Calibration and Validation of EarthCARE's Cloud Profiling Radar Data Products from

O.O. Sy, S. Tanelli

Jet Propulsion Laboratory, California Institute of Technology, USA

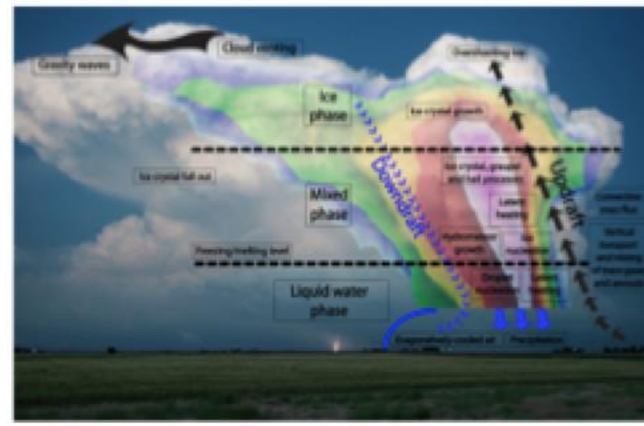
ESA EarthCARE Validation Workshop

Bonn, Germany, Jun 11-15 2018

Science Driver on Next-Generation Atmos Radars – Process Study

- "… **next set(s) of space measurements** should focus on **process studies…**" (2010 WCRP GEWEX Workshop, 2011 Spaceborne Snowfall Measurement Workshop, 2013 Global Precip. & Cloud Meas., 2017 D-train workshop, Decadal Survey 2017, CCP)

- Capture **cloud/precipitation process** via
  - **Multi-frequency** radar data to increase measurement dynamic range & study microphysics
    TRMM → GPM
  - Simultaneous **Doppler velocity** to associate dynamics to hydrometeors
    CloudSat → EarthCARE
  - Capture **time evolution** processes
    - **GEO** radars (e.g. life cycle of cyclones)
    - **LEO** radar **constellation**



GV activities in synergy with CloudSat, GPM and CCP

EarthCARE

Part 1

NASA airborne campaigns:

(APR-3, RainCube, airMASTR)

Synergies and opportunities

Part 2

comparisons vs CloudSat:

Direct comparisons,

Possible applications

Part 3

Forward modeling for algorithm development and validation:

High-Resolution Radar based, or Model Based

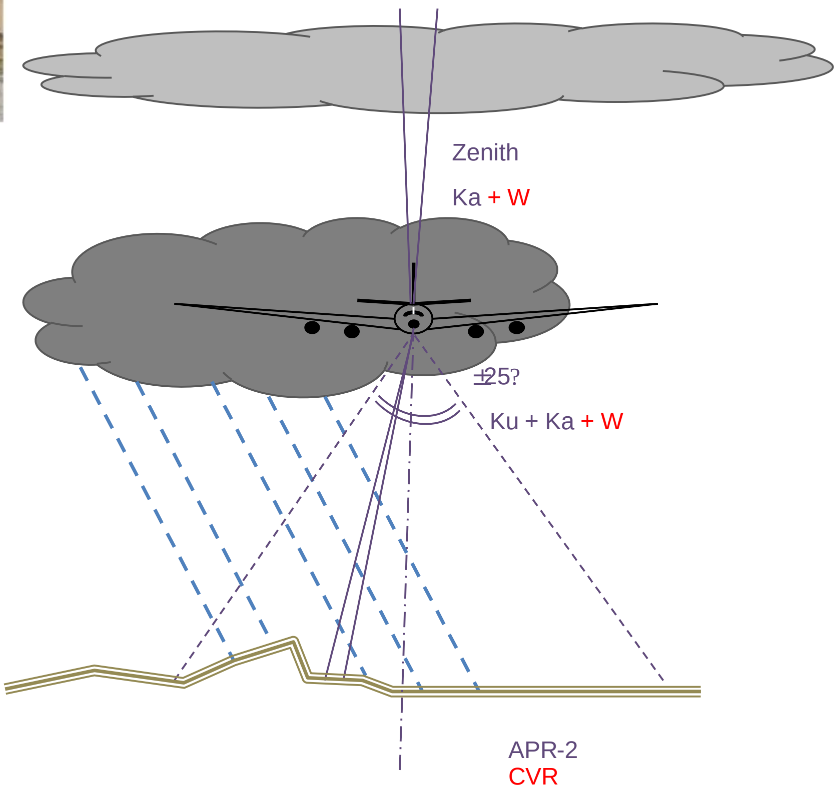
A. APR-3 (AITT started April 2014, S Durden PI)

3 bands, collimated through the scanning antenna on nadir port,
Ka and W also radiate at zenith

1st deployment
ACE RADEX/OLYMPEX 2015

support science of GPM, CloudSat, ACE, CCP, RainCube, SWOT.

Parameters	Ku-band	Ka-band	W- band
Frequency(GHz)	13.4	35.6	94
Polarization	HH, HV	HH	HH
Antenna eff. diameter	0.4 m	0.14 m	0.3 m
Antenna gain	34 dBi	34 dBi	50 dBi
Antenna sidelobe	-30 dB	-30 dB	-30 dB
Antenna scan angle	±25˚	±25˚	±25˚
Polarization isolation	-25 dB	-	-
Peak power	200 W	500 W	1400 W
Bandwidth	4 MHz	4 MHz	4 MHz
Pulsewidth	3 - 20 ms	3 - 20 ms	0.25,0.5, 1ms
PRF (pulse rep. freq.)	5 kHz	5 kHz	5 kHz
Vertical resolution	60 m	60 m	50, 80, 150m
Hor.res.(@10 km alt.)	800 m	1000 m	200 m
Ground Swath	10 km	10 km	10 km
Sens.(@10km range)	10 dBZ	-10 dBZ	-35 dBZ
Doppler precision	0.3 m/s	0.3 m/s	0.3 m/s

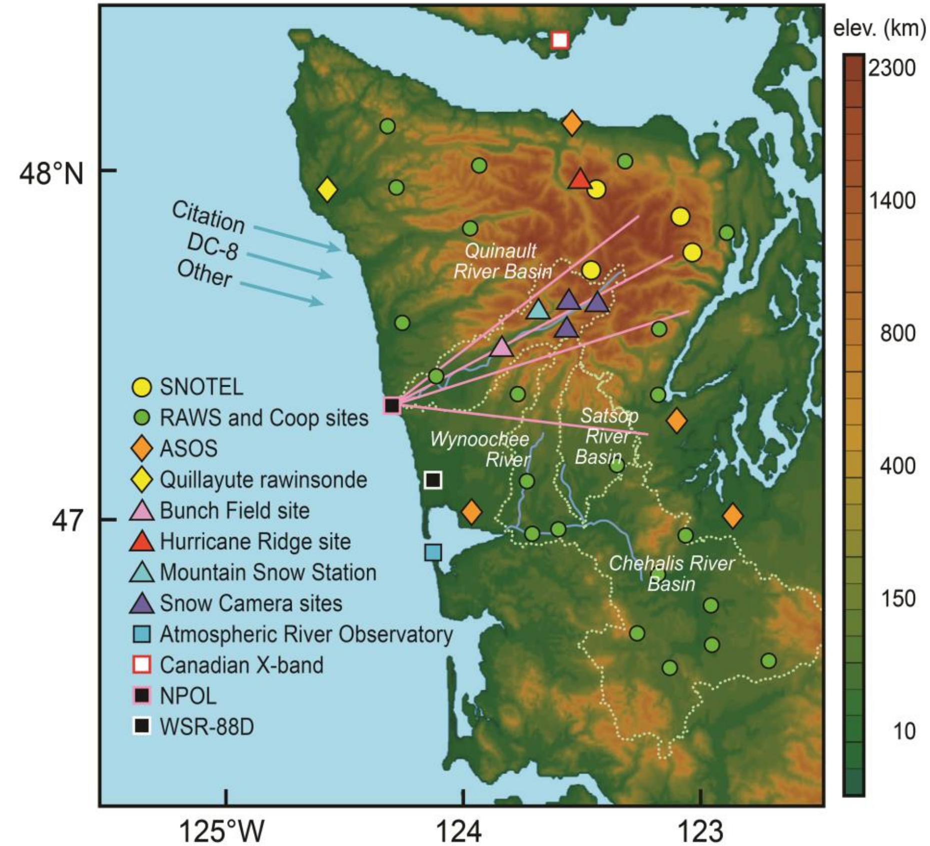


1. Post-Launch (GPM) in the Field
OLYMPEX: *Olympic Mountains Experiment (Pacific NW)*

Nov 2015 – Jan 2016

Science Goals:

- Physical Validation of **GPM Precipitation Algorithms** (rain and snow) for GMI and DPR
- Midlatitude **frontal systems** and modification by complex **terrain**
- Merged **numerical model** and **satellite observations**
- Test **hydrological applications**



Instrumentation:

- **Surface**: Special Rain gauge networks on Quinault and Chehalis, SNOTEL, Time-Lapse Photography, Disdrometers (Parsivel, 2DVD), hot plates, Pluvios
- **Radars**: WSR-88D, NPOL, D3R, MMR, X and W-band from Canada, Potential Radars: C, DOW, Atmospheric River Obs, and others.
- Aircraft: DC-8 **(ed:** with **APR-3)**, UND Citation, ER-2 (ACE/RADEX). Other potential aircrafts: Canadian NRC C580, DOE G-1

Courtesy Lynn McMurdie (UW)

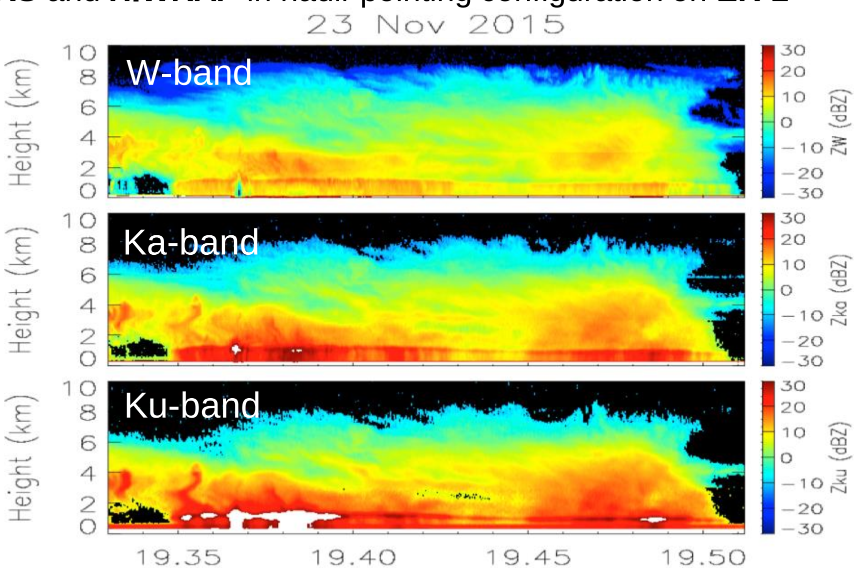
OLYMPEX: GPM/ACE joint Experiment

ACE SWG & **GPM GV program** → 2 joint projects with **multi frequency cloud-precipitation radar**:

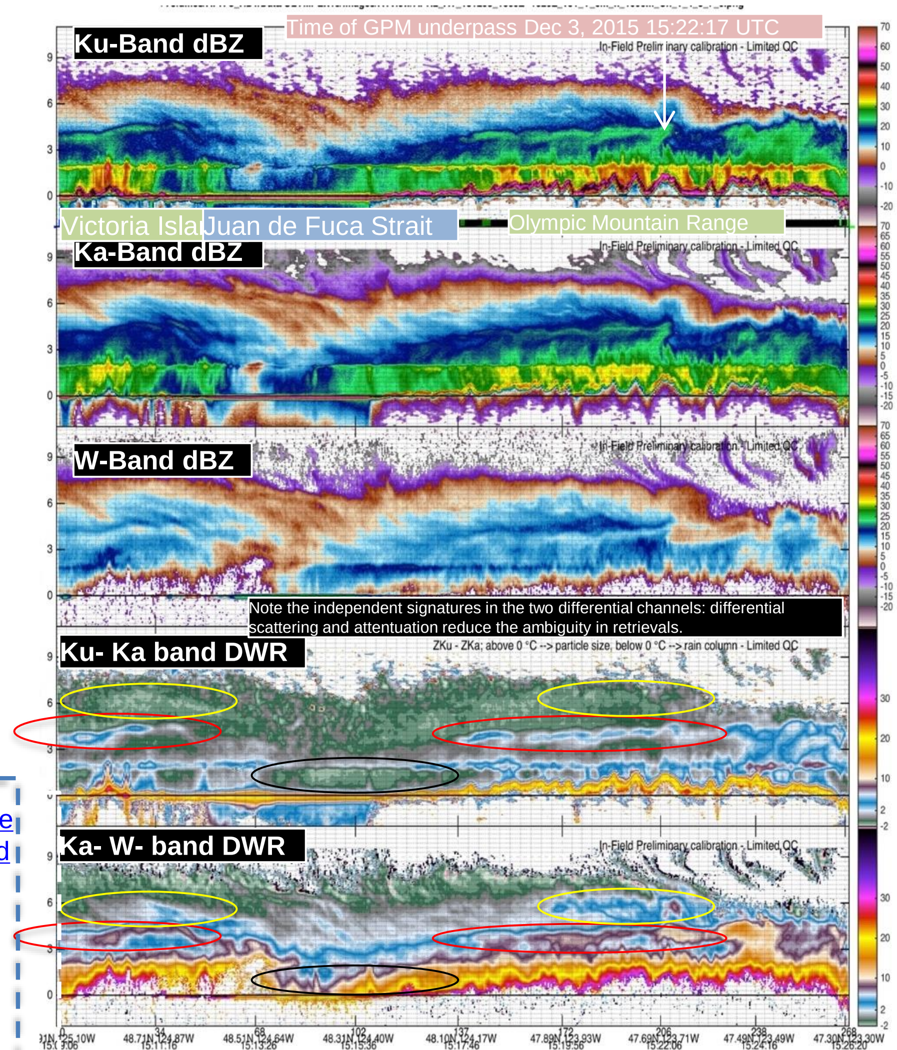
- GPM: multi-freq. radar to better constrain GPM retrievals.
- ACE: refine definition of radar for ACE mission.

- radar measurements from DC-8 & the ER-2
  = proxies to the ACE/CCP radar observables
- Ground-based radar data → complementary view.

CRS and **HIWRAP** in nadir pointing configuration on **ER-2**



APR-3 on DC-8 (ESTO/AITT Program) is the first 3-frequency (Ku, Ka, W), scanning, Doppler, airborne radar.

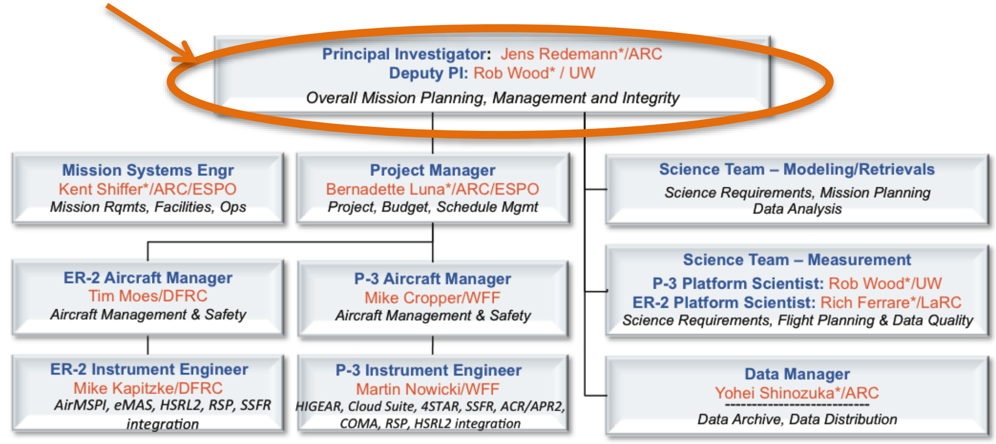


- Heymsfield, A., et al., 2017: Toward Improving Ice Water Content and Snow Rate Retrievals from Radars Part II: Results From Three Wavelength Radar /Collocated In Situ Measurements and CloudSat/GPM/TRMM Radar Data, *J.App.Met.Clim.*
- Chase, R. J., et al., 2018: Evaluation of Triple-Frequency Radar Retrieval of Snowfall Properties using Coincident Airborne In-Situ Observations during OLYMPEX, *Geophys. Res. Lett*
- Leinonen, J., et al., 2018: Retrieval of snowflake microphysical properties from multi-frequency radar observations. *Atmos. Meas. Tech. Discuss.*, (in review)

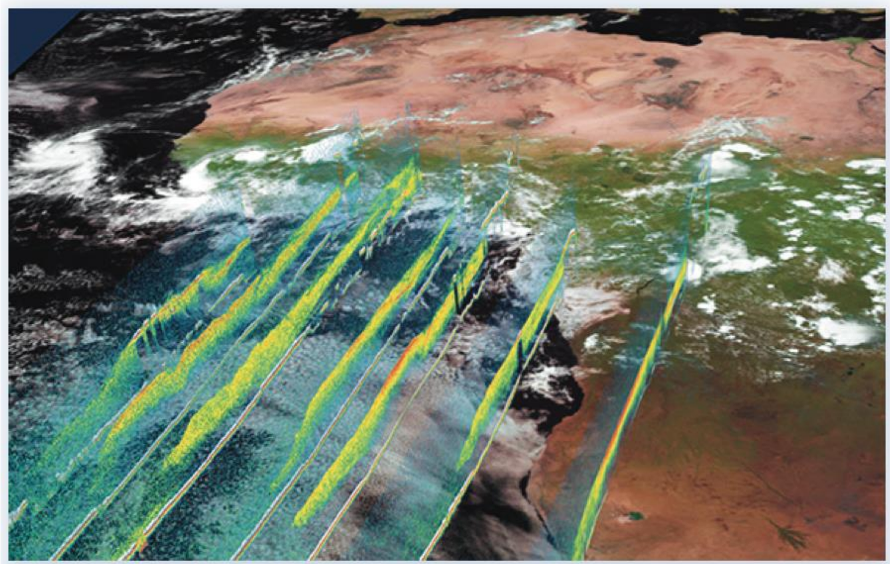
2. ORACLES: selected NASA Earth Venture mission

ORACLES
(ObseRvations of Aerosols above CLouds and their intEractionS)

Principal Investigator: J. Redemann, NASA/ARC



- **climate impacts** of **African Biomass Burning aerosols**.
- **aerosol-cloud interactions in the SE Atlantic**,
  - among largest AOD on the planet.
  - largest inter-model differences in aerosol forcing assessments on the planet.
- multi-year airborne observations



Composite CALIPSO lidar backscatter curtains show pervasive transport of BB aerosol transport during the first week of September 2008 as well as the underlying cloud tops.

COURTESY: J. REDEMANN, ARC

ORACLES instruments and coordinates

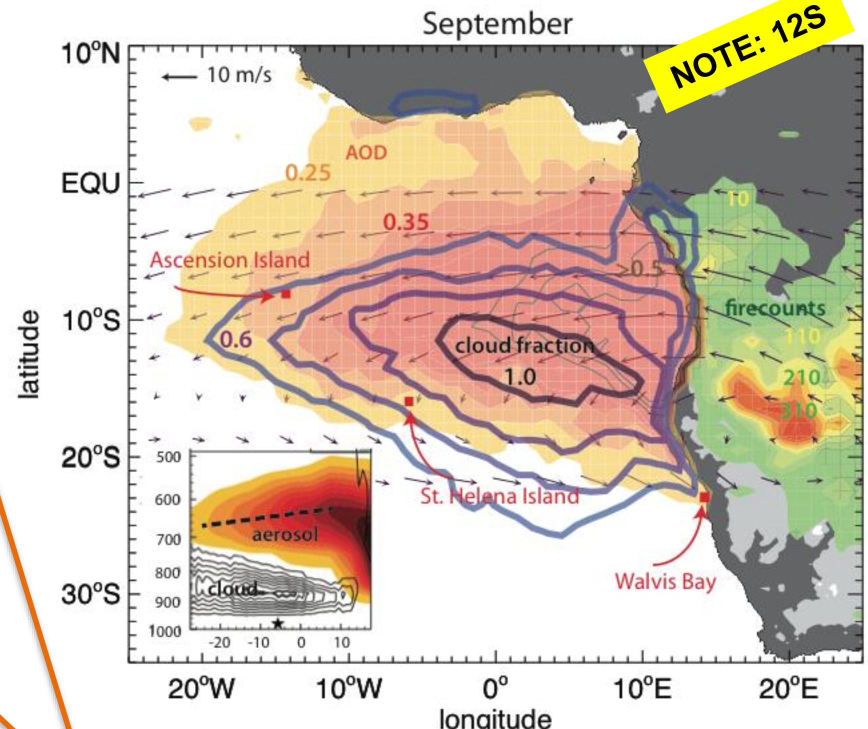
Each IOP is 4 weeks in the **Aug-Sept-Oct** period in 2016, **2017**, and **2018**

Instruments on P-3

Spectrometer for Sky-Scanning, Sun- Tracking Atmospheric Research (4STAR)	Russell (NASA ARC)
Cloud in situ	McFarquhar/Poellot (UI/UND)
Solar Spectral Flux Radiometer (SSFR)	Schmidt/Pilewskie (CU)
CO Measurement Activity (COMA)	Podolske (NASA ARC)
Aerosol & cloud in situ - Hawaii Group for Environmental Aerosol Research (HiGEAR)	Howell/Clarke/Small (UH)
Airborne Cloud/Precipitation Radar (ACR/APR-2)	Tanelli (JPL)
High Spectral Resolution Lidar (HSRL-2)	Hostetler/Ferrare (NASA LaRC)
Research Scanning Polarimeter (RSP)	Cairns (NASA GISS)

Instruments on ER-2

Enhanced MODIS Airborne Simulator (eMAS)	Platnick/Myers (NASA GSFC/ARC
Solar Spectral Flux Radiometer (SSFR)	Schmidt/Pilewskie/Gore (CU/ ARC)
High Spectral Resolution Lidar (HSRL-2)	Hostetler/Ferrare (NASA LaRC)
Research Scanning Polarimeter (RSP)	Cairns (NASA GISS)
Airborne Multiangle SpectroPolarimetric Imager (AirMSPI)	Diner (JPL)



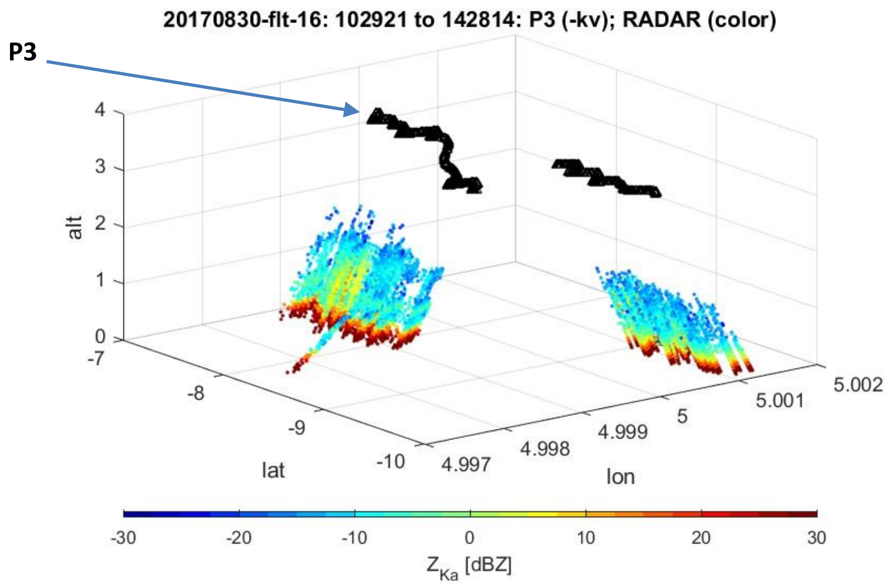
In JAXA EarthCARE GV Science Team

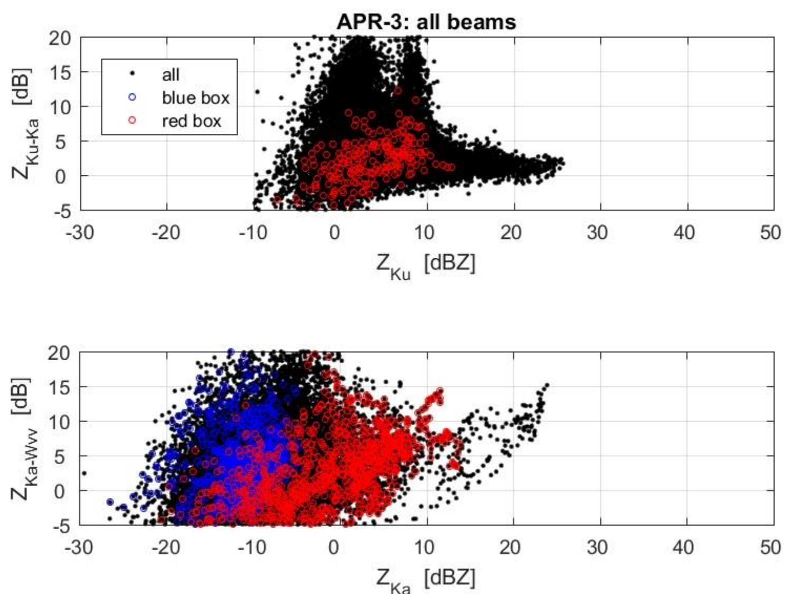
COURTESY: J. REDEMANN, ARC

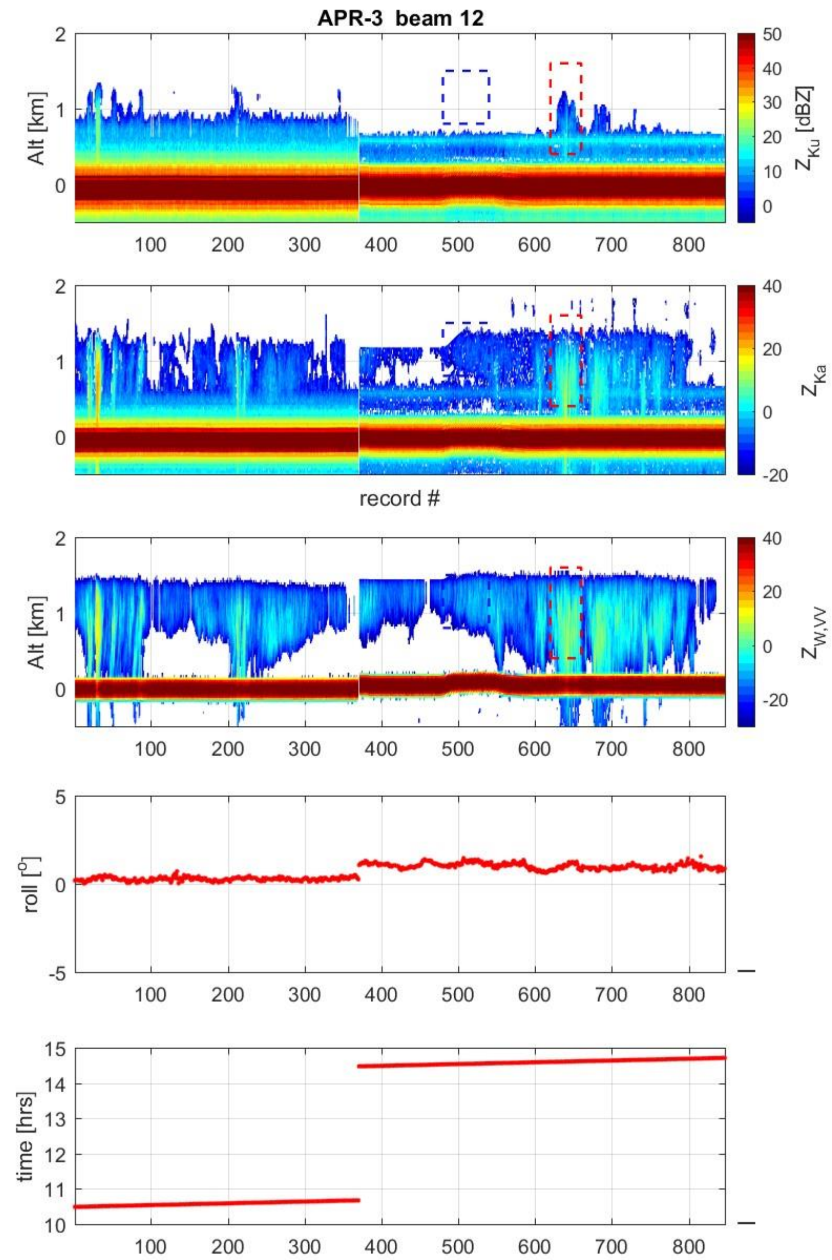
The ORACLES operation

Low-altitude (~60 m) & slow legs
(P3 had in situ probes)

The ORACLES APR-3 data







3. Other existing APR-2 (Ku,Ka) datasets

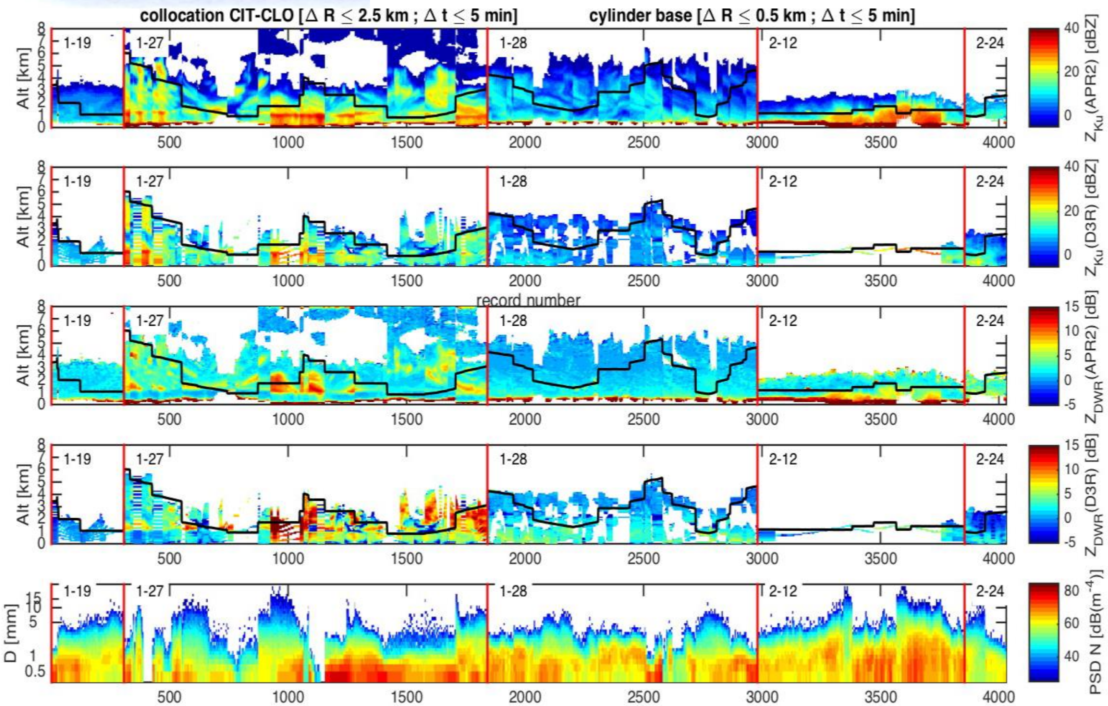
GPM Cold-Season Precipitation Experiment

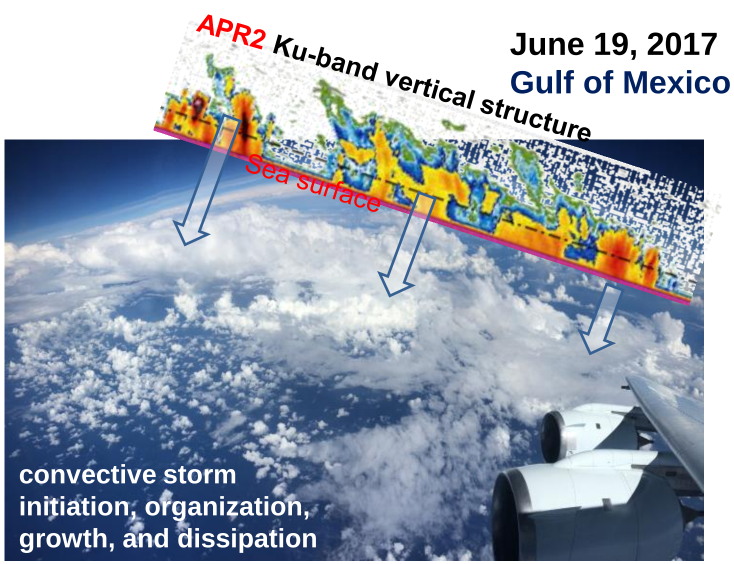
Jan.-Feb. 2012
Toronto, ON

PI: G. Skofronick-Jackson (NASA/GSFC)

2017

PI R. Kakar





With in situ (UND Citation)

Triple co-location (APR2, UNDC, D3R)
Sy et al. 2018 (revision)

3. Other existing APR-2 (Ku,Ka) datasets

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Jan.-Feb. 2012
Toronto, ON

PI: G. Skofronick-Jackson (NASA/GSFC)

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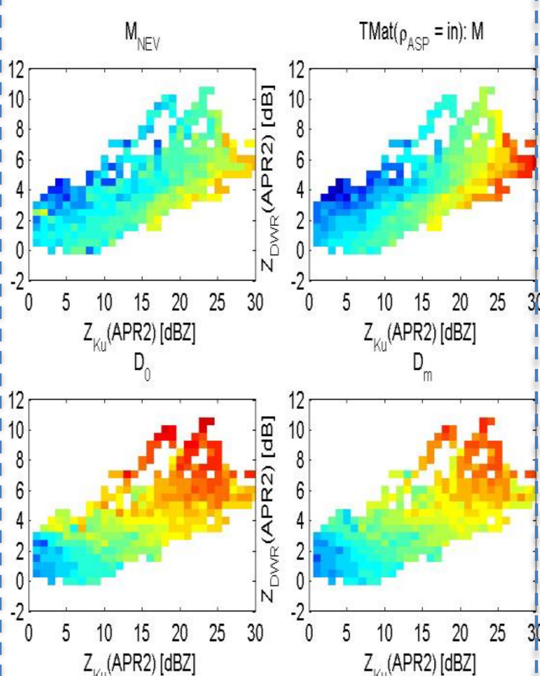
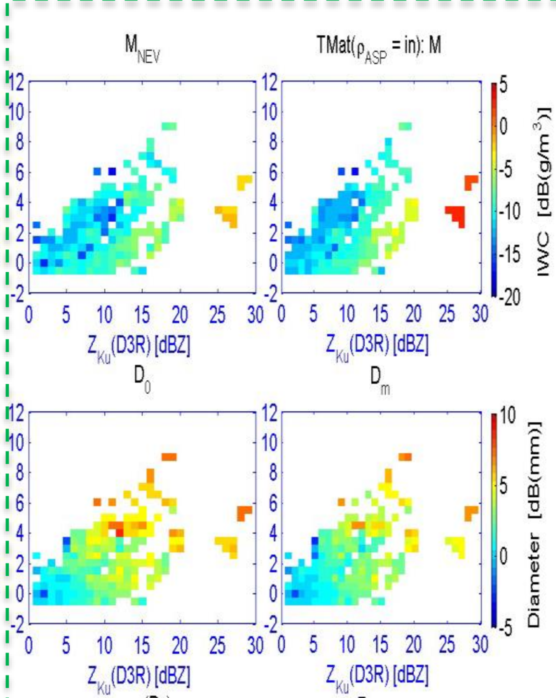
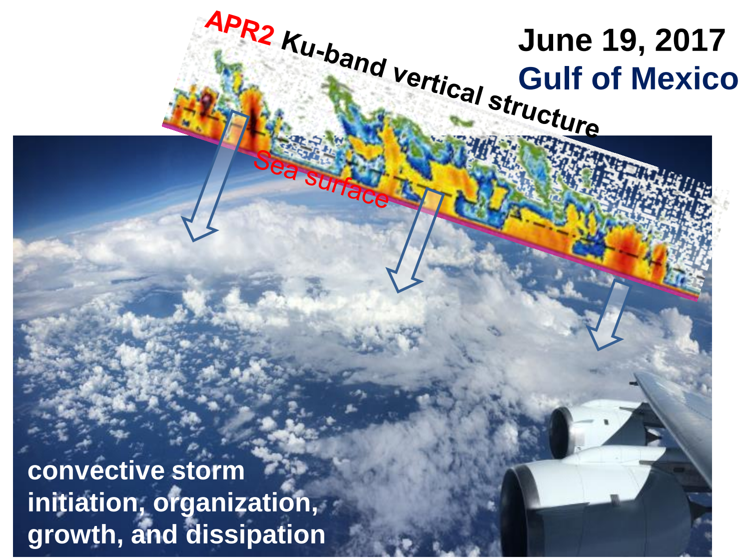


In situ vs *APR2 retriev.*



In situ vs *D3R retriev.*



Sy et al. 2018 (revision)

4: Future APR3 campaigns

- **ORACLES 2018 (Sept-Oct 2018)**

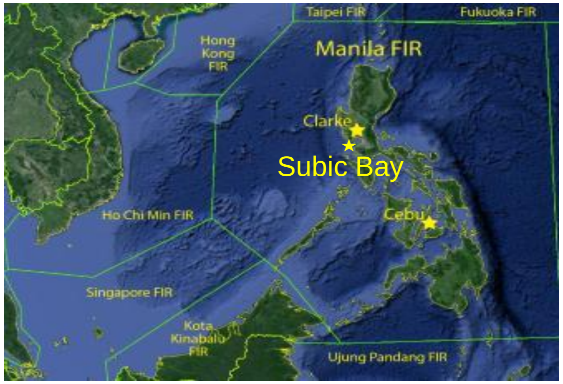
- **CAMP^{2}Ex: Cloud & Aerosol Monsoonal Processes: Philippines Experiment** (Aug-Oct 2019)
  PI J. Reid

Science Questions:

- To what extent are **aerosol** particles responsible for modulating warm and mixed phase **precipitation in tropical environments**?
- To what extent do aerosol induced changes in **clouds and precipitation feedback into aerosol lifecycle**?
- How does the **aerosol and cloud influence on radiation** co-vary and interact?
- How does **land use change affect cloud and precipitation** change?

Priority Measurements:

- Aerosol in-situ microphysics
- Cloud in-situ microphysics
- Cloud/precip remote sensing
- Trace Gases
- Aerosol and wind profiles (lidar)
- Radiation: Solar and IR
- State variables (P,T,U)



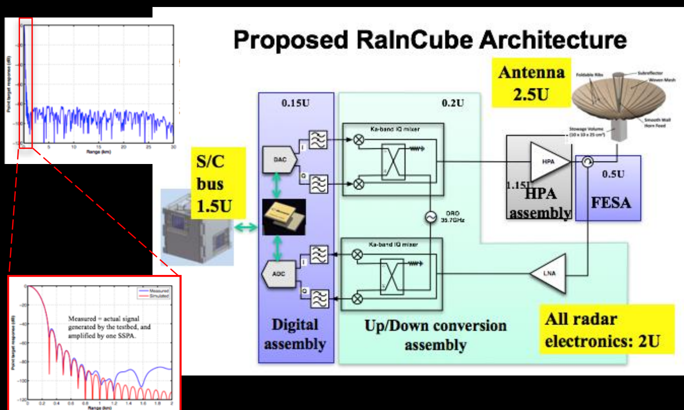
Courtesy F. Seidel (NASA)

NASA P-3B

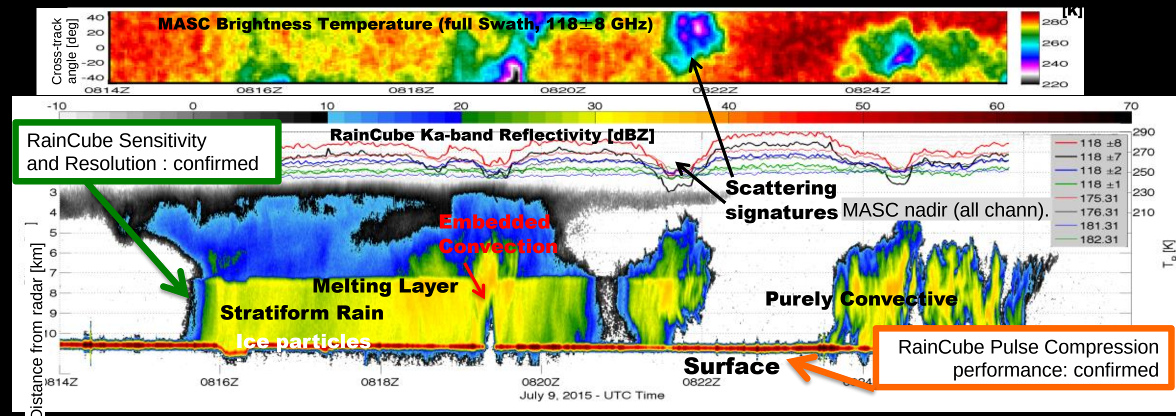
SPEC
Lear 35

B. RainCube (PI Eva Peral)

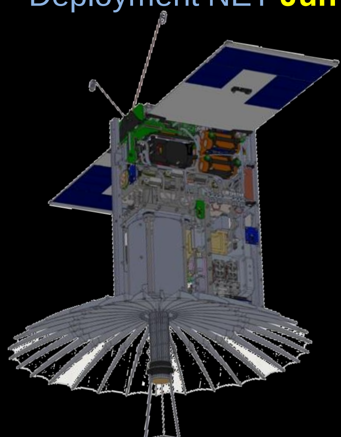
2013
6U Concept
miniKaAR + KaRPDA 0.5 m

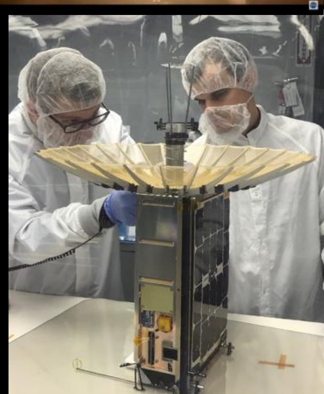


2015
PECAN
Airborne Demo of miniKaAR

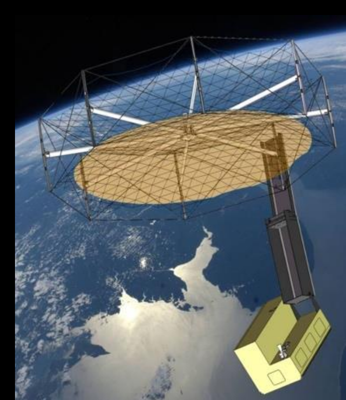


2016-2018
RainCube 6U
Launched to ISS May'18
Deployment NET **Jun'18**





2016-2018
1 m Ka (*)
offset reflector

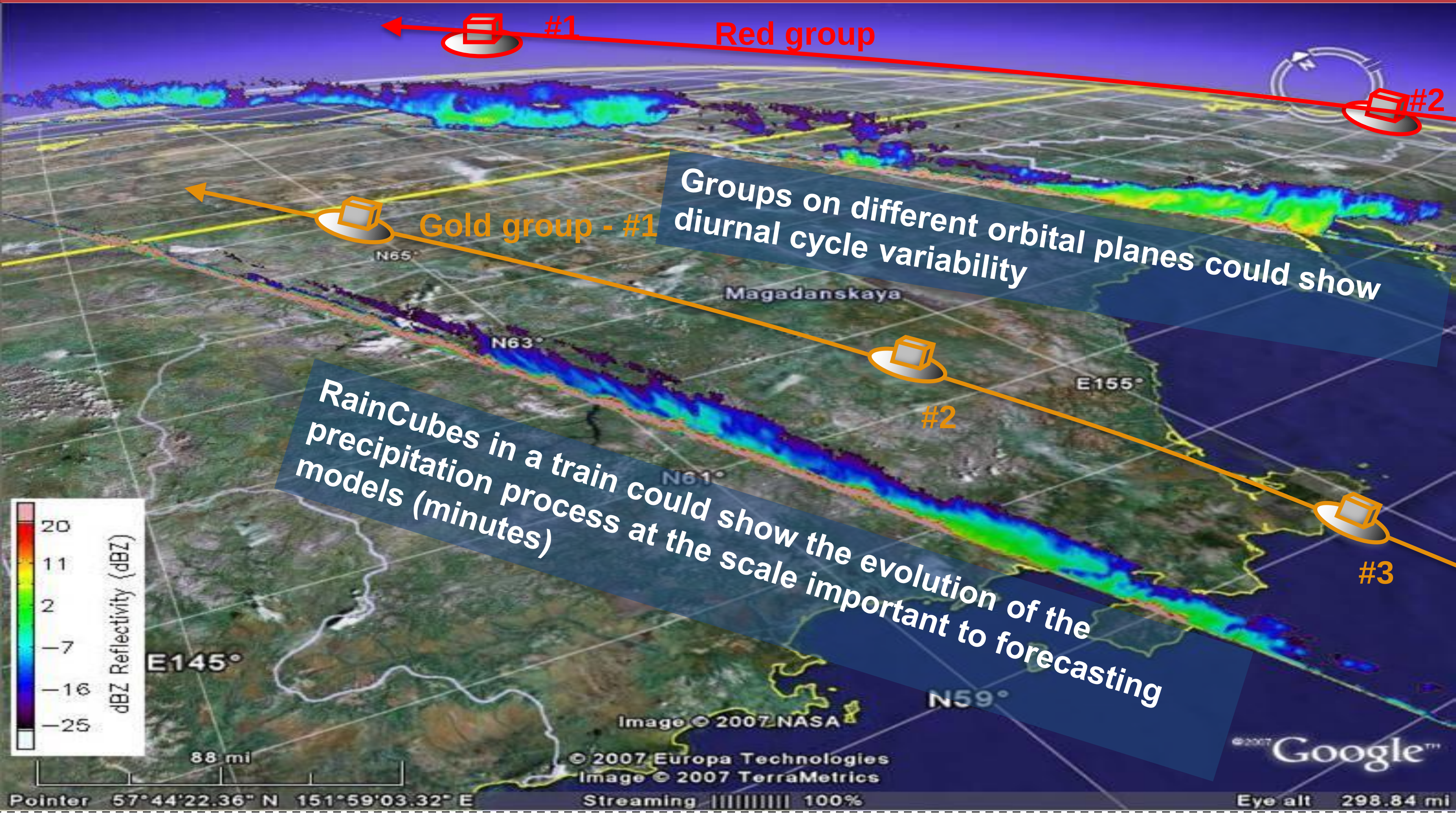


Summary Table
Ka-band
ESTO InVEST and ACT programs

	6U	12 U	50 kg
Antenna size [m]	0.5	1.0	2.0
Sensitivity [dBZ]	15	5-10	0-5
Hor Resolution [km]	8	4	2
Range Res [m]		250	
Beams	1	1-3	1-5
RF Power [W]	10	10-20	10-40

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

RainCube: Science motivation



Z.S. Haddad, O.O. Sy, S. Hristova-Veleva, G.L. Stephens, "Derived Observations From Frequently Sampled Microwave Measurements of Precipitation- Part I: Relations to Atmospheric Thermodynamics", *IEEE TGRS*, vol. 55 (6), 2017

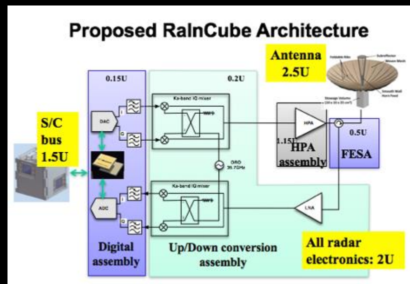
Sy, O.O., Z.S. Haddad, G.L. Stephens, S. Hristova-Veleva, "Derived Observations From Frequently Sampled Microwave Measurements of Precipitation. Part II: Sensitivity to Atmospheric Variables and Instrument Parameters", *IEEE TGRS*, vol. 55 (5), 2017

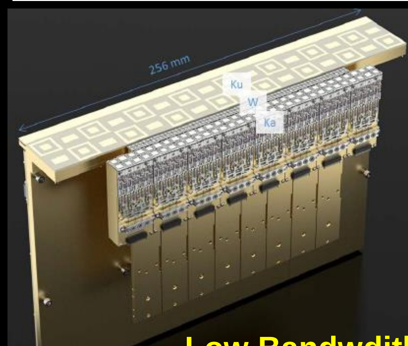
C. Multi-Application SmallSat Tri-band Radar (MASTR)

miniKaAR
back end
reduce # of parts
Simple

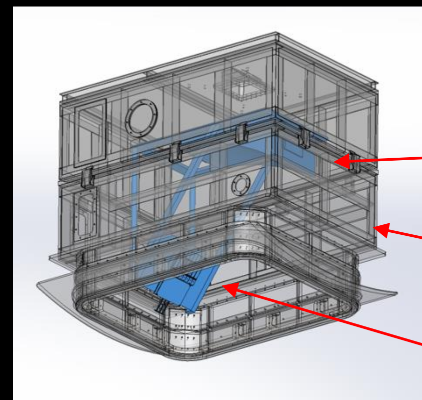
+

3CPR
antenna scheme
scanning
Agile





Airborne Prototype
airMASTR
ESTO IIP – 2017/19 – PI: M. Sanchez-Barbetty



Planned first flight :
Nov 2019

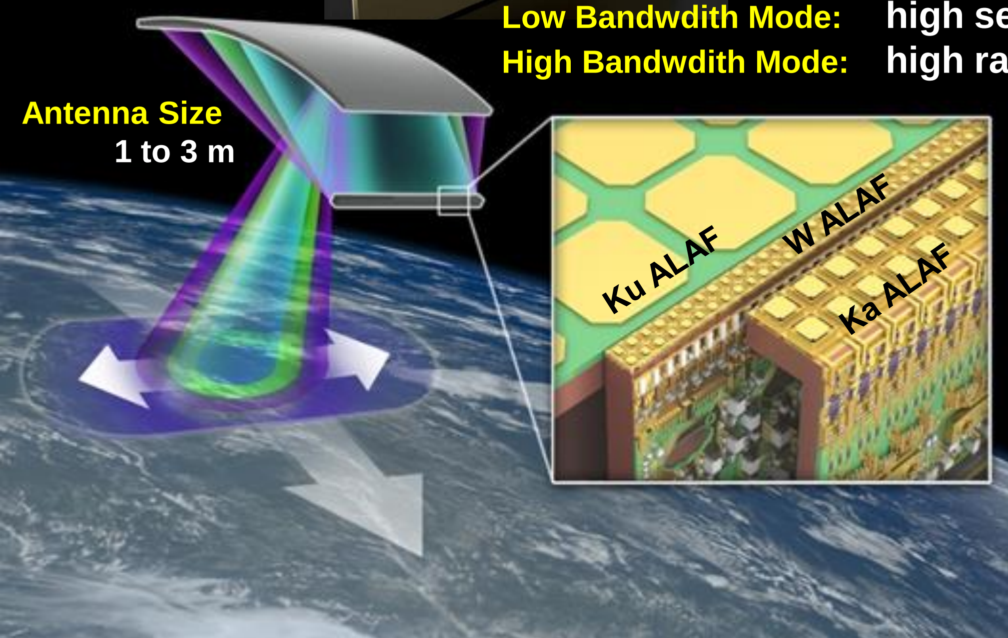
Reflector
(3CPR EM)

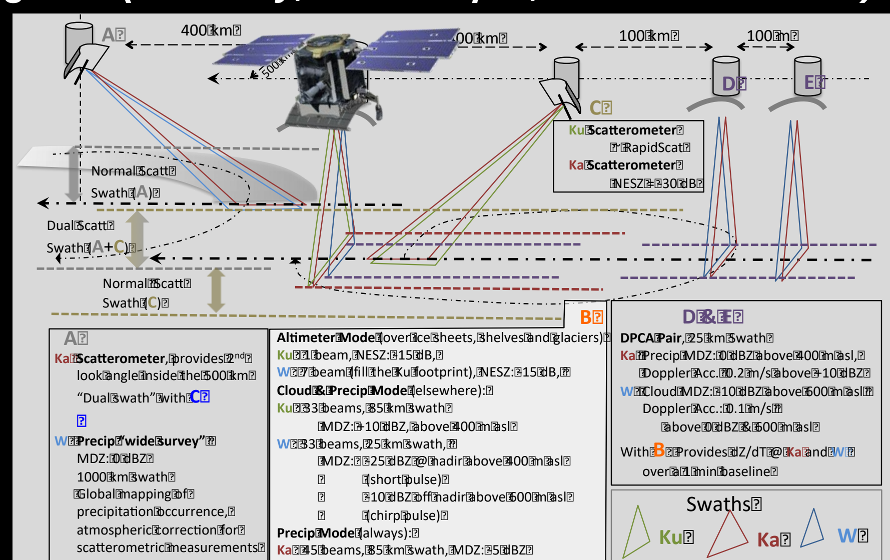
NASA DC-8 Pressure box
(same position as APR-3)

Phased Array Feed
(30 x 4 x 20 cm)

Low Bandwdith Mode: **high sensitivity *(Clouds and Precipitation, Scatterometry)***
High Bandwdith Mode: **high range res *(Altimetry, Snow Depth, Sea Ice freeboard)***

Antenna Size
1 to 3 m





GV activities in synergy with CloudSat, GPM and ACE

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<u>NASA airborne campaigns:</u>

Synergies and opportunities

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<u>comparisons vs CloudSat:</u>

Direct comparisons,

Possible applications

Part 3

<u>Forward modeling for algorithm development and validation:</u>

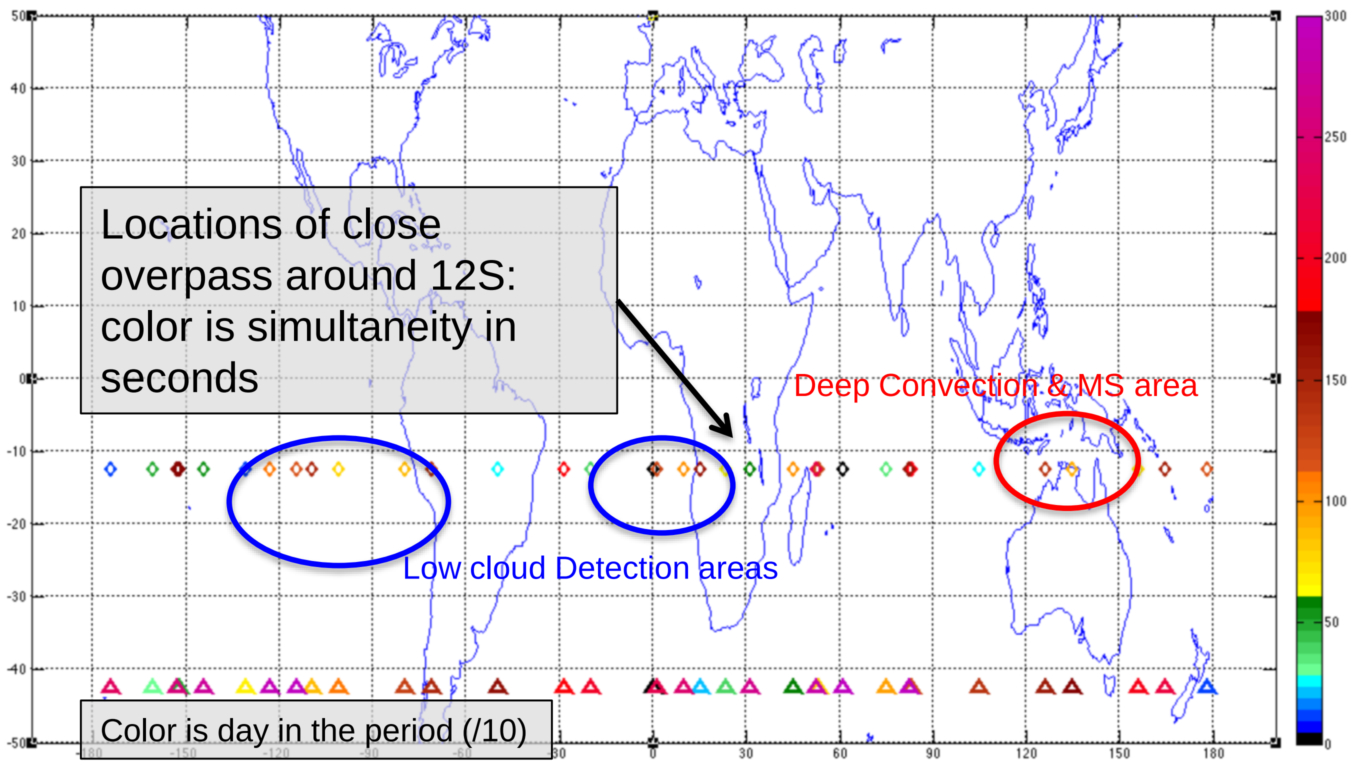
High-Resolution Radar based, or Model Based

Q2: how often will they approach the intersect point within minutes?
Q3: how will the longitude change?

n - SPs	Δθ	AT	XT	Simult	DAYS	LON
	DEG	KM	KM	sec		
0	0.0	0.0	0.0	0.0	0.0	0.0
29	-3.5	-393.6	107.8	112.7	1.0	177.9
60	5.1	567.5	155.3	162.5	2.0	14.9
89	1.6	173.9	47.6	49.8	3.0	199.2
118	-2.0	-219.8	60.2	62.9	3.9	23.5
147	-5.5	-613.4	167.8	175.7	4.9	207.8
178	3.1	347.7	95.2	99.6	5.9	44.8
207	-0.4	-45.9	12.6	13.1	6.9	229.1
236	-3.9	-439.5	120.3	125.9	7.8	53.4
267	4.7	521.6	142.8	149.4	8.9	250.4
296	1.1	128.0	35.1	36.7	9.8	74.7
325	-2.4	-265.7	72.8	76.1	10.8	259.0
354	-5.9	-659.3	180.3	188.8	11.7	83.3
385	2.7	301.8	82.7	86.5	12.8	280.3
414	-0.8	-91.8	25.2	26.3	13.7	104.6
443	-4.4	-485.4	132.9	139.0	14.7	288.9
474	4.3	475.7	130.2	136.3	15.7	125.9
503	0.7	82.1	22.5	23.5	16.7	310.2
532	-2.8	-311.5	85.3	89.2	17.6	134.5
563	5.8	649.6	177.7	186.1	18.7	331.5
592	2.3	256.0	70.1	73.3	19.6	155.8
621	-1.2	-137.7	37.7	39.4	20.6	340.1
650	-4.8	-531.3	145.4	152.2	21.6	164.4
681	3.9	429.8	117.7	123.1	22.6	1.4
710	0.3	36.2	9.9	10.4	23.6	185.7
739	-3.2	-357.4	97.9	102.4	24.5	10.0
770	-5.4	-603.7	165.2	172.9	25.5	207.0
799	-1.9	-210.1	57.6	60.2	26.5	31.3
828	1.6	183.6	50.3	52.6	27.5	215.6
859	-7.0	-777.6	212.6	222.7	28.5	52.6
888	-3.4	-383.9	105.1	110.0	29.5	236.9
917	0.1	9.7	2.7	2.8	30.4	61.2
946	3.6	403.3	110.4	115.5	31.4	245.5
977	-5.0	-557.8	152.7	159.8	32.4	82.5

*Orbit simulation by **R.J. Boain (JPL)***

- ~ **once per day** EC & CS tracks intersect **within 4 minutes of each other**
- intersection point will jump ~ 180˚ (±15˚) in longitude from day to day.
- In approximately 1 month the opportunities will be spread **more or less uniformly across longitudes**.
- For each opportunity, a **stretch of about 15 km will be within 2 km of each other ground tracks**.
- In this example period of 32 days there will be 4 opportunities within 15 seconds, 6 between 15 and 60 seconds, and the rest more than 60 seconds.



Q4: What direct comparisons are possible?

- **Clear air surface return**: data calibration, gas attenuation correction
- **Marine SCu and shallow cloud detection**: EC is expected to improve wrt CS, widespread regions of frequent occurrence lay along the 12-13S latitude.
- **Deep convection**, **impact of Multiple-Scattering and depth of valid Doppler measurements**: the best area is in the warm pool just north of Darwin
- **Cirrus detection and profiling**: almost ubiquitous.
- Almost **everything else** (small isolated convection) should probably not be targeted for direct comparisons due to **low probability** of **co-location (time & space**)
- **Brightness Temperature product**: CloudSat's Tb derived from *noise floor*, calibration vs AMSR-E (accuracy ~2 K, precision ~ 0.5 to 8 K depending on scene). collocated Tb reduces ambiguities of radar-only retrievals.
    - Similar product expected for EC CPR with calibration on CloudSat or GCOM-W

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Synergies and opportunities

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comparisons vs CloudSat:

Direct comparisons,

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Forward modeling:

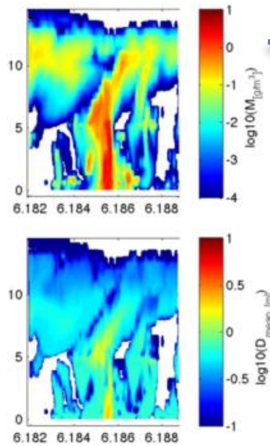
- **High-resolution radar based**
- **Model based**

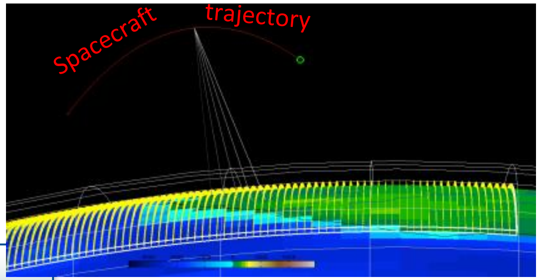
A. NEOS³: NASA Earth Observing Systems Simulator Suite

Now available online to US investigators: https://neos3.jpl.nasa.gov

Account requests: simone.tanelli@jpl.nasa.gov

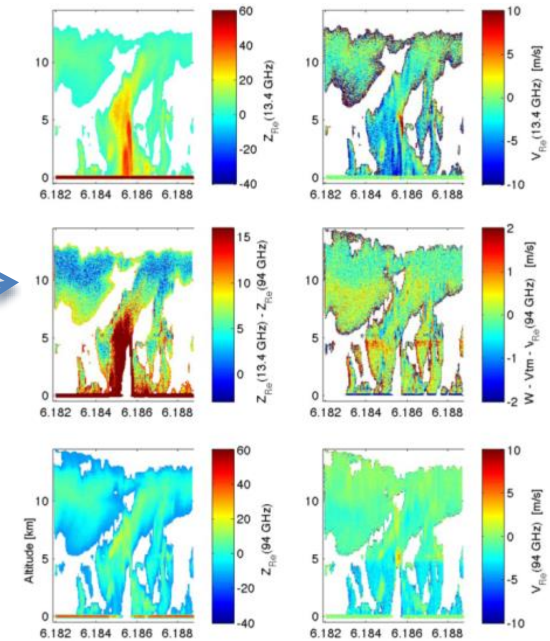
Beta testing phase





IRM Geophysics → SEAM Electromagnetic signatures → ISM Propagation & Instrument/platform specs

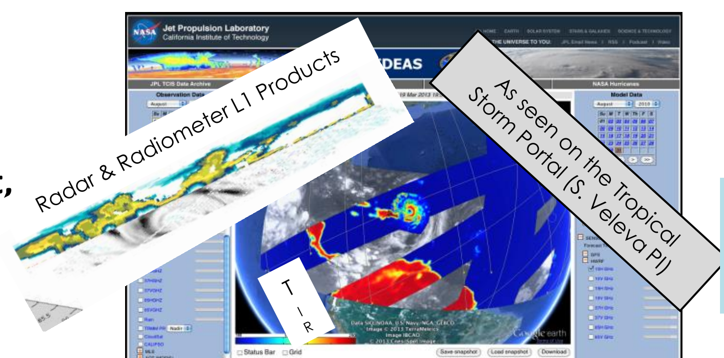
Geophysics (IRM)	Electromagnetic signatures (SEAM)	Propagation & Instrument/platform specs (ISM)
Mass Size Shape	Refractive index	Instrument type
Orientation	Extinction	Antenna pattern
Composition	Absorption	Scanning Orbit
Temperature	Polarization	Pulse integration
Pressure	Scattering Phase	Conical Cross-track
Wind speed	function Albedo	Inclination Angle
Surface roughness	DDSCAT Rayleigh	Elevation angle
Sand fraction	SNOWFAKE T-Matrix	Filters DOMUS
Grain size Density	Geometric Optics	SHDOM Radiative
Soil moisture	HITRAN FASTEM	Transfer Model
Salinity SWE WRF	Emissivity NRCS	Monte-Carlo RTM
LIS DHARMA SAM		SOI



a service-based tool suite providing simulated measurements for a wide range of instruments aimed at remote sensing of the atmosphere, on missions such as EarthCARE, ACE, GPM, A-Train, Nexrad in Space, and others, based on input from atmospheric models.

Allows user to

- **select simulated storm,**
- **specify instrument(s) and orbit,**
- **specify calculation modules and produces expected measurements**

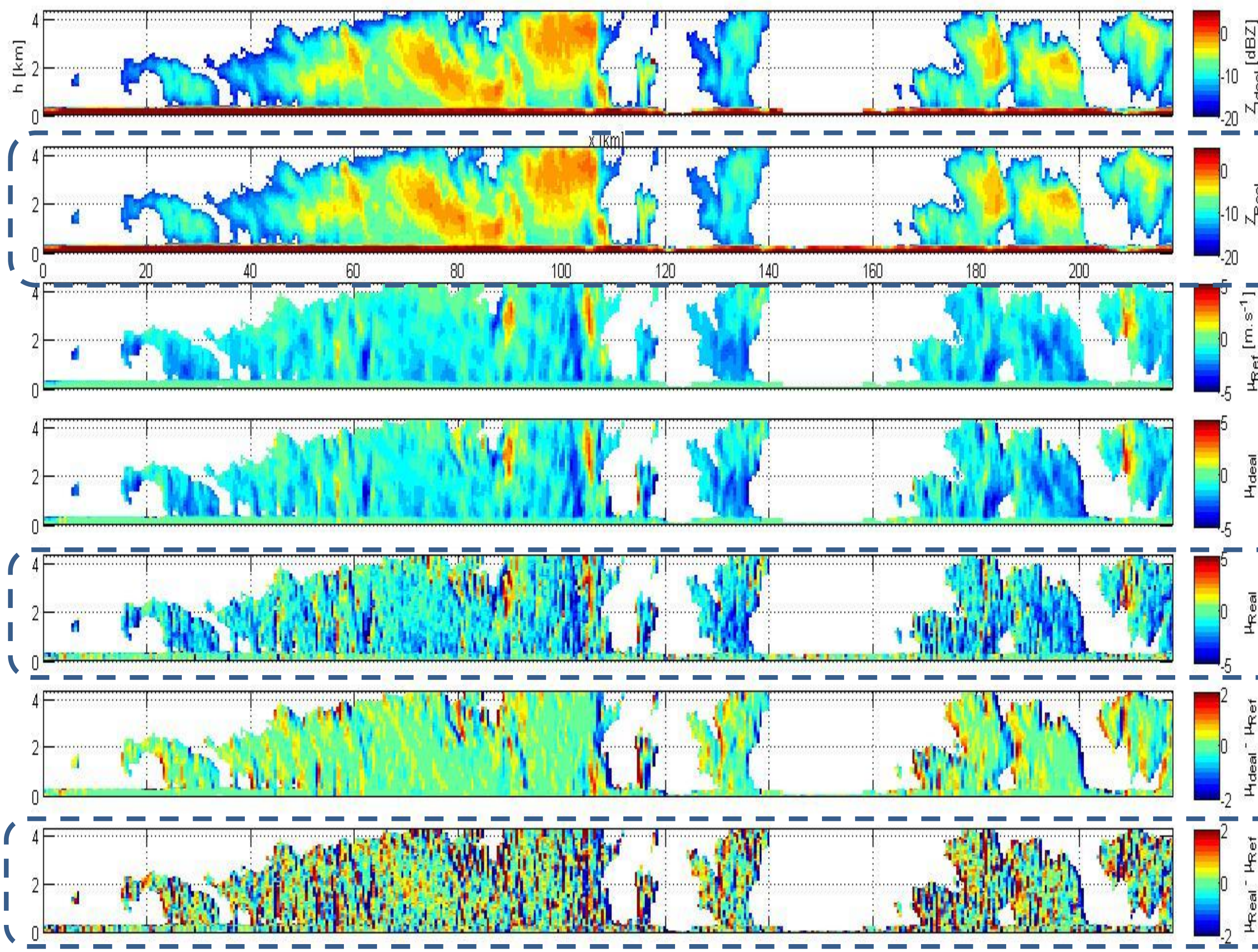


This tool is developed and available. It needs a user base for beta testing, customization, and improvements.

B. Airborne/Ground Doppler Radar data as source generate EC-CPR

- Algorithm: ➢ Input: *Airborne measurement from **NICT** SPIDER radar (W-Band)*
  ➢ *Output: Simulated EarthCARE Doppler products (Z,V)*

Wakasa Bay, Japan, 29 Jan 2003



Reference reflectivity Z_{REF}

EC-CPR reflectivity Z_{EC}

Reference velocity V_{REF}

EC-CPR velocity (idealized) V_{IDEAL}

EC-CPR velocity V_{EC}

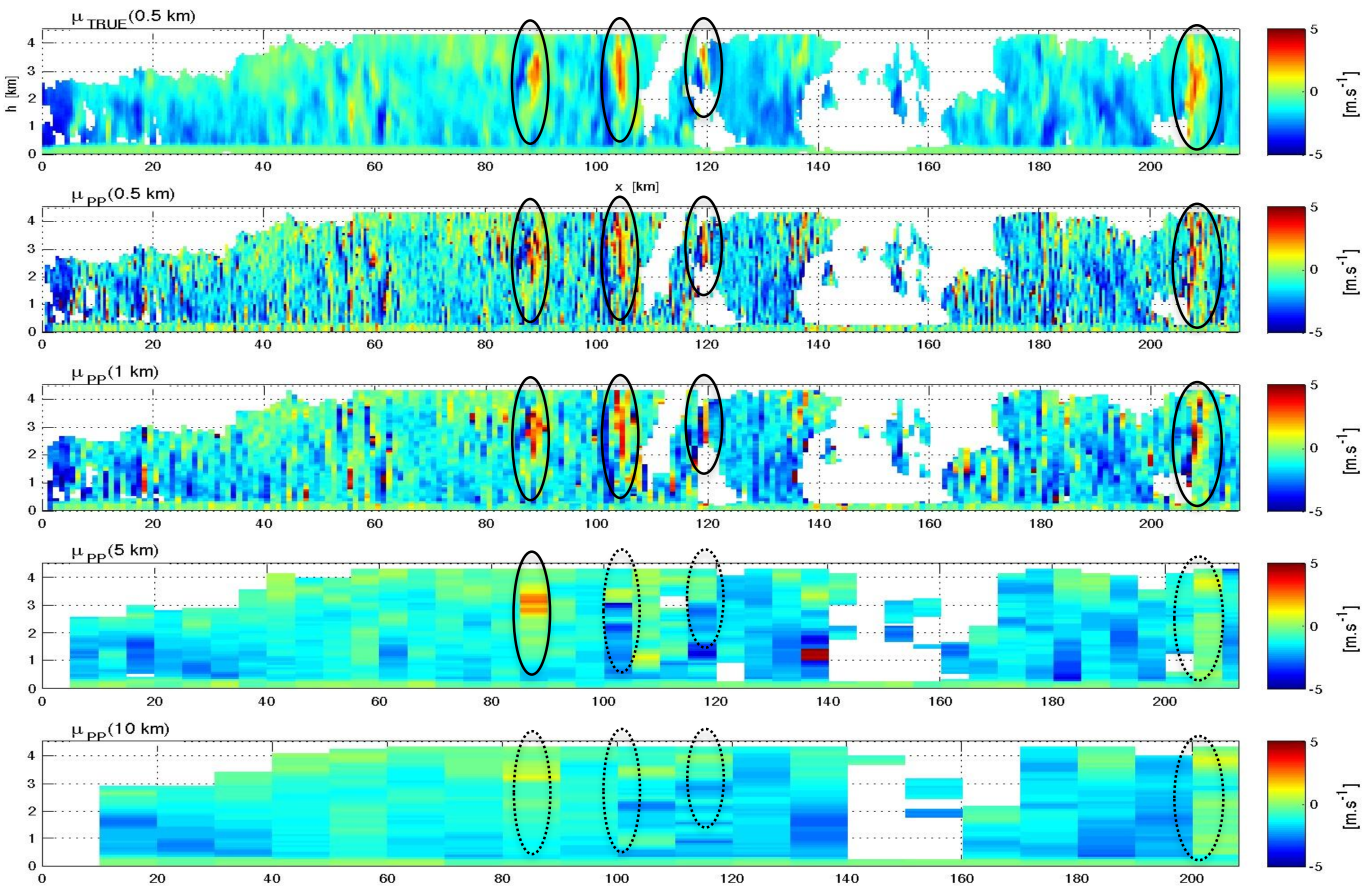
V_{IDEAL} - V_{REF} (NUBF errors)

V_{EC} - V_{REF} (NUBF & decorrel.)

Sy, O.O.; Tanelli, S.; Takahashi, N.; Ohno, Y.; Horie, H.; Kollias, “Simulation of EarthCARE Spaceborne Doppler Radar Products using Ground-Based and Airborne Data: Effects of Aliasing and Non-uniform Beam-Filling”, IEEE TGRS, vol.52, no.2, 2014

EarthCARE Doppler velocity: temporal decorrelation

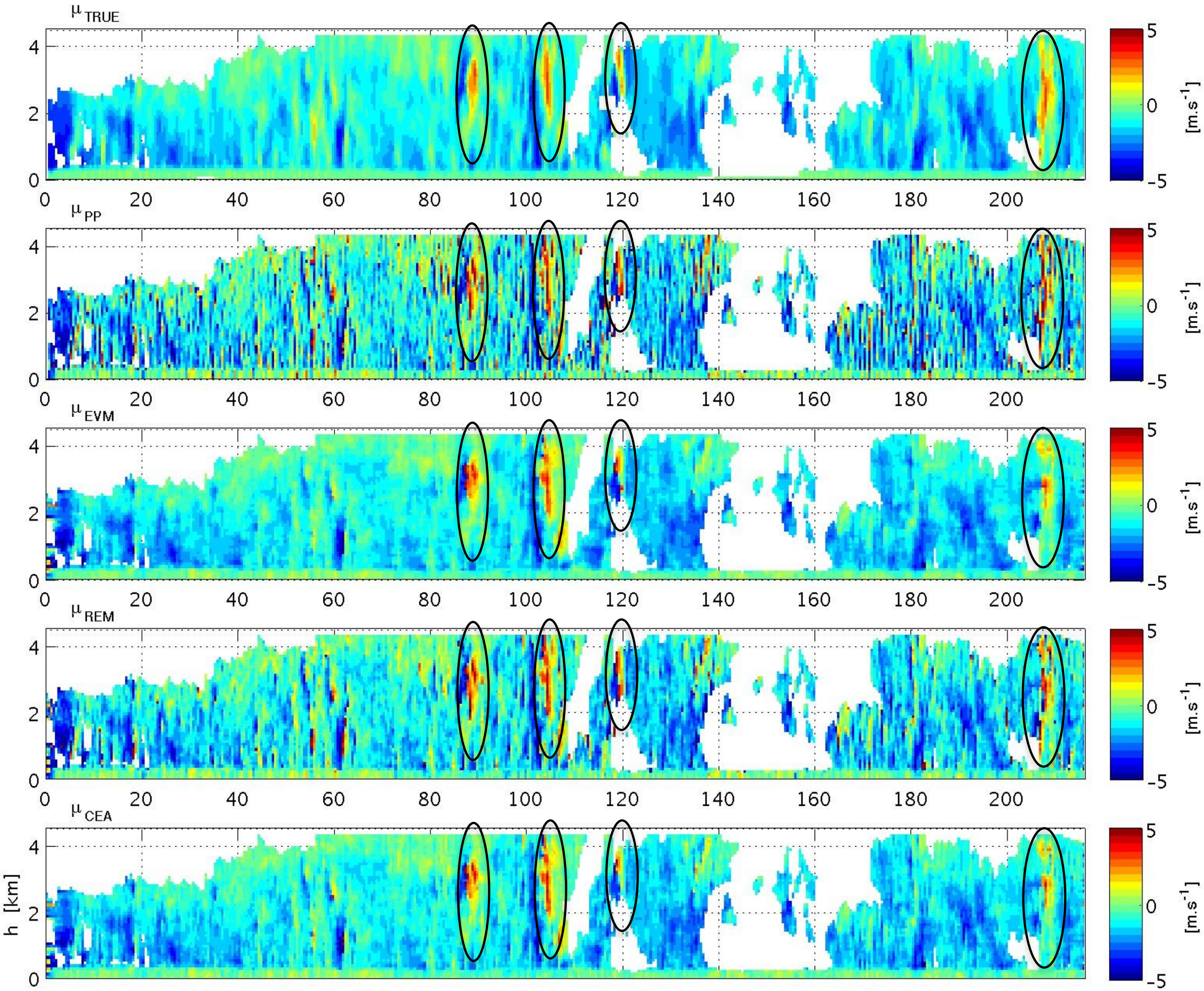
- Standard approach: increase along-track integration length
  from 500 m (level 1B) to N_{INT} * 500 m along-track sampling
  - ✓ $V_{EC}(N_{INT}\ 0.5\ km)$ - $V_{TRUE}(N_{INT} 0.5\ km)$ variance / N_{INT} (noisiness)
    if N_{INT} (I,Q) bursts are independent (theoretical performance)
  - ○ $V_{EC}(N_{INT} * 0.5\ km)$ – $V_{TRUE}(0.5\ km)$ **not always error variance reduction** (when N_{INT} too large)
  - ○ **Coarser sampling** → Problem for retrieval of fine-scale features



$V_{TRUE}(0.5\ km)$	RMSE vs $V_{TRUE}(N_{INT}\ 0.5km)$ actual (theoretical)
$V_{EC}(0.5\ km)$ *Level 1B*	RMSE = 1.27 (1.27) m/s
$V_{EC}(1\ km)$	RMSE = 0.97 (0.90) m/s *smaller noisiness* *features visible*
$V_{EC}(5\ km)$	RMSE = 0.51 (0.40) m/s *3 cells averaged out* *Still aliasing*
$V_{EC}(10\ km)$	RMSE = 0.30 (0.28) m/s *Convective cells* *averaged out*

Matched statistical filter for EarthCARE Doppler velocity

- <u>Matched-filter approach</u>



V_{TRUE}(0.5 km)

RMSE vs V_{TRUE}(0.5km)

V_{EC}(0.5 km)
Level 1B
unfiltered

<u>RMSE = 1.27 m/s</u>

<u>EVM filtered</u>
(min Error variance)
best in rms sense
but not practical

<u>RMSE = 0.53 m/s</u>
Very low noisiness
Minimal aliasing
Most features visible
= best performance achievable by filtering

<u>REM filtered</u>
(max residue entropy)
best in feature Preservation

<u>RMSE = 0.87 m/s</u>
Reduction of noisiness
More conservative than EVM filter
Still some aliasing
Most features visible

<u>RVA filtered</u>
(min residue variance)
As good as EVM (optimal)

<u>RMSE = 0.55 m/s</u>
Performance similar to optimal EVM filter
Still some aliasing
Most features visible

Matched statistical filter for EarthCARE Doppler velocity

- General statistics of EC-CPR simulations

		SPIDER-based			WACR-based		
		PRF = 6.1 kHz	PRF = 7 kHz	PRF = 7.5 kHz	PRF = 6.1 kHz	PRF = 7 kHz	PRF = 7.5 kHz
RMSE [m/s] vs V_{TRUE}(0.5 km) *after integration*	V_{EC}(0.5 km)	1.58	1.18	1.02	1.45	1.04	0.90
	V_{EC}(1 km)	1.07	0.76	0.63	0.99	0.71	0.60
	V_{EC}(5 km)	0.78	0.71	0.70	0.61	0.53	0.52
	V_{EC}(10 km)	0.84	0.82	0.82	0.61	0.56	0.57
RMSE [m/s] vs V_{TRUE}(0.5 km) *after filtering*	EVM filtered	0.53	0.42	0.38	0.35	0.29	0.27
	REM filtered	1.15	0.65	0.53	0.94	0.46	0.36
	RVA filtered	0.59	0.49	0.47	0.39	0.35	0.35

- Conclusions
  - Noisiness of EarthCARE Doppler velocity estimate can be reduced without giving up the along-track sampling of data
  - Proposed matched filters are applicable in practice
  - Bottom-line accuracy could be improved by improving preliminary NUBF corrections (requires finer along-track sampling than 500 m)

Sy, O.O.; Tanelli, S.; Kollias, P.; Ohno, Y., 2014, "Application of Matched Statistical Filters for EarthCARE Cloud Doppler Products", IEEE TGRS, vol.52, no.11, pp.7297,7316, Nov. 2014

Thank you!

For more information:

ousmane.o.sy@jpl.nasa.gov simone.tanelli@jpl.nasa.gov

airMASTR: Mauricio.Sanchez.Barbetty@jpl.nasa.gov
D-Train: zsh@jpl.nasa.gov (Ziad Haddad)
NEOS^3: noppasin.niamsuwan@jpl.nasa.gov

APR3 data sets

- GCPEX: https://ghrc.nsstc.nasa.gov/home/field-campaigns/gcpex
- OLYMPEX: https://ghrc.nsstc.nasa.gov/home/field-campaigns/olympex
- ORACLES: https://espoarchive.nasa.gov/archive/browse/oracles