Jet Propulsion Laboratory
California Institute of Technology

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Boundary-Layer Humidity Sounding Using a G-Band Differential Absorption Radar

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Silver Spring, MD
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The Vapor In-Cloud Profiling Radar (VIPR, ESTO IIP-16)

Presenter: Richard Roy, JPL

Coauthors: Matt Lebsock (PI), Ken Cooper, Jose V. Siles, Luis Millán, Raquel Rodriguez Monje, and Robert Dengler, JPL

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):

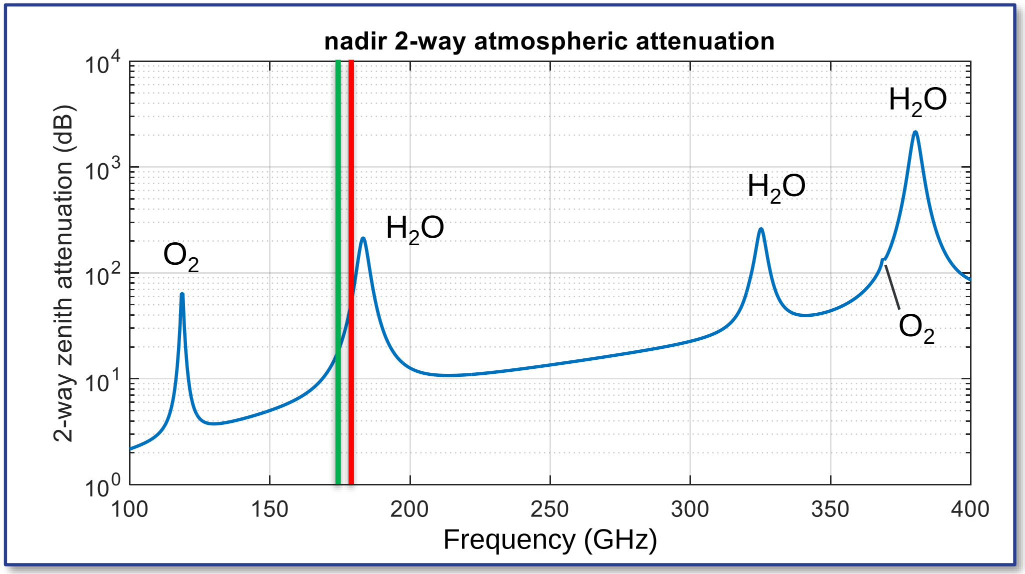
  "Critical atmospheric variables that are **not adequately measured** by current or planned systems are temperature and **humidity profiles** of adequate vertical resolution **in cloudy areas**."

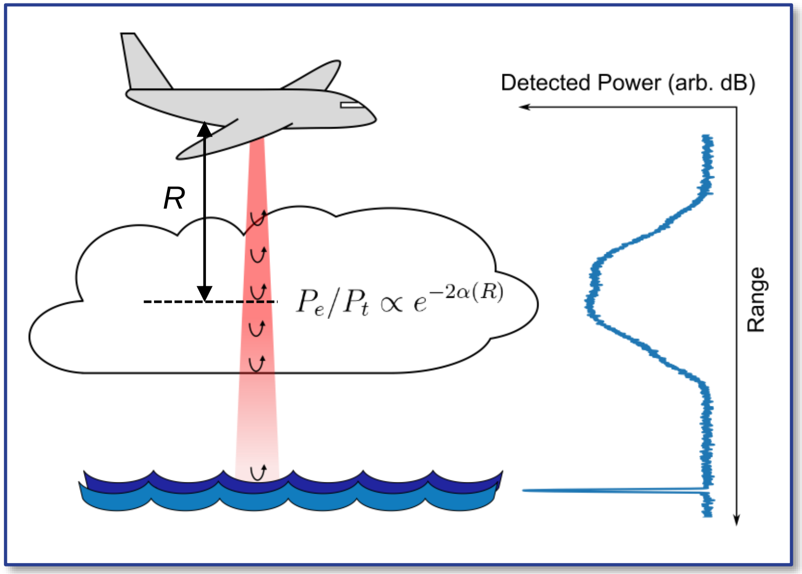
Proposed solution:

- 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 (complementary observations)
- Langley - prototype pressure sounder using O_2 differential absorption, no ranging [1]

[1] Lawrence et al. 2011, doi:10.1016/j.jqsrt.2010.06.001

Measurement basis





- Differential reflectivity between two closely spaced frequencies proportional to absorbing gas density (integrated)

$$\mathrm{dBZ}(r, f_1) - \mathrm{dBZ}(r, f_2) \propto \int_0^r \rho_{\mathrm{gas}}(r')dr'$$

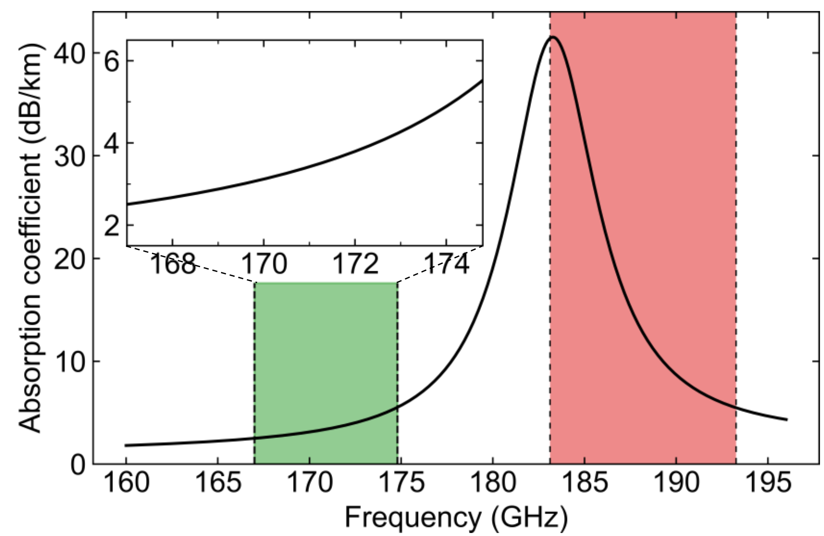
- *Important assumption*: Reflectivity and extinction from hydrometeors independent of frequency
- Frequency dependence from hardware cancels out (common mode)
- Airborne platform ⇒ Surface echoes (total column water)

The vapor in-cloud profiling radar (VIPR)

VIPR

- IIP-16 (PI: Matt Lebsock)
- Entry TRL = 3, exit TRL = 6
- Tunable across 167 to 174.8 GHz band
- Simultaneous cloud/vapor sounding
- Targets boundary layer clouds/precipitation and total column water vapor
- Demonstration flights on Twin Otter in 2019

VIPR frequency band



Red band:
- Sensitivity to upper-tropospheric water vapor (ice clouds)
- Strong attenuation in planetary boundary layer (PBL)
- Transmission prohibited (passive sensors)

Green band:
- Lower absolute absorption ⇒ sensitivity to PBL water vapor
- Profiling (PBL clouds/precipitation) and total column water measurement capabilities
- Fewer transmission restrictions

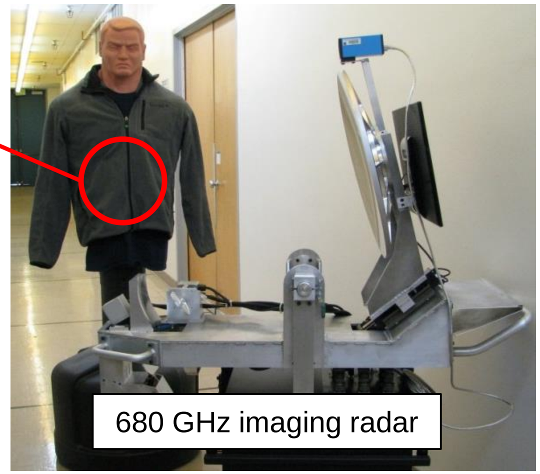
Connection to the Decadal Survey

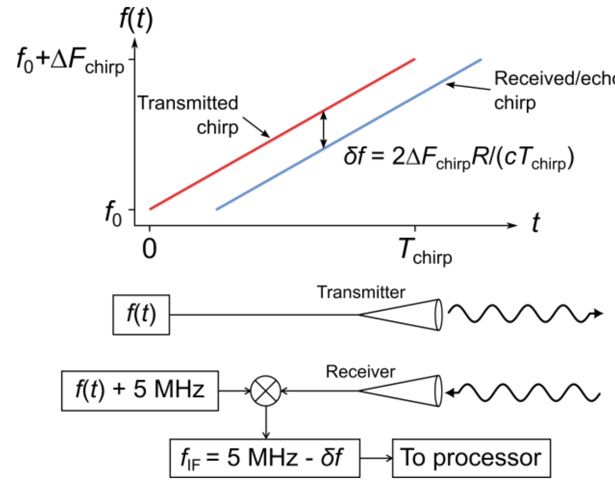
Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
→ **Clouds, Convection, and Precipitation**	**Coupled cloud-precipitation state and dynamics** for monitoring global hydrological cycle and understanding contributing processes including cloud 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

Instrument heritage at JPL

Frequency-modulated continuous-wave (FMCW) radar for security imaging

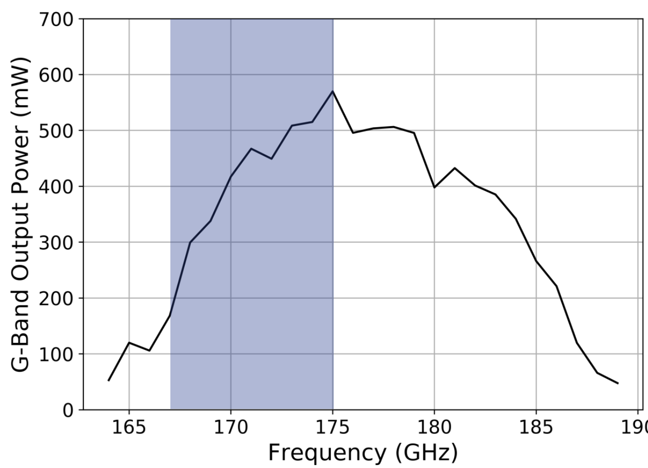
through-clothes detection

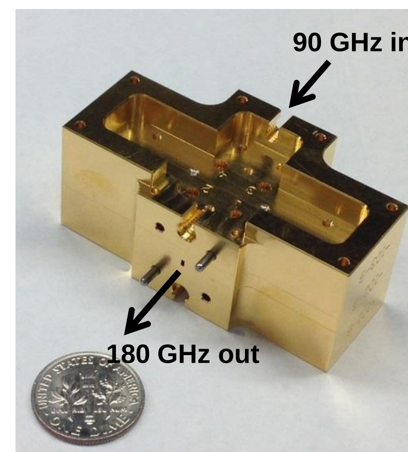




- Extensive THz FMCW radar R&D for security imaging applications
- ESTO funded effort for high-power solid-state sources near 183 GHz (ESTO ACT-13)
- State-of-the-art InP low-noise amplifiers developed for millimeter-wave radiometry and heterodyne spectroscopy

Record output power G-band sources

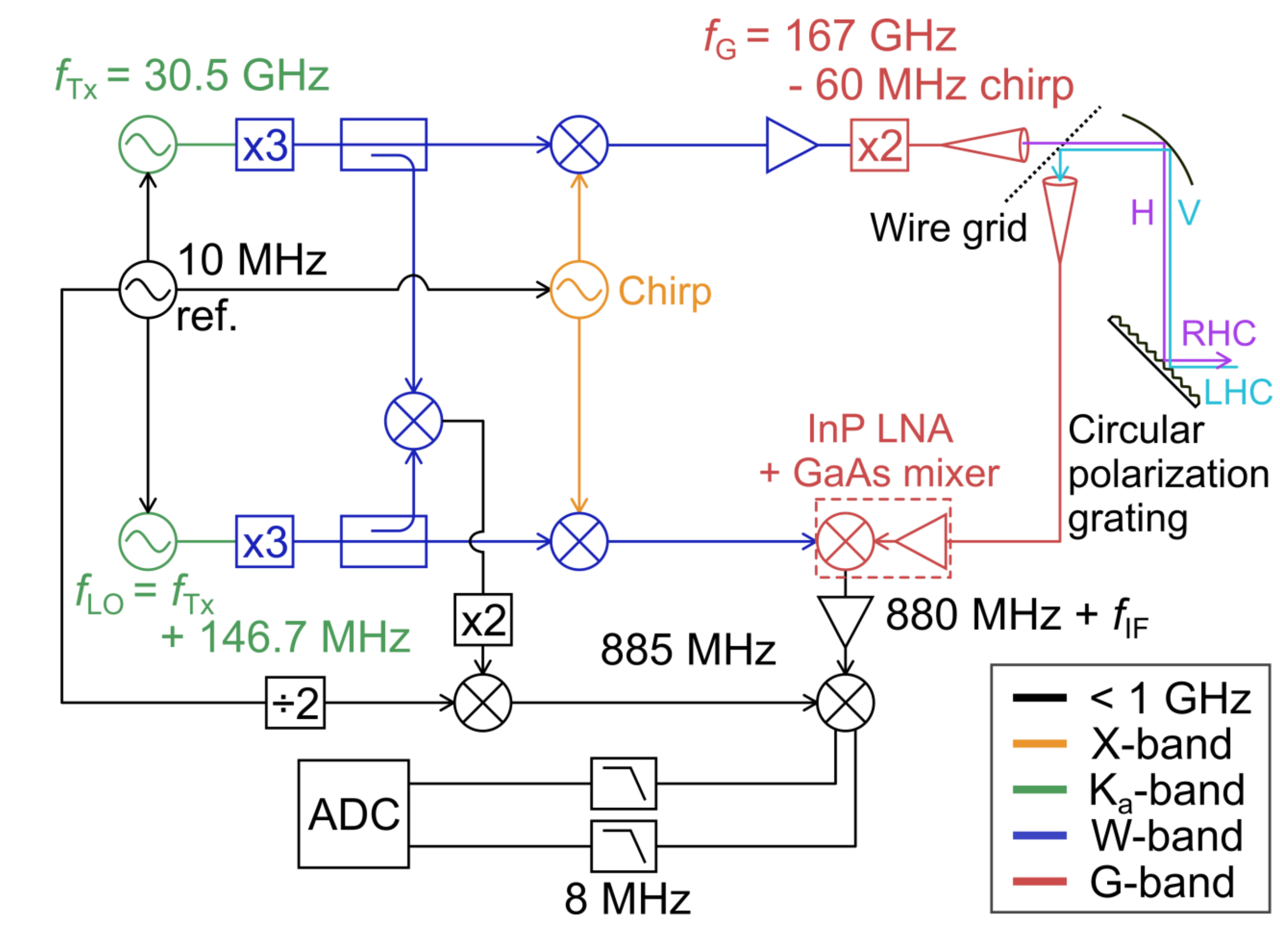




VIPR architecture

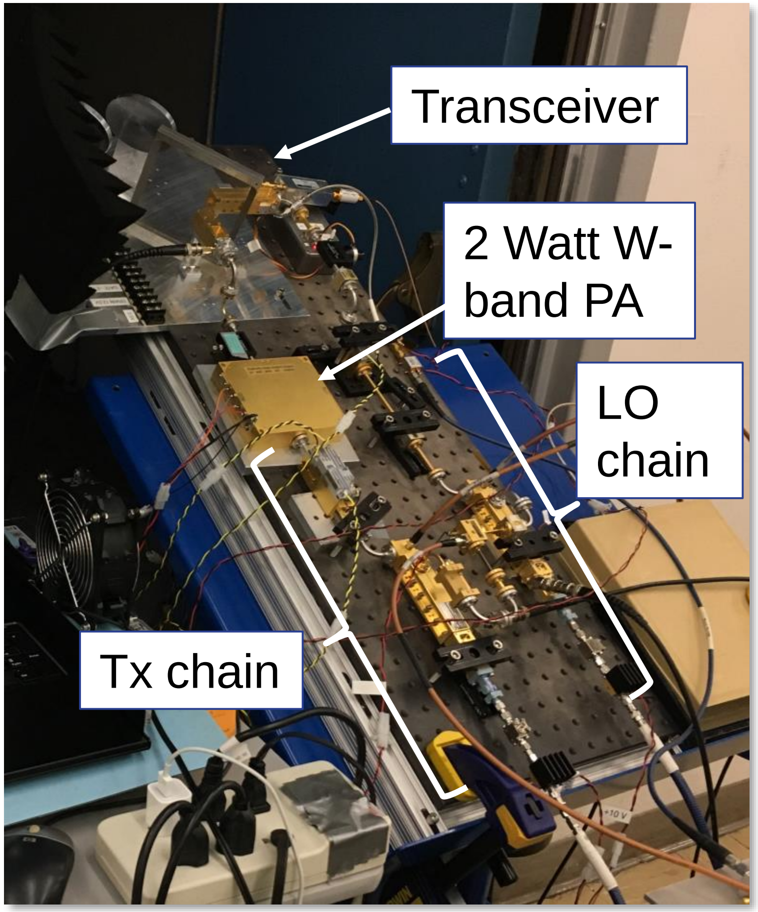
- Transmitter tunable from 167 to 174.8 GHz
- Nominal range resolution 2.5 m
- Very high quasi-optical isolation permits simultaneous operation of Tx/Rx
- Oscillator phase-noise cancellation techniques pioneered at JPL ⇒ thermal-noise-limited detection

VIPR high-level block diagram

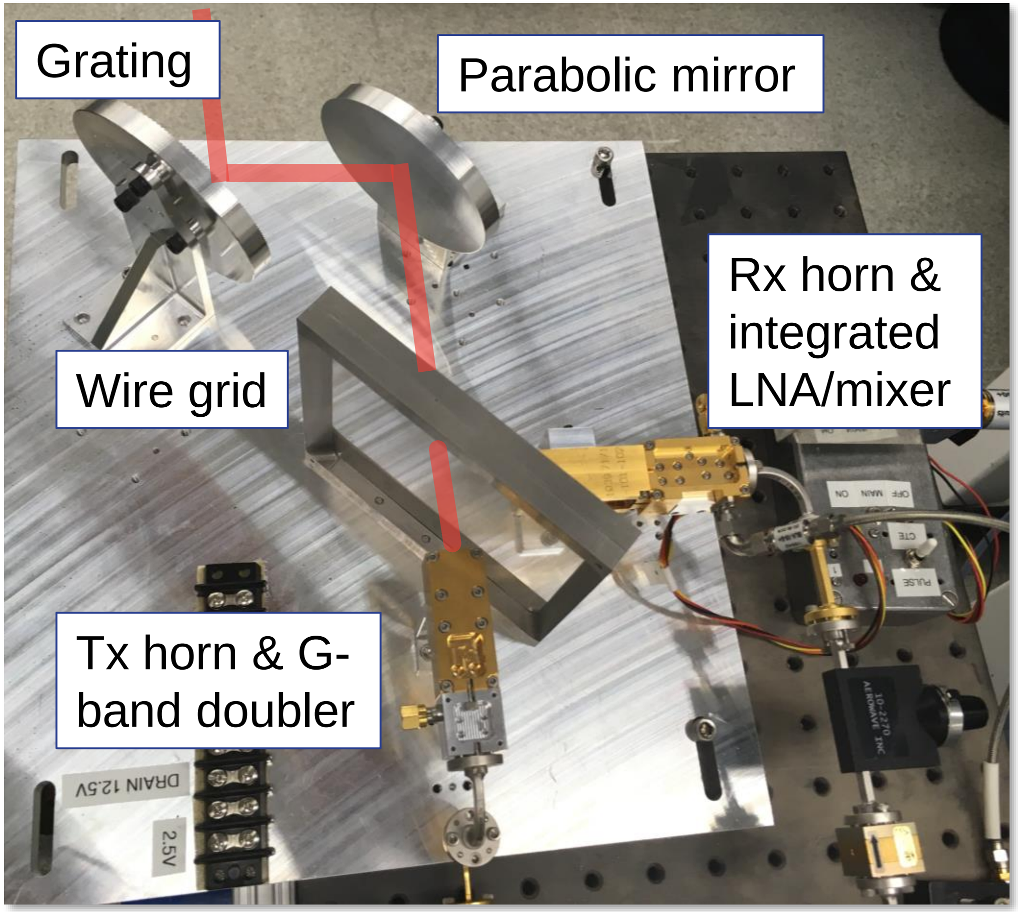


Ground testing setup

Radar front end



Transceiver



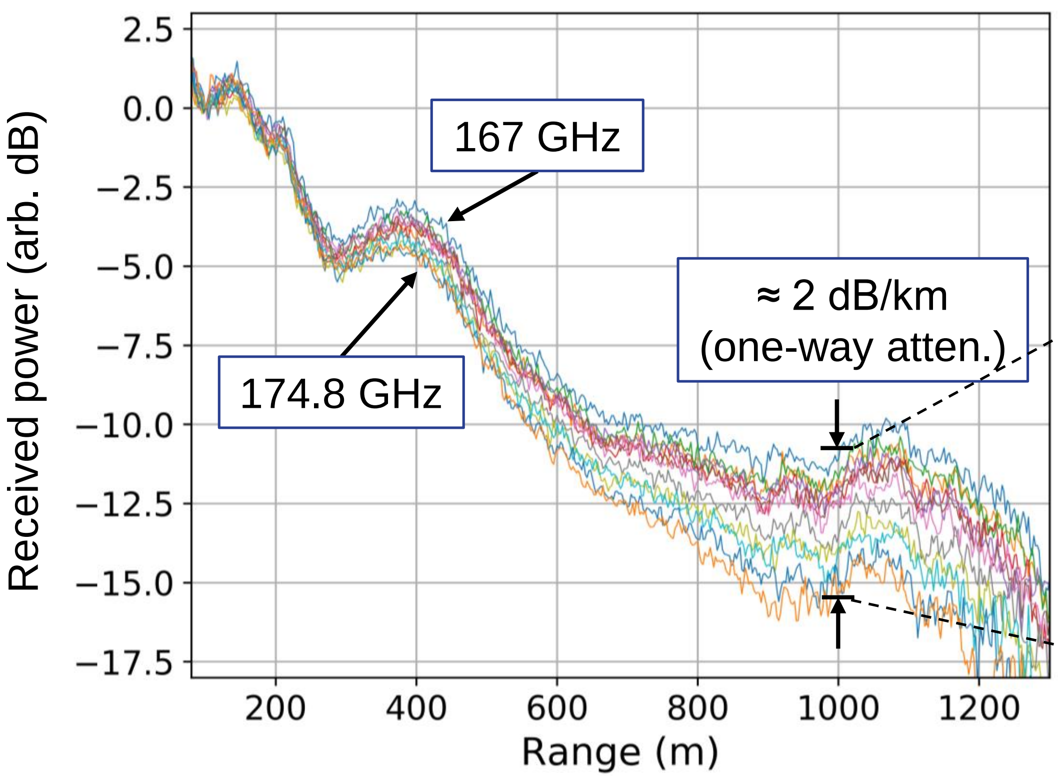
- 100 mW Tx power
- 40 dB antenna gain

Values for initial testing

Rain/cloud field tests @ JPL

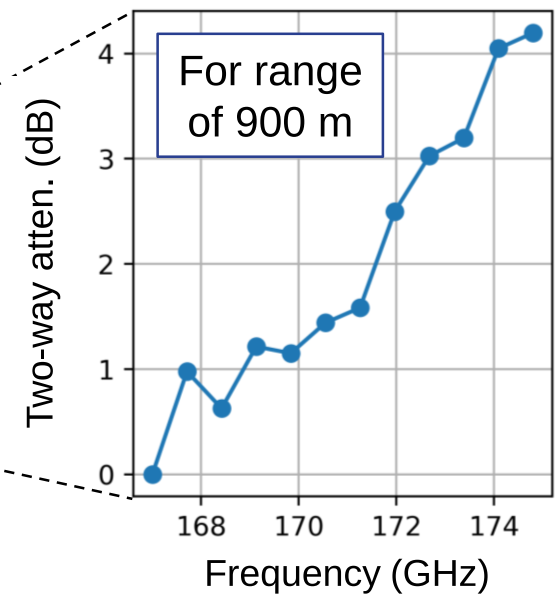
Precipitating clouds

Power spectra normalized to values at 100 m



Reflectivity

$$r^2 P_e(r, f) \propto Z(r) e^{-2\alpha(r,f)}$$



Background noise floor considerations

- Differential measurement derived from ratio of *radar echo power* at two different ranges:

$$\frac{P_e(r_2,f)}{P_e(r_1,f)} \propto e^{-2\alpha(r_1,r_2,f)}, \quad \alpha(r_1,r_2,f) \propto \int_{r_1}^{r_2} \rho(r')dr'$$

One-way optical depth

- But the power we detect is the sum of the echo power *plus* the background noise power:

$$P_d(r,f) = P_e(r,f) + P_n(r,f)$$

- Note:

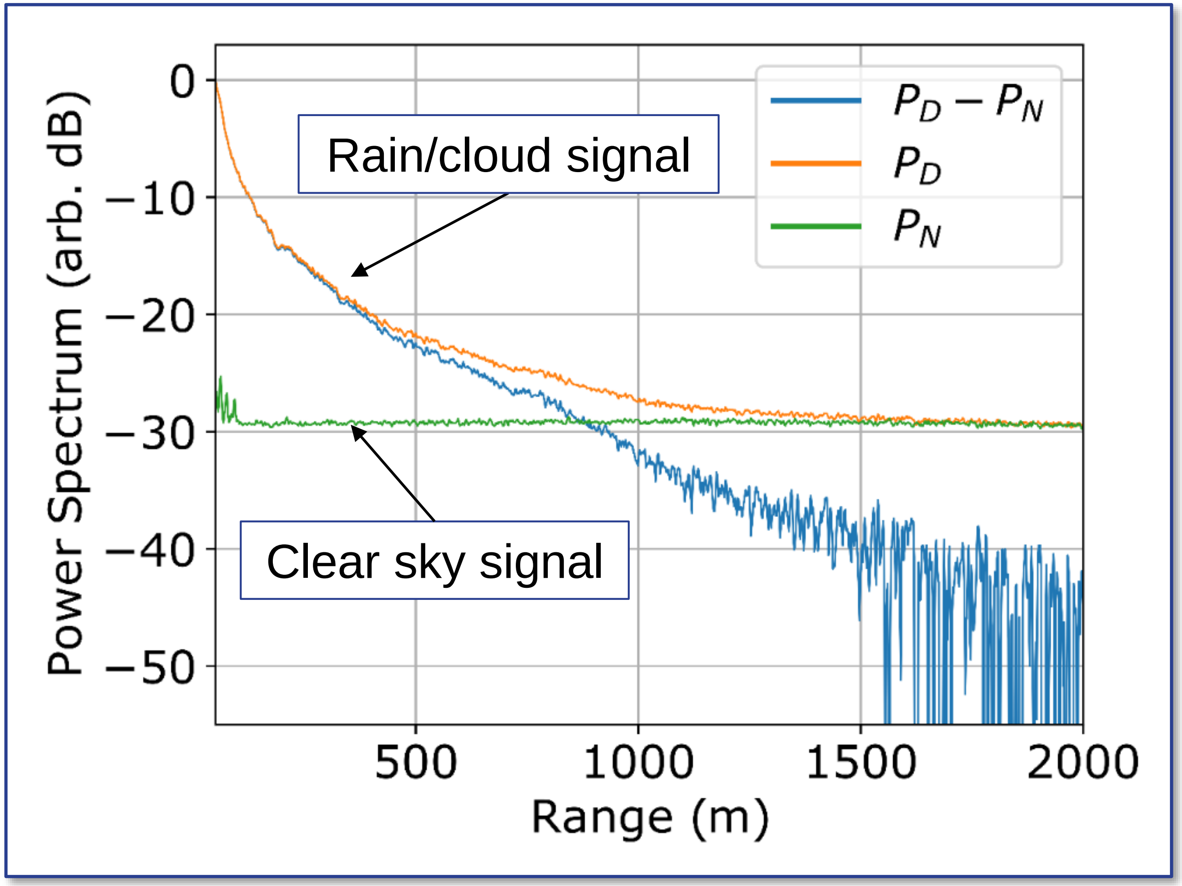
$$P_n(r,f) \neq \text{constant}$$

  - Ripple in the radar IF spectrum
  - Changing scene brightness temperature

⇒ have to acquire and subtract true background noise floor – otherwise clear low-humidity bias for low-SNR

Background noise floor considerations

- Strategy 1:
  - Acquire radar spectrum with clouds/rain present
  - Wait for sky to clear and acquire background spectrum for subtraction



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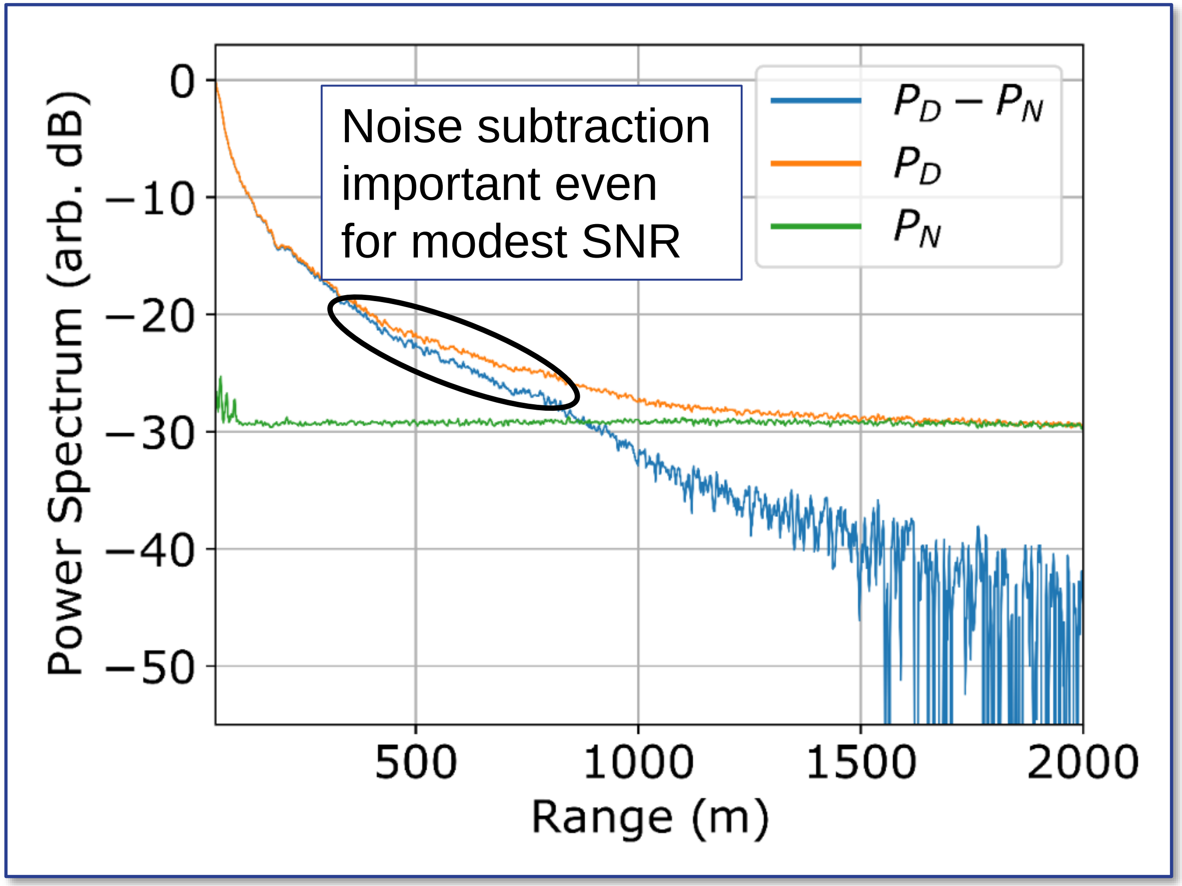
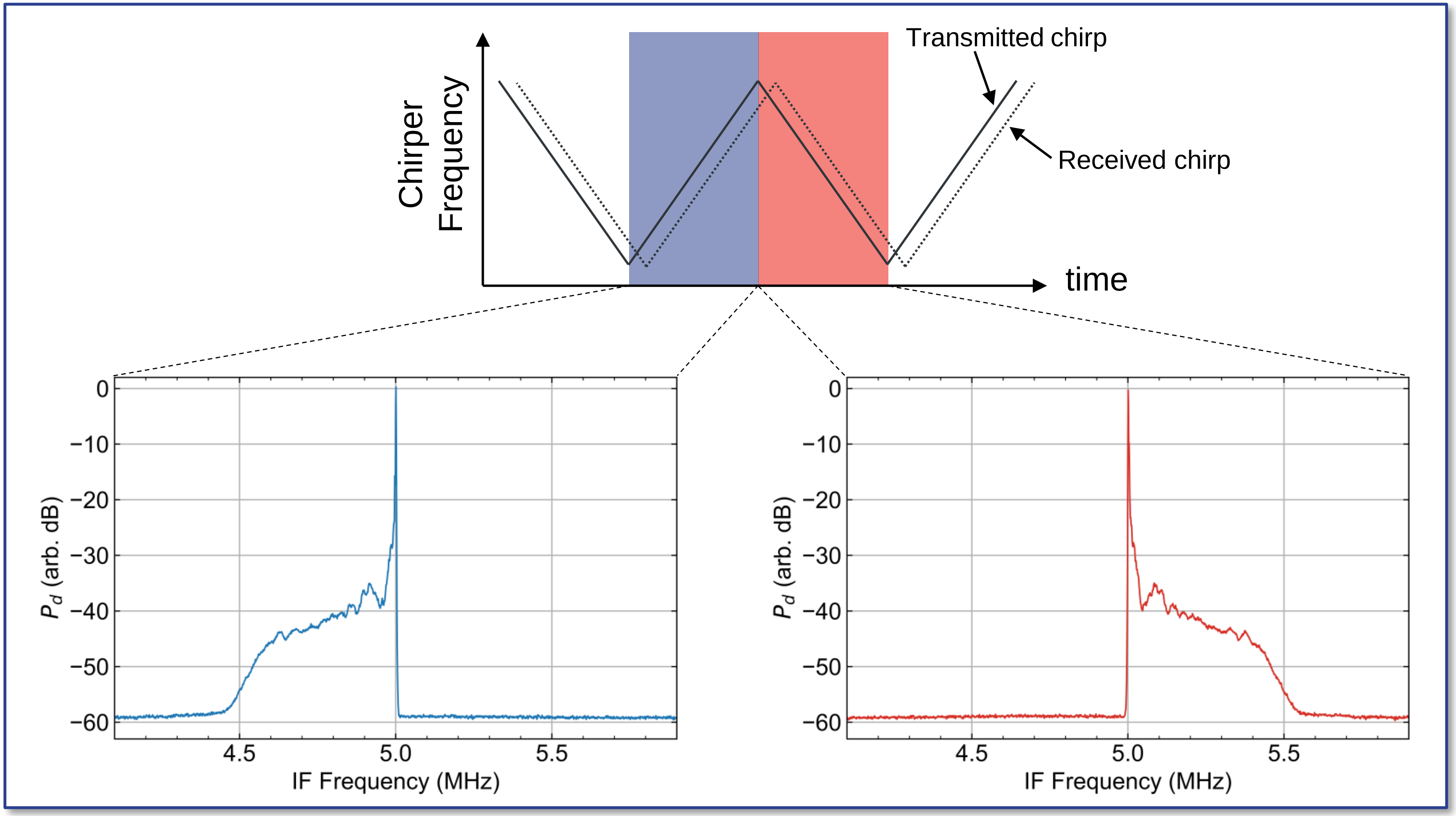
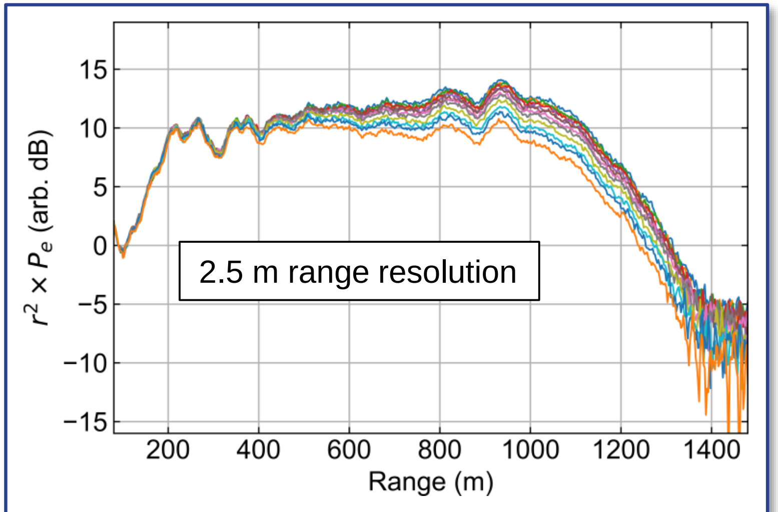


Real-time noise floor subtraction

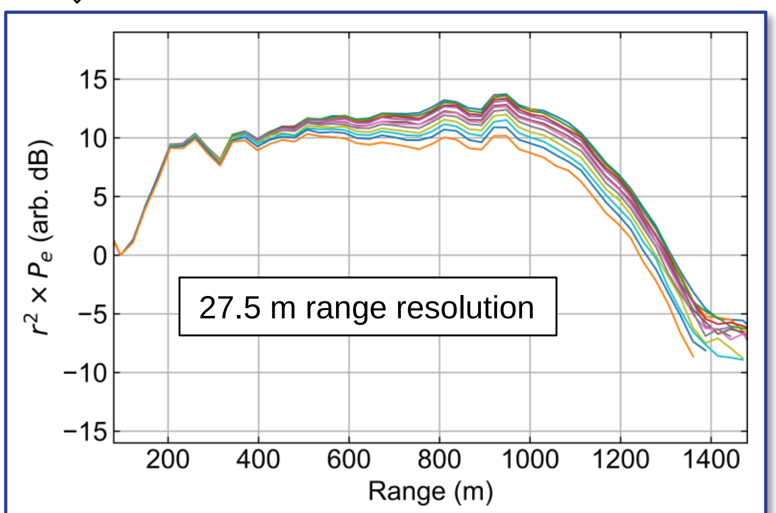
- Strategy 2:
  - — Acquire cloud/rain signal spectrum **and** background noise floor simultaneously by using bidirectional chirp (triangle wave)



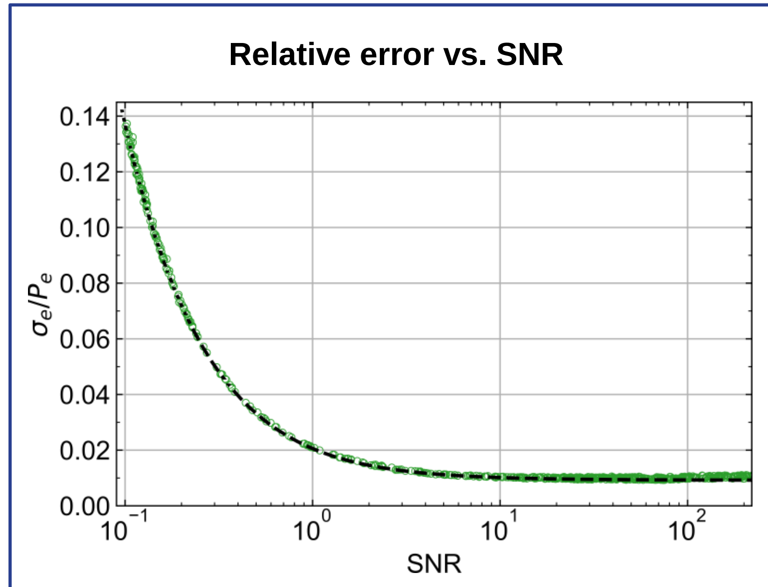
DAR signal processing



Bin (i.e. downsample) radar spectra by factor of 10 to reduce statistical uncertainty

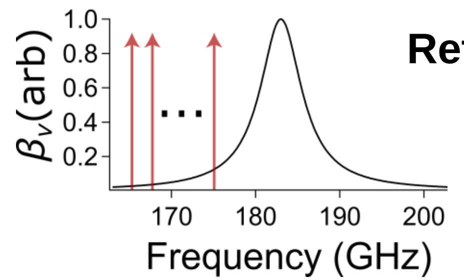


- Measurement error agrees very well with statistical model based on radar speckle noise



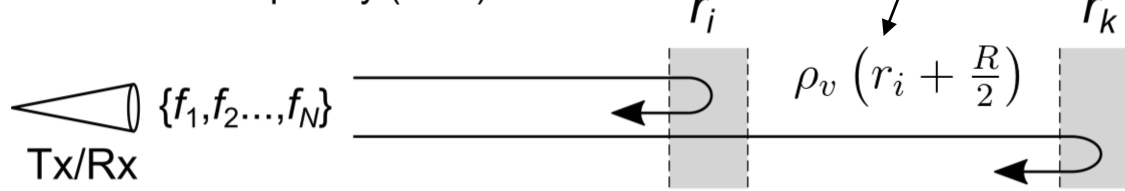
Humidity retrieval

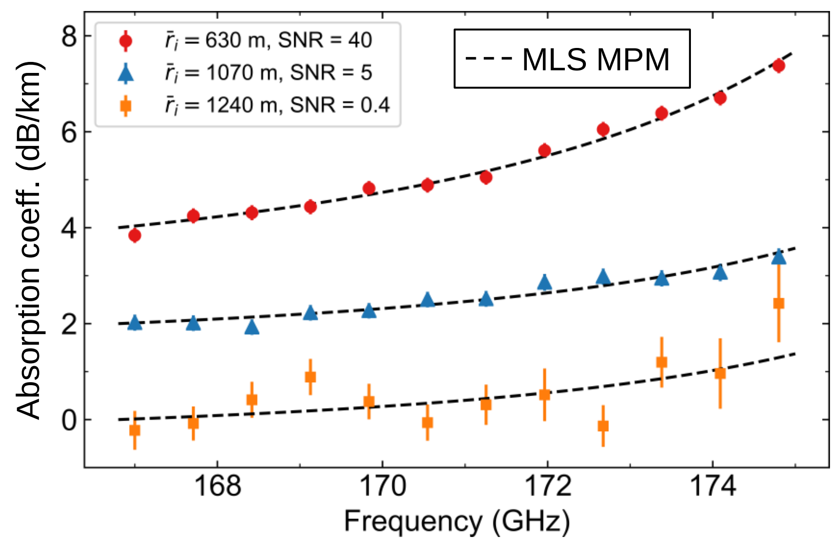
- Fit millimeter-wave propagation model to measured absorption coefficient $\beta_v(f)$ to extract humidity

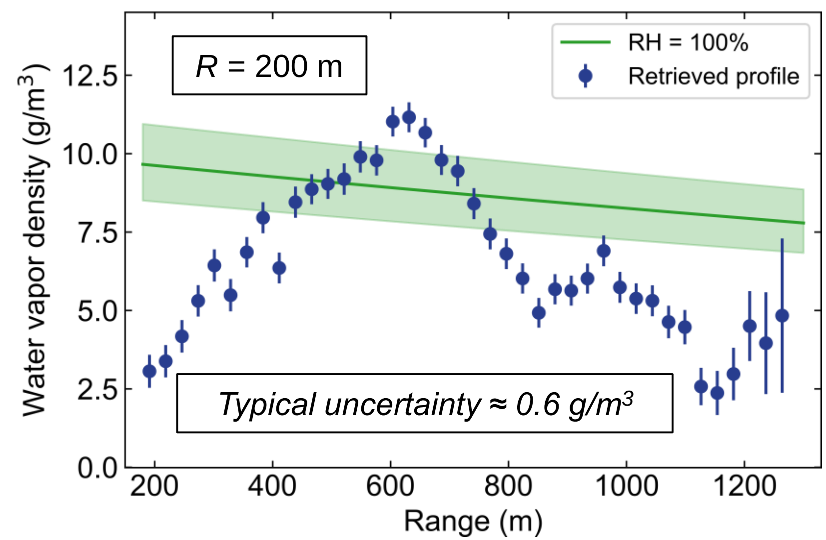


Retrieval step size: $r_k - r_i = R$

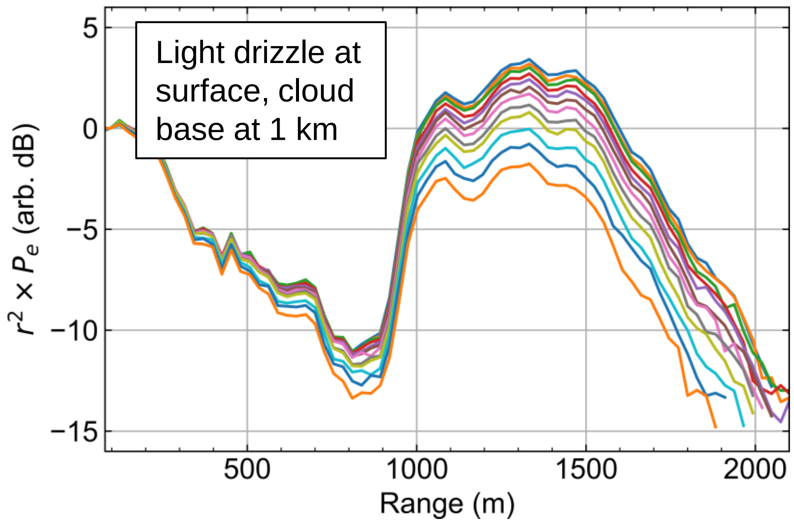
$$\beta_{\text{meas}} = \frac{-1}{2R} \ln \left(\frac{P_e(r_i + R, f)}{P_e(r_i, f)} \right)$$

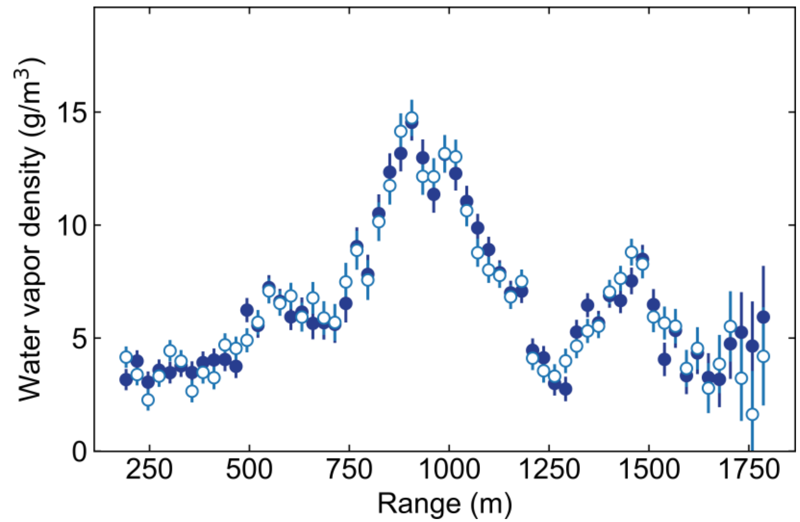


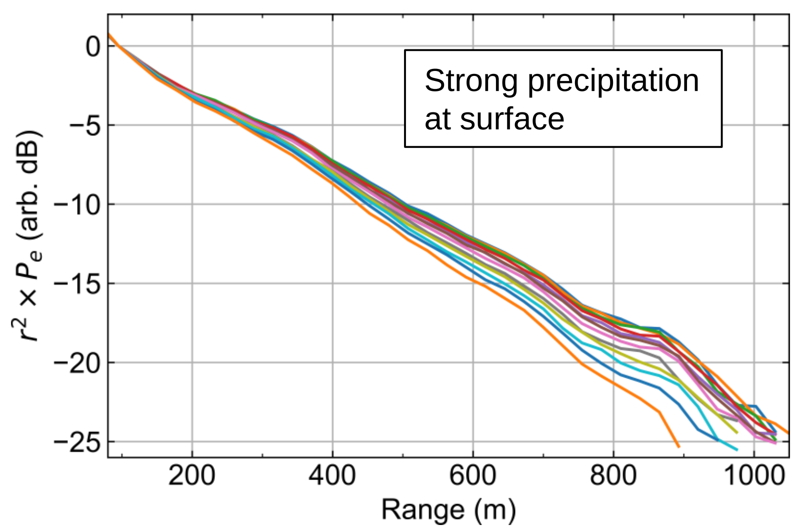


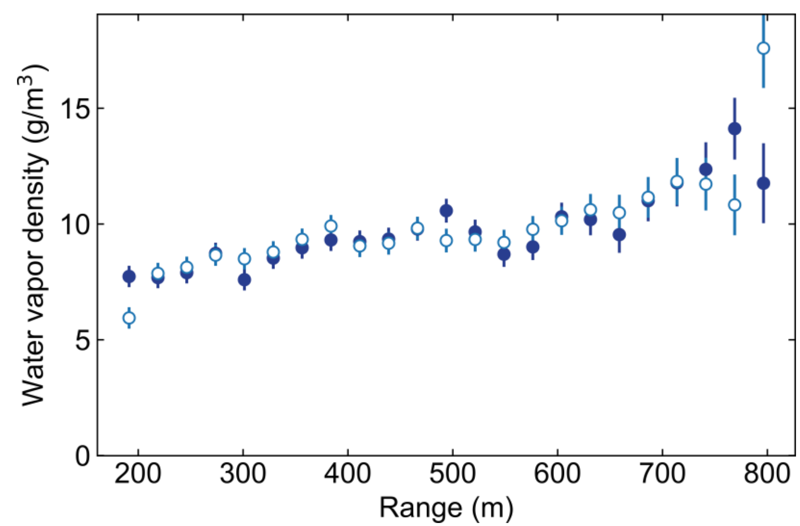


Measurement reproducibility









Conclusions and outlook

The present:

- G-Band differential absorption radar proof-of-concept instrument assembled and preliminary field testing successful
- Real-time background noise floor cancellation using bidirectional chirp
- Capable of measuring both precipitating (large hydrometeors/cross section) and non-precipitating (smaller hydrometeors/cross section) clouds
- Humidity profile retrieval algorithm implemented

The future:

- Installation of 61 cm primary aperture and corresponding 20 dB increase in gain
- Field testing with coincident radiosonde measurements for instrument validation
- Testing from an airborne platform – investigate surface returns for total column water retrieval

Thank you to ESTO for funding the project.

Thank you for your attention

Questions?