Jet Propulsion Laboratory
California Institute of Technology

Deployment of a 170 GHz Differential Absorption Radar in Winter Nor'easters and California Beaches

Ken Cooper
Jet Propulsion Laboratory, California Institute of Technology

June 22, 2023

NASA ESTO Earth Science Technology Forum

JPL Team Members: Matt Lebsock, Luis Millán, Jose Siles, Raquel Rodriguez Monje, Robert Dengler, Ian McCubbin, Juan Socuellamos, Srinivas Prasad Mysore Nagaraja, Rita Meraz Riviera, and Kevin Smalley

We are grateful for project support from ESTO's sequence of ACT, IIP, and AITT programs from 2014-present.

Jet Propulsion Laboratory
California Institute of Technology

Water in the Atmosphere

Water in the atmosphere

Bjorn Stevens and Sandrine Bony

Physics Today **66** (6), 29–34 (2013);
https://doi.org/10.1063/PT.3.2009

- Global average liquid column is only 2.5 cm, and only 0.25% of the atmosphere's mass, yet water in the atmosphere has **huge influence** on Earth's climate:
    - Water condensation during convection is the major driver that achieves radiative balance and sets Earth's temperature.
    - Tropics-to-polar energy flow is 50/50 split between water latent heat and atmospheric temperature.
    - Water vapor is a very strong greenhouse gas, leading to positive temperature feedback (warmer air holds more water vapor).
    - In the form of clouds, increased albedo cools during the day, while at night clouds trap heat.
    - Clouds are the **single largest source of uncertainty** in climate models.

Condensation, atmospheric motion, and cold beer

Physics Today 66 (4), 74–75 (2013);
https://doi.org/10.1063/PT.3.1958

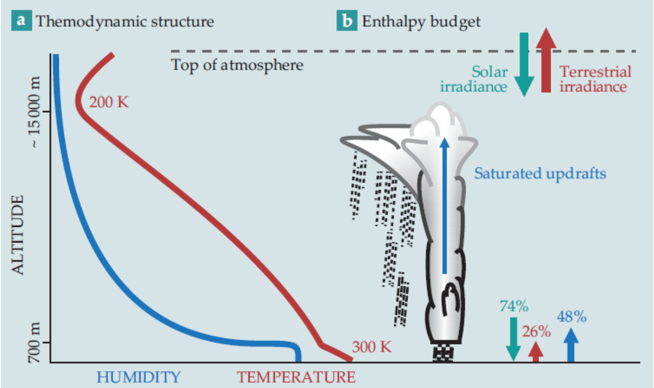
Dale R. Durran and Dargan M. W. Frierson

The latent heat released when water condenses is an important driver of weather phenomena. And as a simple experiment shows, it also makes it tough to enjoy a frosty one in the summertime.

Dale Durran is a professor of atmospheric sciences and **Dargan Frierson** is an associate professor of atmospheric sciences, both at the University of Washington in Seattle.

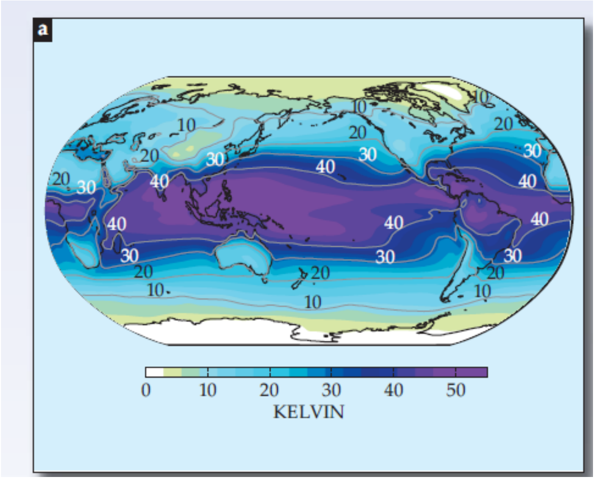
water vapor. The annual mean equator-to-pole contrast in enthalpy at the surface is about equally divided between contributions resulting from gradients in temperature and those from moisture; each gives about a 50-K difference between the equator and the poles. Consistent with that 50-50 split, moist processes account for roughly half of the total heat transport between the tropics and high latitudes.

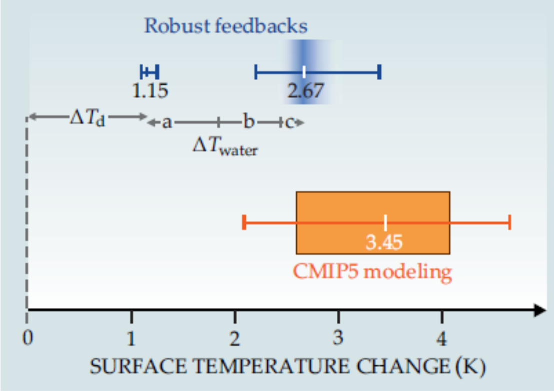
Vertical heat transfer by latent-heat release occurs, for example, in a thunderstorm's updraft core. Like hot-air balloons, the updrafts are warmer than their environment and their ascent is powered by upward buoyancy forces. Rising blobs of air experience a drop in the surrounding atmospheric pressure and cool through adiabatic expansion. Con-



radiative balance components

water vapor abundance expressed in latent heat (Kelvin)





water vapor contribution to climate sensitivity to CO2 doubling

Jet Propulsion Laboratory
California Institute of Technology

NASA Appreciates Vapor/Cloud Measurement Gaps

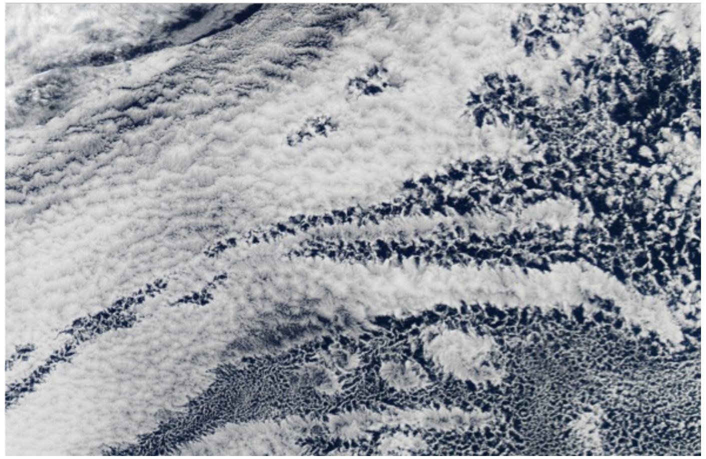
Current humidity remote sensing technology (e.g. passive microwave/infrared, radio occultation, lidar) is often confounded by clouds or terrain, and/or does not provide the desired spatial resolution within Earth's Planetary Boundary Layer (PBL).

Cloud-radar observations are an objective of the current AOS (Atmosphere Observing System) NASA mission: measuring vertical motions, inferring heat transfer.

The Earth Science 2017 Decadal Survey identifies humidity profiles in the PBL as a targeted observable for technology incubation.

The NASA 2021 PBL Study Team report also cites gaps in global humidity profile measurements, emphasizing high spatial resolution in both clear and cloudy conditions.

There is a potential for a large PLB-focused Earth-observing NASA mission in the 2030s.



Water vapor mesoscale (2-2000km) variability in cloudy boundary layers is especially sought after.

TOWARD A GLOBAL PLANETARY BOUNDARY LAYER OBSERVING SYSTEM

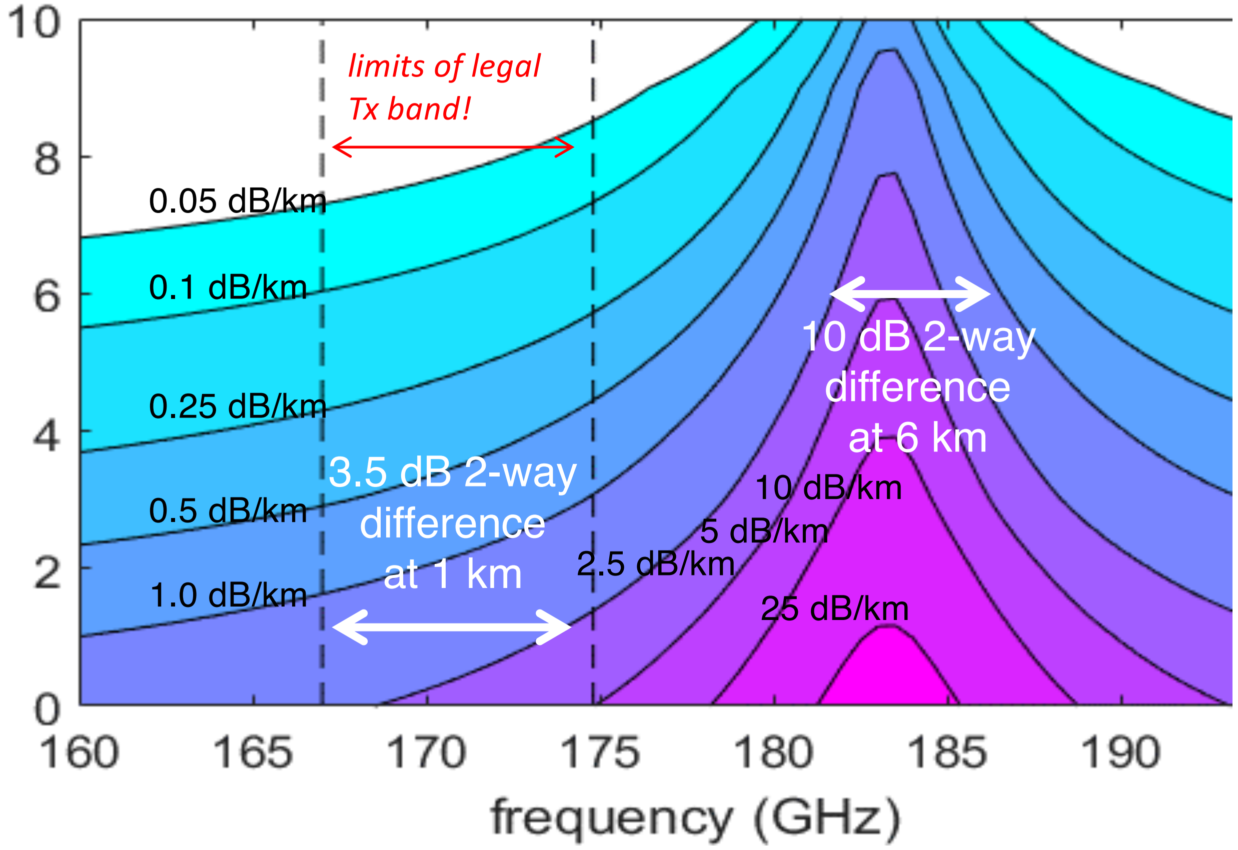
THE NASA PBL INCUBATION STUDY TEAM REPORT

João Teixeira [1], Jeffrey R. Piepmeier [2], Amin R. Nehrir [3], Chi O. Ao [1], Shuyi S. Chen [4], Carol A. Clayson [5], Ann M. Fridlind [6], Matthew Lebsock [1], Will McCarty [2], Haydee Salmun [7], Joseph A. Santanello [2], David D. Turner [8], Zhien Wang [9], Xubin Zeng [10]

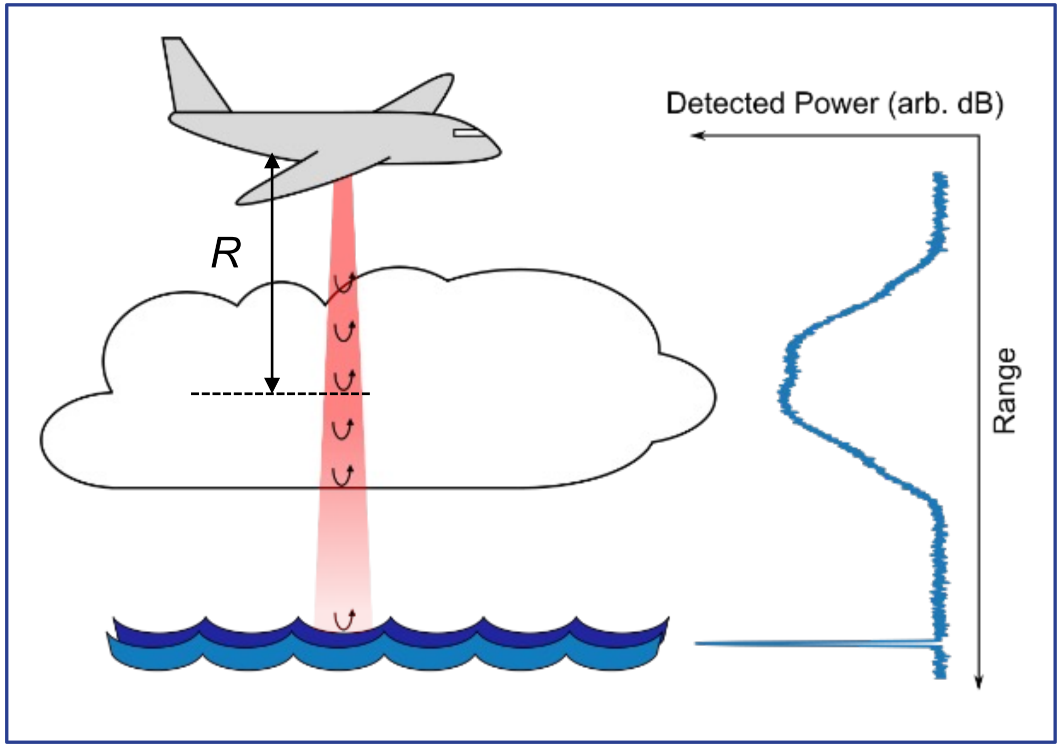
Jet Propulsion Laboratory
California Institute of Technology

VIPR: Vapor Inside-cloud Profiling Radar

183 GHz water absorption in Earth's atmosphere:
(typ. midlatitude conditions)

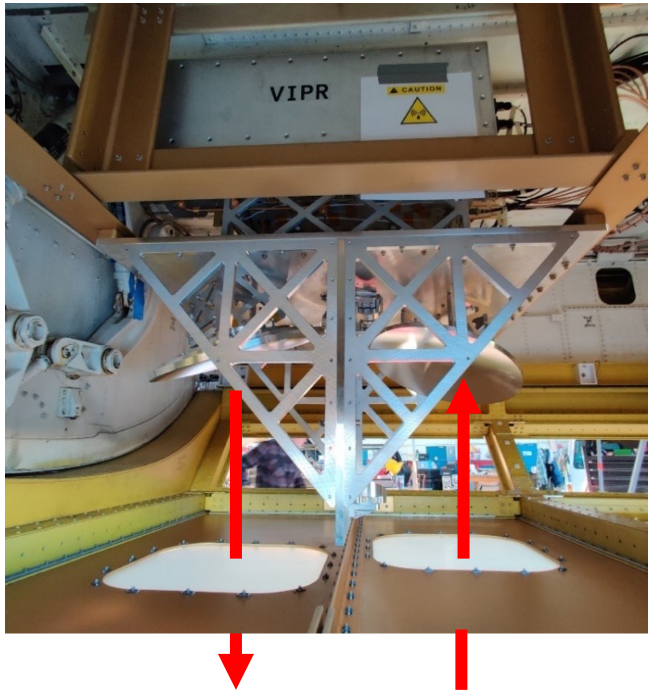


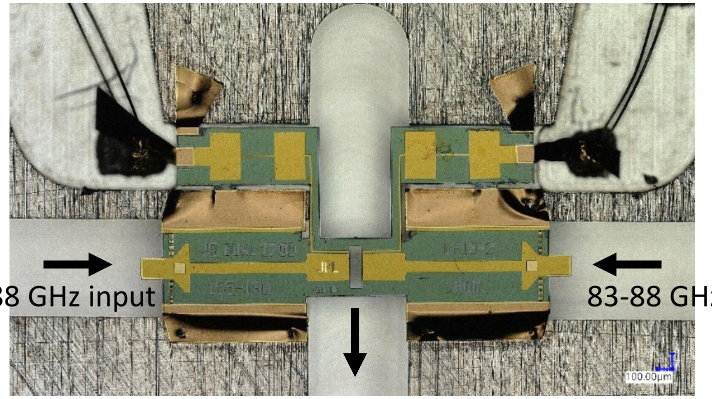
DAR: Differential Absorption Radar

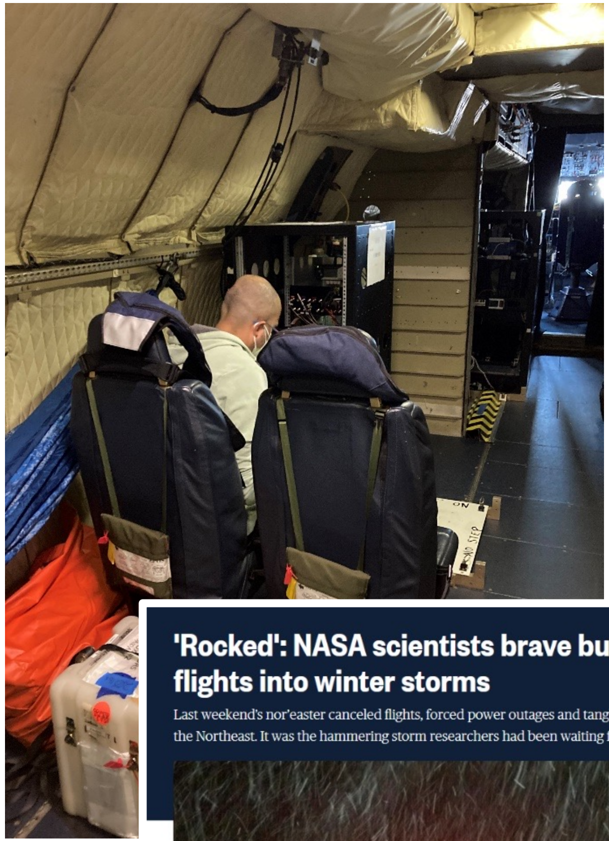


Jet Propulsion Laboratory
California Institute of Technology

Installing VIPR on NASA P3 Aircraft for IMPACTS Ride-Along







- Transmitter: broad-band, two-way power combining Schottky diode 170 GHz frequency doubler
- Achieves 150-250 mW transmit power over 158-175 GHz
- Receiver: G-band InP LNA from JPL/NGC collaboration
- Dual 38 cm diameter off-axis parabolic reflector antennas, 55 dB directivity
- ProSensing Inc. designed and built grooved TPX radomes.

'Rocked': NASA scientists brave bumpy flights into winter storms

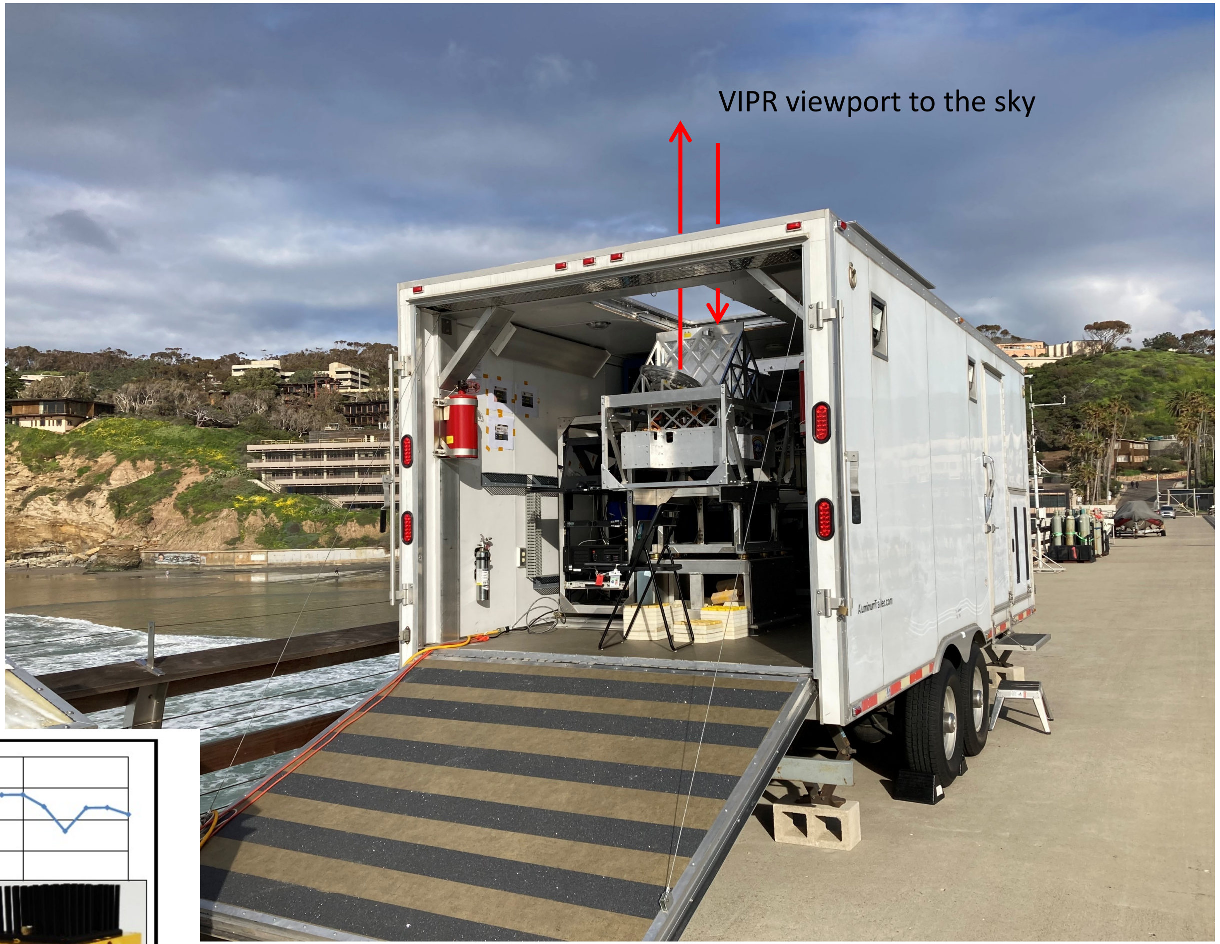
Last weekend's nor'easter canceled flights, forced power outages and tangled traffic throughout the Northeast. It was the hammering storm researchers had been waiting for.

A P-3 Orion landing during a storm at NASA's Wallops Flight Facility in Virginia. NASA

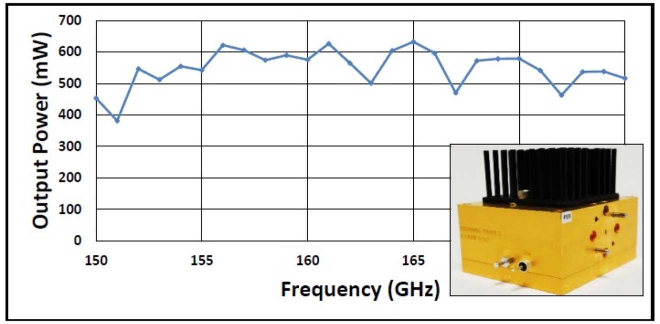
IMPACTS Science Campaign: PI Lynn McMurdie, Univ. of Washington. See McMurdie, Lynn A., et al. "Chasing Snowstorms: The Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) Campaign." *Bulletin of the American Meteorological Society* (2022).

Deployment to Scripps in JPL Cloud-Radar Trailer

EPCAPE = Eastern Pacific Cloud Aerosol Precipitation Experiment (DOE mobile ARM facility, La Jolla, CA)
PI: Lynn Russel of Scripps Institute of Oceanography
Objective is to characterize the extent, radiative properties, aerosol interactions, and precipitation characteristics of stratocumulus clouds.

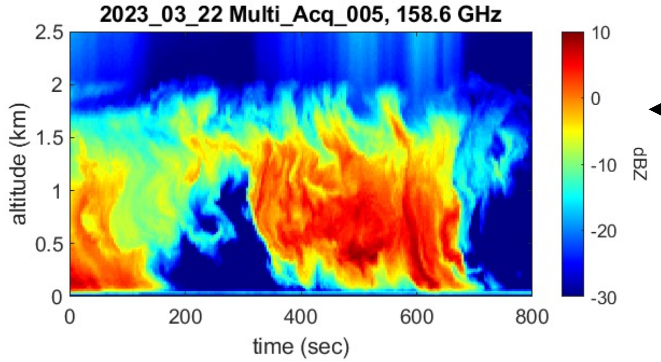


- New InP Teleyne Corp. HBT power amplifiers achieve >200 mW each.
- Virginia Diodes developed and packaged a power-combined unit with >500 mW under NASA-SBIR #80NSSC20C0147.

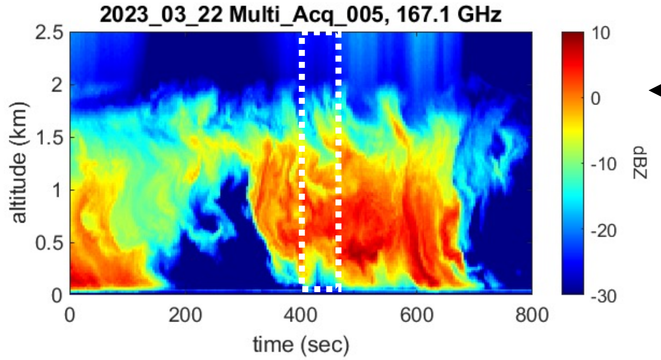


Jet Propulsion Laboratory
California Institute of Technology

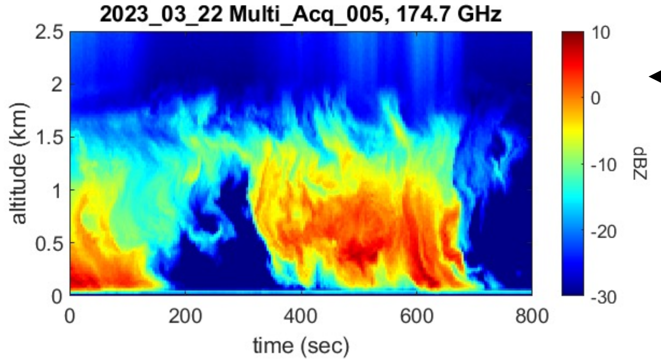
VIPR: Differential Absorption Example from EPCAPE



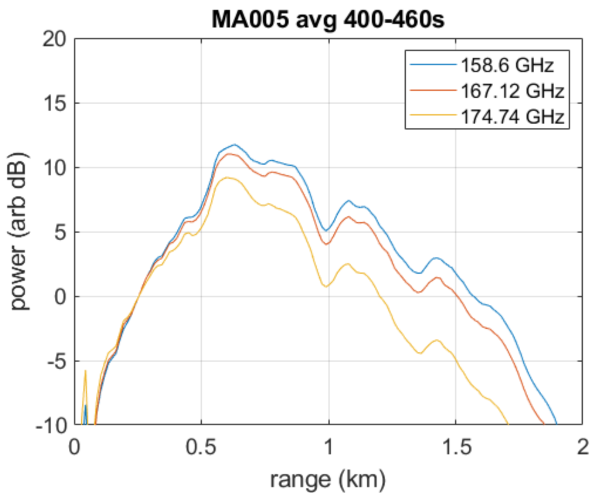
158.6 GHz



167.1 GHz

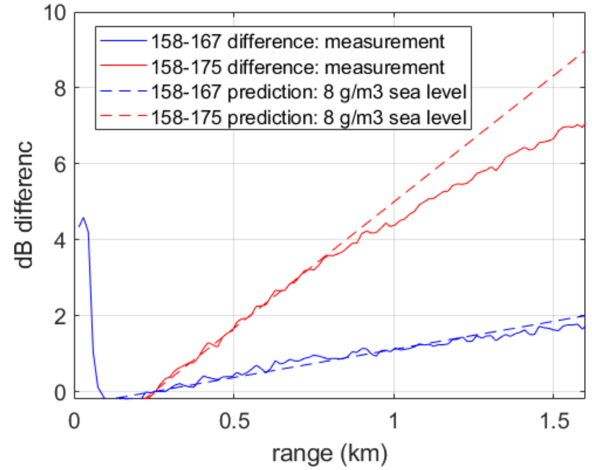


174.7 GHz



1-minute averaged reflectivity, normalized to 0 dB at 250 m

Note how the higher frequencies "peel away" at longer range (altitude).



Attenuation difference

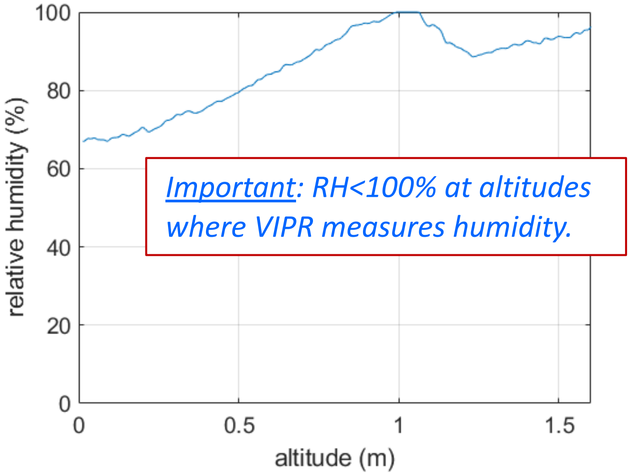
The 8 g/m^3 water vapor density was measured at sea level. Note discrepancy at higher altitude; is it from drier air?

VIPR: Differential Absorption Example from EPCAPE

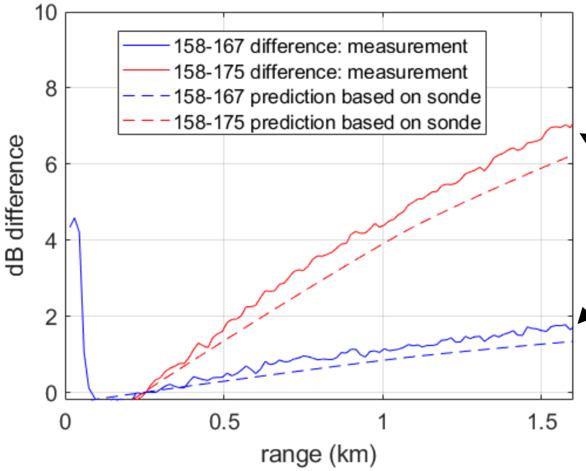
Jet Propulsion Laboratory
California Institute of Technology

Sonde launch from Scripps pier

Sonde-measured humidity

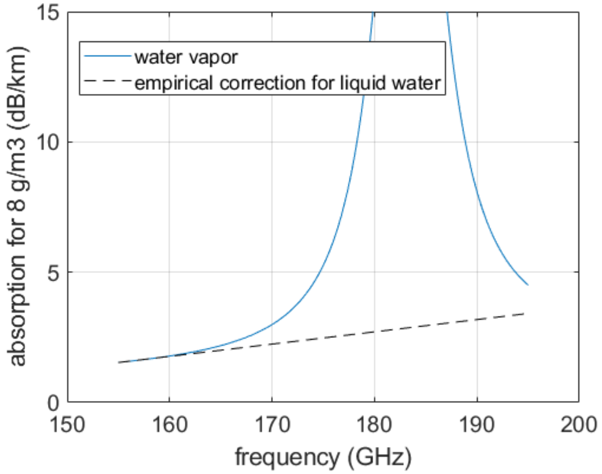


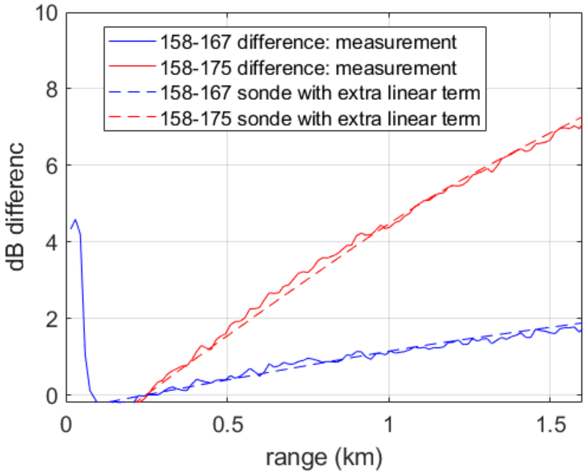
Modeling differential absorption with sonde-measured water vapor & temperature:



remaining discrepancies from liquid water differential attenuation

Modeling differential absorption with additional linear-absorption correction of 0.047 dB/km/GHz:



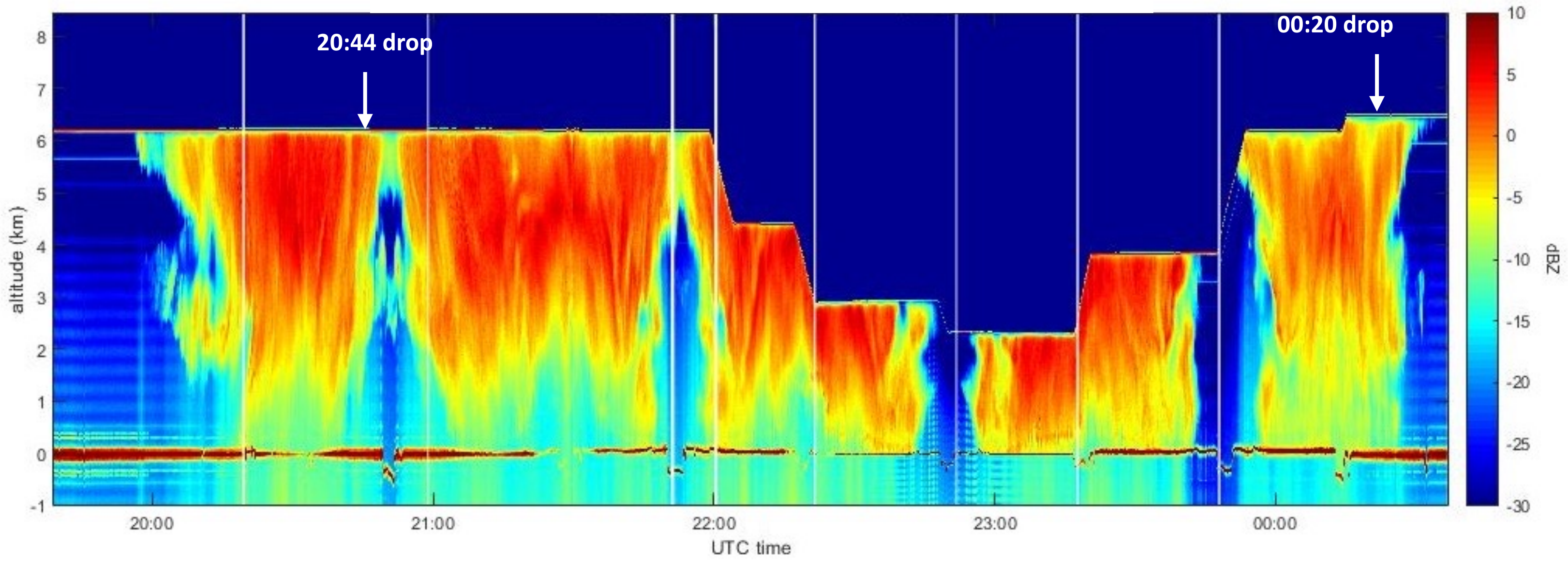


Agreement shows importance of using three frequencies, not two, to remove non-resonant non-vapor component of differential absorption.

Also this will allow us to constrain liquid water content in beam path.

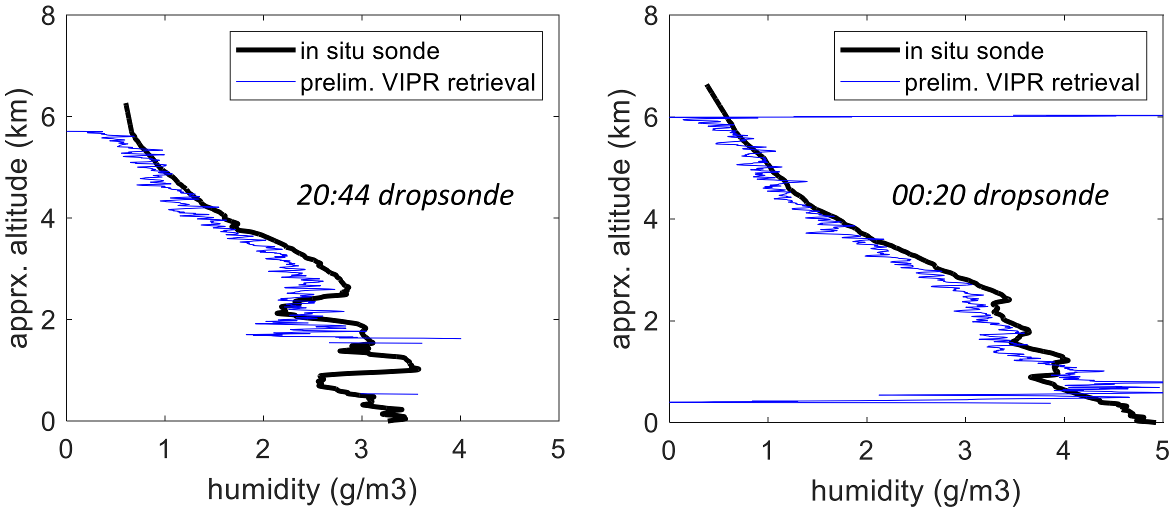
Humidity Retrieval from IMPACTS Deployment

167 GHz cloud/precipitation reflectivity: Jan 14, 2022 flight



- Flight along coastal New England on 1/14/2022
- Cloud and precipitation detection with VIPR at altitudes to above 6 km
- Humidity retrieval analysis shows very good agreement with coincident *in-situ* humidity probes dropped from the airplane

Preliminary humidity retrievals: several minutes of averaging



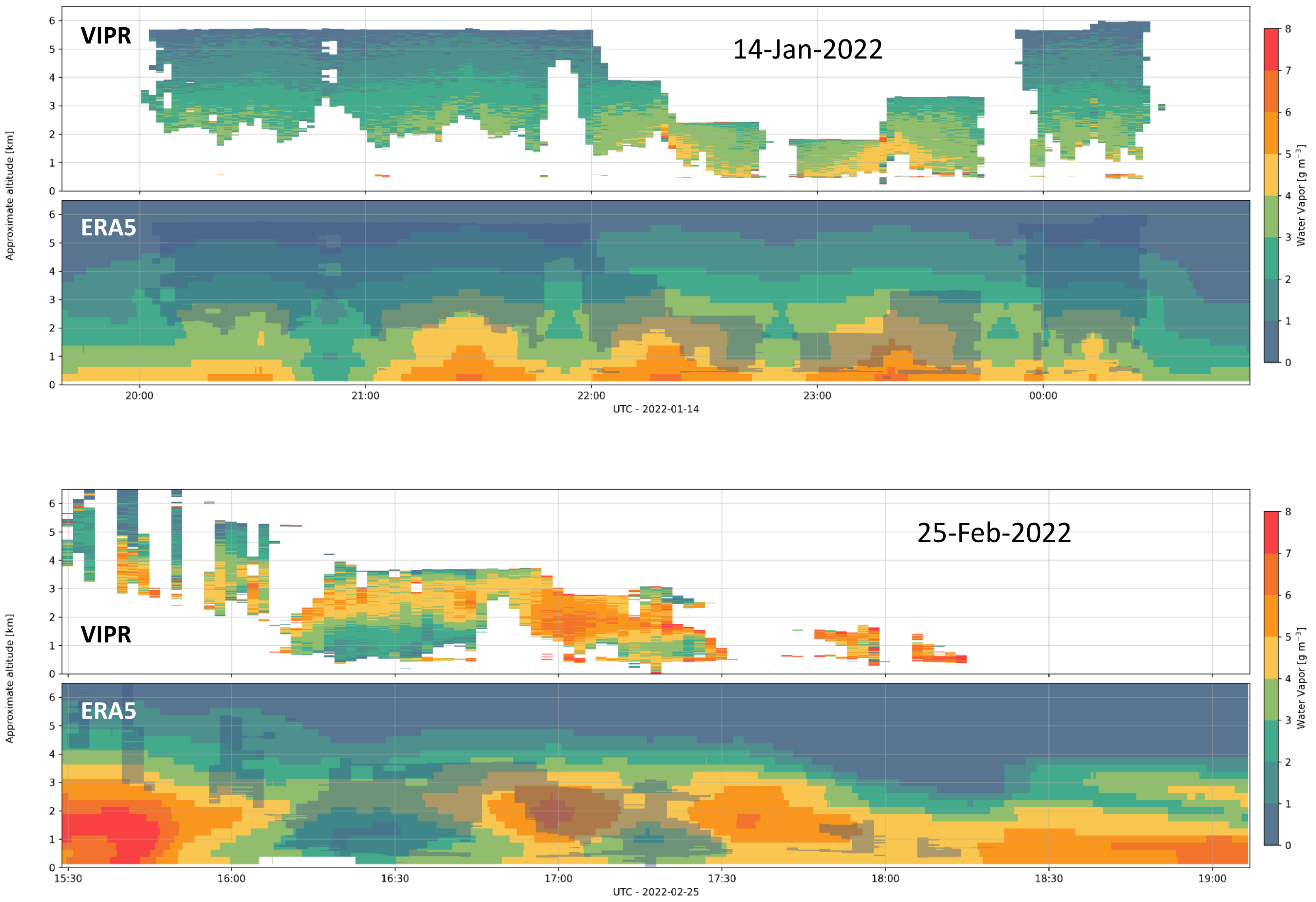
<u>*co-incident VIPR/dropsonde data:*</u>

Black: in-situ dropsonde measurements

Blue: three-frequency VIPR humidity retrieval

Jet Propulsion Laboratory
California Institute of Technology

VIPR-ERA5 Comparison

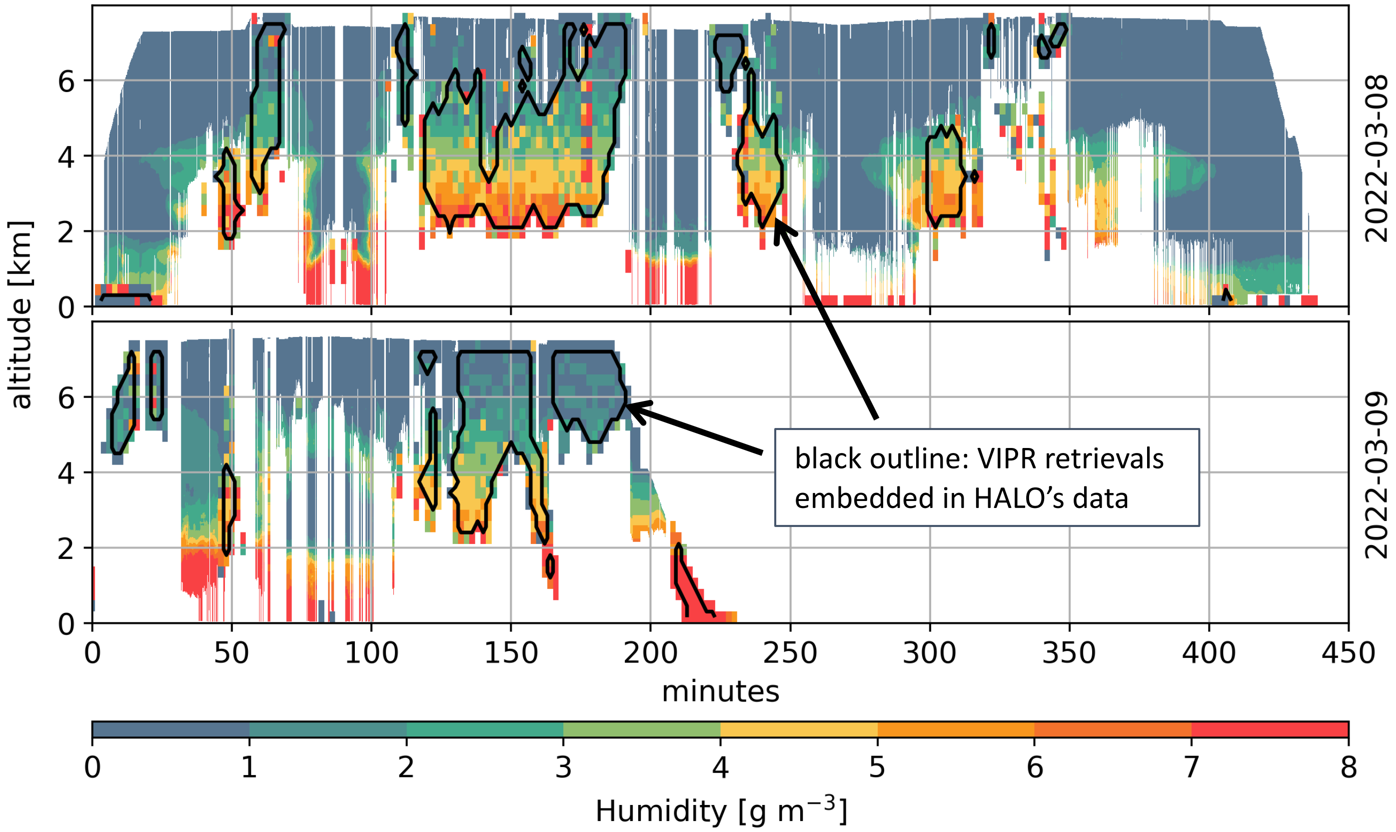


- Generally we see good agreement between VIPR water vapor retrieval ERA5 reanalysis.
- We are currently exploring some discrepancies between VIPR and ERA5 in certain conditions, including isolated, small-scale convection, where the legacy data assimilated into ERA5 does not provide high enough resolution to capture isolated convection.
- This is an example of how VIPR data could be helpful to weather forecasting.

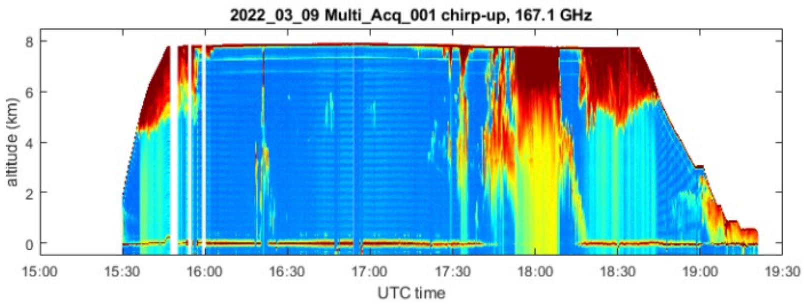
VIPR-HALO Comparison

- HALO (High Altitude Lidar Observatory) is an airborne lidar that performs differential absorption lidar measurements in clear-air using aerosol and molecular scattering. It's a highly complementary instrument to VIPR.
- These results are from March 8-9, 2022 flights under SOA²RSE, a IMPACTS follow-on set of flights led by Amin Nehrir of NASA-Langley.

- VIPR "fills in gaps" where thick clouds preclude HALO measurements
- Measured humidity shows quantitative consistency



HALO lidar instrument (flew with VIPR on P3):

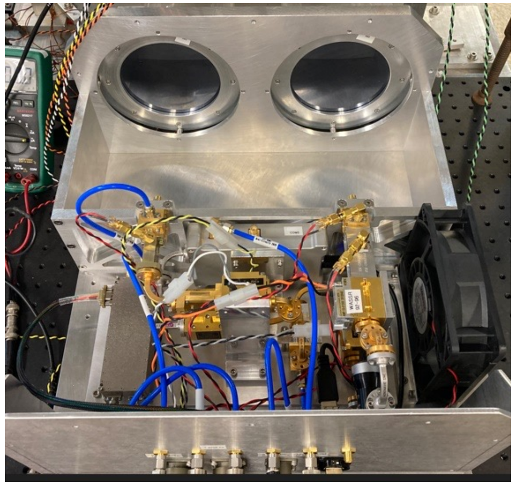


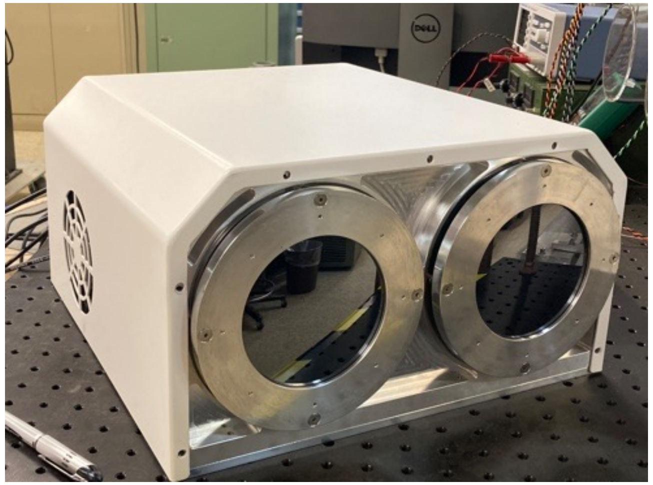
cloud curtain, 3/9/22:
shows cloudy regioins where VIPR retrieves humidity profiles.

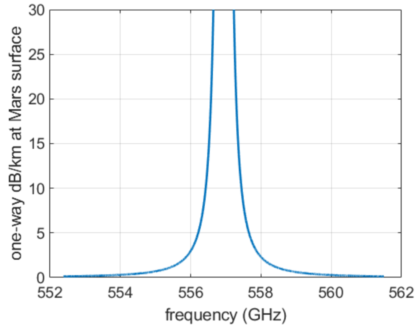
Carroll, Brian J., et al. "Differential absorption lidar measurements of water vapor by the High Altitude Lidar Observatory (HALO): retrieval framework and first results." *Atmospheric Measurement Techniques,* 2022.

Other JPL DAR Directions

Internal JPL R&D investment: coherent staring array of 20-cm diameter 170 GHz solid-state sources. Electronic phase control, electro-mechanical beam steering.







JPL MatISSE: 557 GHz DAR prototype for humidity sounding *on Mars*!

+ Northrop Grumman-led ACT (PI Ken Kreischer): tunable 167-175 GHz Traveling Wave Tube amplifier to reach 100 W for spaceborne VIPR deployment

Conclusions

- Differential Absorption Radar is an extremely promising mm/submm-wave technique requiring collaboration from climate scientists, spectroscopists, RF designers, semiconductor device microfabricators, commercial partners, and radar engineers.

- At 170 GHz, there has been strong investment and interest in potential for mapping humidity in Earth's Planetary Boundary Layer (PBL), a measurement goal highlighted by the NASA's Decadal Survey.

- For eventual spaceborne applications, a major challenge will be to reach much higher (x200) transmit power levels, but paths exist toward that goal.

VIPR Bibliography:

- Millán, et al., "Water Vapor Measurements inside clouds and storms using a Differential Absorption Radar," in preparation.
- Roy, et al., "First Airborne Measurements with a G-band Differential Absorption Radar," IEEE Transactions on Geoscience and Remote Sensing, 2022.
- Cooper, et al., "Improving FM Radar Dynamic Range Using Target Phase Noise Cancellation," IEEE Journal of Microwaves, 2021.
- Roy, et al., "Spaceborne differential absorption radar water vapor retrieval capabilities in tropical and subtropical boundary layer cloud regimes," Atmos. Meas. Tech., 2021.
- Lamer, et al., "First light multi-frequency observations with a G-band radar," Atmos. Meas. Tech., 2020.
- Cooper, et al., "A G-band Radar for Humidity and Cloud Remote Sensing," IEEE Transactions on Geoscience and Remote Sensing, 2020.
- Roy, et al., "Validation of a G-band differential absorption cloud radar for humidity remote sensing," Journal of Atmospheric and Oceanic Technology, 2020.
- Roy, et al., "Boundary-layer water vapor profiling using differential absorption radar," Atmos. Meas. Tech., 2018.
- Siles et al., "A New Generation of Room-Temperature Frequency Multiplied Sources with up to 10x Higher Output Power in the 160 GHz - 1.6 THz Range," IEEE TTST, 2018.
- Cooper, et al., "Atmospheric Humidity Sounding Differential Absorption Radar Near 183 GHz," IEEE Geoscience and Remote Sensing Letters, 2018.
- Millán, et al., "Differential absorption radar techniques: surface pressure," Atmos. Meas. Tech., 2014.
- Millán, L., et al., "Differential absorption radar techniques: water vapor retrievals, Atmos. Meas. Tech., 2016.