Wind Lidar Data Processing and Results from the CPEX-AW Campaign

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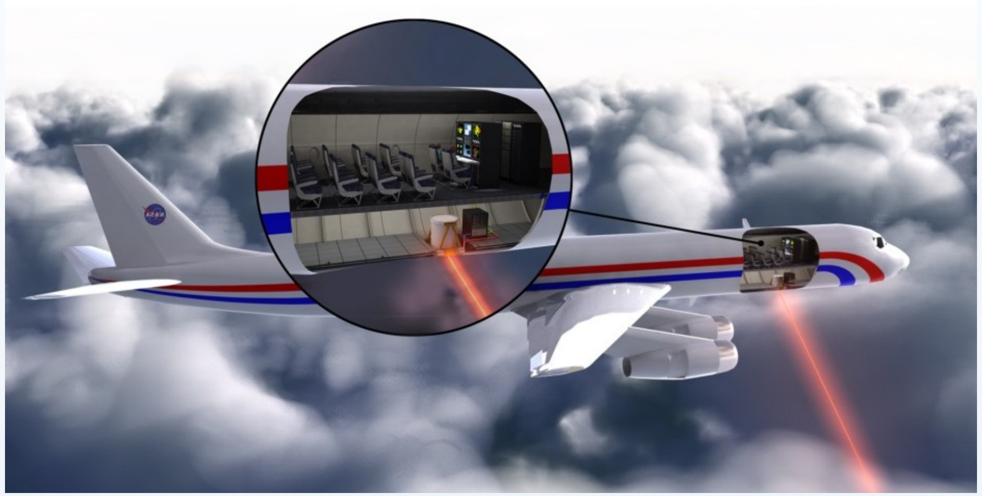
Background

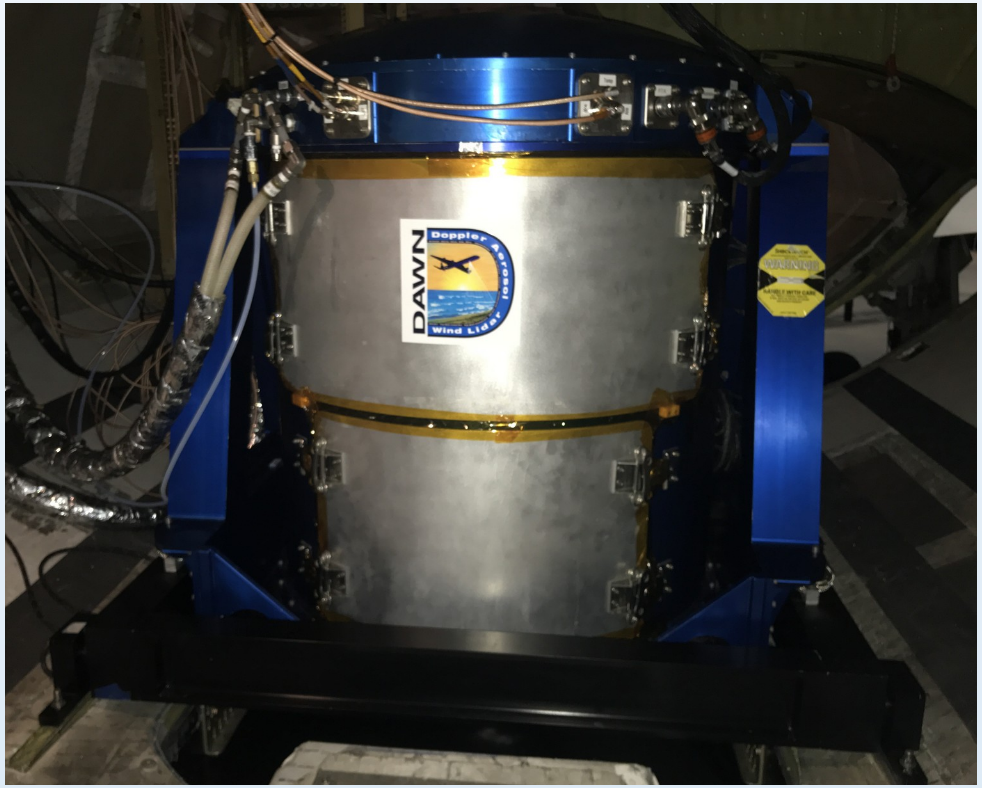
- **An airborne Doppler Aerosol WiNd (DAWN) Lidar System** has been developed and improved at NASA LaRC over the last decade to:
  - demonstrate coherent Doppler lidar (CDL) technology
  - provide wind data for NASA airborne science campaigns,
  - demonstrate would be measured from a space-borne CDL
- **Successful field campaigns:** Polar Winds I and II, Convective Processes Experiment (CPEX), Aeolus Cal/Val Test Flight Campaign, CPEX – Aerosols and Winds (CPEX-AW) .
- **Upcoming field campaign:** CPEX – Cabo Verde (CPEX – CV) in September 2022
- **Data processing algorithms** have been developed and applied successfully to DAWN data acquired during the April 2019 Aeolus Cal/Val Test Flight Campaign and CPEX – AW Campaign

Outline of This Presentation

- LaRC Doppler Aerosol WiNd (DAWN) Lidar system
- CDL measurement concept and wind retrieval algorithm
- 2021 DAWN CPEX – AW field campaign results
- Summary and current/future DAWN applications

Doppler Aerosol WiNd (DAWN) Lidar System





A coherent Doppler lidar at 2.053 µm

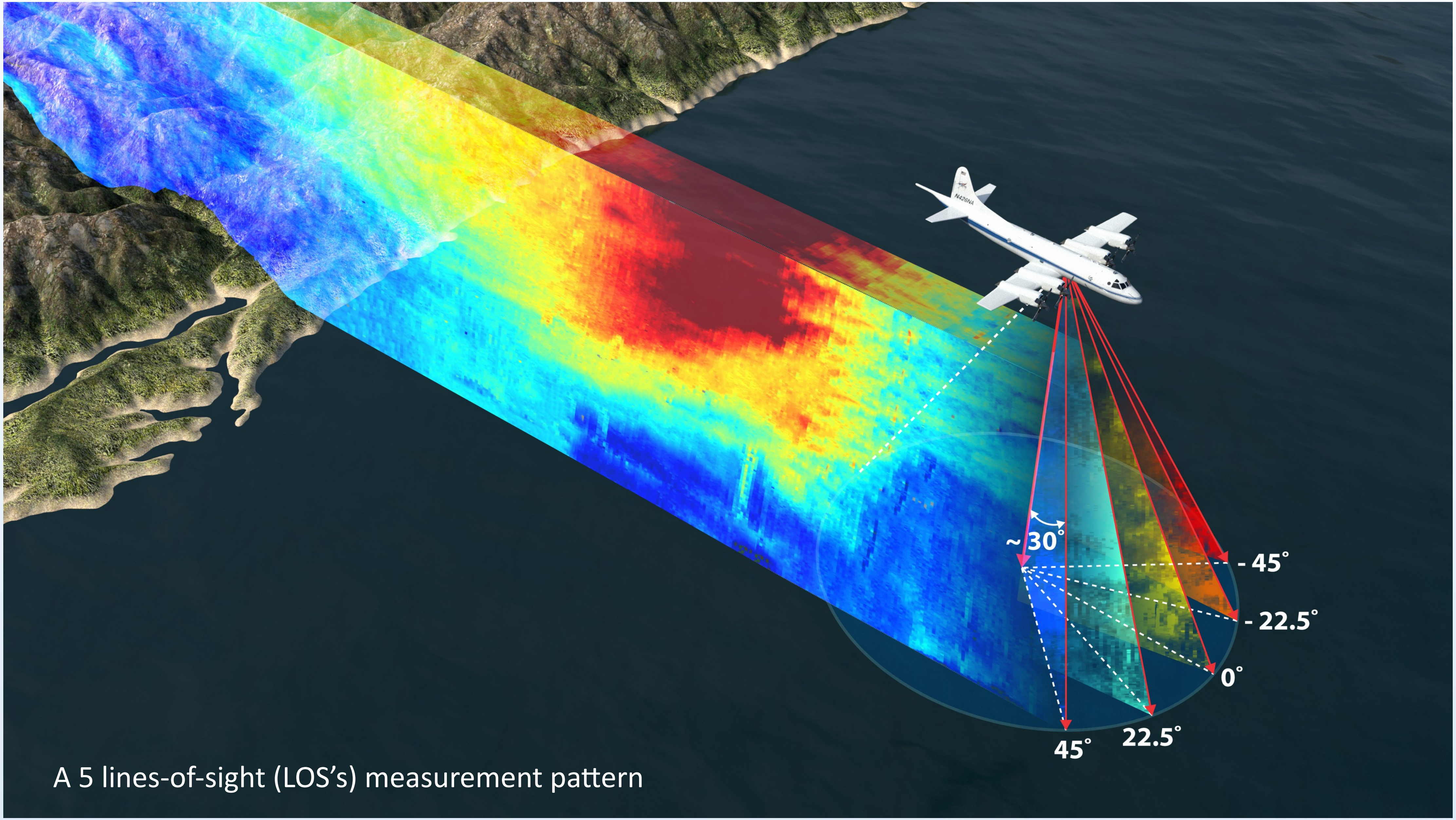
Heterodyne: pulsed oscillator (PO) + CW local oscillator (LO)

Wind-induced Doppler shift in heterodyne (beat) signals

Wind vector derived from multiple direction measurement

DAWN Specifications	
Airplanes Flown	**DC-8 and UC-12B**
Laser Crystal, Wavelength	**Ho:Tm:LuLiF, 2.053 Microns**
Laser Architecture	**Master Oscillator Power Amplifier (MOPA)**
Pumping Source	**Laser Diode Arrays (LDA), 792 nm, 1 ms**
Pulsed Laser Output	**80-100 mJ, 10 Hz, 180 ns**
Telescope Diameter	**15 cm**
Detector	**Dual-Balanced InGaAs PIN**
Scanner	**Step-Stare Rotating Wedge, 30° off Nadir**
Eye Safety	**Safe at any Range**

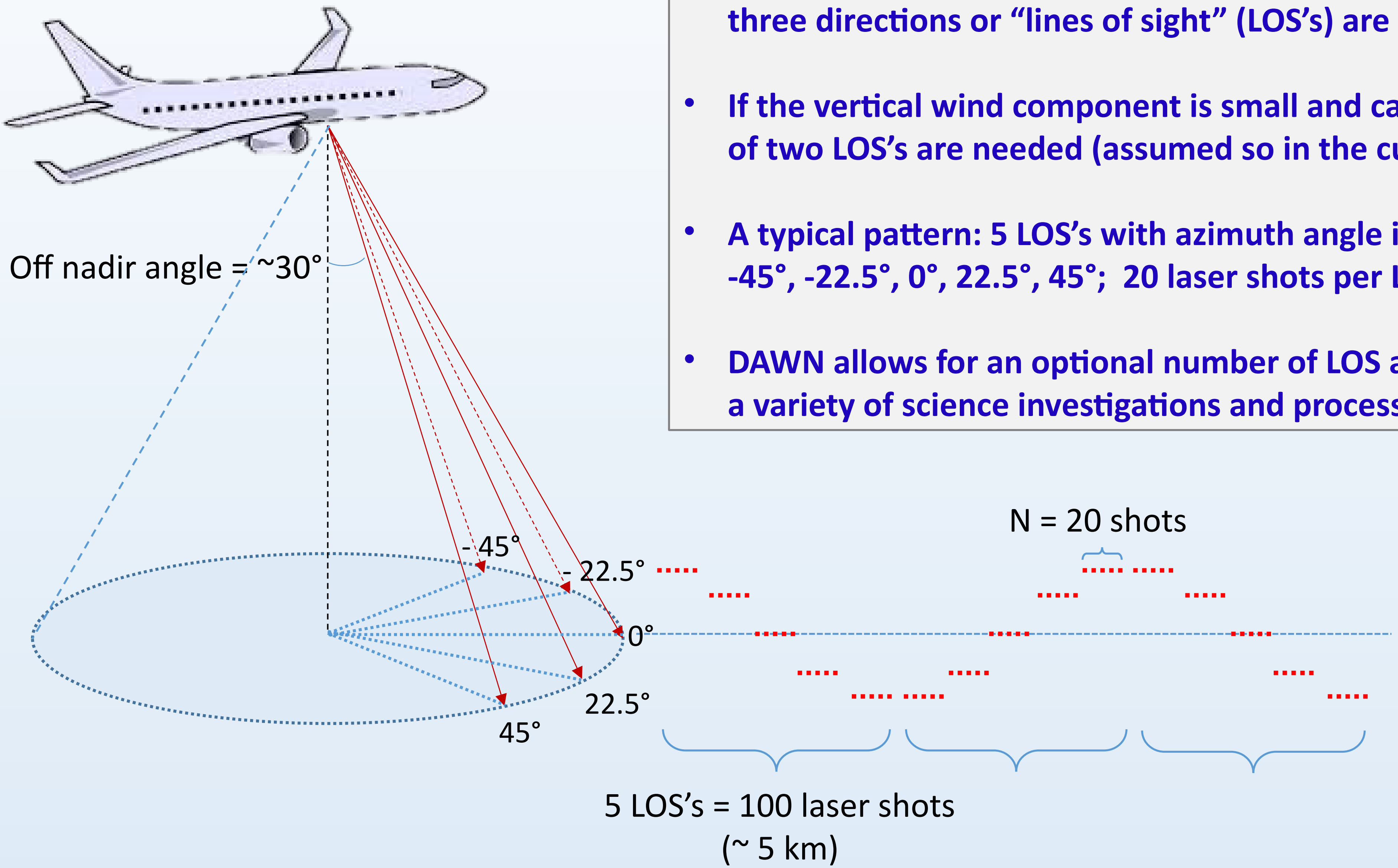
DAWN Airborne Measurement on DC-8



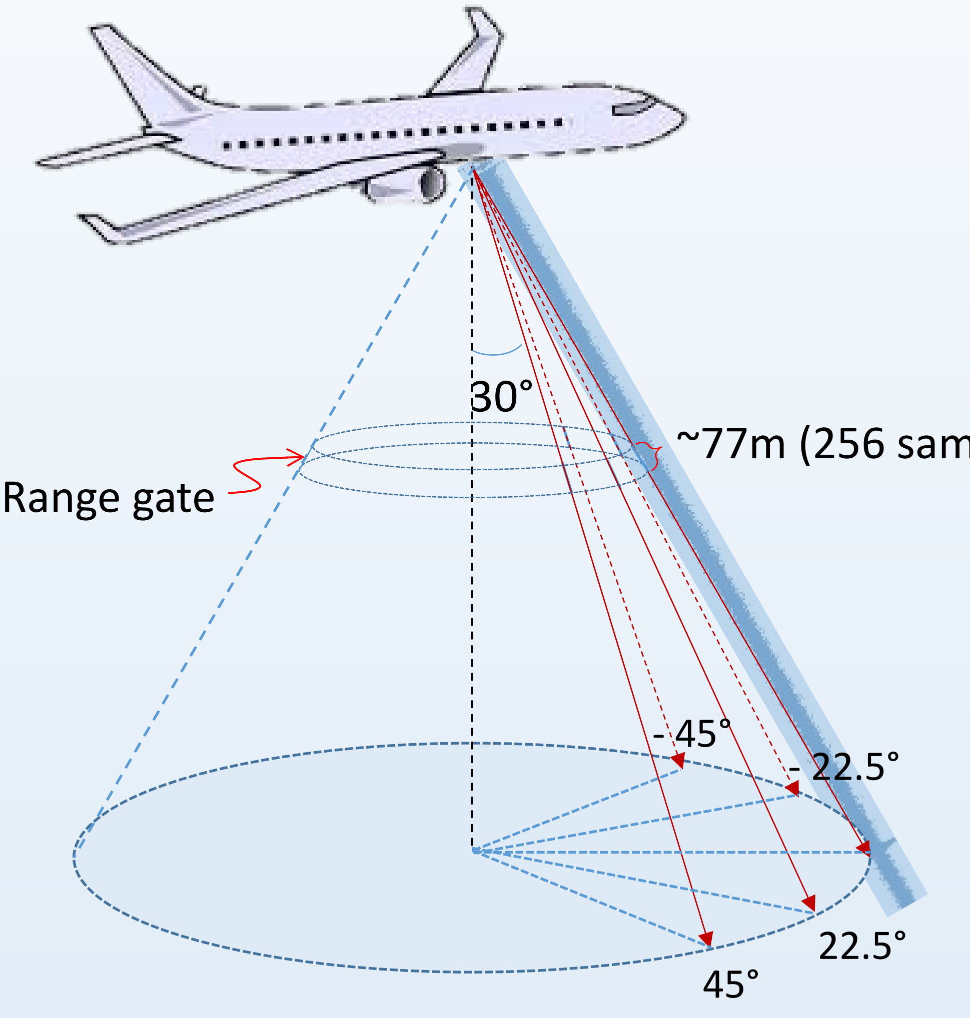
A 5 lines-of-sight (LOS's) measurement pattern

DAWN Multiple Line-of-Sight Measurement

- To determine a wind vector, measurements of wind along at least at three directions or “lines of sight” (LOS’s) are necessary
- If the vertical wind component is small and can be ignored, a minimum of two LOS’s are needed (assumed so in the current algorithm)
- A typical pattern: 5 LOS’s with azimuth angle in the aircraft coordinate of: -45°, -22.5°, 0°, 22.5°, 45°; 20 laser shots per LOS
- DAWN allows for an optional number of LOS and shots per LOS to enable a variety of science investigations and process studies



LaRC Wind Retrieval - Overview



Vertical range gate center spacing = 30 m

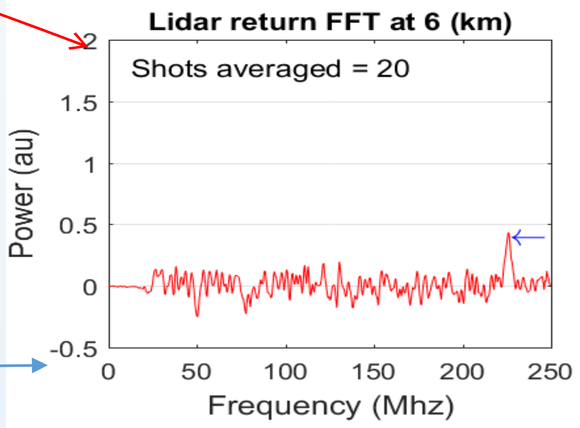
FFT shot 1

FFT shot 2

⋮

FFT shot N

Correct for laser freq. variation, average over N



$$\Delta f_{Doppler,LOS} = f_{PO_{RX}} - f_{LO}$$

$\upsilon_{wind,LOS}$

5 LOS's

Select $\upsilon_{wind,LOS}$

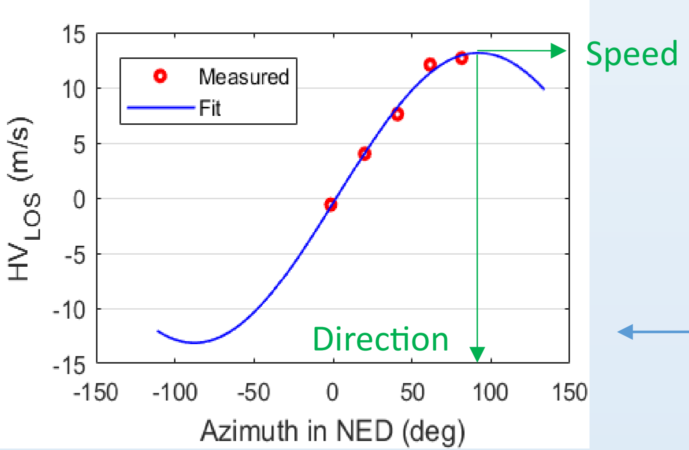
$n \geq 2$ LOS's

Solve $\mathbf{A} \times \mathbf{V}_{wind} = \mathbf{V}^{NED}_{wind,LOS}$

$\upsilon_{airplane,LOS}$

INS/GPS

Aircraft correction



LaRC Wind Retrieval – Primary Error Source

$$\mathbf{A}\times\mathbf{V}_{wind} = \mathbf{V}_{wind,LOS}^{NED}$$

INS/GPS

$$\mathbf{A} = \begin{bmatrix} \sin\theta_{LOS_1}^{NED}\cos\psi_{LOS_1}^{NED} & \sin\theta_{LOS_1}^{NED}\sin\psi_{LOS_1}^{NED} & \cos\theta_{LOS_1}^{NED} \\ \sin\theta_{LOS_2}^{NED}\cos\psi_{LOS_2}^{NED} & \sin\theta_{LOS_2}^{NED}\sin\psi_{LOS_2}^{NED} & \cos\theta_{LOS_2}^{NED} \\ & \cdots & \\ \sin\theta_{LOS_n}^{NED}\cos\psi_{LOS_n}^{NED} & \sin\theta_{LOS_n}^{NED}\sin\psi_{LOS_n}^{NED} & \cos\theta_{LOS_n}^{NED} \end{bmatrix}$$

INS/GPS FFT/Lidar

$$\mathbf{V}_{wind,LOS}^{NED} = \begin{bmatrix} \mathbf{V}_{airplane}\cdot\mathbf{I}_{LOS_1}^{NED} - \lambda\Delta f_{Doppler,LOS_1}/2 \\ \mathbf{V}_{airplane}\cdot\mathbf{I}_{LOS_2}^{NED} - \lambda\Delta f_{Doppler,LOS_2}/2 \\ \cdots \\ \mathbf{V}_{airplane}\cdot\mathbf{I}_{LOS_n}^{NED} - \lambda\Delta f_{Doppler,LOS_n}/2 \end{bmatrix}$$

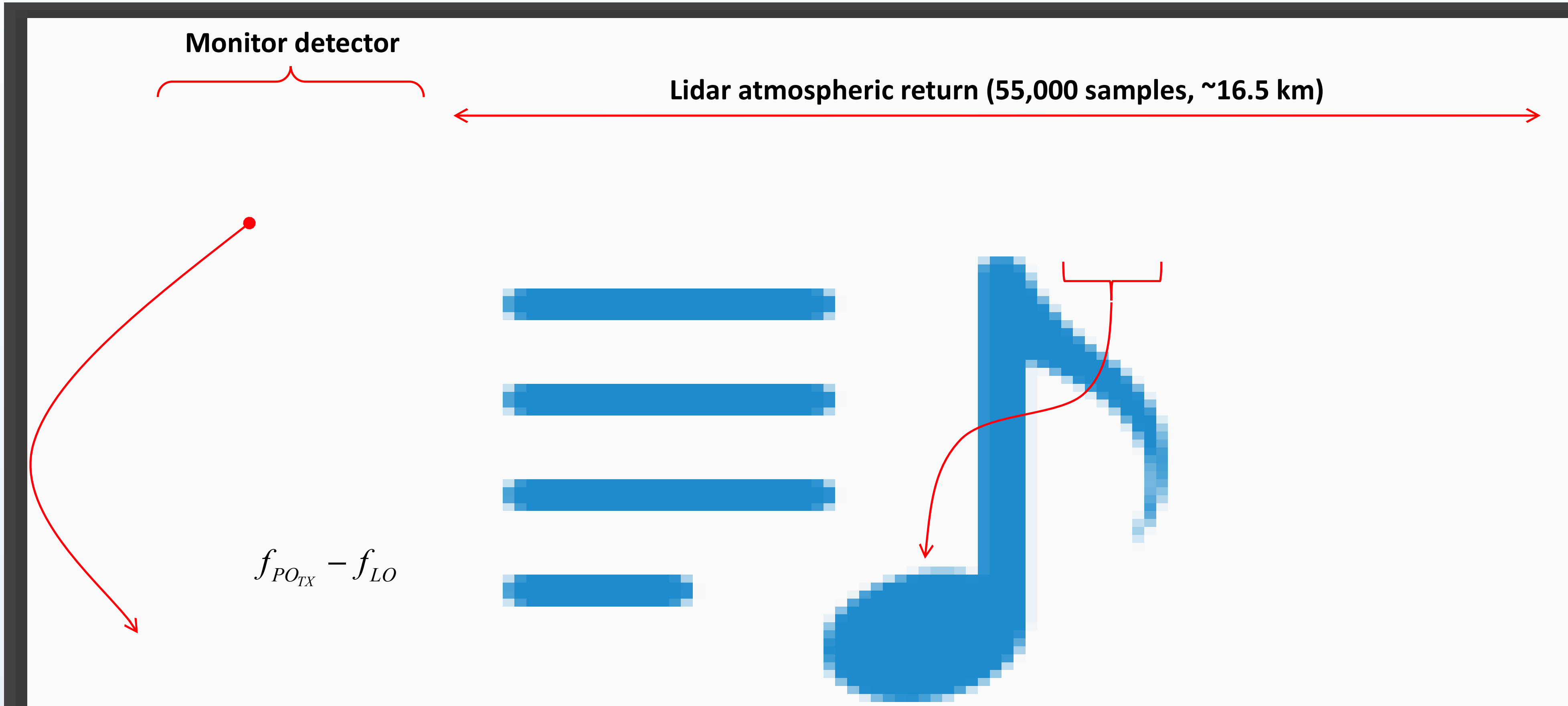
Airplane
Doppler shift

Airplane + wind
Doppler shift

Imperfect correction for airplane induced Doppler shift along each LOS is the primary source, because of the large airplane speed > **200 m/s** for DC-8

NED: north-east-down coordinate; ψ and θ: azimuth and off-nadir angle in NED

Wind Retrieval – Periodogram Average

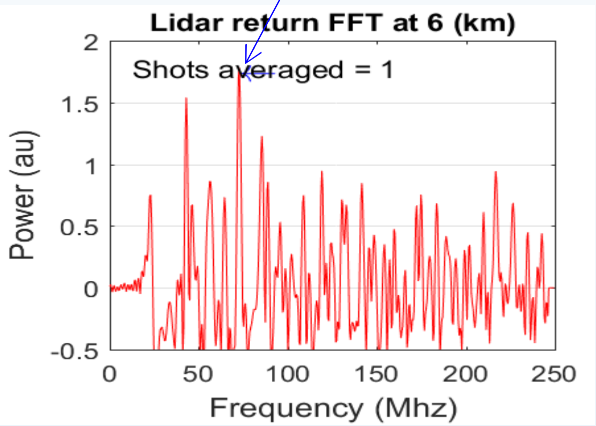


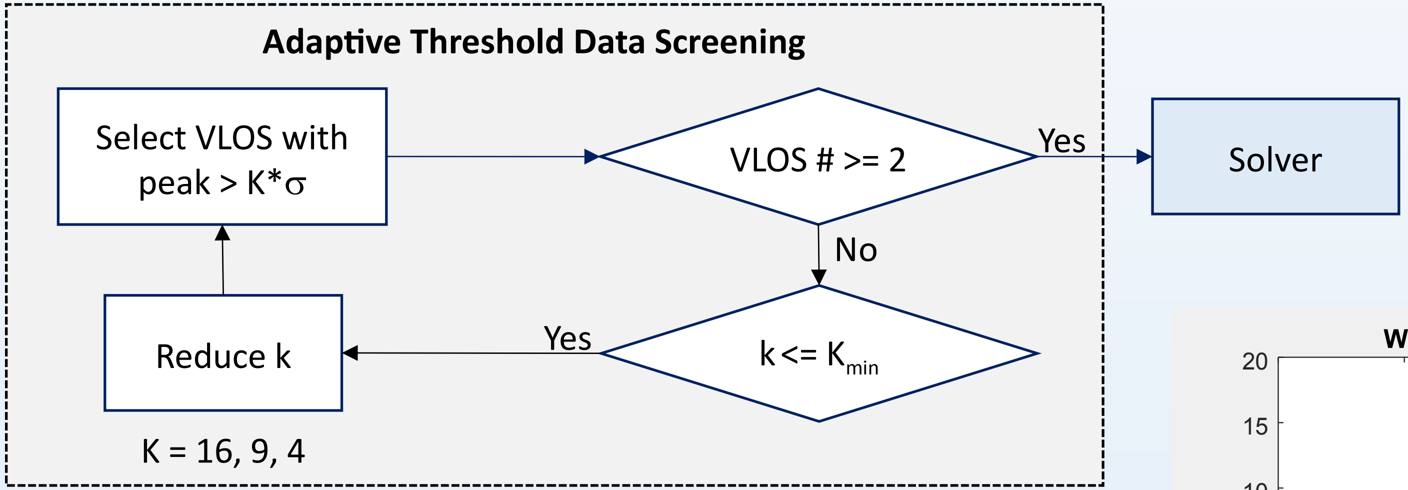
When return signal is weak from low aerosol region, averaging is necessary to successfully measure Doppler shift and wind

Wind Retrieval – Adaptive Threshold Data Screening

If a detected peak in the periodogram is due to a noise spike, when signal is weak

the peak can be detected randomly at any location in the periodogram (20 – 250 MHz)
therefore, it is "poisonous" to wind retrieval and causes large errors,
a noise spike must be excluded in the retrieval


Peak due to noise


Adaptive Threshold Data Screening

Select VLOS with peak > K*σ

VLOS # >= 2

Yes

Solver

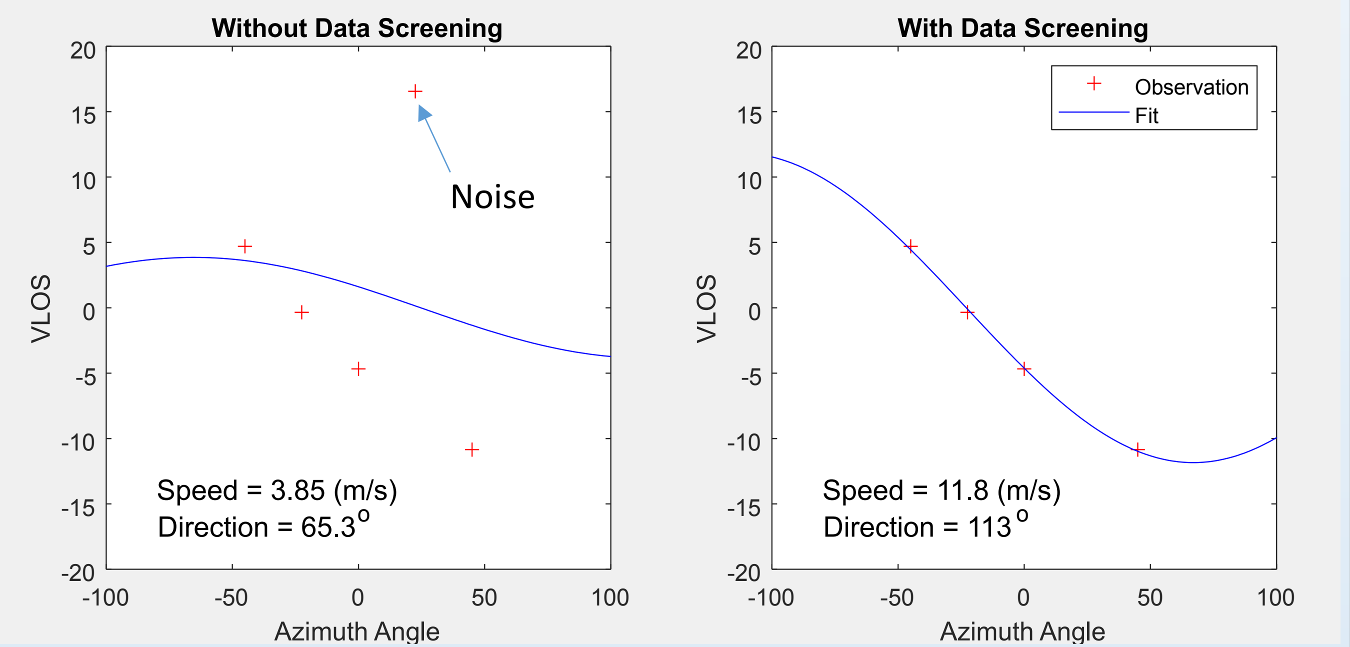
No

$k <= K_{min}$

Yes

Reduce k

K = 16, 9, 4

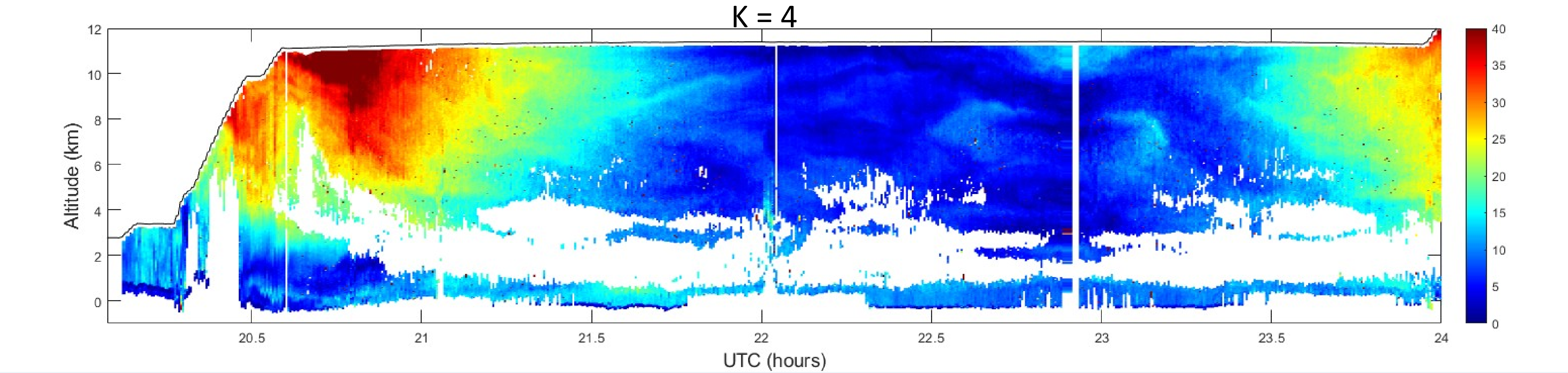


A dilemma: a larger K value can help screen out noise spikes and derive a reliable wind retrieval, but the chance to mis-detect a true signal peak is higher and hence lose some spatial coverage. Wise versa.

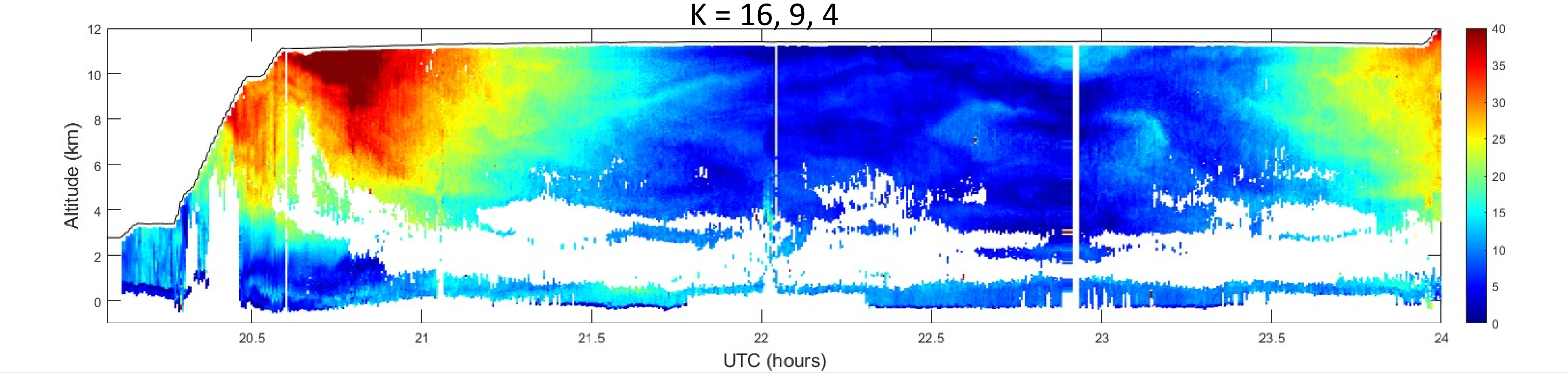
To overcome this, we developed an adaptive threshold data screening algorithm.

Wind Retrieval – Adaptive Threshold Data Screening

Fixed Threshold Data Screening


K = 4

Adaptive Threshold Data Screening

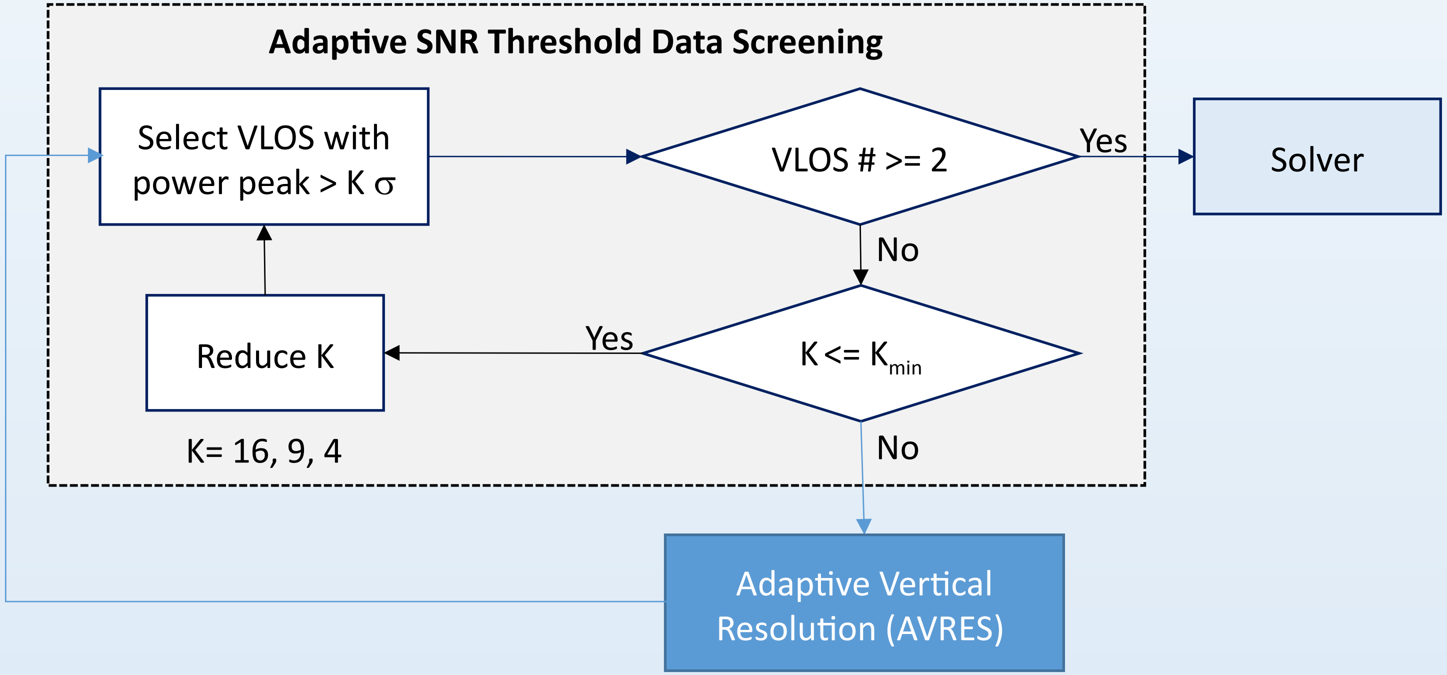

K = 16, 9, 4

Without the adaptive threshold data screening, isolated “dots” are seen due to the contamination of noisy data in the retrieval. Isolated dots are reduced significantly when the adaptive threshold data screening is applied.

Wind Retrieval – Adaptive Vertical Resolution (AVRES)

To further improve the detection of weak lidar returns from low aerosol loading regions, an Adaptive Vertical Resolution (AVRES) integration is utilized:

- If a successful retrieval is not obtained at a single base range gate, spectra from two range gates are averaged, and the retrieval procedure is repeated.
- If a successful retrieval is still not obtained, the average number of range gates is doubled again until a successful retrieval is obtained, or the maximum integration depth (~ 1 km) is reached.



Adaptive SNR Threshold Data Screening

Select VLOS with power peak > K σ

VLOS # >= 2

Yes

Solver

No

$K <= K_{min}$

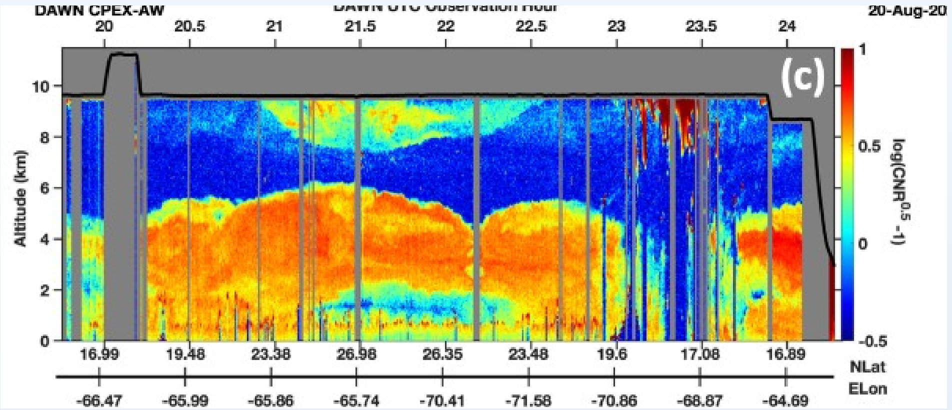
Yes

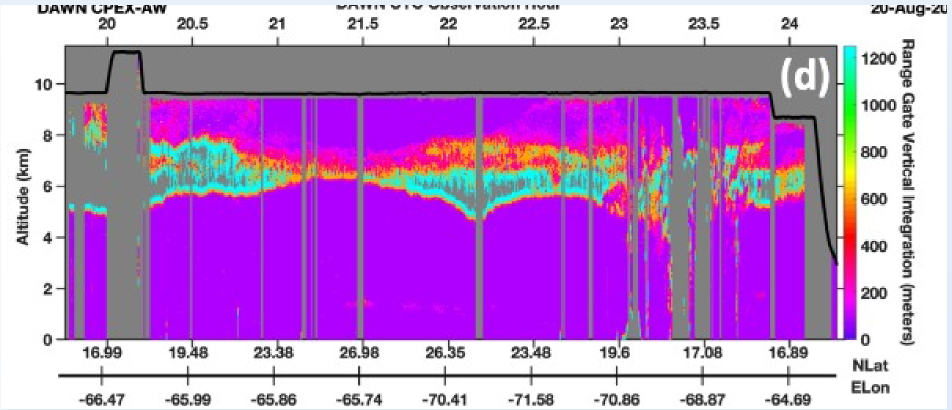
Reduce K

No

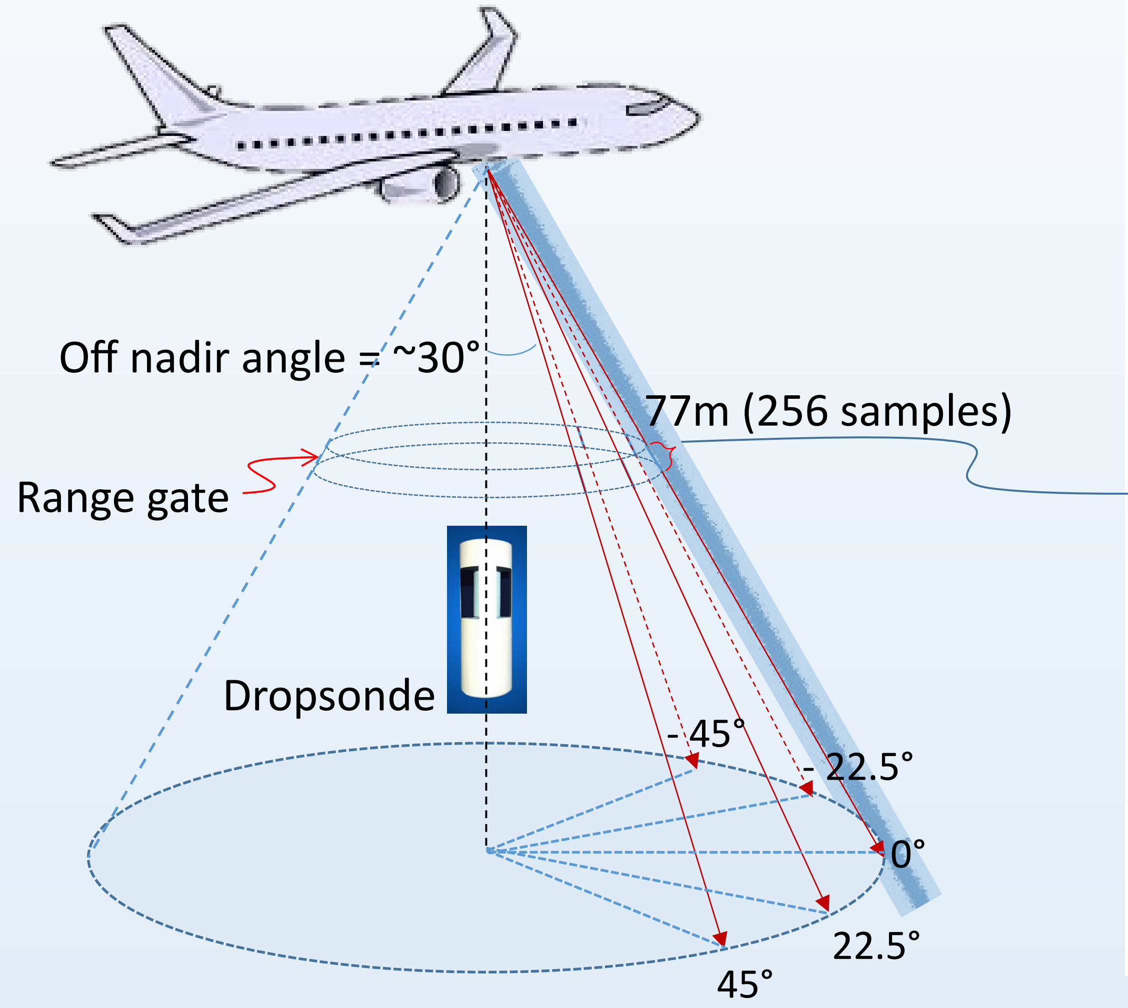
K= 16, 9, 4

Adaptive Vertical Resolution (AVRES)

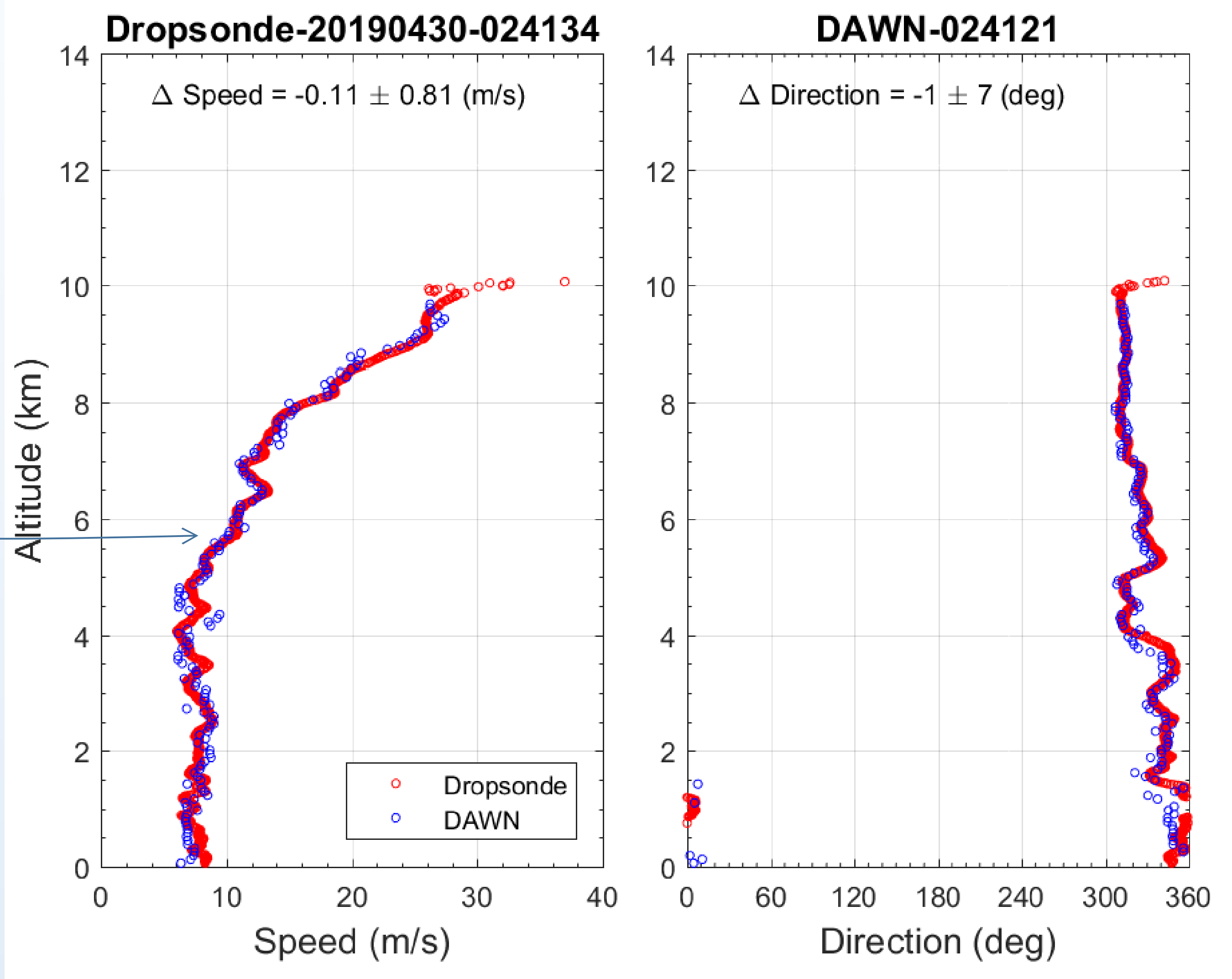




LaRC Wind Retrieval – End Result

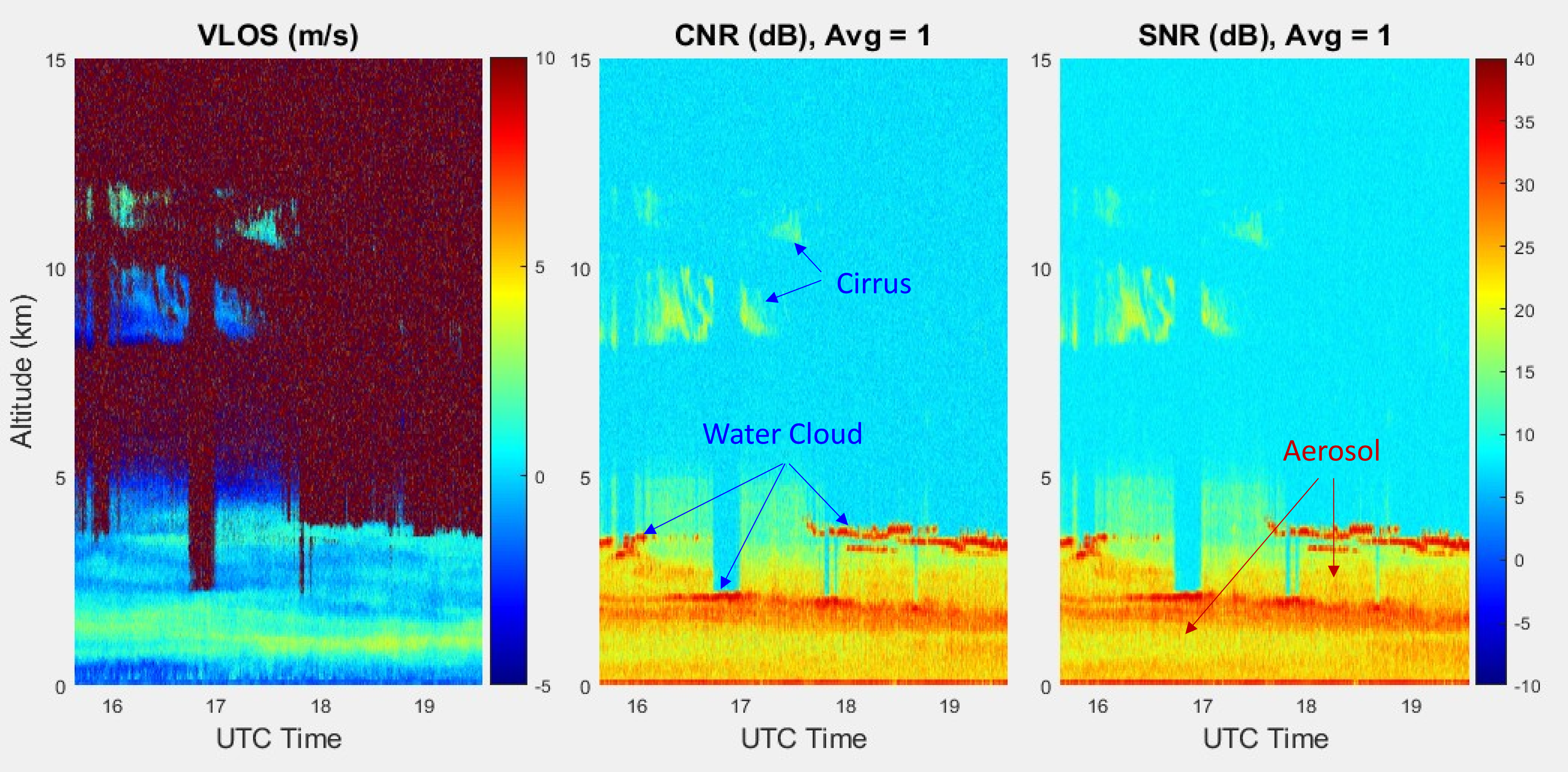


Vertical height spacing = 30 m.



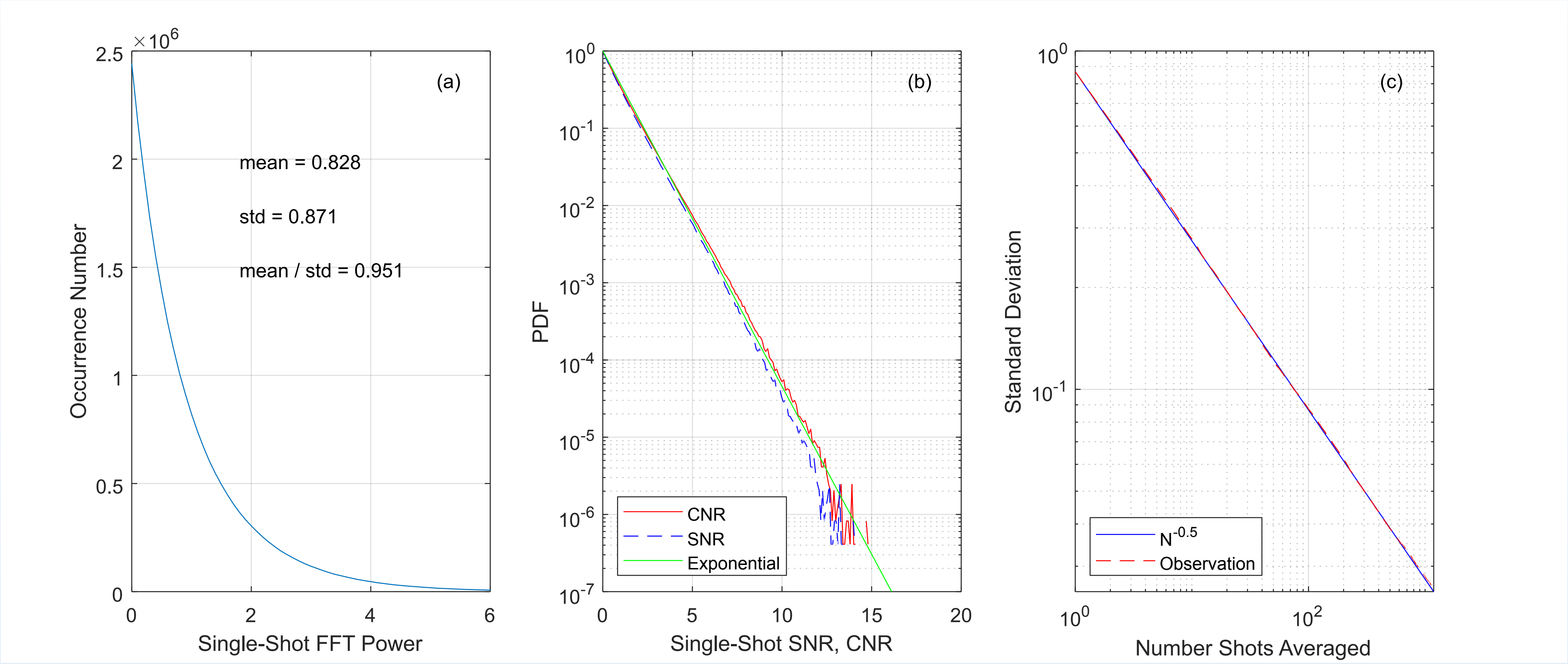
DAWN is able to capture sharp vertical variations in wind with high precision and resolution, data attributes that are essential for process studies

Performance – Ground Test



Left: line-of-sight (LOS) wind velocity; **Middle**: single-shot carrier-to-noise (CNR); **Right**: single-shot signal-to-noise ratio (SNR)
CNR = Peak FFT signal / Noise floor; SNR = Peak FFT signal / RMS noise floor

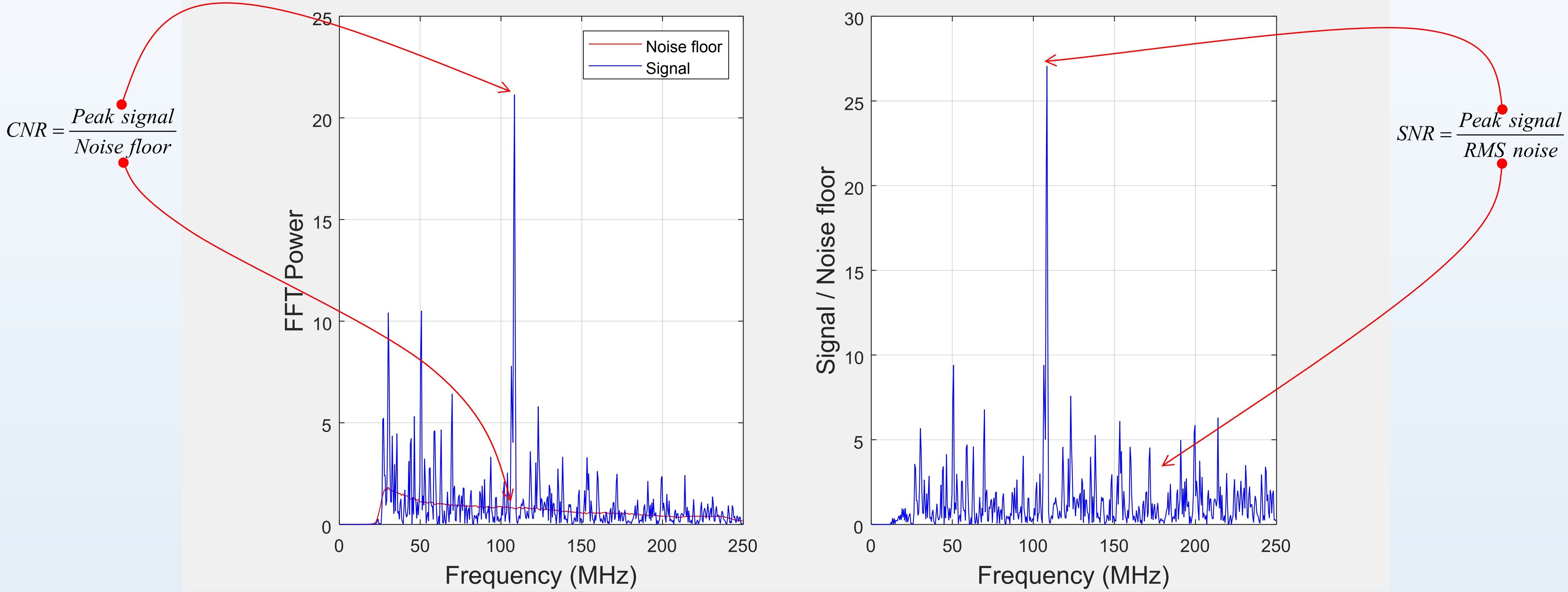
Performance – Ground Test



Distributions of single-shot noise floor (a) and SNR = FFT power/std, CNR = FFT power/mean, and an exponential fit $y = e^{-x}$ (b), and standard deviation as a function of number shots averaged (c) that shows a perfect $N^{-0.5}$.

Performance – Ground Test

Single-shot Periodogram



$$CNR = \frac{Peak\ signal}{Noise\ floor}$$

$$SNR = \frac{Peak\ signal}{RMS\ noise}$$

Noise floor is derived by averaging the FFT spectra of all range gates below the surface for the airborne measurement, or the topmost 20 range gates for the ground test where there are no aerosol backscattering signals

CPEX-AW Field Campaign Based in St. Croix

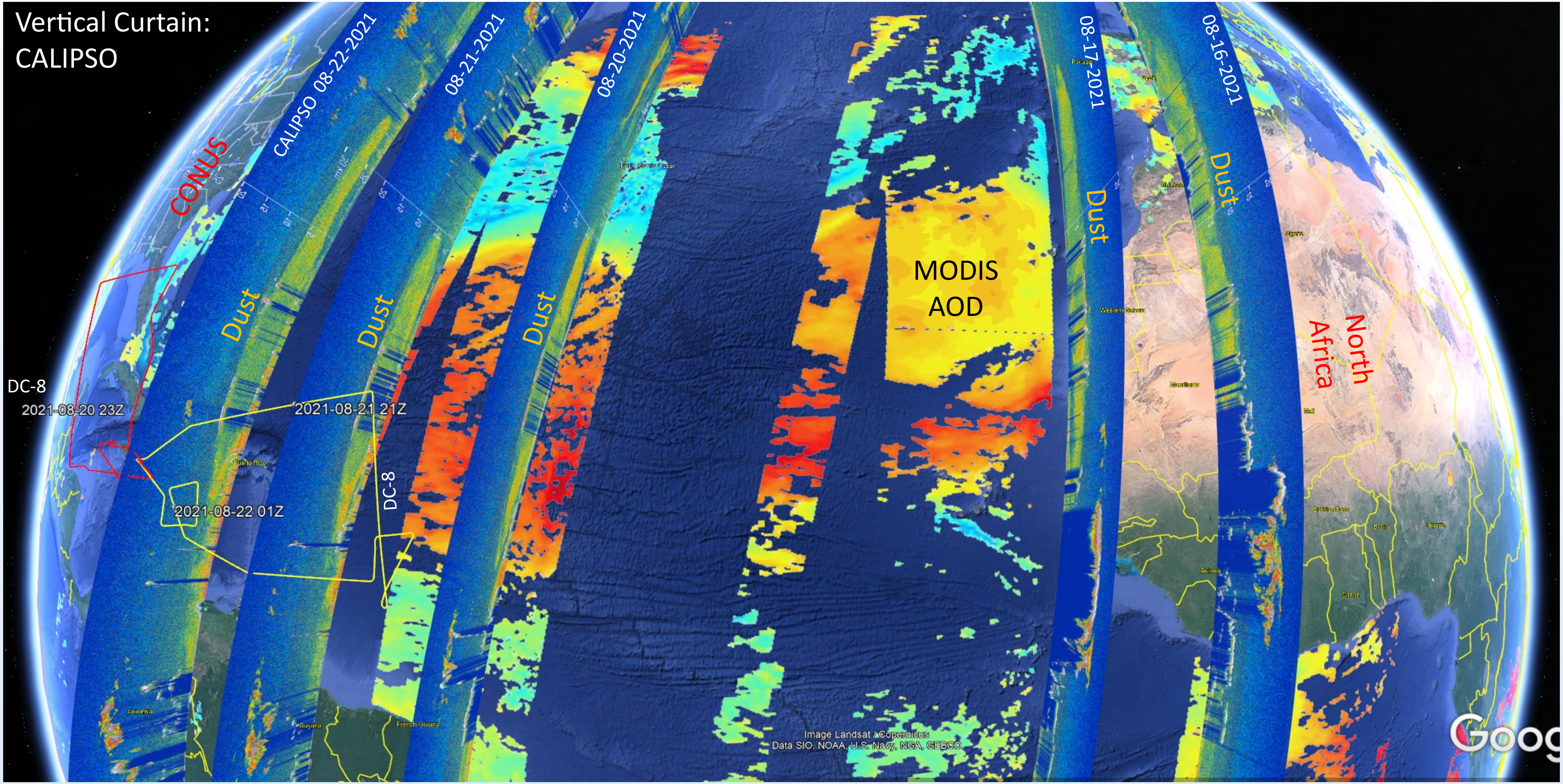
The Convective Processes Experiment – Aerosols & Winds (CPEX-AW) campaign is a joint effort between the US National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) with the primary goal of conducting a post-launch calibration and validation activities of the Atmospheric Dynamics Mission-Aeolus (ADM-AEOLUS) Earth observation wind Lidar satellite in St. Croix.

CPEX-AW is a follow-on to the Convective Processes Experiment (CPEX) field campaign which took place in the summer of 2017 (https://cpex.jpl.nasa.gov/). In addition to joint calibration/validation of ADM-AEOLUS, CPEX-AW will study the dynamics and microphysics related to the Saharan Air Layer, African Easterly Waves and Jets, Tropical Easterly Jet, and deep convection in the InterTropical Convergence Zone (ITCZ). CPEX-AW science goals include:

Science Objectives:

- Better understanding interactions of convective cloud systems and tropospheric winds as part of the joint NASA-ESA **Aeolus Cal/Val** effort over the tropical Atlantic;
- Observing the vertical structure and variability of the **marine boundary layer** (MBL) in relation to initiation and lifecycle of the **convective** cloud systems, convective processes (e.g., cold pools), and environmental conditions within and across the **ITCZ**;
- Investigating how the African easterly waves and dry air and **dust** associated with **Sahara Air Layer** control the convectively suppressed and active periods of the ITCZ;
- Investigating interactions of wind, aerosol, clouds, and precipitation and effects on long range dust transport and air quality over the western Atlantic.

CPEX-AW Field Campaign Based in St. Croix



CPEX-AW First Science Flight

DAWN Speed

DAWN Direction

DAWN (CNR$^{0.5}$-1)

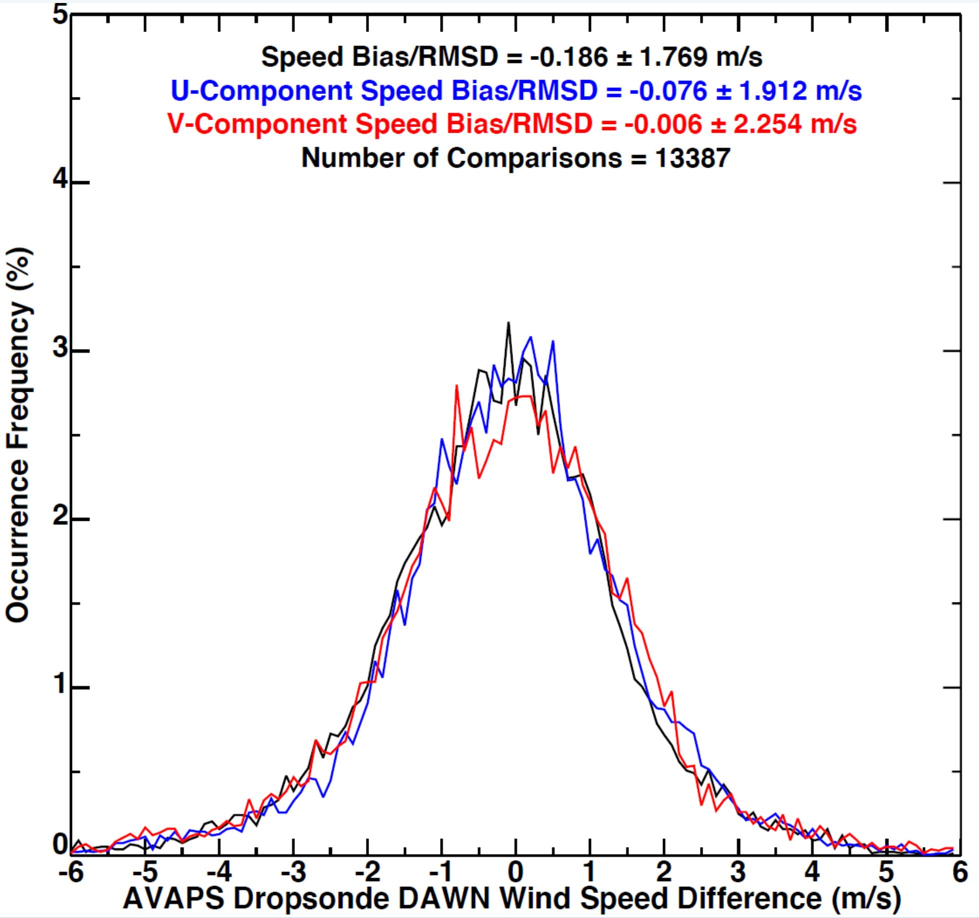
DAWN Range Gate

HALO Backscatter

(e)

DAWN - Dropsonde Comparisons During Aeolus Cal/Val: 91 Sondes

DAWN - Dropsonde	Mean	Standard Dev
Speed (m/s)	-0.19	1.77
U (m/s)	-0.076	1.91
V (m/s)	-0.006	2.25
Direction (deg)	0.11	11.0


Speed Bias/RMSD = -0.186 ± 1.769 m/s
U-Component Speed Bias/RMSD = -0.076 ± 1.912 m/s
V-Component Speed Bias/RMSD = -0.006 ± 2.254 m/s
Number of Comparisons = 13387

DAWN Sensitivity

Question: What is the lower limit of aerosol backscatter that DAWN can retrieve wind?

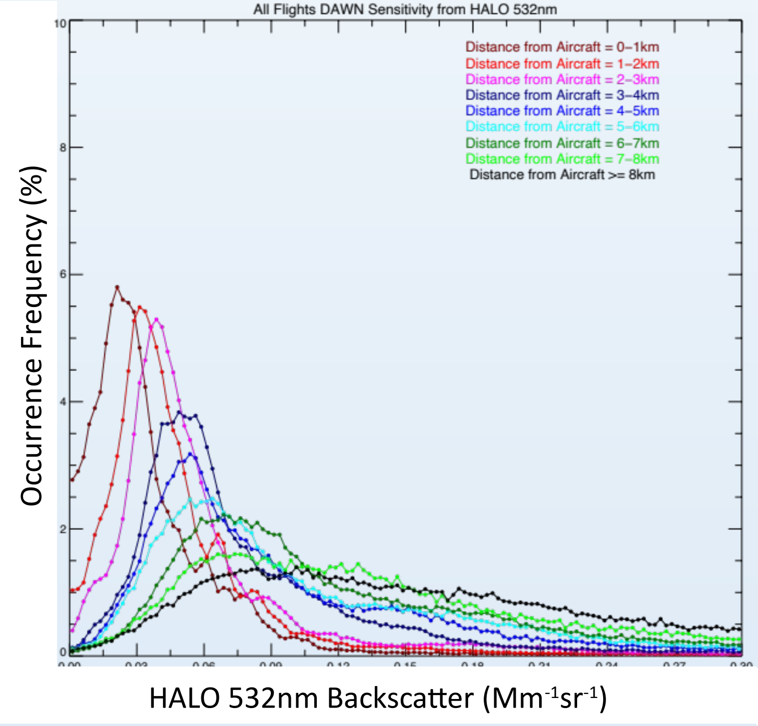
Analysis Method: Time sync and average HALO backscatter to DAWN wind product resolution (256 samples, ~66.5 m) for 5 Aeolus Cal/Val flights in 2019 and all 7 CPEX-AW flights in 2022

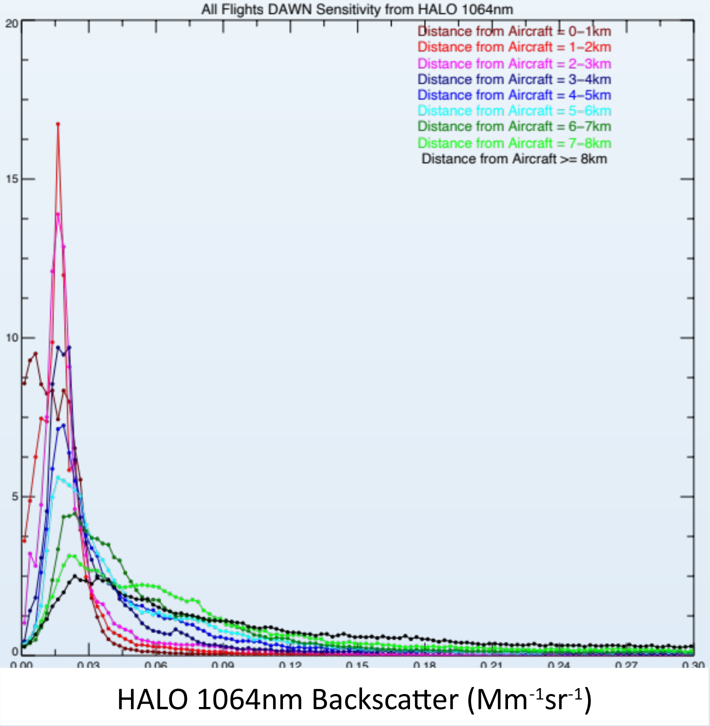
Answer to question: For shot integration <= 100 (typical DAWN operations), winds most often retrieved using single range gate data for aerosol backscatter **$\beta > 4.5\text{x}10^{-8}$ [$m^{-1}sr^{-1}$] at 532 nm** and **$> 2\text{x}10^{-8}$ [$m^{-1}sr^{-1}$] at 1064 nm**, (for comparison, the 532-nm molecular backscatter near the surface is ~ **$1.6\text{x}10^{-6}$** [$m^{-1}sr^{-1}$]).

Winds can be retrieved from $1\text{x}10^{-8}$ [$m^{-1}sr^{-1}$] at the HALO wavelengths, if vertical integration is applied.

The detectable backscatter could be even smaller at the DAWN 2.05-μm wavelength, because of $\beta \sim 1/\lambda^{\alpha}$.

Shift in peaks to the right with increasing distance from aircraft is an evidence for that the lidar sensitivity decreases as increasing range, although the aerosol loading has a similar altitude dependence





Summary

- The airborne Doppler Aerosol Wind (DAWN) Lidar has been developed at NASA LaRC and successfully participated in several field campaigns over the past decade
- Data processing algorithms have also been developed at LaRC, and applied to DAWN data acquired during the April 2019 Aeolus Cal/Val Test Flight Campaign and 2021 CPEX – AW Field Campaign
  - Comparisons between DAWN and 91 dropsonde measurements showed a difference of -0.19 ± 1.77 m/s for wind speed and 0.11 ±11.0° for wind direction
  - Differences most often caused by wind spatial variability and not DAWN lidar “error”. Highly accurate INS/GPS information synced in time with DAWN pulses is crucial for wind retrieval
- DAWN, HALO, and other NASA airborne data have been and will be used for a variety of investigations such as:
  - Validation of space-borne ADM Aeolus Doppler lidar wind speed and aerosol products
  - Developing a better understanding of flows within/near convection that contribute to storm initiation and maintenance, planetary boundary layer (PBL) processes and land/sea fluxes, and flow interaction with topography
  - Validation and development of new geostationary atmospheric motion vector methods using 1-minute imagery
  - NWP/Reanalysis model validation, and data assimilation to improve forecasts
- DAWN, HALO, APR-3, and other instruments will be flying aboard the DC-8 in the upcoming NASA Convective Processes Experiment – Cape Verde (CPEX-CV) campaign based in Cabo Verde in September 2022