# Aerosol Wind Profiler (AWP) Doppler Wind Lidar Airborne Observations During the NOAA Joint Venture 3-D Wind Measurement Demonstration and NASA Active-Passive Profiling Experiment (APEX)

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# Aerosol Wind Profiler Background

**NASA's Langley Research Center (LaRC) and Beyond Photonics were funded by the Earth Science Technology Office (ESTO) in 2017 to develop a next-generation 2-micron heterodyne-based DWL transceiver called the Wind-Space Pathfinder (Wind-SP), featuring key subsystems and technologies designed for space readiness**

- Wind-SP leveraged heritage of the LaRC Doppler Aerosol WiNd (DAWN) lidar initially developed in the late 2000's
- See Bedka et al. (AMT, 2021) and Kavaya et al. (JOAT, 2014) to learn more about DAWN

**Wind-SP generated a two LOS 60 cm telescope concept for wind vector measurement and several new technologies:**

(1) High pulse energy (~60 mJ) and repetition rate (200 Hz) laser transmitter, (Yu et al. CLRC, 2022)

(2) Auto-alignment sensors and actuators for long-term maintenance of peak CDWL performance,

(3) Electro-optic (non-mechanical) selection of the transmit beam path allowing for fast switching between two LOS,

(4) Compact highly-stable and tunable reference lasers allowing for high-precision velocity measurement at long ranges (e.g., ≥ 400 km), while mitigating the impact of the high velocity orbit (Henderson et al. CLRC, 2022).

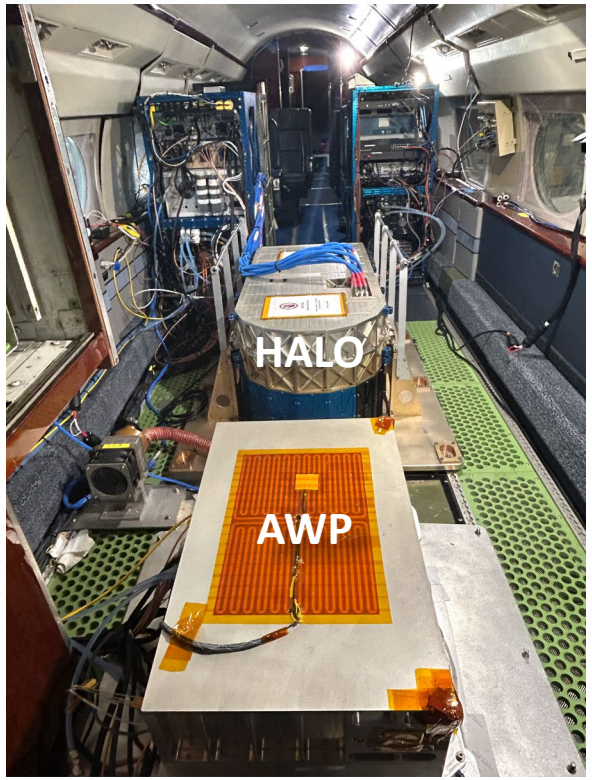
**LaRC was later funded by ESTO, NASA Earth Science Division in late 2019 to integrate the Wind-SP transceiver onto a structure for research aircraft, resulting in the Aerosol Wind Profiler (AWP). Project was completed in December 2022**

# AWP Technical Specifications

| Category | Specification |
|---|---|
| Laser Crystal | Ho:LuLiF |
| Wavelength | 2052.92 nm |
| Pump Geometry | End pumped MOPA |
| Pump Source | Thulium fiber laser, 1940 nm |
| Pump Power | 55 W |
| Pulse Energy | ~40 mJ during 2024 Flights<br>Capable of ~60 mJ (in future AWP version) |
| Pulse Rate | 200 Hz |
| Average Power | 8 W |
| Pulse Duration FWHM | ~250 ns |
| Beam Quality $M^2$ | 1.07 |
| Laser Cavity | 3.6 m folded cavity |
| AWP Dimensions | 0.8 x 0.6 x 0.4 m |
| Instrument Mass | 110 kg |
| Telescope Design | f/8, four mirror folded,<br>off-axis Cassegrain design, ø15 cm<br>primary aperture, 20x expansion ratio |
| Telescope Dimensions | 0.34 x 0.36 x 0.19 m |
| Data Storage | mySQL Database |

**Data from over 68 million laser pulses recorded during 2024 flights**

## AWP and High Altitude Lidar Observatory (HALO) Integrated onto the LaRC Gulfstream-3

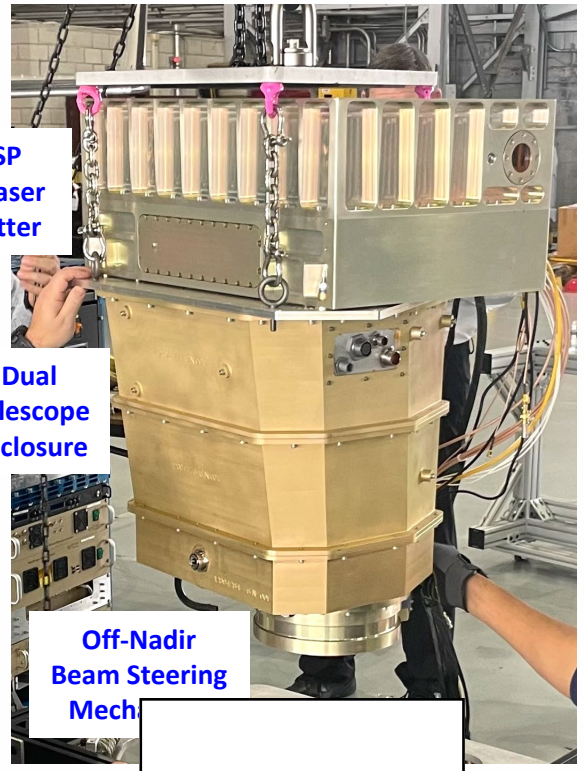



## NASA Langley Gulfstream-3 (N520NA)

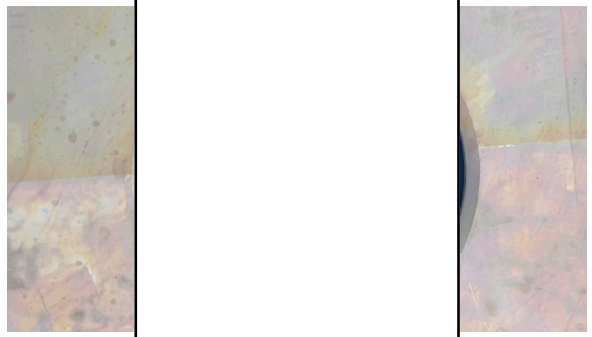


https://airbornescience.nasa.gov/aircraft/Gulfstream_III_-_LaRC

## AWP Doppler Wind Lidar

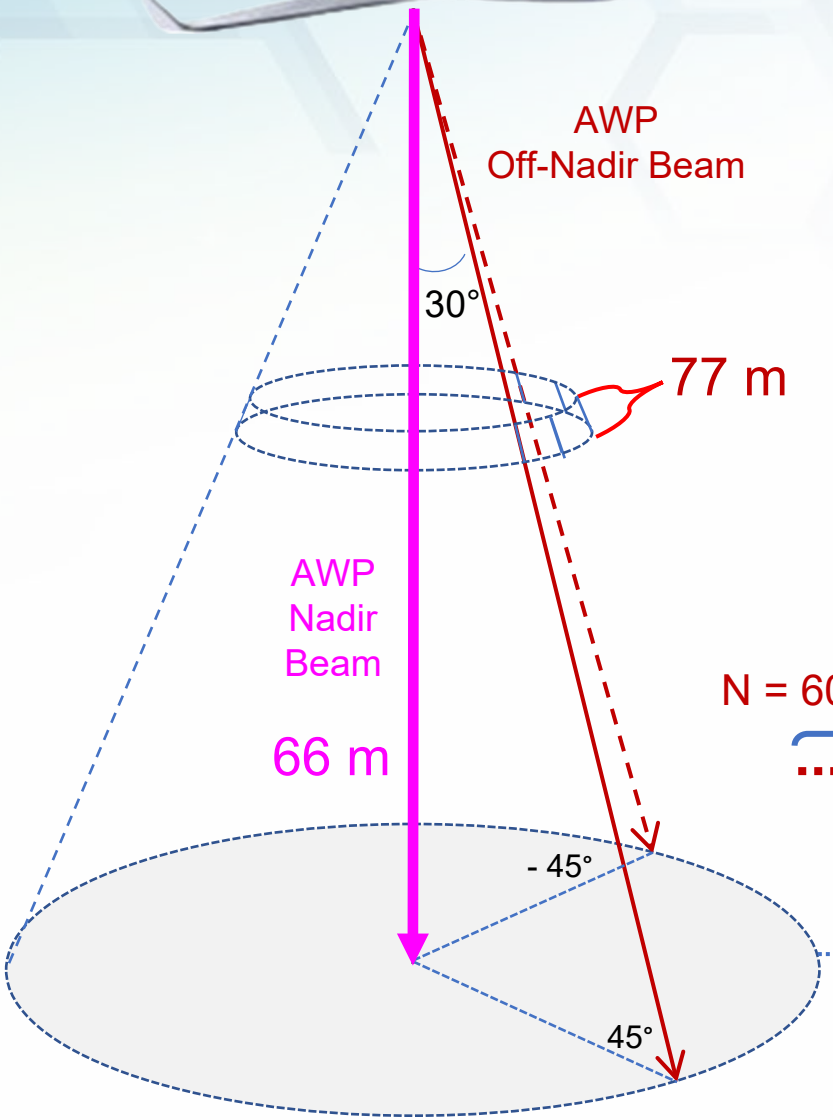



AWP Scan Window



# AWP Doppler Wind Lidar: CONOPS and Retrieval Method





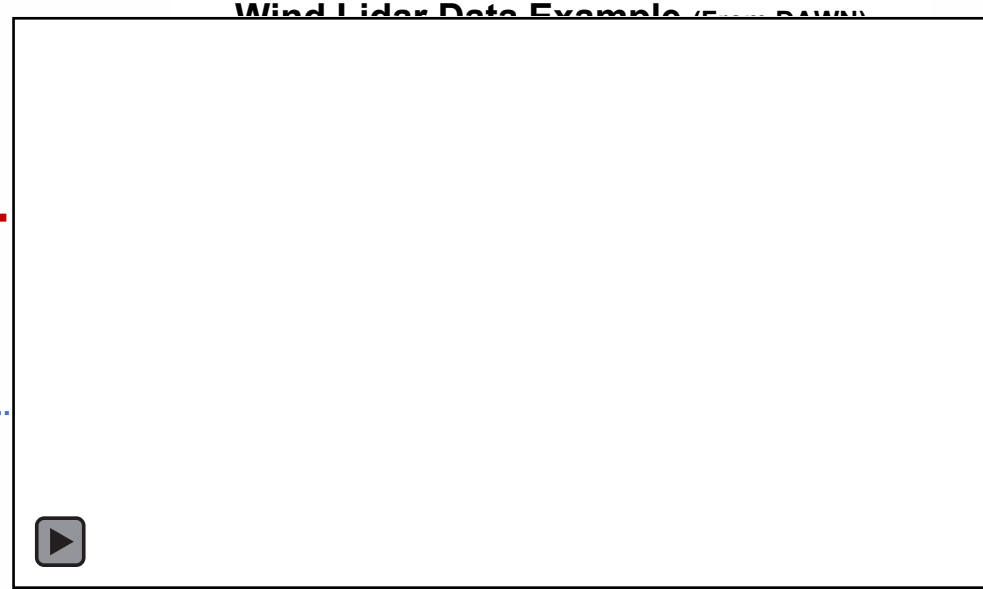

- **AWP pulses at 200 Hz along two beam paths: 1) 30° Off-nadir for vertical profiling of horizontal (U/V-component) wind, and 2) Nadir for profiling of vertical wind (W-component)**
- AWP CONOPS: Variable line of sight (LOS) azimuth with off-nadir pulses at each LOS
- While scanner is moving between LOS, lidar beam is redirected to point nadir
- After scan pattern is complete, off-nadir LOS velocities are derived and the multiple LOS profiles from the scan are combined to derive a wind vector
- Vertical signal integration performed with greater number of raw data samples in FFT calculation in regions with weak signal return
- **Data products at 66 meter vertical and variable horizontal spacing** (settings can be adjusted based on science needs). **600 pulses x 2 LOS equates to ~1.7 km spacing at jet aircraft cruise speed**
- **Products: Signal to Noise Ratio** (a proxy for aerosol backscatter), **horizontal wind speed and direction, vertical wind speed** (coming soon), **QC parameters**

## 2 Line of Sight (LOS) Operation

N = 600 Pulses

N = 200 Pulses

**Wind Lidar Data Example** (From DAWN)

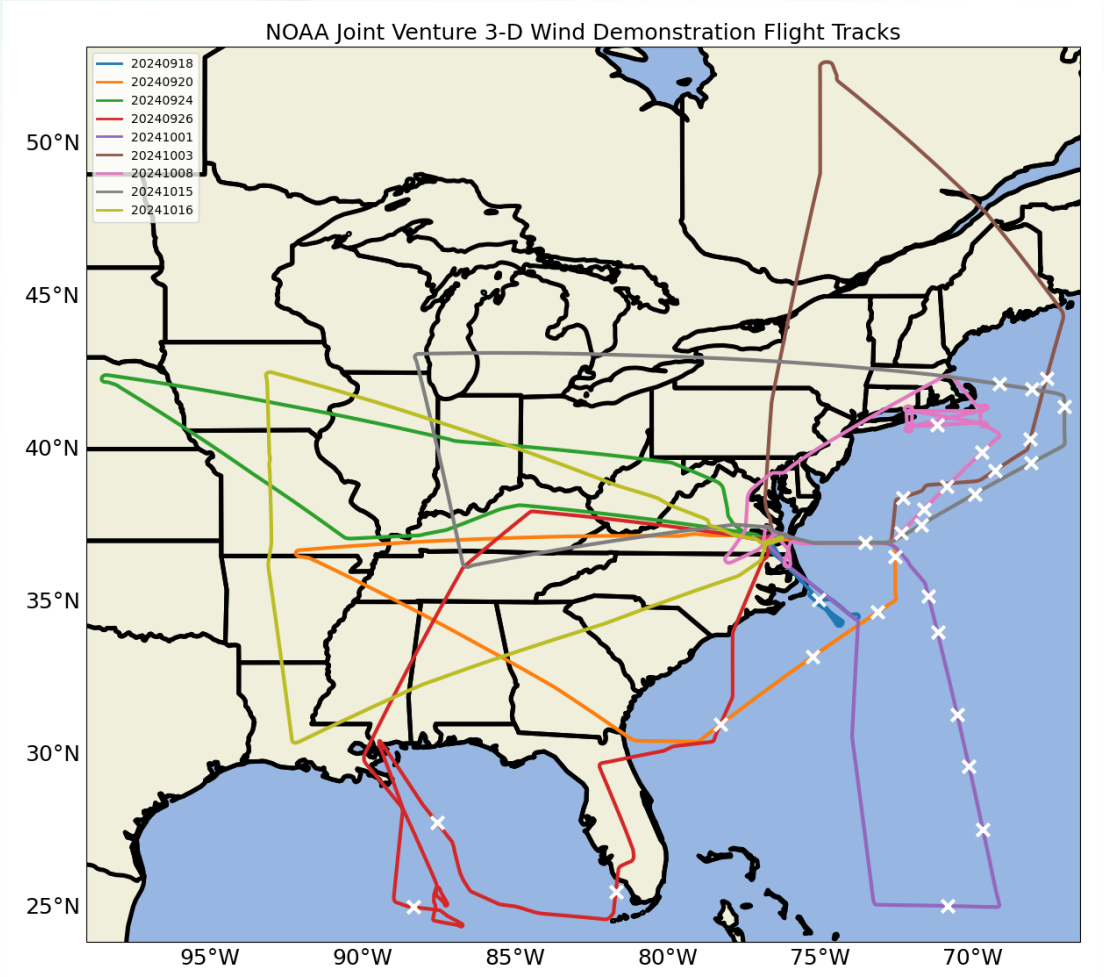


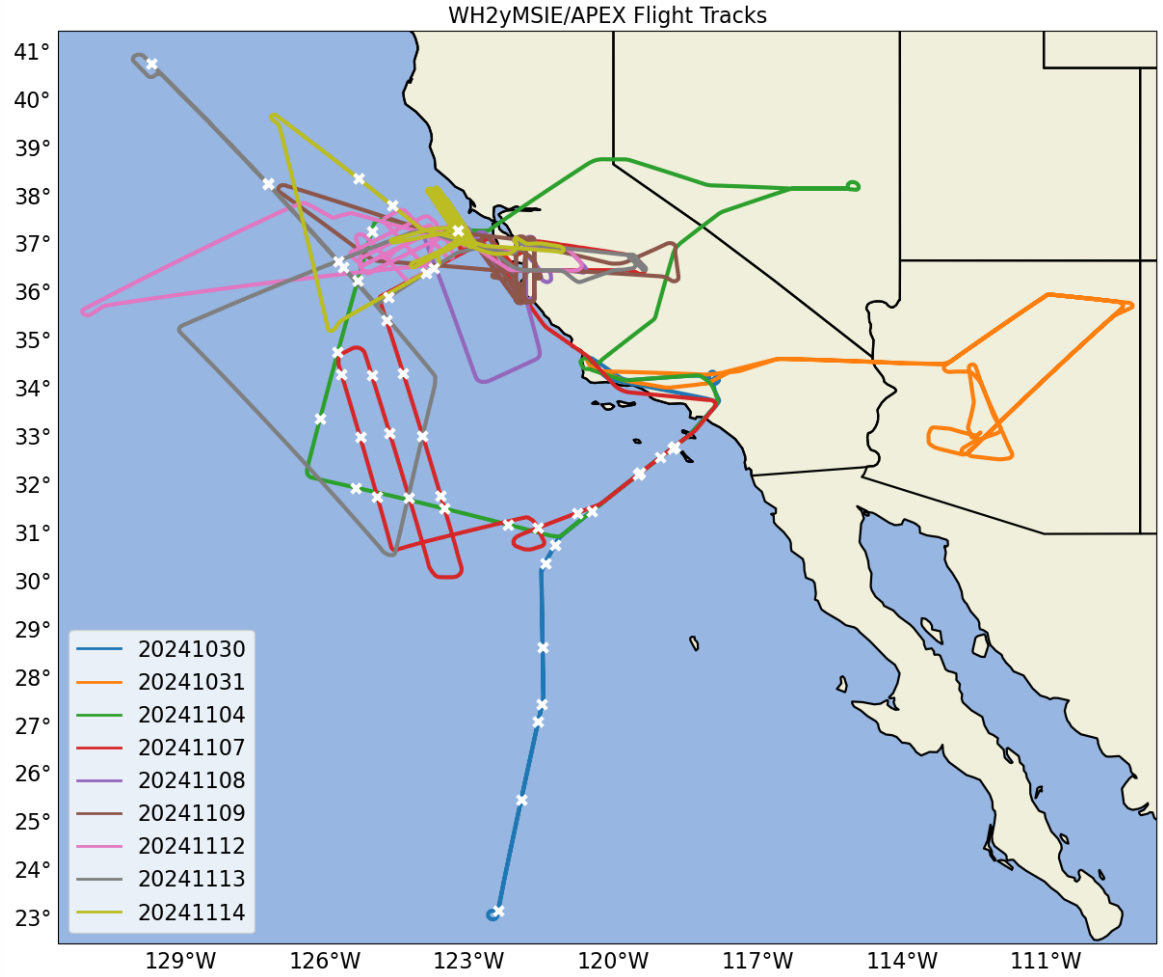
# AWP Flight Campaign Descriptions

- **LaRC was selected by the NOAA Joint Venture Program via the 2022 3-D Winds BAA to fly AWP aboard the NASA LaRC Gulfstream-3 aircraft, collect 3-D wind lidar data, and provide the data to NOAA for their assessment**
  https://www.nesdis.noaa.gov/news/noaa-awards-joint-venture-program-broad-agency-announcements
  - Joint Venture is a NOAA/NESDIS program, designed to work with the private sector, academia and other federal agencies to explore the feasibility and capability of emerging technologies, spacecraft and other mission-specific tools to meet NOAA's mission requirements
- **With the 18 Sept to 15 Oct 2024 NOAA Joint Venture sponsored flights, we are demonstrating:**
  - AWP Doppler 3-D wind and aerosol backscatter observations resulting from varied aerosol, cloud, and weather conditions over and offshore of the U.S.
  - The strengths and weaknesses of AWP and how its measurements compare with dropsondes, satellite-based wind observations, and NWP model predictions
  - How much do AWP measurements improve weather analyses and prediction model forecasts? (in collaboration with NOAA)
  - What AWP data might look like if it were collected from space?
- **AWP also flew with the NASA High Altitude Lidar Observatory (HALO) aboard the Gulstream-3 during the 27 Oct to 15 Nov 2024 NASA WH$^2$yMSIE/Active Passive PBL Profiling EXperiment (APEX) mission**
  - HALO measured aerosol intensive & extensive properties, cloud properties and water vapor profiles via the HSRL and DIAL techniques
  - APEX is a subset of WH$^2$yMSIE, focused on 1) evaluation/validation of emerging passive microwave technology aboard the NASA ER-2 2) creating a benchmark dataset for active (DIAL) / passive IR and microwave sounder retrievals of temperature and moisture for the Decadal Survey PBL Incubation program, and 3) PBL science studies in conjunction with Navy Twin Otter aircraft measurements
- **AWP data shown in this presentation is not yet publicly released, but is close to a final state**

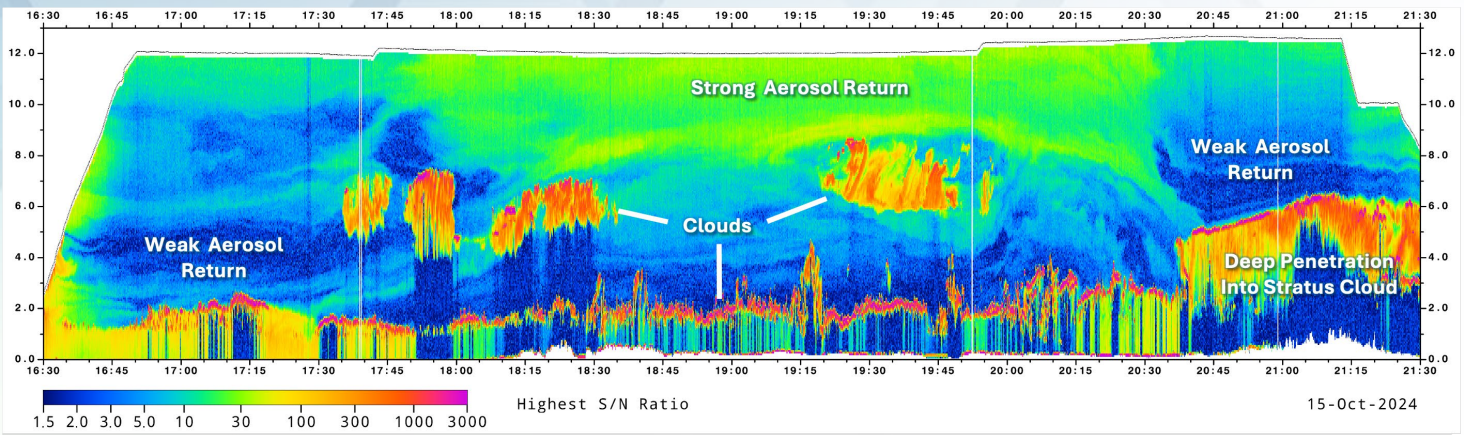
# NOAA 3-D Wind Demo and WH²YMSIE/APEX Flight Track Maps

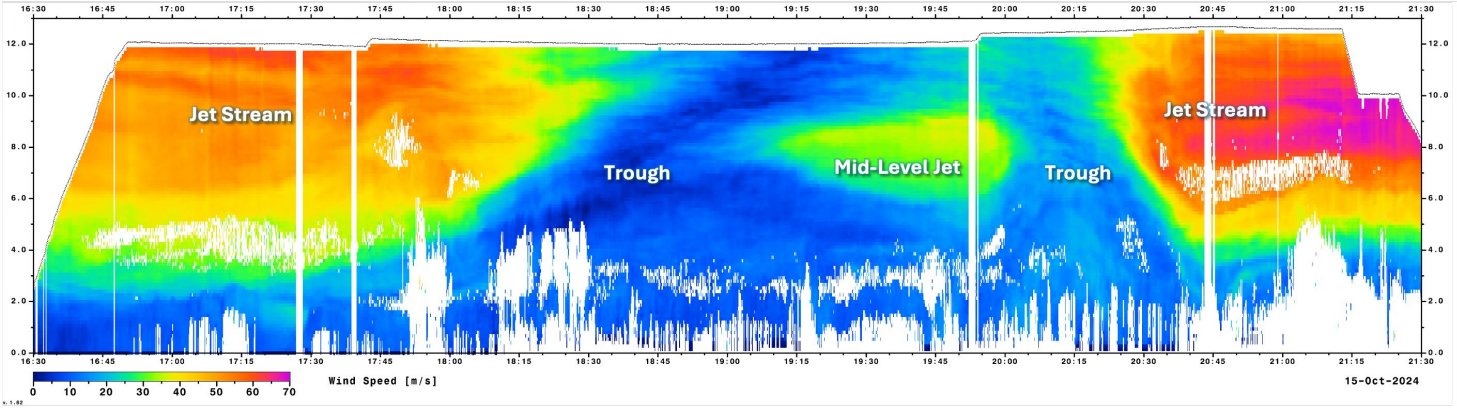
- NASA Gulfstream-3 max endurance is 5.75 hours and altitude ceiling typically limited to 41,000 feet
- 10 flights and 47 flight hours for NOAA 3-D Wind Demo based from Hampton, VA
- 12 flights and 63 flight hours for WH2yMSIE/APEX based from Santa Maria and Moffet Field, CA (Transit flight tracks not shown)
- 70 AVAPS dropsondes released (white x's below)

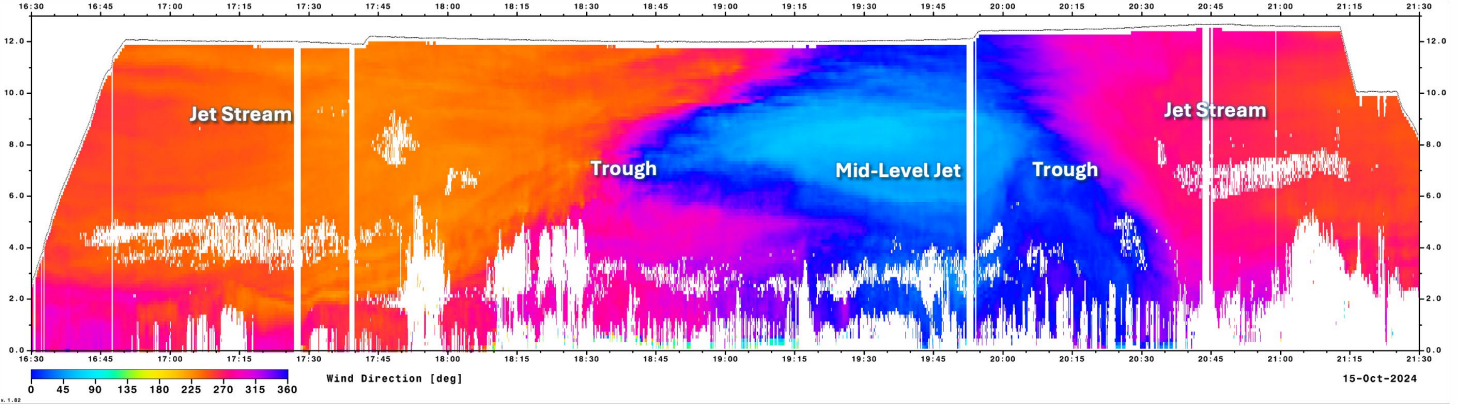


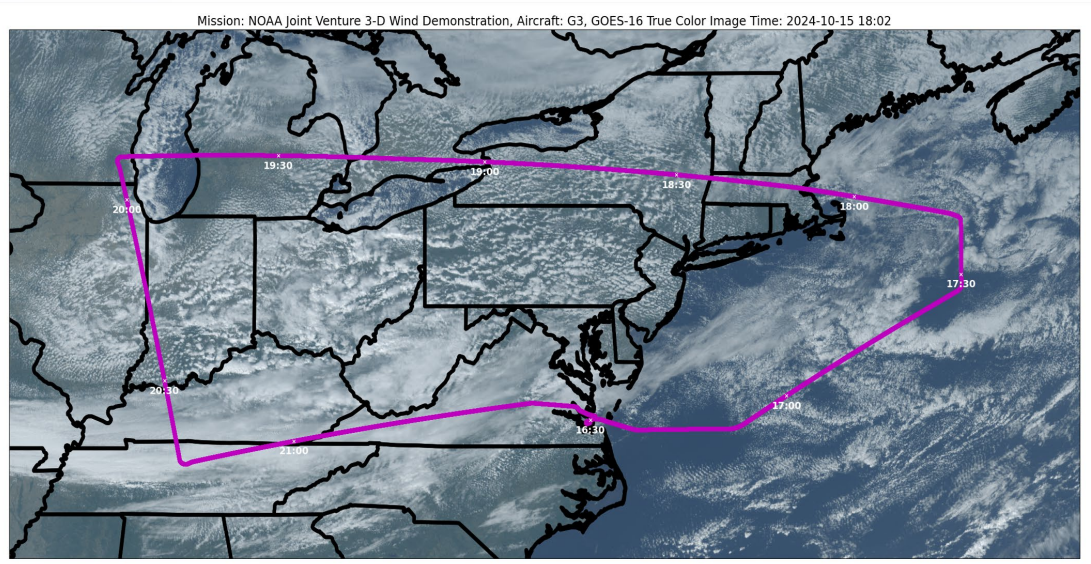



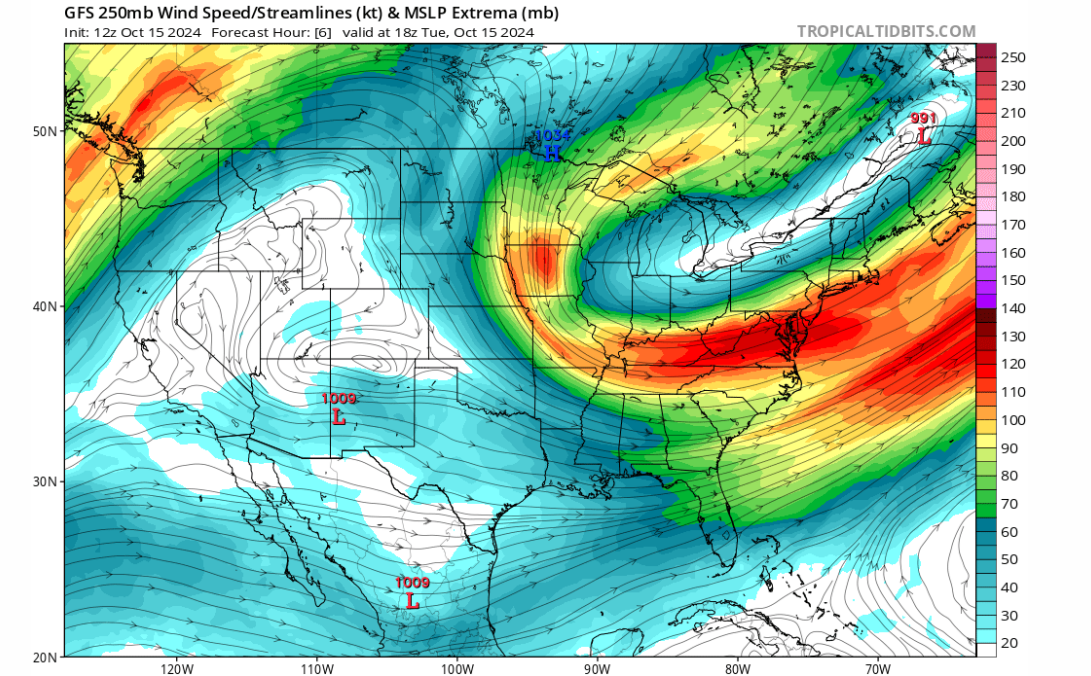
# 15 October 2024 Flight



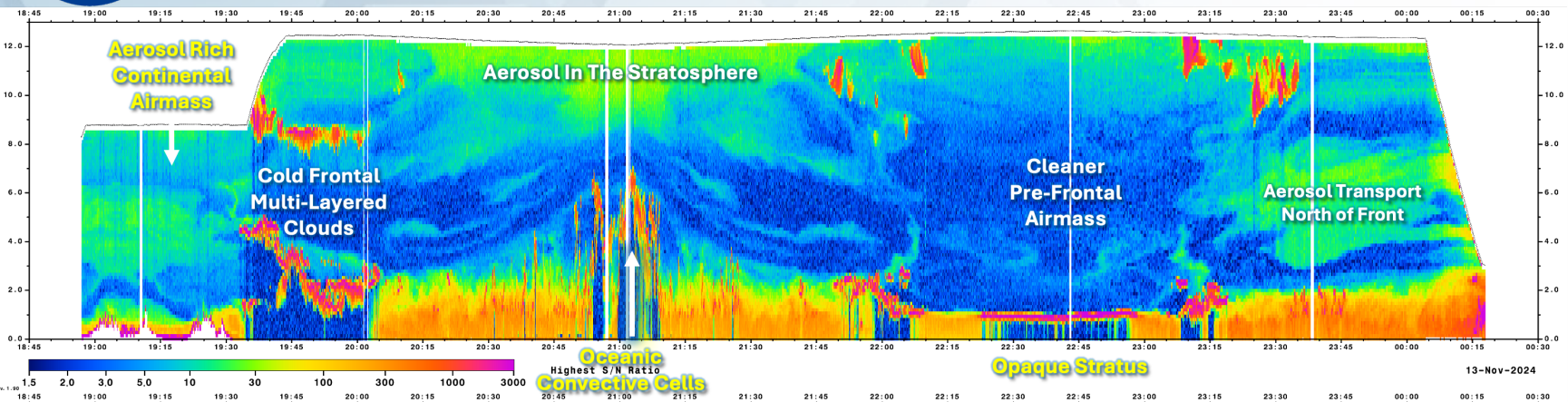



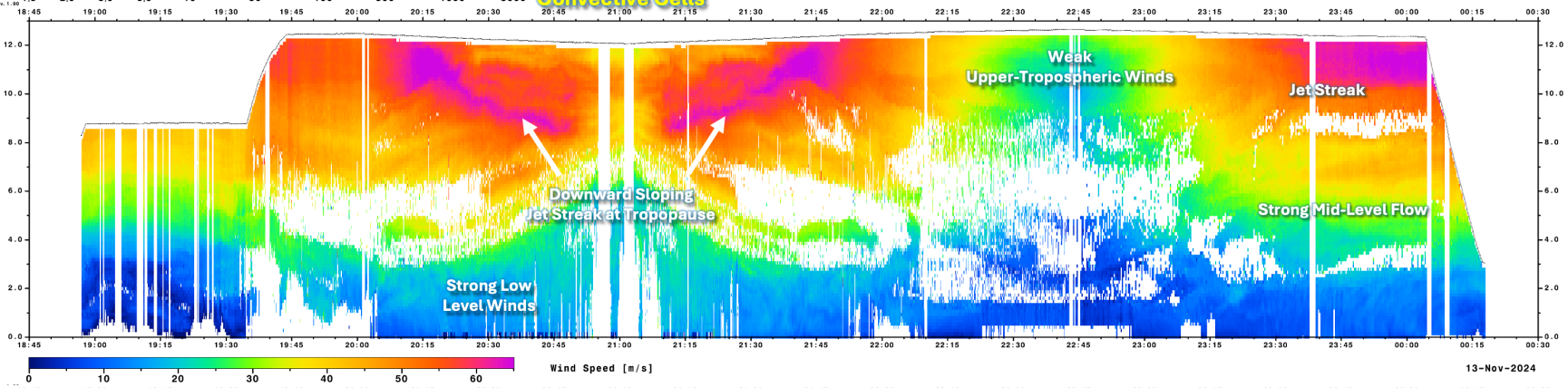



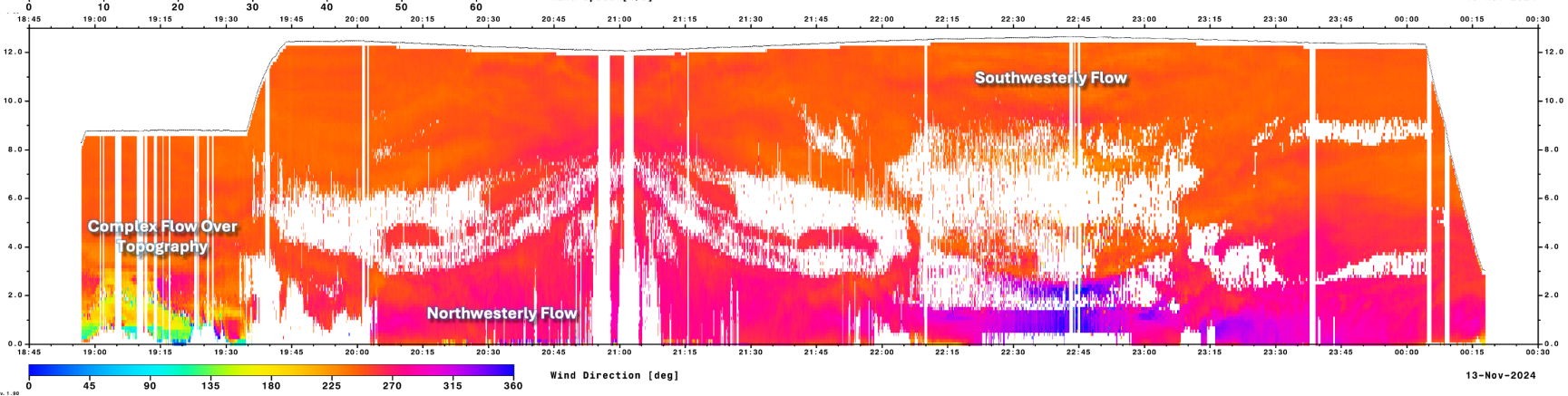



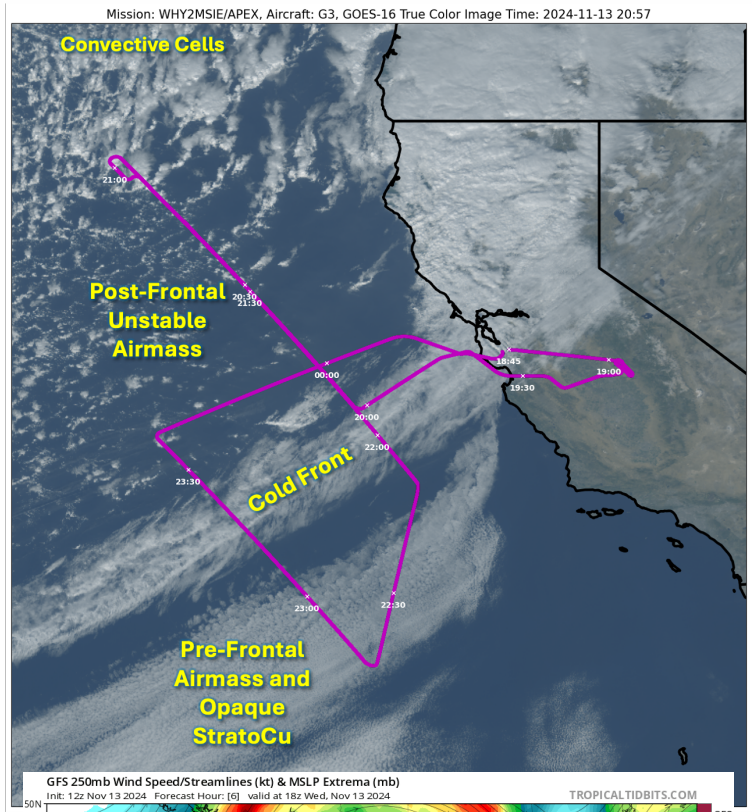



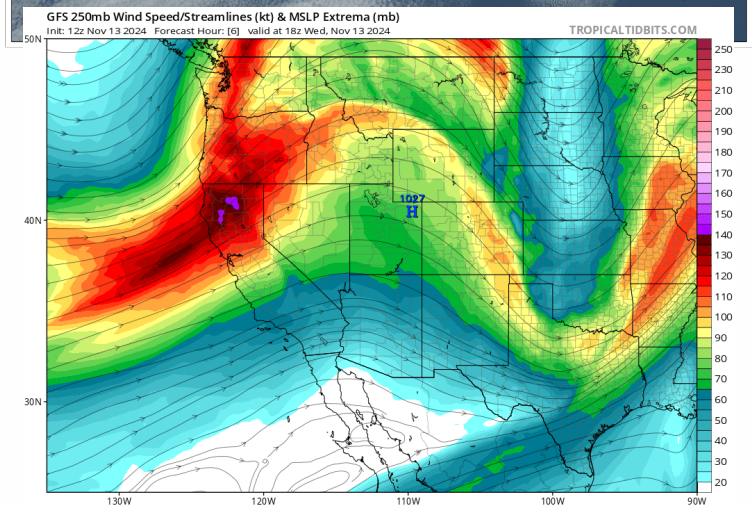
# 13 November 2024 Flight



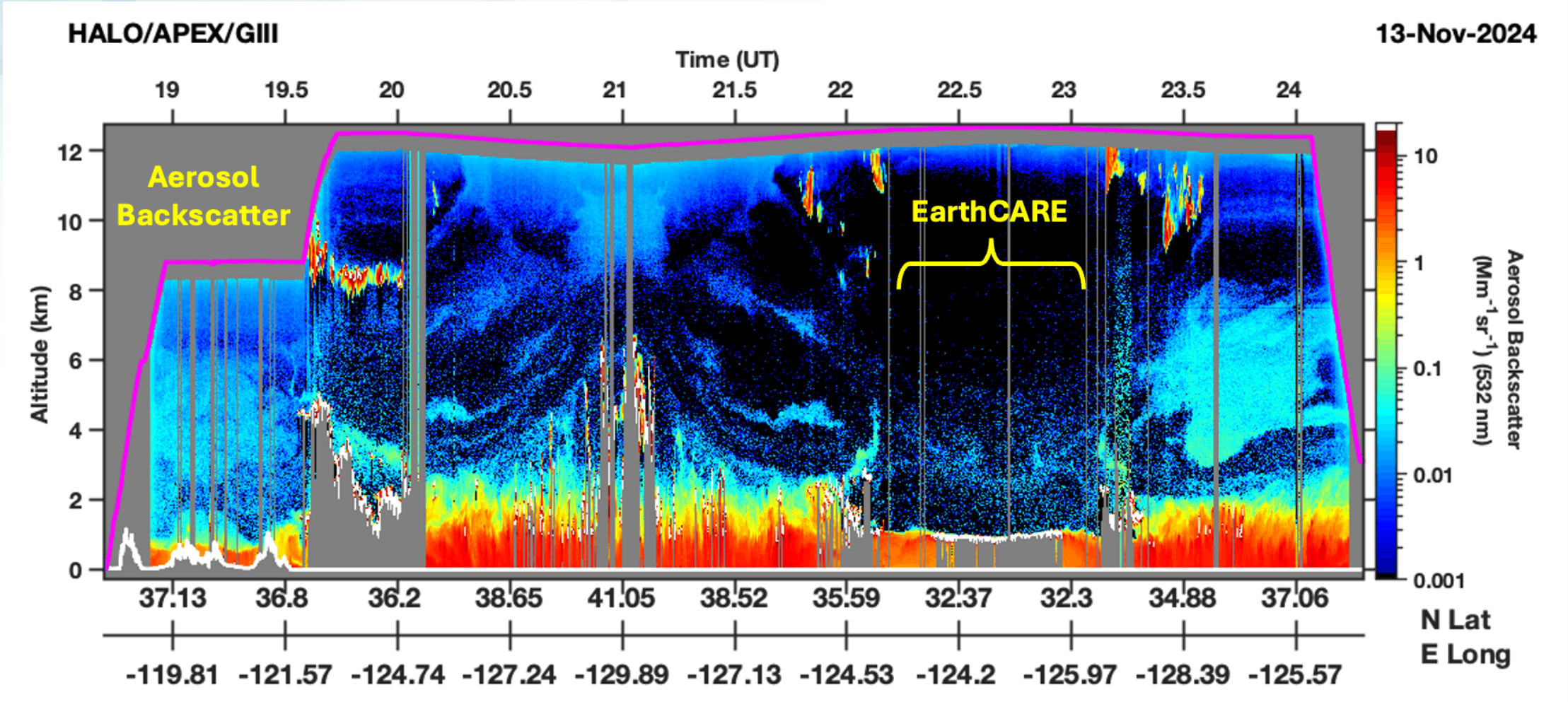



# 13 November 2024 Flight

## *Example of AWP Synergy with HALO HSRL Aerosol and DIAL Water Vapor Profiling*




**AWP and HALO data show the complex coupling between wind, water vapor, and aerosol that can be comprehensively explored with data from the two airborne missions**

HALO Data provided by Amin Nehrir (LaRC)

# 15 November 2024 Flight
# Moffet Field, CA – Hampton, VA Transit

During the transit flight, AWP was operated with longer integrations per LOS than previous flights (7.5 sec vs. 0.75-3 sec) to explore the impact of varying integration on aerosol detection and wind retrieval

Longer integration -> reduced noise floor when FFTs are averaged in retrieval, and greater sensitivity to thin aerosol

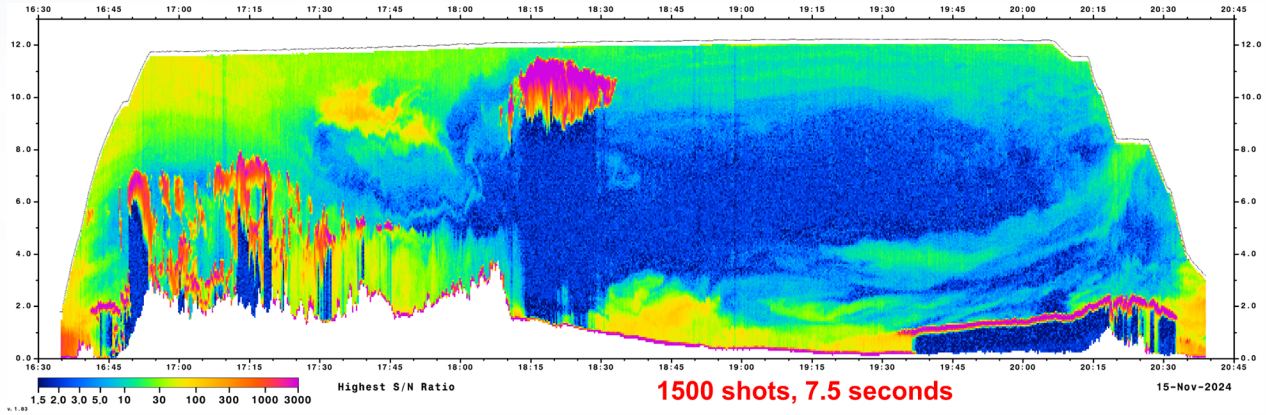
AWP is revealing comparable aerosol layering to HALO 532 nm aerosol backscatter after ~3 sec of integration

PBL aerosol, clouds, and other thicker aerosol plumes are detectable with < 0.25 sec integration

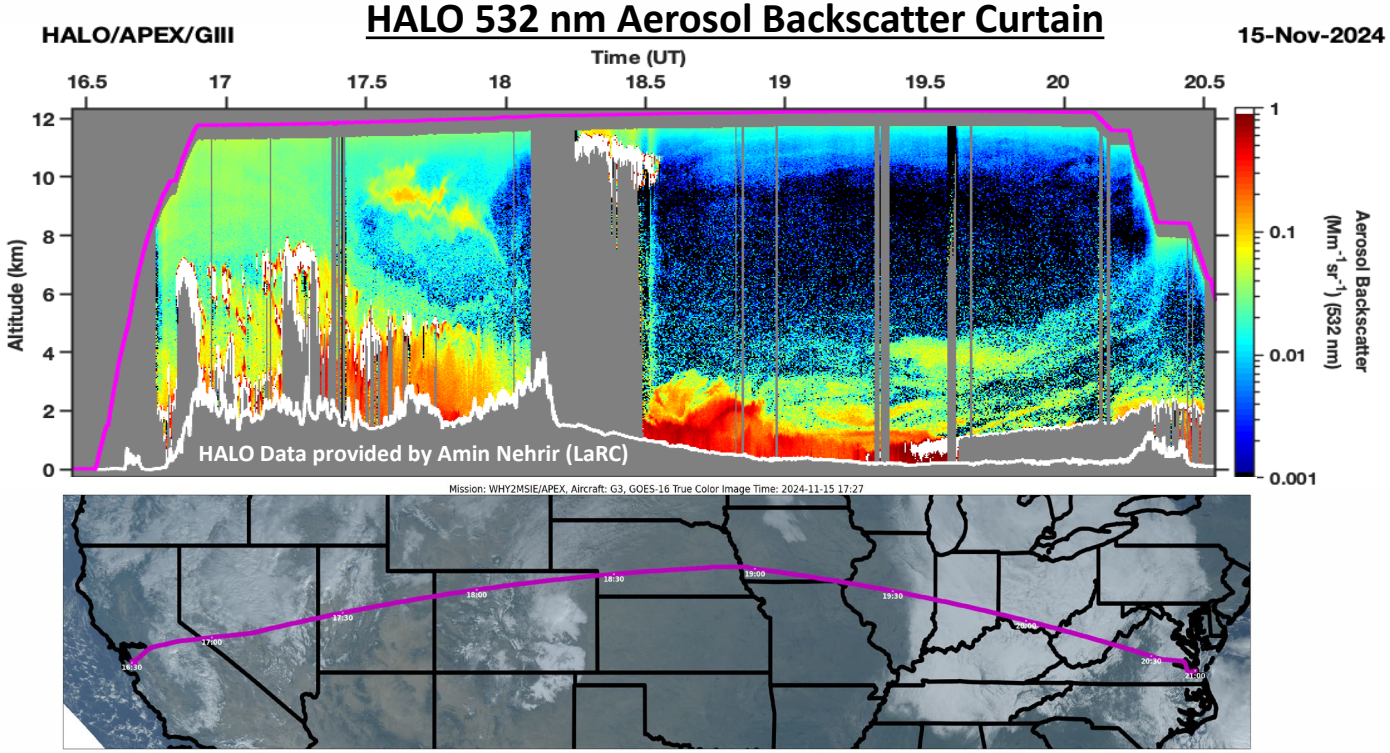
Flexibility with data processing is a favorable attribute of the AWP design, allowing one to optimize data products for science at a variety of spatial scales

Clean atmosphere, like that in the mid-troposphere in the second half of the flight, is an inherent challenge for AWP that is solely dependent on Mie scattering

## AWP SNR With 7.5 sec Integration Duration




## HALO 532 nm Aerosol Backscatter Curtain



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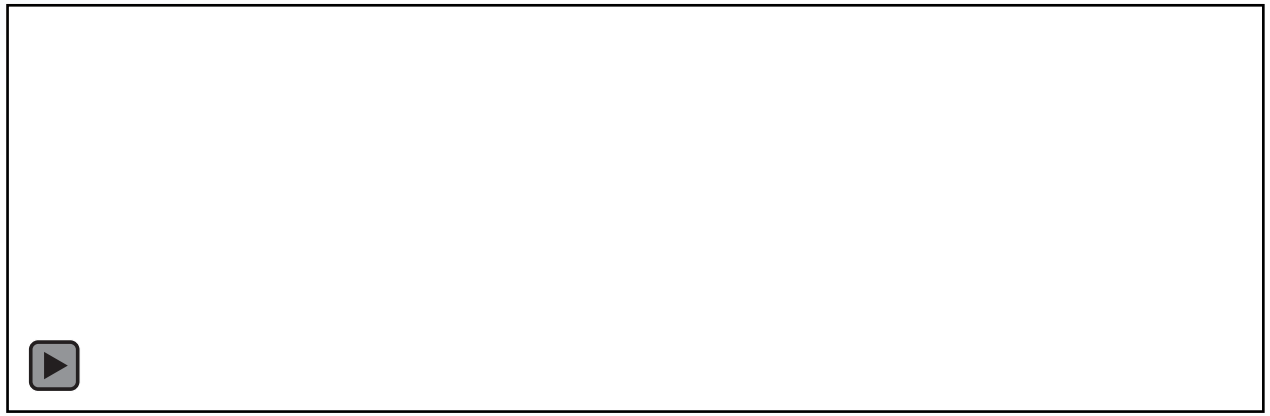
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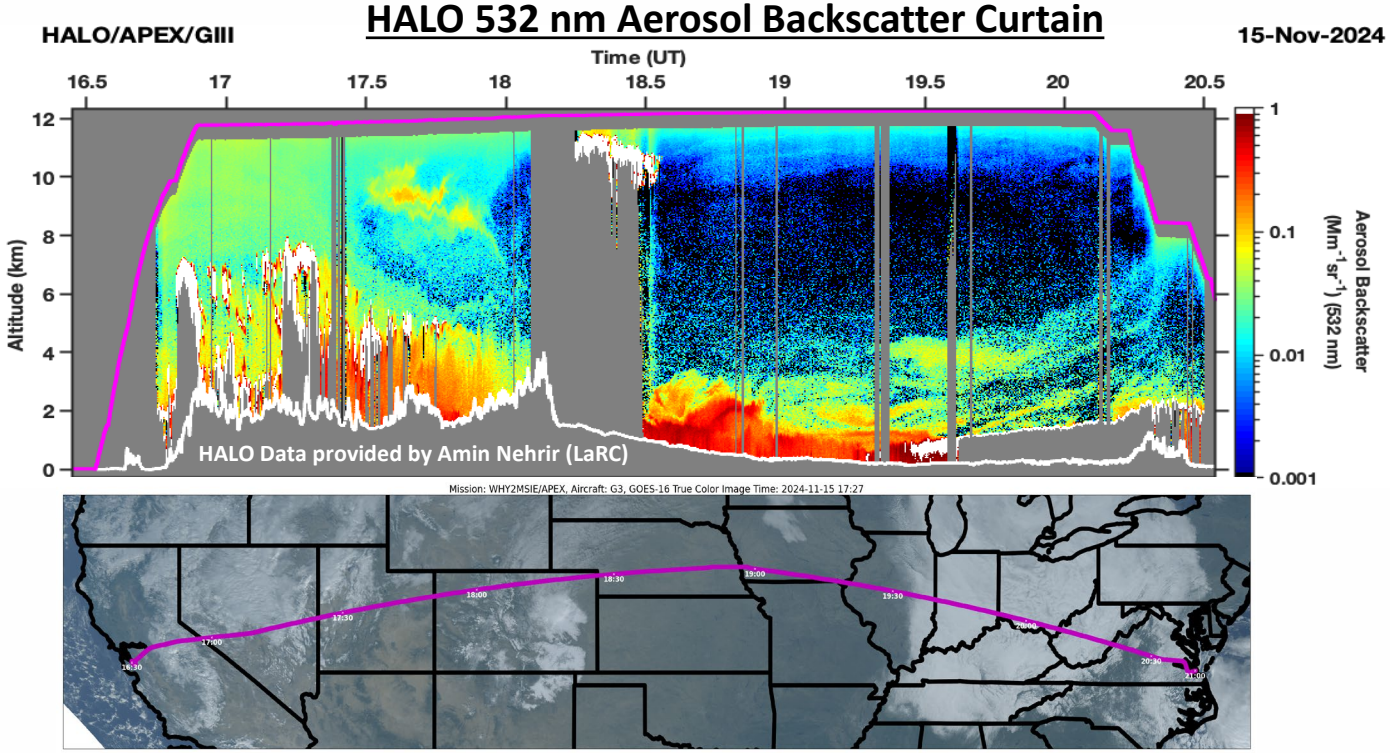
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## AWP SNR Curtain Animation With Varying Integration Duration

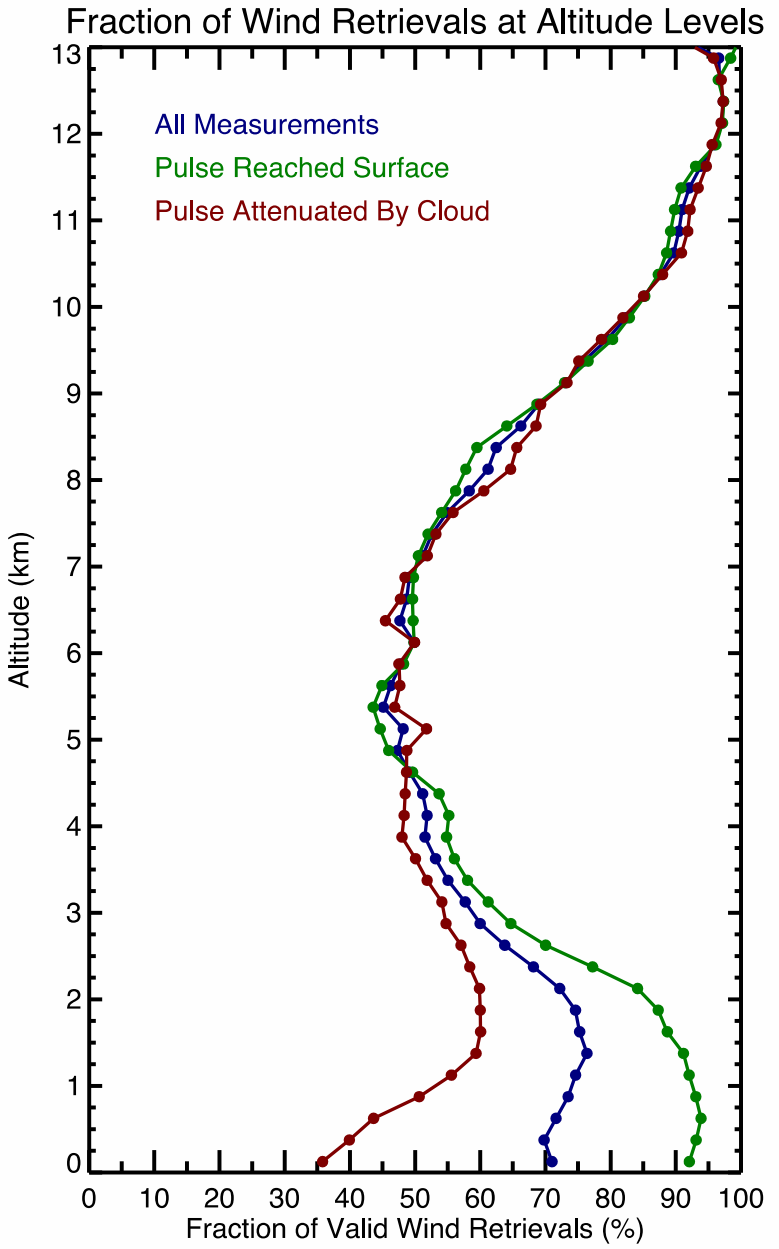


## HALO 532 nm Aerosol Backscatter Curtain



# Wind Vertical Coverage Analysis

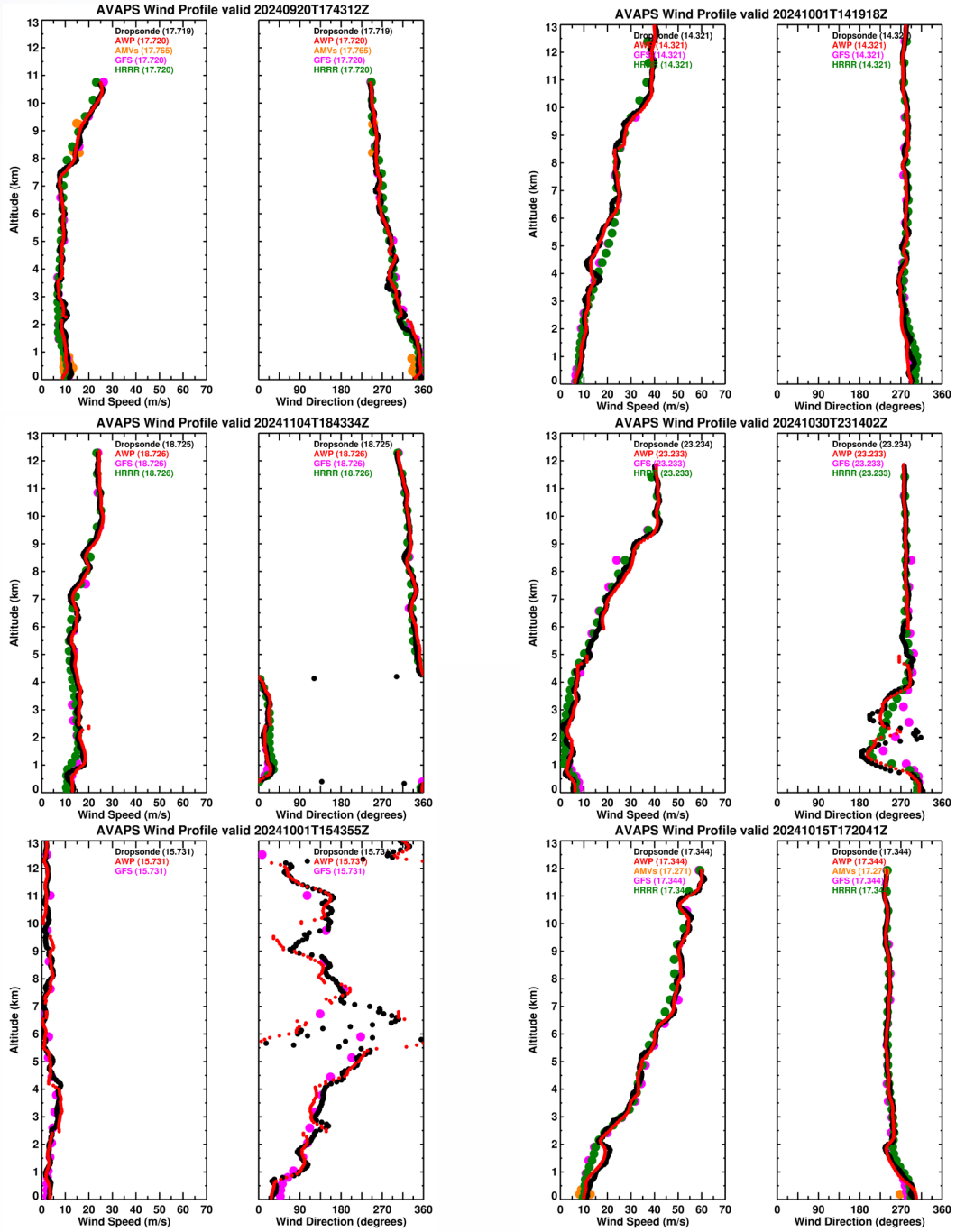
- The vertical coverage of wind retrievals from aerosol and cloud returns quantified for all NOAA 3-D Wind Demo and NASA APEX flights
- Analysis restricted to periods when the Gulfstream-3 was flying ≥ 11.5 km, a nominal cruise altitude for this aircraft
- For profiles where the pulse reached the surface, there was sufficient aerosol backscatter for a wind retrieval for 50-95% of all profile opportunities, highest in the upper-troposphere and PBL
- Aerosol backscatter and retrieval frequency were weakest on average within the 4-7.5 km layer
- Clouds above 5 km were often transparent enough to pulse through, but stratus and thick cumulus at lower levels are too optically thick, resulting in 35% retrieval frequency in the near-surface layer



# AWP Comparisons With AVAPS Dropsonde

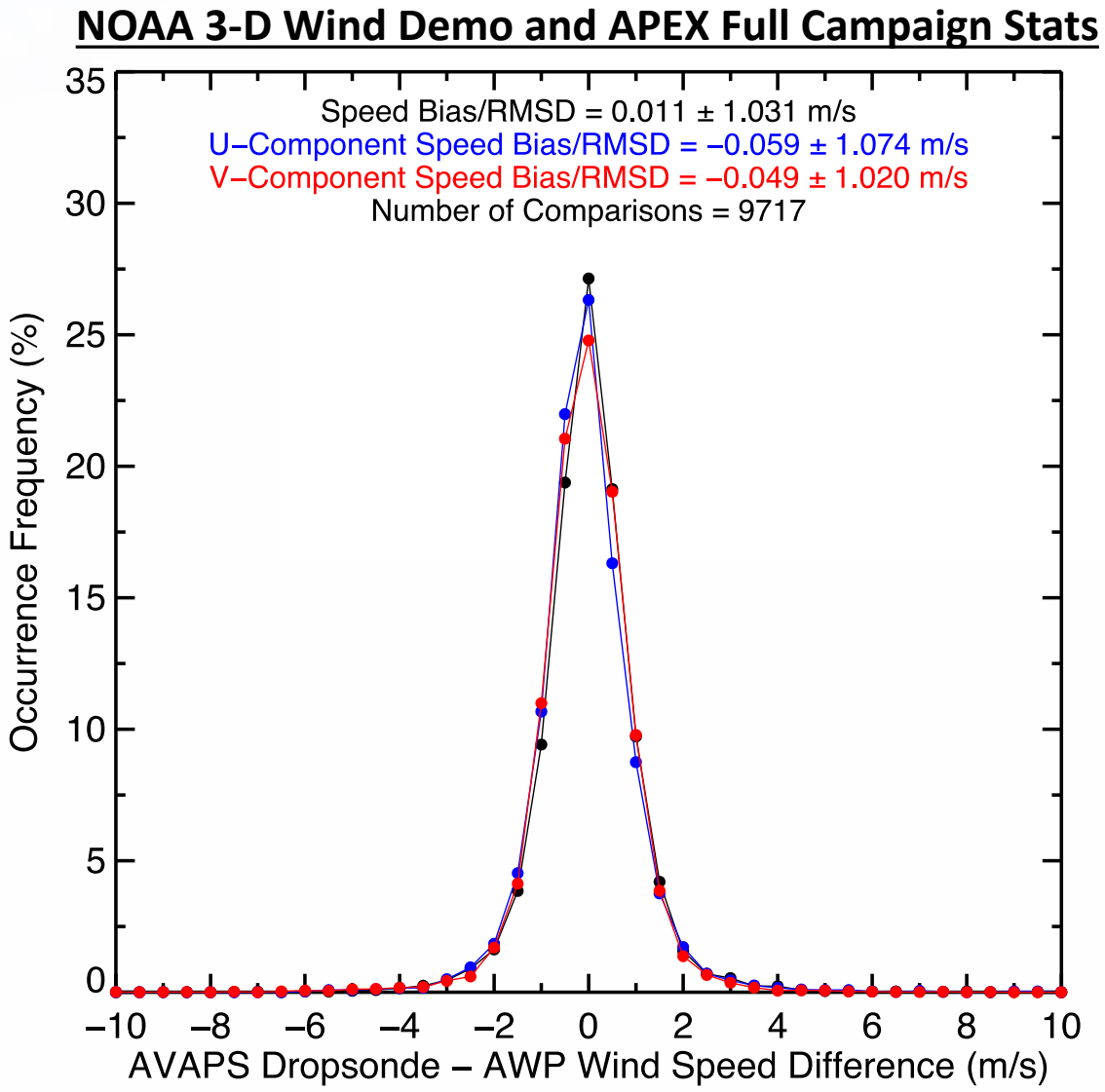
- AWP data was weighted-averaged over a 150 sec window, equating to a 30 km window at aircraft cruise speed, centered on the sonde release
- Averaging done to account for wind spatial variability measured by sonde as it drifts from aircraft track when released from 10+ km altitude
- Outliers, > 10 m/s difference from sonde, were excluded from comparisons: only 0.2% of samples
- AWP exhibits excellent agreement with AVAPS on average, consistent with results achieved from prior wind lidar campaigns with the NASA DAWN instrument (e.g. Bedka et al. 2021; Greco et al. 2020)
- This supports use of AWP as validation for satellite wind observations and NWP model forecasts, as well as for weather process studies

## Examples of AWP, GFS, HRRR, GOES AMV and Sonde Comparisons



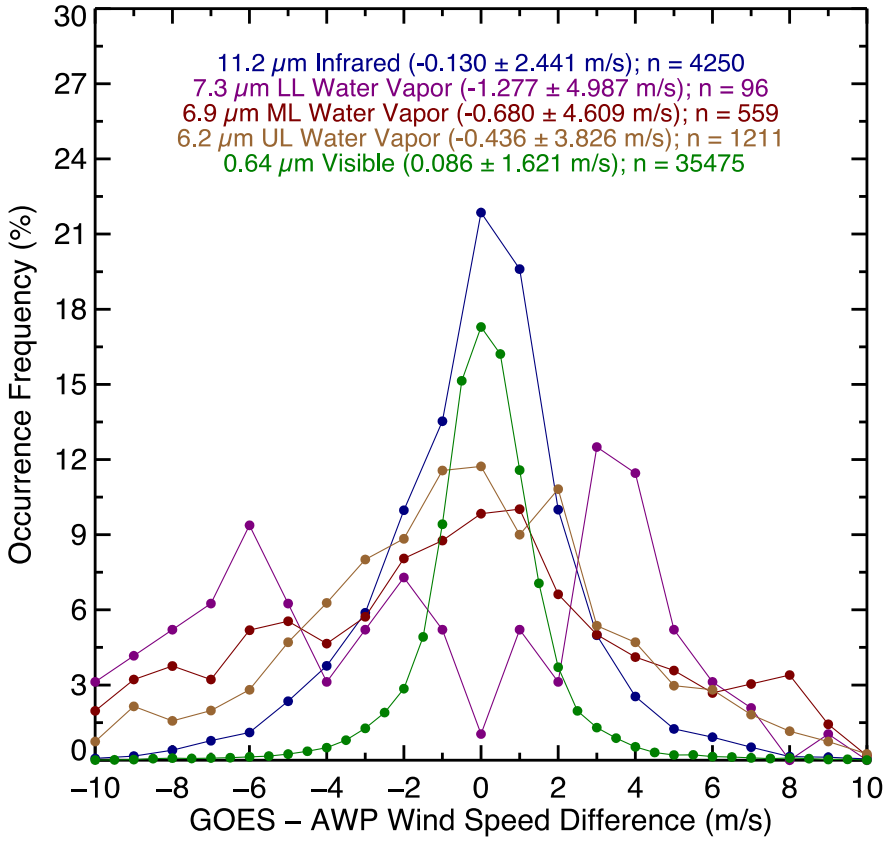
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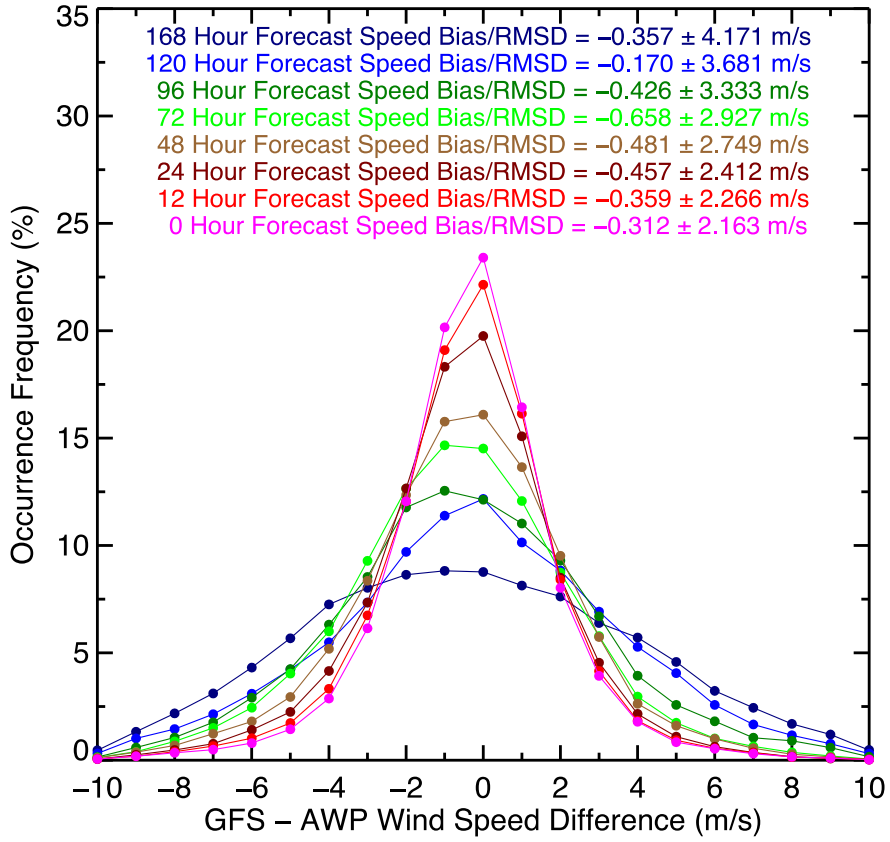
# AWP Comparisons With GOES-16/18 Atmospheric Motion Vectors and NOAA GFS Model Analyses / Forecasts

## GOES-16+18 AMVs




- **Visible AMVs were most precise, but are limited to the 0-3 km altitude layer where winds are weakest on average**
- **When analyzed as a function of % difference from AWP winds, visible, IR window, and 6.2 µm water vapor AMV were extremely comparable (not shown). ~50% of these AMVs were within 10% of AWP speed**

## GFS Model Initial Analysis and Forecasts




- **GFS wind uncertainty relative to AWP steadily increased with increasing forecast lead time**
- **Uncertainty increased by 25% at 48 hours, 50% at ~96 hours, and 100% after 168 hours (7 days)**
- **We are also currently analyzing NOAA HRRR model data with this analysis framework**

# Summary and Future Plans

- The NASA Aerosol Wind Profiler (AWP) collected data across ~110 flight hours in a diversity of geographic locations, wind/weather regimes, and aerosol/cloud conditions to demonstrate instrument performance during the NOAA Joint Venture 3-D Wind Demo and NASA WH$^2$yMSIE/APEX missions
- In these first AWP science missions, the instrument demonstrated excellent reliability, and the capability to measure aerosol/cloud backscatter and vector wind profiles with high precision, detail, and vertical coverage required for a range of weather process studies, especially those focused on the planetary boundary layer (PBL)
- AWP data will be delivered to NOAA in February 2025, and we will make data publicly available via NASA thereafter
- AWP will fly aboard the new NASA 777 aircraft in Jan-Feb 2027 during the North American Upstream Feature-Resolving and Tropopause Uncertainty Reconnaissance Experiment (NURTURE), designed to advance knowledge of the processes that lead to extreme high-impact weather (HIW) events during the winter
- NASA LaRC is building a copy of AWP that will generate higher pulse energy (~60 mJ at 200 Hz) for use in future campaigns, while also supporting technology developments and design studies that would enable a path to space
- We look forward to discussing/partnering on future campaigns and space mission concepts with the community!

**THANK YOU! CONTACT: kristopher.m.bedka@nasa.gov**