Lidar measured wind profiles from space

An overview of Doppler lidar technology and comparison with current and future wind measurement capabilities

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With special thanks to the Ball Aerospace OAWL development team & partners, including Mike Hardesty and Sunil Baidar of CU-CIRES

Topics

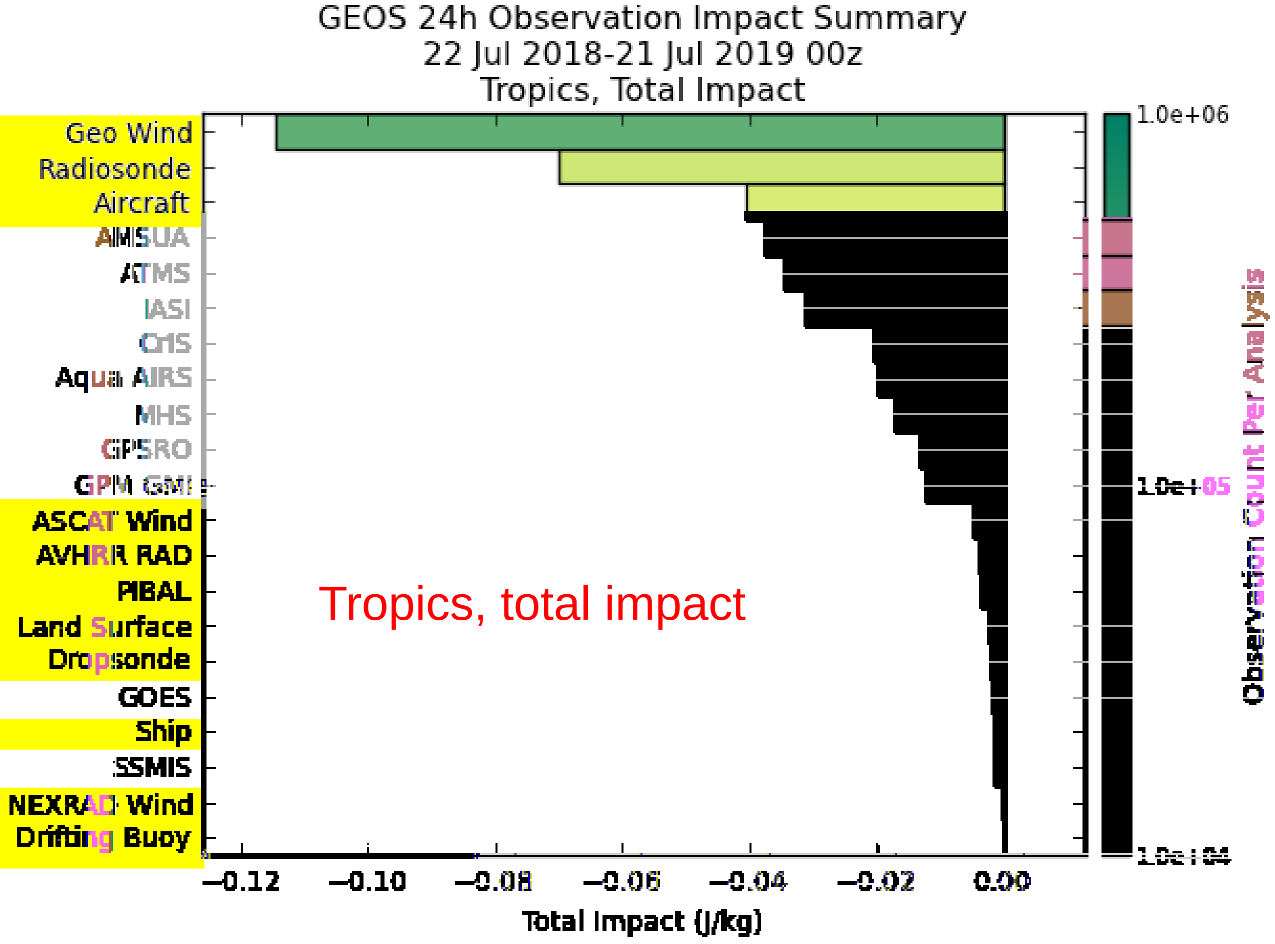
- Wind Measurements
  - What do we have now?
  - Why a Doppler lidar from space?
  - Aeolus
- Doppler Wind lidar observations
  - Wind lidar basics
  - Wind lidar technologies (including Aeolus)
  - The OAWL approach
- Shaping Future Wind Missions
  - Scales
  - Active & Passive Synergy
  - Mission concepts – building on Aeolus
- Next Steps & Questions for Discussion

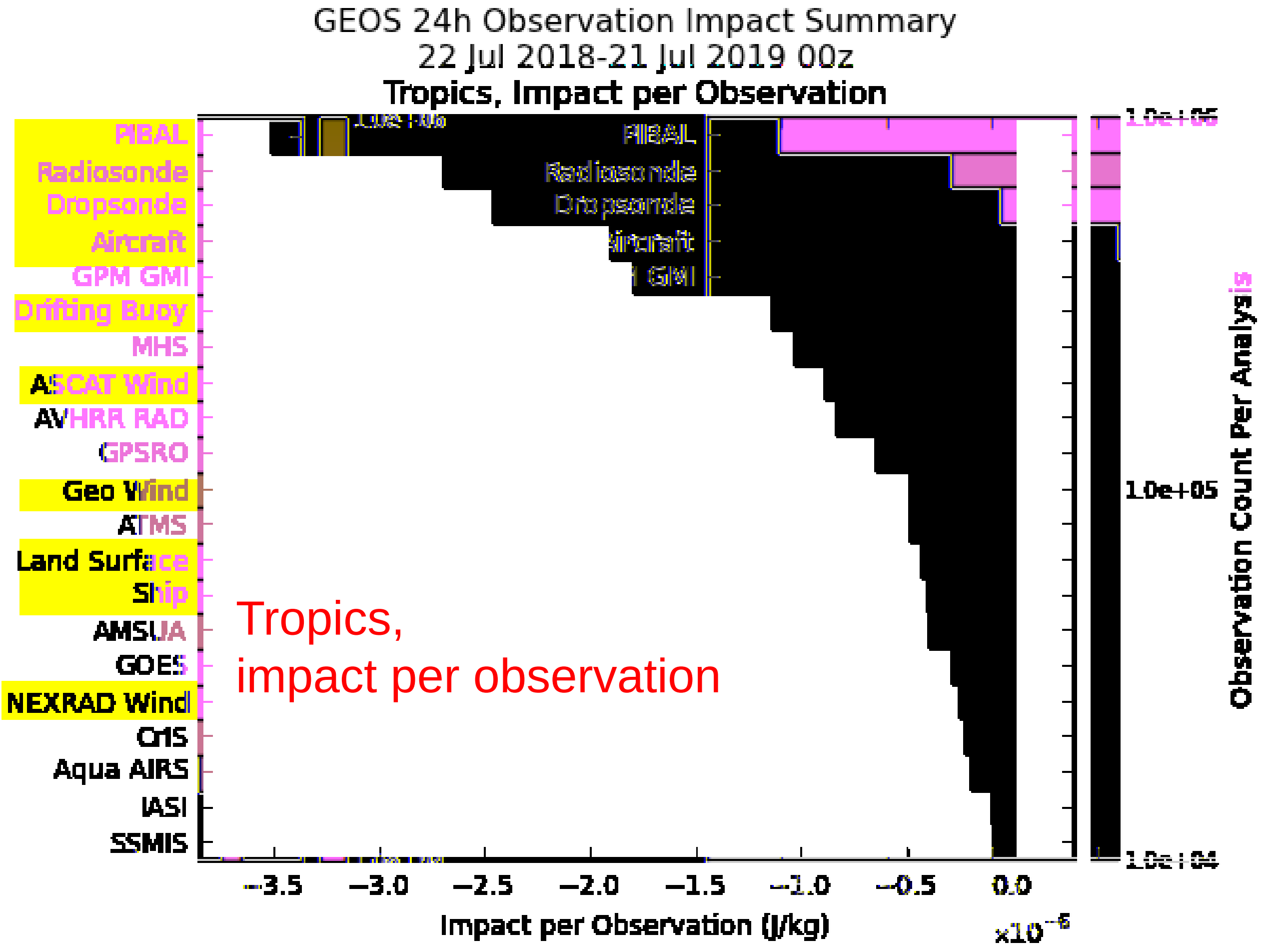
WIND MEASUREMENTS

Wind observations have strong impacts on forecast

GEOS-5 Impact Summaries: July 2018-July 2019, Tropics

Observations that include winds (retrieved or measured)



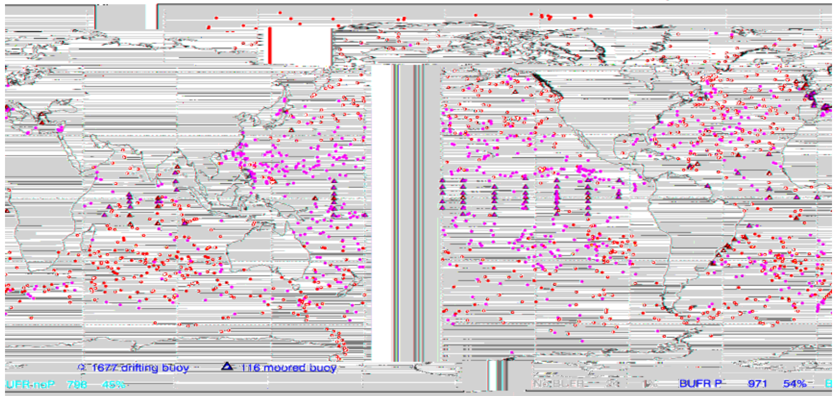


WMO: The greatest unmet observational need is still winds

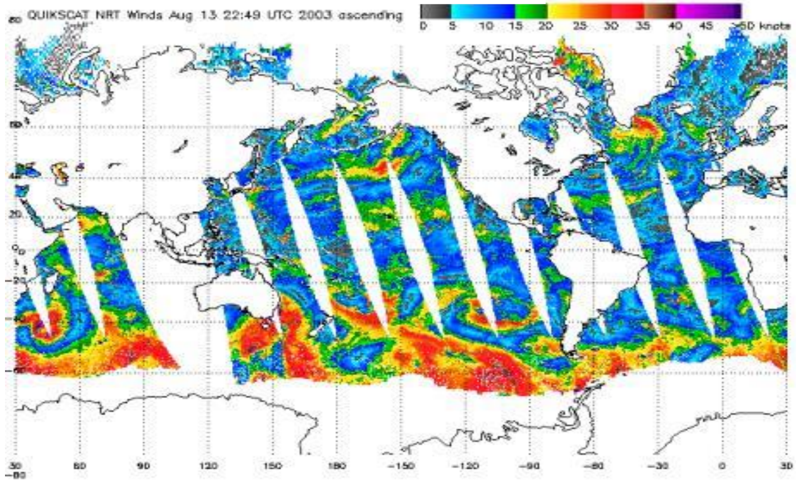
Existing global winds measurements

Surface

Surface Buoys

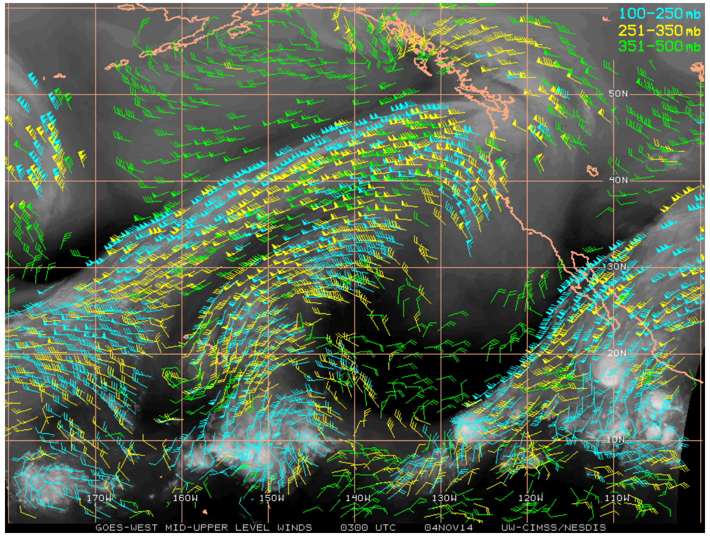


Scatterometry



Motion Vector

(aerosol/cloud tracking)

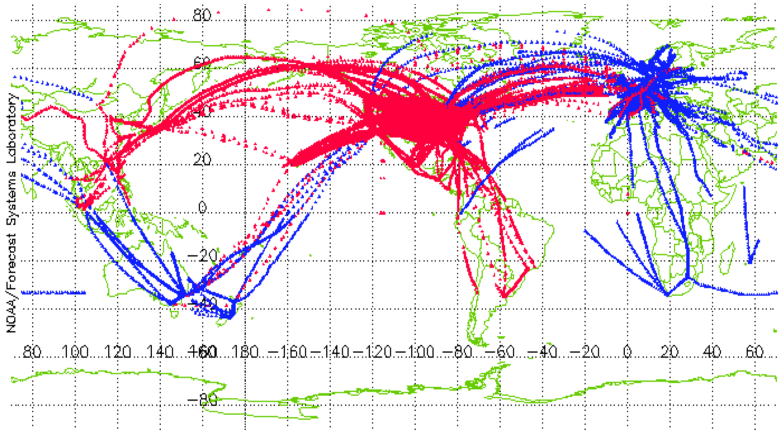


Visible or water vapor channels
Requires 3 cloud images, cloud brightness temp, cloud mask, cloud height, cloud top pressure
(for Water Vapor: GFS forecast temperature profile)

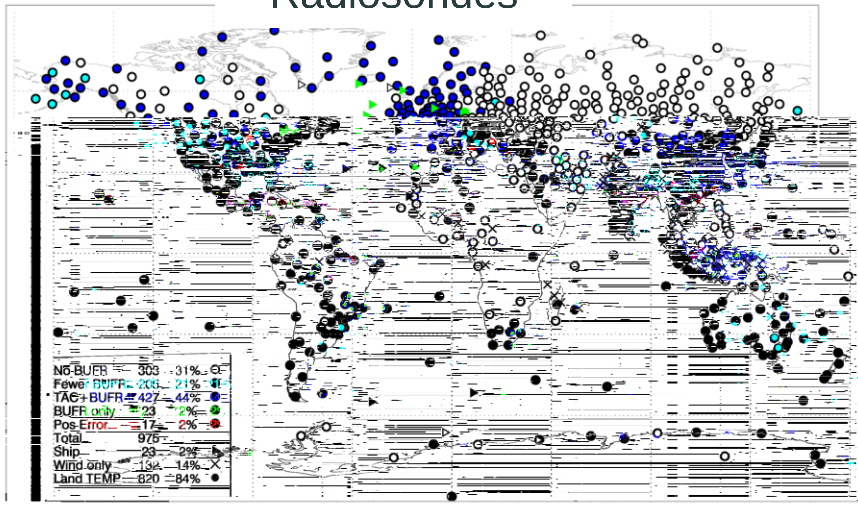
Requires Cloud/WV Features

In-situ Profiling

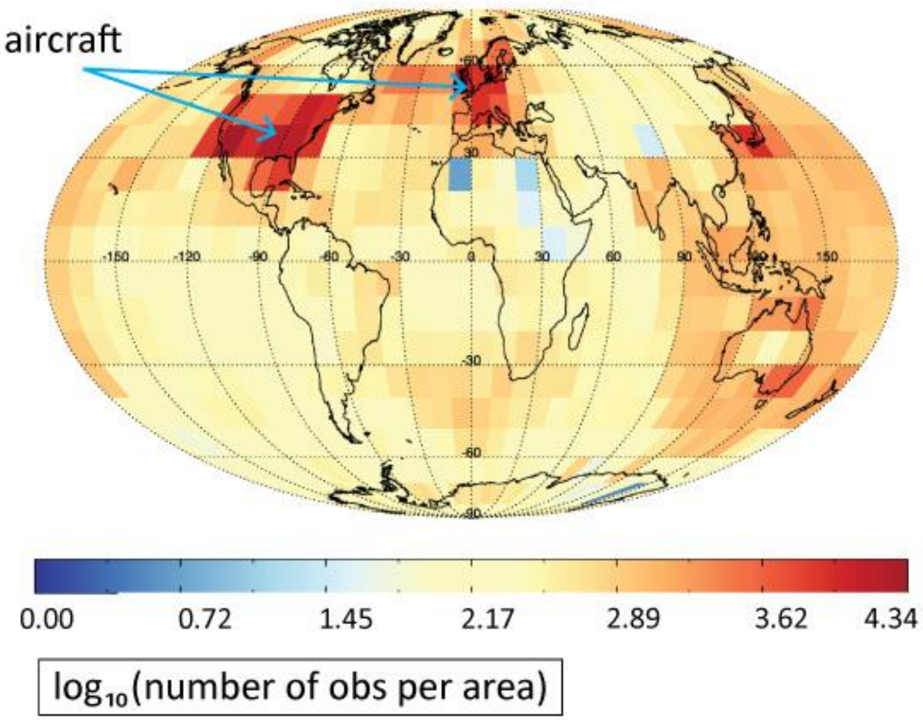
Aircraft



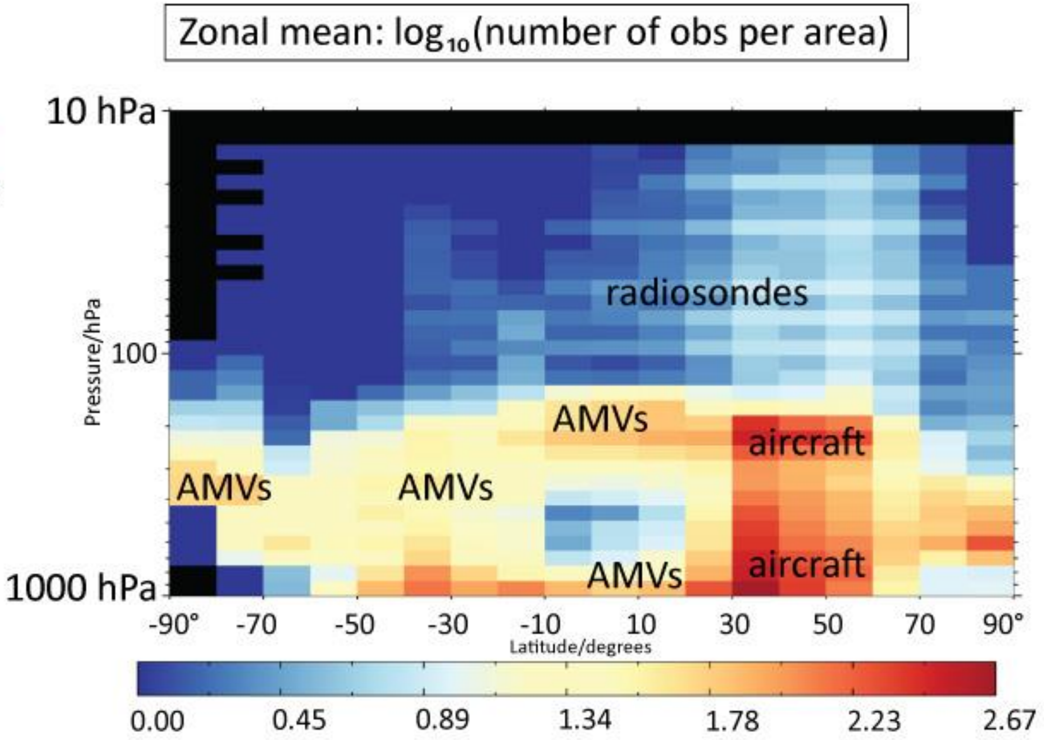
Radiosondes



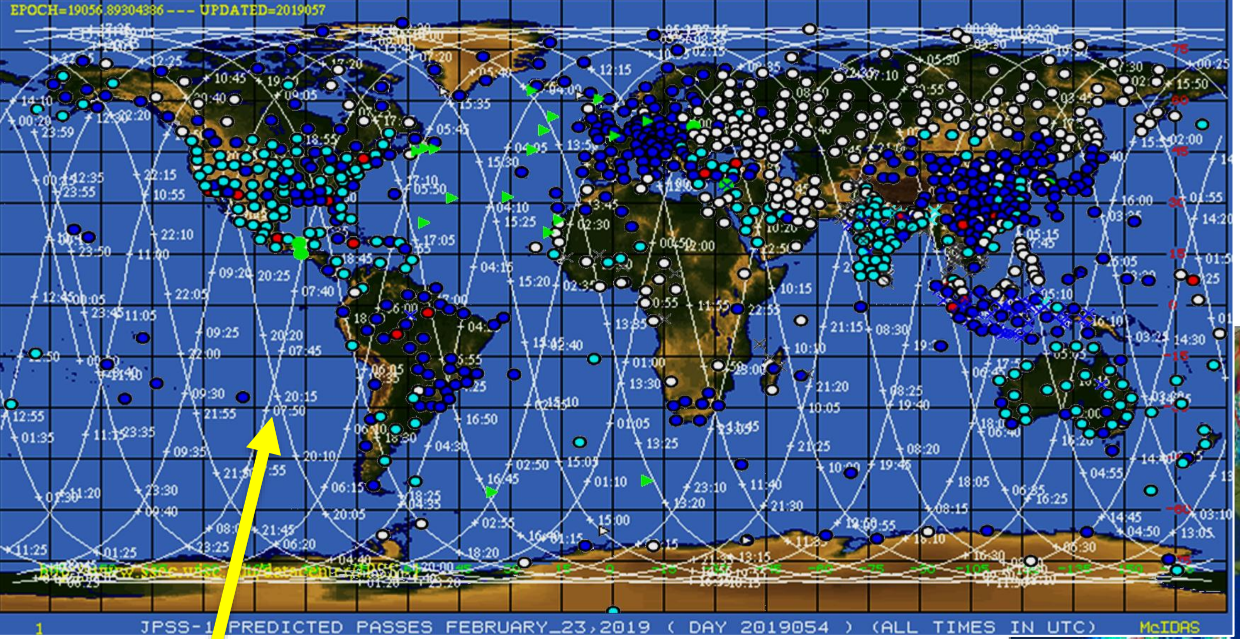
Wind assimilated in an ECMWF LWDA cycle (Oct. 2016)



- Uneven distribution
- Upper troposphere and stratosphere still poorly sampled



- Images from Lars Isaksen and Michael Rennie, ECMWF: https://www.ecmwf.int/en/about/media-centre/science-blog/2018/improving-forecasts-new-wind-data-esas-aeolus-mission



Space-based Doppler Wind Lidar builds on CALIPSO

- 24 hrs of JPSS orbits + radiosonde sites
- CALIPSO data + wind profiles (vs. back trajectories)
- Analysis greatly improved with more ocean + Southern Hemisphere wind observations
- Options for UTLS

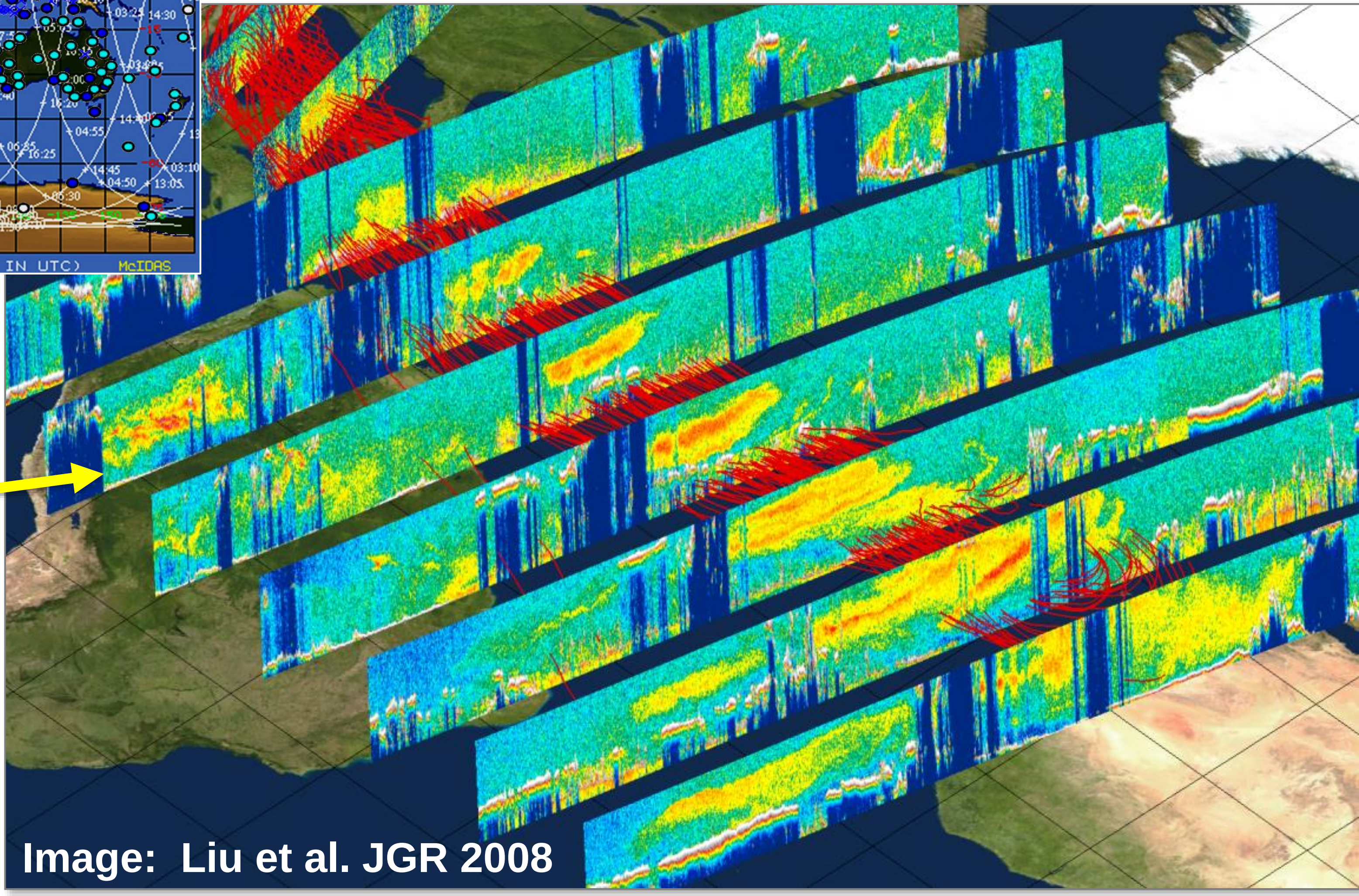
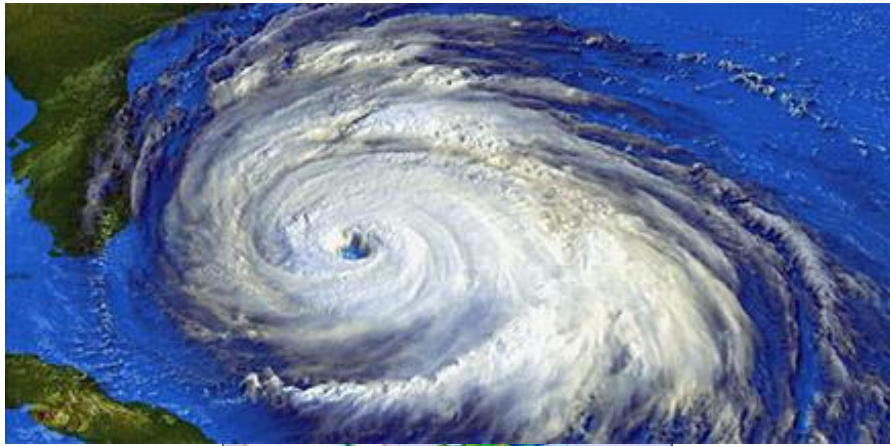


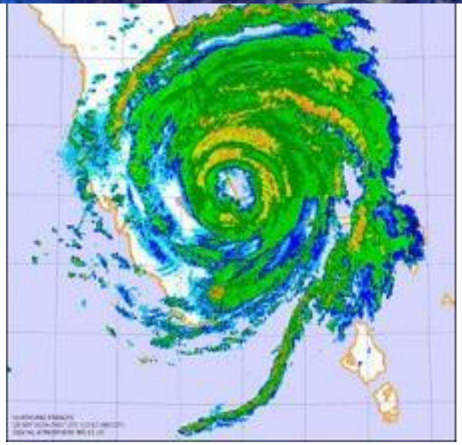
Image: Liu et al. JGR 2008

Wind lidar for operational weather

- Space-based DWL can provide
  - Direct measurements of altitude resolved wind profiles to initialize forecast models and observe large scale dynamics
  - Provide Global coverage: including oceans, tropics, and SH

- Multiple OSSE/OSE/etc. studies over decades show significant predicted impact:
  - Baker et al., *Bulletin of the American Meteorological Society*, 1995
  - Marseille, et al., *Proc. 5th Intl. Winds Workshop, EUM-P, 2000*
  - Riishojgaard et al., *J. Applied Meteorology*, 2004
  - Stoffelen, et al., *Quarterly J. of the Royal Met. Soc.*, 2006
  - Marseille, G.J., A. Stoffelen, & J. Barkmeijer, *Tellus* A, 2008 (2 papers)
  - Weissman & Cardinali, *Quarterly J. of the Royal Met. Soc.*, 2007
  - Atlas, et al., *IEEE IGARSS*, 2010
  - Baker, et al., *Bulletin of the American Meteorological Society,* 2014
  - Ma et al., *Journal of Atmospheric and Oceanic Technology*, 2014
  - Atlas, et al. *Journal of Atmospheric and Oceanic Technology,* 2015





- ESA's Aeolus operating on orbit – starting to look at impact of lidar wind measurements.

ESA’s Aeolus Mission: Atmospheric LAser Doppler Instrument (ALADIN)

Launched 22 August 2018

Single-look
(60%-70% of 2 looks)

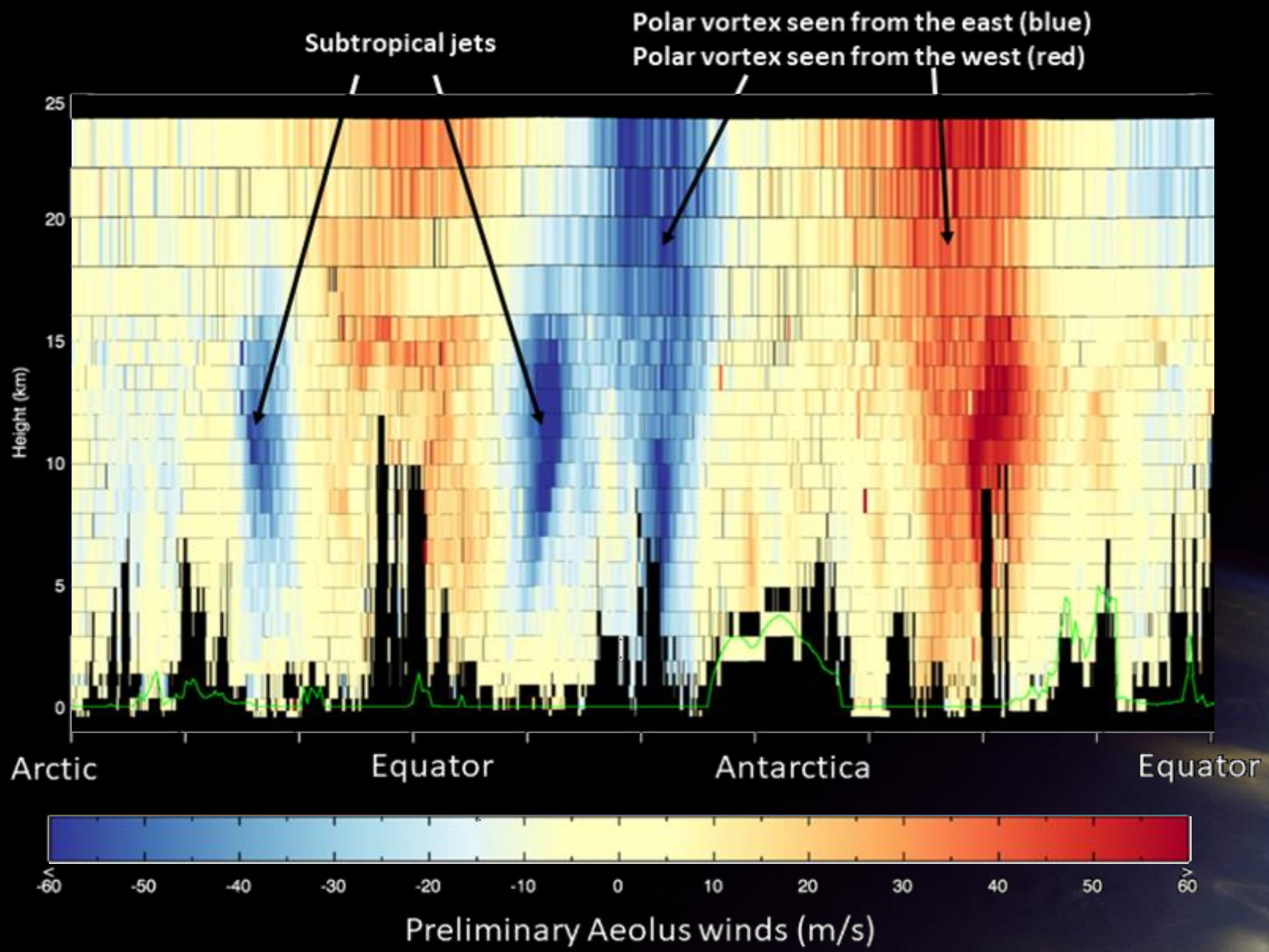
Two Direct Detection channels: Aerosol & Molecular (full troposphere) - both at 355 nm

Sun-synchronous, dusk/dawn orbit, 320 km

3 year mission (consumables)
no planned follow-on (yet)

Courtesy Anne Grete Straume

ESA's Aeolus Mission: Atmospheric LAser Doppler Instrument (ALADIN)



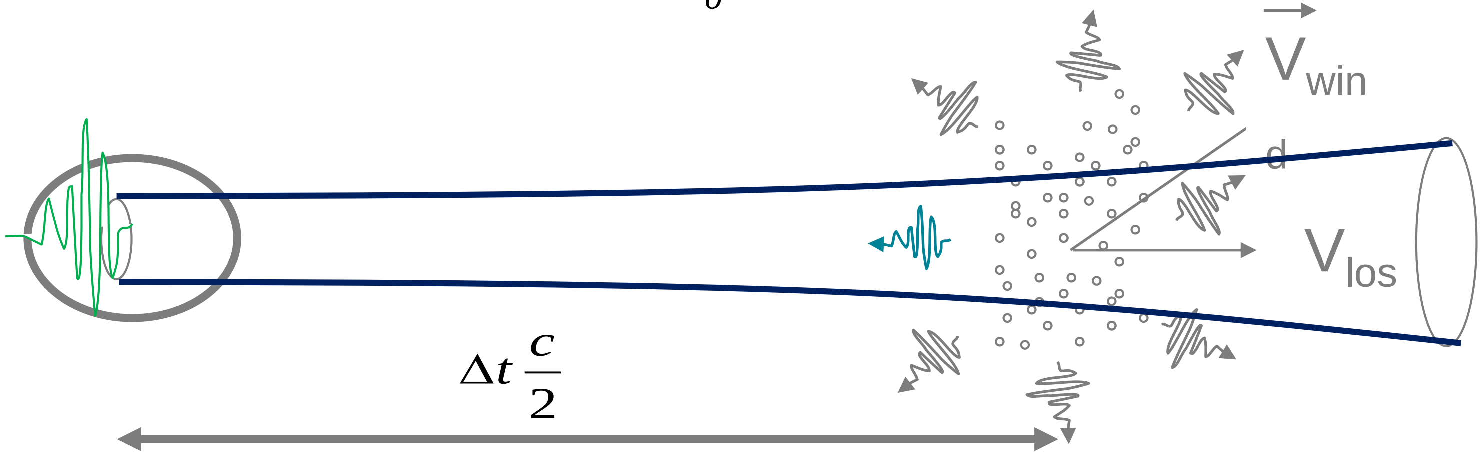
Images: ESA

DOPPLER WIND LIDAR OBSERVATIONS

Principles of Doppler Wind Lidar

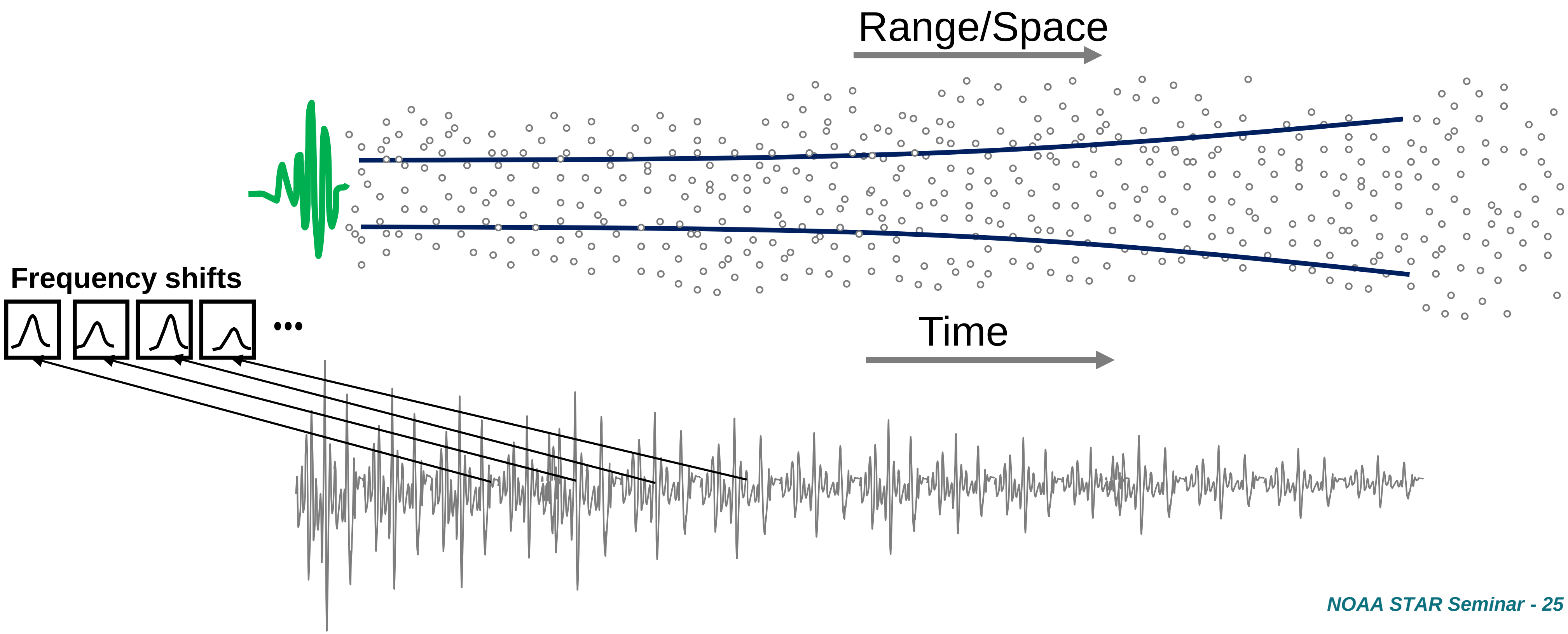
- Laser pulse is sent into the atmosphere (10-200-5000 times per second)
- The pulse scatters off the atmosphere in all directions
- Part of the scattered light returns to be detected – lidar backscatter, β
- If winds move the scattering targets, they impose Doppler shifts on the return light
- This Doppler shift depends on wind speed angle relative to the line of sight (LOS)

$$\delta f_{Doppler} = \frac{2V_{LOS} f_0}{c} = \frac{2V_{LOS}}{\lambda_o}$$



Distributed targets

- As the pulse propagates out, continuous signals are scattered back to the telescope and detected
- Time of return tells the range to each portion of the atmosphere
- Process signals to calculate range-resolved Doppler shifts
- Resolution depends on power, range, desired precision, etc.



Doppler Wind Lidar

What it does

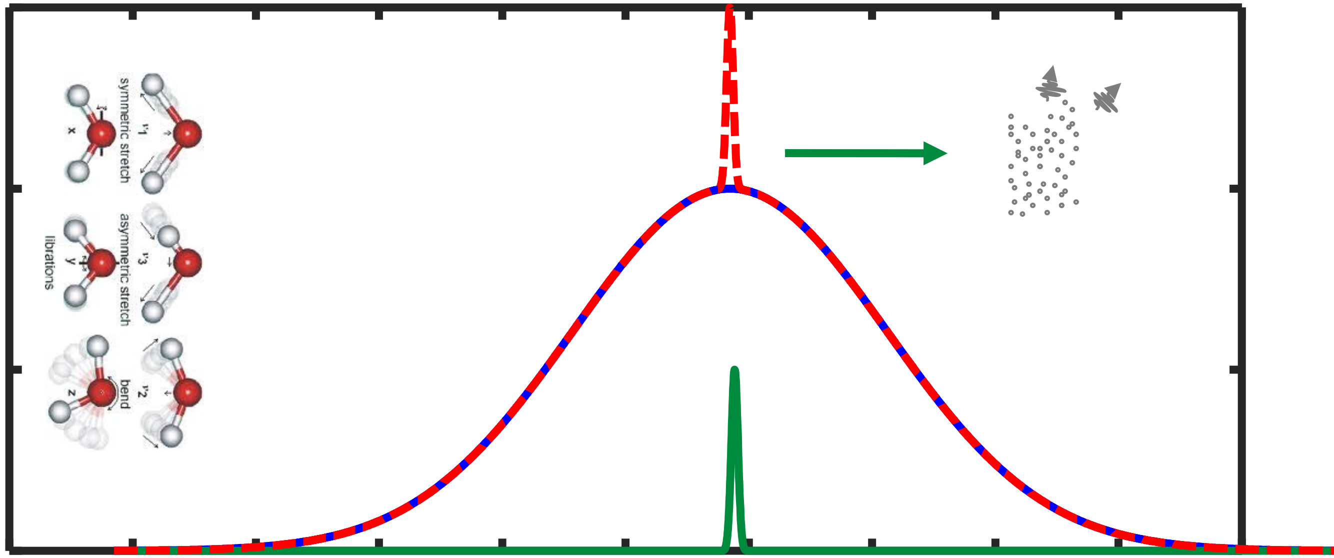
- Provides direct measurements of LOS wind speed profiles
  - range-resolved – "sonde-like" – but averaging & accumulation along the curtain provides a more representative measurement for a grid cell than point samples
  - no tracking or multiple satellites or revisit time is required
  - Systems with molecular channels don't require aerosol layers
- Provides accurate & precise observation to anchor other measurements and models
- Multiple looks/scans → retrieve horizontal wind speed & direction

What it doesn't do

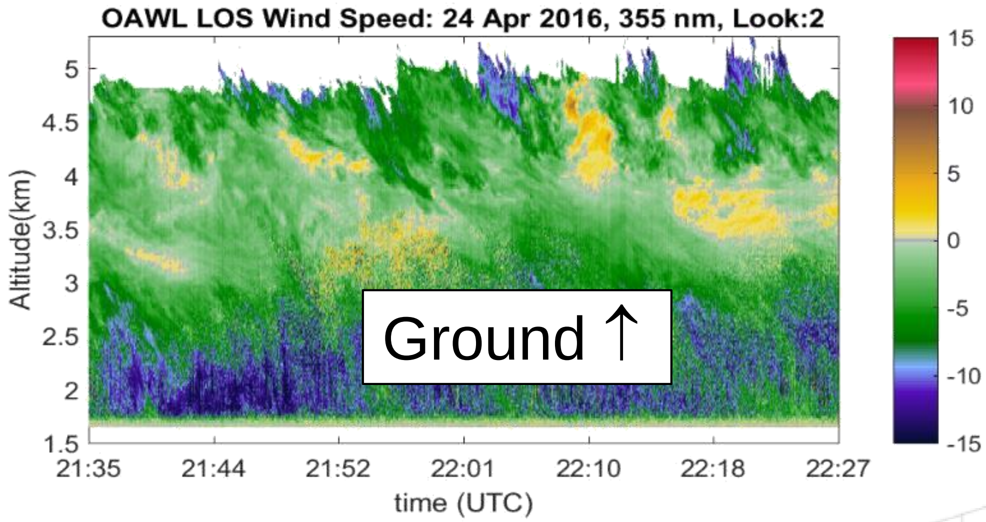
- See through thick clouds (same as CALIPSO)
- From space
  - Provide a horizontal swath from space– profiles provided along orbit path
  - Provide frequent revisit times
    - Lots of coverage over 24 hours, but observations vary in location
    - A rate vs. a static variable
  - Measure small scale turbulence

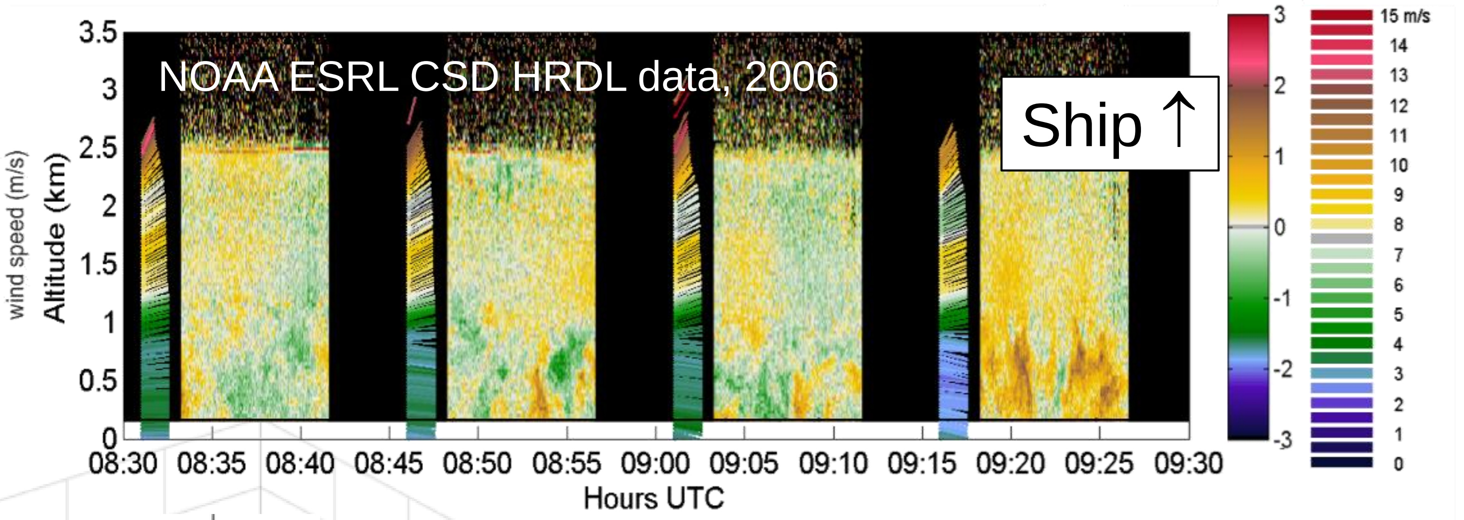
Atmospheric lidar return

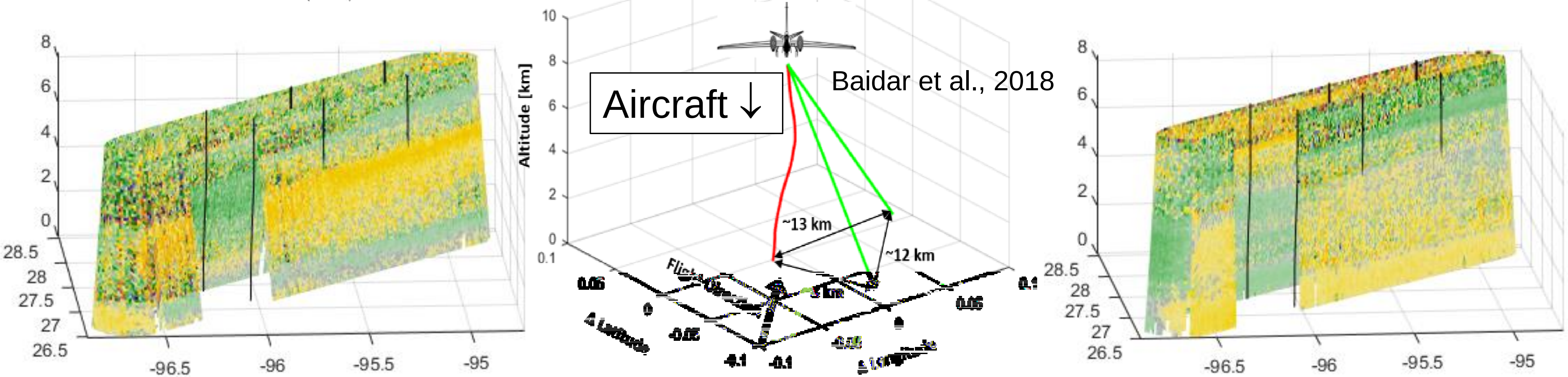
- Elastic scatter aerosol/cloud (“Mie”) returns – mostly lower troposphere
  - Narrow bandwidth (< 100 MHz FWHM)
  - Easier to resolve precise frequency shifts,
  - Inconsistent opportunities – most are in the lower troposphere and cloud layers
- Doppler broadened molecular (Rayleigh-Brillouin) returns
  - Wide bandwidth (~1-3 GHz FWHM, based on wavelength, atmospheric temperature, pressure, and composition)
  - Harder to resolve precise frequency shifts
  - Molecules are consistently available (best coverage)



Wind Lidar data examples: Sub-orbital

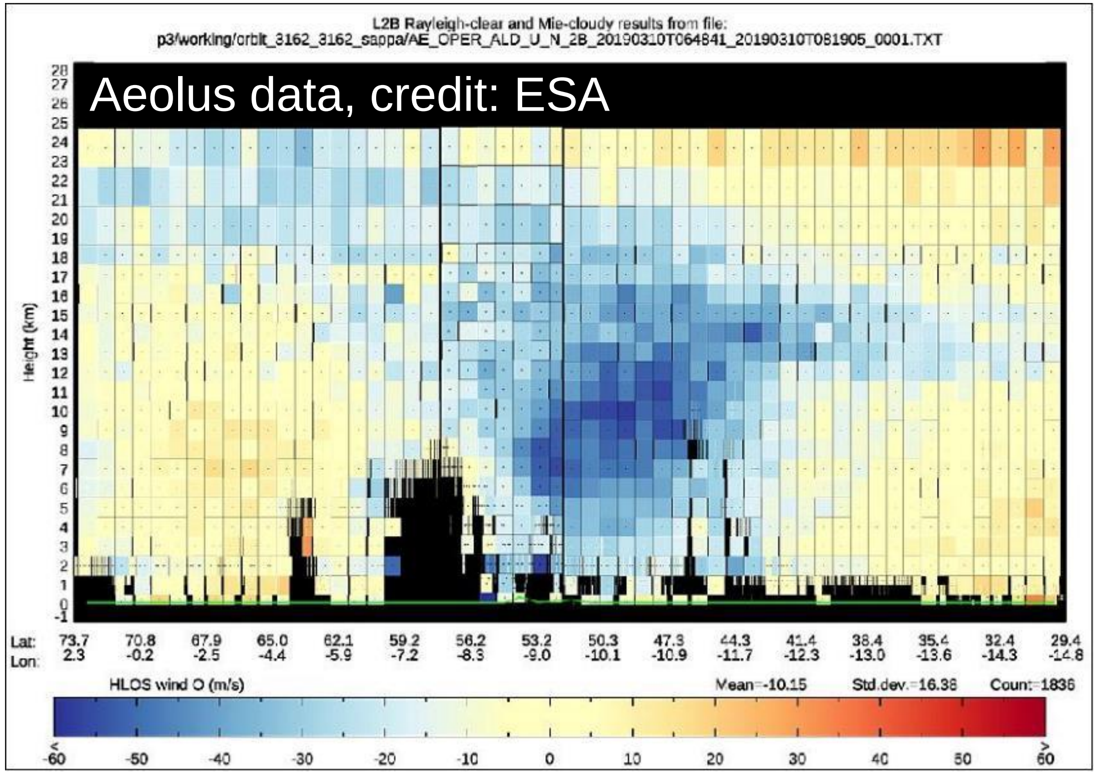


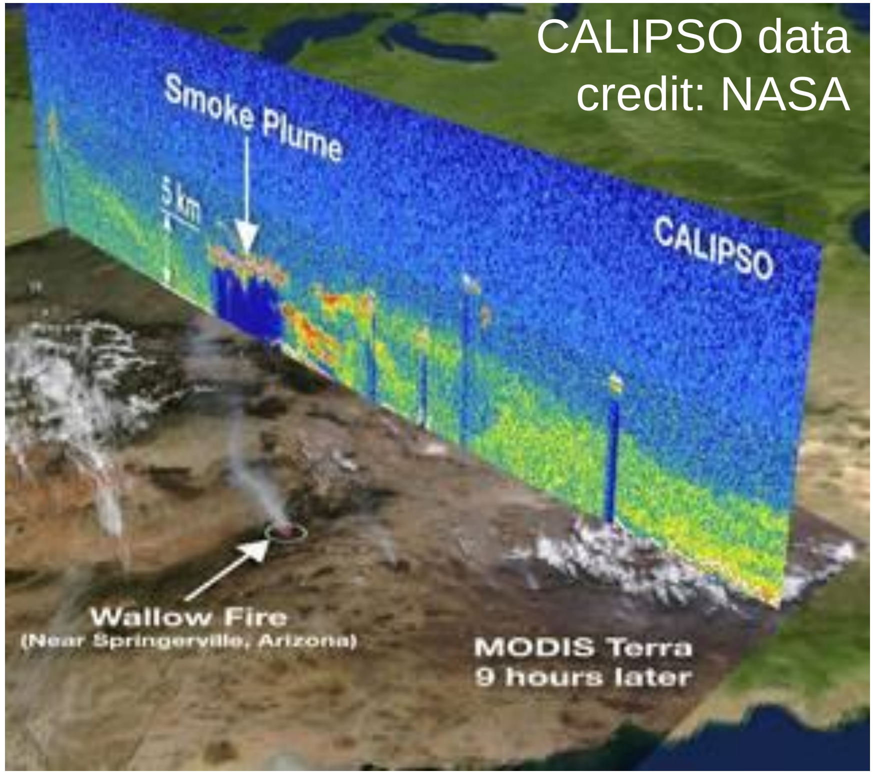




Wind lidar data: Space-based

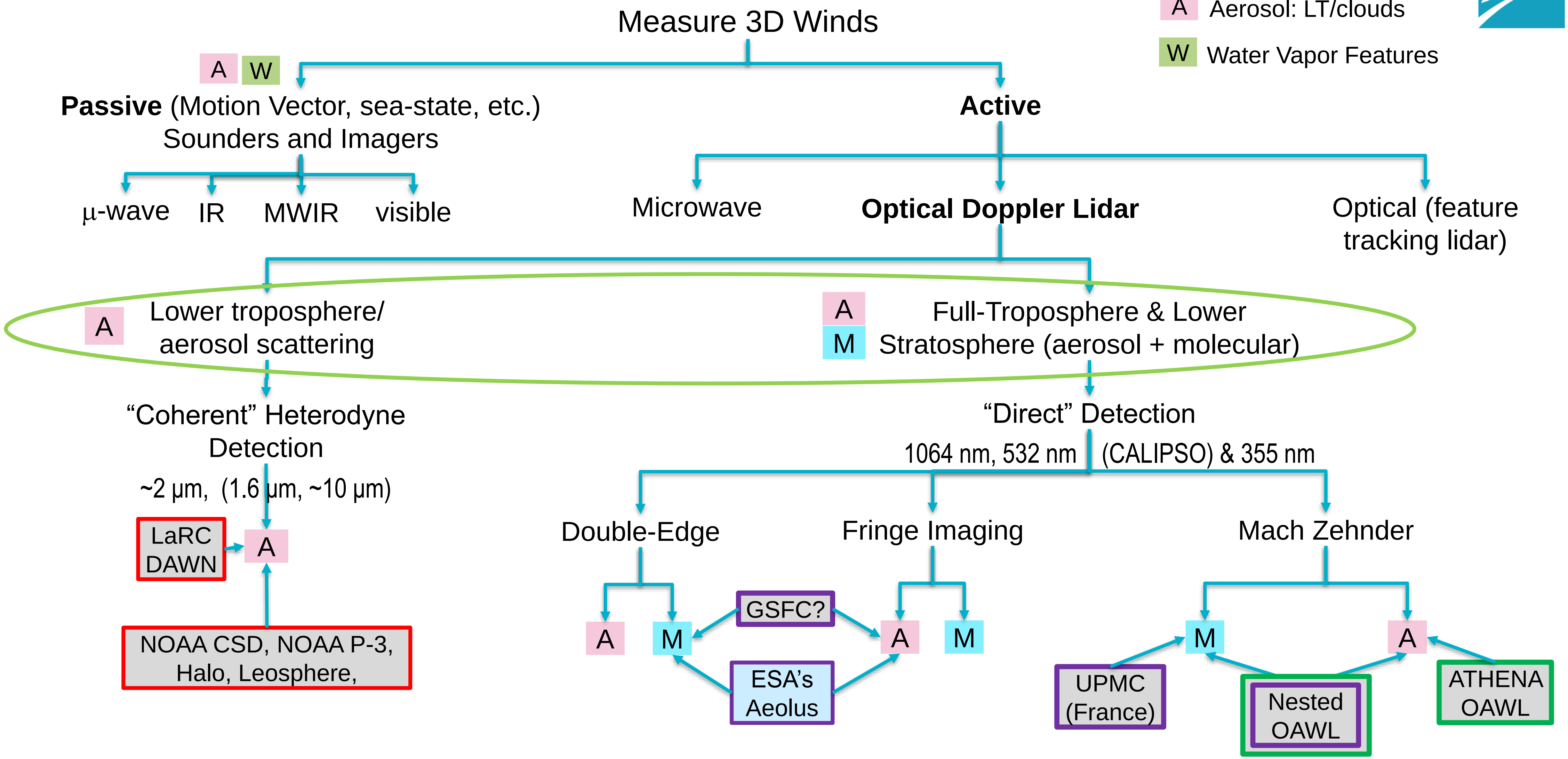
- Global curtains of wind profiles can add vertical dimensions to sounder & imager swath data
- Like CALIPSO & now Aeolus, the lidar “swath” is vertical – a curtain vs. a carpet





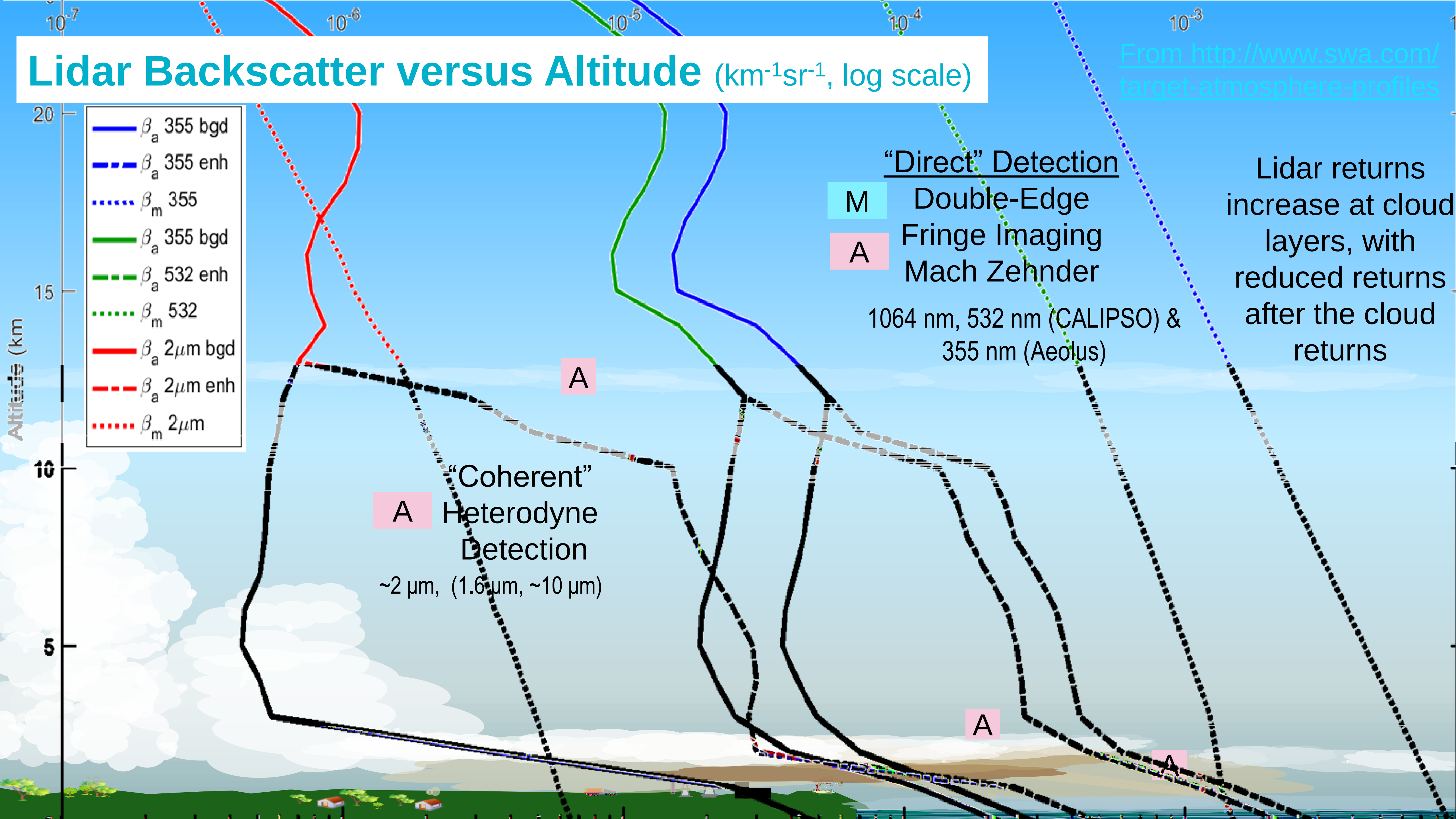
Observing Atmospheric Winds from Space

M Molecular: UT/LS
A Aerosol: LT/clouds
W Water Vapor Features



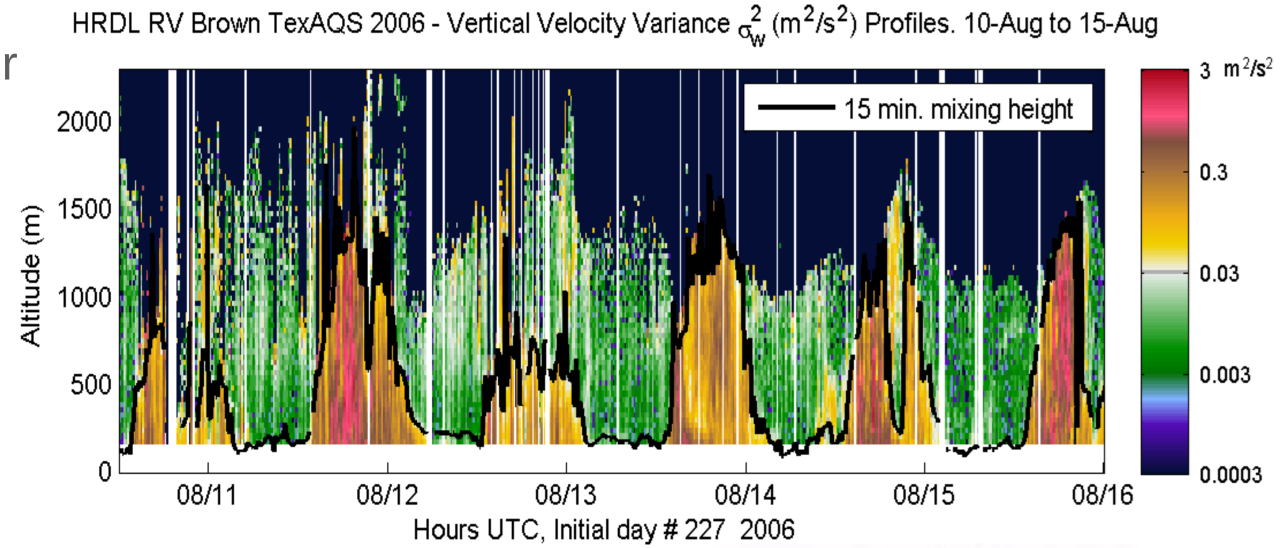
Lidar Backscatter versus Altitude (km^{-1}sr^{-1}, log scale)

From http://www.swa.com/target-atmosphere-profiles

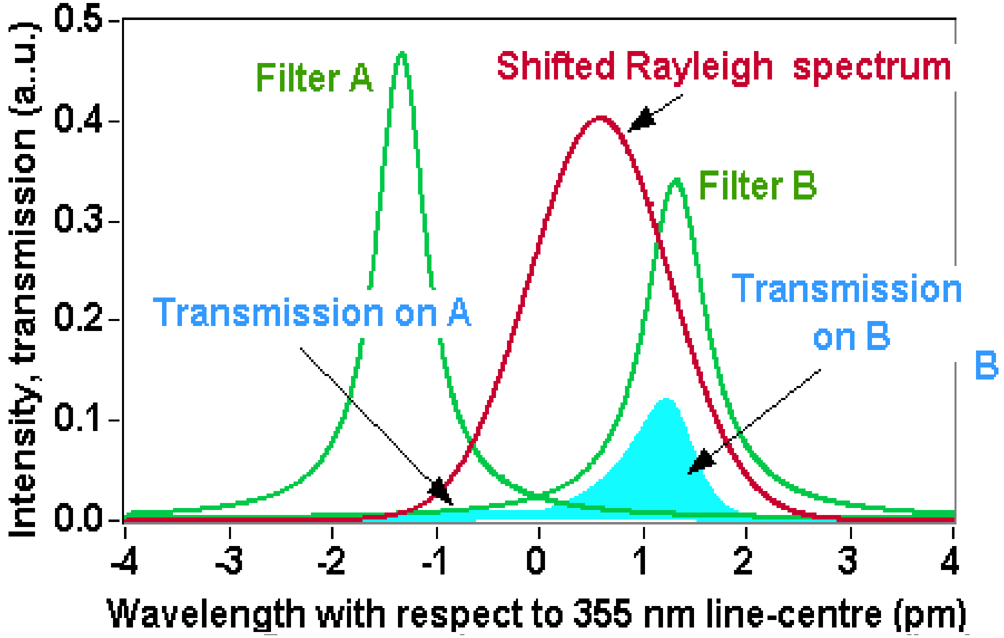


Coherent Detection Wind Lidars: used frequently in sub-orbital boundary layer/lower-troposphere research

- Typically eye-safe, 1.5-10 μm wavelengths - great for PBL studies where sufficient aerosols are present
- NOAA ESRL CSD: Mini-MOPA, HRDL, TEAC0, Micro-Dop
- NOAA AOML: CTI Army system on P3 aircraft
- Coherent Technologies Inc. (now LMCT)
  - Wind Tracers (ground, airports)
  - Airborne Systems: DC-8 (NASA ACLAIM), P3 (Navy & NOAA), DLR Falcon, some DoD applications.
- Beyond Photonics
  - Folks formerly at CTI/LMCT
  - Currently working DAWN for Langley
- Leosphere (Vaisala)
- Halo Photonics (UK)
- NASA Langley (DAWN on the NASA DC-8)



Principle of wind measurement with ESA’s Aeolus ALADIN



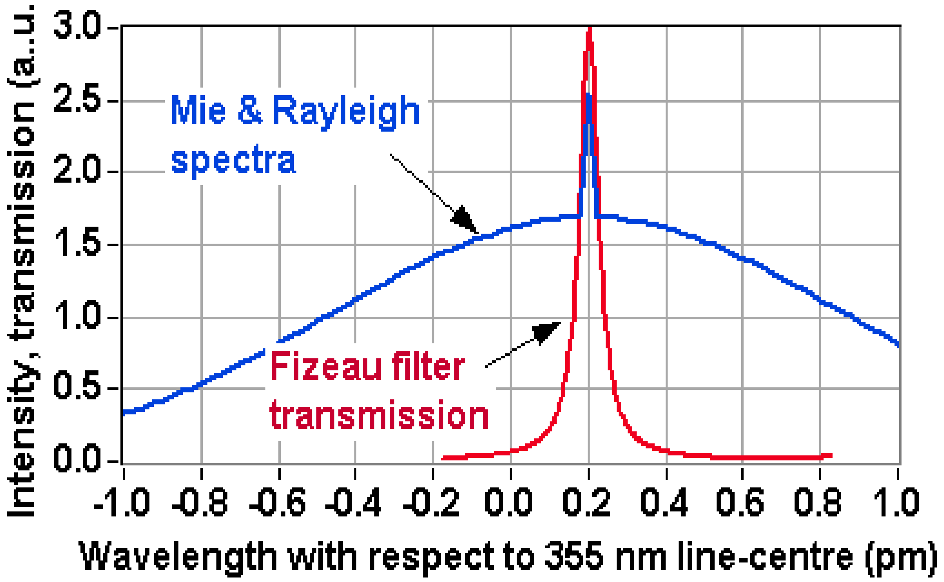


Figure from U. Paffrath

Atmospheric LAser Doppler INstrument
ALADIN

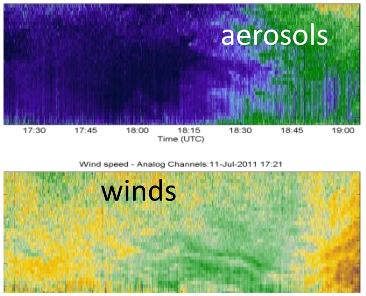
- Direct-Detection Doppler Lidar at 355 nm
- 2 types of etalon spectrometers to analyse backscattered return signal
  - Double edge Fabry-Perot etalon for spectrally broad molecular return (Rayleigh, like NASA GSFC’s TWiLiTE system)
  - Fizeau etalon “Fringe Imaging” spectrometer narrows in on shifts in the spectrally narrow aerosol/cloud (Mie) returns

GOING BEYOND: NASA/Ball CALIPSO Lidar >13 Years on orbit!

ESA's ADM Aeolus (single look – 355 nm Aerosol & Molecular)

Ball Aerospace's Optical Autocovariance Wind Lidar (OAWL) - Aerosol & Molecular

*NASA ESTO funded grants (no profit)



NSOSA study
ESDS

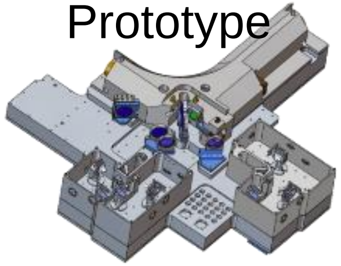
EVI-4 **ATHENA-OAWL** 532 nm
Aerosol winds ISS Mission concept
(TMCO rated Selectable)

Operational Airborne mission development

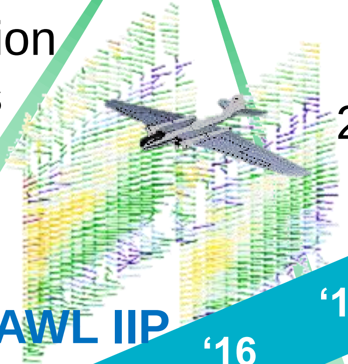
Global 3D winds

Full tropospheric operational wind lidar

Quadrature Mach Zehnder Interferometer Laboratory Prototype



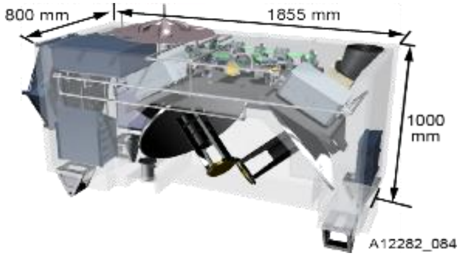
OAWL Mission concepts



ESA's Aeolus Launch 22/08/19

On-orbit Operational Demonstration: dual lines of sight

Operational Space Demonstration Flight build

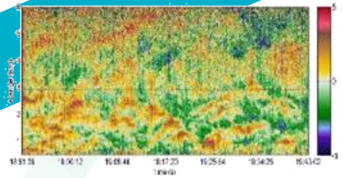


*HAWC-OAWL IIP

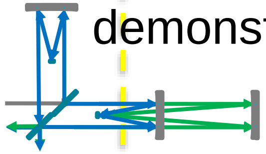
*GrOAWL 2016 demo

*OAWL-ACTs

*OAWL-IIP 2011 demo



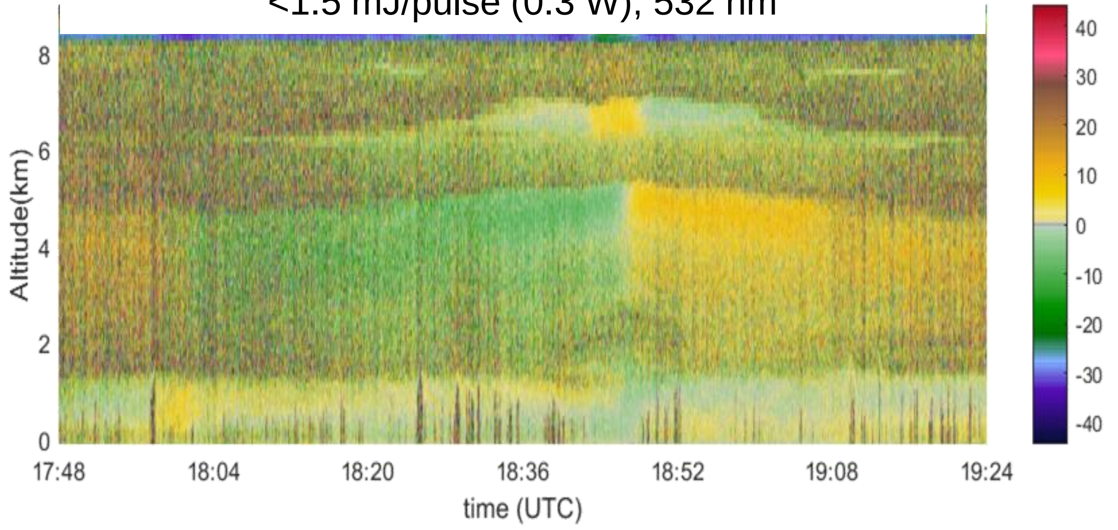
Nested OAWL full troposphere demonstration



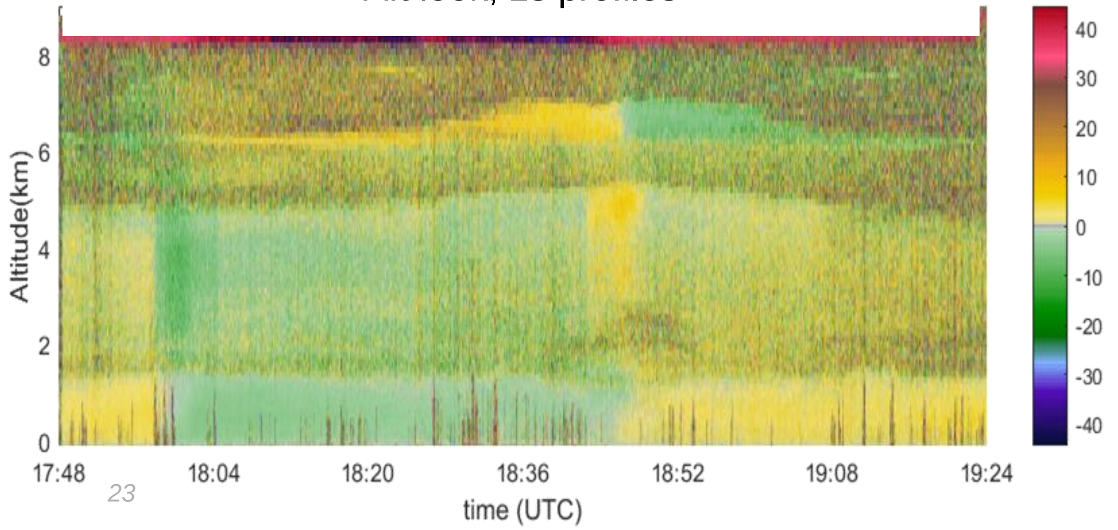
'09 '10 '12 '13 '14 '15 '16 '17 '18 '19 '20 '21 '22 '23 '24 '25 '26 '27 '28 '29 '30

Airborne OAWL Validation: Simultaneous two-look wind profiles

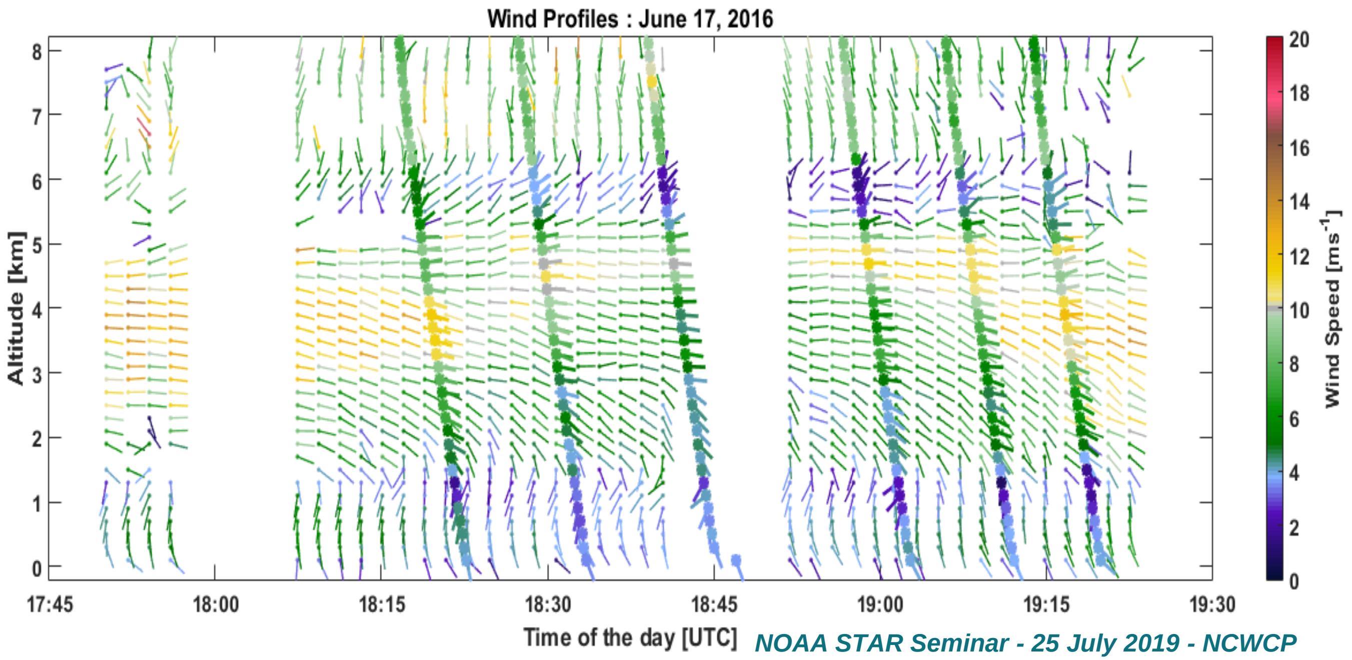
17 June 2016: Forward look, 1s profiles,
<1.5 mJ/pulse (0.3 W), 532 nm



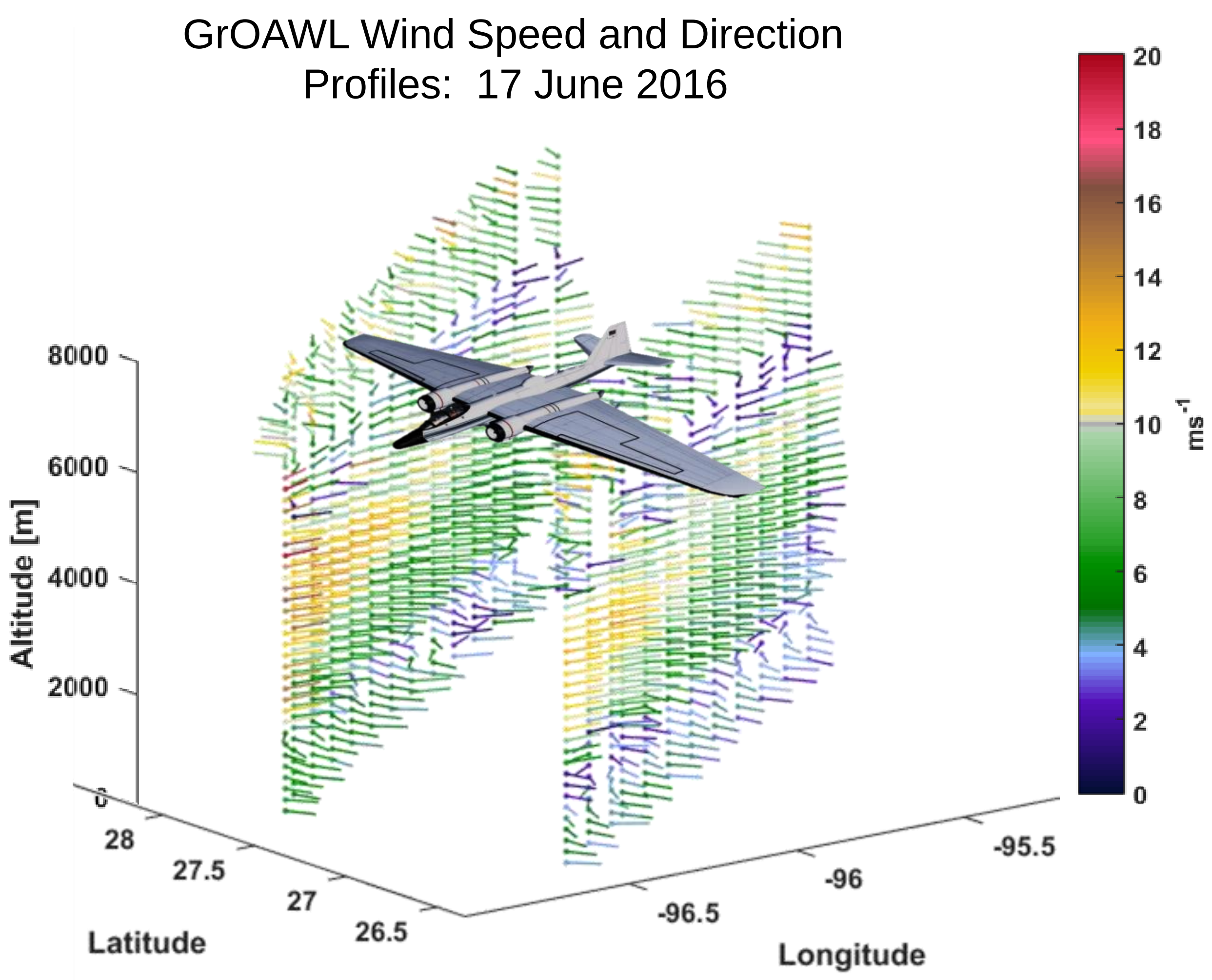
Aft look, 1s profiles

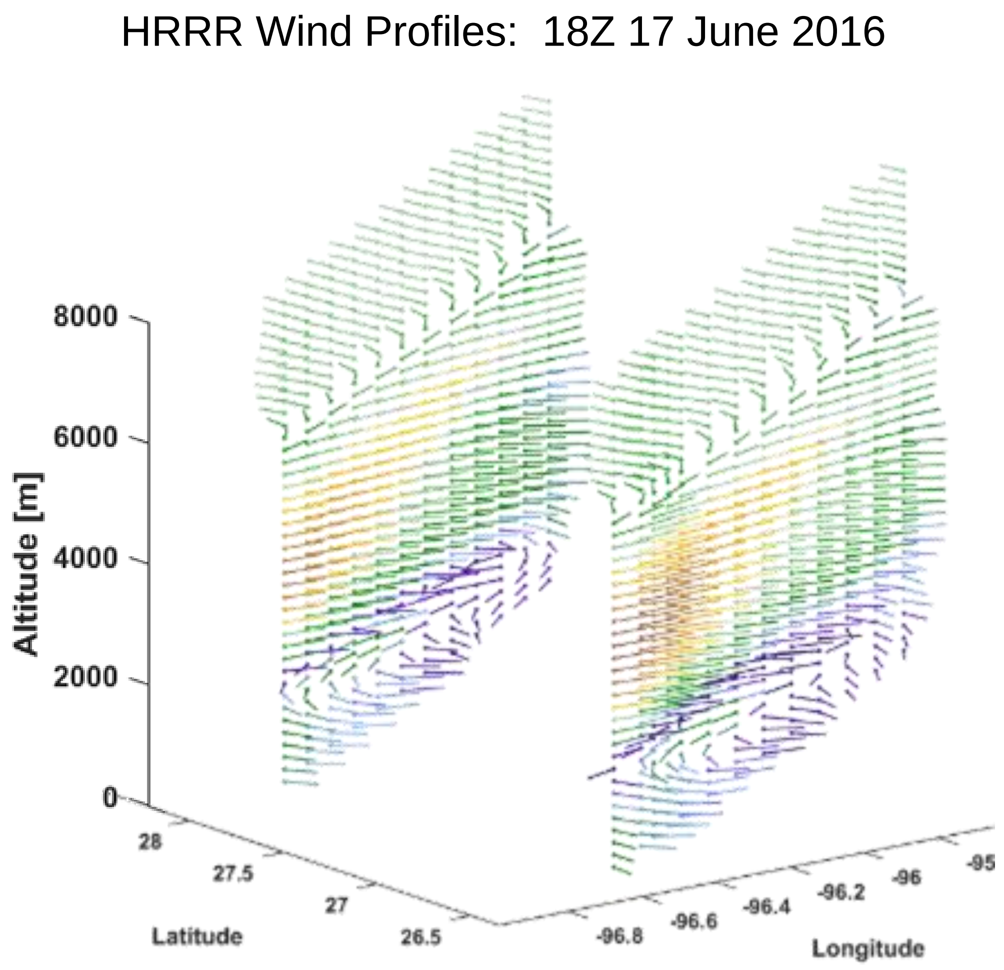


- Autonomous Green OAWL ("GrOAWL") Airborne Demonstrator built, flown (WB-57), validated, and scaled to space
- Left: Dual 45° Line of Sight (LoS) wind speed data sets – can combine to get speed & direction (below)
- **See: Tucker et al., 2018 & Baidar et al., 2018, *J. Atmos. & Ocean. Tech,***



GrOAWL airborne measurements over the Gulf of Mexico captured spatial variability predicted by NOAA's HRRR

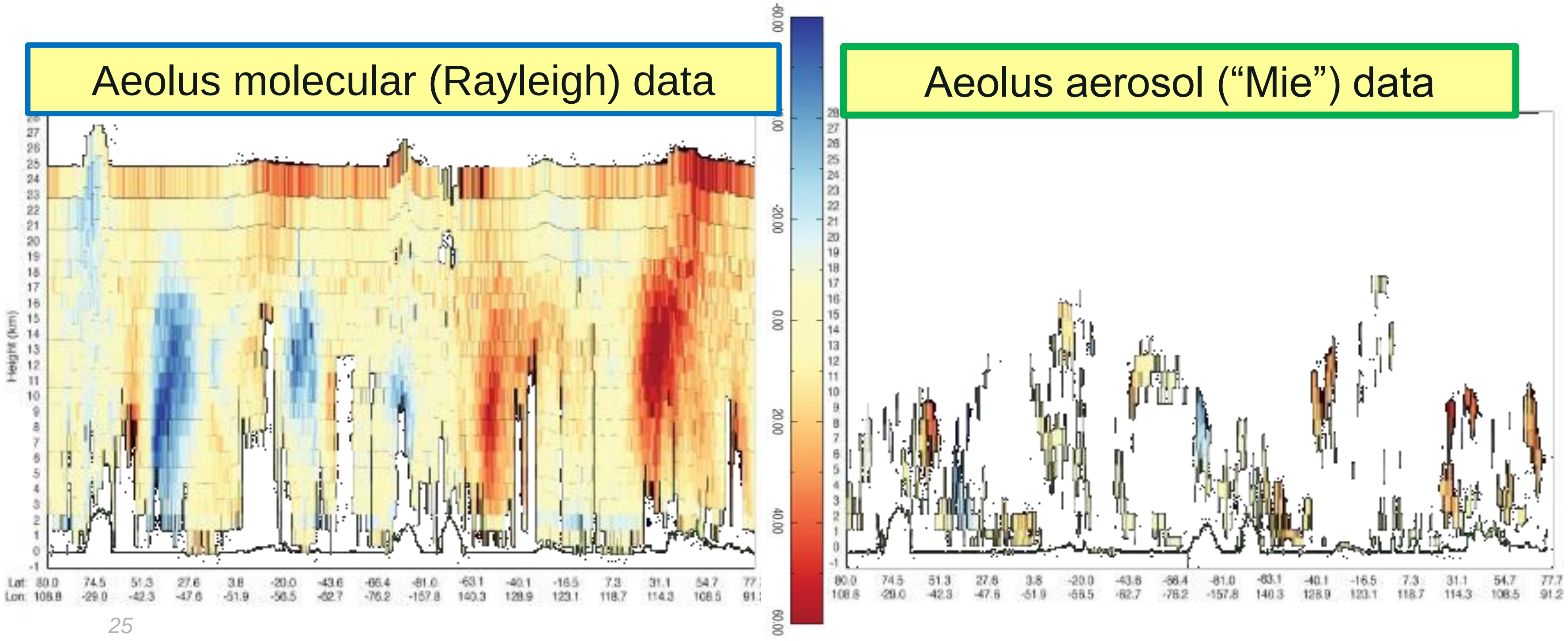


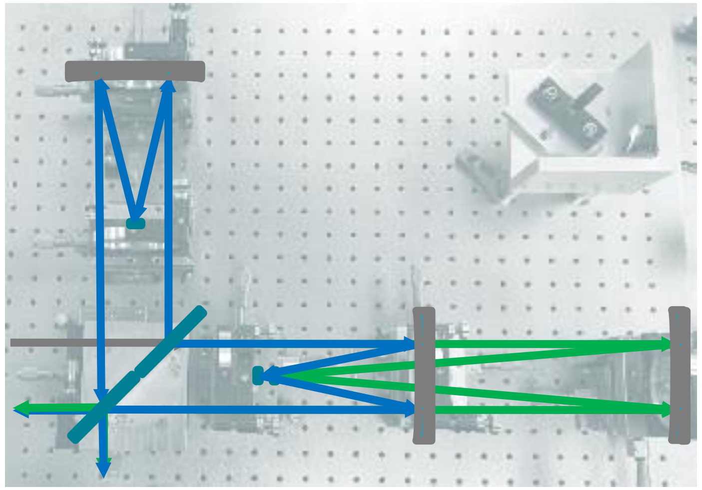


Images: Sunil Baidar, CIRES/NOAA ESRL CSD

Nested-OAWL path to Full Atmospheric Wind Profiles

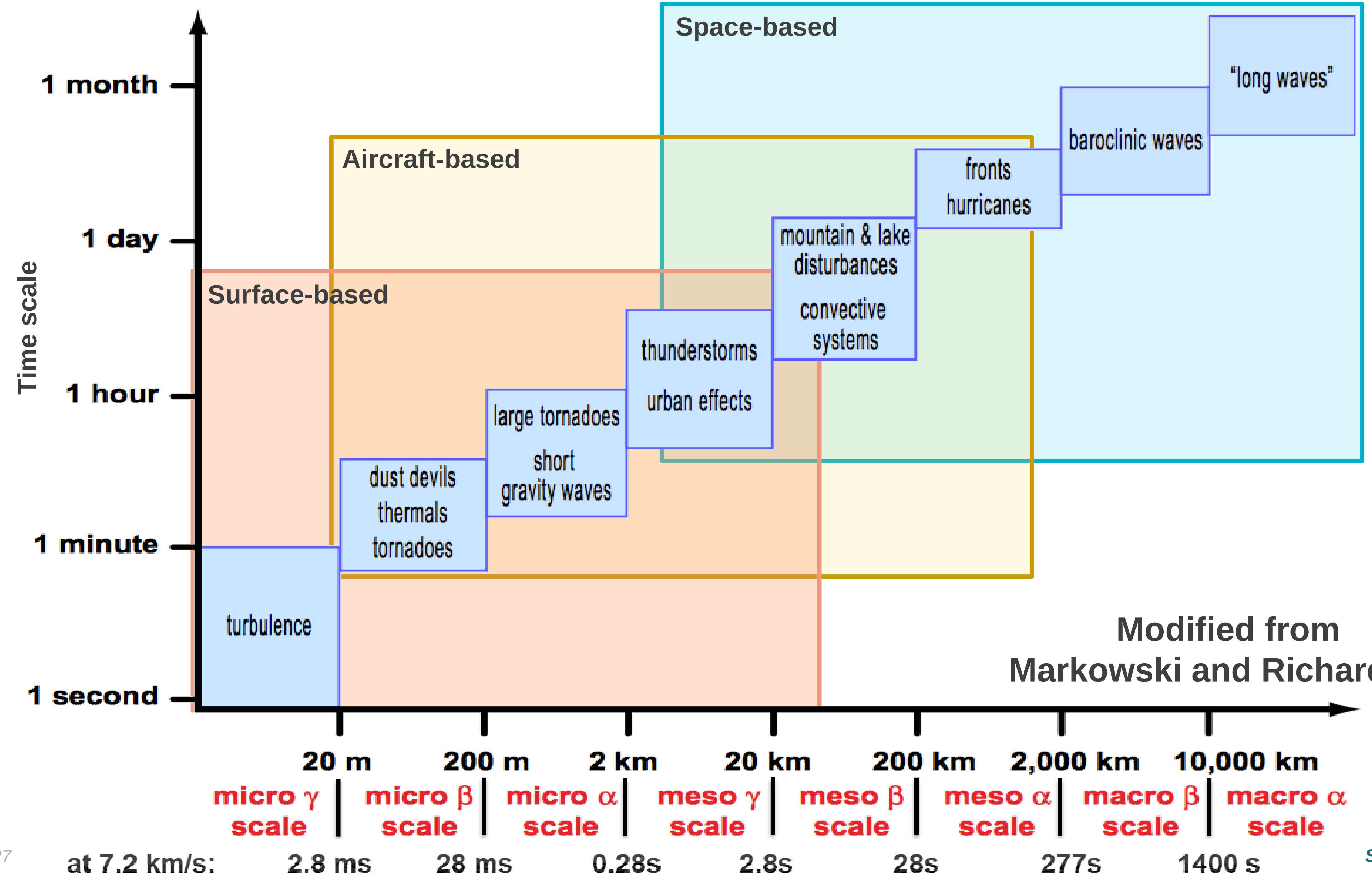
- Current Ball IRAD demonstrating the Nested interferometer to provide Aerosol winds @ 532 nm (long OPD) and Molecular winds @ 355 nm (new short OPD)
- *Both wavelengths* simultaneously generated in the *same laser, both OPDs* in the *same interferometer.*
- DARPA-funded effort developed a UV-only short OPD OAWL interferometer



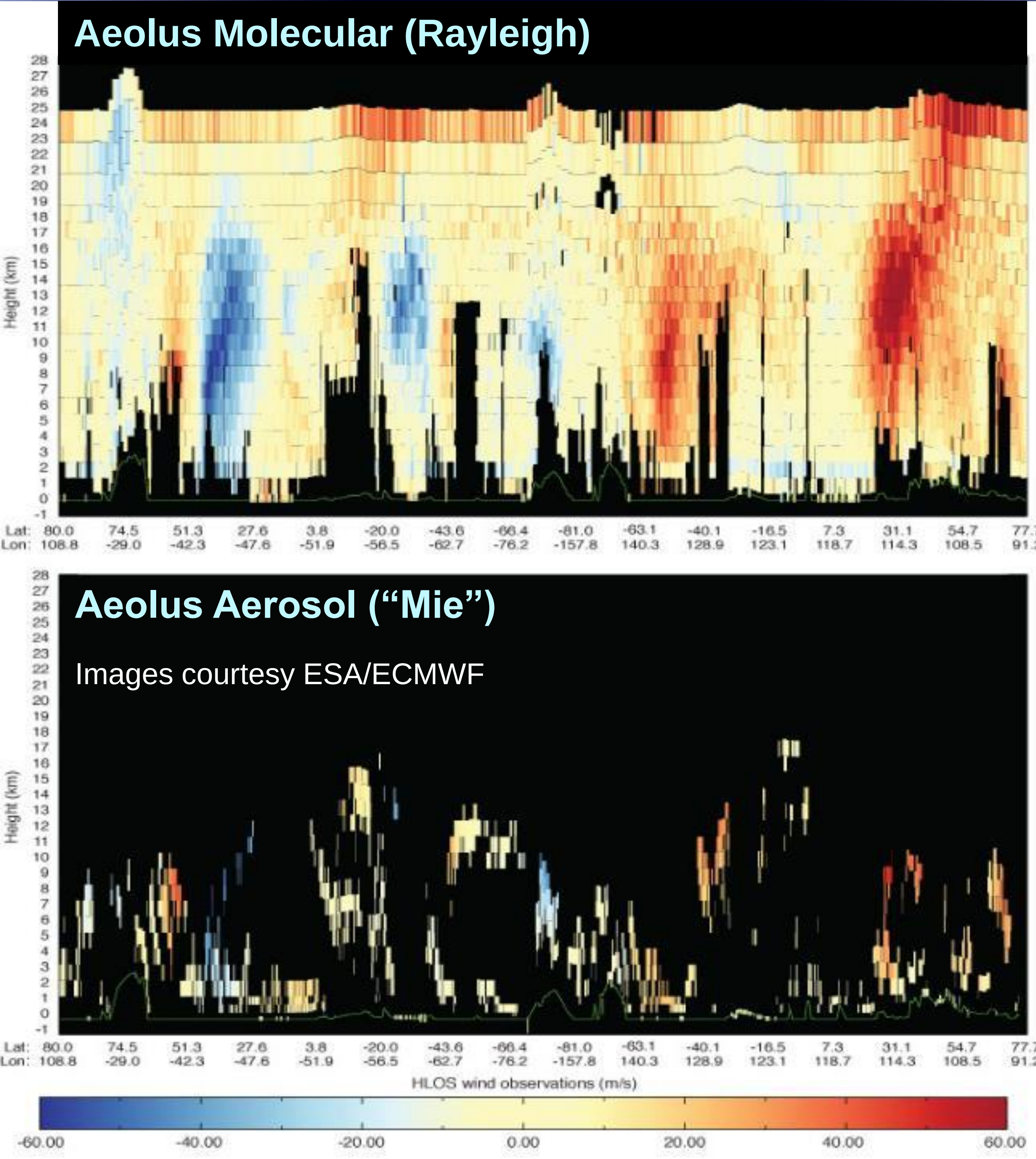


SHAPING FUTURE WIND MISSIONS

Scales of atmospheric processes

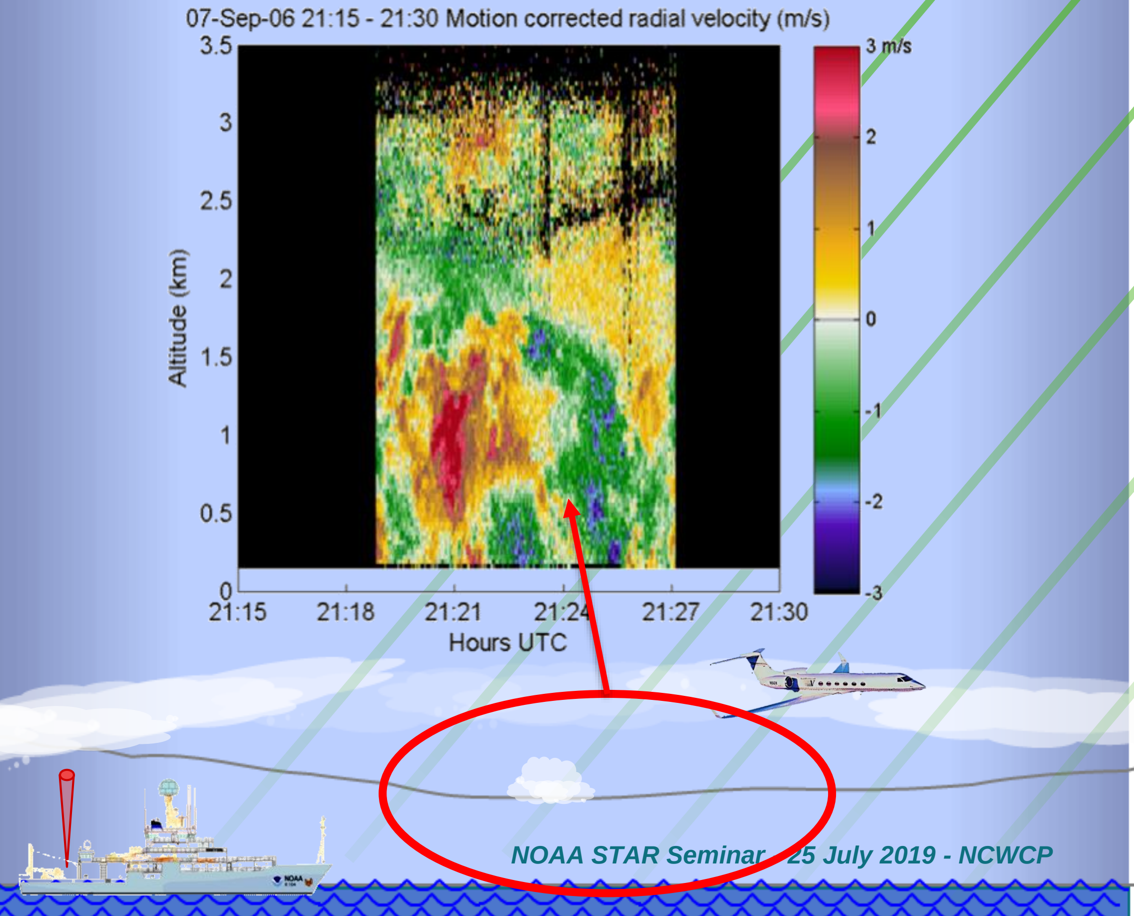


Modified from Markowski and Richardson



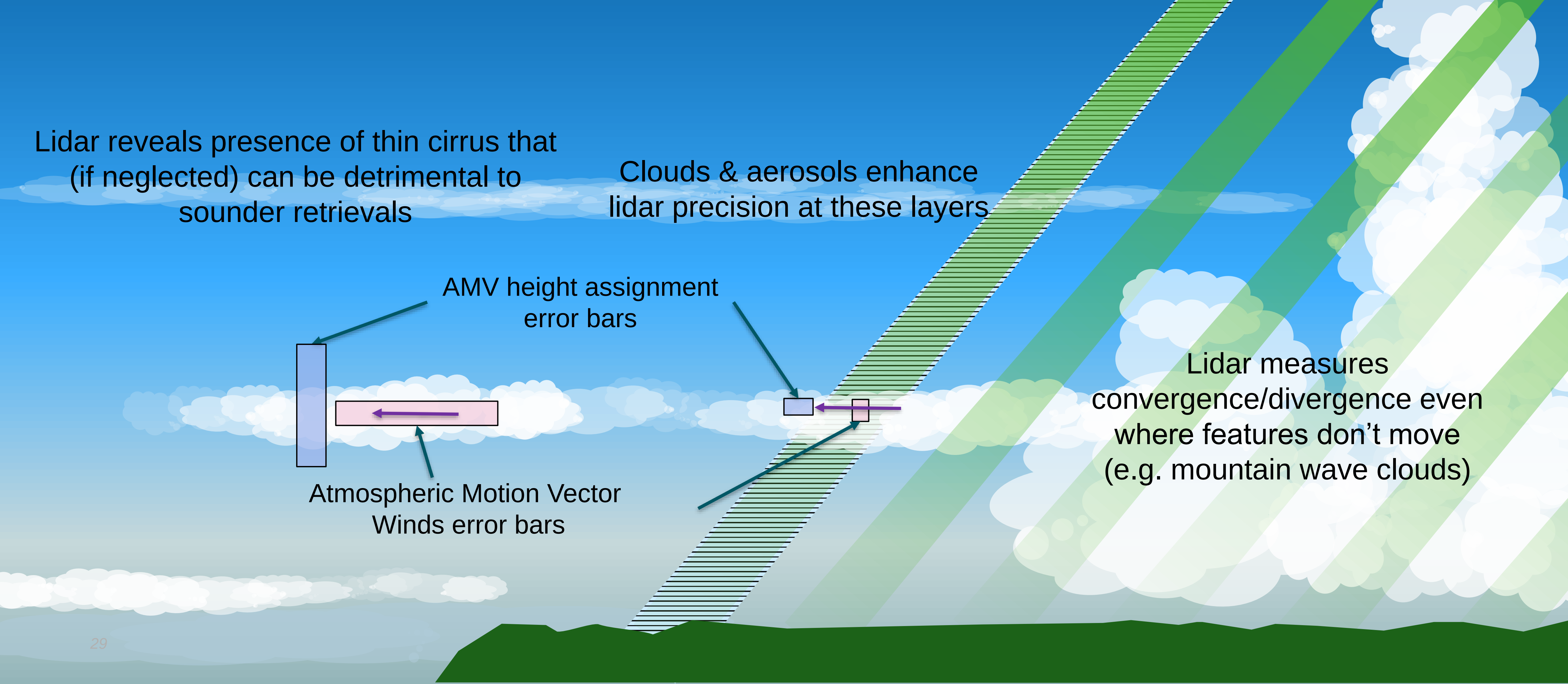
Doppler Lidar Applications

- Space: Global winds
- Aircraft: Regional winds, some PBL
- Ship/Ground: PBL focus, some upper troposphere



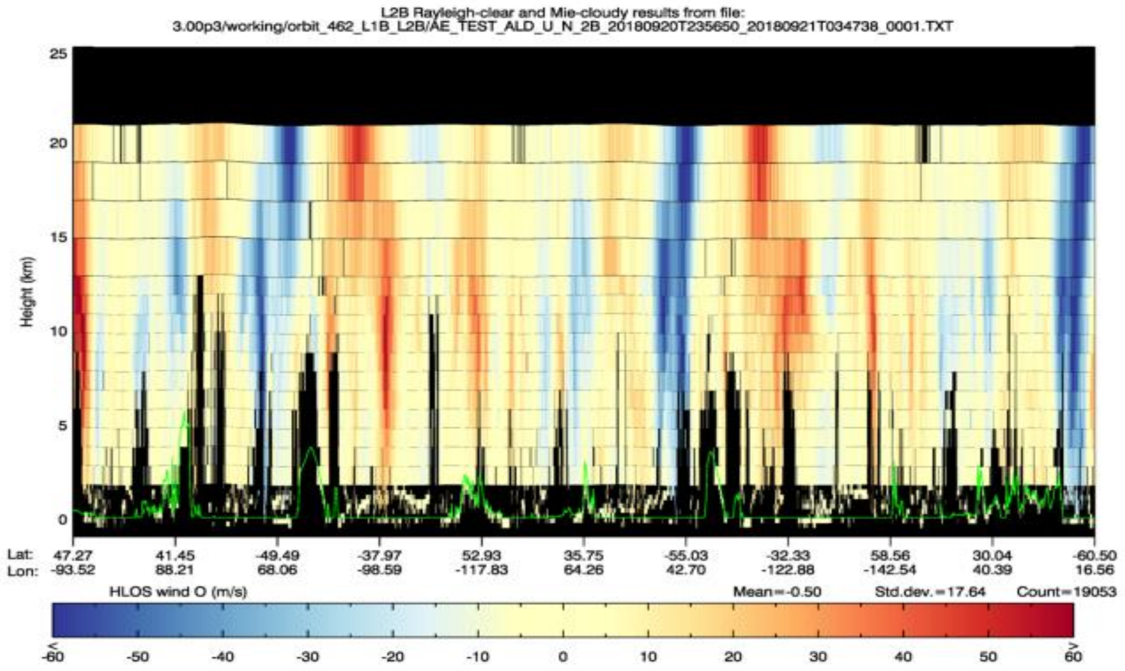
Range resolved Lidar anchors cloud heights to improve AMV results…

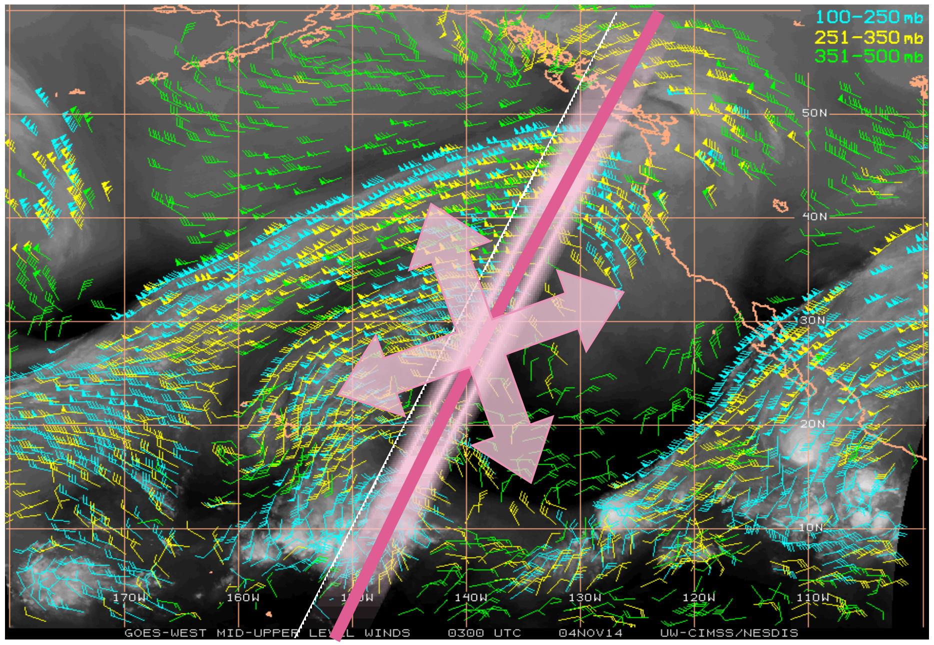
See Folger & Weissman, (2014 & 2016)



Possible Mission Architecture

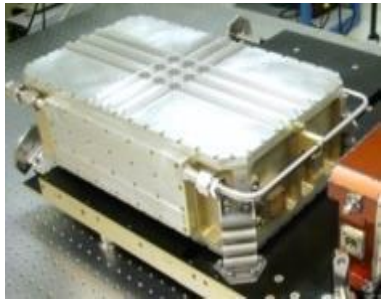
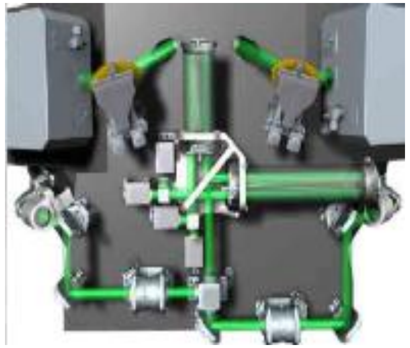
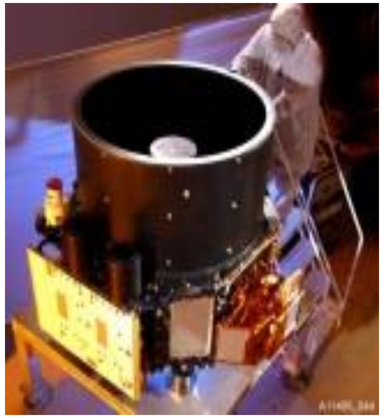
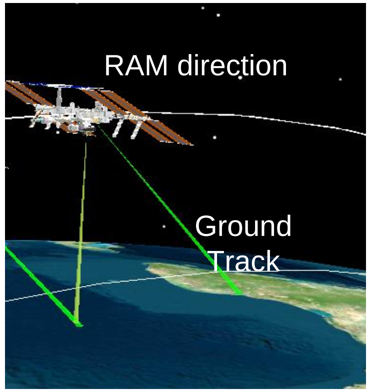
- Aerosols (including clouds) and water vapor features → AMVs
- True clear air (no aerosols, low water vapor)
  - Aeolus Molecular lidar winds are providing lots of previously un-measured data
- AMV + molecular Doppler channel for space-based operation
  - Lidar anchors AMV ←→ AMV extends lidar
- Studies
  - How far (swath) does the anchor hold?
  - What is the overall benefit for lidar + AMV data?

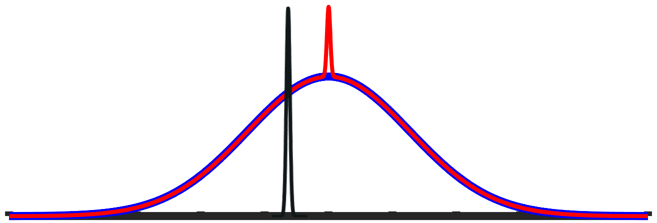




The OAWL approach builds on Aeolus & CALIPSO

- Laser - Nd:YAG doubled (CALIPSO) & tripled (AEOLUS)
- High Mach Zehnder interferometer throughput efficiency enables two lines of sight for less uncertainty
- Relaxed technical requirements for the laser, telescope, Tx/Rx alignment, field-of-view, etc. → less risk/costs
  - No frequency locking requirement
  - Wide FOV for alignment margin (like CALIPSO)
  - Pressurized laser (like CALIPSO)
- OAWL detectors & real-time processors → increased flexibility in processing parameters, altitude gate size, etc.
- Fewer and simpler calibration requirements
- No Mie contamination of the OAWL Rayleigh channel

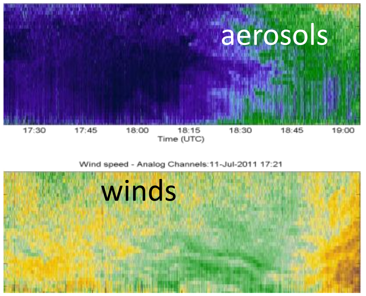


GOING BEYOND: NASA/Ball CALIPSO Lidar >13 Years on orbit!

ESA's ADM Aeolus (single look – 355 nm Aerosol & Molecular)

Ball Aerospace's Optical Autocovariance Wind Lidar (OAWL) - Aerosol & Molecular

*NASA ESTO funded grants (no profit)



NSOSA study
ESDS

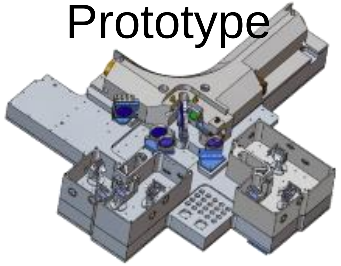
EVI-4 **ATHENA-OAWL** 532 nm Aerosol winds ISS Mission concept (TMCO rated Selectable)

Operational Airborne mission development

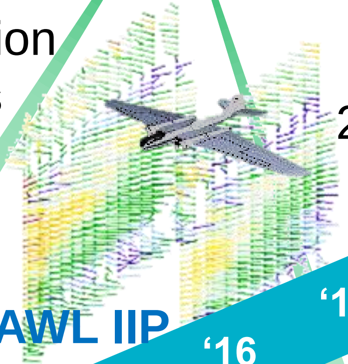
Global 3D winds

Full tropospheric operational wind lidar

Quadrature Mach Zehnder Interferometer Laboratory Prototype



OAWL Mission concepts

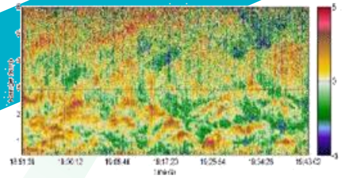


ESA's Aeolus Launch 22/08/19

*HAWC-OAWL IIP

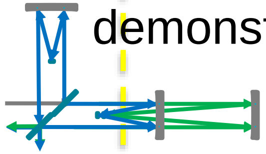
*GrOAWL 2016 demo

*OAWL-ACTs

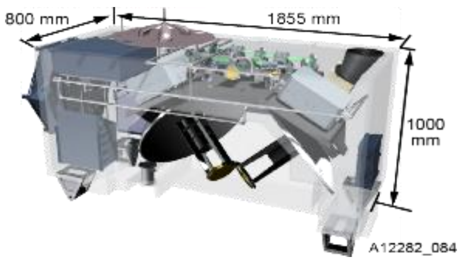


*OAWL-IIP 2011 demo

Nested OAWL full troposphere demonstration



Operational Space Demonstration Flight build



On-orbit Operational Demonstration: dual lines of sight

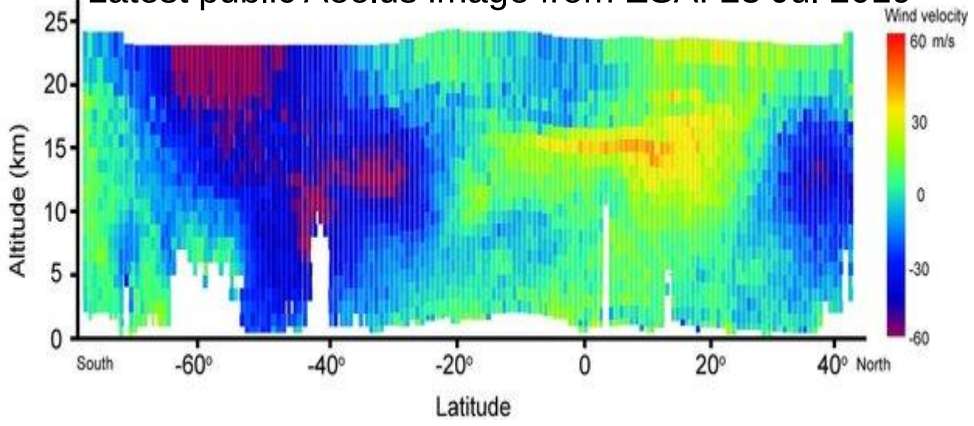
'09 '10 '12 '13 '14 '15 '16 '17 '18 '19 '20 '21 '22 '23 '24 '25 '26 '27 '28 '29 '30

NEXT STEPS & QUESTIONS FOR DISCUSSION

Research to Demonstration to Operations

- ESA/ECMWF/KNMI/DLR/etc.
  - invested a lot of time and funding to advocate and then prepare for Aeolus
  - instrument modeling, technical demonstrations, data processing, data assimilation, data dissemination, etc.
  - Aeolus airborne demonstrator (DLR's A2D) for the mission – preparation and validation

Latest public Aeolus image from ESA: 23 Jul 2019



- What could we all be doing to better advocate and prepare for a US mission?
- Current/Next steps
  - STAR: continue working with Aeolus data to understand and maximize impact
  - Ball: demonstrate OAWL molecular channel to provide full tropospheric winds
  - Community
    - Study/understand/optimize roles for passive and active wind sensing; "Yes, AND…"
    - Start shaping the next generation wind lidar mission to meet NWP needs
  - Potential: OAWL Aircraft integration and flight test hours for NOAA to demonstrate observations in space-like format and test optimal configurations and data types for future architectures.

To think about: Shaping a future US wind lidar mission starts now

- What does NOAA and, specifically, STAR & the NWP community hope to get out of a winds mission?
  - Full troposphere vs. certain parts?
  - Large scale global winds from orbit?
  - Detailed PBL studies (from aircraft/surface obs)?
- What is the maximum resolution (horizontal-along track, and vertical) that supports an operational demonstration?
  - Is Aeolus resolution & performance good enough?
  - What data/science improvements are desired over Aeolus?
  - What are we willing to trade to keep costs down? Resolution? Duty cycle? Vertical coverage? Horizontal coverage?
- How many look-angles or lines-of-sight?
  - Aeolus finding (Horanyi et al. 2014): Single LOS provides 60%-70% the impact of dual-LOS on same satellite.
  - Assimilation: LOS winds provides more impact than horizontal winds
  - Two looks on same satellite, or two smaller satellites for double coverage?
- How would you take advantage of variable/flexible sampling/processing?

Wind Lidar Mission Trades

Wind Speed precision (uncertainty)

Wind Speed accuracy (bias)

Vertical coverage

Vertical resolution

Horizontal resolution

Total Coverage

Systems Engineering

Laser wavelength, power

Telescope size, quality

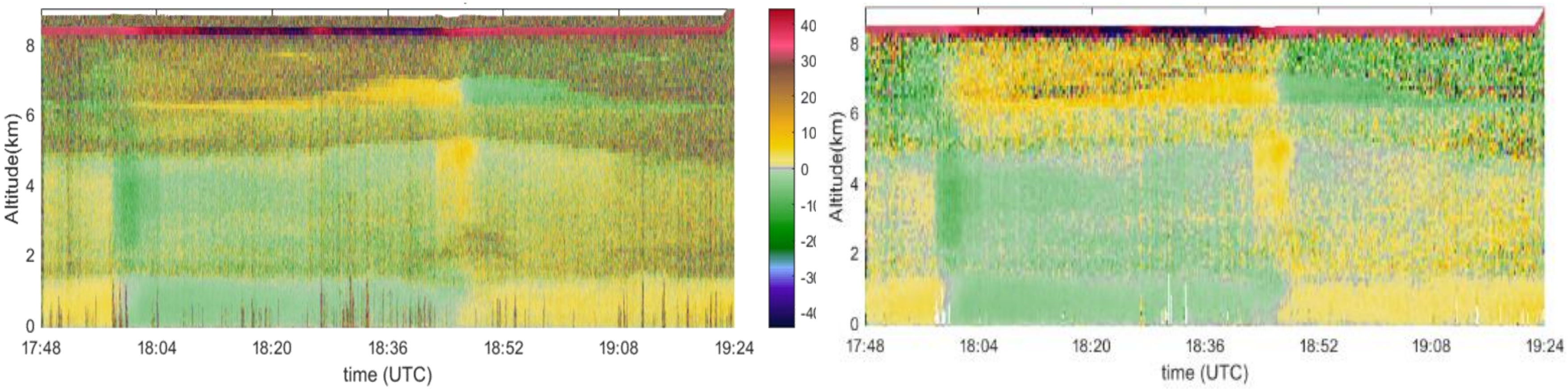
Type of Doppler shift frequency discriminator*

Orbit inclination, altitude

Aerosol distribution

Risk tolerance/budget

1s processing
Less vertical coverage, more uncertainty, more horizontal resolution



10s processing
More vertical coverage, less uncertainty, less horizontal resolution

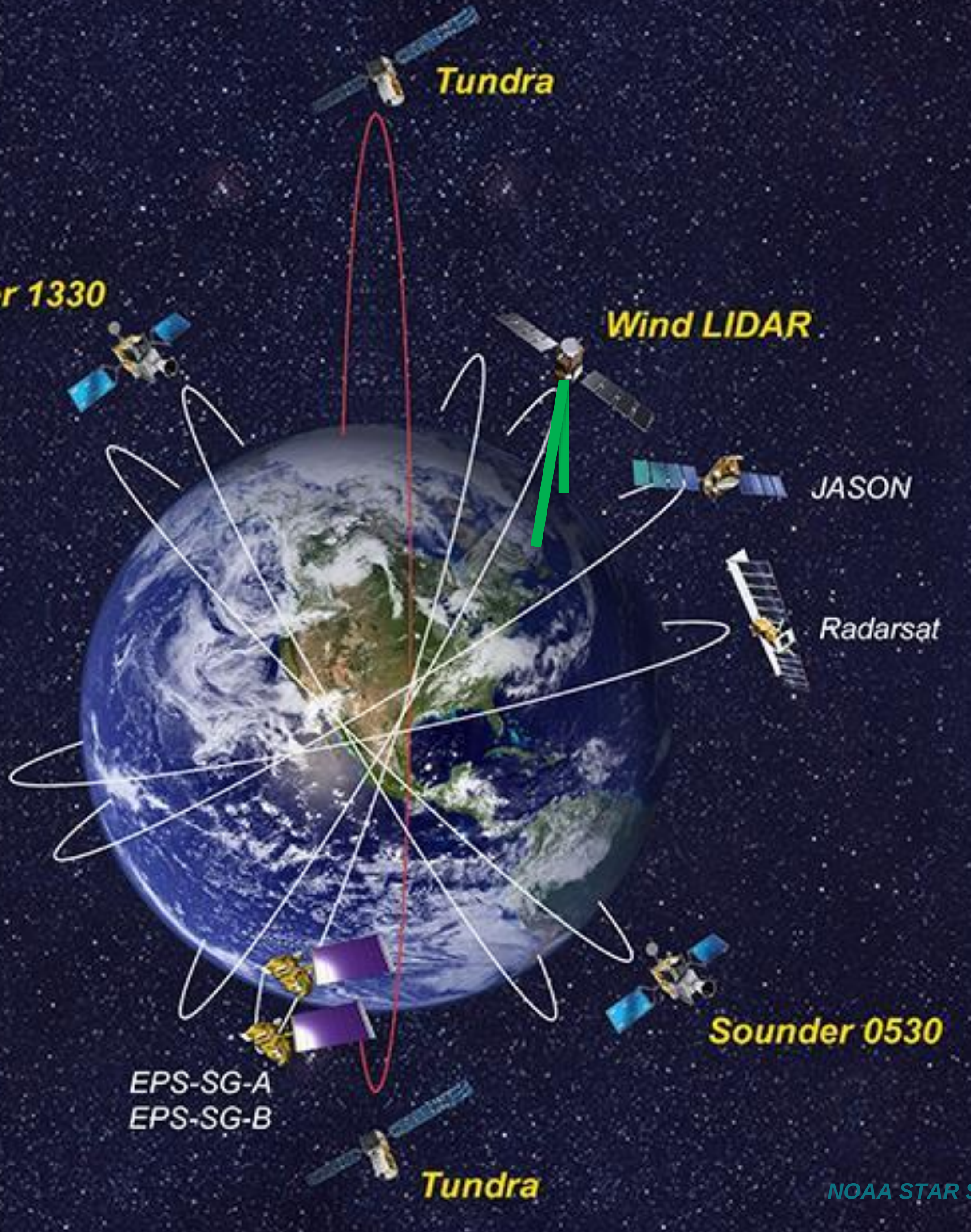
Summary – Thank you!

- Potential impact of full tropospheric wind measurements (including BL winds and UTLS) from lidar has been shown through OSSEs
- ESA-Aeolus' successes and lessons benefit the whole community
  - Demonstrated we can measure winds from space - the technology is available
  - Aeolus data is already showing impact and ESA is providing NOAA with a fantastic resource to test wind lidar data assimilation & impact
  - ESA/EUMETSAT are receptive to collaboration on a next generation winds mission. Discussions are underway in Europe. Perhaps NOAA could weigh in if interested.
- For NWP, the community needs to advocate for a winds mission with full tropospheric coverage. Current NASA wind lidar investments are focused on Decadal Survey based PBL studies (incubation for next DS).
- The 2016 ATHENA-OAWL Earth Venture proposal, a design to cost approach focused on extra-tropical weather and tropical cyclone research, was rated *selectable* - another indication of readiness of the technology
- The OAWL approach provides a high TRL, reduced risk, wind lidar mission, with options for full molecular channel (follow-on to Aeolus)
- Ball continues to invest in OAWL to enable wind observations through the full troposphere.

BACKUP/EXTRAS


CZCS - Coastal Zone Color Scanner 1978
SAGE - Stratospheric Aerosol and Gas Experiment 2 1984
ERBS - Earth Radiation Budget Satellite 1984
SBUV/2 - Solar Backscatter Ultraviolet Radiometer 2 1984
Radarsat 1995
GFO - Geosat Follow-on 1998
QuikSCAT - Quick Scatterometer 1999
SRTM - Shuttle Radar Topography Mission 2000
QuickBird 2001
SAGE-III Meteor-3M 2001
ICESat - Ice, Cloud, and Land Elevation Satellite 2003
CALIPSO - Cloud-Aerosol Lidar and Infrared Pathfinder 2006
CloudSat 2006
WorldView-1 2007
WorldView-2 2009
Suomi NPP 2011
OMPS - Ozone Mapping Profiler Suite 2011
OLI - Operational Land Imager 2013
WorldView-3 2014
GMI - Global Precipitation Measurement Microwave Imager 2014
JPSS-1 2017
OMPS-2 2017
SAGE-III ISS 2017
COSMIC-2 2019
TEMPO >2019
GEMS >2019
OLI-2 2020
WSF-M >2023
Ball
D3463

NEXT GENERATION OPERATIONAL LEO WEATHER ARCHITECTURE

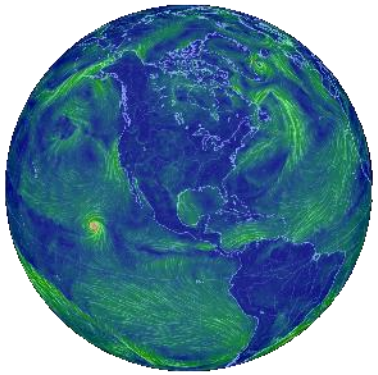


Based on NOAA's Satellite Observing System Architecture (NSOSA) Study

Mission motives – really-simplified

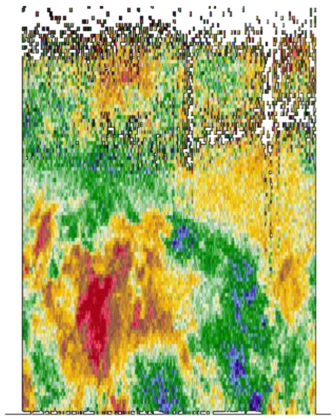
NOAA Requirements: focus on improving NWP, Protecting Lives and Property

- Global initialization of forecast models that use tested model physics
  - Global coverage
  - Variable scales (model grids)
- Research on model physics



NASA Requirements: Science. Processes, Modeling, Pre-operational

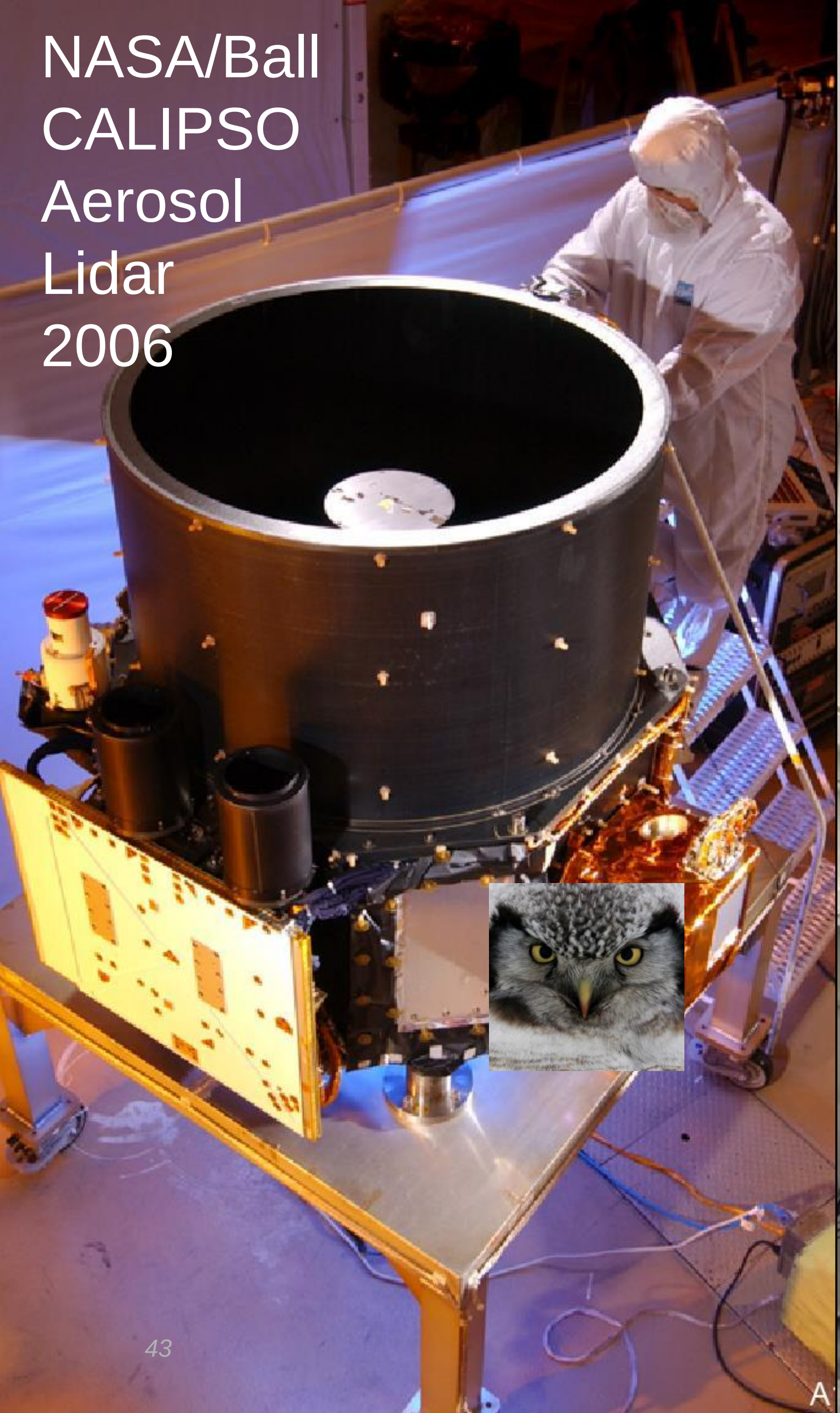
- Research to update model physics
  - Focused coverage
  - Variable scales
  - PBL emphasis
  - ESDS driven science

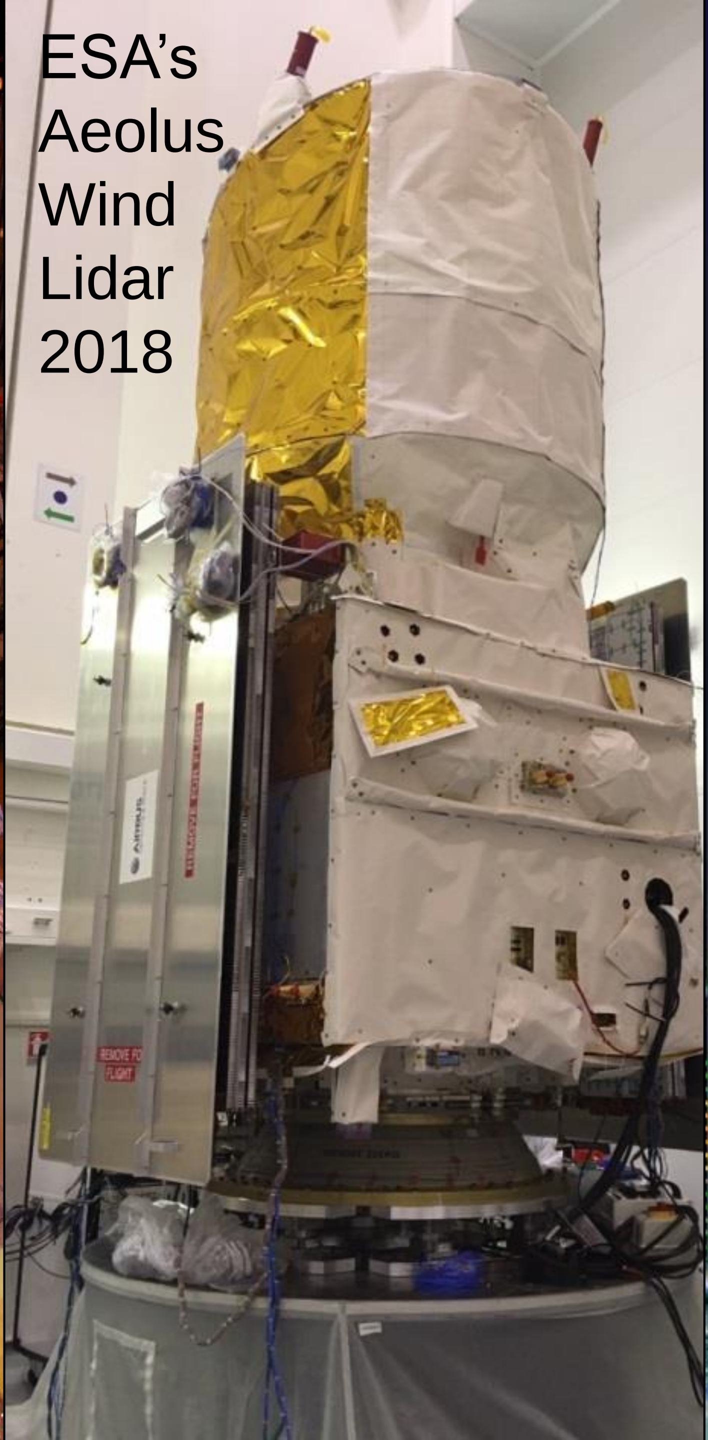


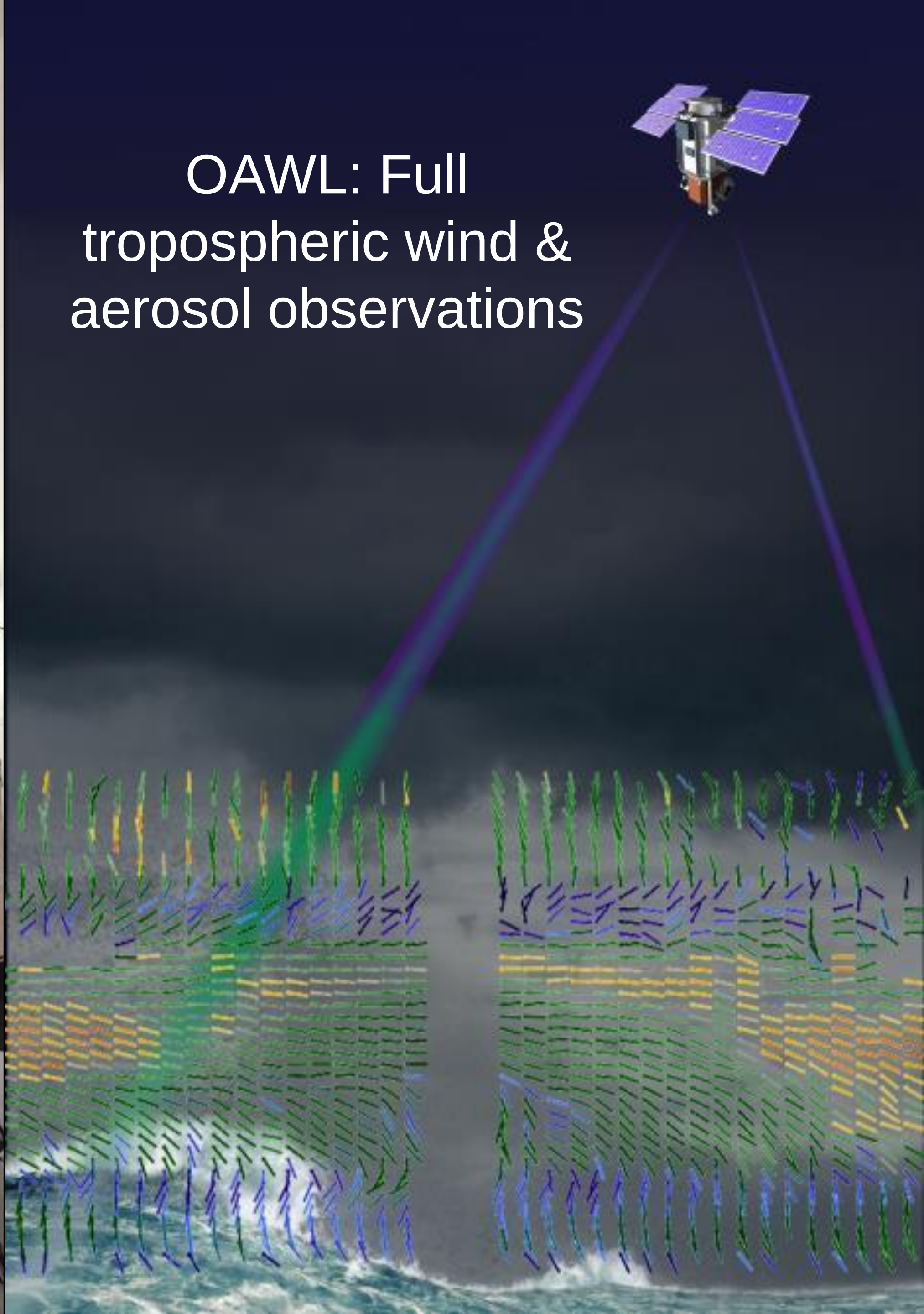
A well-planned mission can provide something for everyone

Additional Discussion

- Are NASA's current technical investments aligned with NOAA's priorities?
  - NASA Investments – no investment in molecular/upper tropospheric observations since 2015
  - Since 2017, all NASA focus is internal at Langley on heterodyne DAWN for PBL, with multiple successful Airborne demonstrations looking at lower tropospheric winds.
  - TRL (Technology Readiness Levels) – no heterodyne 2 micron laser system has flown in space. Current lasers are in early developmental phase.
  - Potential for Earth Explorer – lessons learned from ATHENA-OAWL


NASA/Ball
CALIPSO
Aerosol
Lidar
2006


ESA's
Aeolus
Wind
Lidar
2018


OAWL: Full
tropospheric wind &
aerosol observations

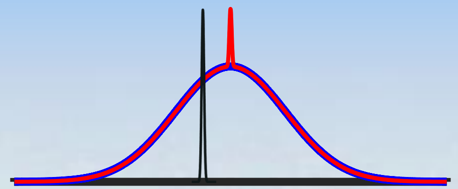
Advantages of OAWL approach

Like Aeolus, OAWL offers a path to *full* atmospheric lidar wind profiles – and adds a second look

Wrapping fringes for removal of platform-motion-induced Doppler offsets in processing

FPGA-based pulse/sample accumulation enables pulse-to-pulse phase referencing→ relaxed laser frequency and pointing stabilization requirements

Narrow range gates provide precise cloud height estimation



Nested OAWL provides aerosol & molecular channels (no cross calibration required)

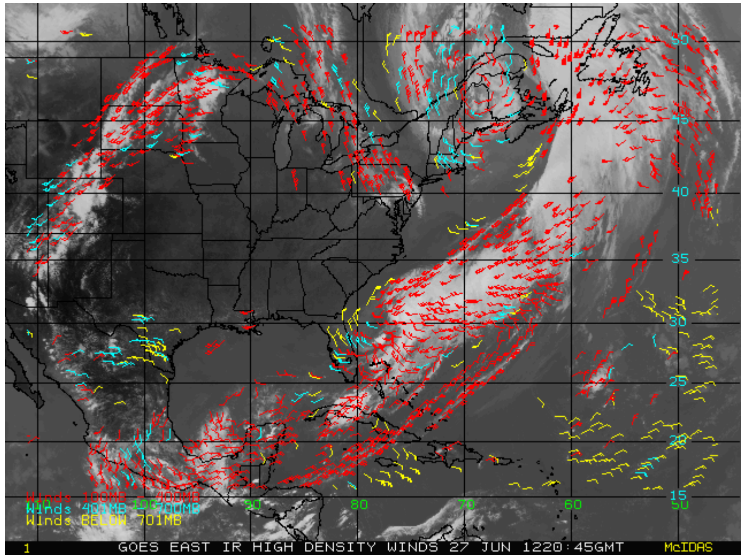
No atmospheric linewidth calibrations required for OAWL Doppler measurements,
No aerosol "contamination" of molecular signal

Wide field of view receiver provides overlap margin (like on CALIOP)

The MZ Interferometer's high throughput efficiency → enables two lines of sight

Aircraft Demonstrations/Validation

Lidar & Atmospheric Motion Vectors (AMVs)



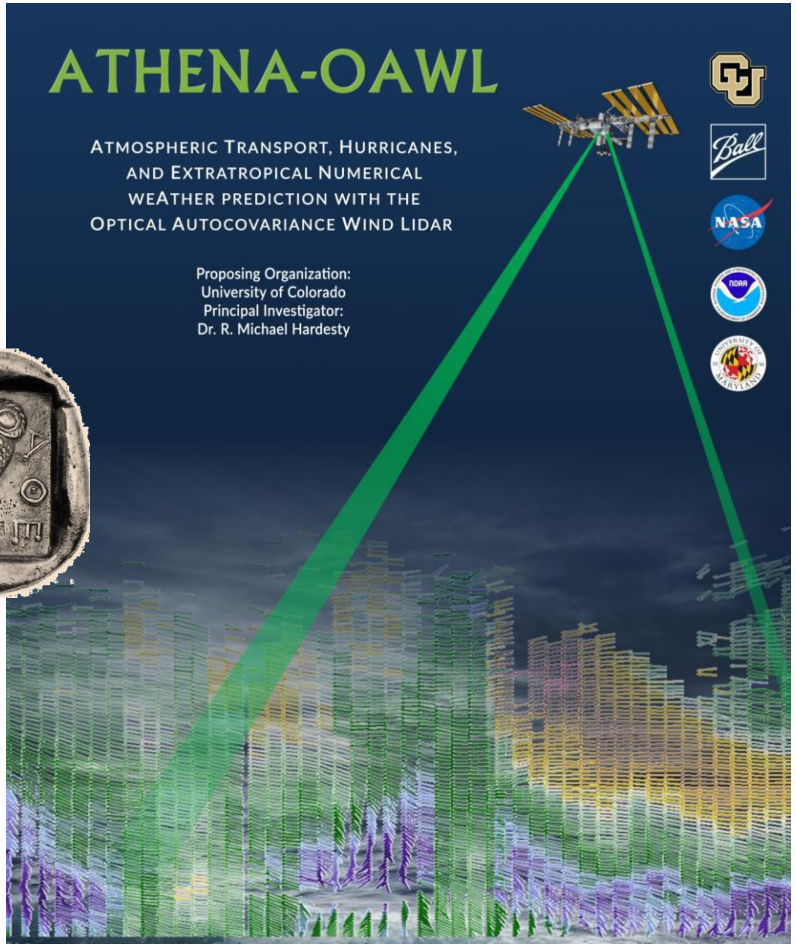
- Cloud Drift and WV
- GEO: GOES/Himawari8/MeteoSat/etc., Visible and IR
- Polar: MODIS Cloud Drift Winds (Arctic, Antarctic, Aqua, Terra), AVHRR (Arctic, MetOp-B), VIIRS (Arctic)

- Height Assignment Uncertainty
  - Up to 70% of AMV error (Velden & Bedka, 2009)

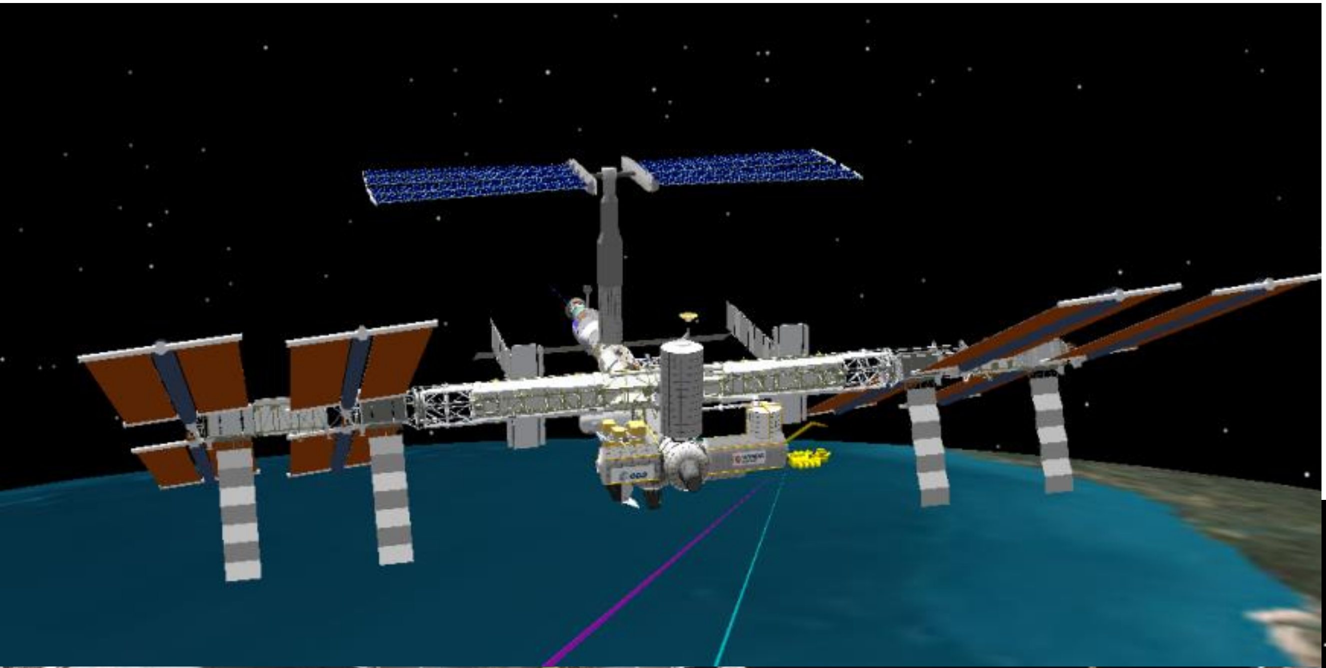
- Using CALIPSO to assign heights
  - Folger & Weissman, (2014 & 2016): used CALIPSO cloud height measurements to anchor *Meteosat-10* AMV layer heights
  - Up to **15% improvement** in co-located (50km, 30 min.) AMVs vectors from Metosat-10.
  - lidar-based height bias adjustments (from previous days) resulted in up to 7% improvement, affecting all AMVs

ATHENA-OAWL: path-finding science for next-generation global weather prediction and climate analysis

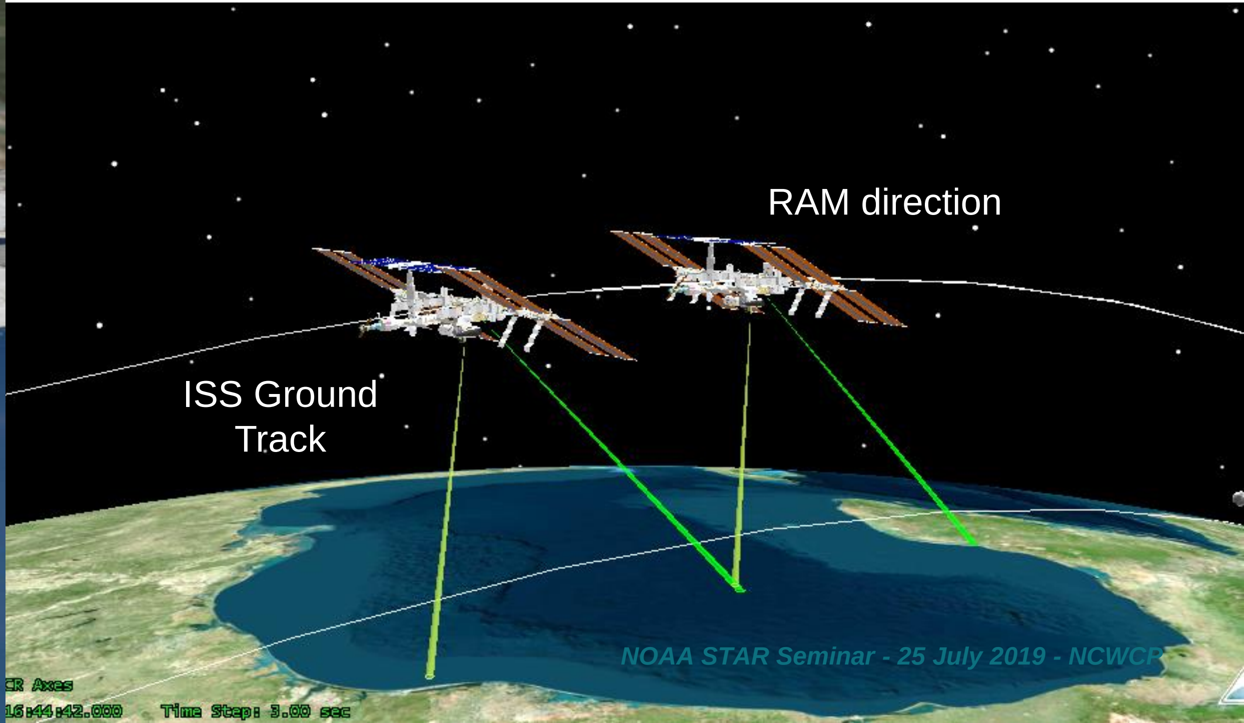
- **ATHENA-OAWL: A**erosol **T**ransport, **H**urricanes, and **E**xtra-tropical **N**umerical we**A**ther using **OAWL.**
- ***Design-to-cost approach*** to NASA Earth Venture Instrument (EVI) based on heritage systems (mostly CALIPSO)
- EVI– *first proposed in 2013* was the first full US wind lidar mission concept developed, costed, and proposed in decades: Rated **Category 3**
- Re-proposed in 2016. Announced February 2018, rated **Category 2 (Selectable)**.
- Objectives: Co-located wind and aerosol profiles to provide:
  - breakthroughs in modeling and prediction of low and mid-latitude weather and climate.
  - better understanding of relationships between aerosol radiative forcing, atmospheric dynamics and the genesis and lifecycle of tropical cyclones
  - understanding of the impacts of long-range dust and aerosol transport on global energy and water cycles, air quality, and climate.



ATHENA-OAWL Earth Venture Mission for the ISS



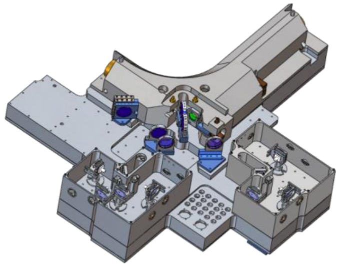
- Japanese Experimental Module: JEM-EF chosen for mass/power, cooling availability
- Beams point off-nadir 40º inboard
- Forward + Aft views separated by 90º (±45º from cross-track)

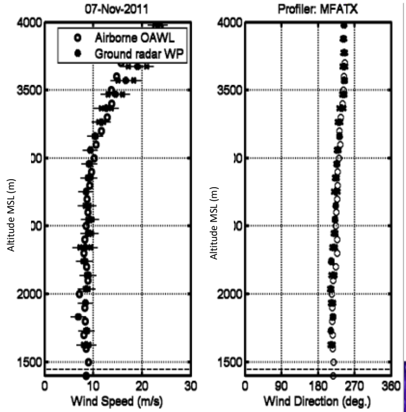


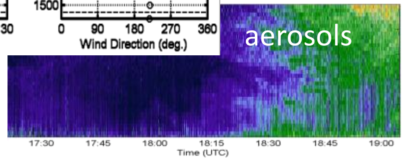
OAWL: Optical Autocovariance Wind (& Aerosol) Lidar

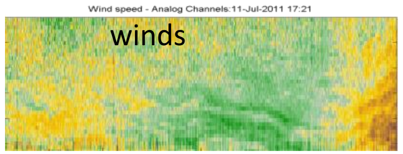
Since ~2003, Ball has worked in a public-private partnership with NASA, NOAA, and weather/wind lidar communities to advance space-based wind lidar technology and fill the global wind measurement gap.

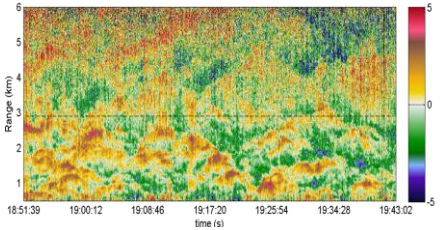
1999-present: Ball designs, mission concepts, build and test of OAWL patented, field-widened, four-channel, Mach-Zehnder interferometer, mission concepts, and retrieval/processing algorithms

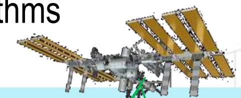






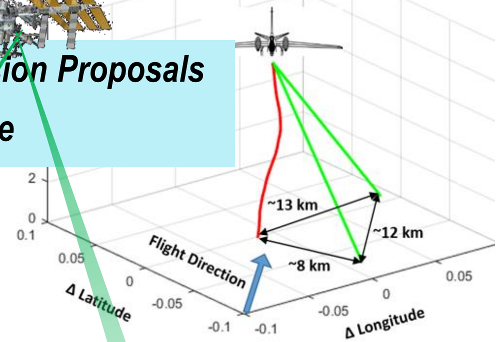


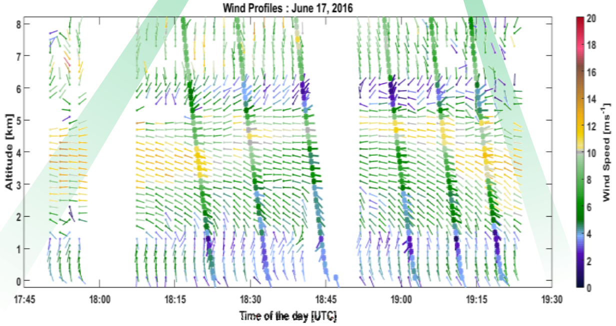


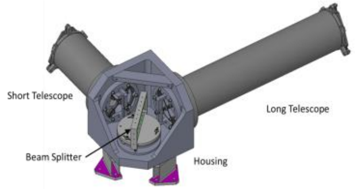


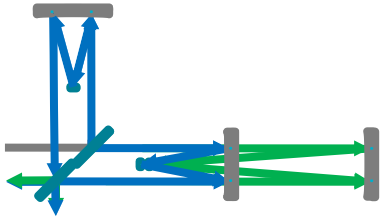
2013 & 2016 ATHENA-OAWL Mission Proposals

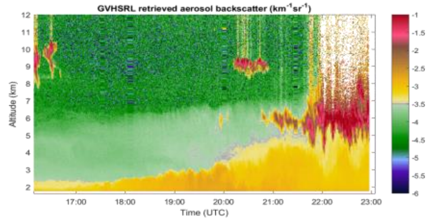
EVI4 rated selectable

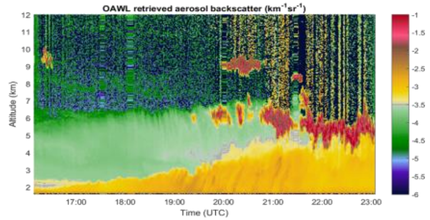












2008-2012: OAWL IIP-07

- Breadboard system
- 355 nm only, 4x channels
- Single look 12" telescope
- Ground validation with NOAA Coherent system
- Autonomous flights on NASA WB-57

2012-2015: HOAWL ACT

- Breadboard System
- Demonstrate 532 nm wavelength channels & depolarization channels
- Initial HSRL Aerosol retrieval algorithms

2015-2017: ATHENA-OAWL Venture-Tech: GrOAWL

- Airborne demonstrator System (WB-57)
- 2-lasers = 400 Hz eff. PRF
- 4x 532 nm channels
- 2 looks, 2 telescopes to demonstrate geometry for space-based operation

2014-2017: HAWC-OAWL IIP

- Dual look, dual-wavelength winds + cross-polarization system
- New Invar interferometer build
- DC-8 hardware design/build

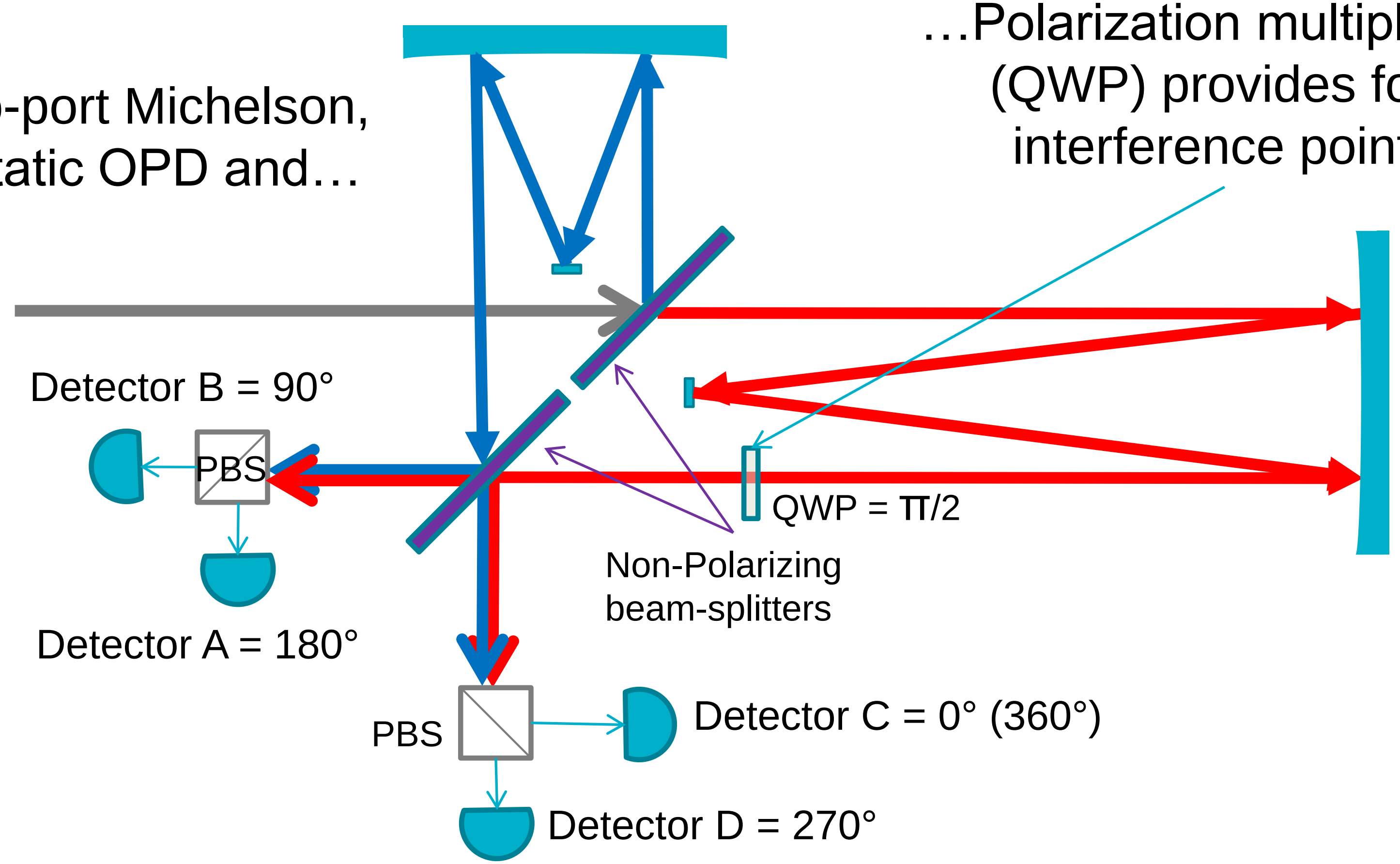
2018-2019: Ball IRAD

- **HSRL** demonstrations
- **Nested-OAWL:** Dual-wavelength aerosol & molecular winds
- Full tropospheric profiling

Optical Autocovariance Wind Lidar (OAWL):
Field-Widened, Quadrature Mach Zehnder Interferometer (QMZI)

Like a two-port Michelson, but with static OPD and…

…Polarization multiplexing (QWP) provides four interference points



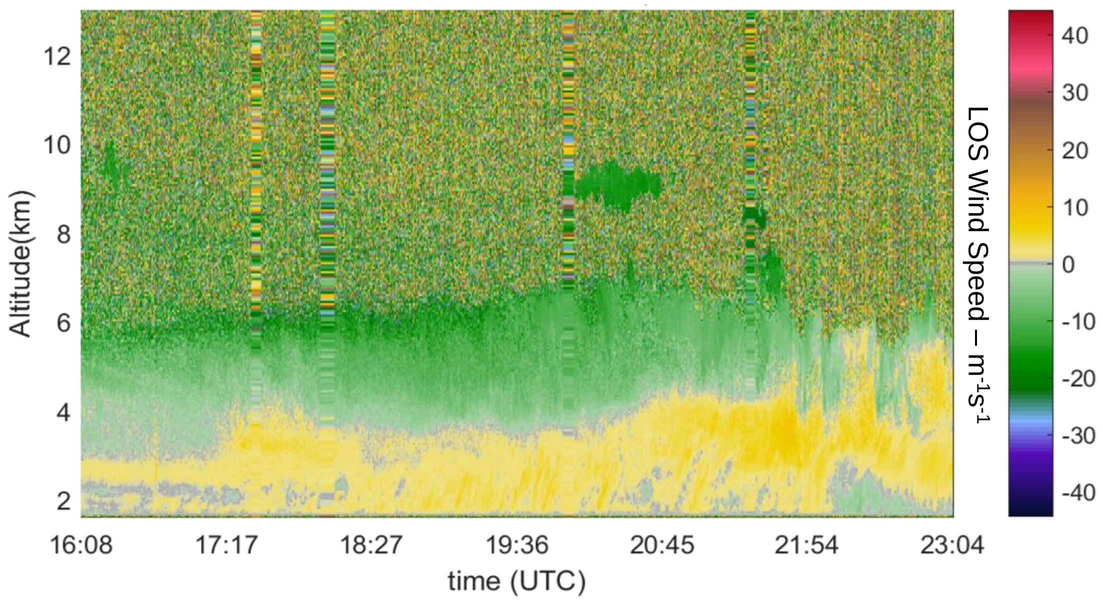
Field-widening via cat-eye design

0.9 m OPD

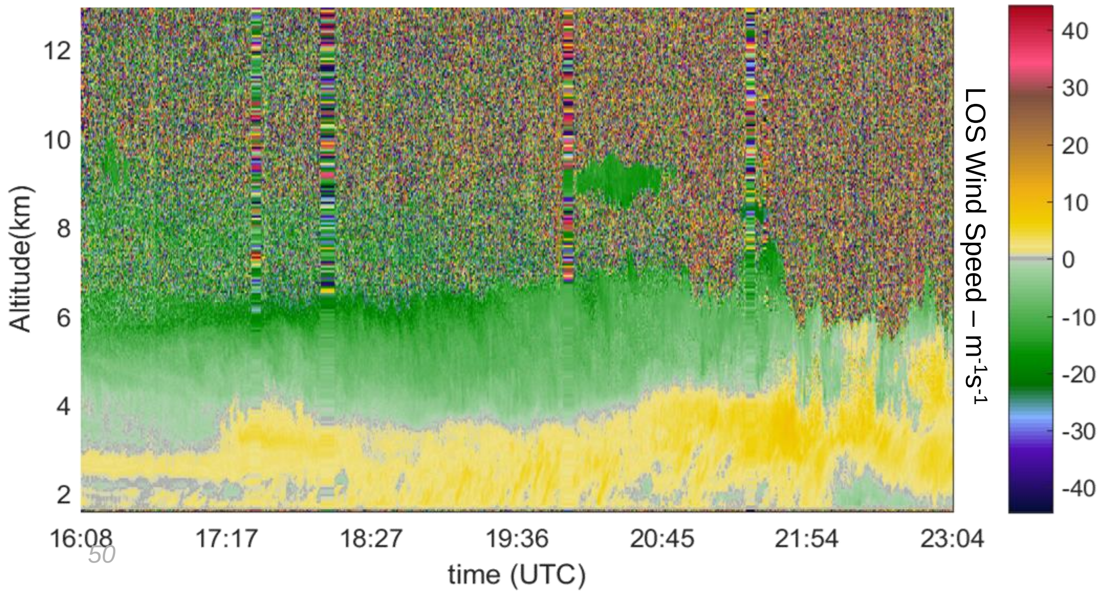
HAWC-OAWL Winds & Aerosol Backscatter

- Ground-based observations
  - Pointing 30° El, 270° Az.
- Dual wavelength (355 nm & 532 nm) OAWL aerosol winds & aerosol backscatter coefficients

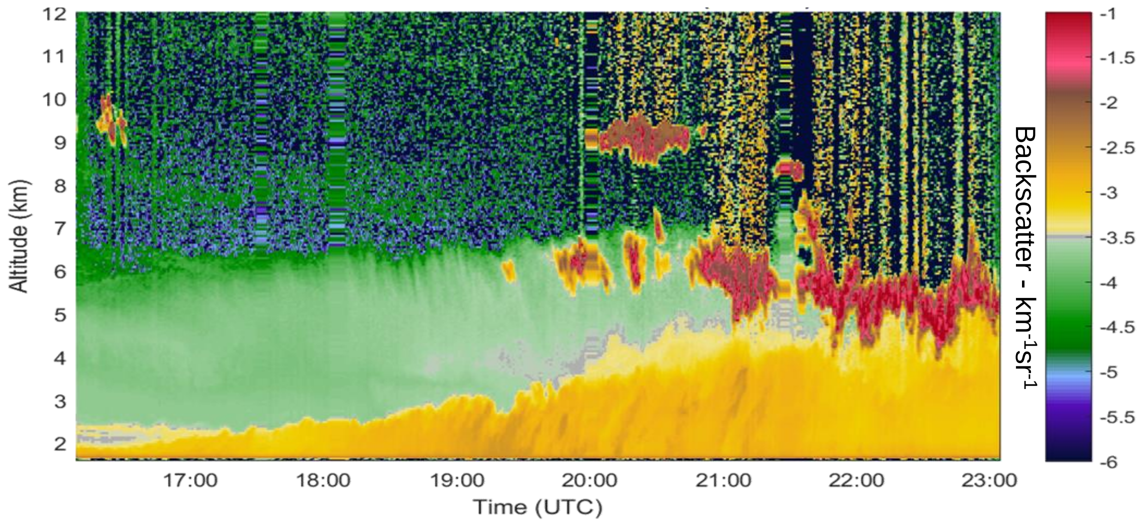
OAWL LOS Winds (m/s): 355 nm



OAWL LOS Winds (m/s): 532 nm

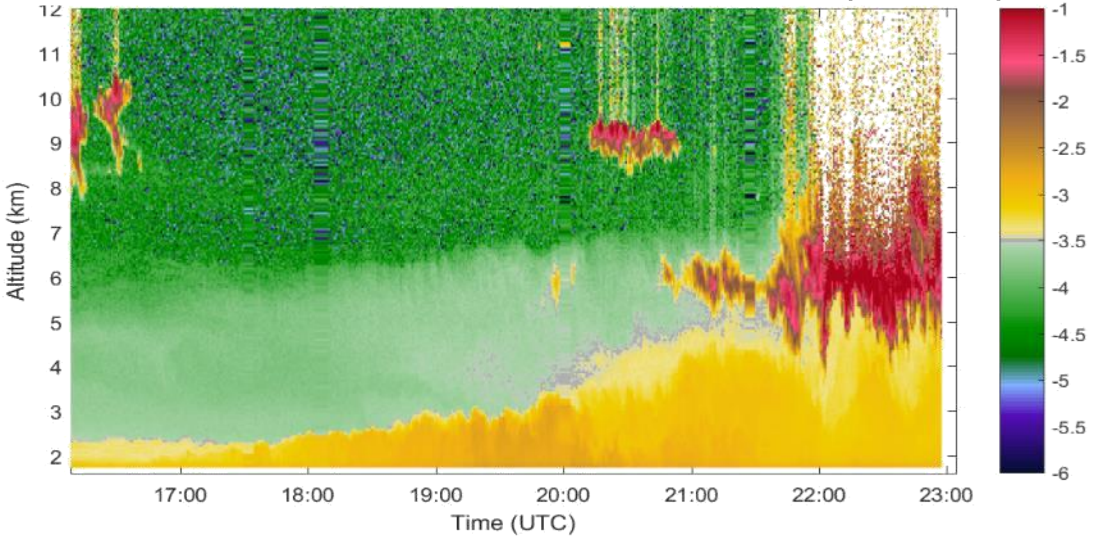


OAWL 532 nm aerosol backscatter coefficient ($km^{-1}sr^{-1}$)

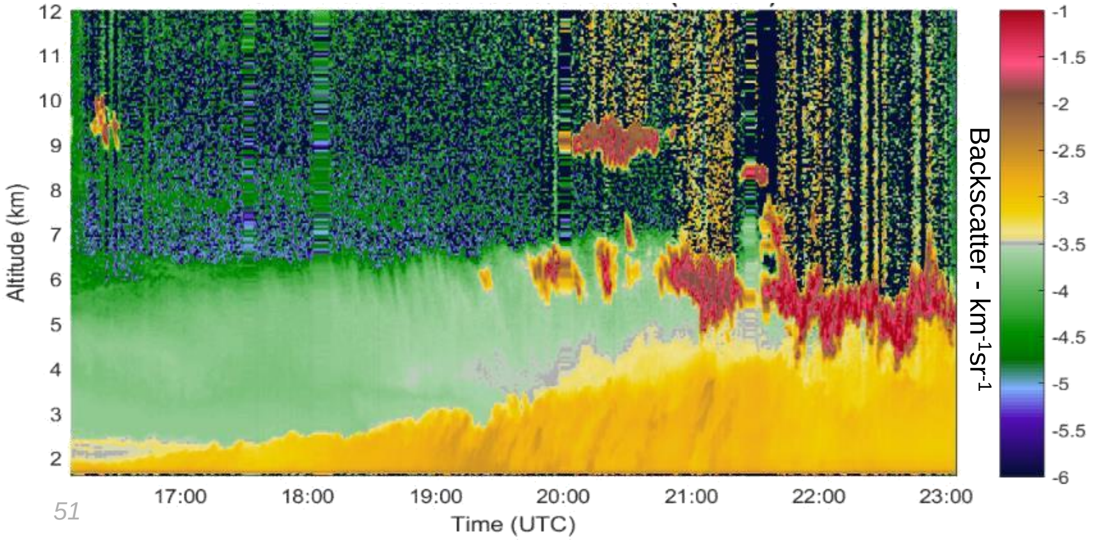


Preliminary comparison: aerosol backscatter coefficient

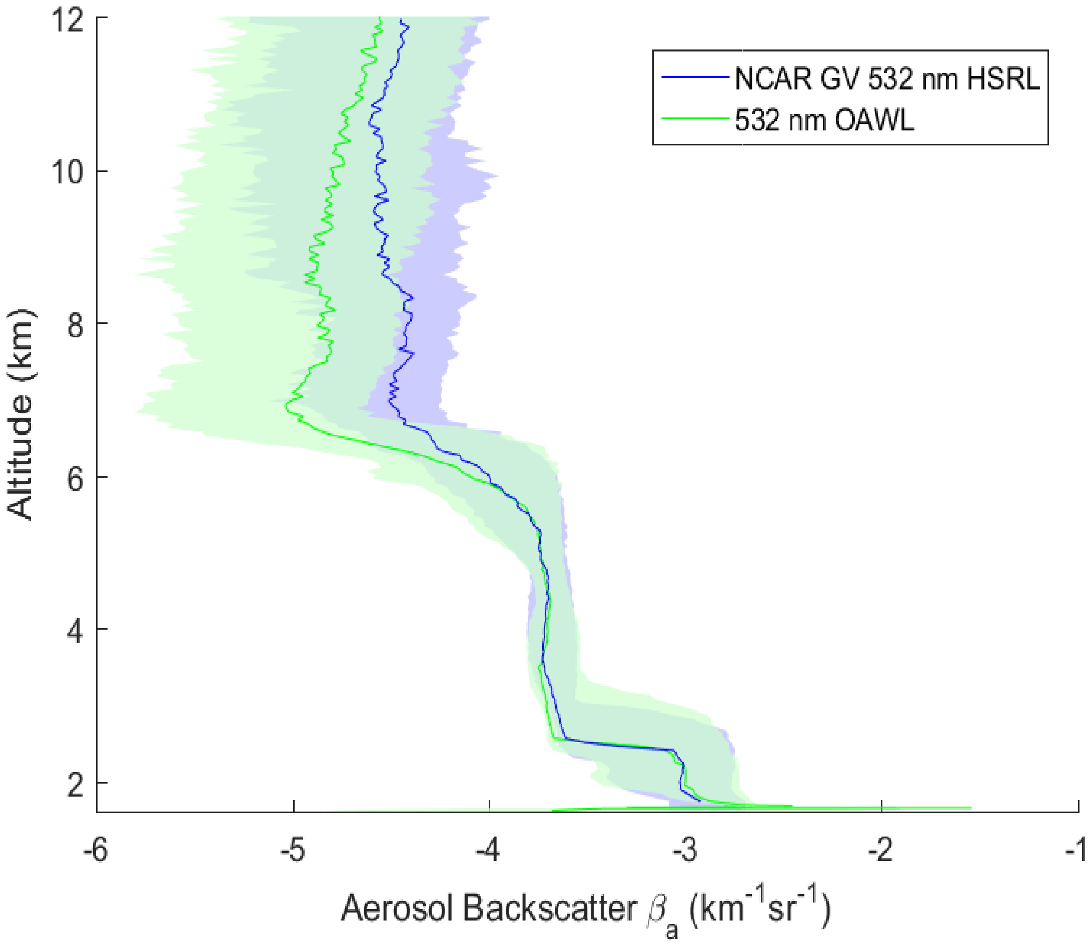
GV-HSRL aerosol backscatter coefficient ($km^{-1}sr^{-1}$)

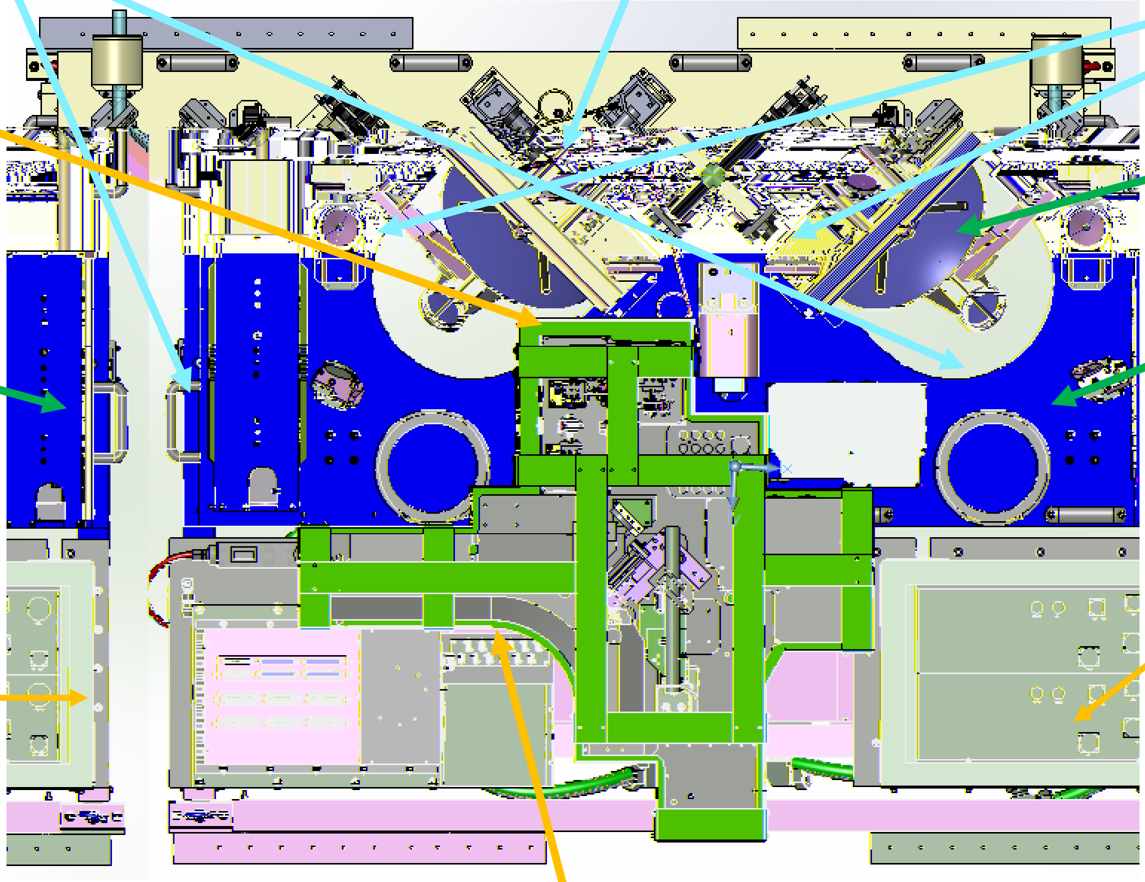


OAWL aerosol backscatter coefficient ($km^{-1}sr^{-1}$)



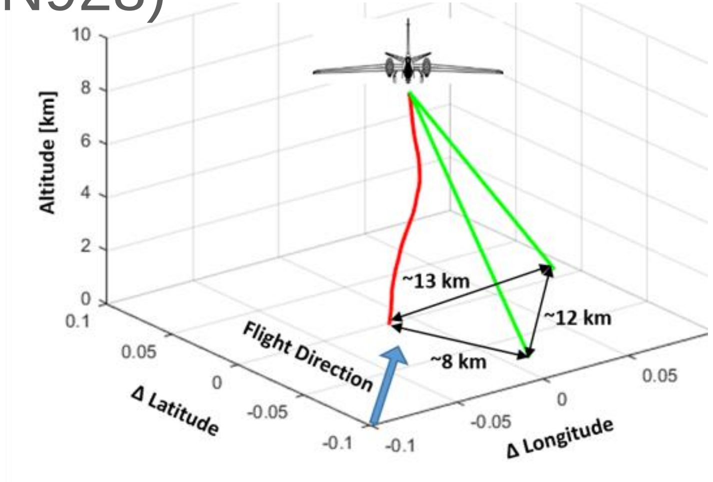
NCAR data courtesy of
Matt Hayman and Scott Spuler

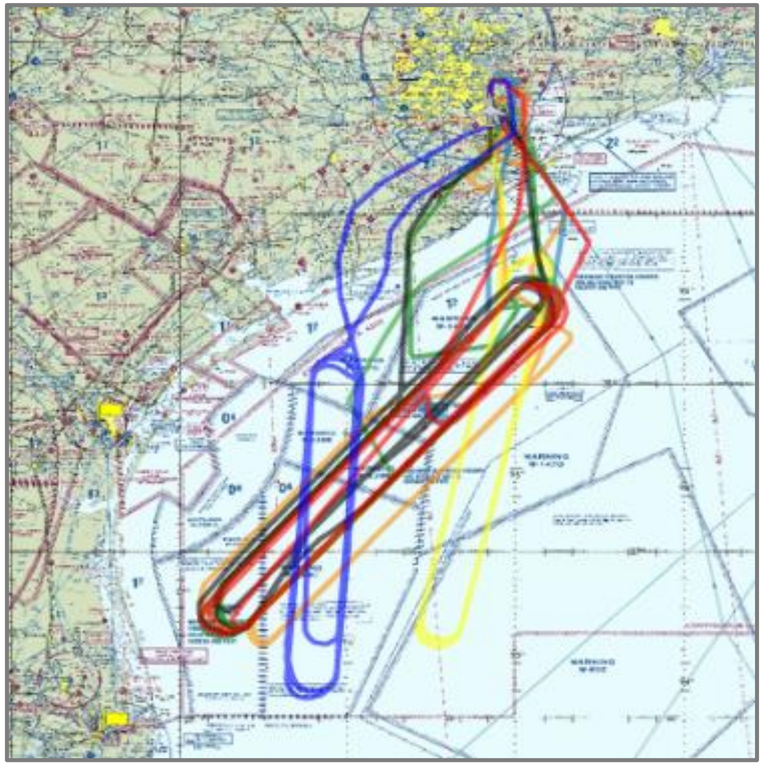



Boresight mechanisms maintain overlap
2 telescopes/looks couple into a single interferometer receiver
~30 cm diameter Cassegrain telescopes
Dedicated GPS/IMU (200 Hz)
Variable 532 nm output power
New build of 2nd Fibertek OAWL Laser set up to interleave pulses with original
Refurbished OAWL IIP Fibertek Laser
Fibertek Laser Electronics
Custom Payload Controller and real-time winds processor
Direction of flight
Fiber coupled OAWL Interferometer

AOVT GrOAWL Airborne Flight Testing

- Deployed on NASA WB-57 (N928)
- Ellington Field, Houston, TX
- May-June 2016
- 8 flights
  - 5 engineering
  - 3 validation
- Remote/Co-pilot operation
- Racetrack patterns over the Gulf of Mexico
  - Revisit times: ~1hr/loop
  - Launched dropsondes from the aircraft (48 total)

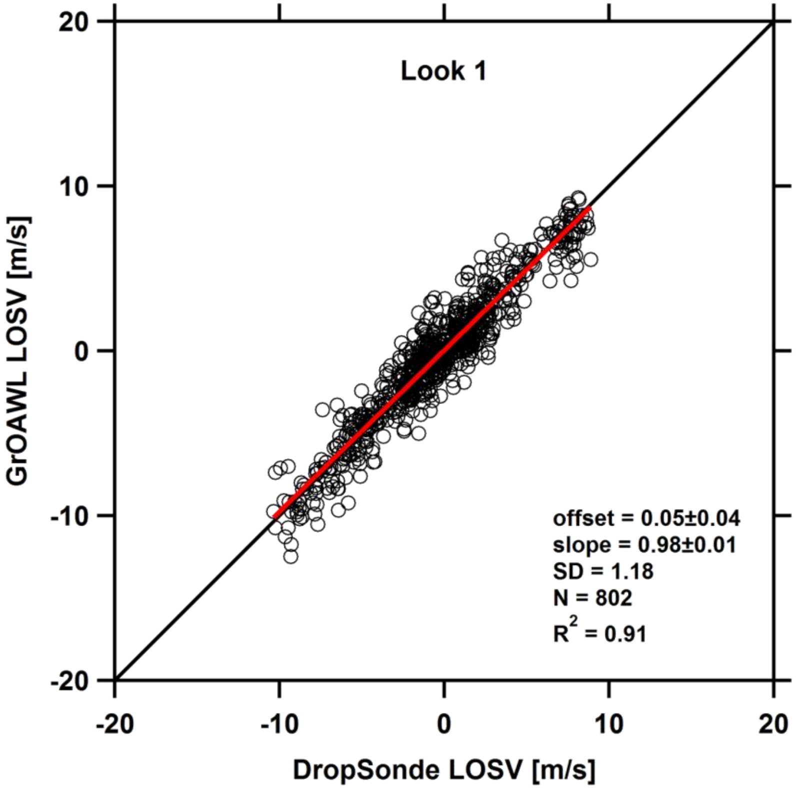


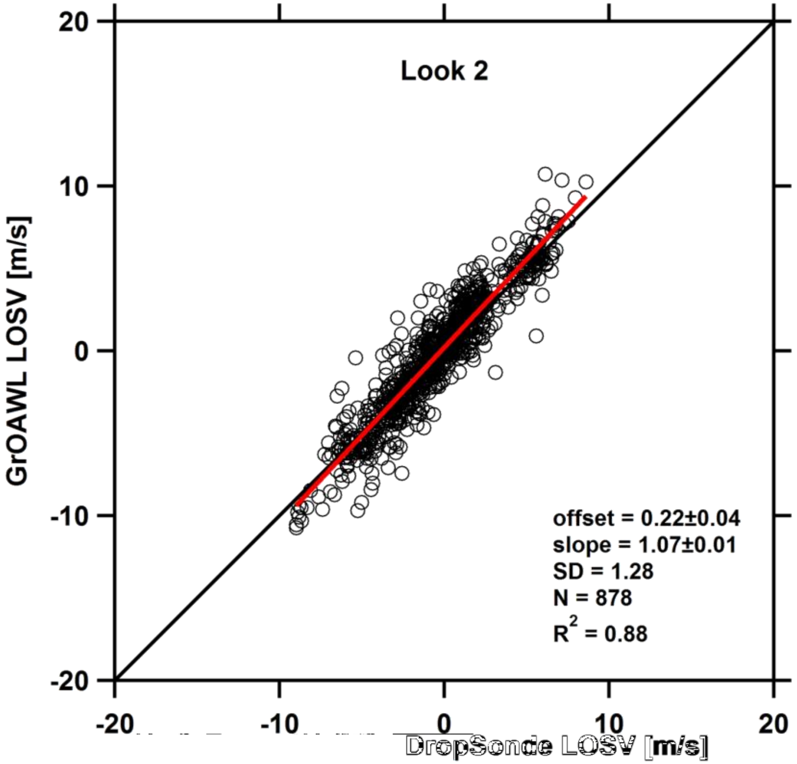


GrOAWL Line of Sight Wind Speed Measurement Accuracy

- 21 total dropsondes from 3 validation flights
- Dropsonde data is considered the “True Value”
- **8 km** spatial averaging of **10 second** profiles to better estimate the GrOAWL accuracy (**1 minute**)

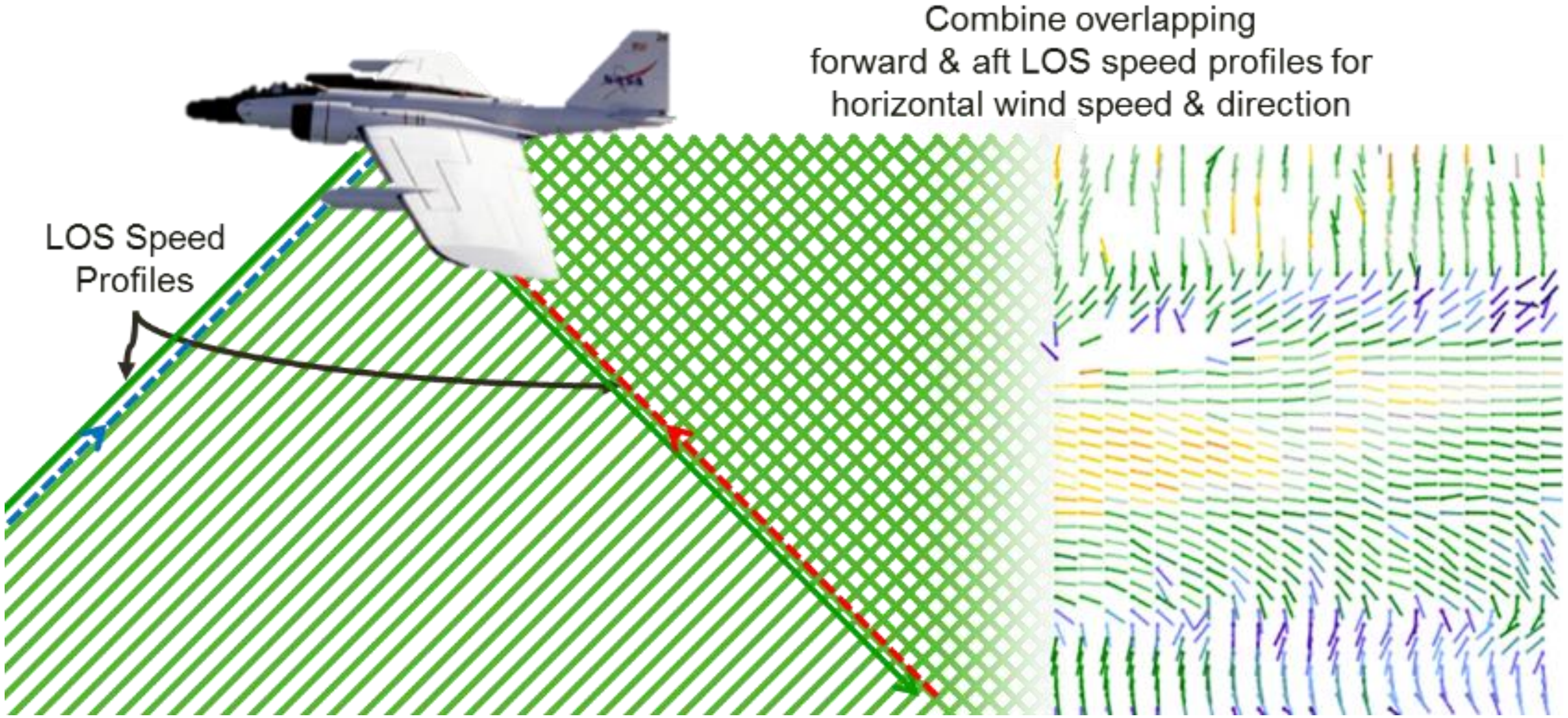
Fit slopes of 0.98 and 1.07





Two look LOS wind speeds → wind profiles

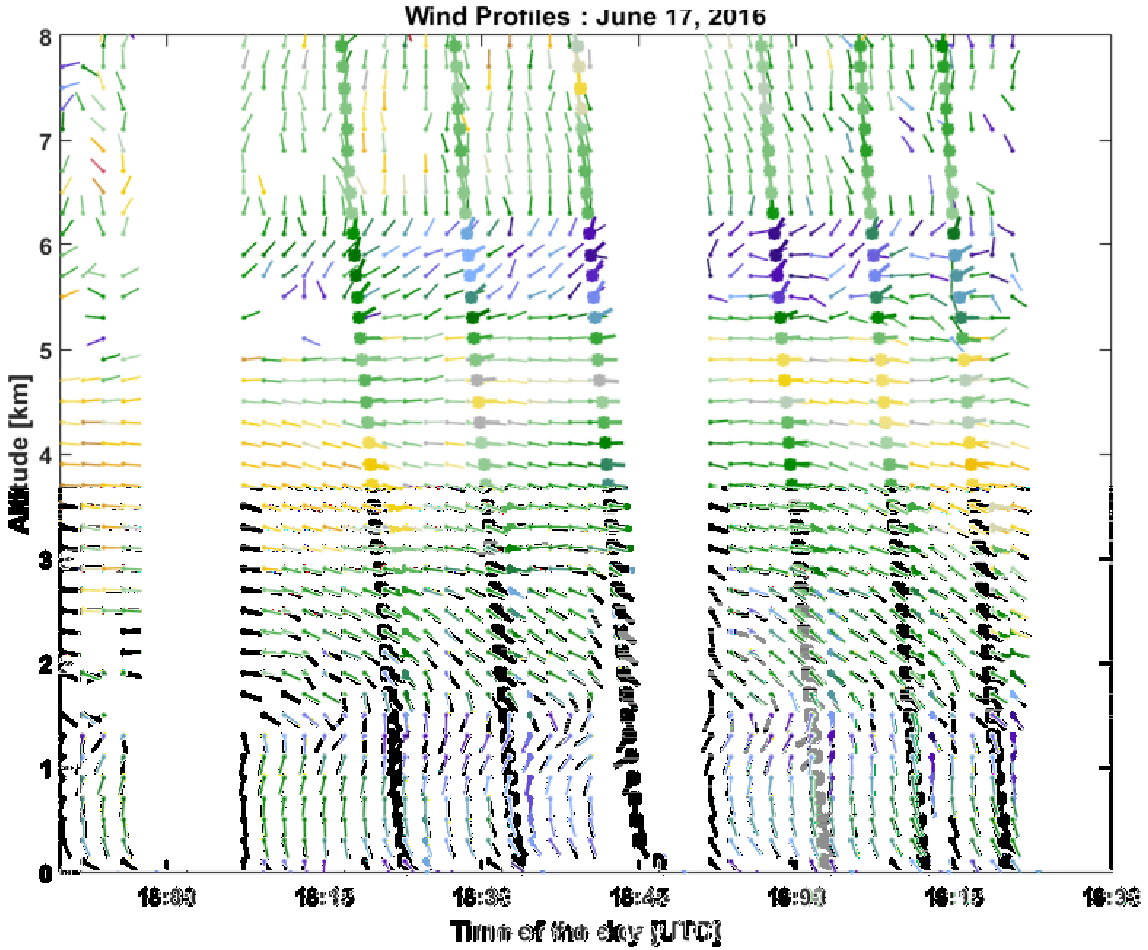
- Can assimilate vertically resolved winds from separate lines-of-sight → preserves the most information
- Can also combine 2 look LOS winds to retrieve wind speed and direction profiles
- Retrieval is based on classic radar/lidar "VAD" techniques



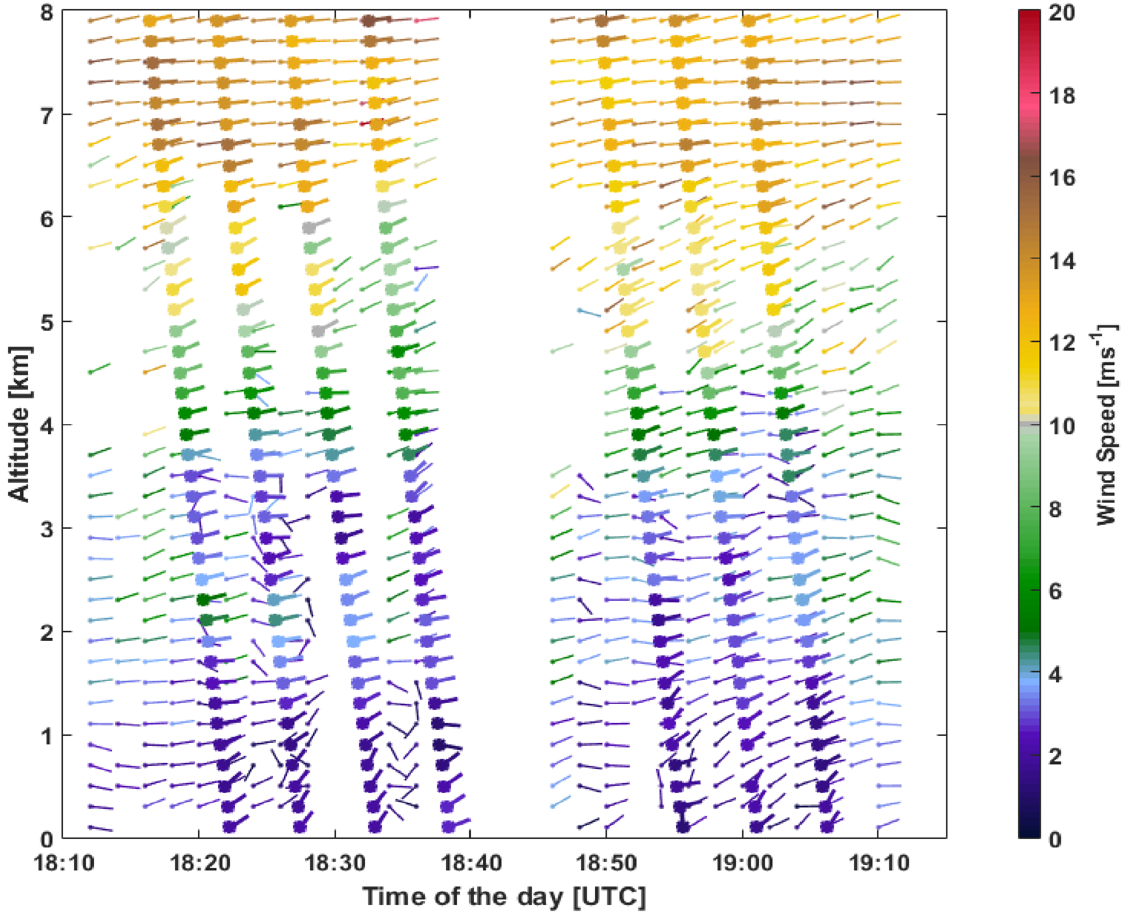
Wind barbs: color indicates wind speed, and line (dot at the time of the profile) line points into the wind direction

GrOAWL vector winds validated with YES High Definition Sounding System (HDSS) dropsondes (ONR)

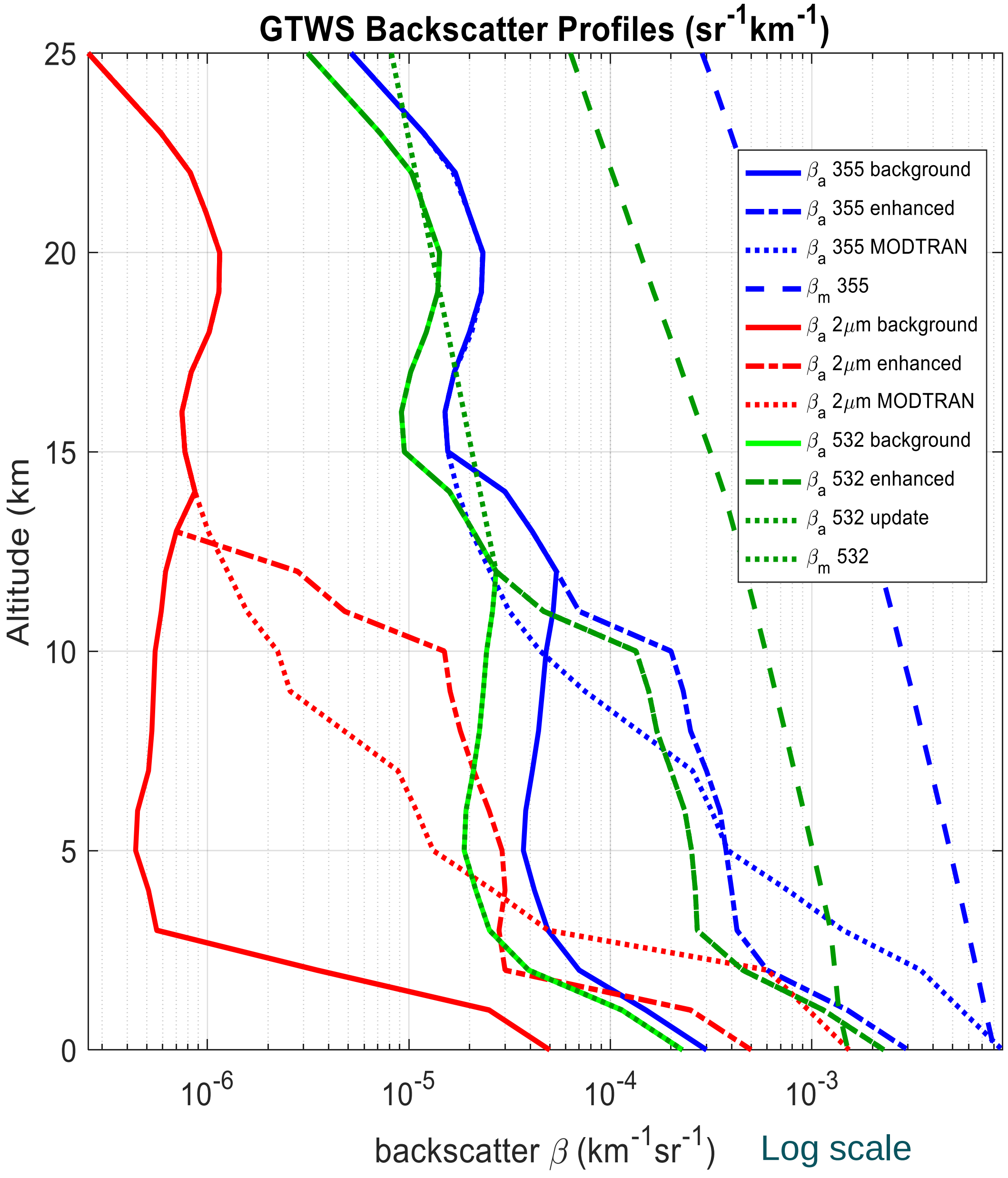
June 17, 2016



June 21, 2016



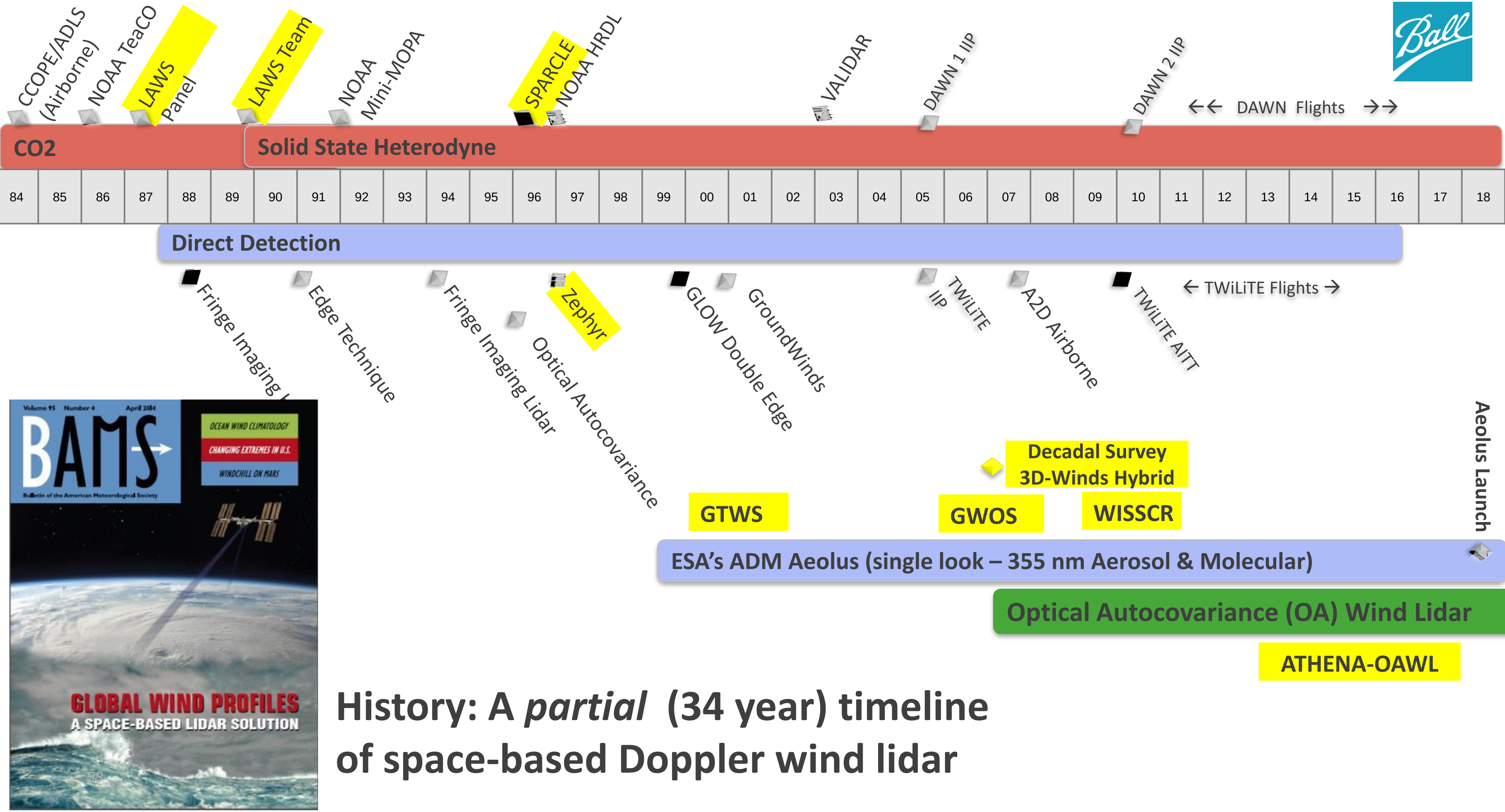
Images: Sunil Baidar, CIRES/NOAA ESRL CSD



Atmospheric Backscatter

- Backscatter scaling with wavelength:
  - **Aerosol scattering: scales as $\lambda^{-1.5\text{-}3+}$**
  - **Molecular scattering scales as λ^{-4}**
- Longer wavelengths (e.g. 2 µm)
  - Larger aerosols present in the PBL & aerosol/cloud layers
  - Less atmospheric extinction, but less coverage
- Shorter wavelengths (532 & 355 nm)
  - More scattering from aerosol/cloud layers
  - Scattering off of smaller particles present in Upper-troposphere/Lower-Stratosphere
  - Molecular scattering
  - High TRL lasers, telescopes, & detectors

These properties factor strongly into which lidars are best for a given application

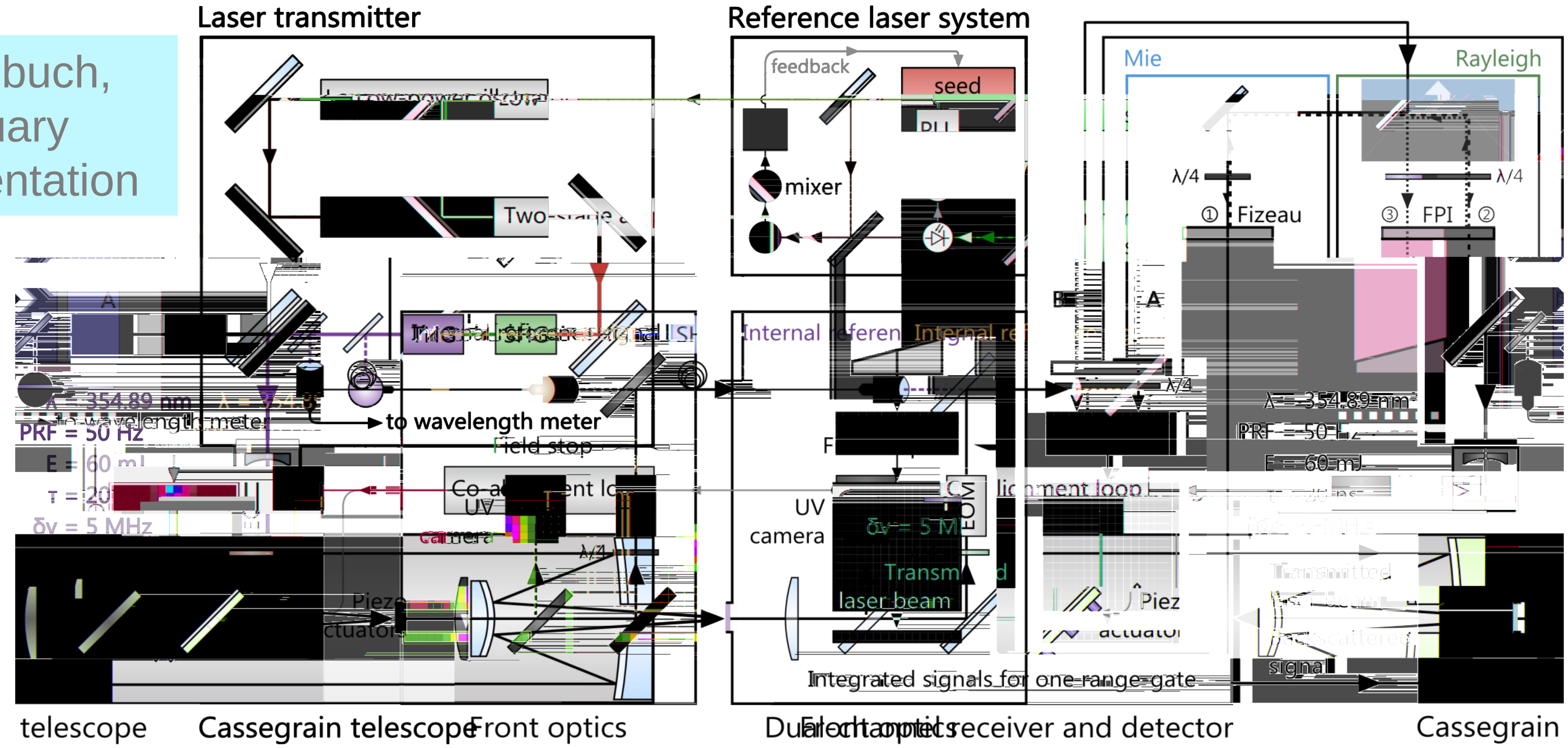


History: A *partial* (34 year) timeline of space-based Doppler wind lidar

ALADIN airborne demonstrator A2D for Aeolus

representative for the satellite ALADIN especially for spectrometers and detector ACCD; in operation at DLR since 2005 with airborne campaigns in 2009, 2015, and 2016

From Reitebuch, et al. February 2018 presentation

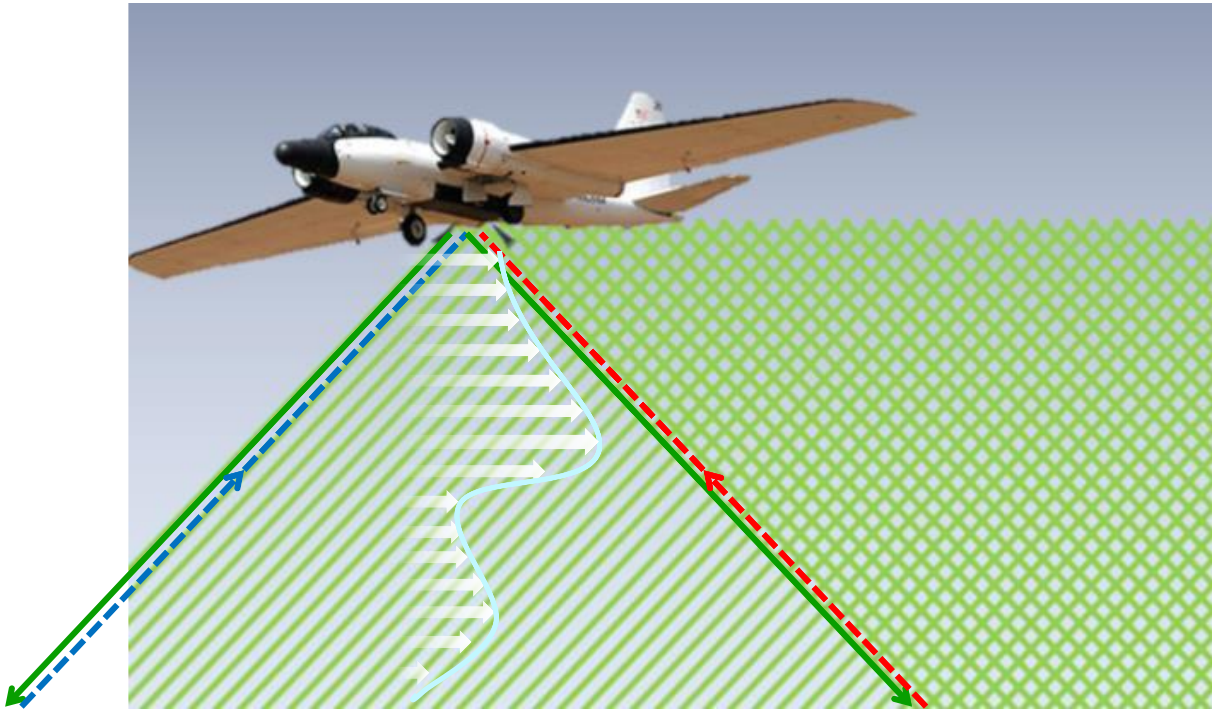


Lemmerz et al. (2017), Laser performance, Appl. Opt.
Lux et al. (2018), NAWDEX 2016 results, **AMT** Disc.

Measuring Doppler Shifts

Backscattered laser light from moving atmosphere (wind) is Doppler frequency shifted by an amount related to the wind speed relative to the laser line of sight (V_{LOS})

- Red-shift: relative/projected winds are moving toward the lidar
- Blue-shift: relative/projected winds are moving away from the lidar



$$\delta f_{Doppler} = \frac{2V_{LOS} f_0}{c} = \frac{2V_{LOS}}{\lambda_o}$$

f_o: outgoing laser pulse frequency
λ_0: outgoing laser pulse wavelength
c: speed of light