OAWL through HAWC-OAWL (w/ FIDDL and HOAWL)

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ESTO Earth Science Technology Office

Agility to Innovate, Strength to Deliver

Ball Aerospace & Technologies Corp.

OAWL: **Optical Autocovariance Wind Lidar**

Flexibility for wind observations

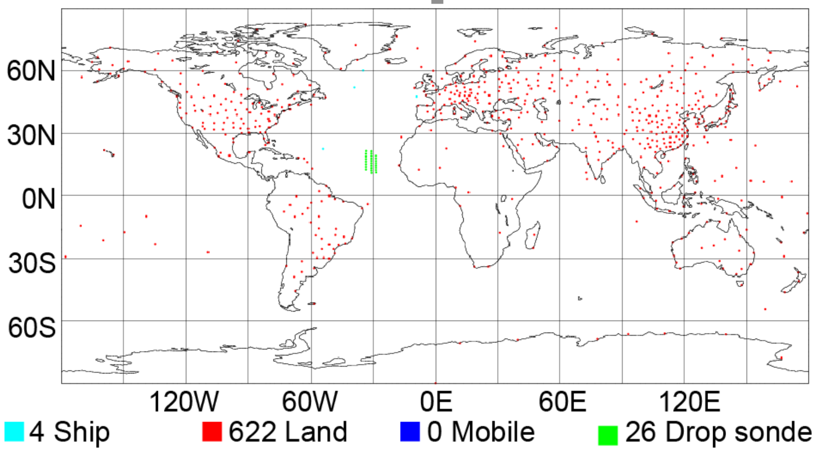
OAWL is a Doppler lidar designed to measure wind from aerosol backscatter at 355 nm *and/or* 532 nm

One laser for global winds & aerosols.

The Global Observing System for Weather

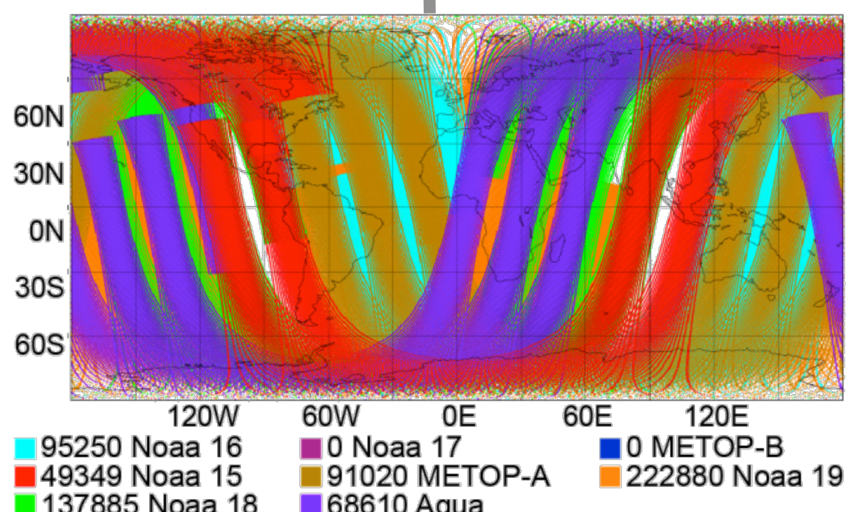
Heavily skewed toward mass observations

Wind profiles radiosondes



From the Fifth WMO Impact Workshop, May 2012 (Riishojgaard): Highest ranking contributors to weather forecast skill are mostly winds measurements –
Investment in additional winds observations is a high priority.

Mass fields

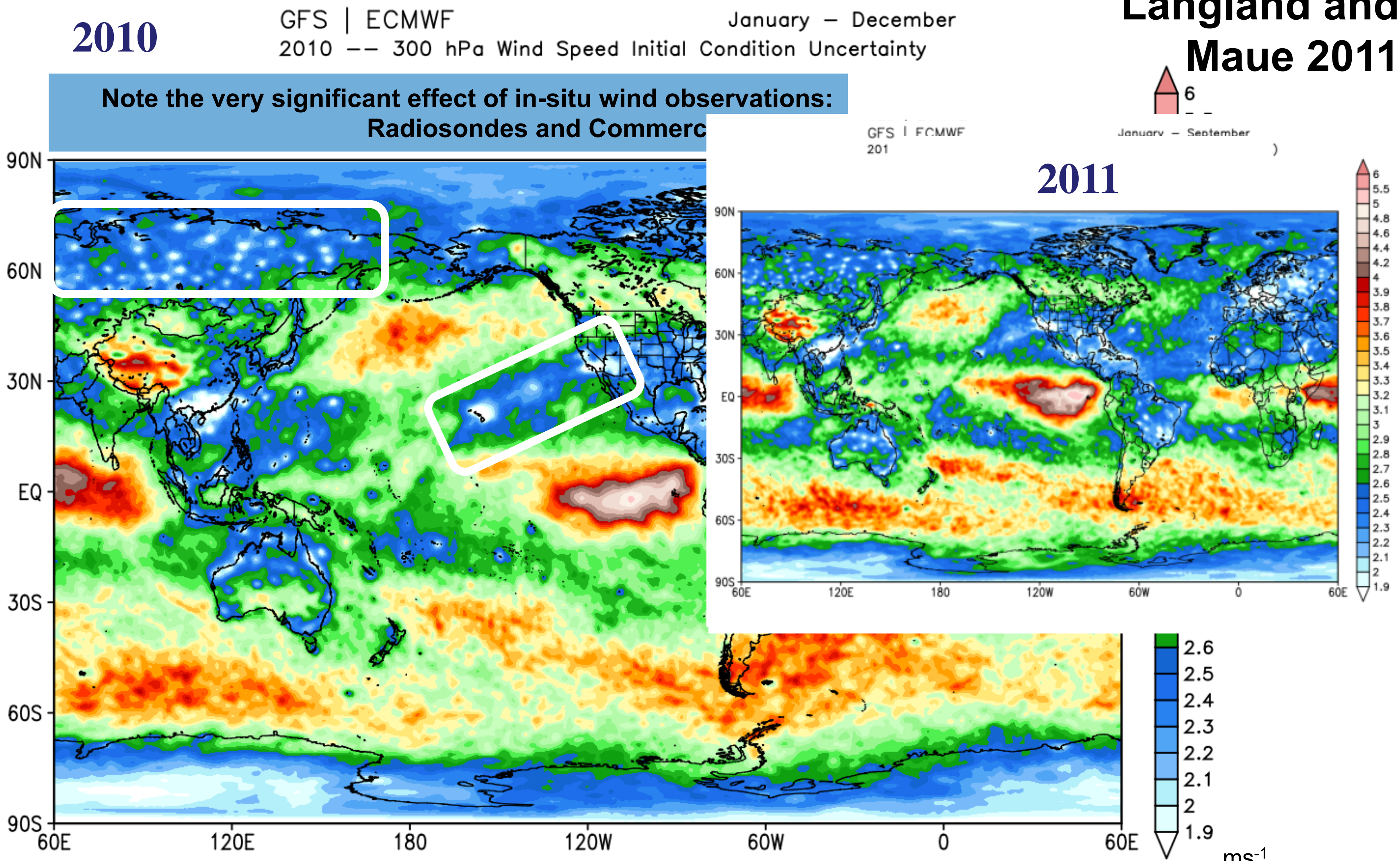


300mb Wind Speed (2010) GFS / ECMWF

<u>*Langland, Sedona 2012*</u>

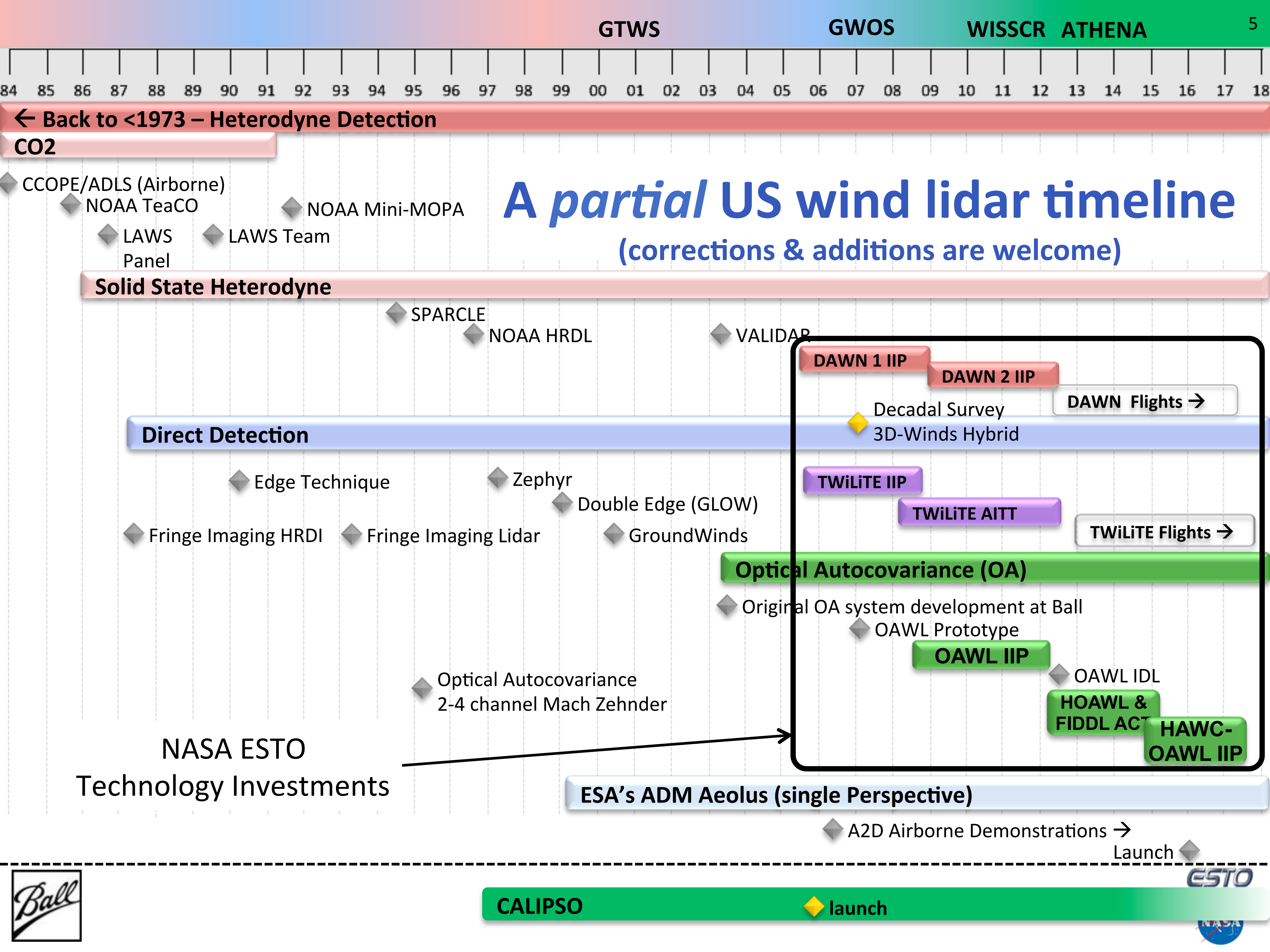
Root-Mean Square of Analysis Differences: 300mb Wind Speed

Langland and Maue 2011



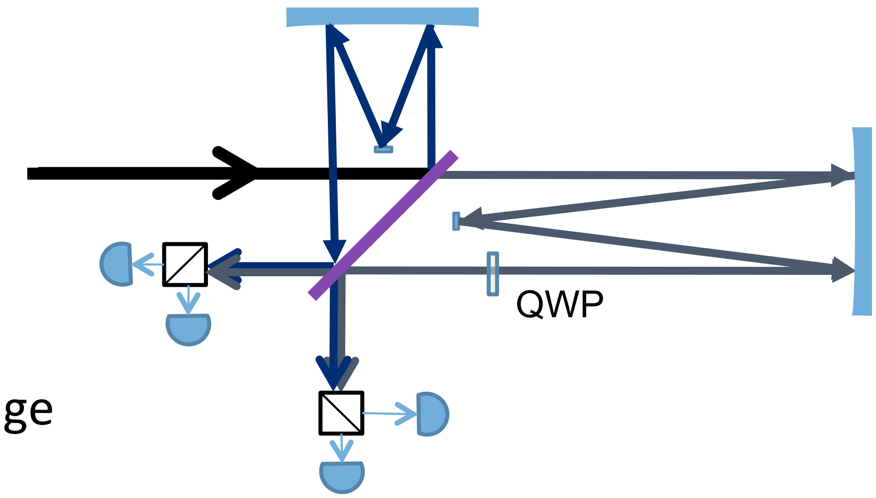
A *partial* US wind lidar timeline

(corrections & additions are welcome)



Optical Autocovariance

- ~1m OPD Mach-Zehnder Interferometer (MZI) w/ field-widening - enables use of larger telescopes (e.g. > 8 mrad FOV)
  - Patent #s: US7929215B1, US8077294B1

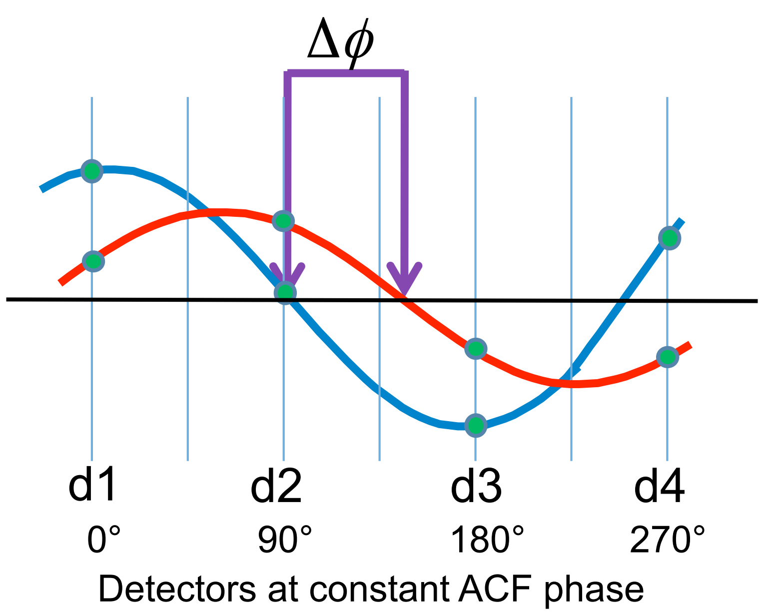


- Four channels sample interferometer fringe phase (wind) and amplitude (aerosol).
  - Outgoing "T0" pulse
  - Atmospheric Return

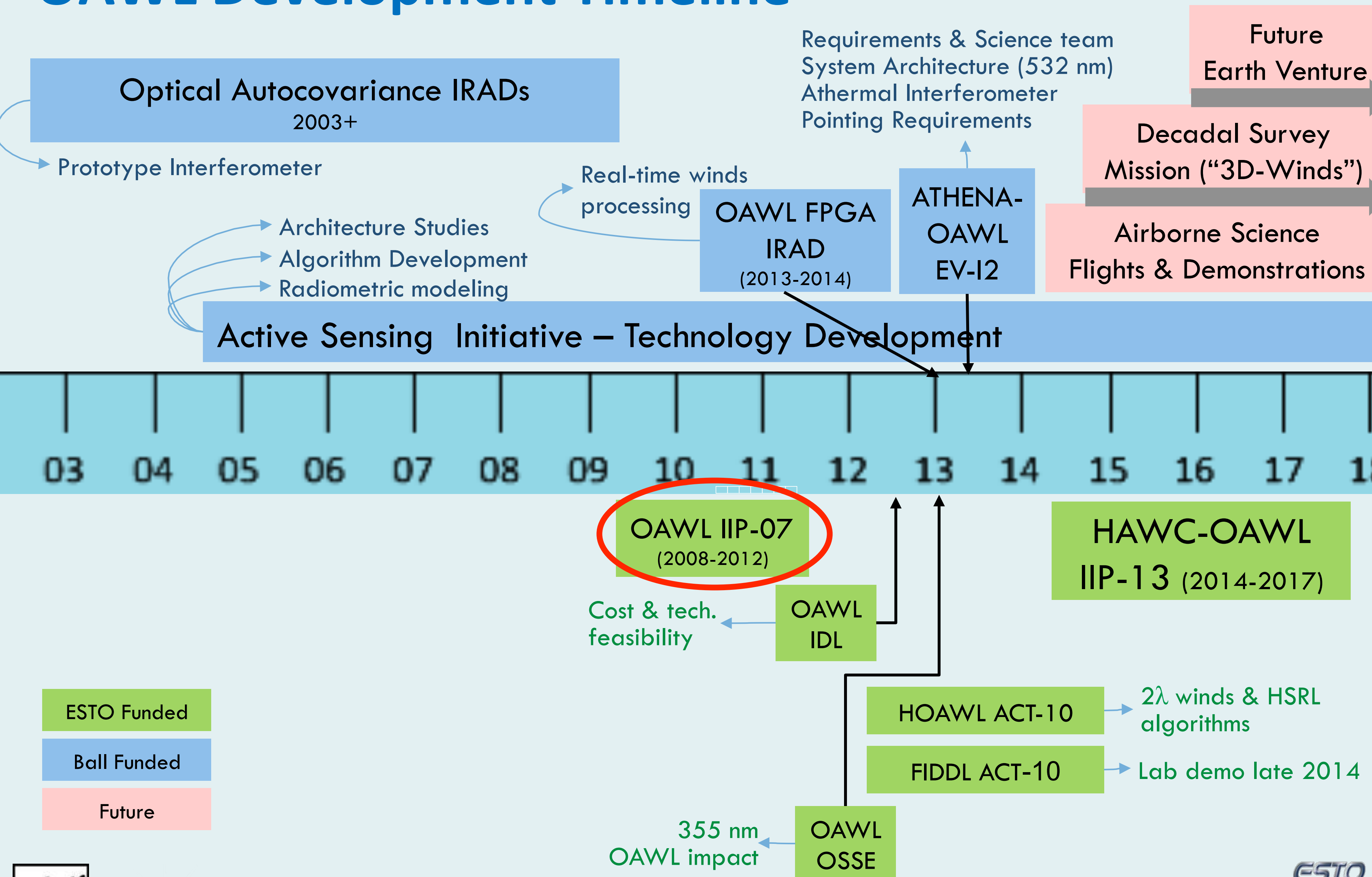
- Fringes wrap – no "out of band" concerns, no laser pulse-to-pulse stability req.

- The phase difference $\Delta\phi$ is related to the line-of-sight wind speed, V_{LOS} by

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



OAWL Development Timeline

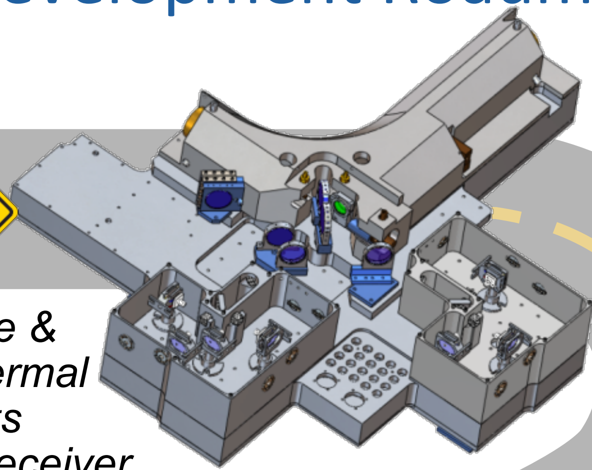


OAWL IIP-07 Development Roadmap

ENTER TRL 2.5

IRAD developed, Field Widened, Mach-Zehnder Interferometer Receiver

Vibe & Thermal tests of receiver



Turn the OAWL receiver into a wind lidar system

(add laser, telescope, COTS data acquisition, autonomous operation software, and wind processing algorithms)

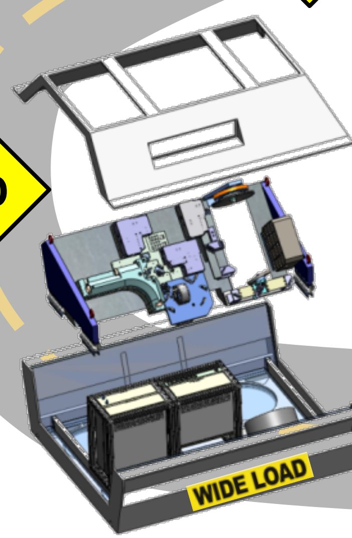
TEST

Ground Validations w/ NOAA DWL: TRL4

BUILD

Build, and certify breadboard level components for aircraft flight

(frame, vibration isolation, optical window assembly, thermal controls, and autonomous control software → in the WB-57 pallet)



*Challenge: Demonstrate OAWL concept & measurements, operating **autonomously** from the NASA WB-57 aircraft*

TEST

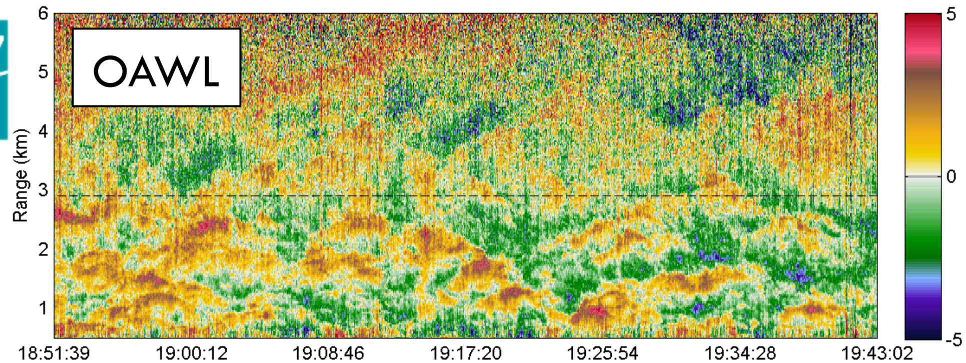
IIP-07 EXIT

System Description: OAWL

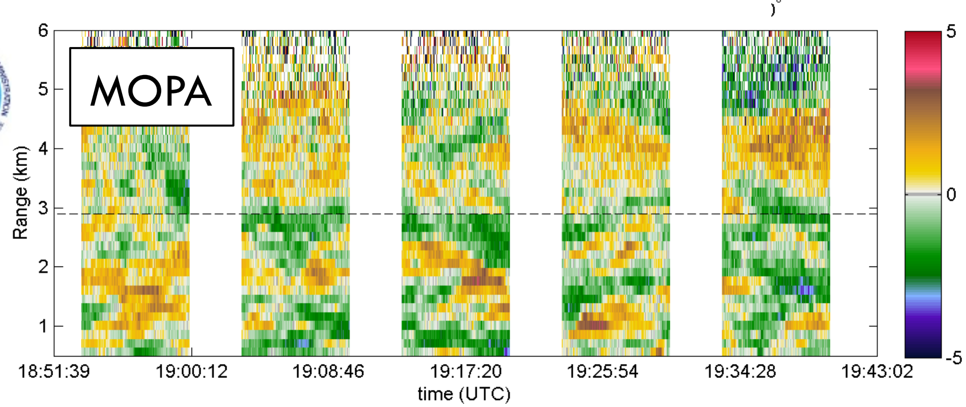
Parameter	OAWL –IIP	HOAWL/HAWC-OAWL
Wavelength	355 nm	355 nm & 532 nm
Laser power (pulse energy, PRF)	~4W (~20 mJ/ 200 Hz)	~4W/[illegible]available (532 attenuated for eye-safety)
Effective Telescope Diameter (with Obscuration)	~25 cm	~same/TBD
Interferometer OPD	~0.9 m	Same interferometer
Views	Ground: horizontal Airborne: 45^{o} off nadir, starboard	Ground: horizontal Airborne: two looks, 45^{o} off nadir, 90^{o} azimuth separation

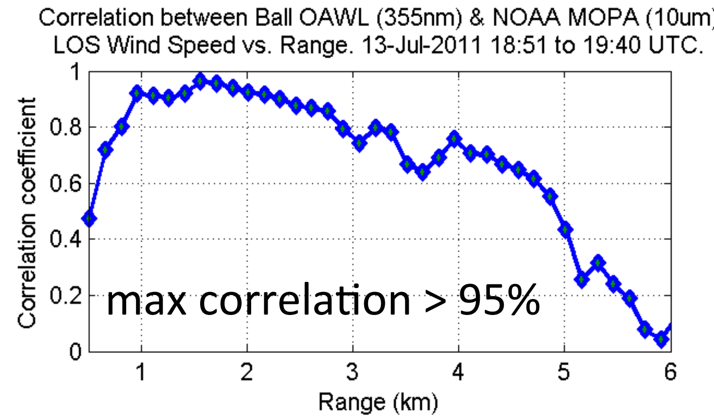
OAWL July 2011 Ground Validation

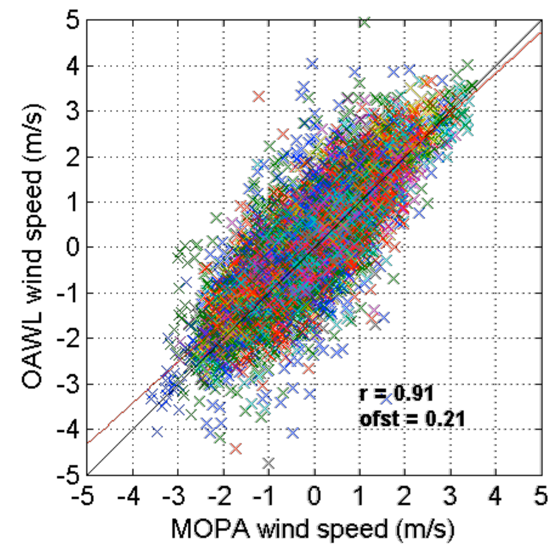
with NOAA's Active Remote Sensing Group



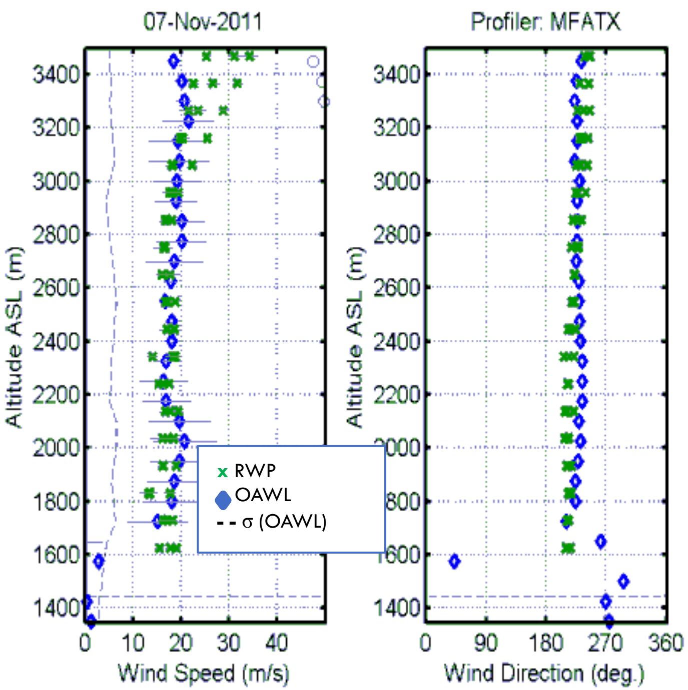
50 minutes

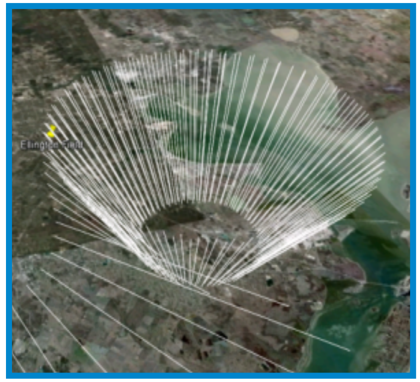


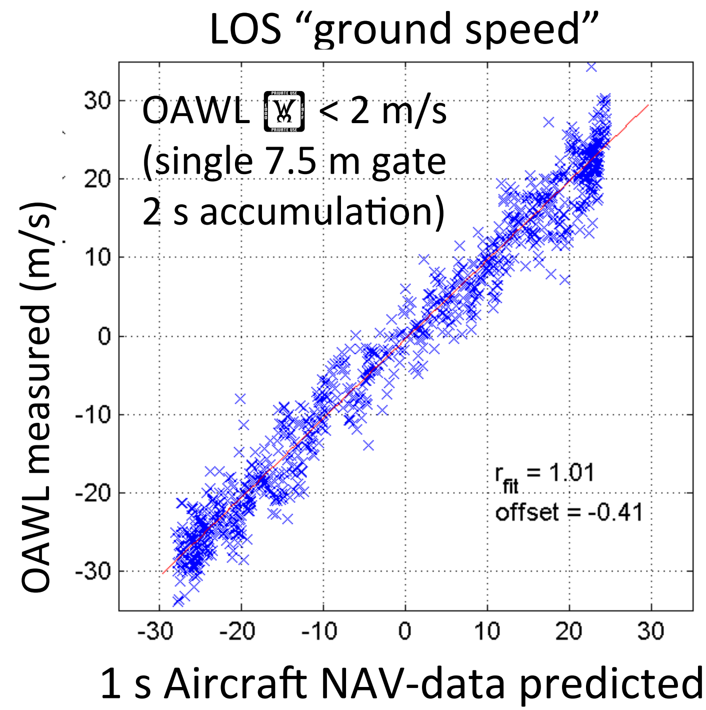




2011 Autonomous OAWL Flight Tests: NASA WB-57







Breadboard OAWL Airborne Demonstration:

- **autonomous operation**
- **measured Doppler shifts** from ground, clouds and aerosols (winds).

OAWL Sound Bites: parts of the big picture

ESTO-funded Advanced Component Technology (ACT) Tasks

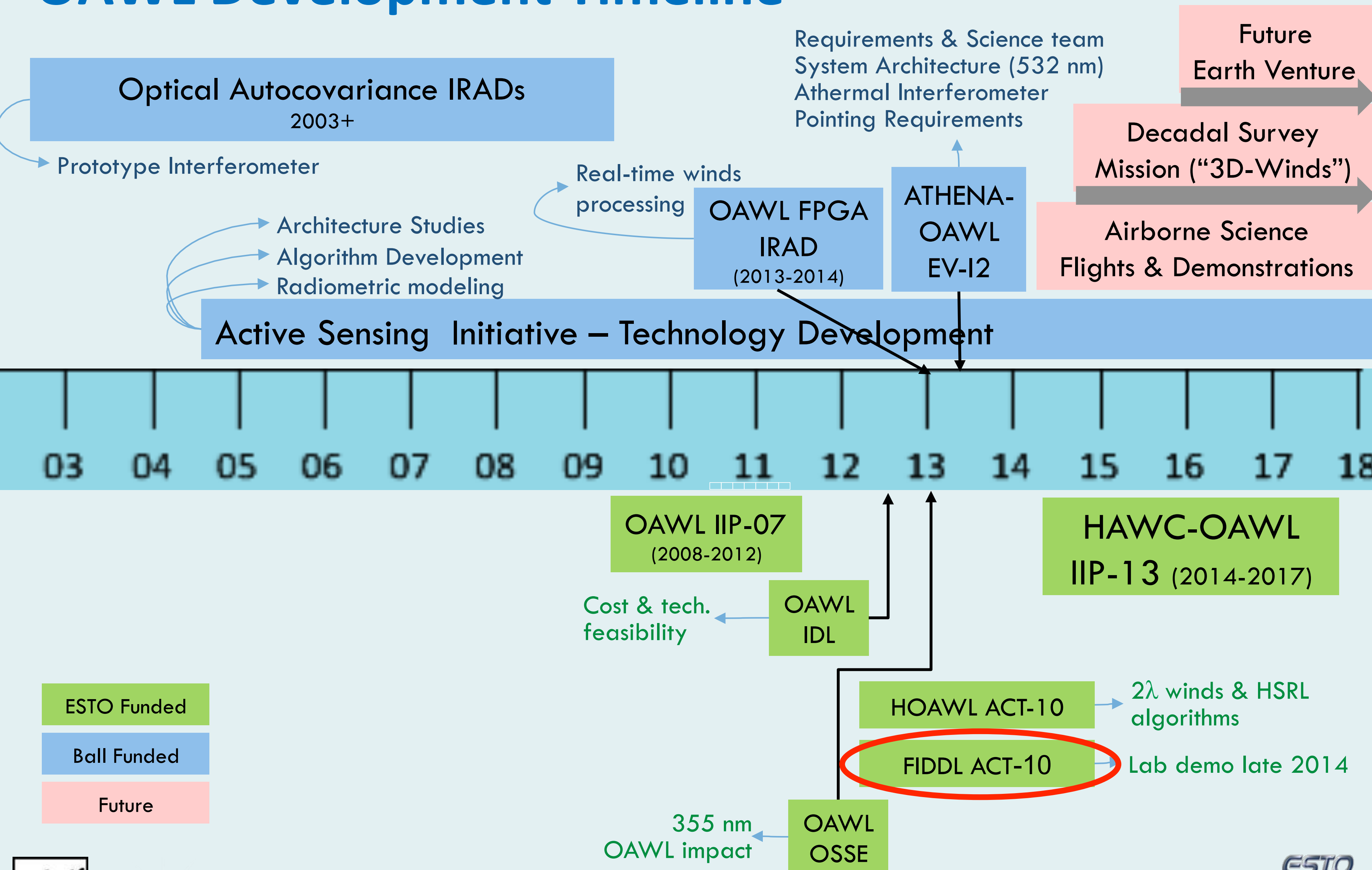
FIDDL: Fabry-Perot for the Integrated Direct Detection Lidar

- **Operating at 355 nm** → build a molecular component to pair with the 355 nm OAWL aerosol winds system
  - Aerosol & molecular channels use same UV laser, same telescope
  - Aerosol + molecular returns together cover more of the atmosphere - can use overlapping data to refine winds

HOAWL: High Spectral Resolution Lidar using OAWL

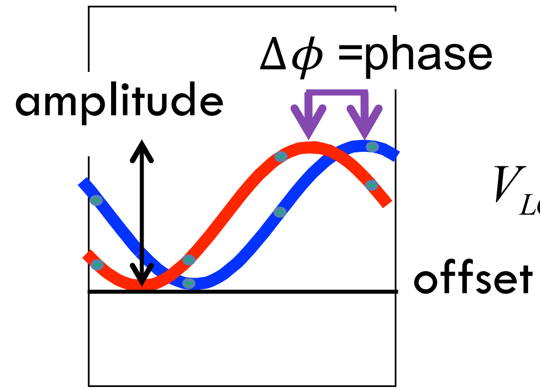
- **Operating at both 355 *and* 532** → the aerosol OAWL system provides information about atmospheric aerosol ratios: HSRL
  - Single laser can provide both wavelengths
  - Double the aerosol winds, and add HSRL measurements.
  - Result: Aerosol transport → chemical weather

OAWL Development Timeline

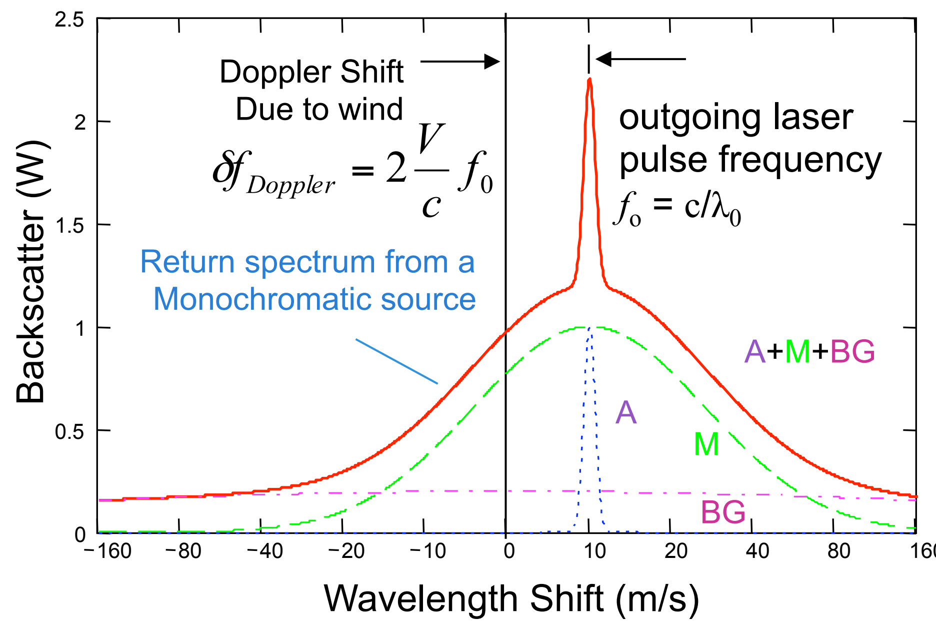


Atmospheric lidar return

- OAWL Mach-Zehnder interferometer fringe contrast depends on the illumination.
- Aerosol backscattered laser return has a narrow bandwidth → good fringe contrast in the interferometer
- Doppler broadened Molecular return has a wide bandwidth → adds offset, no fringe

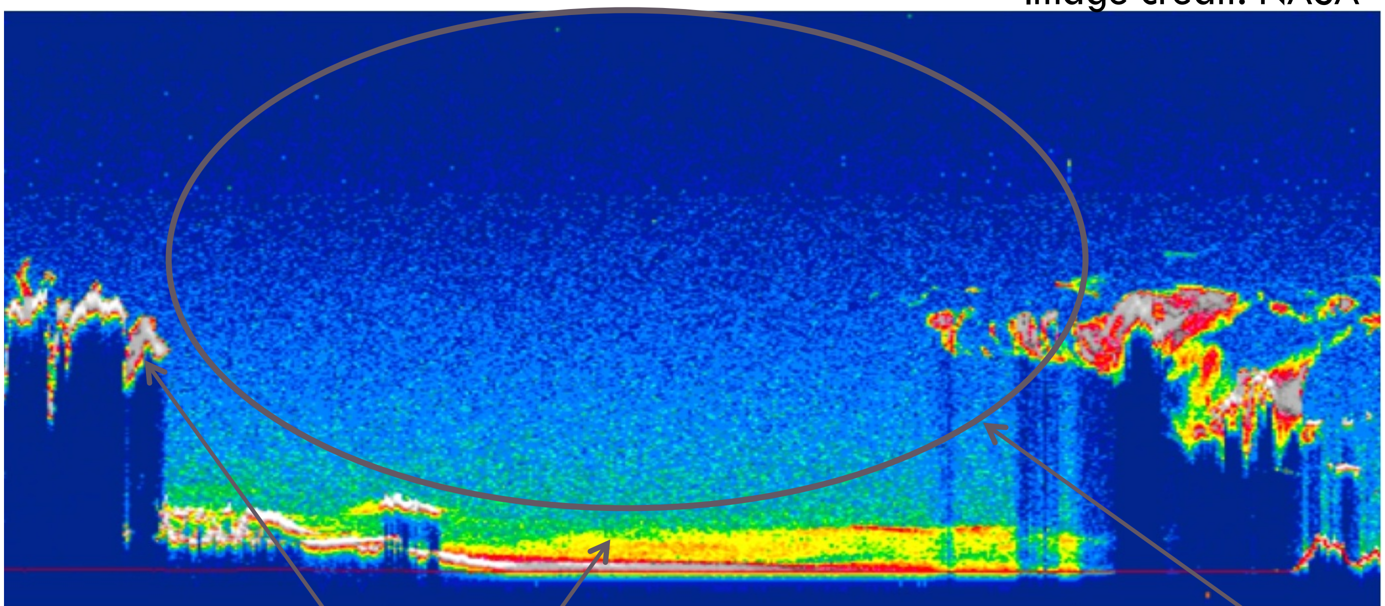


$$V_{LOS} = \frac{\Delta\phi\lambda c}{2\pi(2OPD)}$$



Aerosol vs. molecular wind lidars

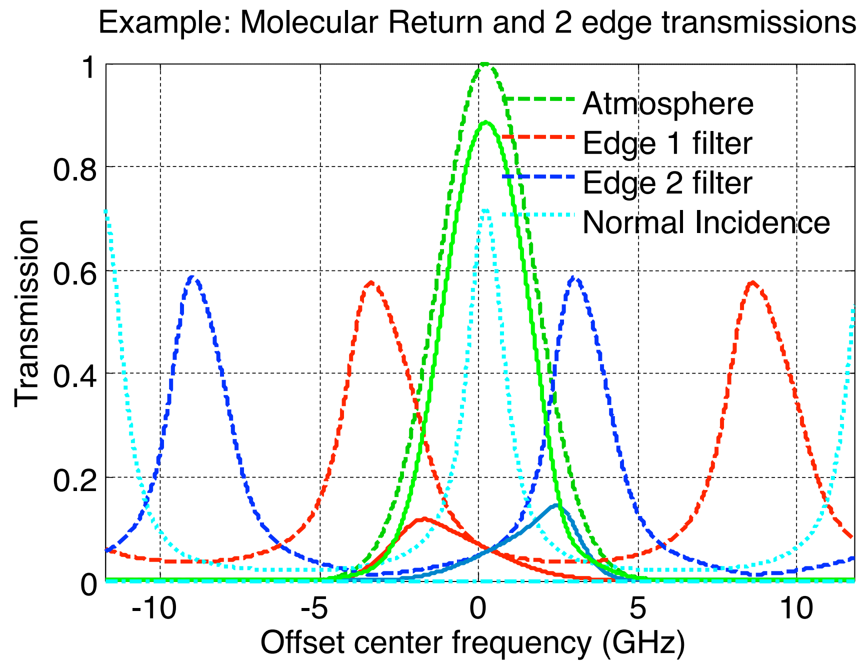
Image credit: NASA



- Aerosol wind lidars
  - Less opportunity for backscatter.
  - Higher precision measurement (narrow bandwidth).
- Molecular wind lidar
  - More opportunity for backscatter
  - Lower precision measurement (wide bandwidth from the Doppler-broadened molecular backscatter)

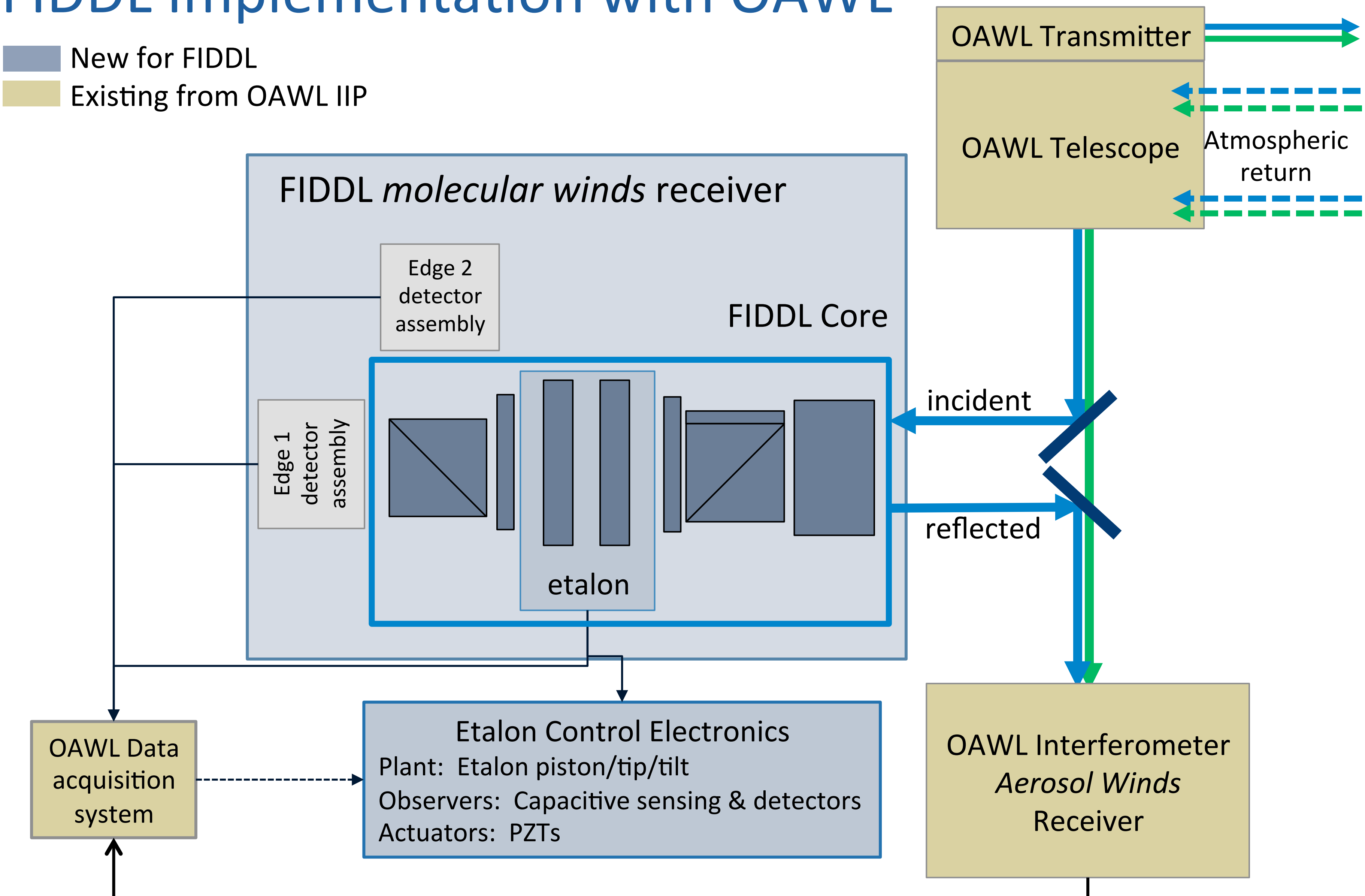
FIDDL

- A Double-Edge, Fabry-Perot, Doppler lidar receiver that "passes" the aerosol portion of the lidar return spectrum to OAWL.
  - FIDDL uses 355 nm *molecular* returns
  - OAWL uses the 355 nm *aerosol* returns (reflected from FIDDL)



- Provide precise etalon gap control for the double-edge approach
  - <0.025% FSR at 355 nm (@ 100's Hz rate)
  - Translates into <0.5 m/s error *before* any pulse accumulation.
- Demonstrate alternative approach to achieving two edge filters
  - Angle tuning and polarization → 2 edges out of a single aperture/etalon
  - Allows for smaller optic, or larger field of view on a single larger optic.
    - 1" etalon aperture, etalon finesse ~=9

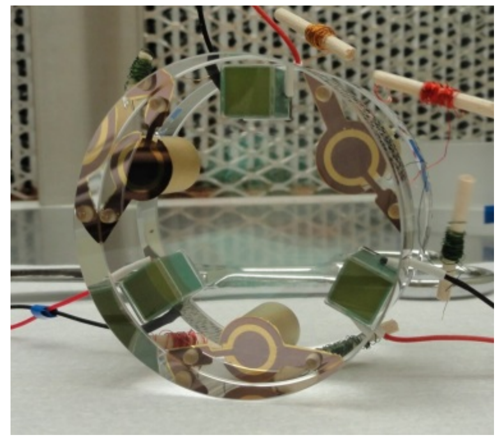
FIDDL Implementation with OAWL

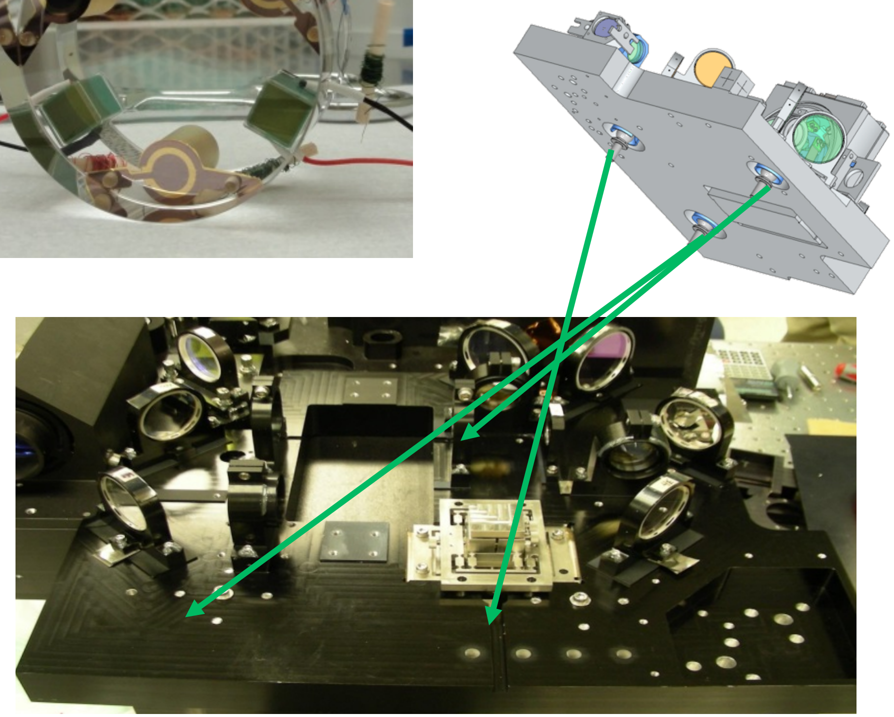


FIDDL ACT Summary

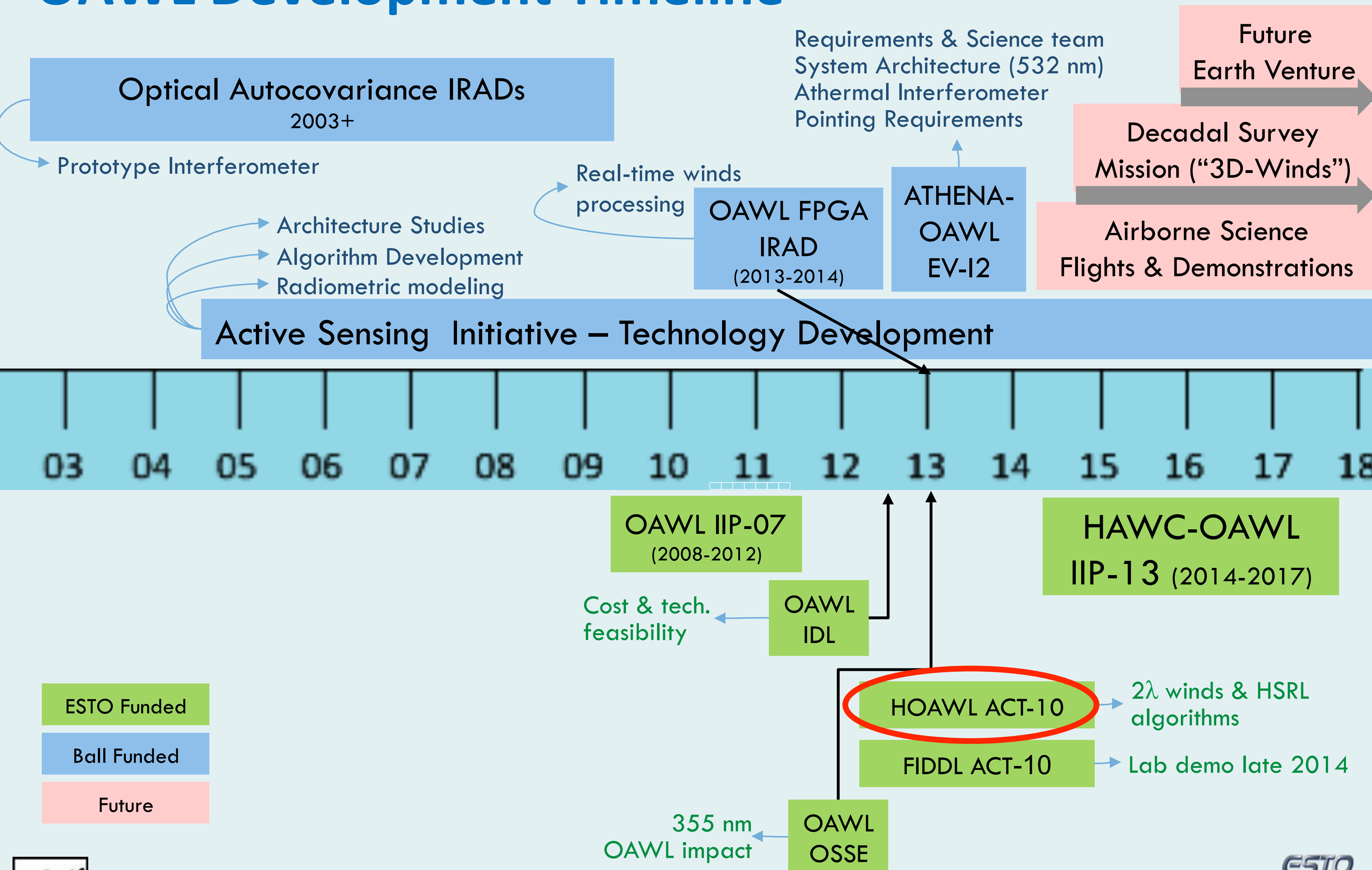
- **Electrical**
  - Boards & cabling designed, built, and tested
  - Demonstrated low-noise capacitance measurement(<6aF at kHz rate)
  - Integration with etalon in progress
- **Optical**
  - Etalon delivered (>4 mo. delay)
    - Returned for rework: shorted capacitive sensors due to poor gold plating.
    - Electrical checkout complete – caps at 20-24 pF vs. ~15 planned)
  - Optical system (up to etalon) aligned.
- **Mechanical:**
  - Etalon housing and Bench w/ Kinematic mount for attaching to the OAWL bench

- **Up Next: Final Integration, Testing, & Winds Demonstration**



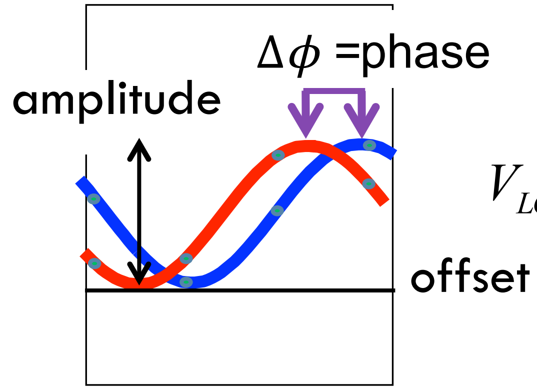


OAWL Development Timeline



Atmospheric lidar return - again

- Narrow-bandwidth aerosol return has a narrow bandwidth → fringe
- Doppler broadened molecular return has a wide bandwidth → adds offset, no fringe
- Products:
  - Phase of fringe → wind speed
  - Amplitude of fringe →aerosol portion
  - Offset of fringe → molecular portion (no wind information)



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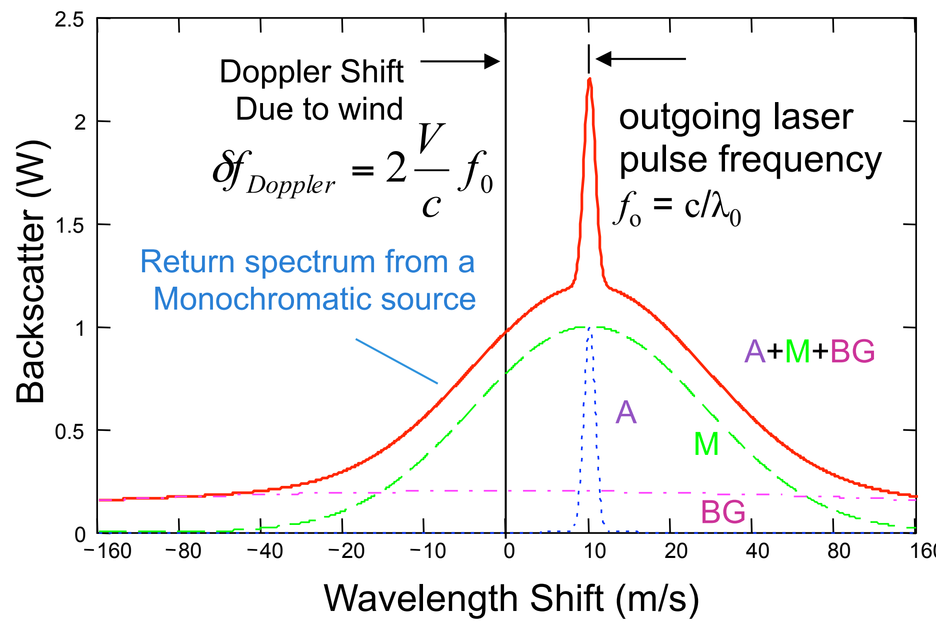
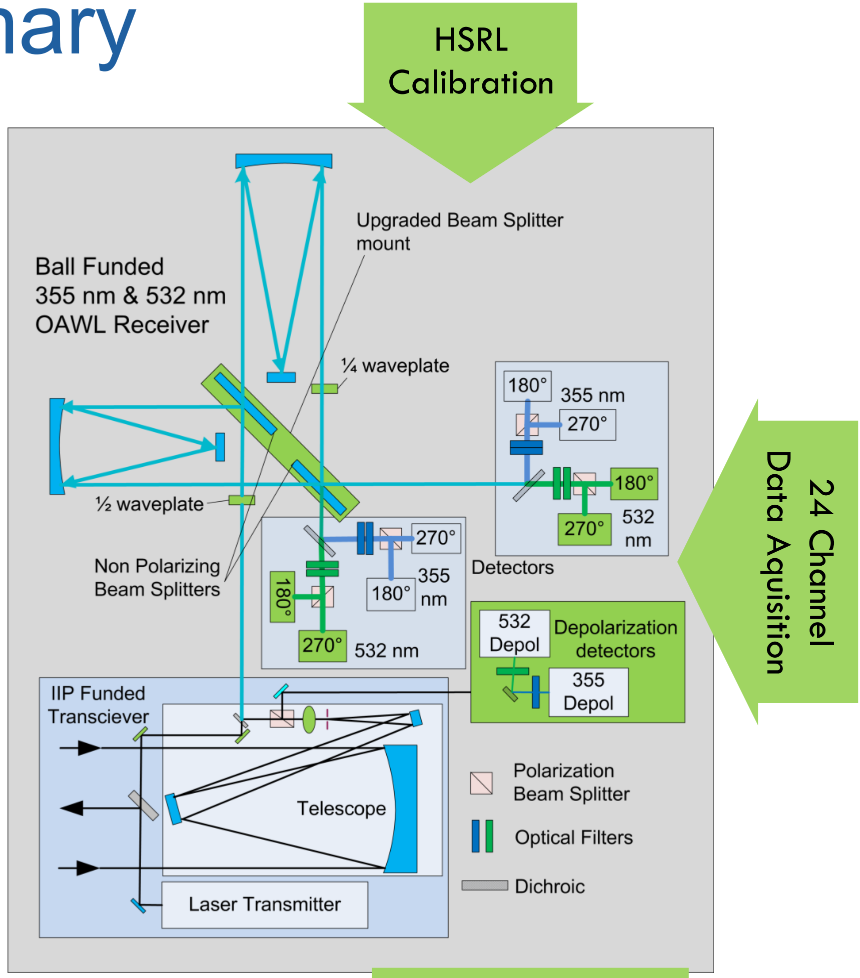


HOAWL Executive Summary

- High Spectral Resolution Lidar with OAWL
- The HOAWL ACT adds 532 nm wavelength & HSRL retrievals to OAWL 355 nm aerosol winds
  - Potential Aerosol + Winds mission combinations
  - New data products for science community: Transport information = Chemical Weather
- Built on all the OAWL IIP Hardware
  - Upgraded components to measure at both 355 nm AND 532 nm wavelengths
  - Established HOAWL error budgets and calibration factors for HSRL products
  - Developed algorithms for HSRL retrievals



Wind speed
HSRL: 2β + 2α + 2δ
532 nm & 355 nm

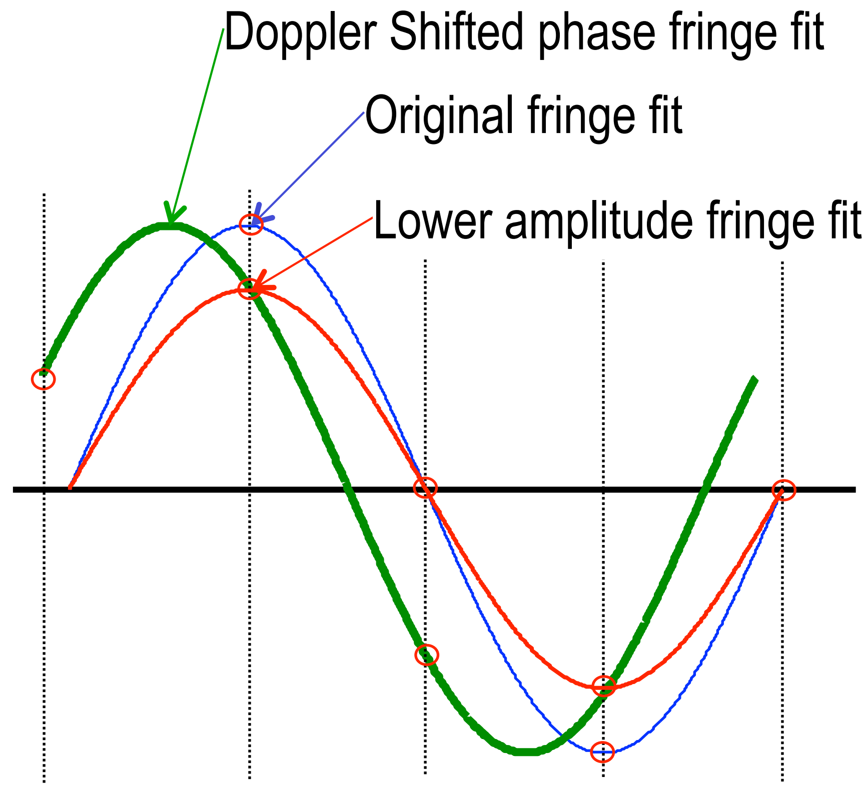
HSRL & Winds

OAWL fringe fitting: 2+2 = winds + HSRL

- Sampling with four (4) detectors provides the same amount of information as
  - "2" detectors for Doppler shift (e.g. double edge)
  - "2" detectors for aerosol ratio (e.g. aerosol & molecular channels)

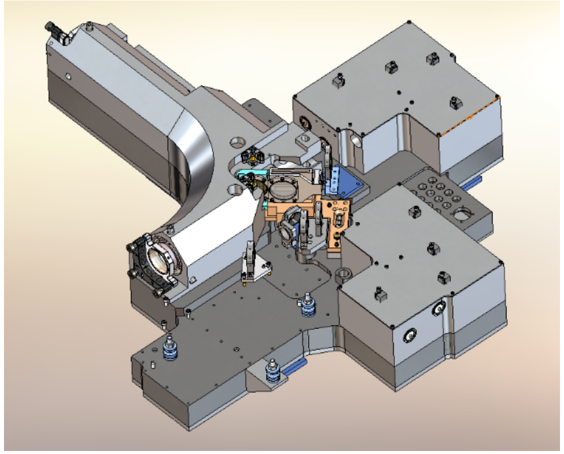
- By fitting a fringe sinusoid to four (4) points OAWL constrains the fringe measurement
  - fringe amplitude → aerosol content
    - No biases due to aerosol/molecular ratio variability
    - better HSRL = better winds measurement.

    AND
  - fringe phase → Doppler shift
    - Platform motion does not affect HSRL measurement
    - Enables off-nadir HSRL measurements (better for ocean studies)



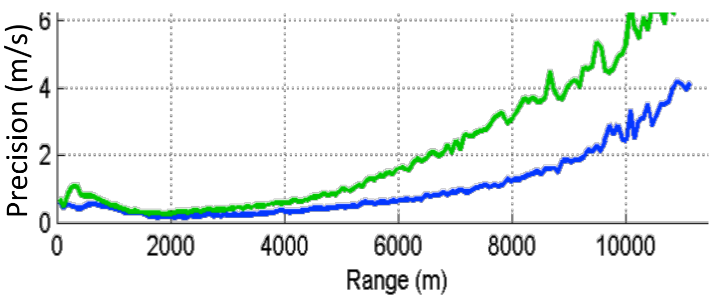
HOAWL Achievements

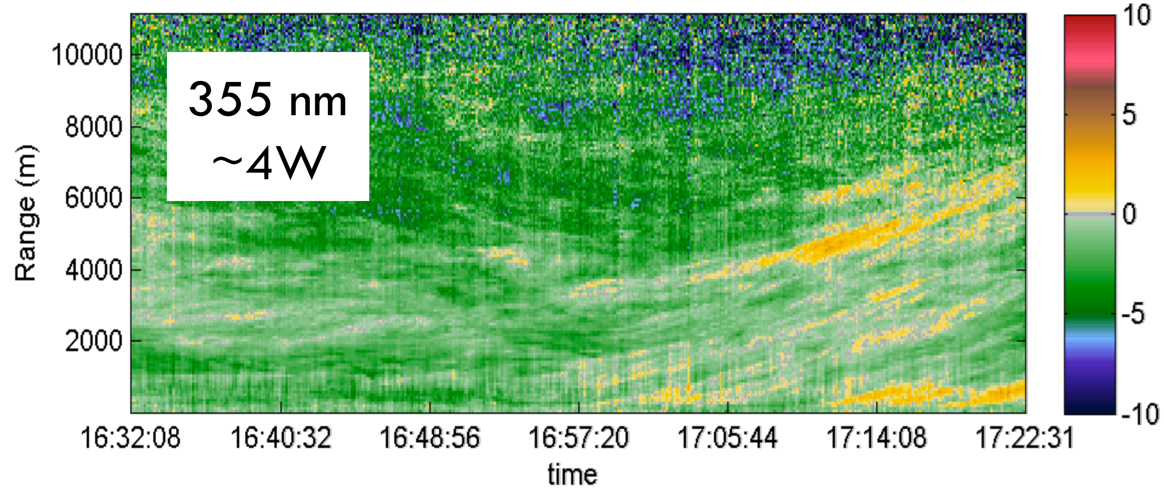
- Opto-Mechanical Rework: Designed/Built/Installed/Aligned
  - Dual wavelength collimator, dual wavelength ½ and ¼ waveplates, and time-zero path
  - New kinematic beamsplitter/beam-combiner mount
  - Installed IRAD-developed depolarization module
- Electrical Rework:
  - 532 nm and 355 nm calibrated and tuned
  - Added 2nd data acquisition card
    - 24 channels vs 10 on OAWL IIP-07
  - Identified and attenuated multiple electronic noise sources
- Modeling/Algorithms
  - Developed and tested HSRL retrieval algorithms
  - Developed full system model and error budget
  - Fed improvement requirements to HAWC-OAWL
- Testing
  - System calibration
  - Initial HSRL measurements – TRL 3
  - Preliminary validation efforts

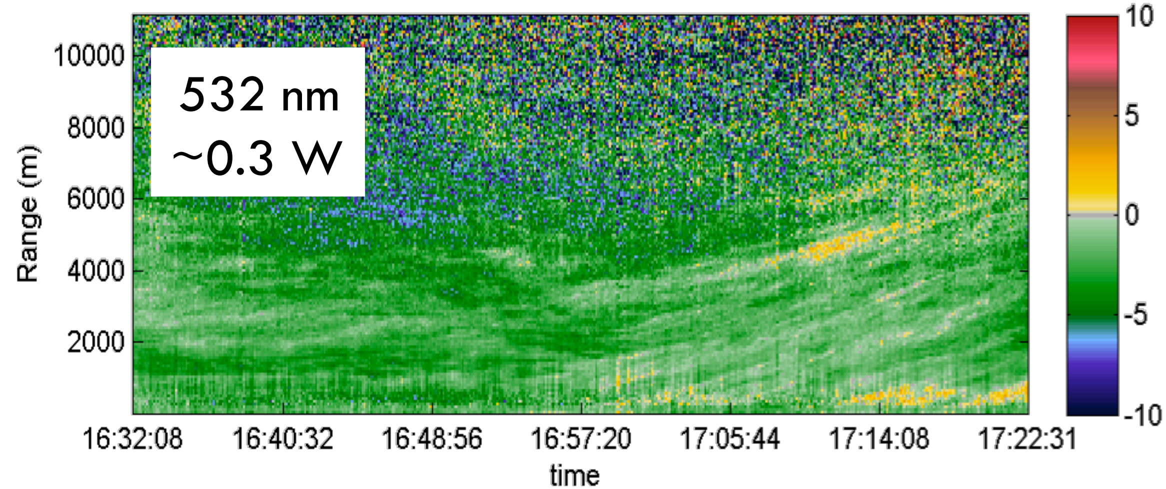


355 & 532 nm Winds: HOAWL ACT

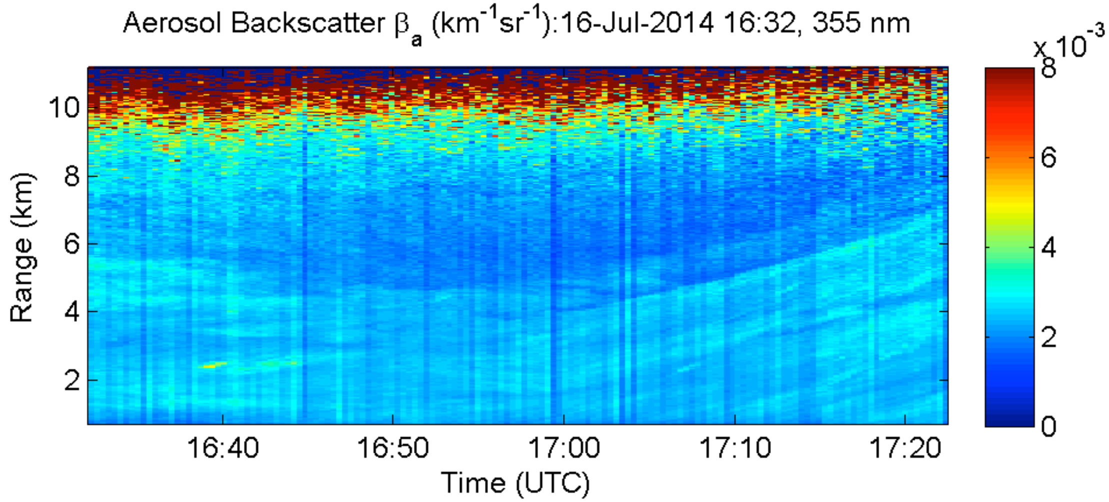
- Strong (~0.3 km^{-1}) extinction day
- Horizontal views out to > 11km (analog)
- 75m, 6s accumulation

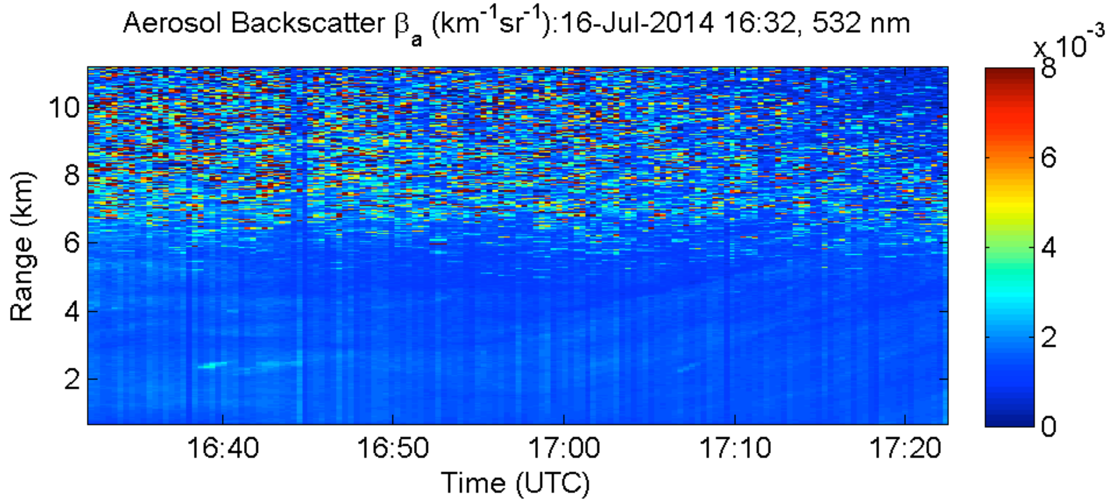






HSRL Estimates: Aerosol Backscatter

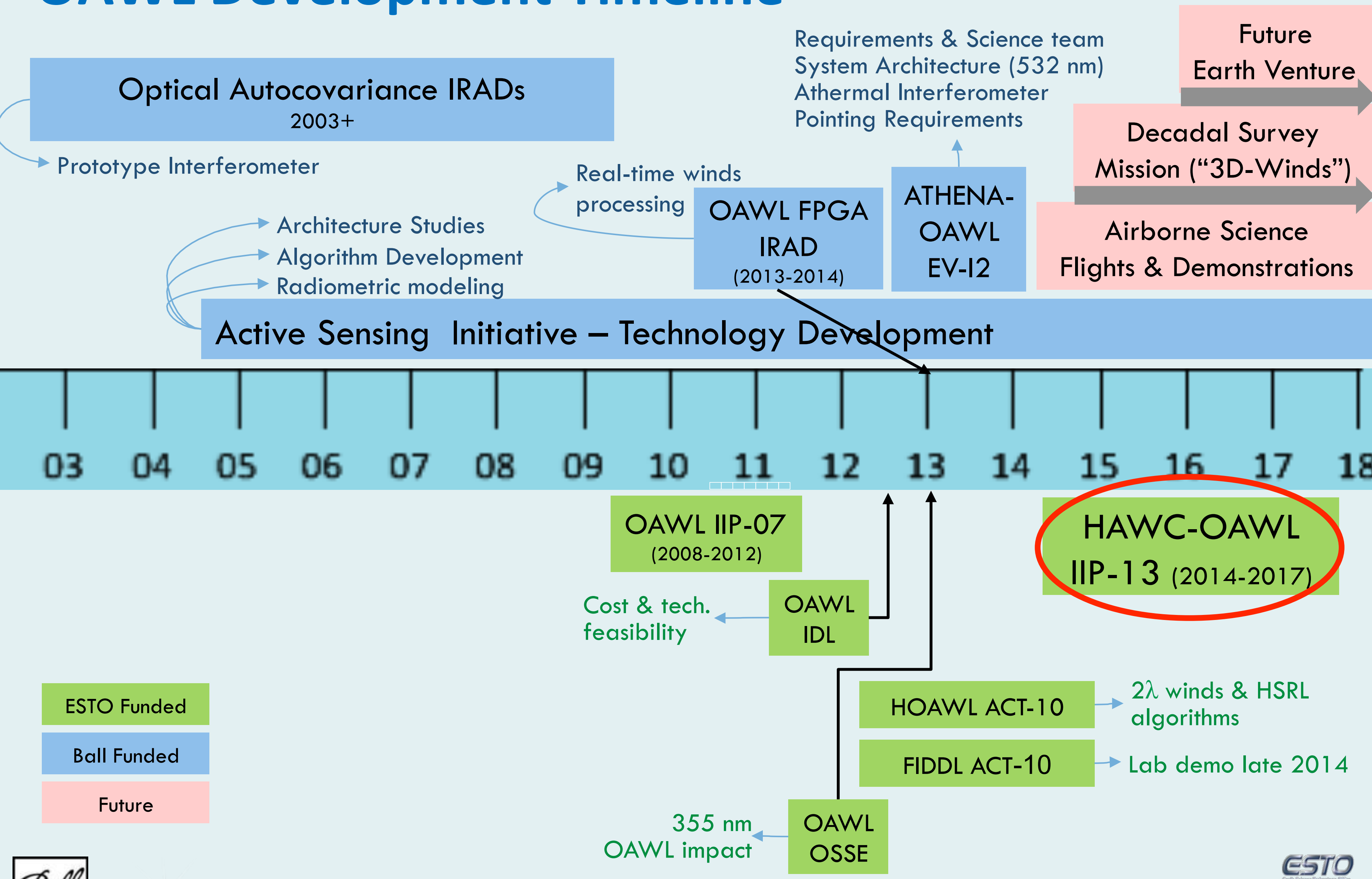




355 (top) and 532 (bottom) aerosol backscatter.

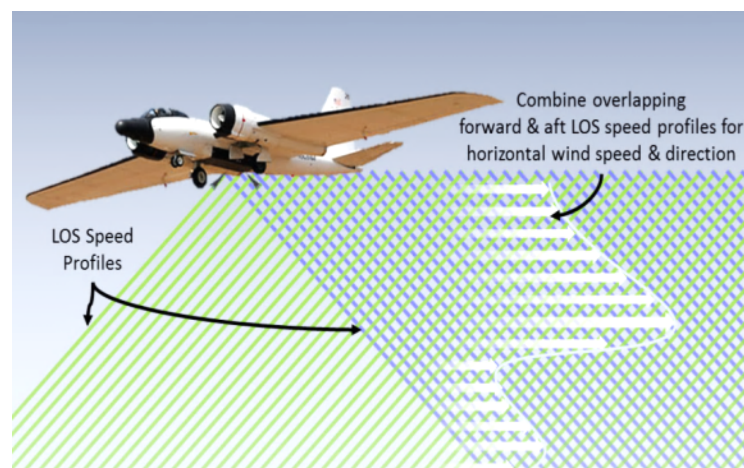
“stripes” indicate additional calibration is required

OAWL Development Timeline



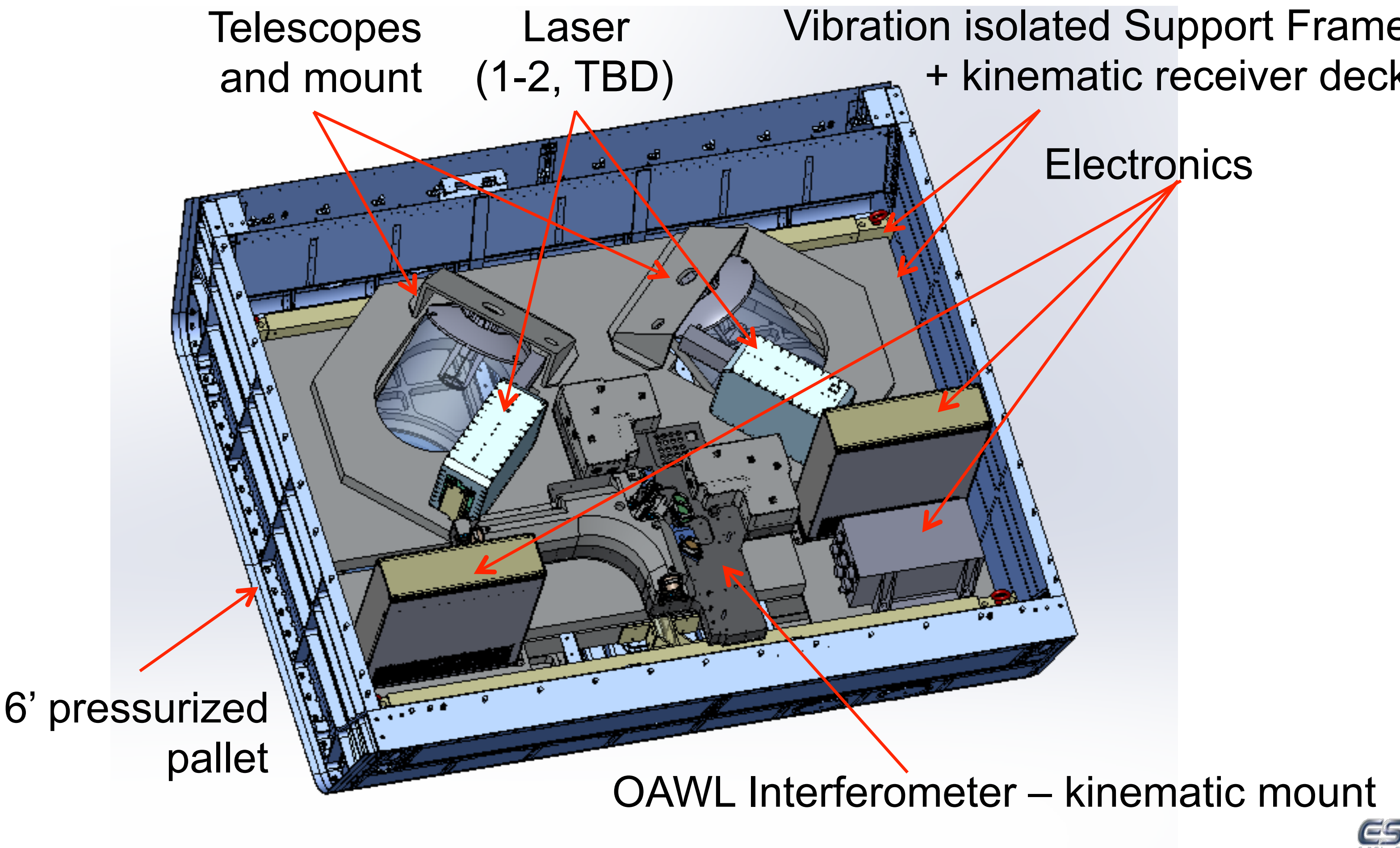
HAWC-OAWL IIP-13

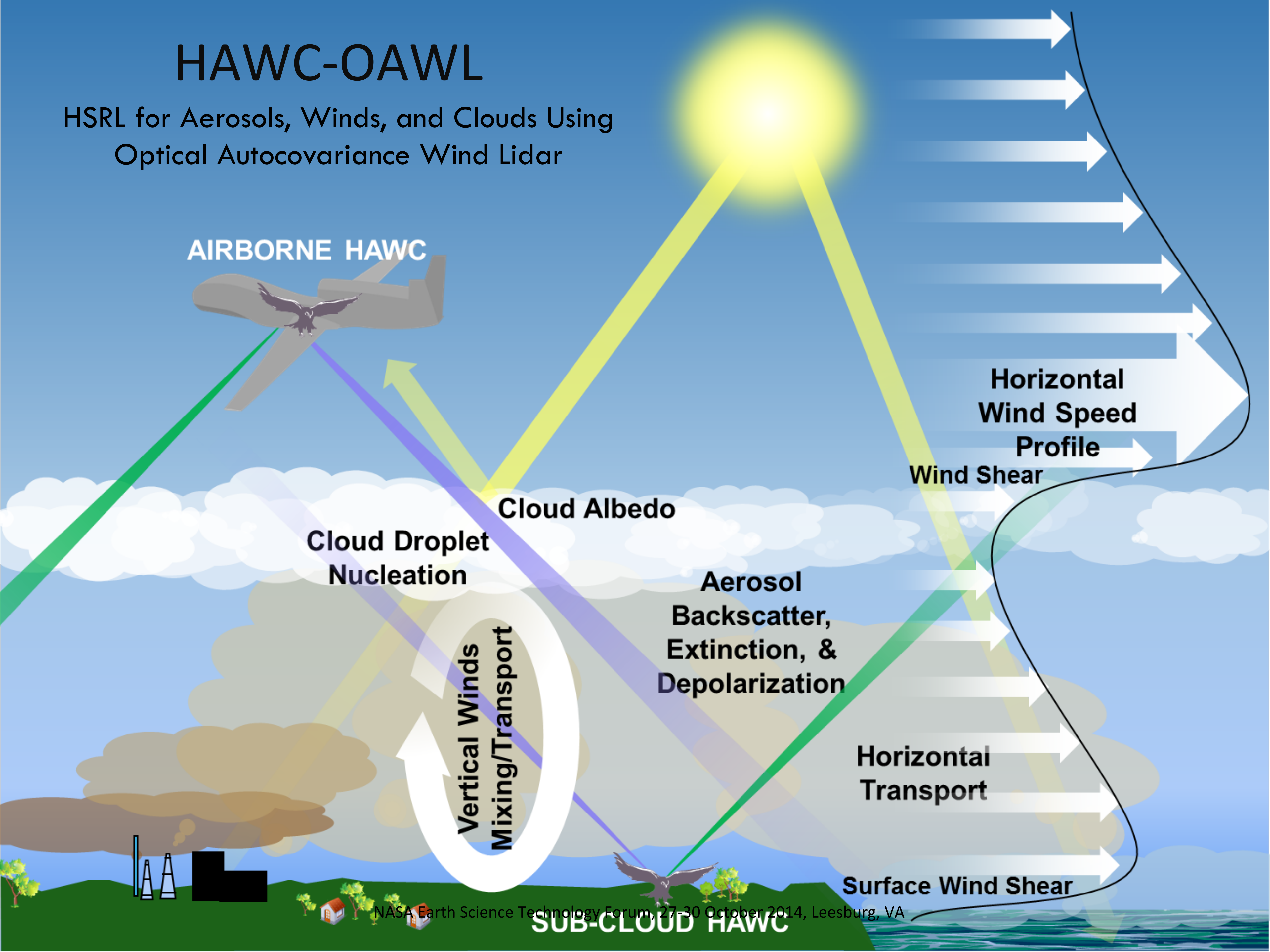
- HSRL (High Spectral Resolution Lidar) for Aerosols, Winds, and Clouds (HAWC) using Optical Autocovariance Wind Lidar (OAWL)
- **OAWL**: 355 nm & 532 nm airborne aerosol wind measurements
  - Two looks – one per wavelength
- **HAWC**: Add concurrent HSRL (aerosol) retrievals to OAWL winds
  - Cloud/aerosol backscatter ([illegible]), extinction ([illegible]), and depolarization ([illegible]) …
  - 355 and 532 nm wavelengths (color ratios)
- New Aerosol transport data products → **Chemical Weather**
  - Potential for Aerosol + Winds mission combinations



HAWC-OAWL preliminary airborne system layout

- Fit into the NASA WB-57 pressurized pallet w/ floor modifications
- Autonomous operation with pilot "eye-safety" control



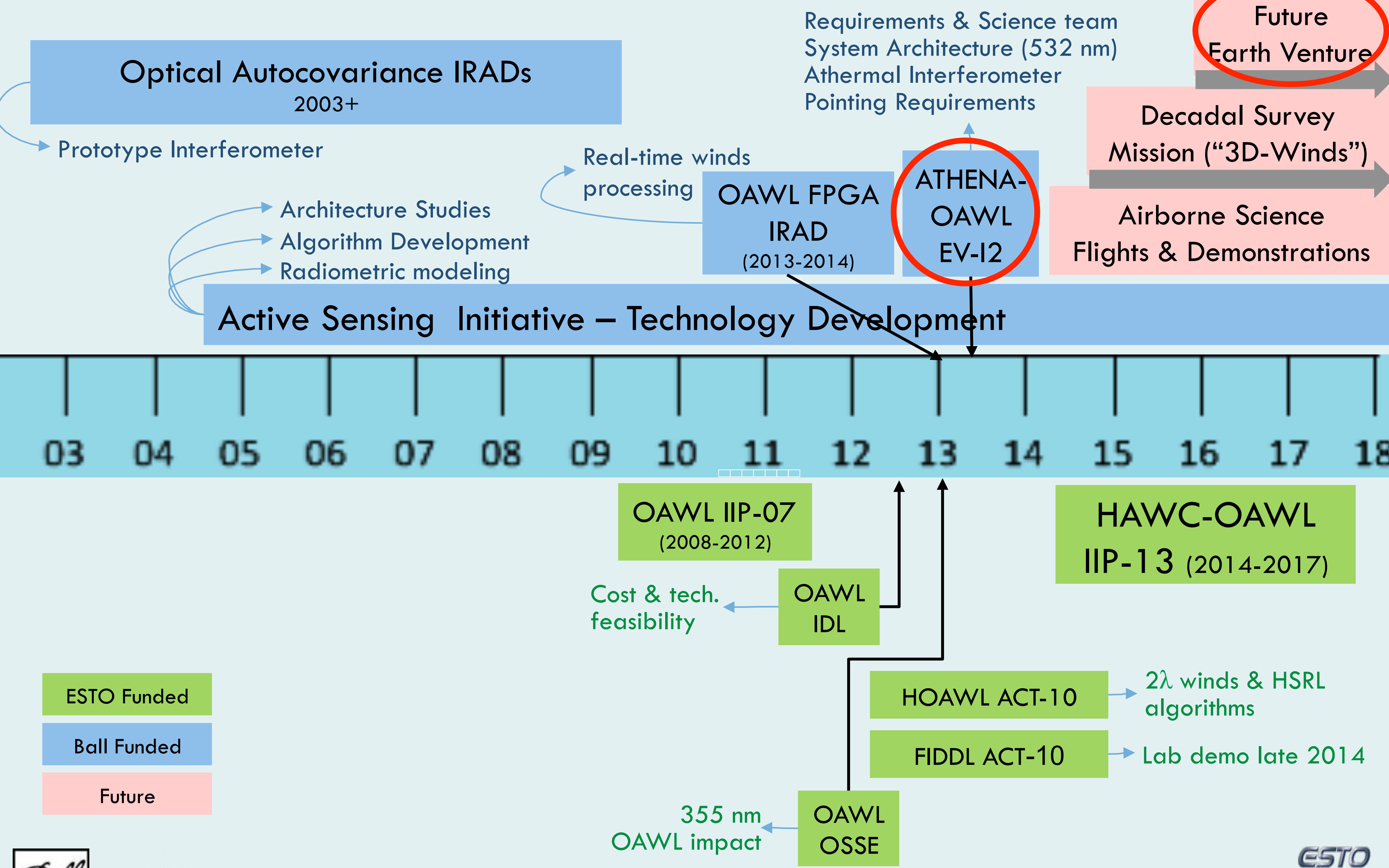

HAWC-OAWL
HSRL for Aerosols, Winds, and Clouds Using Optical Autocovariance Wind Lidar
AIRBORNE HAWC
Horizontal Wind Speed Profile
Wind Shear
Cloud Albedo
Cloud Droplet Nucleation
Aerosol Backscatter, Extinction, & Depolarization
Vertical Winds Mixing/Transport
Horizontal Transport
Surface Wind Shear
SUB-CLOUD HAWC

HSRL + Winds = Aerosol Transport Lidar

- HAWC-OAWL to measure Winds *and* Aerosol properties
  - Wind & Aerosol properties in one measurement
  - Partner with NCAR and Langley scientists to develop products

- Applications
  - Pollution transport & allocation
  - Weather AND pollution forecasts
  - Atmospheric rivers (Possible collaboration w/ NOAA G-IV for this)
  - Fire monitoring, control
  - Wind shear, turbulence, and wake vortex alerts - near airports
  - Relationships between surface conditions and clouds
  - Turbulence & aerosol impact
  - Mixing vs. mixed layer heights
    - Pollution emission studies
    - Understanding of layering and transport

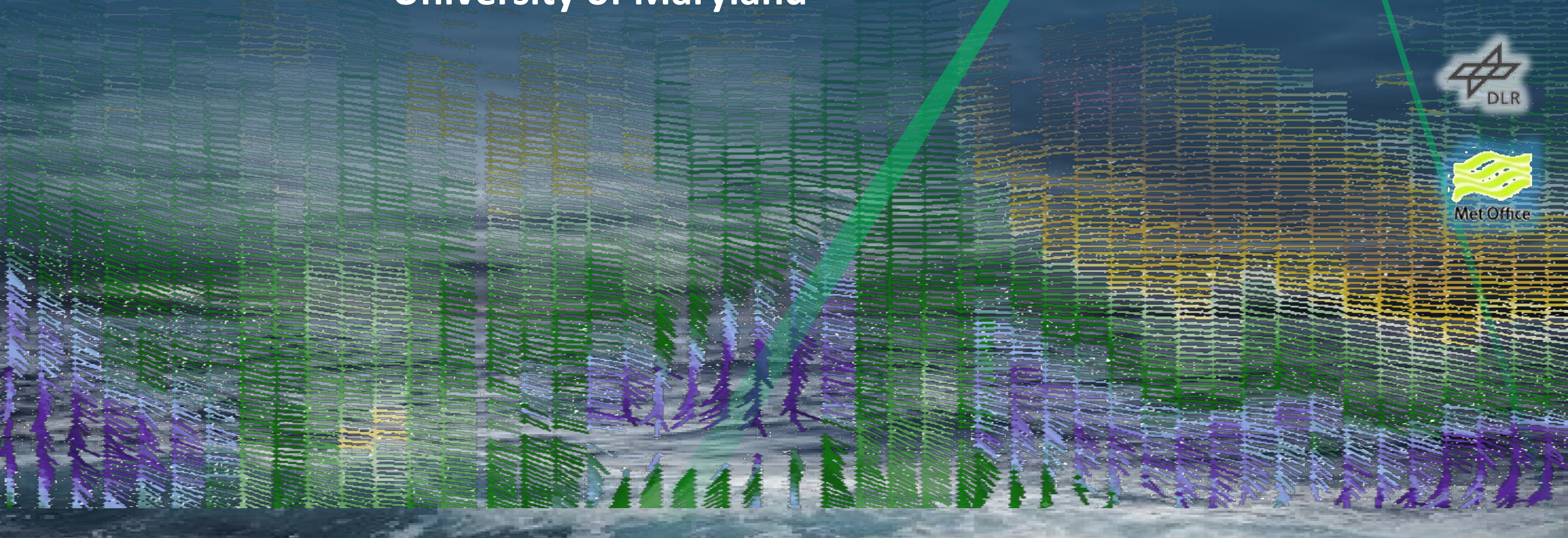
OAWL Development Timeline



ATHENA-OAWL

Atmospheric Transport, Hurricanes, and Extratropical Numerical weAther prediction using the Optical Autocovariance Wind Lidar

PI: Dr. Lars Peter Riishojgaard
University of Maryland



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

- ATHENA-OAWL: Design-to-cost approach based on heritage systems (e.g. CALIPSO lidar components, Fibertek Lasers, Star Trackers, etc.)
- Co-located wind and aerosol profiles
- Mission Objectives:
  - 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.
- NASA, NOAA, DoD, and International team members
- Proposed to NASA's 2013 Earth Venture Instrument (EV-I) Opportunity
  - GEDI won this round
  - ATHENA-OAWL airborne demonstrator a possibility: two 532 nm lasers, two looks

Summary

- **OAWL-IIP-07** demonstrated the Optical Autocovariance approach through
  - First full system development
  - Ground validation
  - Preliminary Autonomous Flight tests
- **FIDDL and HOAWL –** advancing understanding of the OAWL system and its wind + HSRL capabilities at 355 nm and 532 nm wavelengths.
- **HAWC-OAWL IIP-07** will demonstrate the two-look, two wavelength (355 & 532 nm) aerosol winds + aerosol properties system.
- **ATHENA-OAWL** – A **design-to-cost** approach to a pathfinder winds mission using only the 532 nm wavelength