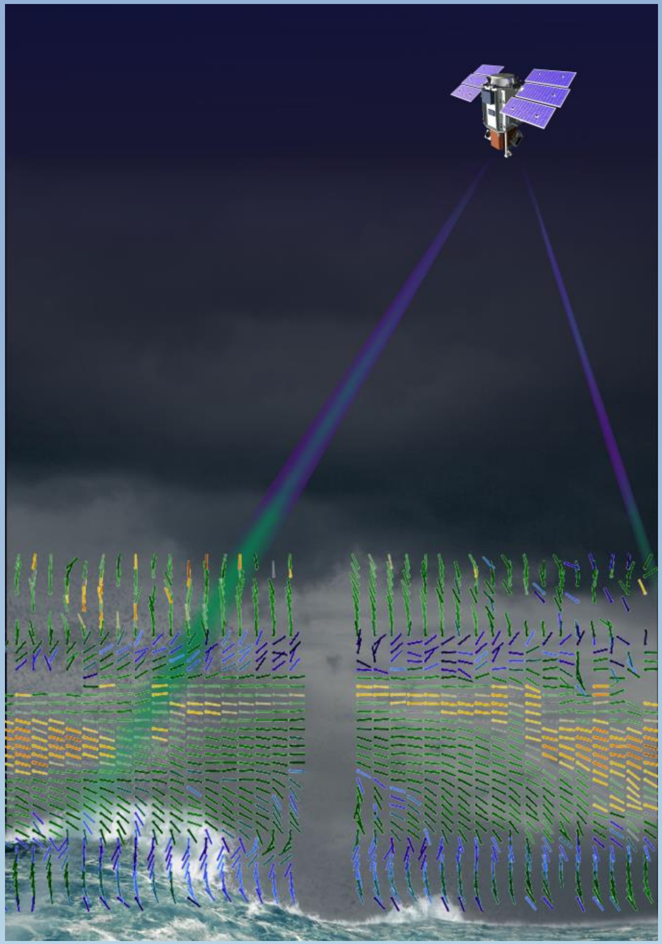

OAWL: High TRL Doppler Wind Lidar for 3D Winds Mission Demonstration

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Sunil Baidar, Mike Hardesty
NOAA/CU-CIRES

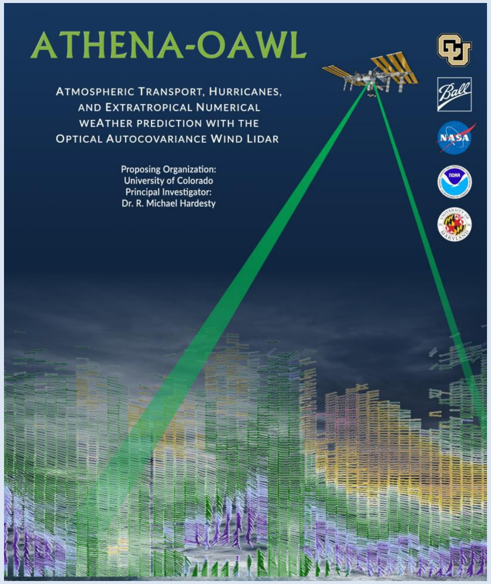
August 23, 2017

NOAA Emerging Technologies Workshop

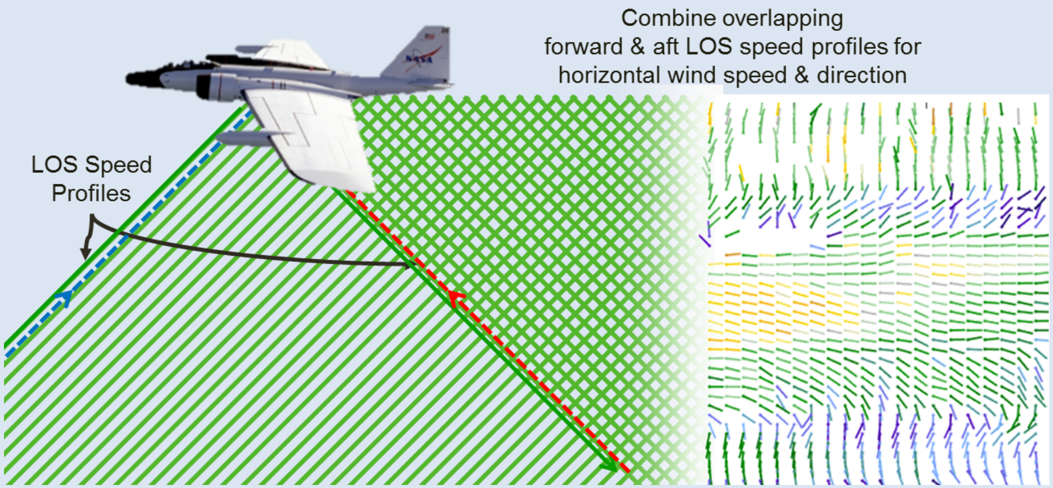
Optical Autocovariance Wind Lidar (OAWL)

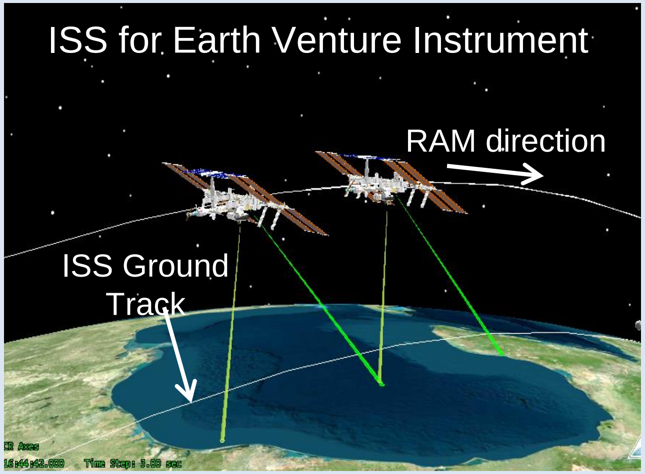
- Optical Autocovariance Wind Lidar (OAWL)
- Capability: Directly measure wind speed and direction profiles; options for full atmospheric profile coverage (UTLS)
  - Airborne: DC-8
  - Proposed Space-based: ATHENA-OAWL mission concept Earth Venture Instrument, ISS
  - Future Space-based: Free Flyer (e.g. LEO)
- Development
  - Technical design/development @ Ball Aerospace
  - Funding: Ball Aerospace Internal Research and Development (IRAD) and NASA Earth Science Technology Office (ESTO)
  - Partnerships: Fibertek, NASA-WB-57 NOAA-ESRL-CSD/CU-CIRES, ONR, Y.E.S.

Optical Autocovariance Wind Lidar (OAWL)



- Space: ATHENA-OAWL Mission Concept
  - Based on CALIPSO technology (laser, telescope, etc.)
  - First proposed full US DWL mission in decades
- Airborne: OAWL Demonstrator/science systems
  - GrOAWL (532 nm) – WB-57
  - HAWC-OAWL (532 & 355 nm) - DC-8
- Key capability & distinguishing innovation
  - Two line of sight Doppler lidar wind measurements can provide continuous curtains of wind speed and direction profiles
  - Smaller, high TRL, laser wavelengths provide winds in low aerosol regions

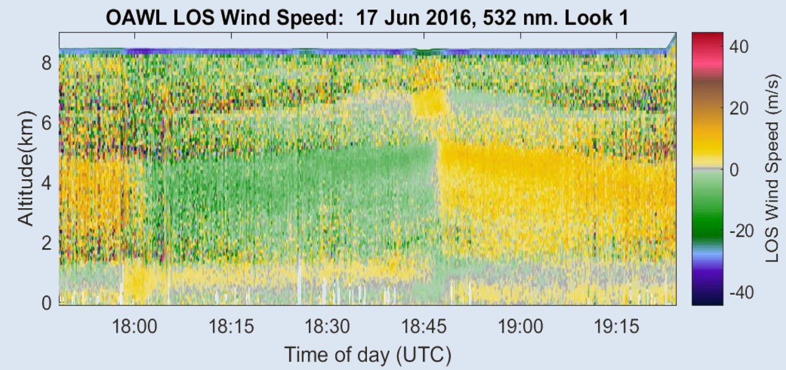


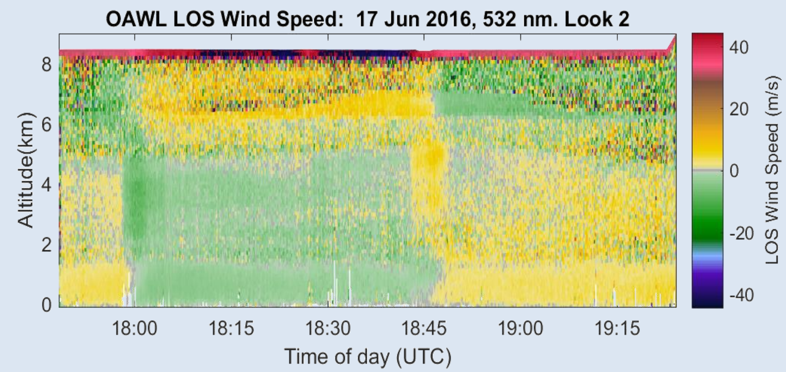


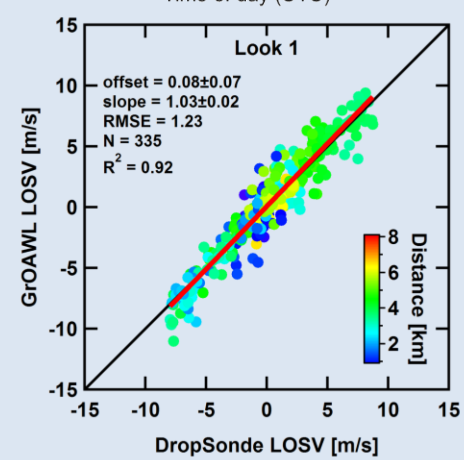
Optical Autocovariance Wind Lidar (OAWL)

Emerging
Technologies

- Early Successes for OAWL
  - IIP 2007: Ground-based and demonstrations and validation with NOAA ESRL Doppler Wind lidars, Airborne demonstration and validation with Radar wind profilers
  - Earth Venture Instrument mission proposals (2013 and 2016)
  - IIP 2013: Two look, two wavelength system devleopment
  - Earth Venture Technology Development: competed funding to build and fly an airborne demonstrator for EV-I4 concept with two looks







Optical Autocovariance Wind Lidar (OAWL)

OAWL: Like CALIPSO data with wind profiles… with option for upper troposphere

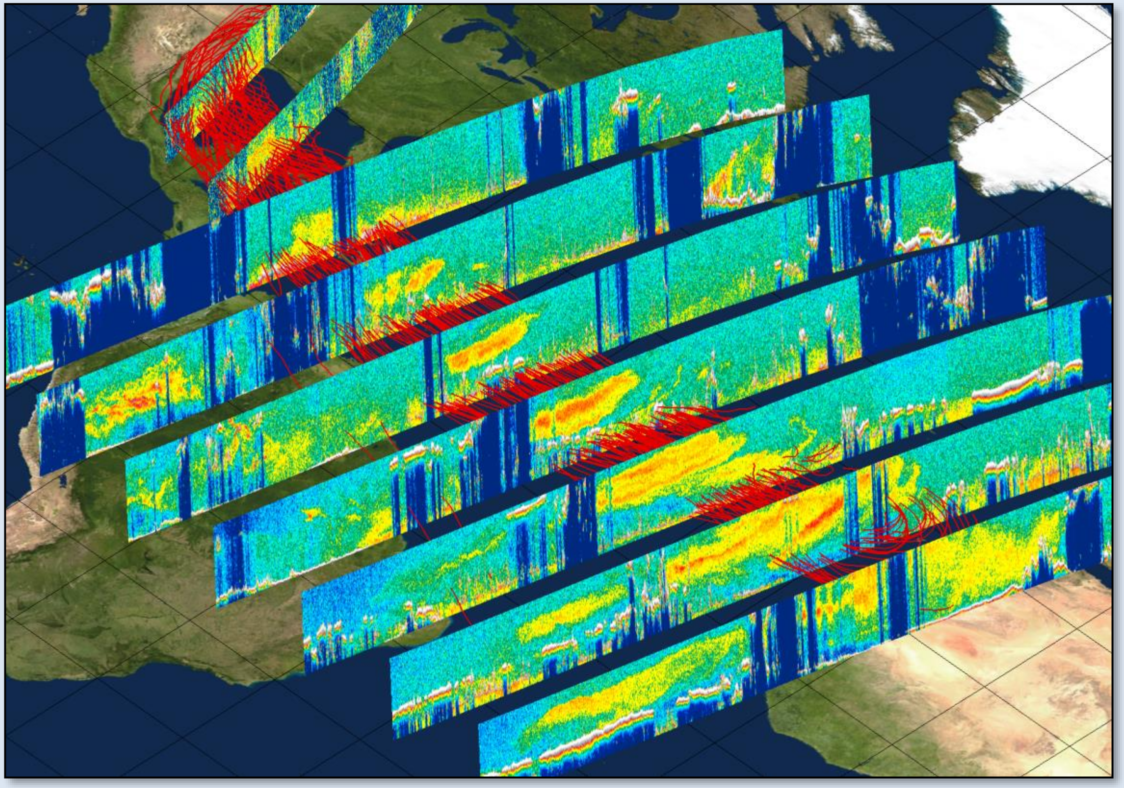
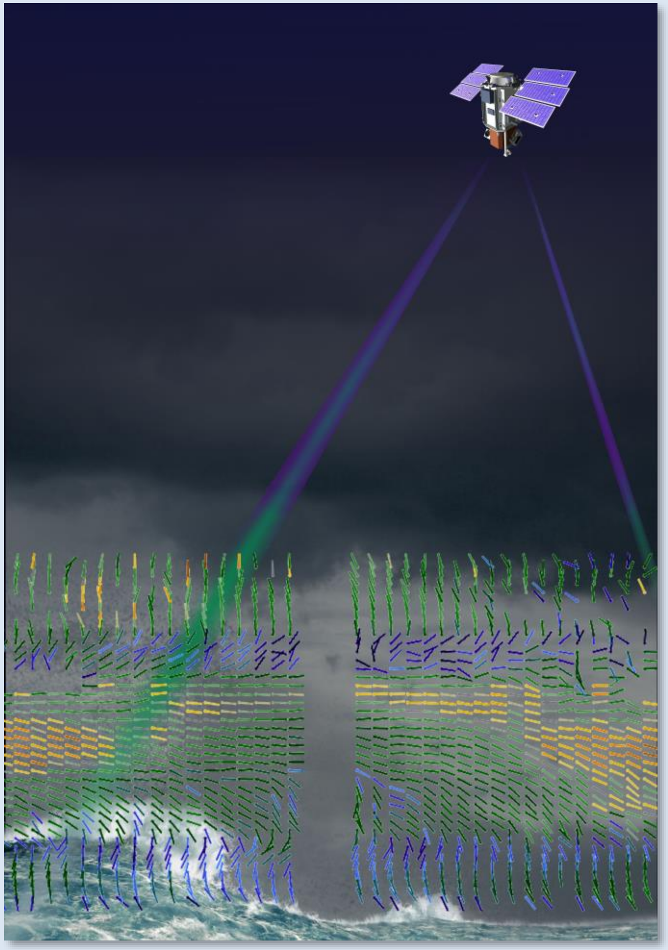


Image: Liu et al. JGR 2008

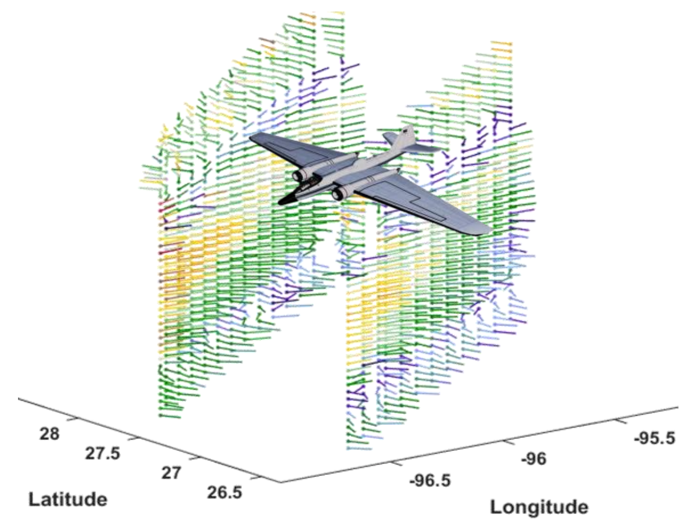


Optical Autocovariance Wind Lidar (OAWL)

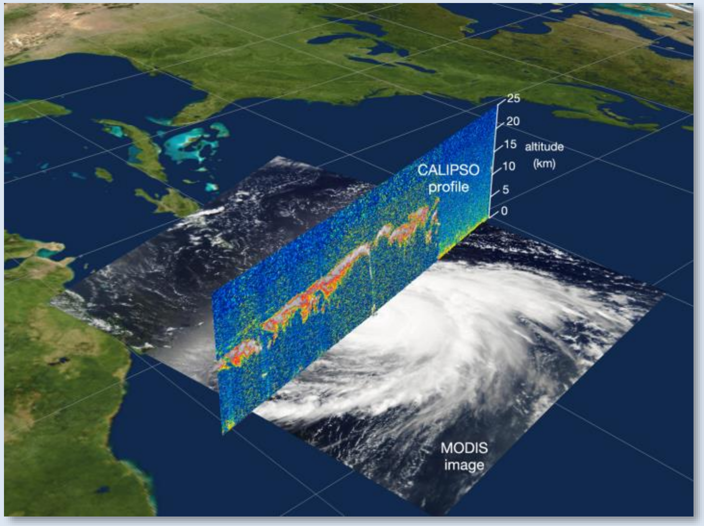
Emerging Technologies

Anticipated impacts of DWL

- **Mission services and service gaps filled/improved with this capability**:
  - 3D Winds measurements: Equivalent data of hundreds more radiosondes/day
  - Orbit provides measurements distributed over the oceans and lower hemisphere
- **Efficiencies to be realized with this capability**:
  - Multiple satellites may be reduced
  - Better vertical resolution data than otherwise might be acquired through many sounding satellites
- **Anticipated user information needs satisfied by this capability**:
  - Direct wind profile data to source weather models
  - Improved motion-vector winds uncertainty by "locking down" cloud/aerosol layer heights
  - Upper tropospheric, clear-air winds
- **How will society ultimately benefit from this capability?**
  - Improved weather forecasts → safer society (land, sea, and air), economic improvements, etc.



Airborne GrOAWL Wind Speed and Direction Profiles: June 2016



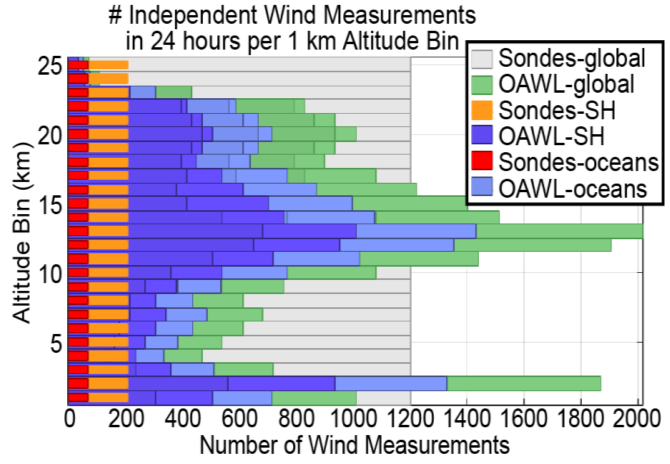
Optical Autocovariance Wind Lidar (OAWL)

Emerging Technologies

Anticipated impacts of ATHENA-OAWL

- Data assimilation of ISS OAWL data into forecasting models expected to:
  - extend the useful range of medium-range forecasts by at least 4 h in the mid-latitudes
  - Reduce RMS wind error in the tropics by 10% in the 24 h forecast.

- Expectation substantiated by:
  - Stoffelen et al. 2006: OSSE conducted for *ADM-Aeolus;* showed simulated DWL data improves 500 hPa medium-range forecasts in the Northern Hemisphere extratropics by an average of 0.4 days (9.6 hours),
  - Riishojgaard et al. 2012 and Atlas et al. 2015: Doppler wind lidar OSSE study results (including for a two-look OAWL system)
  - Horányi et al. 2014: Observing System Experiments (OSEs) with actual wind observations
  - Langland and Baker 2004: Forecast Sensitivity Observation Impact (FSOI) analysis applied to the NASA GEOS-5 data assimilation system
  - Folger and Weissmann (2014): impact of lidar cloud height assignment on AMV data



Predicted performance based on low-power system with conservative "background mode" aerosol model

OAWL: optimized to meet science objectives

System Optimization Wavelength	Aerosol Higher precision, reduced vertical coverage	Aerosol & Molecular Reduced precision, greater vertical coverage (UTLS)
355 nm	• Strong aerosol backscatter for good aerosol precision (1 ms) • molecular return shot noise • Low background noise **OAWL IIP**	• Aerosol AND molecular both add signal (fringe) → good SNR through the troposphere • Low background noise **Airborne Systems UPMC**
355nm & 532 nm	• Aerosol winds at 2λ (see above) • + Aerosols at two wavelengths **HOAWL, HAWC**	• Nested OAWL System: - 355: short OPD for Molecular - ←532: long OPD for Aerosol
532 nm	• Lowest risk/cost approach to aerosol winds **ATHENA-OAWL/GrOAWL**	• short OPD not optimal for 532 nm due to less molecular return

Optical Autocovariance Wind Lidar (OAWL)

Emerging Technologies

Anticipated impacts specific to OAWL

- ATHENA-OAWL design based on high TRL/high heritage CALIPSO lidar
- OAWL Wavelength(s):
  - 532 nm and/or 355 nm see enhanced backscatter off a large range of aerosol sizes
  - OAWL may be optimized to provide molecular channel using 355 nm wavelength

Desired Attribute		Space-based OAWL	Airborne OAWL
Geo Coverage	Global	• ISS orbit: > 80% of Earth's surface • Free-flyer: Global coverage	Regional coverage only, based on aircraft
Horizontal Resolution	200 km	$\leq$ 100 km (exceeds desired performance)	
Vertical Resolution	2.0 km	0.2 - 1.0 km (exceeds desired performance)	
Parameter Accuracy	1.5 m/s	$\leq$ 0.5 m/s (exceeds desired performance	
Vertical Domain	10 m to 16 km	Surface to 25 km altitude (exceeds desired performance)	
Update Interval	6 hours	• ISS orbit: Repeat is ~ 3 days, but different times of day • Polar Orbiting/Sun Synchronous: 16 days (single spacecraft); 8 days (two spacecraft)	Dependent on # of sensors deployed and size of regional coverage;
Data Latency	(not listed, but of great interest to weather models)	<1 hour when TDRSS is available	Low-data rate wind profiles in near real-time using SatCom, based on aircraft selected

Additional Information

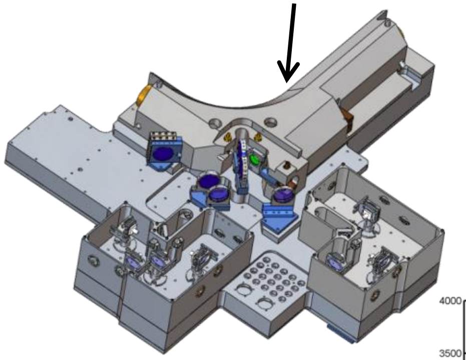
- http://www.ball.com/aerospace/programs/oawl
- Papers/Presentations
  - http://cires1.colorado.edu/events/lidarworkshop/LWG/ :(Previous meetings back to 2007)
  - Tucker, Coherent Laser Radar Conference (CLRC), 2013: http://www.tsc.upc.edu/clrc/wp-content/uploads/Manuscripts/clrc2013_submission_19.pdf
  - and 2016: https://clrccires.colorado.edu/4pagesummaries/F/F5.pdf and https://clrccires.colorado.edu/presentations/F/F5.pdf
  - Baidar, CLRC 2016: https://clrccires.colorado.edu/4pagesummaries/F/F6.pdf
  - Weimer, CLRC 2016: https://clrccires.colorado.edu/presentations/F/F8.pdf
  - Tucker, SPIE Optics and Photonics, 2015: https://spie.org/Publications/Proceedings/Paper/10.1117/12.2190792
- ESTO Tasks
  - OAWL: http://www.estotechnology.us/techportfolio/pdf/quadCharts/1509.pdf
  - HOAWL: http://www.estotechnology.us/techportfolio/pdf/quadCharts/1770.pdf
  - FIDDL: http://www.estotechnology.us/techportfolio/pdf/quadCharts/1791.pdf
  - GrOAWL: http://www.estotechnology.us/techportfolio/pdf/quadCharts/1913.pdf
  - HAWC-OAWL: http://www.estotechnology.us/techportfolio/pdf/quadCharts/1857.pdf
- ETW 2017 Poster Session

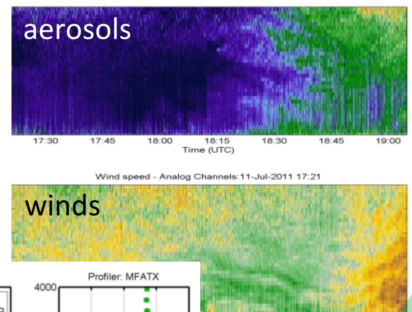
The Evolution of OAWL

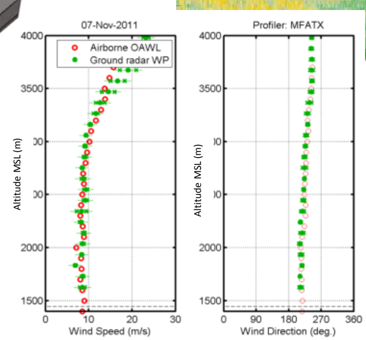
Since 2003, Ball has worked in a public-private partnership with NASA and weather/wind lidar communities to advance space-based wind lidar technology and fill the global wind measurement gap.

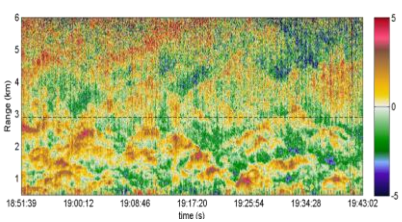
2013 & 2016 ATHENA-OAWL Mission Proposals

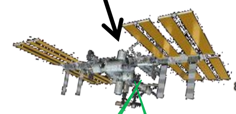
1999-present: Ball design, build and test of OAWL receivers, mission concepts and retrieval/processing algorithms

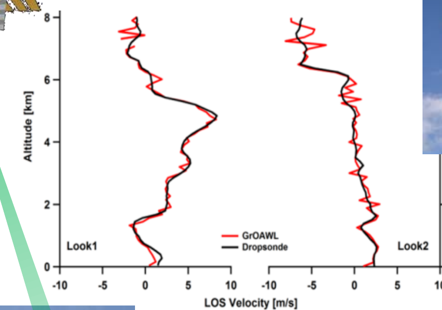


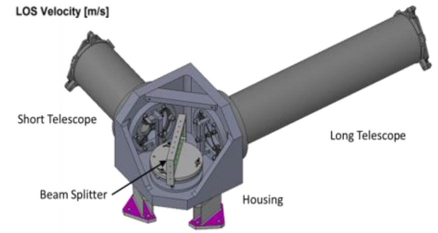












2008-2012: OAWL IIP-07

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

2012-2015: HOAWL ACT

- Breadboard System
- Demonstrate 532 nm wavelength channels & depolarization channels
- Total 10 channels
- 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

2014-2017: HAWC-OAWL IIP

- Two look airborne system (build on GrOAWL)
- Dual Wavelength + depol. Channels
- Updated interferometer build and demonstration
- Hardware design/build for DC-8 integration

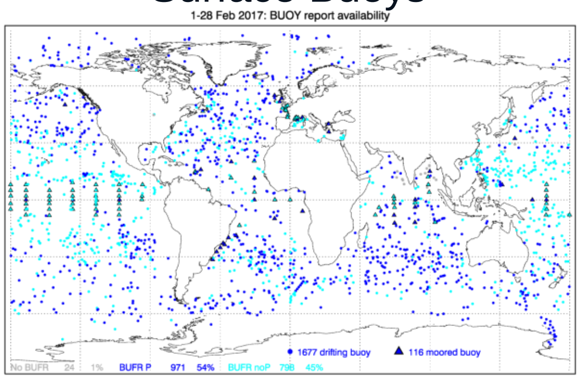
EXTRAS

Existing global winds measurements

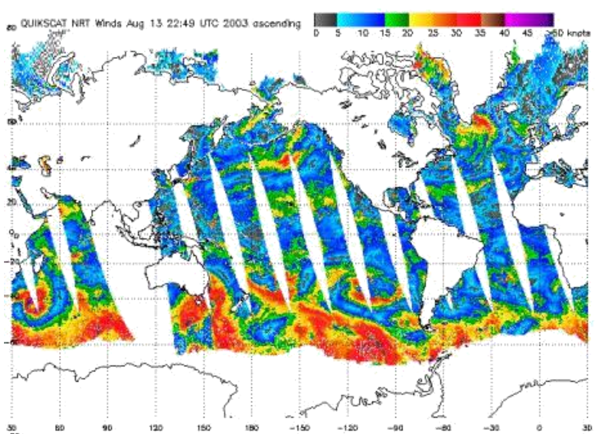
Emerging Technologies

Surface Only

Surface Buoys

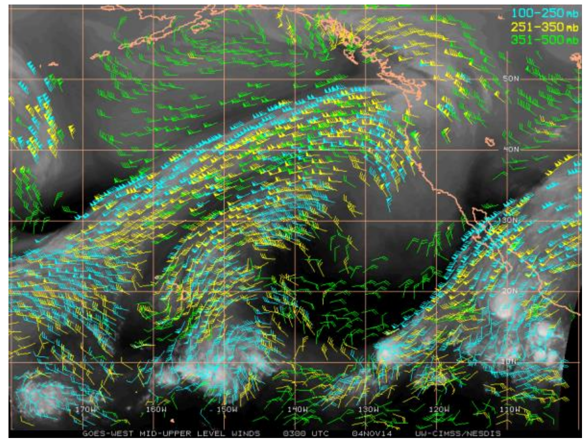


Scatterometry (Quickscat)



Motion Vector

(aerosol/cloud tracking)

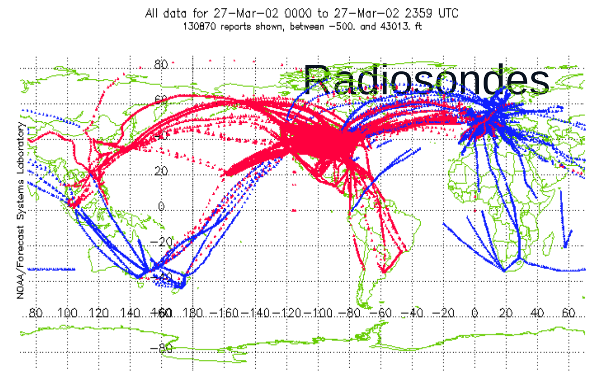


Visible or water vapor channels
Requires 3 cloud images, cloud brightness temp, cloud mask, cloud height, cloud top pressure (for Water Vapor: GFS forecast temperature profile)

Requires Cloud/WV Features
Limited Altitudes

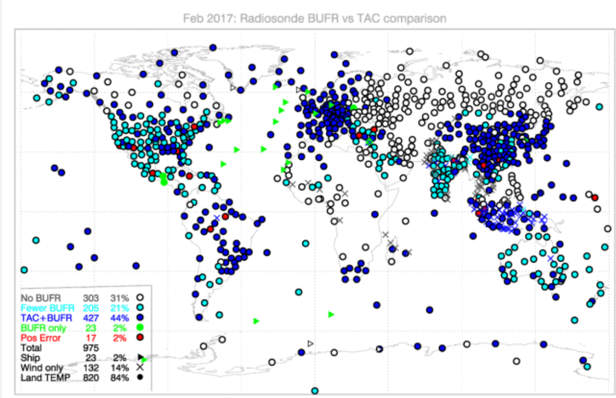
In-situ Profiling

Aircraft



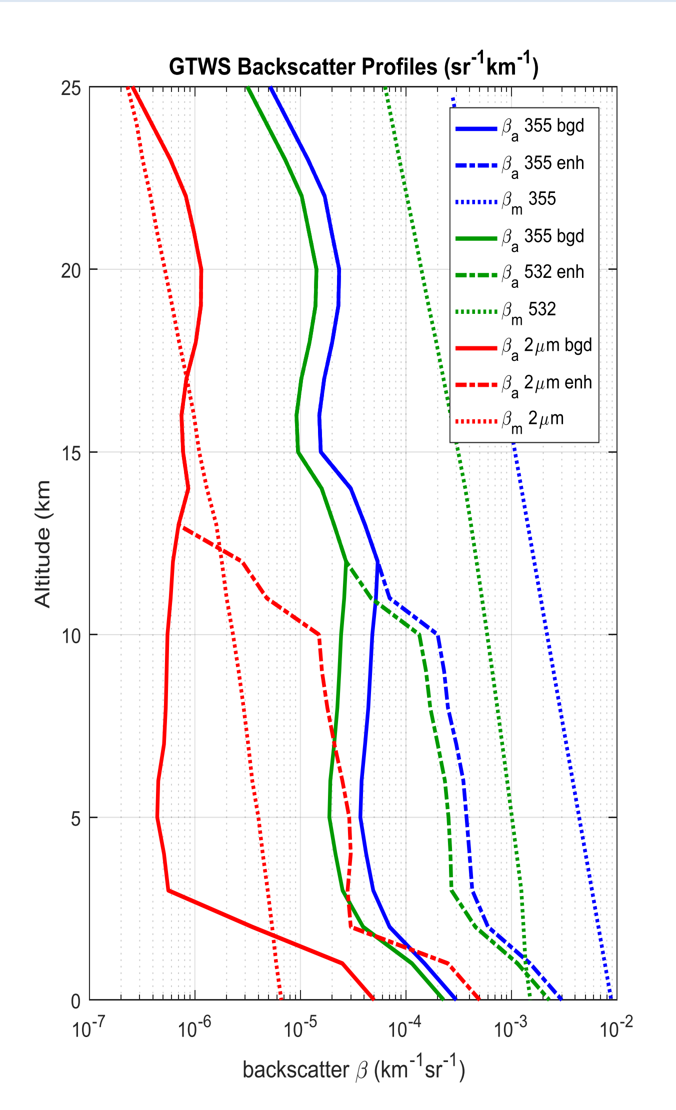
Land-based coverage

Radiosondes



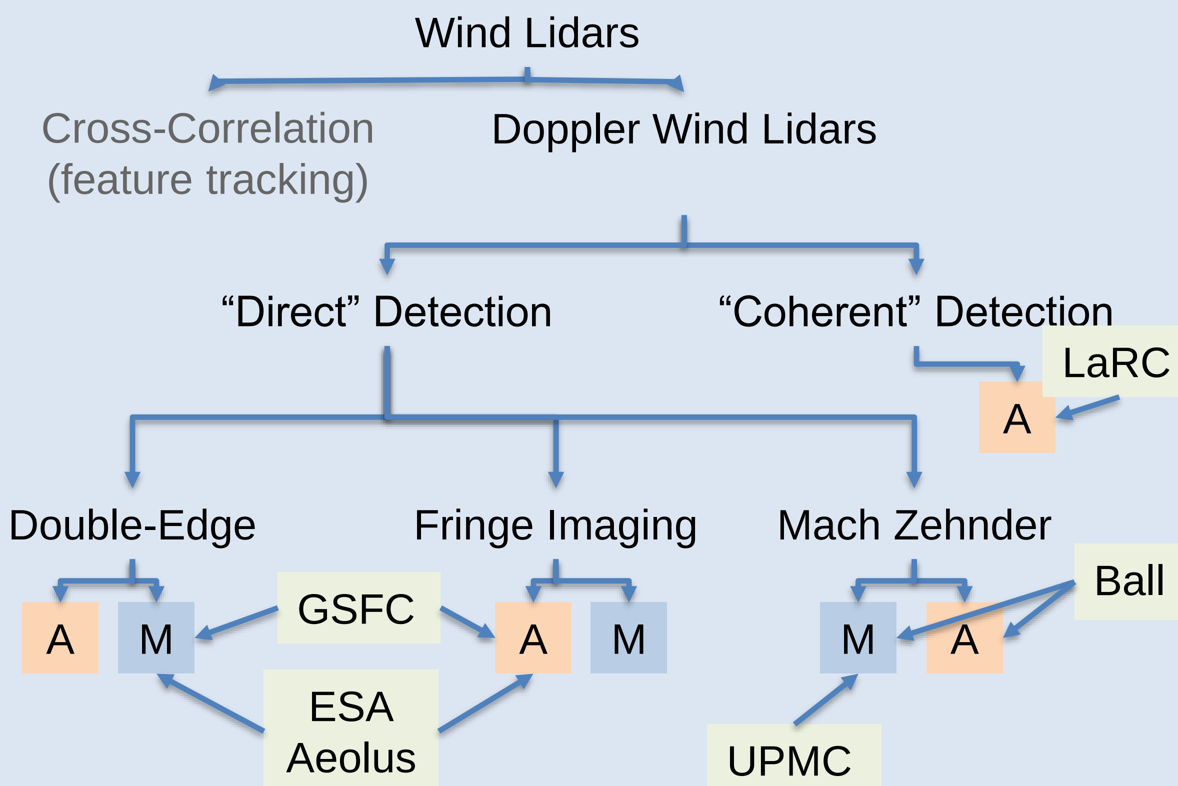
Wind Lidars and the atmosphere

Emerging Technologies



M — Molecular: UT/LS (small wavelengths, eg. 532 nm & 355 nm)

A — Aerosol: LT/clouds (most lidar wavelengths)

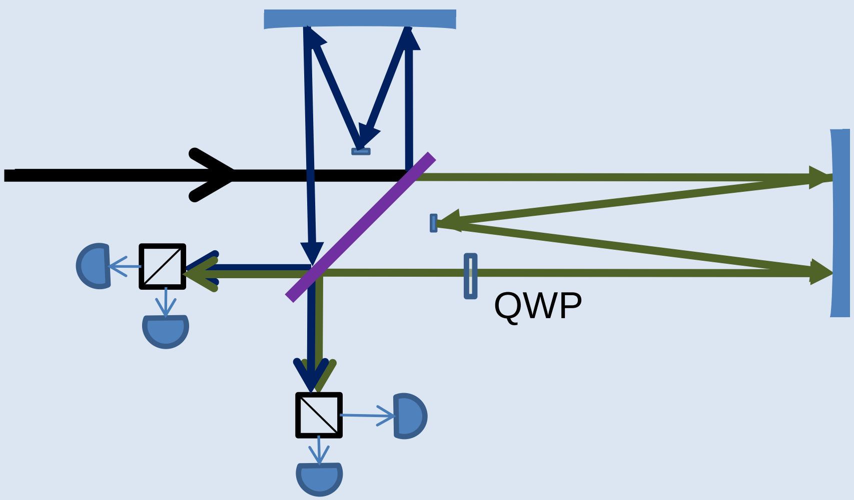


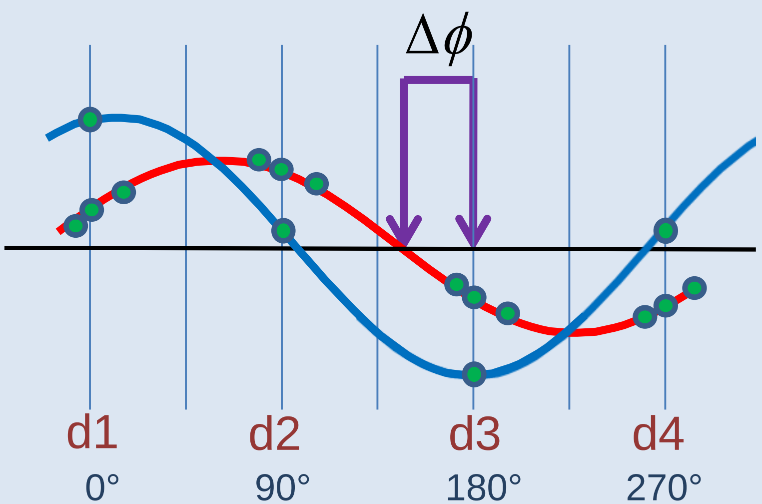
Optical Autocovariance Wind Lidar (OAWL)

Emerging Technologies

- Field-widened, Mach-Zehnder Interferometer (MZI): Patent #s: US7929215B1, US8077294B1
- Four detector channels sample interferometer fringe phase (wind) and amplitude (aerosol).
  --- Outgoing "T0" pulses
  --- Atmospheric Returns at range
- Fringes wrap – no "out of band" concerns. Unwrap 2π jumps (100 m/s discontinuities) in processing.
- Likewise, platform motion translated to phase, "wrapped" and added to T0 phase offset.
- T0 phase offset used to adjust detector returns for every pulse - prior to accumulation/phase fit: no laser pulse-to-pulse stability requirements
- After accumulation, the shifted detector values are fit to determine the return phase, $\Delta\phi$, related to the line-of-sight wind speed, V_{LOS} by

$$V_{LOS} = \frac{\Delta\phi\lambda c}{2\pi(2OPD)}$$



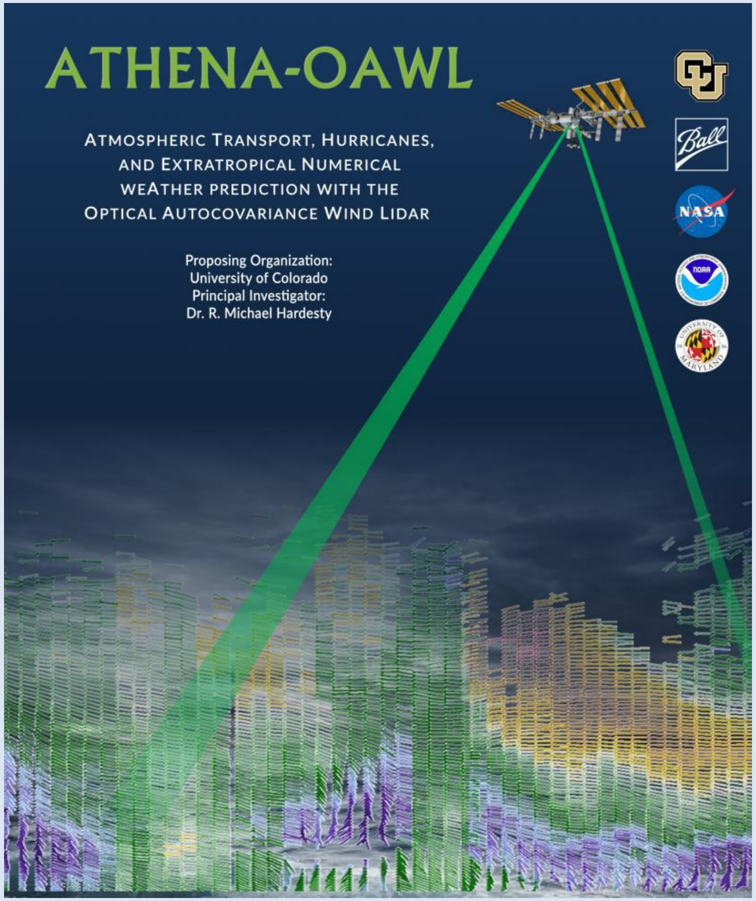


Detectors at constant ACF phase

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

Emerging Technologies

- **ATHENA-OAWL: A**erosol **T**ransport, **H**urricanes, and **E**xtra-tropical **N**umerical we**A**ther prediction using **OAWL.**
- ***Design-to-cost approach*** to NASA Earth Venture Instrument based on heritage systems
- Co-located wind and aerosol profiles 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.



OAWL for Full Atmosphere Wind Profiling

- OAWL path to *full* atmospheric wind profiles
  - Measure aerosol winds @ 532 nm – more precision using the ***existing*** long OPD
  - Measure molecular winds @ 355 nm – more coverage using a new short OPD
  - BOTH wind measurements can achieved by using two systems or a "nested" interferometer:
  - Short (**molecular**) OPD is "nested" *inside* the long (**aerosol**) OPD: "Nested OAWLs"
  - Same detectors as used for the dual wavelength OAWL

- 355 nm lasers:
  - Aeolus has qualified a 355 nm wavelength laser for space
  - Fibertek also working qualification of 355 nm HEUVD laser system

Upper atmosphere – molecular
Lower atmosphere – aerosol