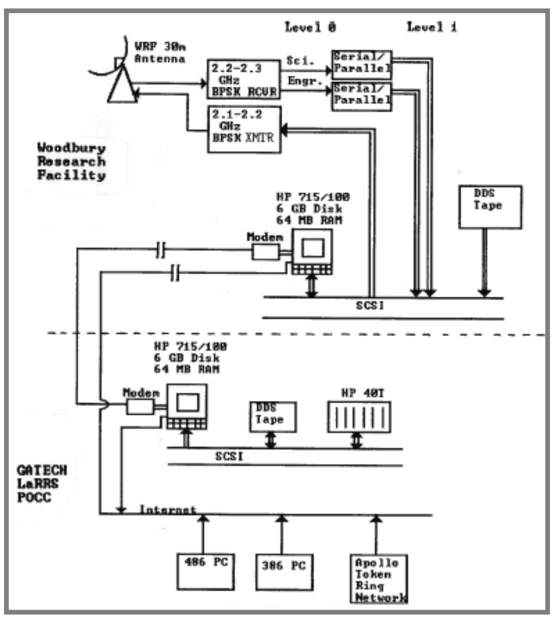


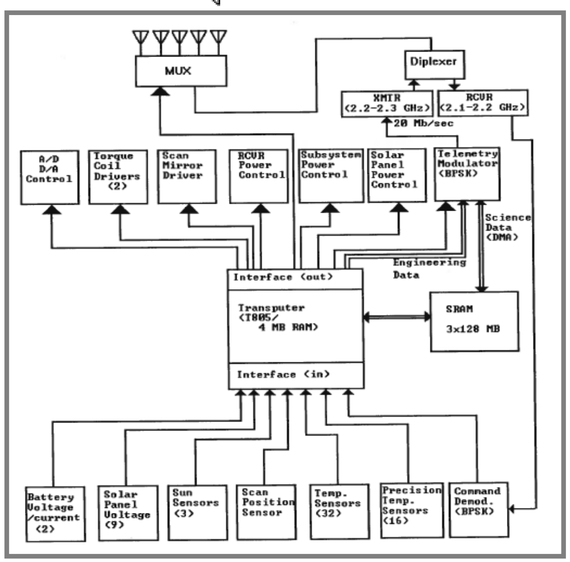


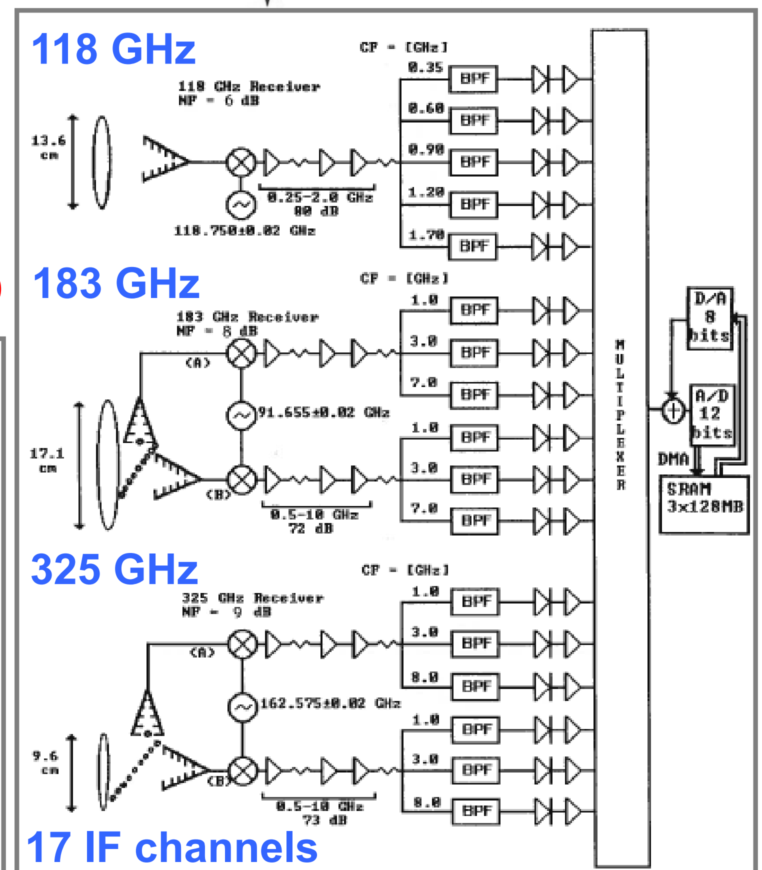
133 kg 55W
~75x90 cm (!)
~US$9.5M (2016)





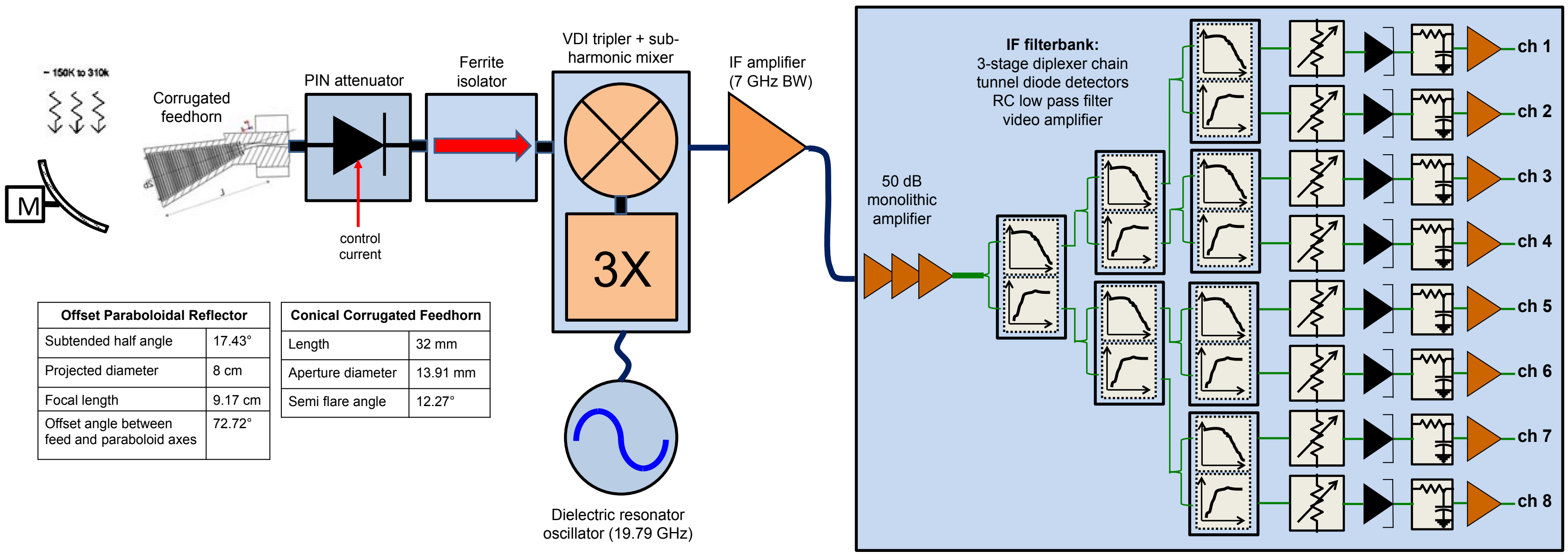






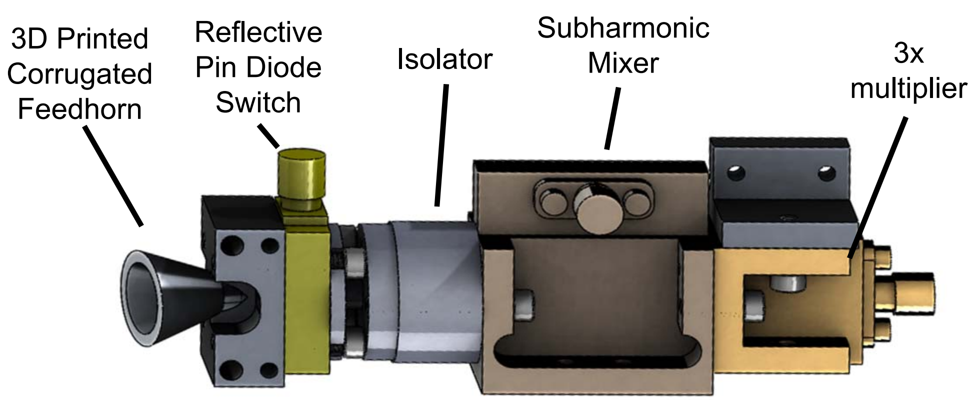
*Gasiewski (PI), P.G. Steffes, D.H. Staelin, G. Stephens, J. Wang (NASA STEDI program, AO URSA 01-94)

PolarCube Radiometer Architecture



Offset Paraboloidal Reflector	
Subtended half angle	17.43°
Projected diameter	8 cm
Focal length	9.17 cm
Offset angle between feed and paraboloid axes	72.72°

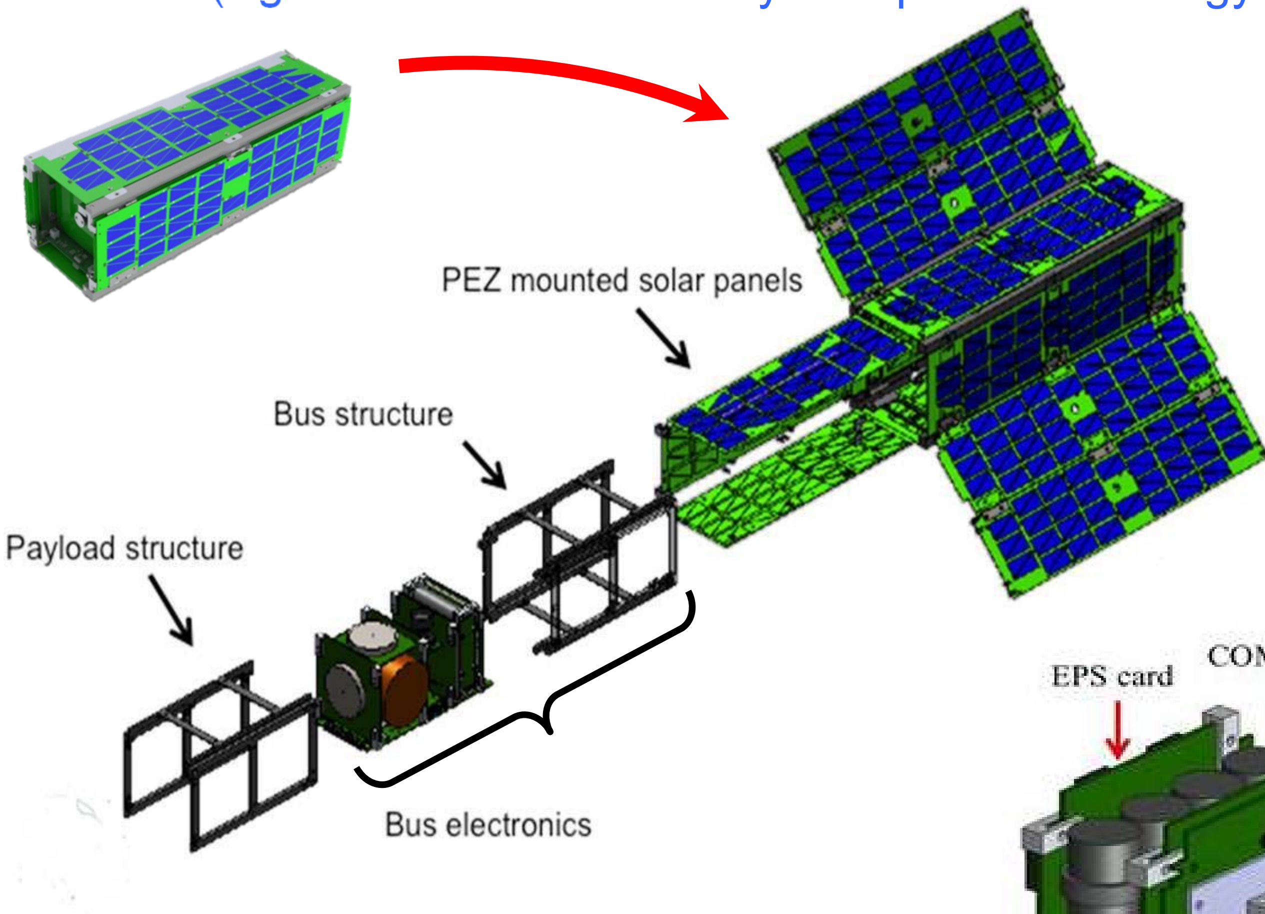
Conical Corrugated Feedhorn	
Length	32 mm
Aperture diameter	13.91 mm
Semi flare angle	12.27°



- Subharmonic mixer with tripler (VDI) and diplexer/filter bank, detectors, video amps, 24 bit ADC.
- Eight double sideband channels uniformly sample surface to ~18 km altitude.
- Two-point (cold space, reflective PIN diode/isolator) calibration.

ALL-STAR - Bus Architecture

(Agile Low-cost Laboratory for Space Technology Acceleration Research)

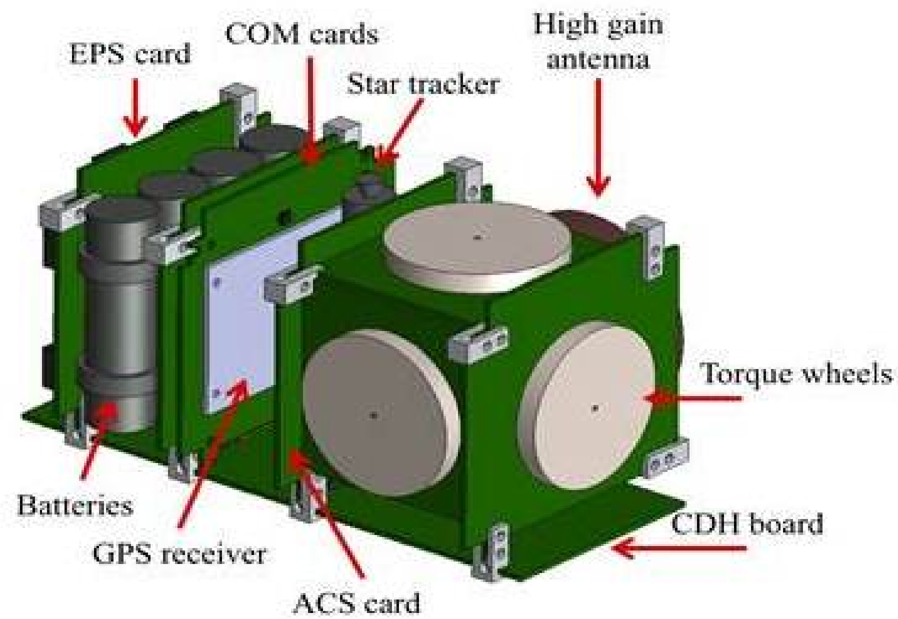


Bus:

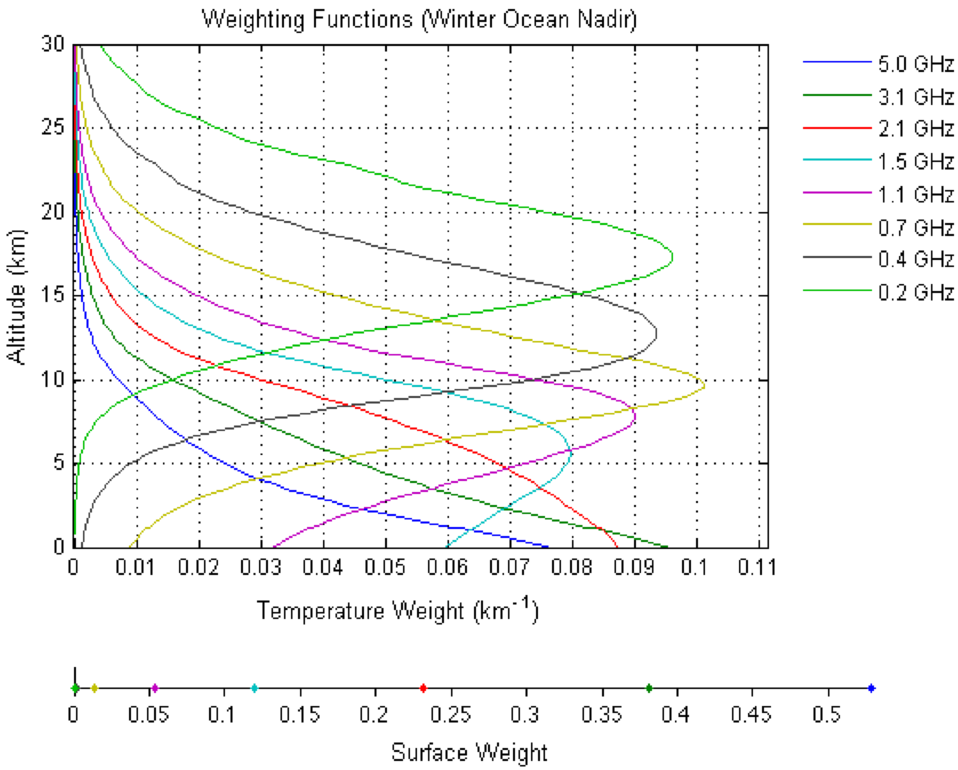
- **3U CubeSat format**
- **Three-axis stabilized (1° point / 0.2° knowledge)**
- **35 W peak power / 37 W-hr**
- **1.5U avionics module**
- **1.5 GB data storage**
- **CU developed subsystems using OTS components**

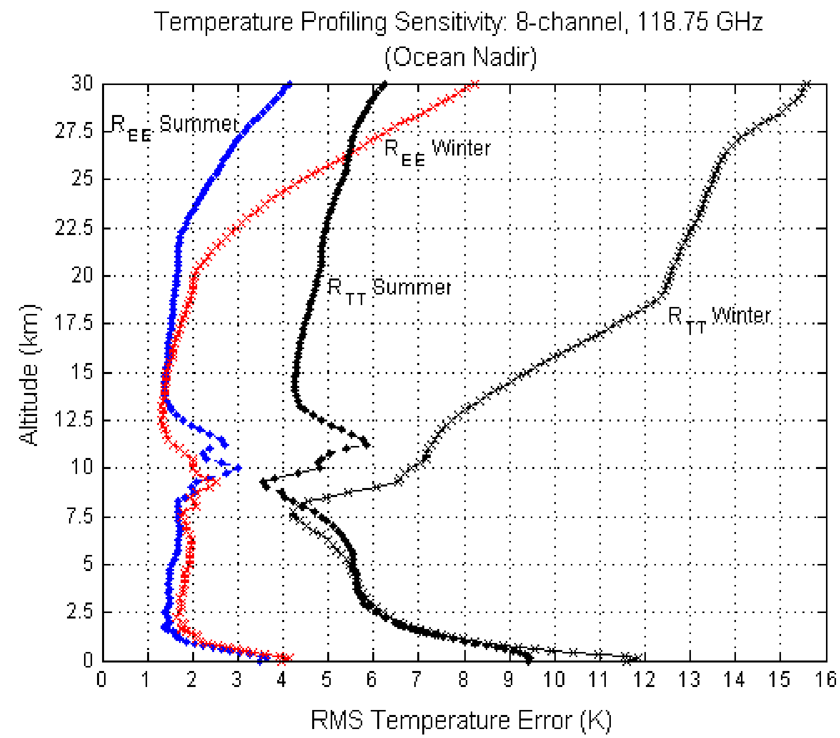
Payload:

- **1.5U Payload Extension Zone (PEZ)**
- **2 kg mass**
- **10 W nominal / 4.5 W avg max power**



RF Response & Retrieval Performance



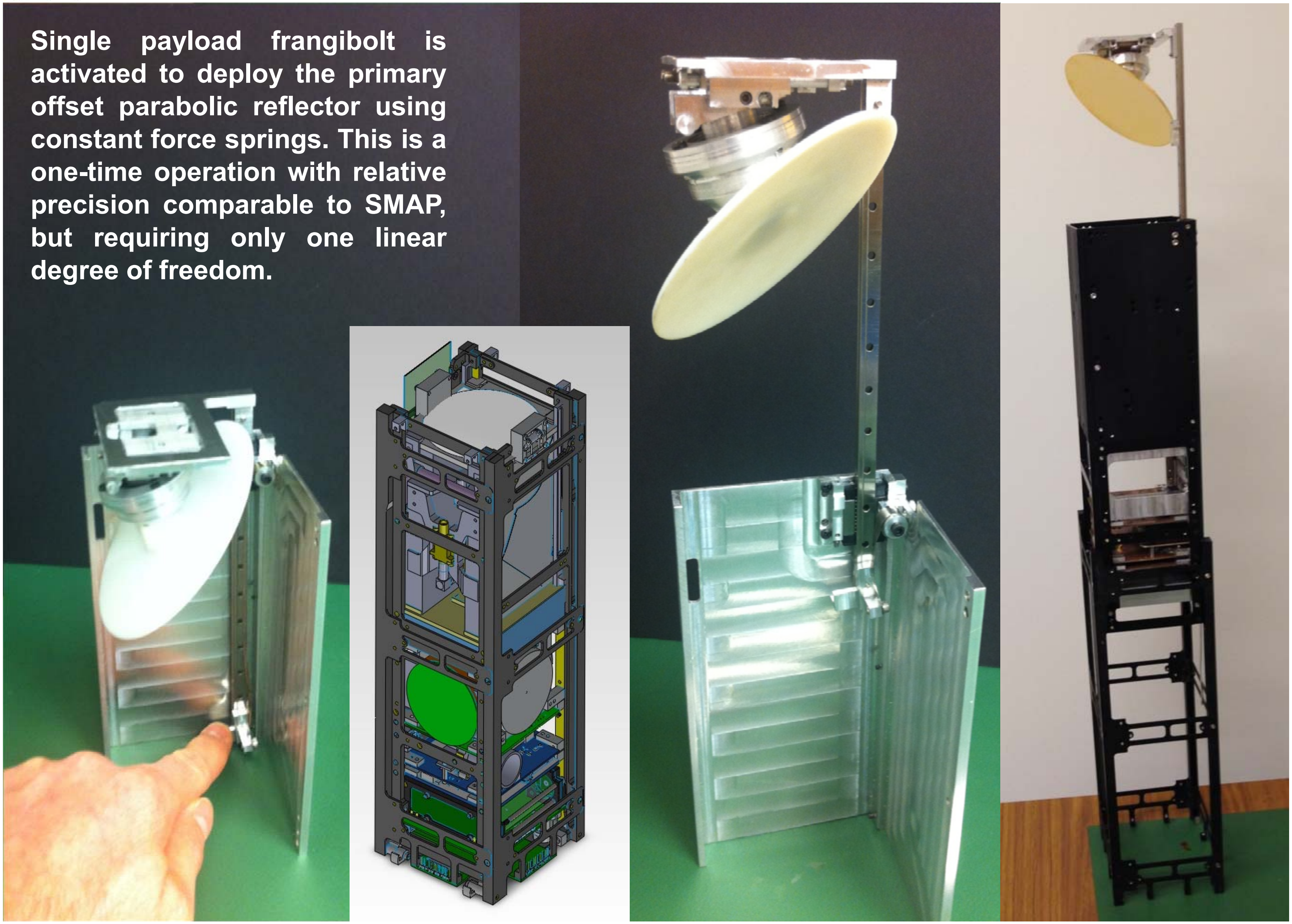


Channel #	8	7	6	5	4	3	2	1
IF f_c (MHz)	5000	3100	2100	1500	1100	700	400	200
BW (MHz)	2600	1200	800	400	400	400	200	100
Noise RMS (K)	0.356	0.503	0.603	0.857	0.861	0.882	1.39	2.18

- COTS VDI receiver (<7dB NF) and DRO reduces the above noises significantly.

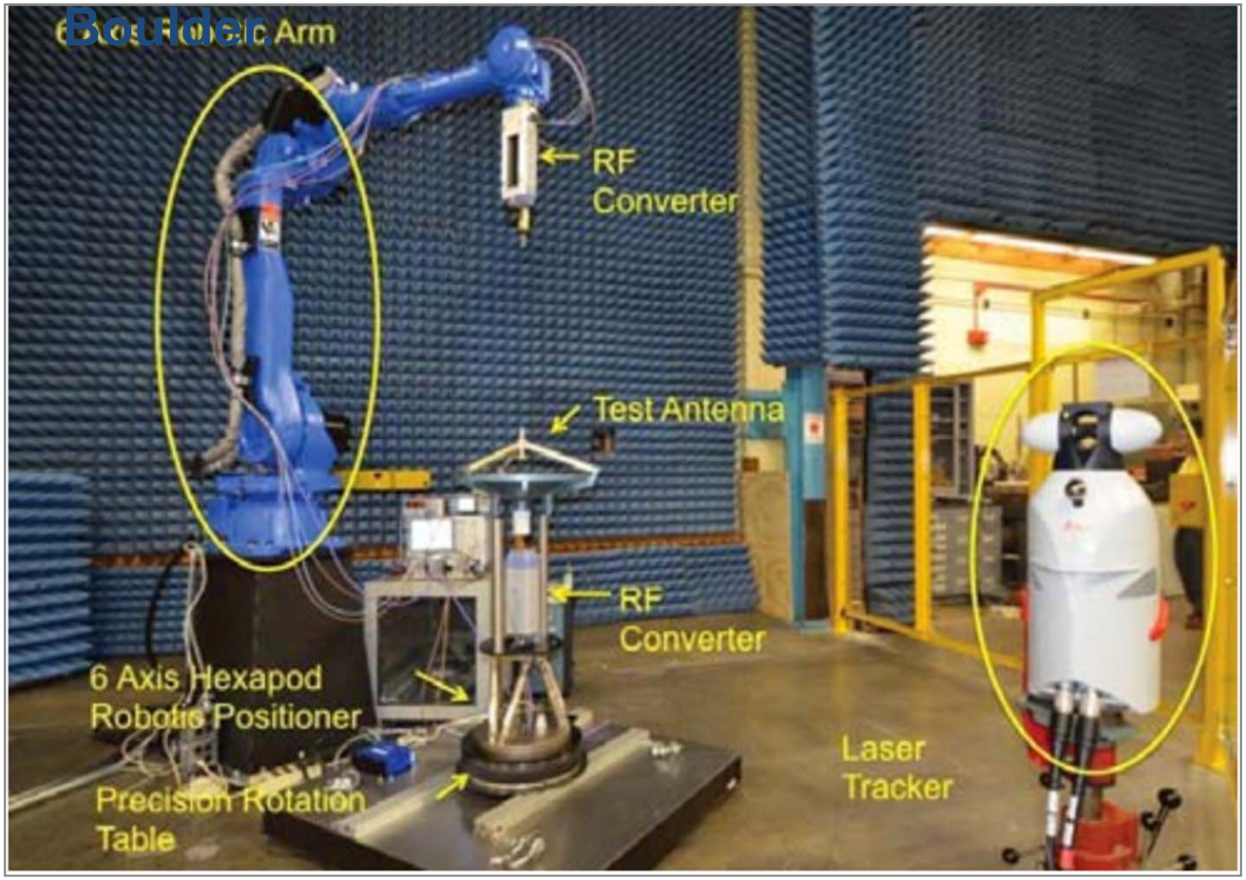
PolarCube Reflector Deployment

Single payload frangibolt is activated to deploy the primary offset parabolic reflector using constant force springs. This is a one-time operation with relative precision comparable to SMAP, but requiring only one linear degree of freedom.



NIST CROMMA PolarCube Study

CROMMA is the NIST Configurable Robotic Millimeter-wave Antenna facility at NIST, Boulder



Reference: D. Novotny, J. Gordon, et al., "Performance Evaluation of a Robotically Controlled Millimeter-Wave Near-Field Pattern Range at the NIST", 7th European Conference on Antennas and Propagation, 2013.

- **Can measure highly accurate antenna pattern over 3π st**
- **< 0.01°pointing accuracy over the entire near-field scan**
- **At 118.75 GHz (2.53 mm), a positioning accuracy of ~λ/100 is achievable.**
- **Plan to compare test results with theoretical analysis to develop pre-launch total gain pattern.**

Summary

- A large-aperture geosynchronous microwave sounder or a dense low-cost LEO fleet satisfies the sampling requirements necessary for “precipitation locking.”
- First-frame Extended Kalman Filter locking using iterative LMMSE in a variational scheme are encouraging, but a state-dependent background covariance is critical.
- PolarCube is a very low cost forerunner of similar inexpensive fleet-deployed satellites to satisfy PATH objectives for numerical weather forecasting.
- Significant improvements in time and space resolution of current microwave sounder/imagers and reduced costs, risk, and latency could be expected from a follow-on fleet.