AWP: NASA's Aerosol Wind Profiler Coherent Doppler Wind Lidar

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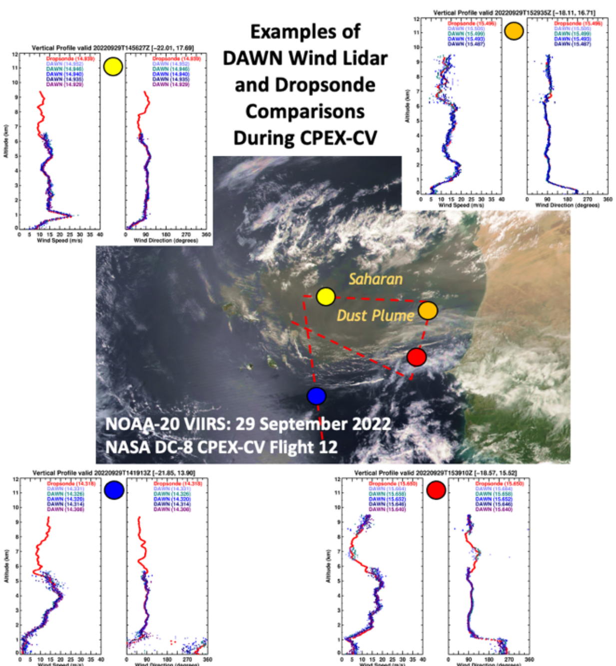
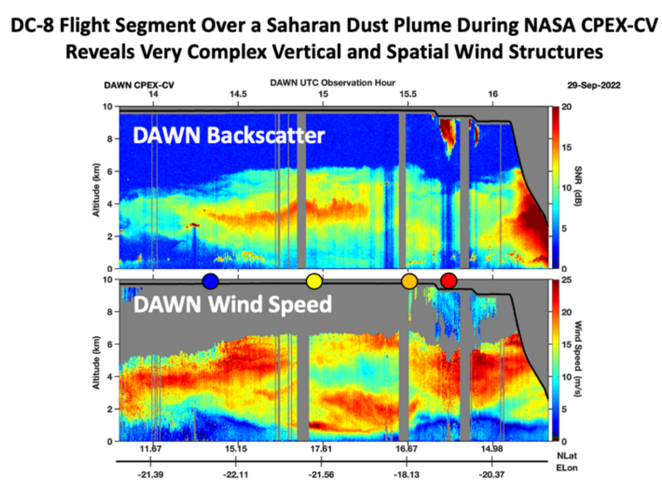
***Abstract*— A new airborne coherent Doppler Wind Lidar (DWL) instrument has been implemented leveraging NASA's development of the 2-micron Wind-Space Pathfinder (Wind-SP) lidar transceiver. A technology development project, Wind-SP refined and demonstrated numerous components required for a coherent-detection space wind lidar instrument. Aerosol Wind Profiler (AWP) transitioned this transceiver into an airborne wind lidar capable of providing full 3-D wind vector retrievals. AWP operates with laser pulse energy and repetition rate combination required for high spatial and vertical resolution wind profiling from space. Operation from aircraft platforms will yield very strong signal return required for detailed process studies at <2km spatial and <100m vertical resolution under most conditions. AWP will serve as NASA's wind calibration and validation instrument for future space-based wind observations over the coming decades, while also providing data supporting space wind lidar simulation studies. The AWP instrument is introduced and preliminary results from recent AWP demonstration flights are presented.**

Keywords—Wind Lidar, Coherent Detection Lidar, Doppler Lidar, Airborne Science, NASA

I. Introduction to NASA Coherent-Detection Doppler Wind Lidar Development

NASA Langley Research Center (LaRC), with contributions from industry partners, have been developing technology and building DWL instruments for more than two decades. We specialize in the development of coherent-detection DWLs, operating in the near-IR at a ~2 µm wavelength. Aerosol particle movement causes a Doppler shift to the frequency of backscattered light, that coherent DWLs detect and use to retrieve a wind profile [1]. Development began with the Doppler Aerosol WiNd (DAWN) lidar which has flown on 7 campaigns





DAWN Validation Compiled Across Five NASA Airborne Campaigns

PolarWinds-2 2015; CPEX 2017; Aeolus Cal/Val 2019; CPEX-AW 2021; CPEX-CV 2022

DAWN – Dropsonde Wind Speed RMS Difference	DAWN – Dropsonde Wind Speed Bias	Number of DAWN – Sonde Comparisons
1.69 m/s	-0.08 m/s	76,576

Greco et al. (Remote Sens. 2020); Greco et al. (Atmosphere, 2020); Bedka et al. (AMT, 2021)

Figure 1 (left) A NOAA-20 VIIRS true color composite image showing a Saharan dust plume moving westward from the African coast. This plume was sampled by several profiling instruments including DAWN along the NASA DC-8 flight track shown (dashed red lines. Dropsondes were released at several points along flight track (color spots). Comparison between DAWN data (cool colors) and dropsonde data (red lines) demonstrate close agreement. (upper-right) DAWN lidar backscatter (SNR) and wind speed retrievals over a 2.5 hour period along the DC-8 flight track. Vertical grey lines indicate aircraft rolls where current wind retrieval algorithms don't work. Other grey regions indicate insufficient aerosol backscatter signal resulting in no wind retrieval. (lower-right) A compilation of wind speed bias and RMS difference (precision) between all DAWN-dropsonde co-locations across DAWN's 5 most recent field campaigns.

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aboard NASA aircraft. DAWN recently operated for over 140 hours during the 2021 Convective Processes Experiment – Aerosols and Winds and 2022 Cabo Verde (CPEX-AW and CPEX-CV respectively) campaigns, collecting valuable wind measurements within and around tropical convection, Saharan Air Layers, and many other phenomena. An example of a DAWN data during one CPEX-CV flight is shown in Fig. 1 (upper right), within the Saharan dust plume depicted by the NOAA-20 VIIRS image in Fig. 1 (left). Aerosol backscatter and winds were retrieved with ~4 km horizontal and 30 meter vertical spacing in the DAWN curtain plots (Figure 1-upper right). The curtains show complex wind and backscatter patterns throughout the plume. Comparisons between DAWN vector wind profiles (cool colors) and dropsonde profiles at four points along the DC-8 flight track (red lines, Fig. 1-left) show that DAWN is very accurately observing these wind patterns. Dropsondes were released throughout the five most recent flight campaigns that DAWN has flown. A comparison of 76,576 co-located DAWN vertical bins and dropsonde profile data shows nearly unbiased wind speed retrievals with an uncertainty of 1.69 m/s (Fig. 1-lower right). Winds with such high precision are necessary to study the details of atmospheric processes, as well as to serve as validation for other wind observing systems like the Aeolus DWL [2] or geostationary satellite atmospheric motion vectors [3].

Building on experience with DWL technology and DAWN, NASA LaRC, Beyond Photonics, and Simpson Weather Associates were provided funding by the NASA Earth Science Technology Office (ESTO) to develop a next-generation DWL transceiver called the Wind-Space Pathfinder (Wind-SP). The four goals of the Wind-SP program were to:

- Assess the feasibility of a conceptual space mission design focusing on the International Space Station JEM-EF platform to obtain atmospheric aerosol and wind profile observations, and additionally validating atmospheric and lidar performance models for future wind lidar mission design optimization
- Develop and demonstrate key coherent DWL subsystems and component technologies towards space readiness that have the highest risk for space
- Demonstrate an operational ground-based wind-profiling lidar incorporating the advanced subsystem technologies
- Develop a follow-on roadmap to achieve Technology Readiness Level (TRL) 6 for all DWL components

The Wind Space Pathfinder (Wind-SP) project began on April 1, 2017, and an operational ground-based horizontal-wind-profiling lidar was completed in April 2022, with a 20-month COVID delay. Many technologies needed for a space DWL were developed and demonstrated. These technologies include: improved transmitters with high pulse energy and pulse repetition rate for long range wind measurements; auto-alignment sensors and actuators for long-term maintenance of optimal coherent DWL performance; electronic control of the beam path allowing for multiple viewing angles (allowing vector wind measurements) with no moving parts; compact highly-stable and tunable reference lasers allowing for high-precision measurement of velocity at long ranges (> 400 km) while mitigating the impact of platform velocity; and low-mass carbon-fiber-composite structures to support the lidar system [4]. The Wind-SP laser can generate 56 mJ pulse energy with 180 ns pulse width at 200 pulses/second, while maintaining very high beam quality (M^2=1.07), performance considered to be necessary for space-based operation [5]. Though pulse energy is lower than DAWN, the 20x higher pulse rate improves the overall lidar system Figure of Merit (FOM) by a factor of 2.5 [1] and enables better aerosol sensitivity and penetration into the planetary boundary layer (PBL). Wind-SP was designed with

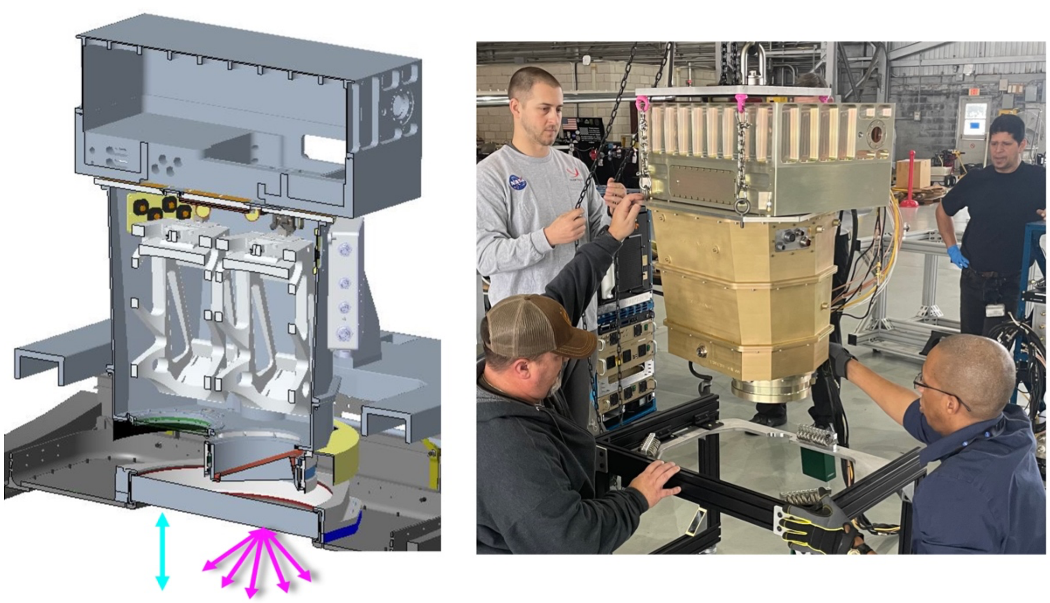

Figure 2 (left) A cross section of the AWP instrument showing the transceiver (top), dual beam expanders (middle), and the beam path orientations (cyan and magenta). (right) A photo of the fully assembled AWP instrument during integration activities prior to its January 2023 flight test aboard the NASA Gulfstream-3.

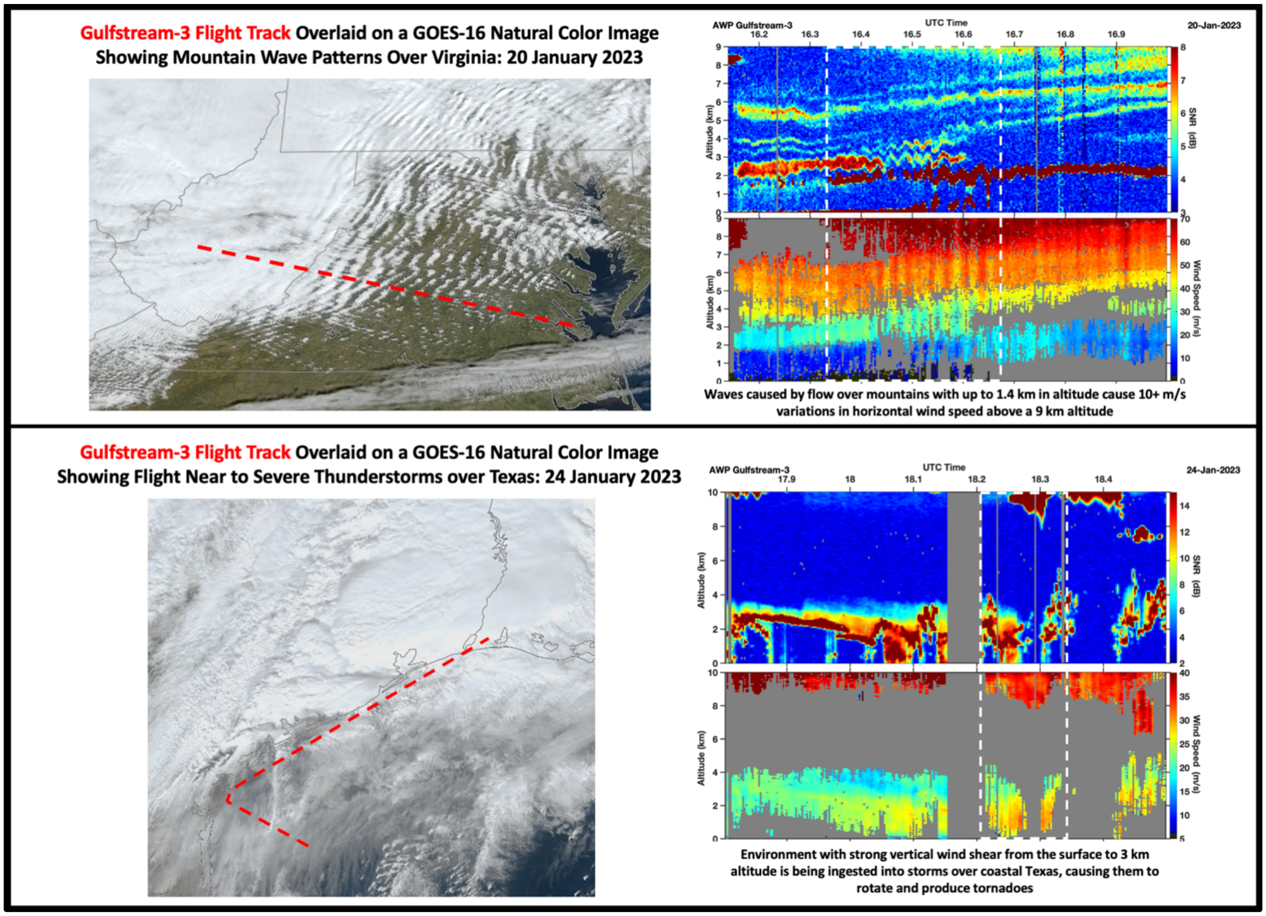

Figure 3 : (top) Preliminary AWP lidar backscatter (SNR) and wind speed retrievals over a 50-minute period on 20 January 2023 along the NASA Gulfstream-3 flight track (red dashed line) shown atop the GOES-16 image (left). Mountain waves over Virginia (white rectangle) were the primary atmospheric feature observed during this flight segment. (bottom) AWP backscatter and wind speed retrievals over a 45-minute period on 24 January 2023 along the Gulfstream-3 flight track (red dashed line) shown to the left. Rapidly accelerating planetary boundary layer wind flow (white rectangle) that contributed to the development of tornadic storms over Texas and Louisiana in the hours following the AWP observations were the primary atmospheric features of interest.

two alternating laser beam paths / lines of sight (LOS), that would be oriented 45° (fore LOS) and 135° (aft LOS) from the spacecraft ground track, enabling vector wind retrievals.

II. THE NASA AEROSOL WIND PROFILER (AWP)

The Wind-SP team was awarded additional ESTO and NASA Earth Science Division funding to integrate the Wind-SP transceiver onto a structure for operation aboard various research aircraft, resulting in the Aerosol Wind Profiler (AWP). An AWP instrument model and a photo of the assembled instrument is provided in Fig. 2. Laser pulses from the two beam paths are directed downward through parallel beam expanders. One beam is sent through a rotating scanner prism where it is directed 30° off-nadir, analogous to DAWN operation, providing vertical profiles of horizontal winds at < 100 meter spacing between vertical levels. While the scanner is rotating from one azimuth angle to another, the beam is directed to the second beam path illuminating the nadir LOS, providing vertical profiles of vertical wind speed. Aircraft angle-of-attack is compensated so that the nadir beam is oriented as close to vertical as possible. AWP would therefore collect true 3-D wind vector observations, and to the best of our knowledge, will be one of the most capable airborne DWL instruments in the world.

AWP was first demonstrated in January 2023 aboard the NASA Langley Gulfstream-3 aircraft. Examples of preliminary AWP data from these initial engineering test flights are shown in Fig. 3. AWP was run at 57% laser energy for these tests, generating ~32 mJ/pulse compared to 56 mJ at full energy. Therefore, aerosol backscatter intensity and vertical coverage of successful wind retrievals were lower than they will be when AWP is used for future science campaigns. During one flight, several vertically stratified aerosol layers of unknown origin were observed over Virginia, which were deformed by mountain waves from strong wind flow over the Blue Ridge mountain range (Fig. 3-top-right). The mountain waves modified the wind flow in the vertical column above the ascending and descending nodes of the wave patterns by up to 10 m/s (dashed rectangle). High resolution measurements that AWP provides are critical for observing terrain-induced wind patterns. Another flight sampled inflow into severe thunderstorms over coastal Texas. There was abundant cloud cover along flight track, but the high AWP rep rate enabled intermittent profiling down to the ocean surface (Fig. 3-bottom). A corridor of especially strong vertical wind shear was evident near Houston, where wind speed increased to above 30 m/s at a 2 km altitude. This shear supported rotating storm updrafts that generated tornadoes across Texas and southern Louisiana in the hours after the AWP observations. AWP will be used for its first science campaign in October 2023 and September 2024 as part of a NOAA Joint Venture Program 3-D Wind measurement opportunity [6]. The Joint Venture program is 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.

III. Science Needs for Doppler Wind Lidar Measurements and a Look Ahead

Measurements of 3-D wind fields and aerosol backscatter profiles with high precision/resolution and low bias demonstrated by DWLs are necessary for understanding a spectrum of atmospheric processes such as turbulent sensible and latent heat fluxes, aerosol and pollution transport, cloud formation/evolution, and the development of weather systems including mid-latitude and tropical cyclones, and severe thunderstorms. Existing wind observations from satellite atmospheric motion vectors, passive microwave imagers, and scatterometers do not provide the spatial and vertical detail to resolve key details of these phenomena, especially in the vertical dimension. The importance of new wind measurements was noted in the 2017 National Research Council "Decadal Survey for Earth Science Applications" [7] as being necessary to address many "Most Important" and "Very Important" science questions, in addition to many other questions related to a better understanding of planetary boundary layer (PBL) processes. The NOAA Satellite Observing System Architecture (NSOSA) study [8] also identified that lack of global wind profile measurements is a major gap in our space-based observing system. Improved wind profiling was deemed to have great potential to improve NWP model performance [9]. Experiences with operating DWLs during numerous field campaigns gives us confidence that AWP will expand upon DAWN capabilities, and collect new and innovative data with the necessary resolution and precision to address key weather and climate science questions. We seek for AWP to serve as NASA's primary wind profiling sensor for use in atmospheric process studies and for satellite wind Cal/Val. We also continue to support laser transmitter and other technology developments that could contribute to a future coherent-detection DWL satellite mission.

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