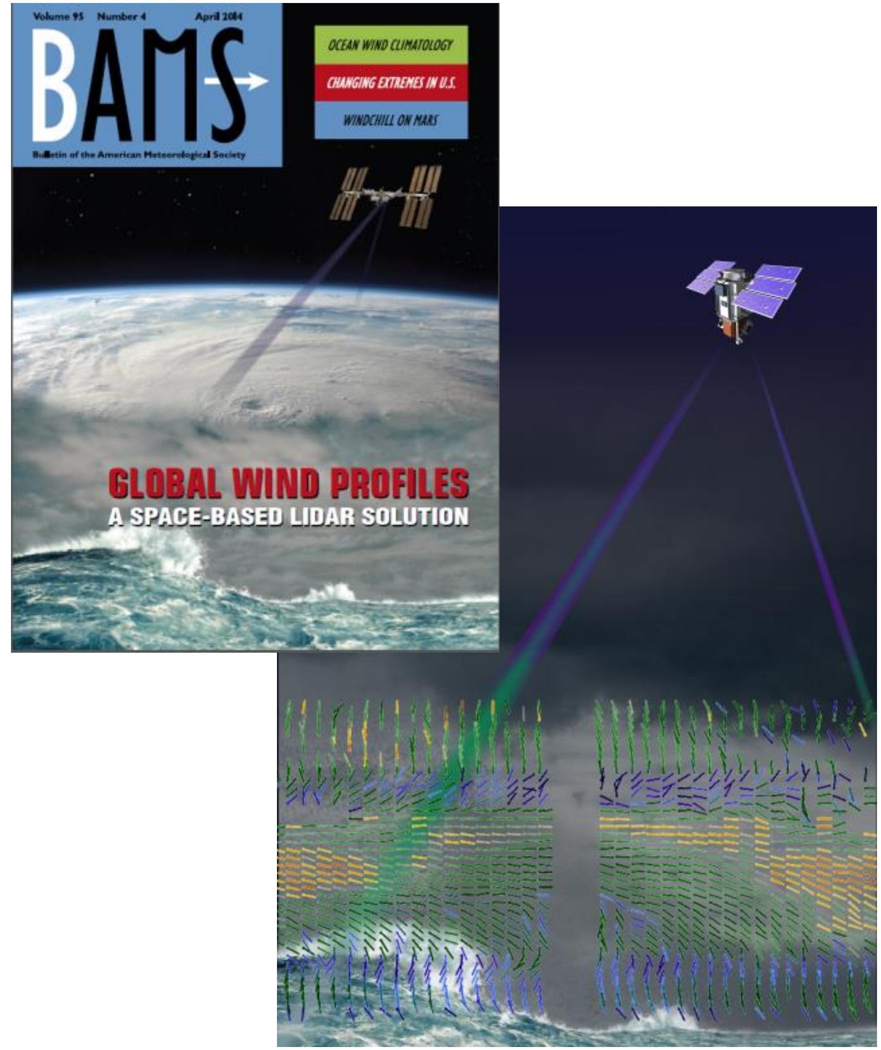
SATELLITE-BASED GLOBAL WIND PROFILING TO IMPROVE NUMERICAL WEATHER PREDICTION

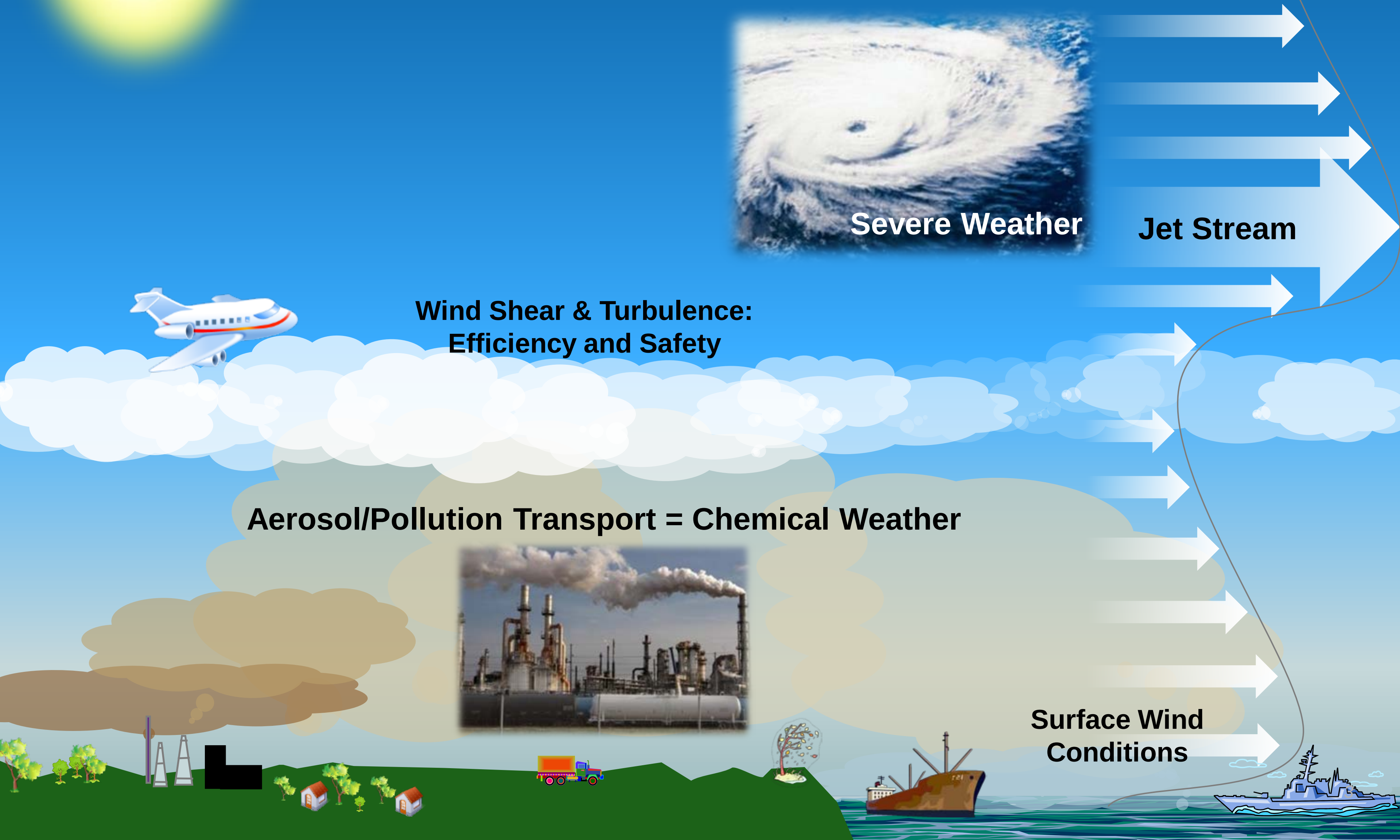
S. Tucker, C. Weimer – Ball Aerospace

Optical Autocovariance Wind Lidar (OAWL) to Provide Global Wind Profiling

- Since 2003, Ball has been working with the weather and wind lidar communities to advance space-based wind lidar technology to help fill the global wind measurement gap.
- ESA's Aeolus system expected to launch December 2017; no planned follow-on
- OAWL is the only U.S. Doppler Wind Lidar technology with a high heritage path to space
  - Nd:YAG laser already proven in space especially for 532 nm
  - OAWL is like CALIPSO in its direct detection approach, wavelength, optics, filters, etc.
  - ~$20M of Ball and NASA funding invested in demonstrating this technology
- OAWL technology has been proven in ground and airborne demonstrations.
- High TRL OAWL technology is ready to be demonstrated on orbit.

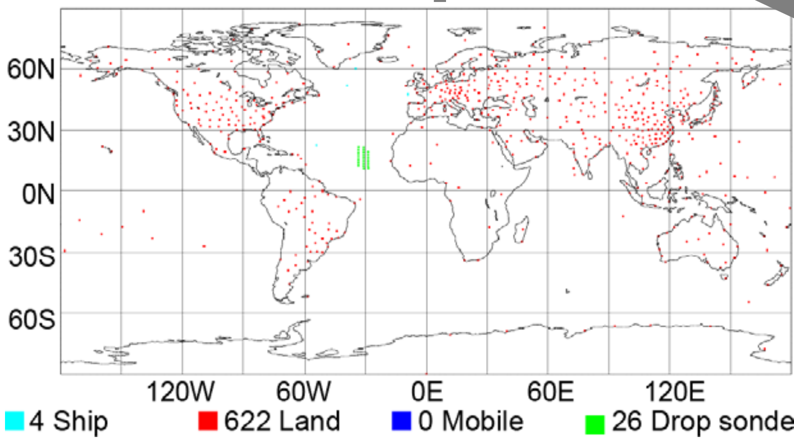


Winds and weather affect us all – locally, globally, politically, & economically.



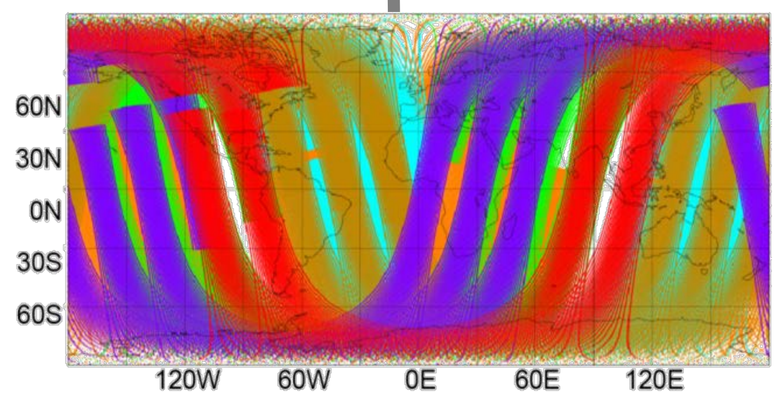
World Meteorological Organization (WMO)

Wind profiles:
radiosondes



"There is a need to invest in enhanced wind observations in the tropics and over the oceans especially…. Development of satellite-based wind profiling systems remains a priority for the future global observing system."
(WMO-2012)

Mass fields

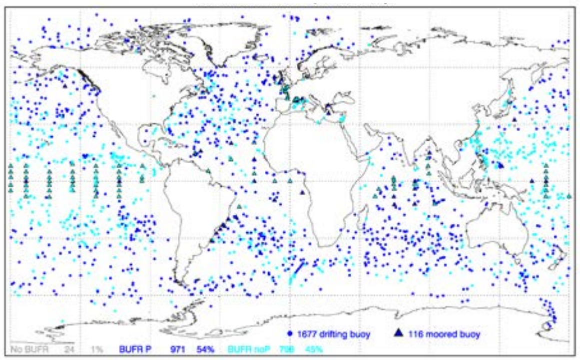


The Global Observing System is heavily skewed toward mass observations

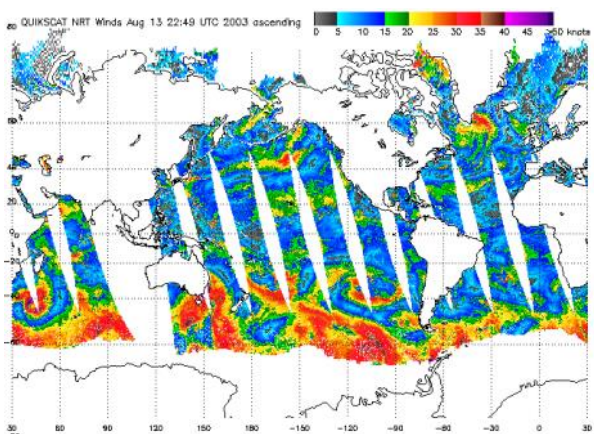
Existing global winds measurements

Surface

Surface Buoys

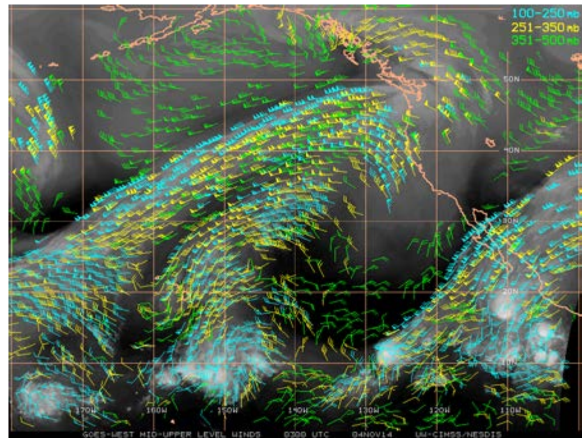


Scatterometry (Quickscat)



Motion Vector

(aerosol/cloud tracking)

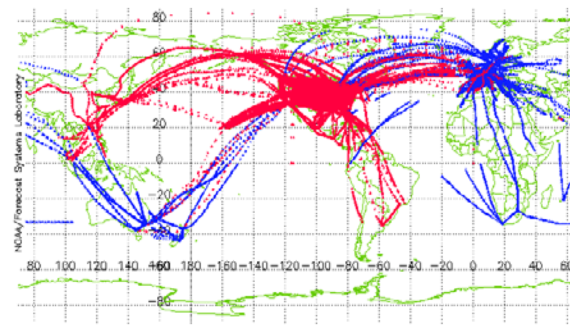


Visible or water vapor channels
Requires 3 cloud images, cloud brightness temp, cloud mask, cloud height, cloud top pressure (for Water Vapor: GFS forecast temperature profile)

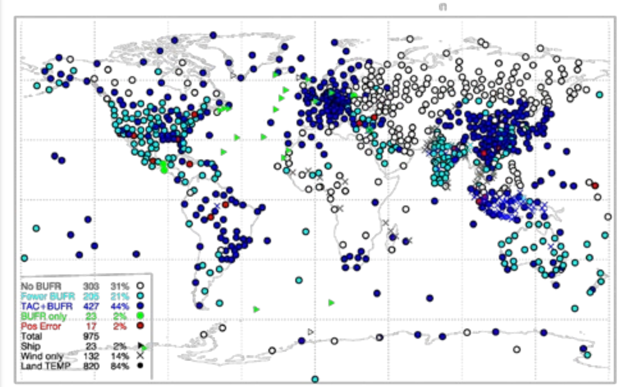
Requires Cloud/WV Features

In-situ Profiling

Aircraft 7-Mar-02 2359 UTC 00. and 43013. ft



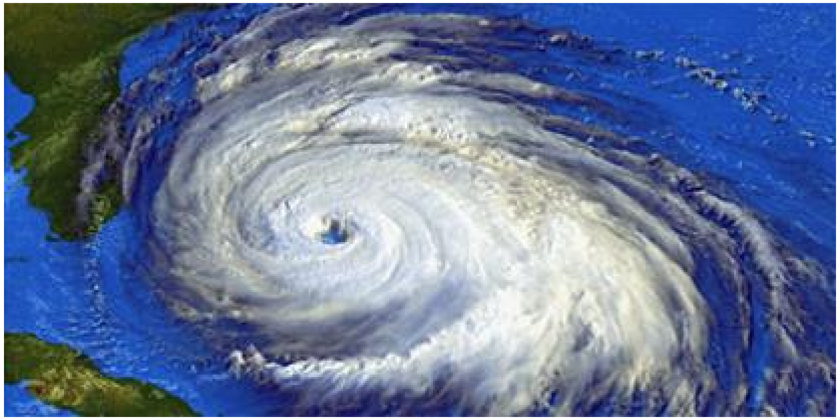
Radiosondes

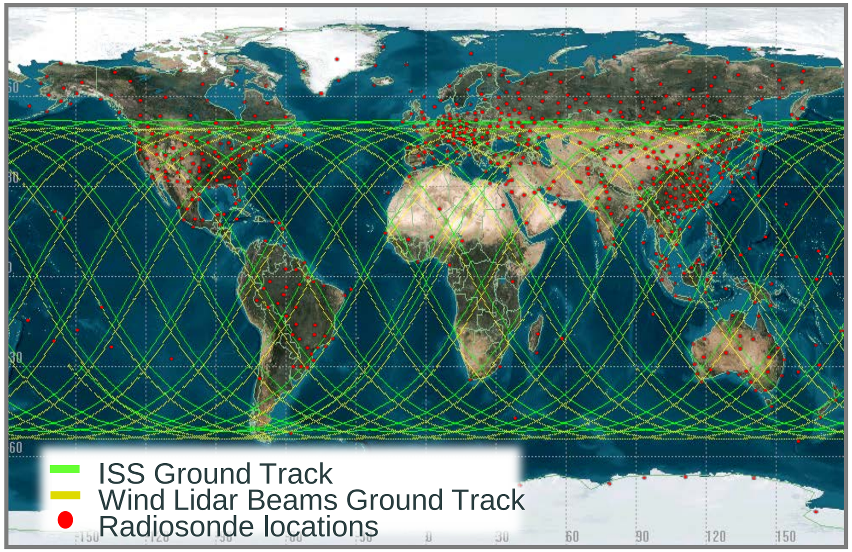


Space-Based Doppler Wind Lidar (DWL)

The greatest unmet observational need is winds

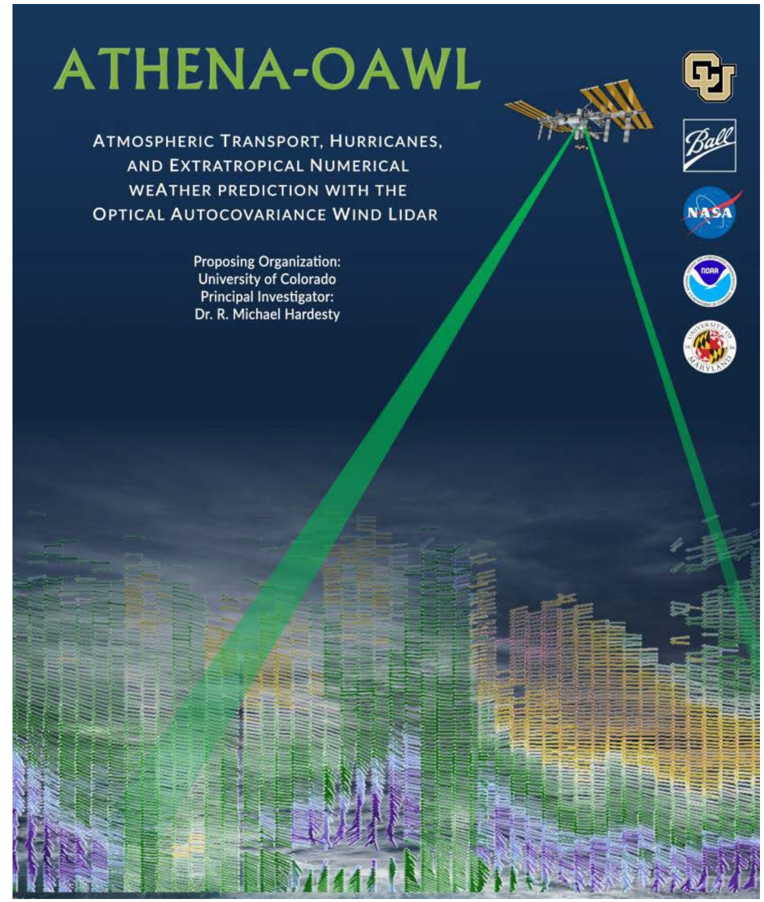
- Numerical Weather Prediction needs winds to initialize models
  - *especially* over the oceans and mid-latitudes
  - wind profiles (kinematics) over oceans (esp. tropics)
- Space-based DWL can provide:
  - Direct measurements of altitude resolved wind profiles
  - Measurement of convergence & divergence
  - Global coverage → most importantly over the oceans and in the tropics
- ESA's Aeolus wind lidar to launch in December 2017: one line of sight (e.g. one component of the wind field).





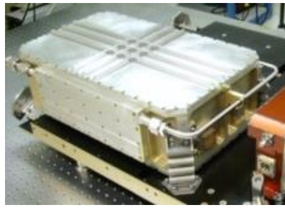
ATHENA-OAWL: path-finding science for next-generation global weather prediction and climate analysis

- **ATHENA-OAWL:** **A**erosol **T**ransport, **H**urricanes, and **E**xtra-tropical **N**umerical we**A**ther 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.



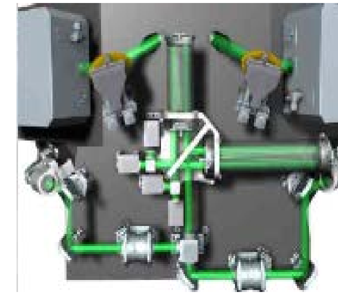
THE ATHENA-OAWL INSTRUMENT

Design-to-cost approach

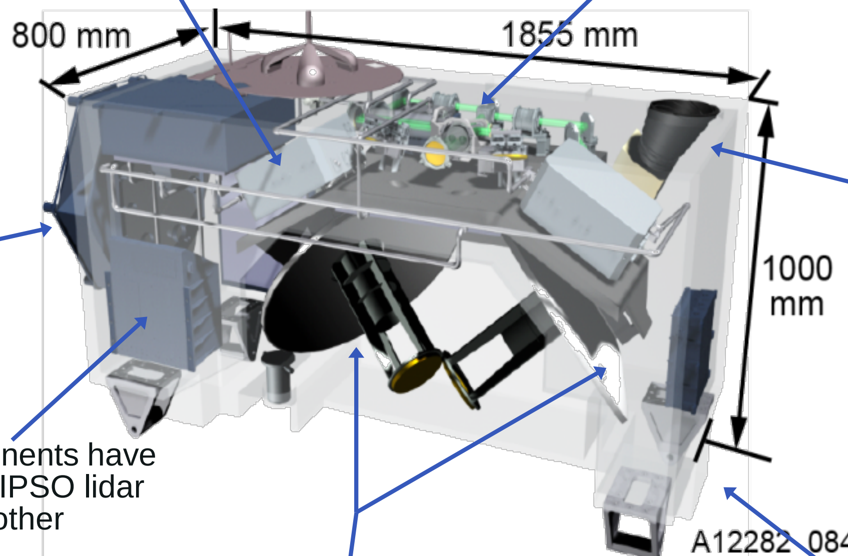


ESTO-funded Fibertek 532 nm (and UV)) laser development & qualification

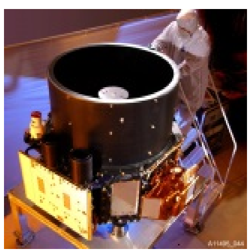
The proven OAWL interferometer system



ISS enabling capabilities: power, cooling loop, and TDRSS → providing low latency for the ATHENA measurements

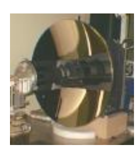


Star tracker system provides pointing knowledge for LOS wind speed accuracy



Most OAWL components have heritage in the CALIPSO lidar (2006 launch) and other space-based missions

The autonomous OAWL prototype system in the NASA WB-57 pallet (2011) - on par with JEM-EF mass, volume, power and cooling capabilities.



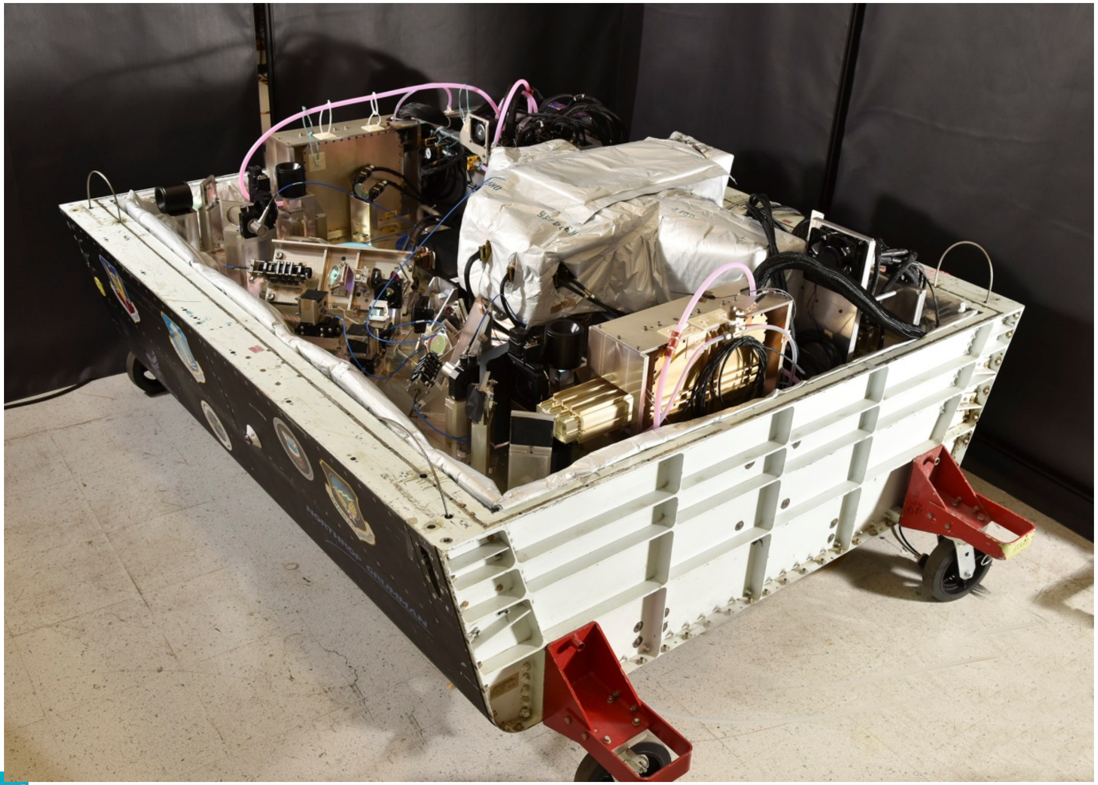
GDIT (Axsys) telescopes like those used for CALIOP, CATS, and GLAS

ATHENA-OAWL Venture Tech
The Green-OAWL Airborne Demonstrator

- ATHENA-OAWL Venture Tech (AOVT): Venture Technology funding from NASA ESSP
- Mach-Zehnder based direct detection aerosol wind lidar (OAWL)
- Built a two-look airborne system configuration to demonstrate the two look concept for space-based platforms
- Two lasers – both operate at the 532 nm (green) wavelength *and* 355 nm (UV) wavelength.

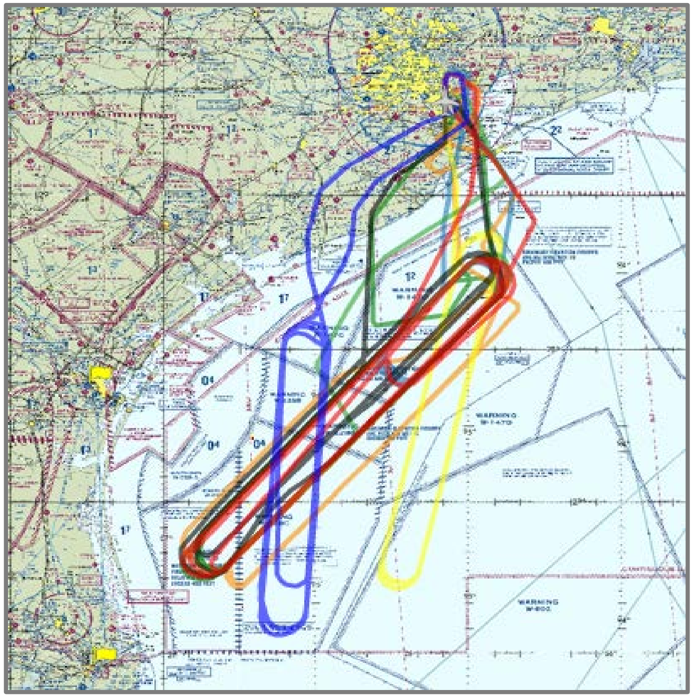
NASA WB-57 Aircraft Integration of OAWL

- WB-57 pallet: pressurized to 5 psi above ambient exterior above 8000 ft
- Two custom pallet floor panels with custom windows
- Custom fluid loop cooling system integrated into floor panels
- GrOAWL instrument, vibration isolation, & environmental control



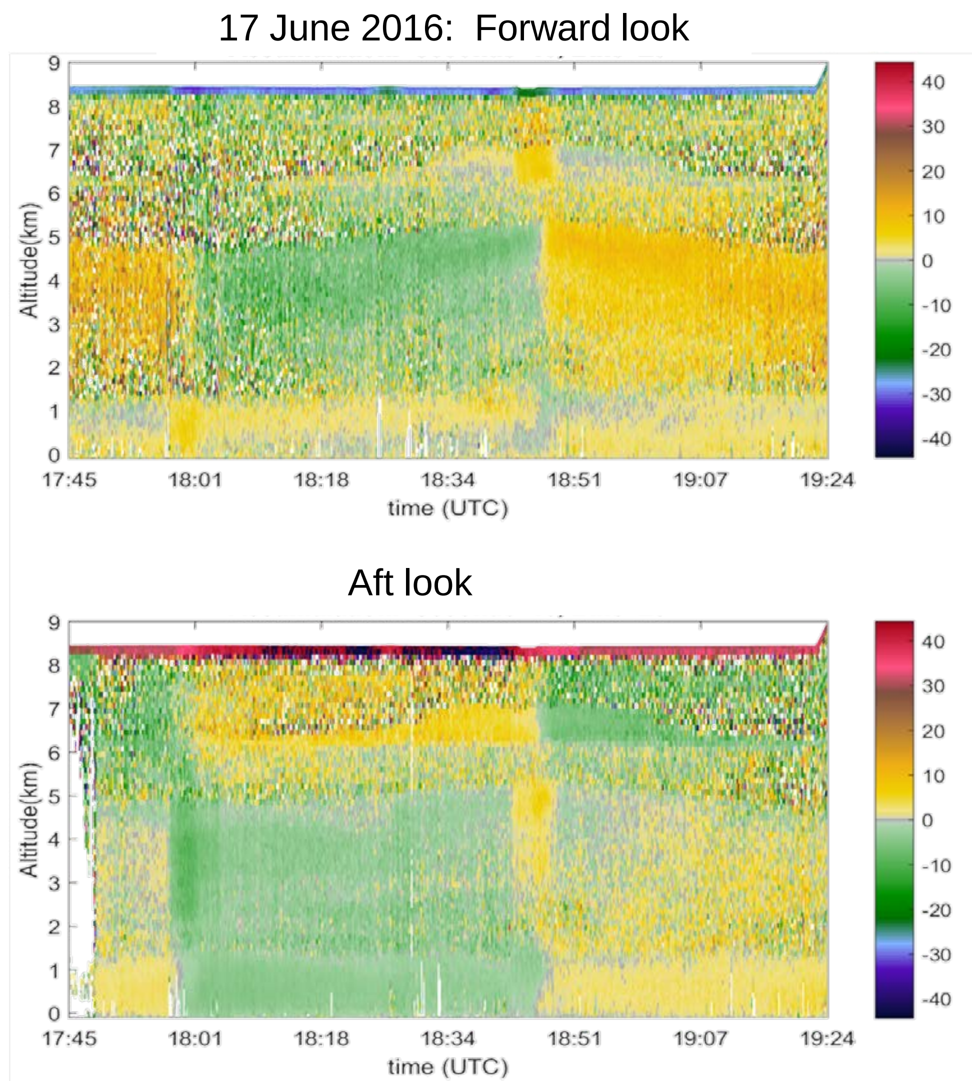
AOVT GrOAWL Airborne Flight Testing on NASA's WB-57 Jet (N928)

- Ellington Field at Johnson Space Center.
- Remote/autonomous operation: from backseat (laser ops) or ground
- INMARSAT satellite link for ground control/telemetry
- 8 flights, ~38 flight hours
- Racetrack flight patterns over the Gulf of Mexico:
  - revisit times (~1 hr/loop)
  - Opposite views of atmosphere region
- Flew over warning areas to allow:
  - Real-time flight pattern variability: altitude adjustments, cloud avoidance, airspace coordination, etc.
  - Testing with variable laser output power
  - **Dropping ONR/Yankee Environmental Systems sondes for winds validation**

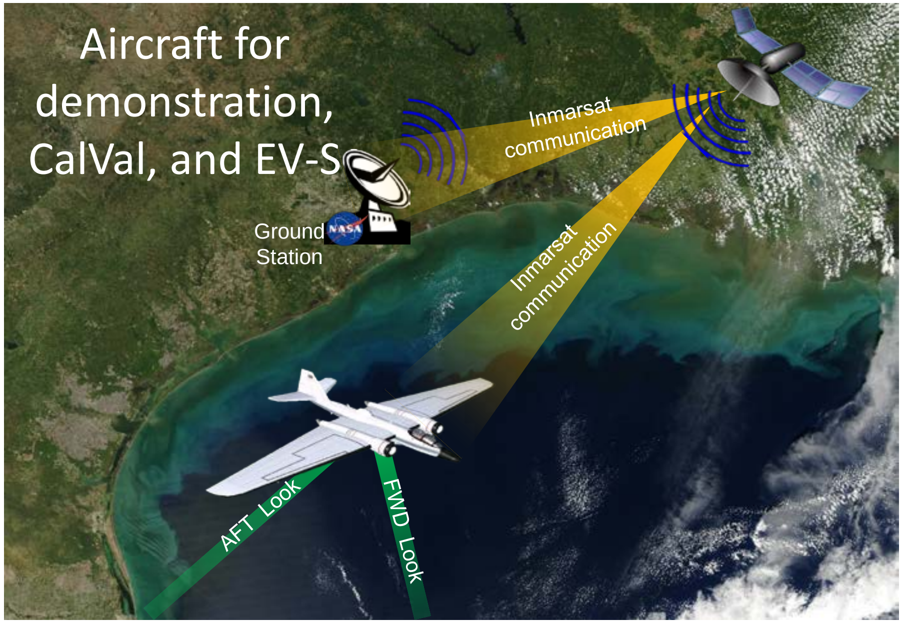


Simultaneous two-look LOS wind speed profiles

- Only **1.5 mJ/pulse** (0.3 W) at 532 nm wavelength
- Daytime operation
- Scattered clouds at ~1km altitude
- 8.5km altitude, 12 km slant path to the surface
- Clean atmosphere: very low aerosol backscatter
- Two-separate looks measure two different Doppler shifts based on projections of the wind speed onto the lidar beams.



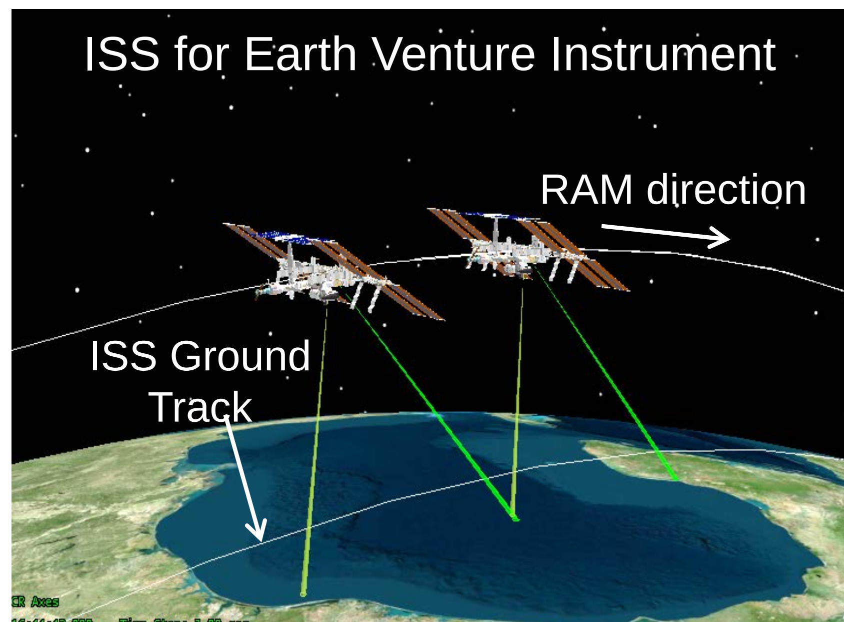
GrOAWL/ATHENA-OAWL: two continuous looks



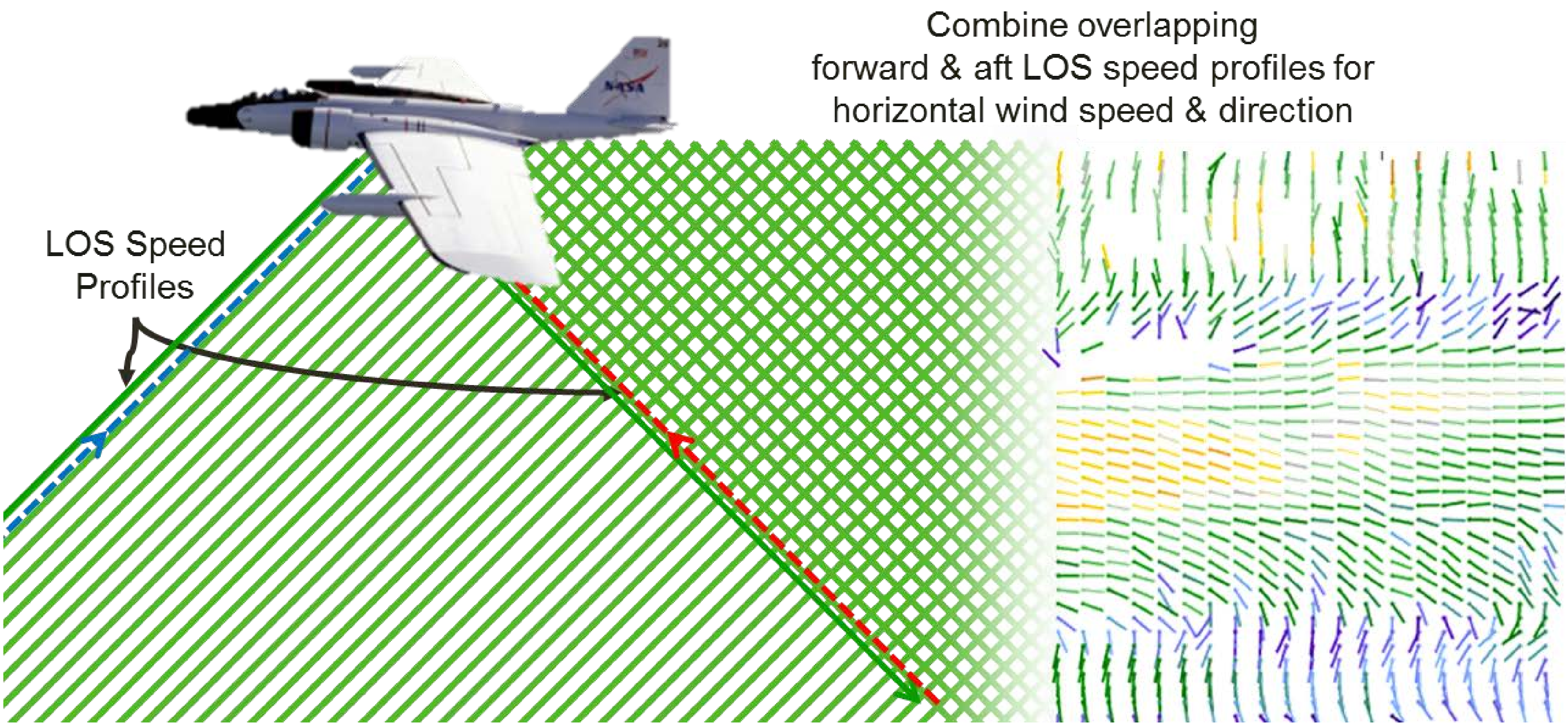
The GrOAWL validation flights provided the first (known) investigation and demonstration of the continuous two-look approach desired for a space-based mission.

Two looks enables:

- **Continuous line coverage** of observations at all layers (vs. switching)
- **Continuous U & V components for NWP**
- Two looks of GrOAWL data can be **combined into continuous speed & direction profiles**

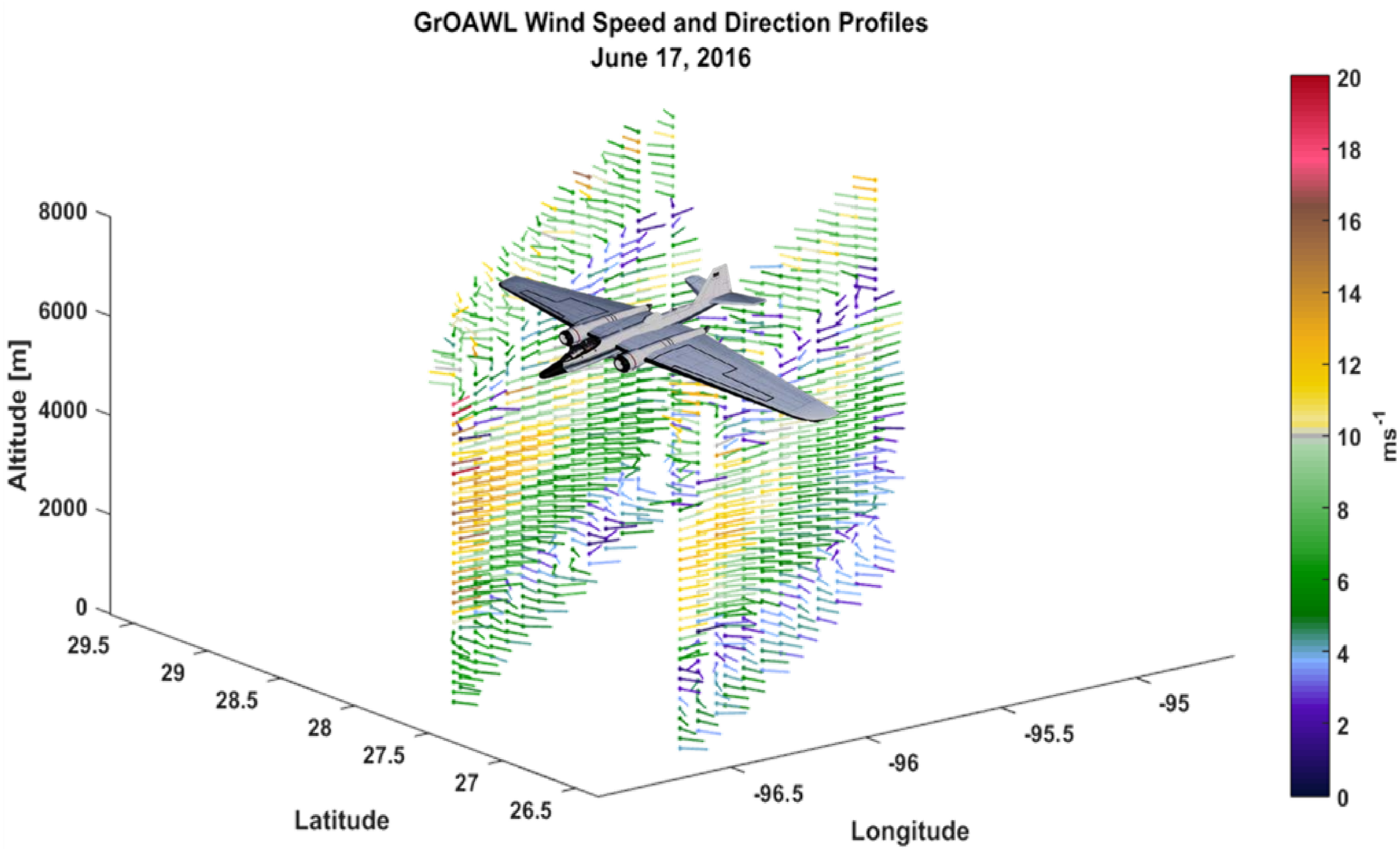


Two look LOS wind speeds → wind profiles

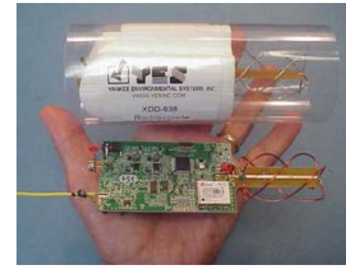


Wind barbs: color indicates wind speed, and line (dot at the time of the profile) line points into the wind direction

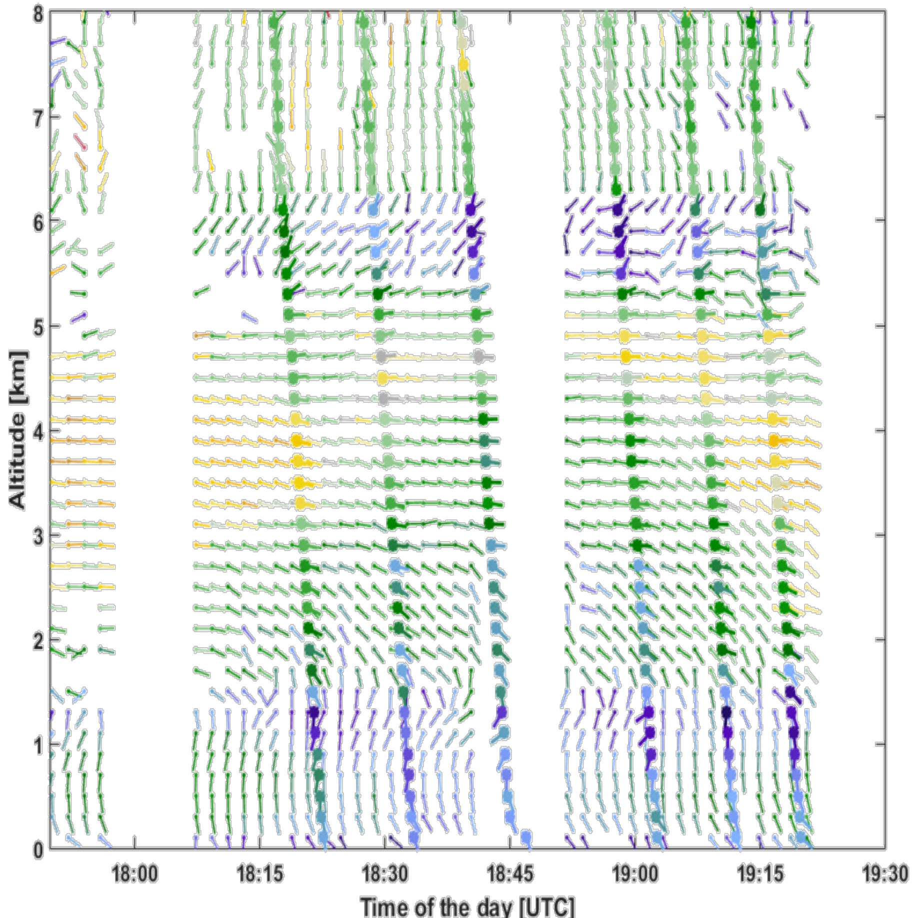
Airborne mapping of winds over the Gulf of Mexico



GrOAWL and YES High Definition Sounding System (HDSS, ONR) dropsonde profiles



June 17, 2016



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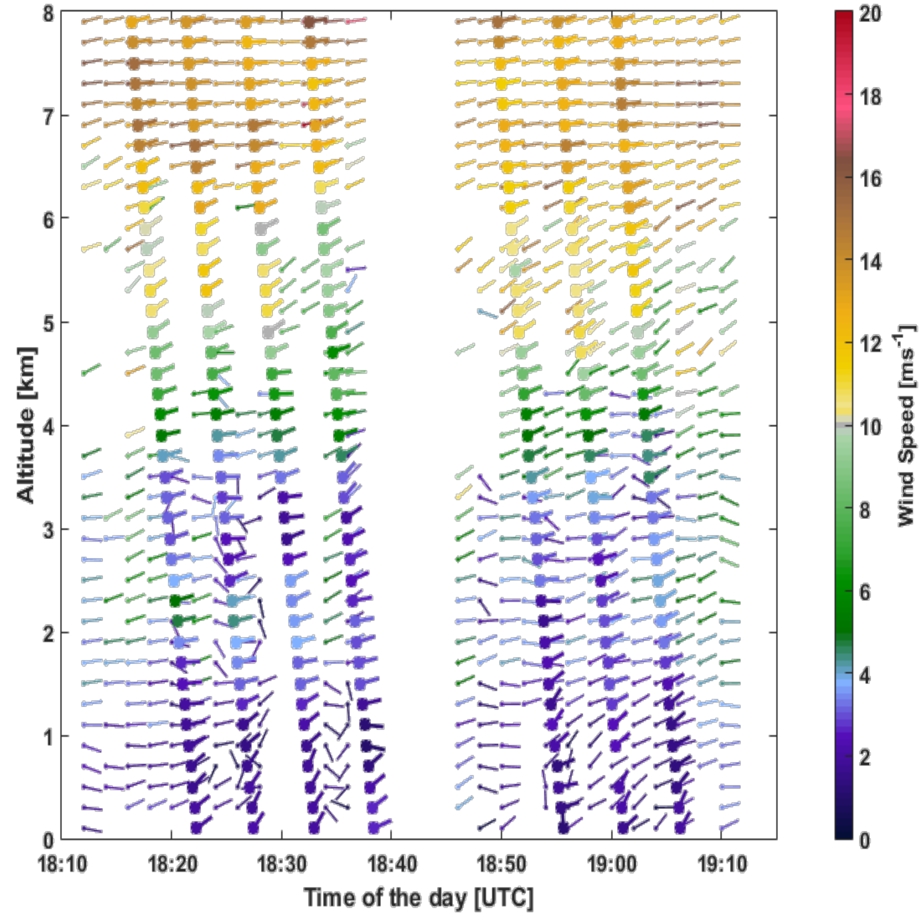
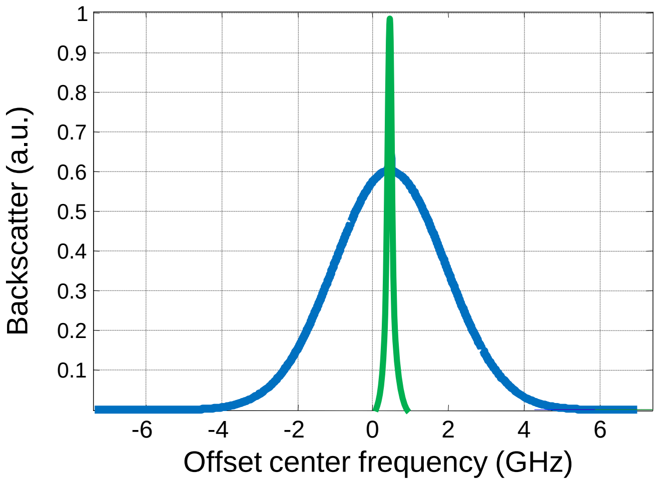
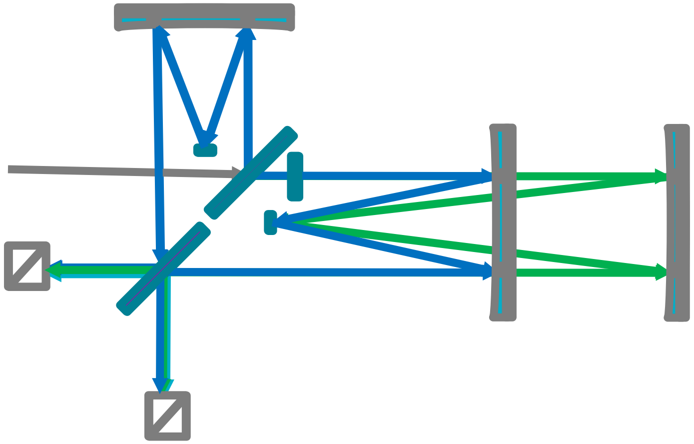


OAWL for Full Atmosphere Wind Profiling

- ESA's Aeolus: Space-based wind lidar
  - 355 nm wavelength for both aerosol (Fizeau) and molecular (double-edge) channels
- OAWL also has a path to *full* atmospheric wind profiles.
  - currently measuring winds from aerosols at 532 nm & 355 nm using long OPD MZI.
  - Bruneau et al. 2003 demonstrated 355 nm (UV) molecular winds with short OPD MZI.
  - OAWL system concept in development
    - Lower-tropospheric, aerosol winds @ 532 nm (long OPD)
    - Upper trop/lower Stratosphere: molecular winds @ 355 nm (short OPD)
  - Nest the short OPD inside the long OPD. For BOTH wind measurements in a single interferometer: ***"Nested OAWL"***

Upper atmosphere – molecular
Lower atmosphere – aerosol





OPD: Optical Path Difference

Summary: wind lidar measurements

Space based wind lidar is expected to provide:

- Improved tropical cyclone intensity and track forecasts
  - protect assets/infrastructure
- Improved wind forecasts for
  - Flight operations
  - In-flight aircraft refueling
  - Combat search and rescue
  - UAS and high altitude balloon operations
  - Precision air-drop operations
- Direct wind measurement data to support
  - Air quality and visibility
  - Transport and dispersion models for planning and response

- ESA's Aeolus will launch Dec. 2017
  - Cal/Val planning now: US participation in Cal/Val is still in planning phases – seeking funding.
  - No planned follow-on
- OAWL – based on CALIPSO technology – is ready for space
  - Could also provide CALIPSO-like aerosol measurements
- ISS mission like ATHENA would provide low-cost approach to technology demonstration
- Free flyer mission to provide more power, more coverage → more forecast impact.

Thanks to:

- ESTO for IIP and ACT development funding
- ESSP and ESTO for the Venture-Technology funding
- The Ball GrOAWL engineering team
- Fibertek (Floyd Hovis)
- The NOAA-ESRL/CU-Boulder-CIRES science team
- Mark Beaubien of Y.E.S. & ONR for dropsonde validation support
- The engineering team, crew, pilots, and program staff of the WB-57 for all their excellent flight support

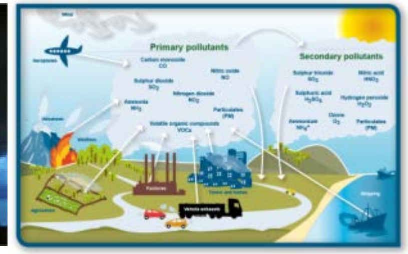
Nested OAWLS

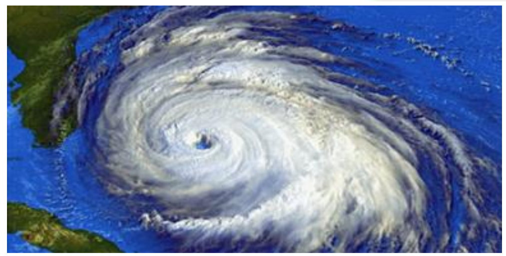
EXTRAS

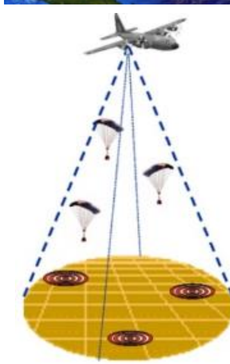
OAWL Applications

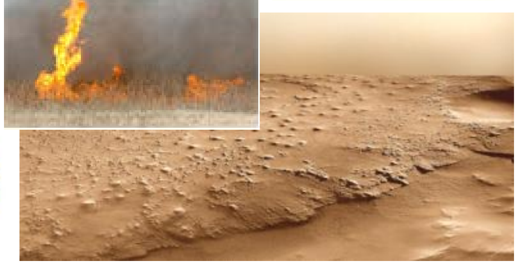
Airborne OAWL

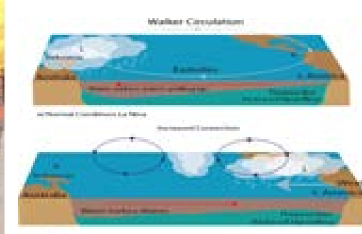
- Earth Science Campaigns
  - Hurricane Observations and Forecast Improvement
  - Severe Storms monitoring (e.g. w/ microwave)
  - Heat flow to the Arctic (aerosol transport, SST winds/temps)
  - Fire weather
  - ENSO/Ocean Winds
  - Air quality transport (Pacific Coast)
- Commercial Applications
  - Ship based ocean wind sensing
  - Insurance – storm prediction studies
  - Aviation – improved aviation forecasts, safety
  - Mixing: wind farms, emissions from factories, fields, pipelines, etc.
- Defense Applications
  - Spacecraft launch conditions
  - Vertical TakeOff and Landing (VTOL)
  - Theater area maritime and terrestrial weather forecasting
  - Gunship wind sensing
  - Precision Air Drop

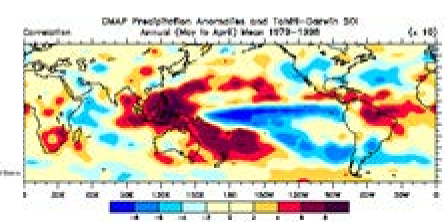












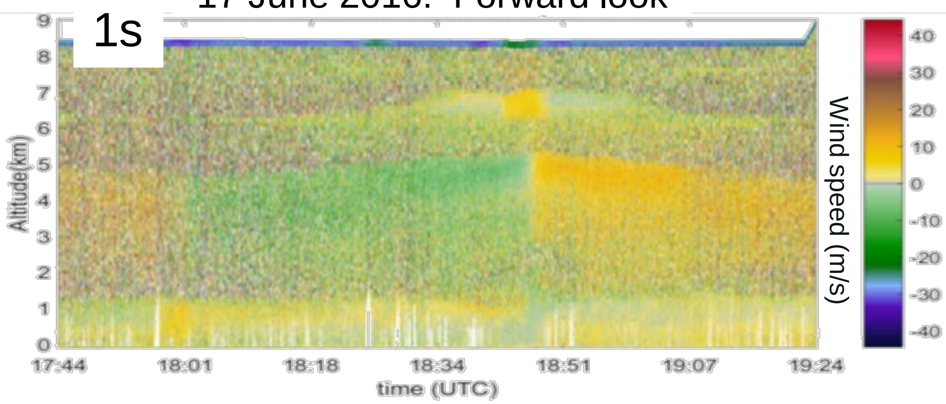
Space-Based OAWL: includes items at left, at larger scales.

- <u>Numerical Weather Forecasting</u>
  - Estimated $200M/year, per hour of forecast improvement
  - Operational weather data
  - Commercial weather
  - Military applications
- Global aerosol/pollution transport
  - Chemical Weather:
  - Air quality forecasting & pollution attribution
  - Transport/dissemination of infectious agents
- Planetary Winds (Mars)
- Global heat transport (Arctic warming)

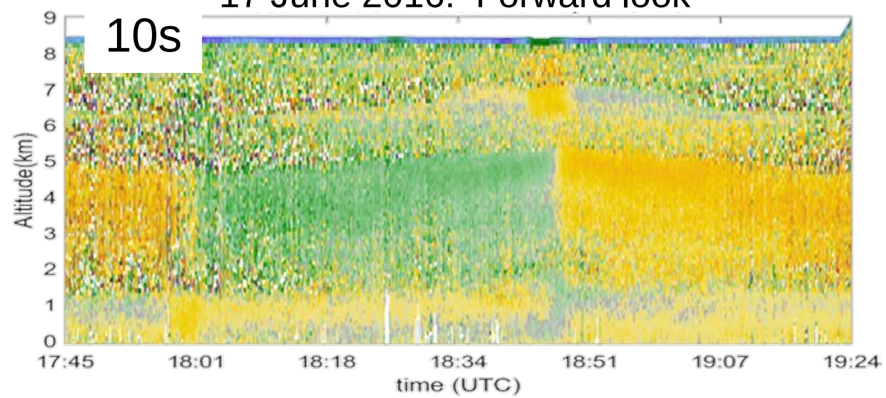
Simultaneous two-look LOS wind speed profiles

- Wind speed processing accumulation is variable based on trade between precision and time or range resolution

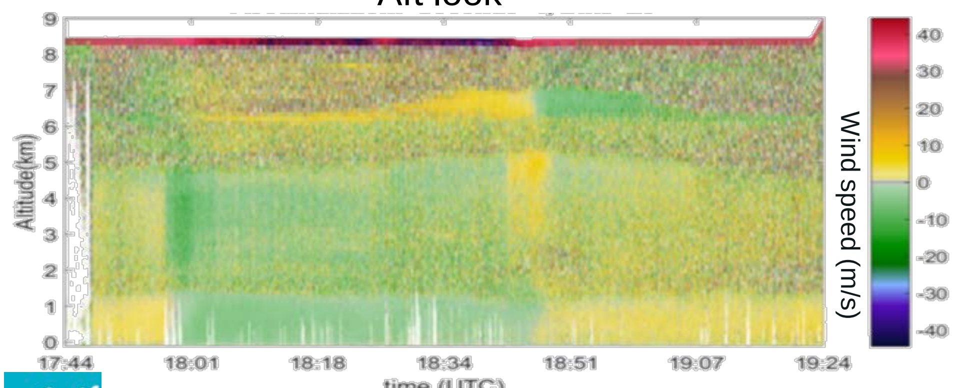
17 June 2016: Forward look



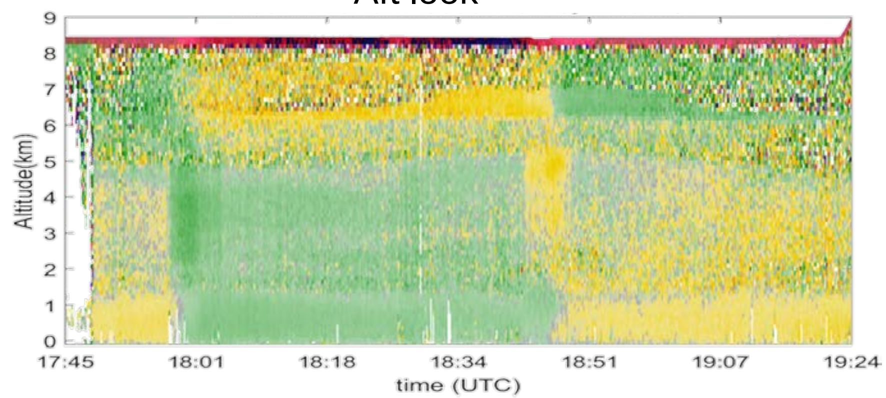
17 June 2016: Forward look



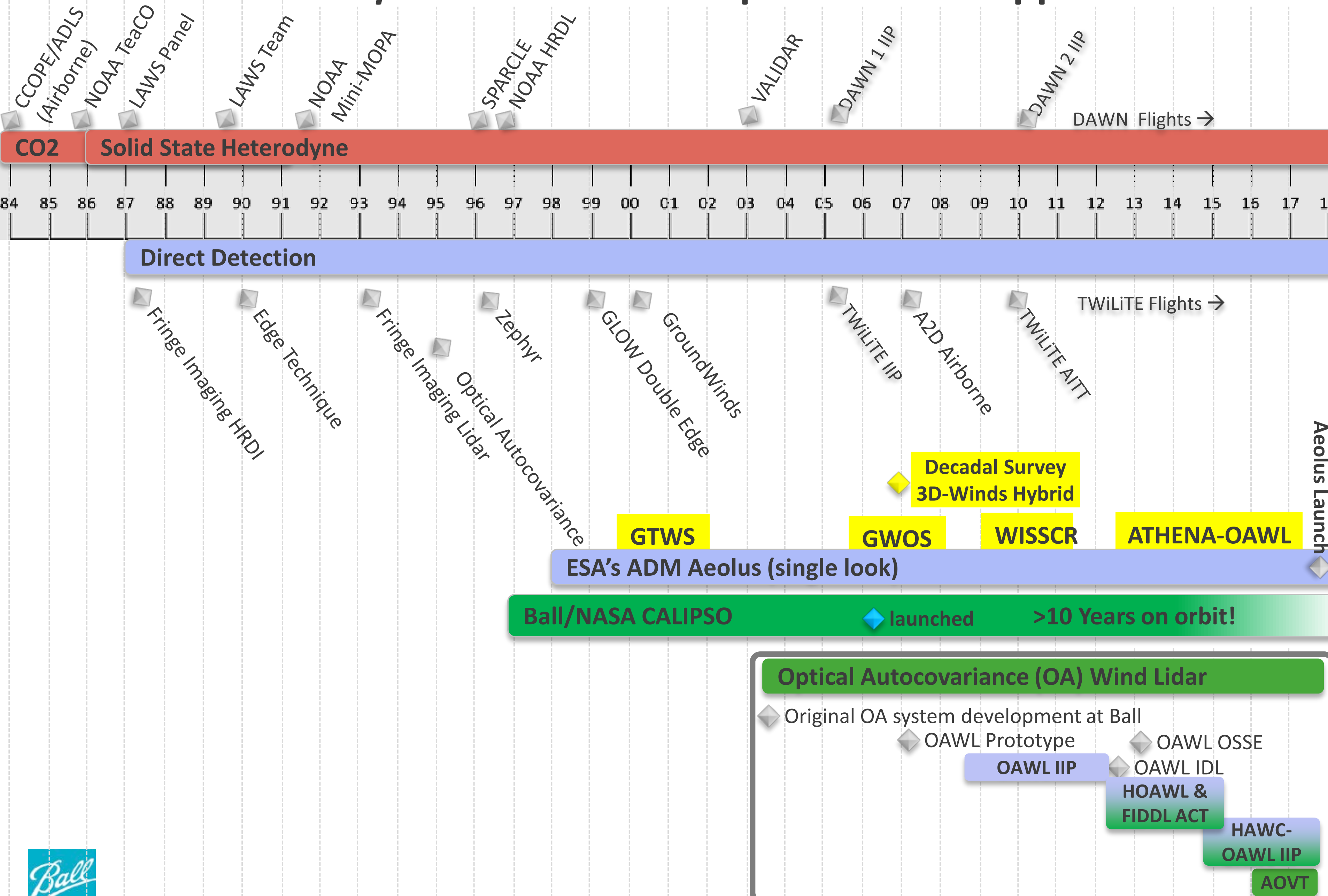
Aft look



Aft look



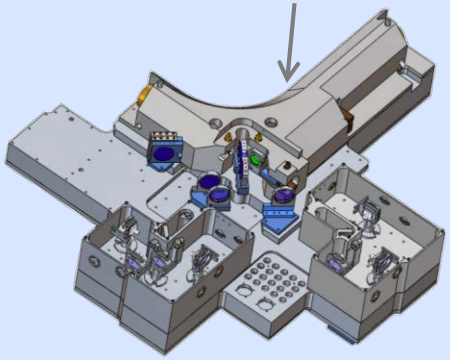
A *partial* timeline of space-based Doppler wind lidar

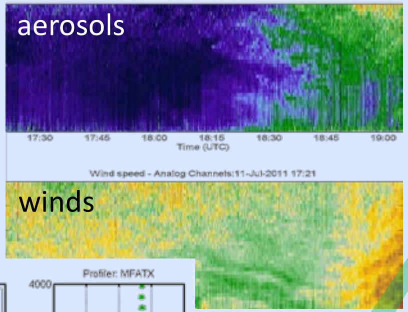


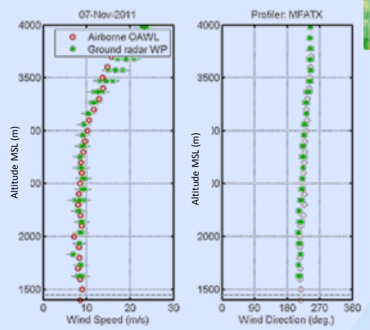
The Evolution of OAWL

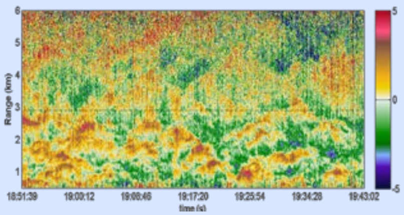
2013 & 2016 ATHENA-OAWL Mission Proposals

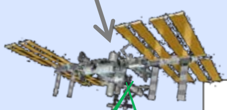
1999-present: Ball design, build and test of OAWL receivers, mission concepts and retrieval/processing algorithms

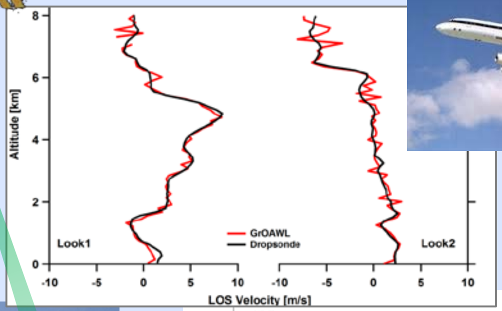


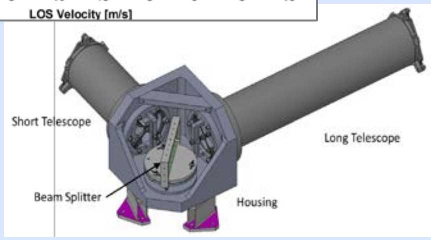












2008-2012: OAWL IIP-07

- 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

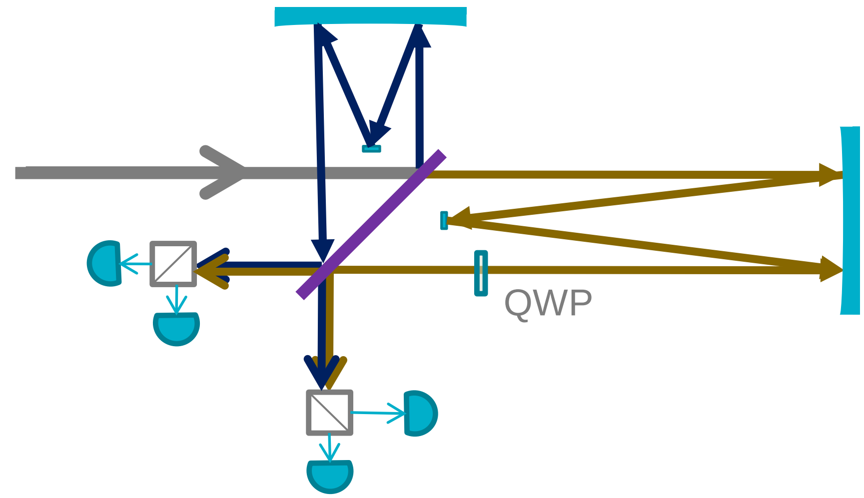
2014-2017: HAWC-OAWL IIP

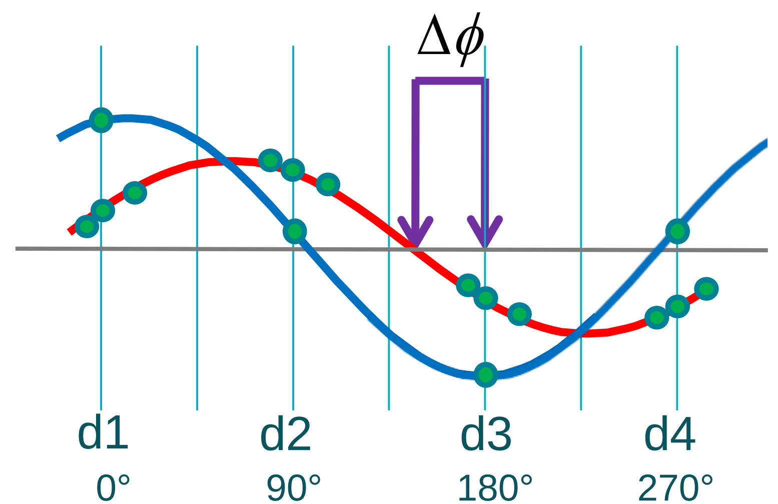
- Two look airborne system (build on GrOAWL)
- Dual Wavelength + depol. Channels
- Athermal interferometer build and demonstration
- DC-8 hardware design/build

Optical Autocovariance Wind Lidar (OAWL)

- 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.
- Platform motion translated to phase, added to T0 phase offset and "wrapped"
- 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