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Validation of the Vapor In-cloud Profiling Radar (VIPR):
A G-band differential absorption cloud radar for boundary-layer humidity remote sensing

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Scientific motivation

Problem:

- Existing remote sensing platforms have limited ability to retrieve *high-resolution, unbiased* water vapor profiles in the presence of clouds
- Problem recognized by NWP community (WMO, 2018):

  "Critical atmospheric variables that are **not adequately measured** by current or planned systems are temperature and **humidity profiles** of adequate vertical resolution **in cloudy areas**."

Proposed solution:

- Utilize range-resolved radar signal *and* frequency-dependent attenuation on flank of 183 GHz water vapor absorption line, so-called *differential absorption radar* (DAR)
- Microwave analog of differential absorption lidar (DIAL) – but can measure inside clouds and precipitation (complementary observations)

Differential absorption radar (DAR)

DAR principle: Exploit the strong frequency dependence of atmospheric attenuation near H_2O absorption line to derive range-resolved maps of humidity

- Near the 183 GHz line, atmospheric absorption dominated by water vapor:

$$\beta_{\mathrm{atm}}(r, f) = \rho_v(r)\kappa_v(f)$$

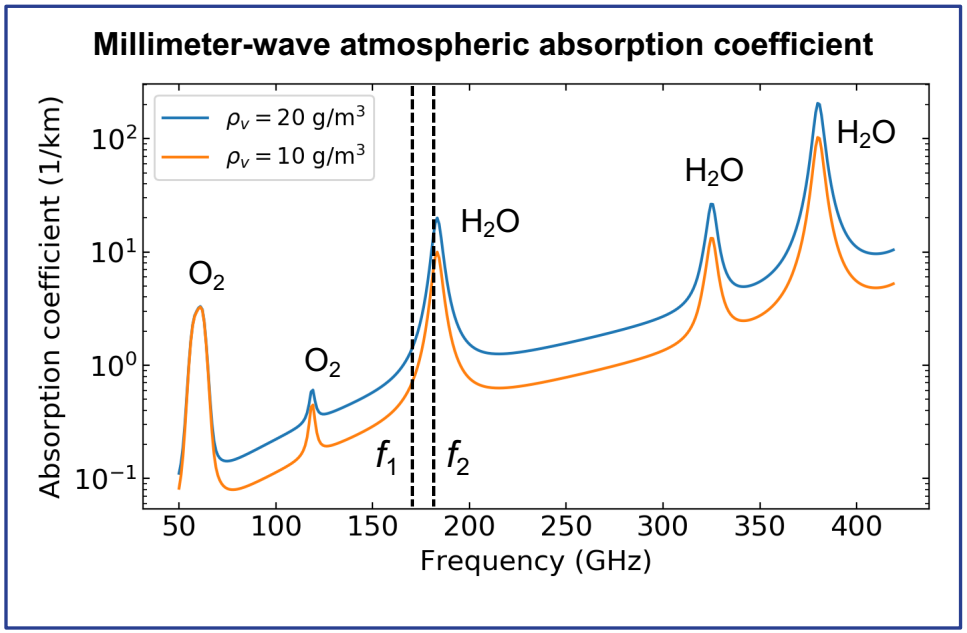
Water vapor density — Absorption cross section

- For small changes in the radar frequency $f_1 \rightarrow f_2 = f_1 + \delta f$, dual-frequency ratio provides *direct measurement of water vapor density*:

$$\mathrm{DFR}(r) = \mathrm{dB}Z(r, f_1) - \mathrm{dB}Z(r, f_2)$$

$$\propto \int_0^r dr' \rho_v(r') \left[\kappa_v(r', f_2) - \kappa_v(r', f_1)\right]$$

$$\Rightarrow \quad \rho_v(r) \propto \frac{1}{\Delta r} \frac{\mathrm{DFR}(r + \Delta r) - \mathrm{DFR}(r)}{\kappa_v(f_2) - \kappa_v(f_1)}$$



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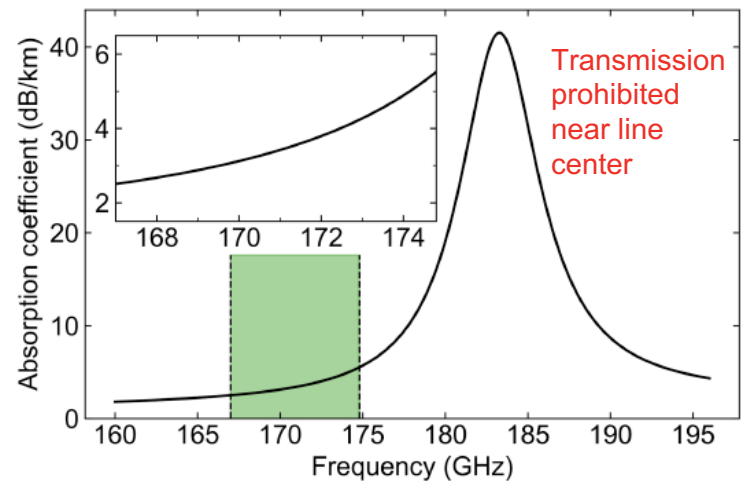
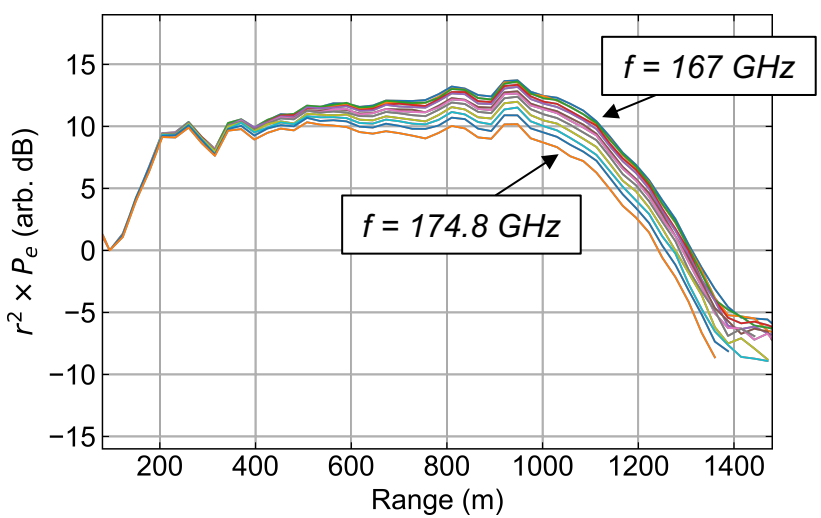
The Vapor In-cloud Profiling Radar (VIPR)

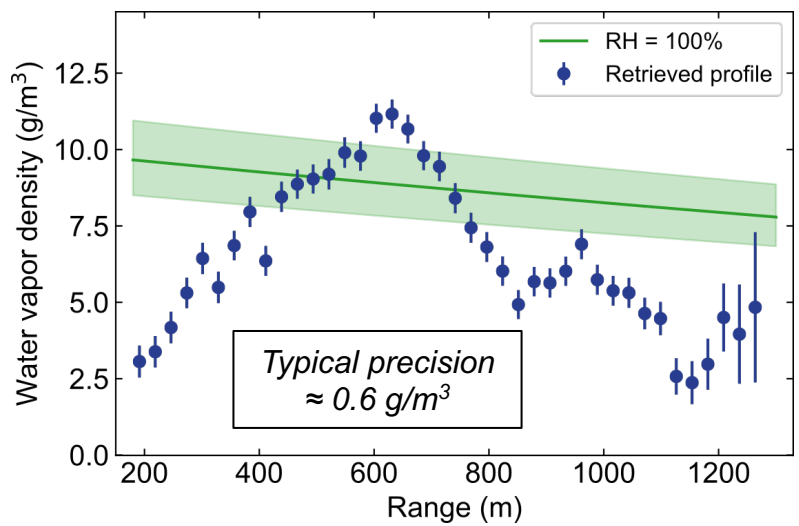
- NASA ESTO-funded instrument incubation project – proof-of-concept for future satellite applications
- First all-solid-state cloud radar above 100 GHz, tunable from 167 to 174.8 GHz
- Targets PBL humidity profiles and column water vapor
- Recent field deployment at ARM SGP site for validation of in-cloud humidity profiles
- Airborne deployment on Twin Otter (ongoing)

VIPR frequency band



Early in-cloud humidity retrievals from ground-based measurements (unvalidated)





R. Roy *et al. Atmos. Meas. Tech.*, 11, 6511-6523 (2018)

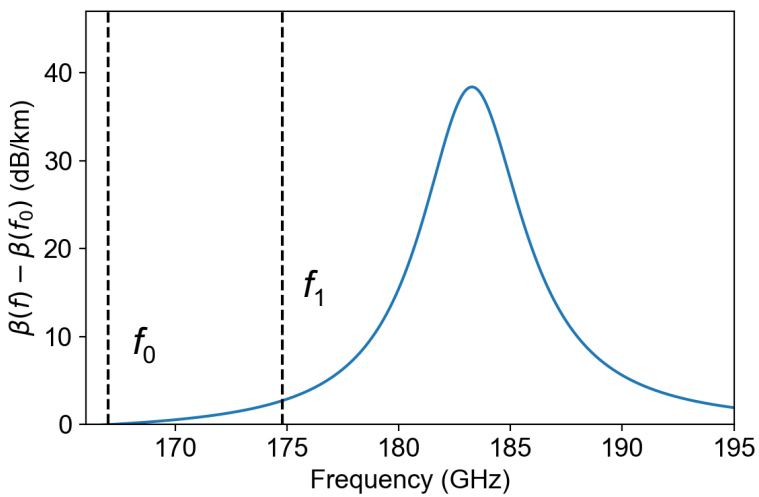
Connection to Decadal Survey

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Clouds, Convection, and Precipitation	**Coupled cloud-precipitation state and dynamics** for monitoring global hydrological cycle and understanding contributing processes including cloud feedback	Radar(s), with multi-frequency passive microwave and sub-mm radiometer	X		
Atmospheric Winds	**3D winds in troposphere/PBL** for transport of pollutants/carbon/aerosol and water vapor, wind energy, cloud dynamics and convection, and large-scale circulation	Active sensing (lidar, radar, scatterometer); or passive imagery or radiometry-based atmos. motion vectors (AMVs) tracking; or lidar**		X	X
Planetary Boundary Layer	**Diurnal 3D PBL thermodynamic properties and 2D PBL structure** to understand the impact of PBL processes on weather and AQ through high vertical and temporal profiling of PBL temperature, moisture and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar; and lidar** for PBL height			X
Surface Topography and Vegetation	**High-resolution global topography** including bare surface land topography ice topography, vegetation structure, and shallow water bathymetry	Radar; or lidar**			X

Systematic error sources

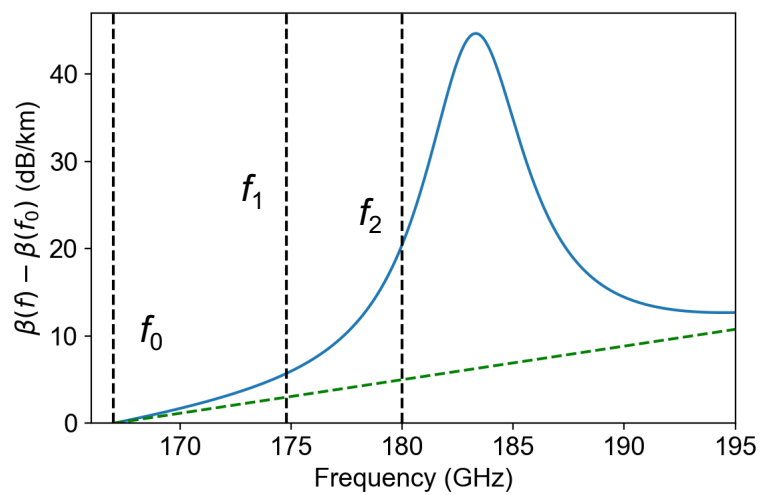
$$\underbrace{\beta(f) - \beta(f_0)}_{\text{Measured differential extinction coefficient}} = \underbrace{\rho(\kappa(f) - \kappa(f_0))}_{\text{Differential absorption from water vapor}} + \underbrace{\frac{f - f_0}{2R}\frac{\partial}{\partial f}\left(\ln\left(\frac{Z_c(r_i, f)}{Z_c(r_j, f)}\right) + 2R\beta_h(f)\right)\Bigg|_{f_0}}_{\text{DAR bias from frequency-dependent hydrometeor backscatter and absorption}}$$

The ideal DAR case



- If cloud particle scattering is independent of frequency, a 2-frequency measurement gives humidity directly

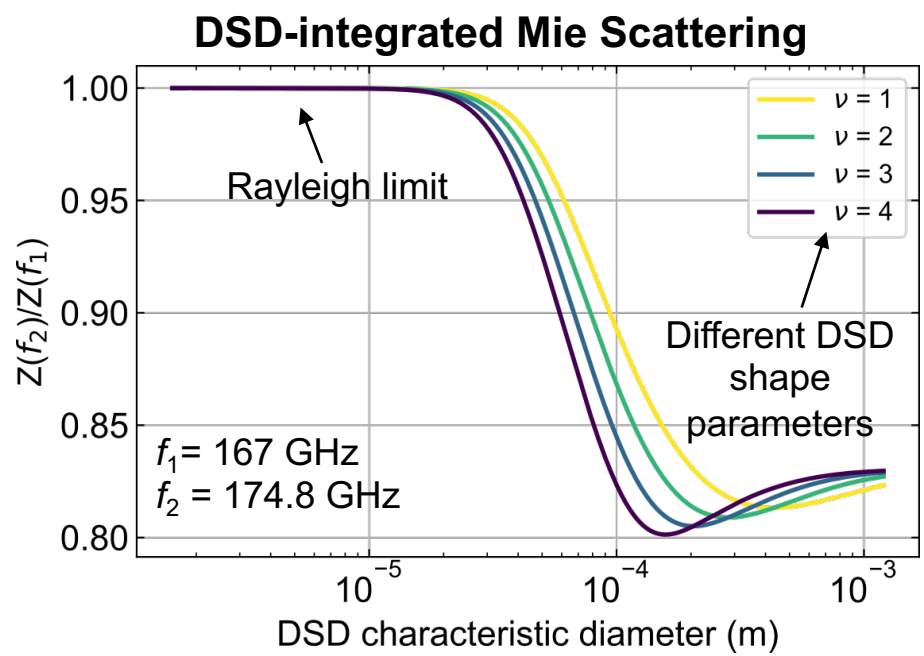
The realistic case



- Observations show that the linear term can be large, and is dominated by the differential backscattering term
- 3-frequency (or more) measurement permits simultaneous determination of linear slope and humidity

Regularized least squares retrieval

- Since VIPR Tx bandwidth is constrained, we limit biases by:
  1. Use new retrieval algorithm to include systematic uncertainty in differential backscatter and penalize unphysical gradients of humidity
  2. Averaging profiles over 10 minutes to smooth out drop size distribution (DSD) heterogeneity
- Note: **No a priori used** – linear system is fully determined



Retrieval methodology

State vector def.

$$\mathbf{x} = [\ln(\mathbf{Z}_r(f_1)), \boldsymbol{\rho}_v]$$

f_1 (log) reflectivity profile

Humidity profile

Forward model

$$[\mathbf{y}(f_i)]_j = \ln(Z_{\text{obs}}(r_j, f_i))$$

$$\mathbf{F}(\mathbf{x}, \mathbf{b}) = \mathbf{K}\mathbf{x} + \mathbf{b}$$

Measurement error

$$\mathcal{C}(\mathbf{x}) = (\mathbf{y} - \mathbf{F}(\mathbf{x}, \mathbf{b}))^T (\mathbf{S}_y + \mathbf{S}_e)^{-1} (\mathbf{y} - \mathbf{F}(\mathbf{x}, \mathbf{b}))$$

$$+\delta^{-2}\mathbf{x}^T\mathbf{A}\mathbf{x}$$

Systematic uncertainty

Humidity gradient penalty term

Regularized least squares retrieval

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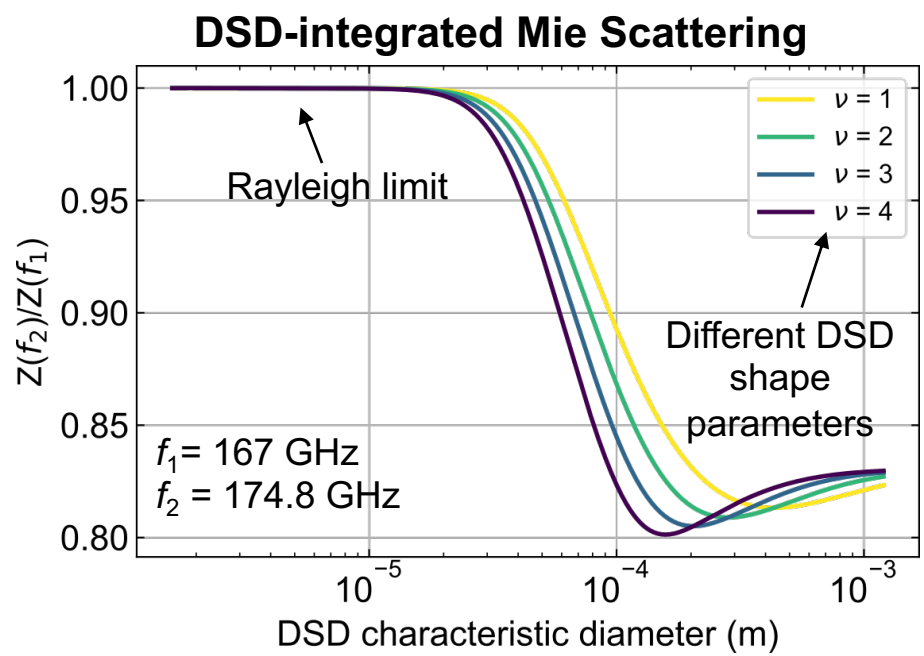


Direct inversion (problem is linear in state vector)

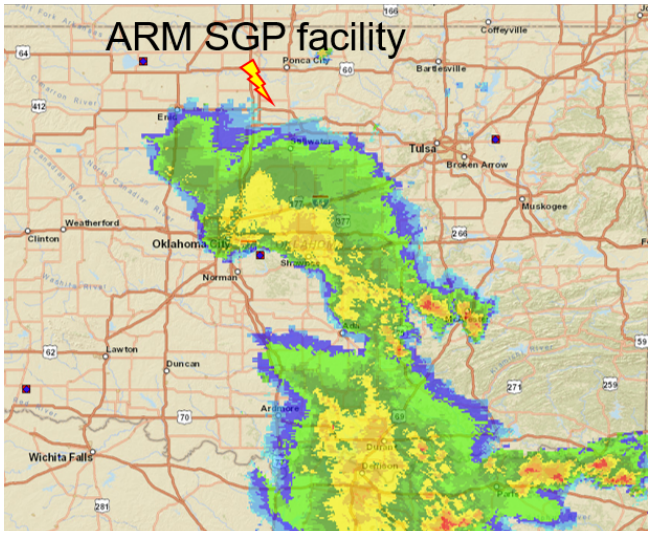
Estimated state vector

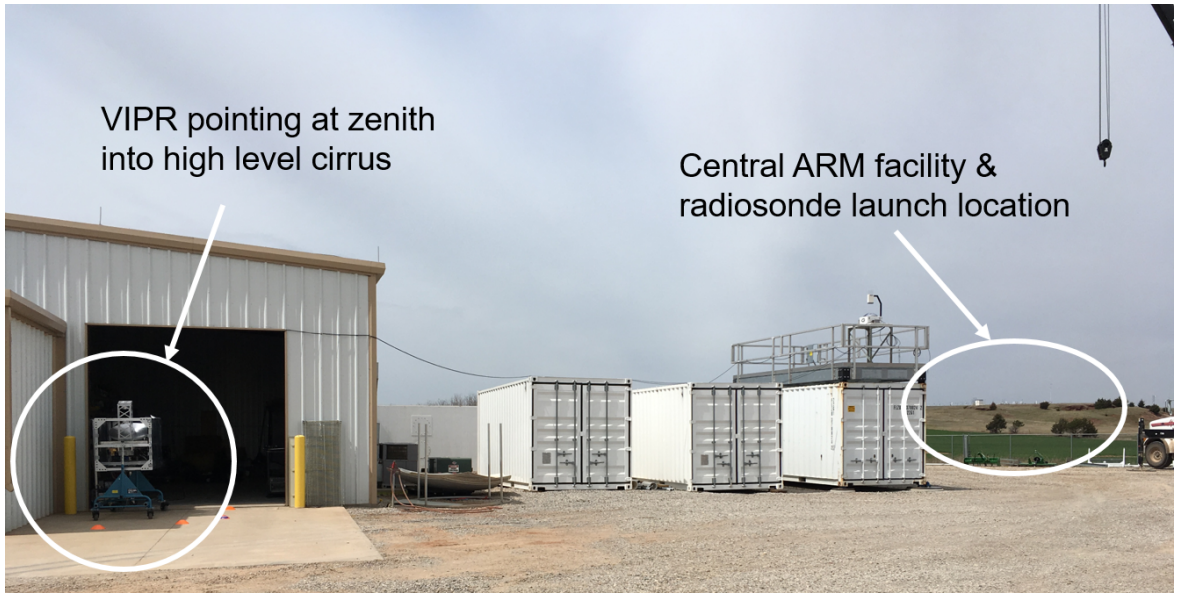
$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \mathcal{C}(\mathbf{x}) \quad \Rightarrow \quad \hat{\mathbf{x}} = \left[\mathbf{K}^T(\mathbf{S}_y + \mathbf{S}_e)^{-1}\mathbf{K} + \delta^{-2}\mathbf{A}\right]^{-1} \mathbf{K}^T(\mathbf{S}_y + \mathbf{S}_e)^{-1}(\mathbf{y} - \mathbf{b})$$

Estimated covariance matrix

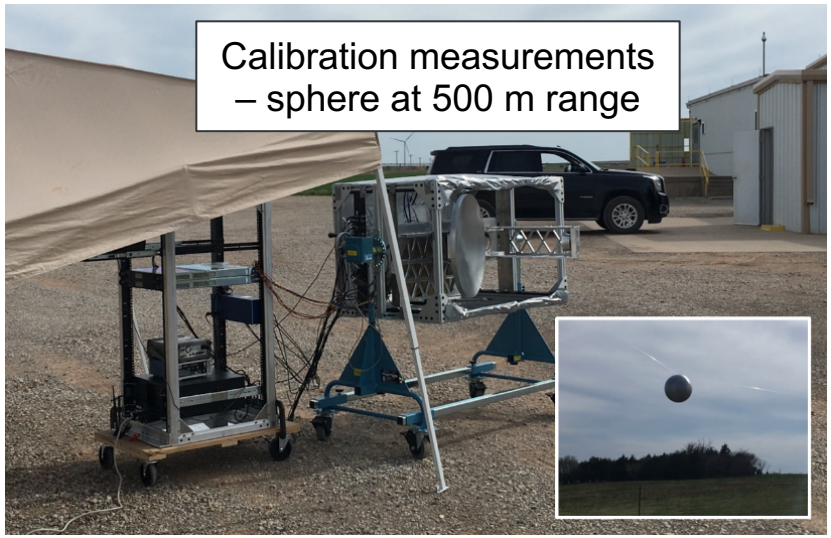
$$\hat{\mathbf{S}}_x = \left(\mathbf{K}^T(\mathbf{S}_y + \mathbf{S}_e)^{-1}\mathbf{K} + \delta^{-2}\mathbf{A}\right)^{-1}$$

Deployment at ARM SGP site





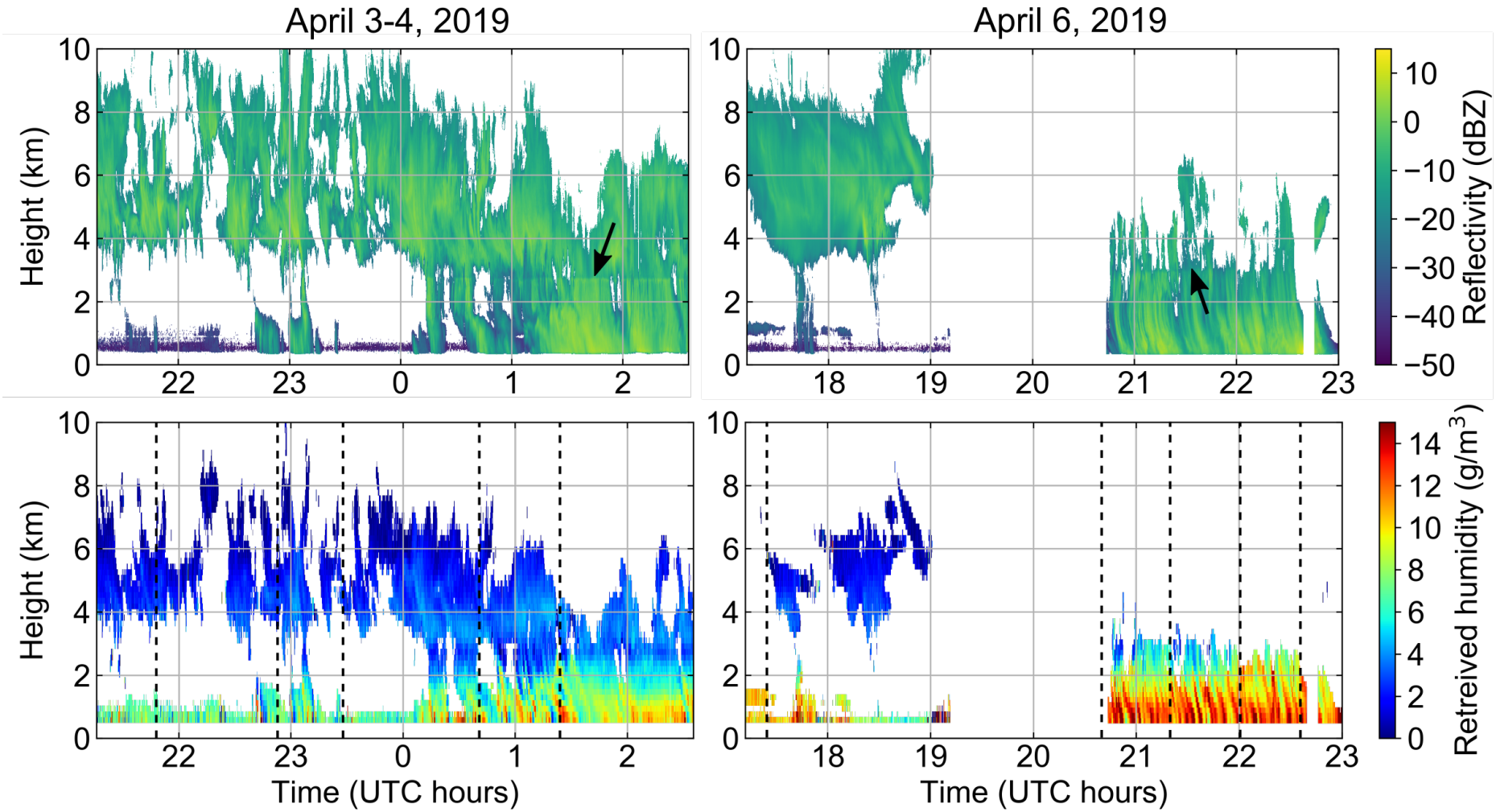
- VIPR deployed from April 2-14, 2019
- Multiple convective systems passed through during the intensive observation period
- Performed radar calibration with high-sphericity calibration targets
- 4x daily radiosonde launches at ARM – supplemented with JPL supplied sondes (launched at will)
- Additional ARM humidity measurements include Raman lidar, passive microwave and infrared



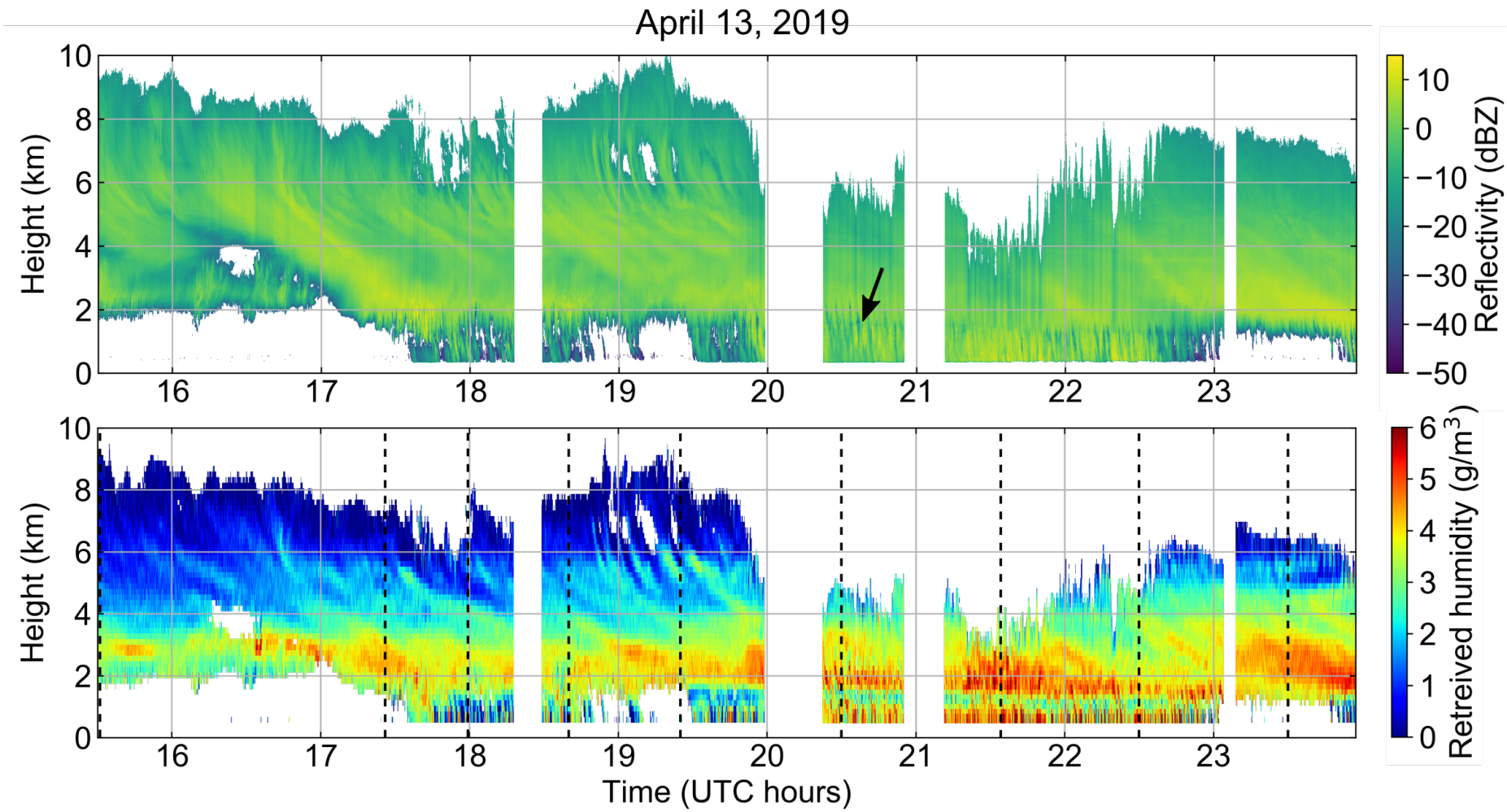
Measurement and retrieval time series

Radar parameters used at ARM

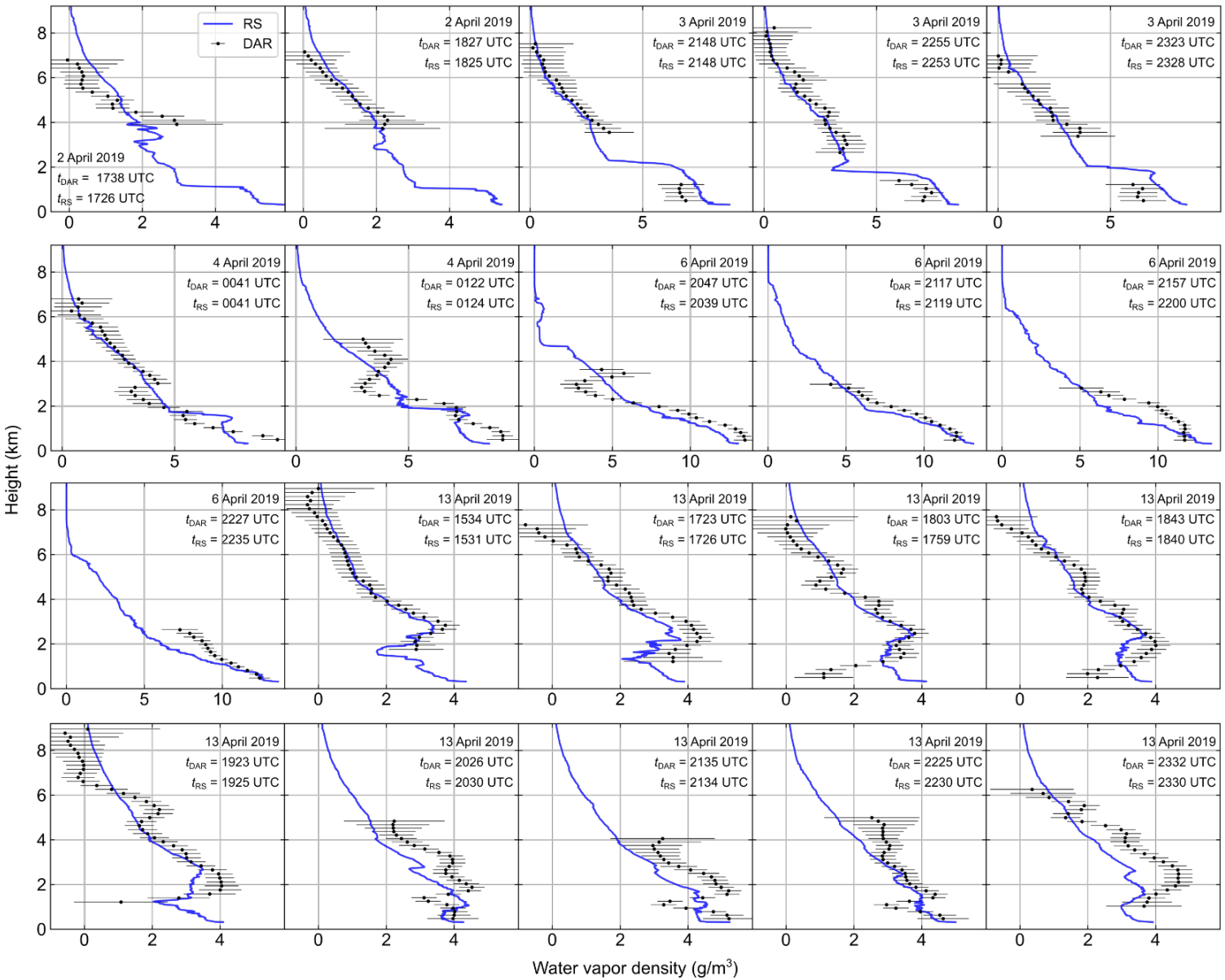
- 2 transmitted frequencies – 167 and 174.8 GHz
- Chirp bandwidth = 10 MHz (15 m range res) over 1 ms
- 2000 pulses averaged per frequency
- Time resolution ~ 5 sec



Measurement and retrieval time series



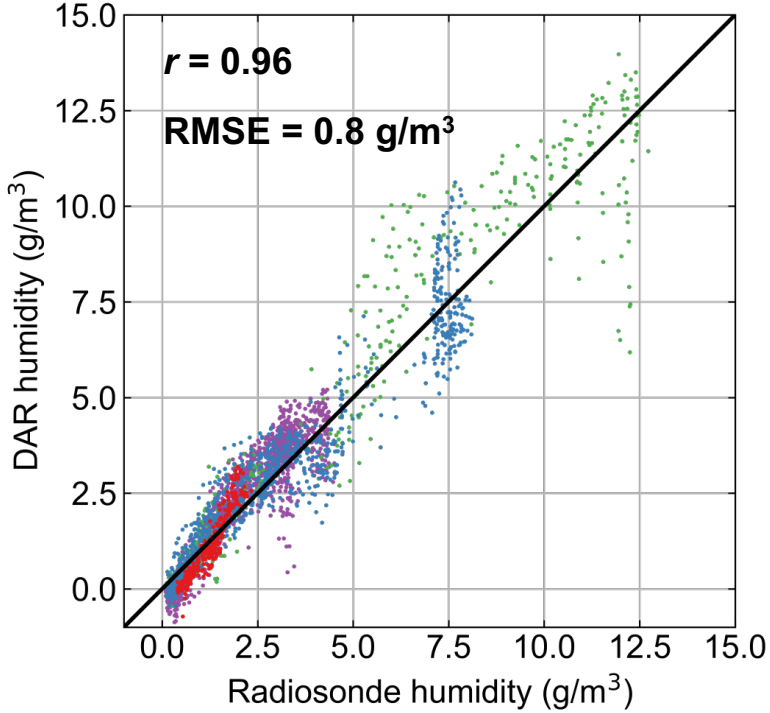
Radiosonde comparisons

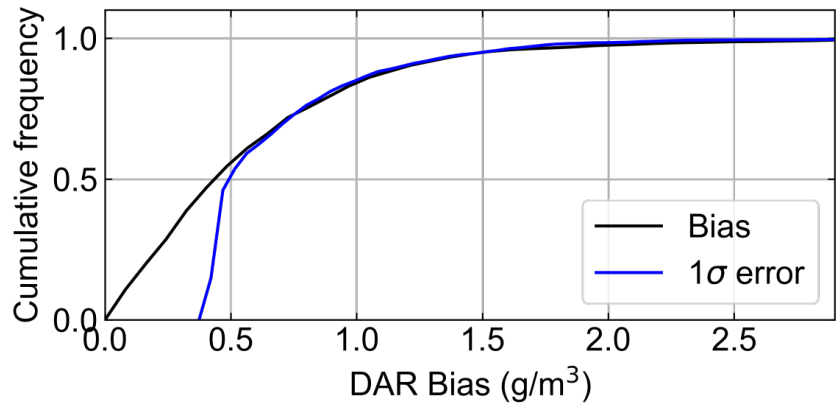


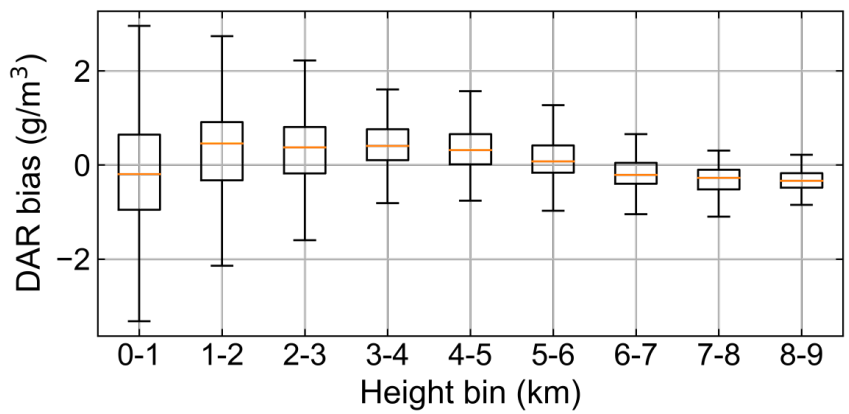
10-minute averages of DAR retrieved humidity with coincident radiosonde humidity profiles

DAR vertical resolution = 200 m

In-cloud profiling summary statistics



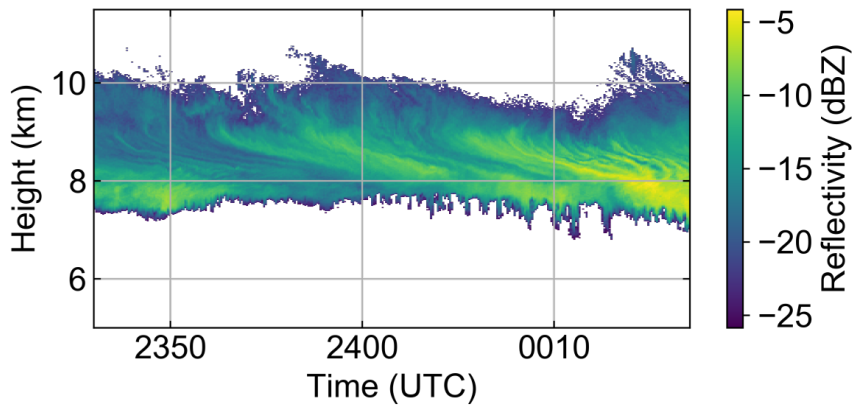


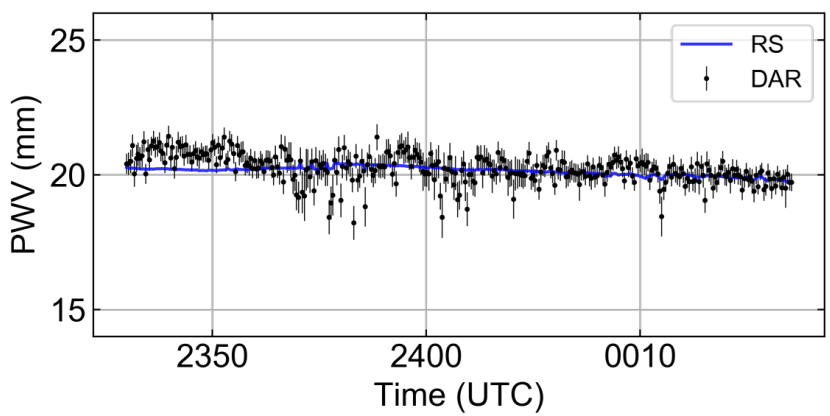


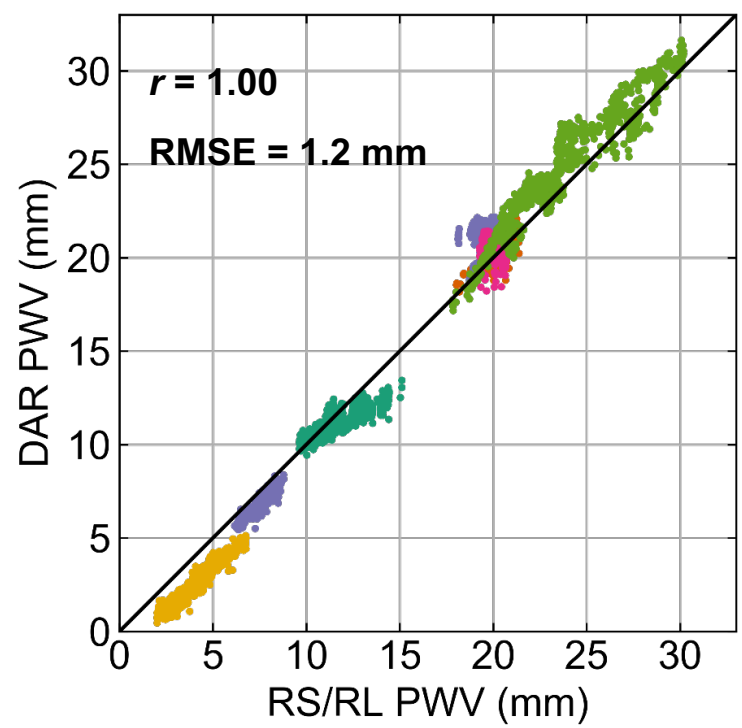
R. Roy *et al*. *J. Atmos. Oceanic Tech.*, submitted

Partial column water vapor

- Measure integrated absorption up to cloud base – proxy for airborne/spaceborne total column water vapor measurement
- Precipitable water vapor (PWV) product validated against both radiosondes and the ARM water vapor Raman lidar







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Conclusions and outlook

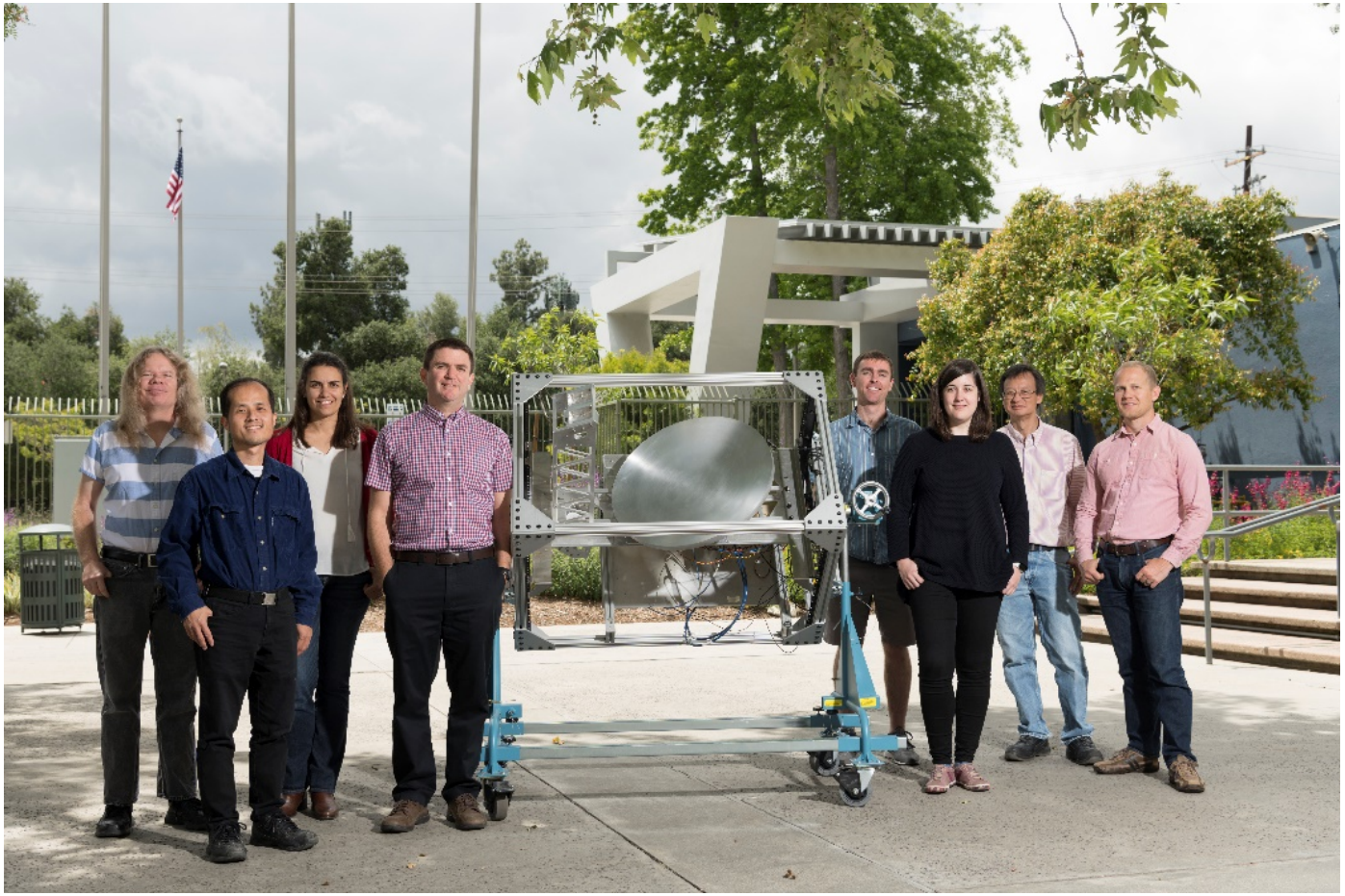
Past and present:

- Development of first all solid-state cloud radar above W-band
- Demonstrated first-ever remotely sensed profiles of water vapor inside of clouds
- Recent field-deployment at ARM SGP for validation of humidity profiling and column water vapor products
- Instrument hardware modified for aircraft deployment – flights aboard Twin Otter aircraft ongoing

Future outlook and prospects for space:

- Potential solution to hydrometeor bias = extending transmit band to 155 GHz
- Humidity profiling from space with order 100 W transmitter (technical challenge)
- Lower power transmitter (1-10 W) can perform TCWV measurements with *ubiquitous temporal, surface, and cloud coverage*
- Coordinated field campaign with water vapor DIAL, passive sounders, and in-situ sensors needed to characterize instrument synergy and combined capability

Questions?



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