First Demonstration of an Optical Autocovariance Direct Detection Doppler Wind Lidar (OAWL)

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June 23, 2011

ESTO IIP Grant NNX08AN36G

NASA Earth Science Technology Forum
Pasadena, CA

Acknowledgements

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Scott Edfors – FPGA code

Bill Good- Aircraft/logistics specialist

Chris Grund – PI, system architecture, science/systems/algorithm guidance, electrical engineering, lidar eng.

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Miro Ostaszewski – Mechanical Engineering

Bob Pierce - Optical Engineering

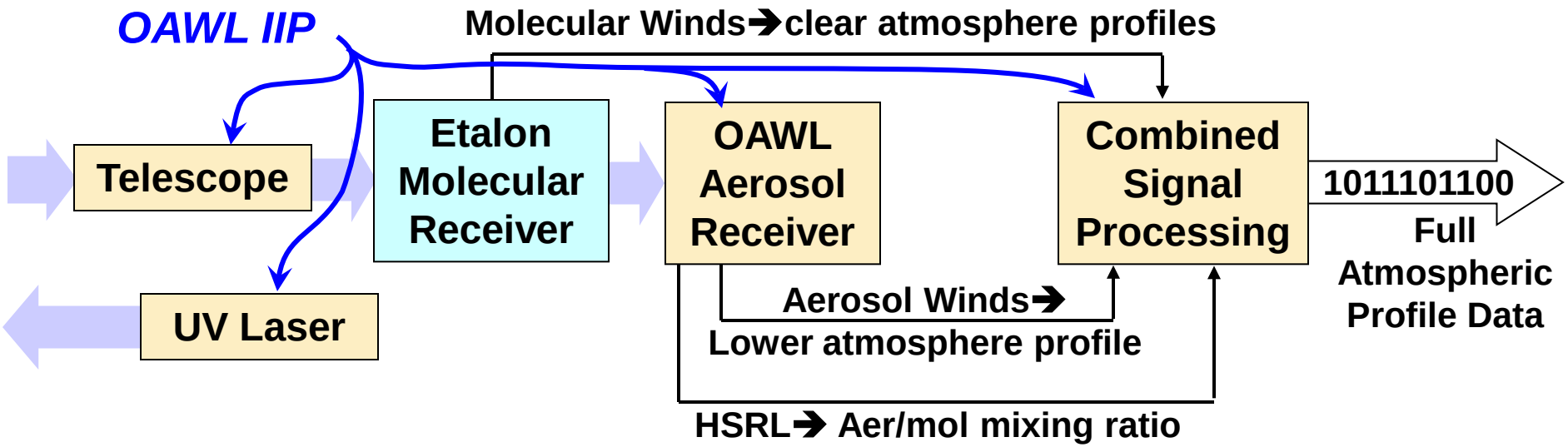
Jennifer Sheehan - Contracts

Sara Tucker – Technical Manager, Signal Processing and Algorithm specialist

Carl Weimer – Space Lidar Consultant

Support for the IIP is gratefully acknowledged under *NASA ESTO IIP grant : NNX08AN36G*

IDD: Single-laser All Direct Detection Hybrid Solution for 3D-Winds



Integrated Direct Detection (IDD) wind lidar approach:

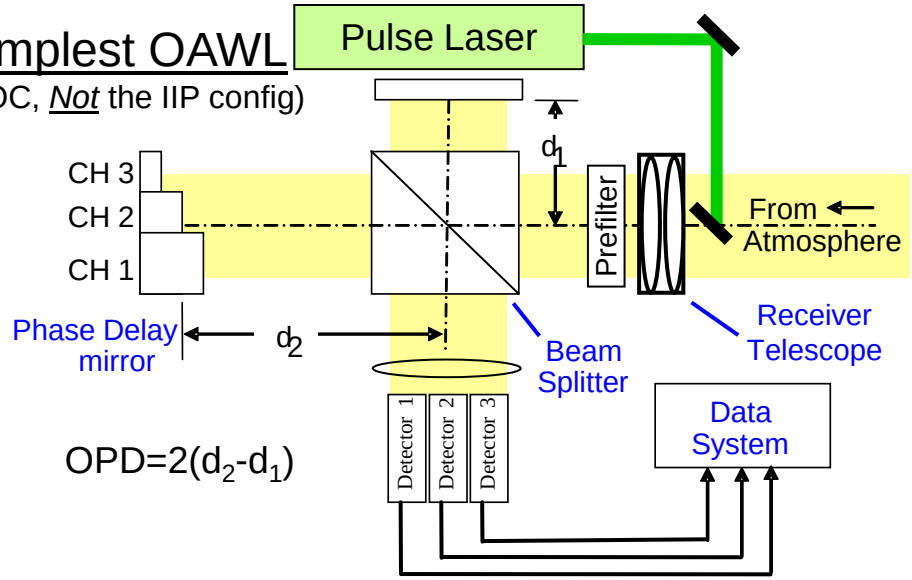
- Etalon (double-edge) uses the molecular component, but largely reflects the aerosol.
- OAWL measures the aerosol Doppler shift with high precision; etalon removes molecular backscatter reducing shot noise
- OA-HSRL retrieval determines residual aerosol/molecular mixing ratio in etalon receiver, improving molecular precision
- Result:
  - single-laser transmitter, single wavelength system
  - single simple, low power and mass signal processor
  - full atmospheric profile using aerosol and molecular backscatter signals

Ball Aerospace patents pending

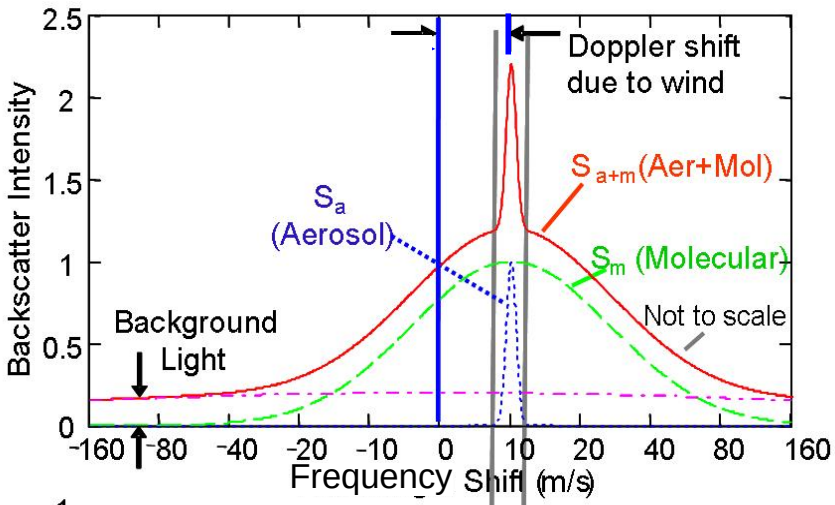
Optical Autocovariance Wind lidar (OAWL) approach

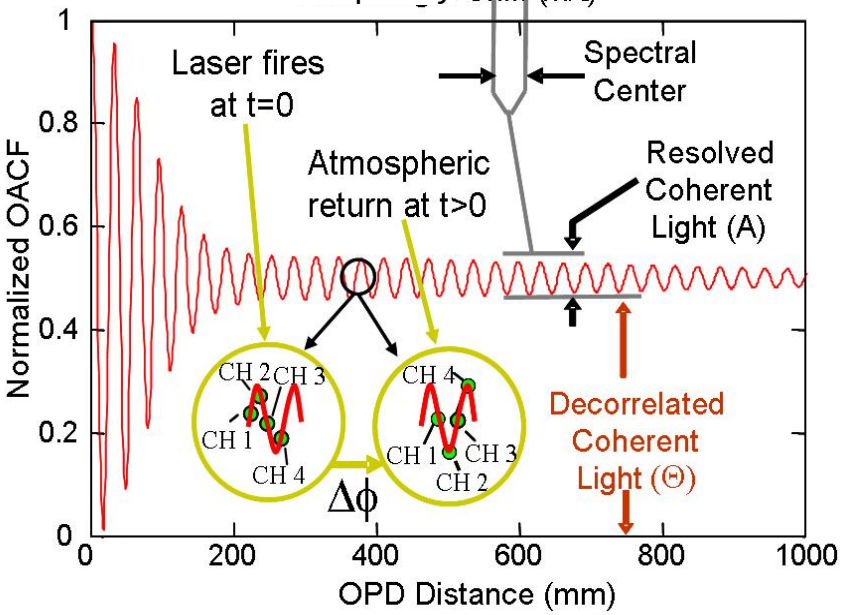
Simplest OAWL

(POC, *Not* the IIP config)



OPD=2(d_2-d_1)





Optical Autocovariance Wind Lidar (OAWL):

Velocity from OACF Phase: $V = \lambda * \Delta\phi * c / (2 * (OPD))$

OA- High Spectral Resolution Lidar (OA-HSRL):

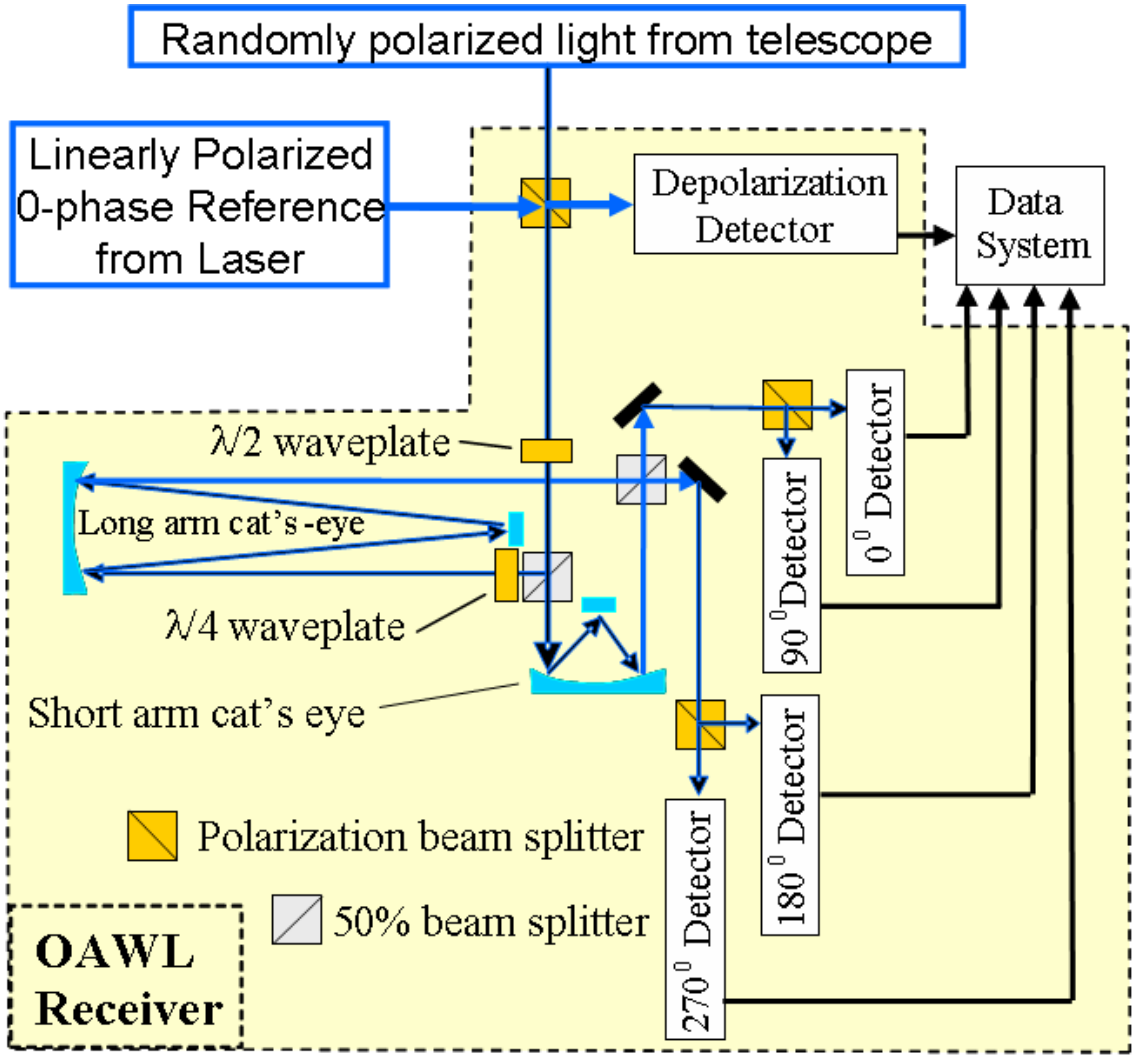
$A = S_a * C_{aA} + S_m * C_{mA}$, $\Theta = S_a * C_{a\Theta} + S_m * C_{m\Theta}$

Yields: **Volume extinction cross section, Backscatter phase function, Volume Backscatter Cross section, from OACF Amplitude**

- ***No moving parts / Not fringe imaging***
- ***Allows Frequency hopping w/o re-tuning***
- ***Simultaneous multi-λ operation***

$\Delta\phi$ = phase shift as fraction of OACF cycle

OAWL Receiver Uses Polarization Multiplexing to Create 4 Overlapping Interferometers – Field Widening to demonstrate a path to large collecting optics for space



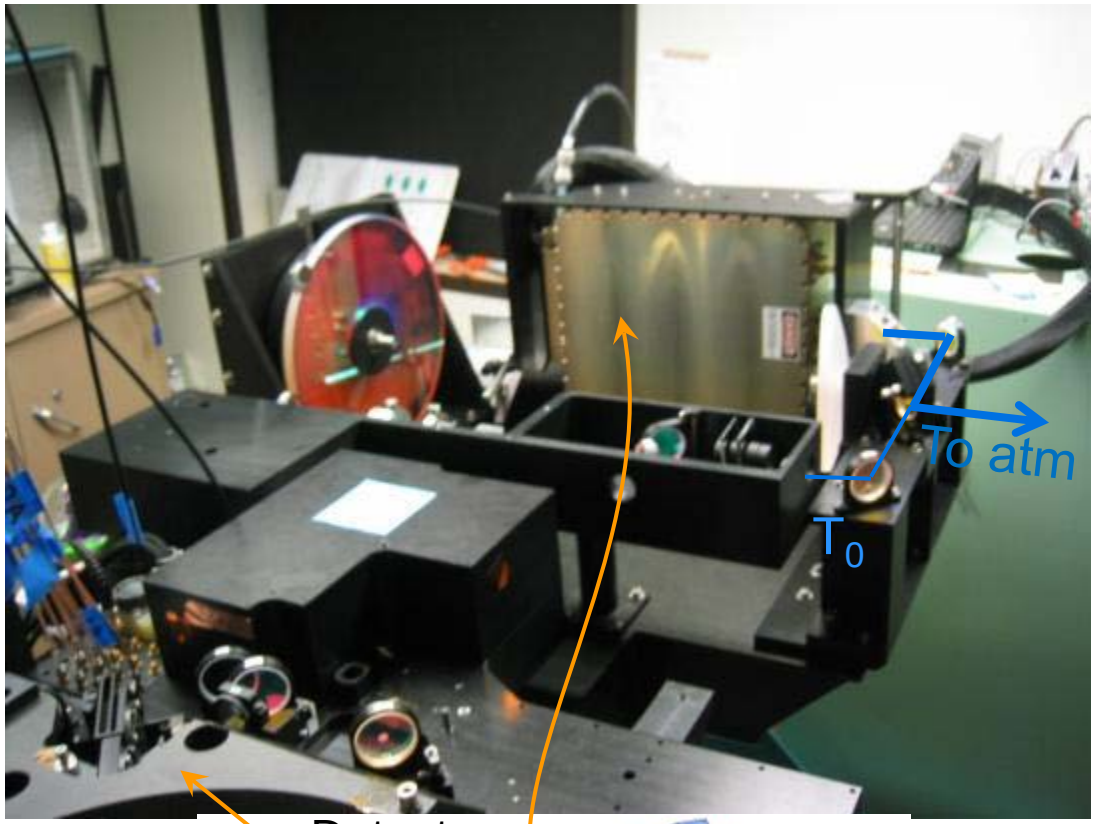
- Mach-Zehnder-like interferometer allows 100% light detection on 4 detectors
- Cat's-eyes field-widen and preserve interference parity allowing *wide alignment tolerance, practical simple telescope optics*
- Receiver is achromatic, facilitating simultaneous multi-λ operations (multi-mission capable: Winds + HSRL(aerosols) + DIAL(chemistry))
- Very forgiving of telescope wavefront distortion saving cost, mass, *enabling HOE optics for scanning and aerosol measurement*
- 2 input ports facilitating 0-calibration

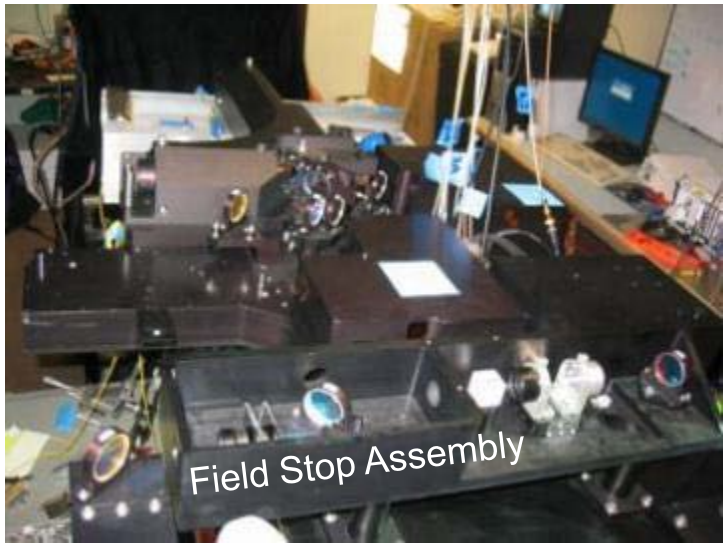
Ball Aerospace & Technologies patents issued

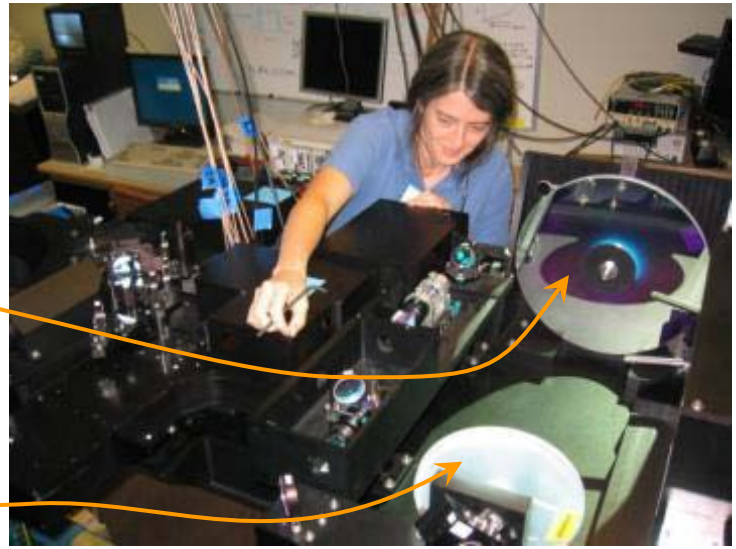
OAWL IIP Objectives

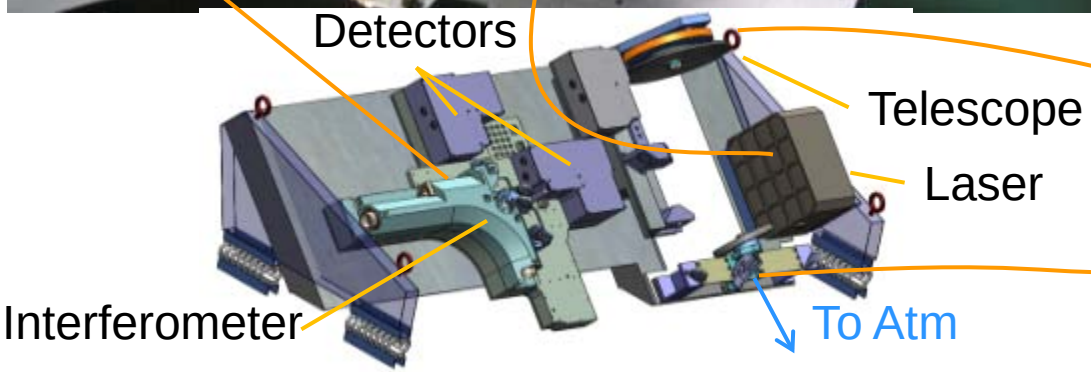
- Demonstrate OAWL wind profiling performance of a system designed to be directly scalable to a space-based direct detection DWL (i.e. to a system with a meter-class telescope 0.5J, 50 Hz laser, 0.5 m/s precision, with 250m altitude resolution).
- Raise TRL of OAWL technology to 5 through high altitude aircraft flight demonstrations.
- Validate radiometric performance model as risk reduction for a flight design.
- Demonstrate the robustness of the OAWL receiver fabrication and alignment methods against flight thermal and vibration environments.
- Validate the integrated system model as risk reduction for a flight design.
- Provide a technology roadmap to TRL7

OAWL DWL System Completed Under the IIP









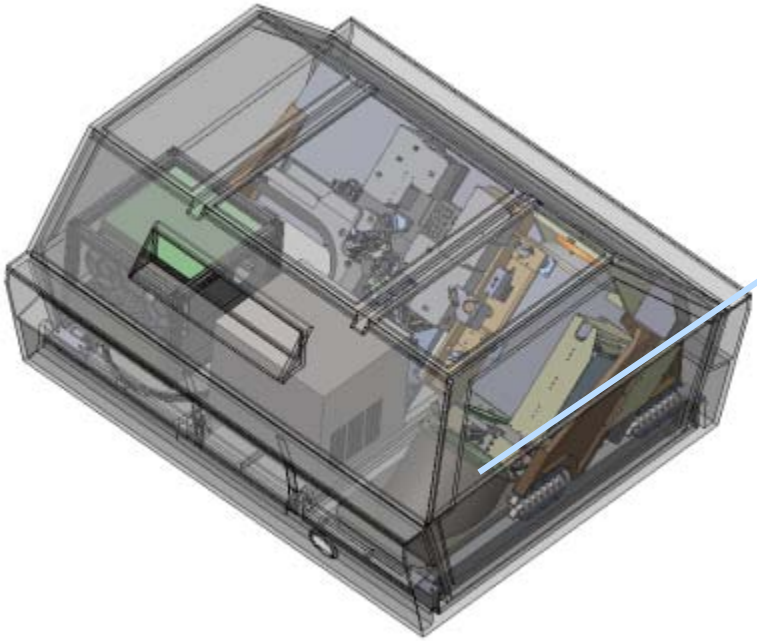
OAWL IIP Flight System and Status

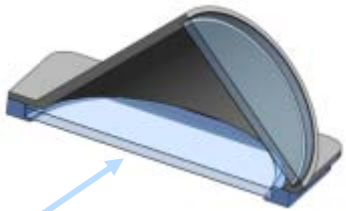
- OAWL fits in a WB-57 pressurized pallet
- Optical system fixed mounted at 45 deg
- Double window provides symmetric wave front distortion
- Components fabricated – support frame fit checks and environmental control system installation in progress

- OAWL System Mass – 202 kg
- Electronics Mass – 111 kg
- Thermal Control Enclosure – 10 kg
- Laser – 10 kg
- Telescope – 27 kg
- Sub-Bench – 17.7 kg
- Miscellaneous (10 % of Total) - 38kg

Total ~415 kg

6' pressurized WB-57 pallet





Double window reduces astigmatism due to bowing under pressure at altitude

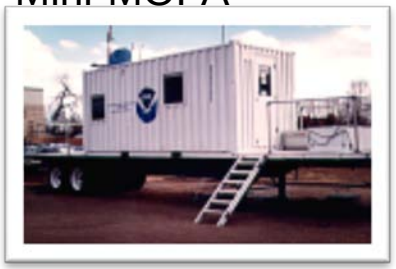
OAWL Ground Validation with NOAA's mini-MOPA

Planned July 2011

General plan:

- LOS comparisons between OAWL and NOAA's mini-MOPA Coherent Detection Doppler lidar.
- OAWL
  - located inside Table Mountain T2 building
  - 2 windows providing E and N/NE views
  - Laser safety plan complete and FAA approved
- mini-MOPA
  - LOS pointing may be interspersed with VAD scans to provide full vector contextual wind profiles

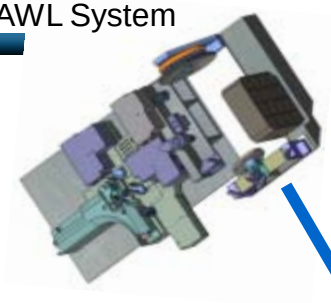
Mini-MOPA



OAWL Airborne Validation Experiments

NOAA Mini-MOPA
Coherent Doppler Lidar

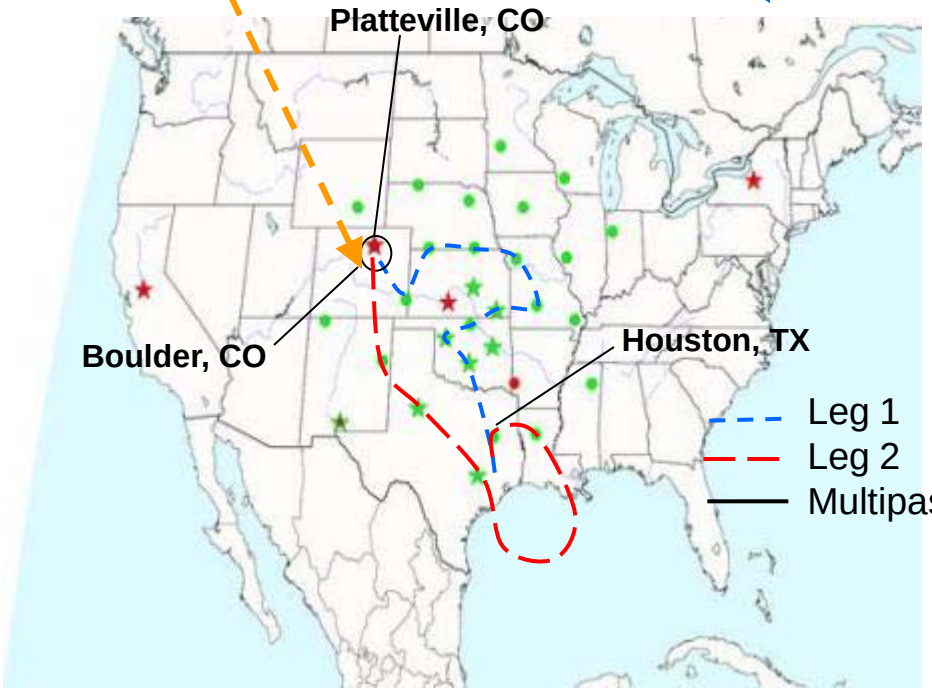
OAWL System

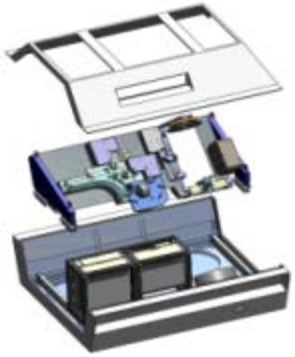


Airborne OAWL vs. Ground-based Wind Profilers and mini-MOPA Doppler Wind Lidar

(15 km altitude looking down along 45° slant path (to inside of turns).

Many meteorological and cloud conditions over land and water)





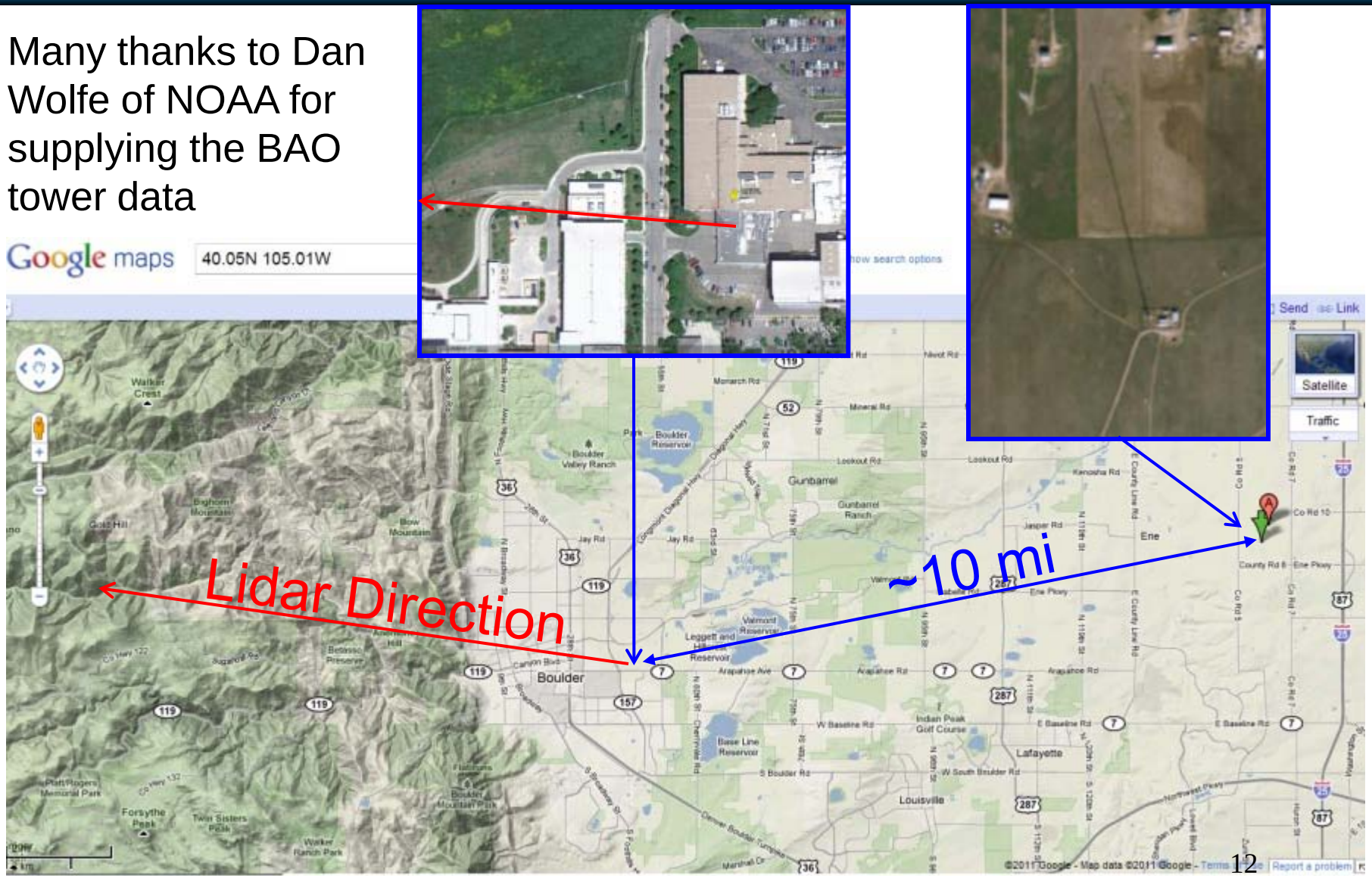
October 2011

** **Wind profilers in NOAA operational network**

Engineering Shake-out In Progress:
First OAWL Wind Measurements

Engineering Shake-out: Test Range (not ideal)

Many thanks to Dan Wolfe of NOAA for supplying the BAO tower data



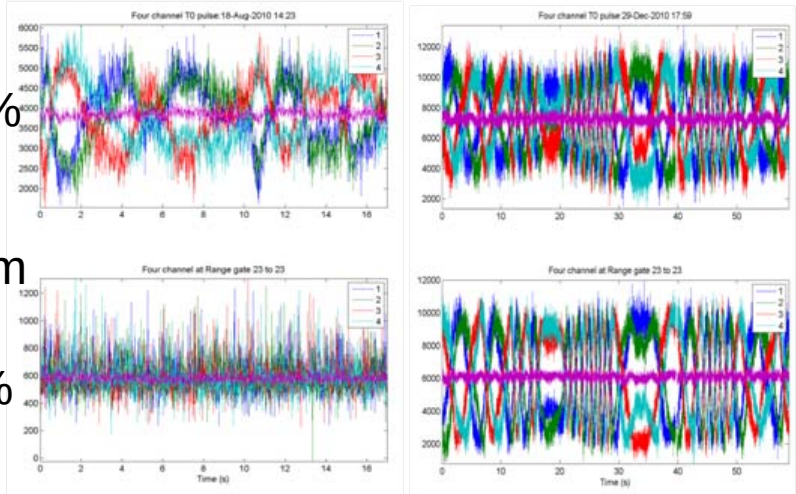
Fir\st attempts: *No Winds*
Problem #1: Loss of Field Widening
(resolved in Dec. 2010 by receiver alignment rework)

Contrast Before After

- Compare August HT results (left) to 29 December 2010 results (right)

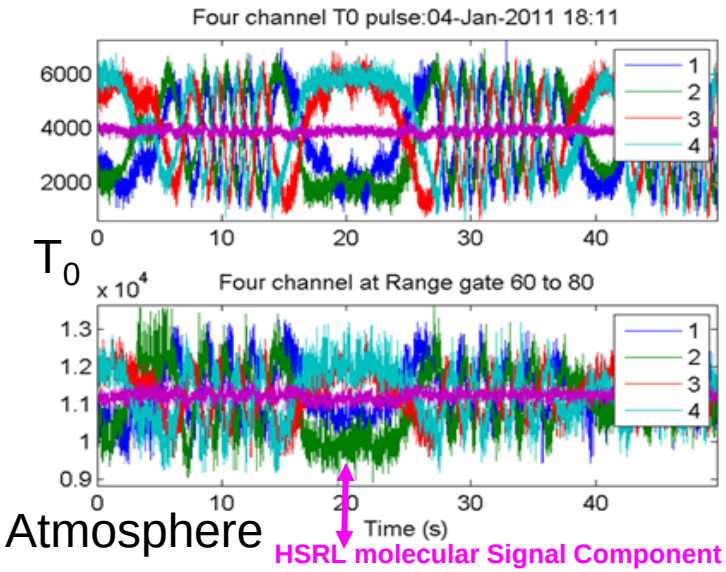
T_0 55%

90m HT 2%



T_0 >80%

90m HT >80%



- The problem with the receiver was a displacement of the input beamsplitter that caused a shearing of the beams in the 2 interferometer arms

- Omitted staking of the input beamsplitter mount (through a hard to see injection hole) allowed this beamsplitter to shift, probably shifted during vibe testing (and perhaps residual alignment error in the first implementation)

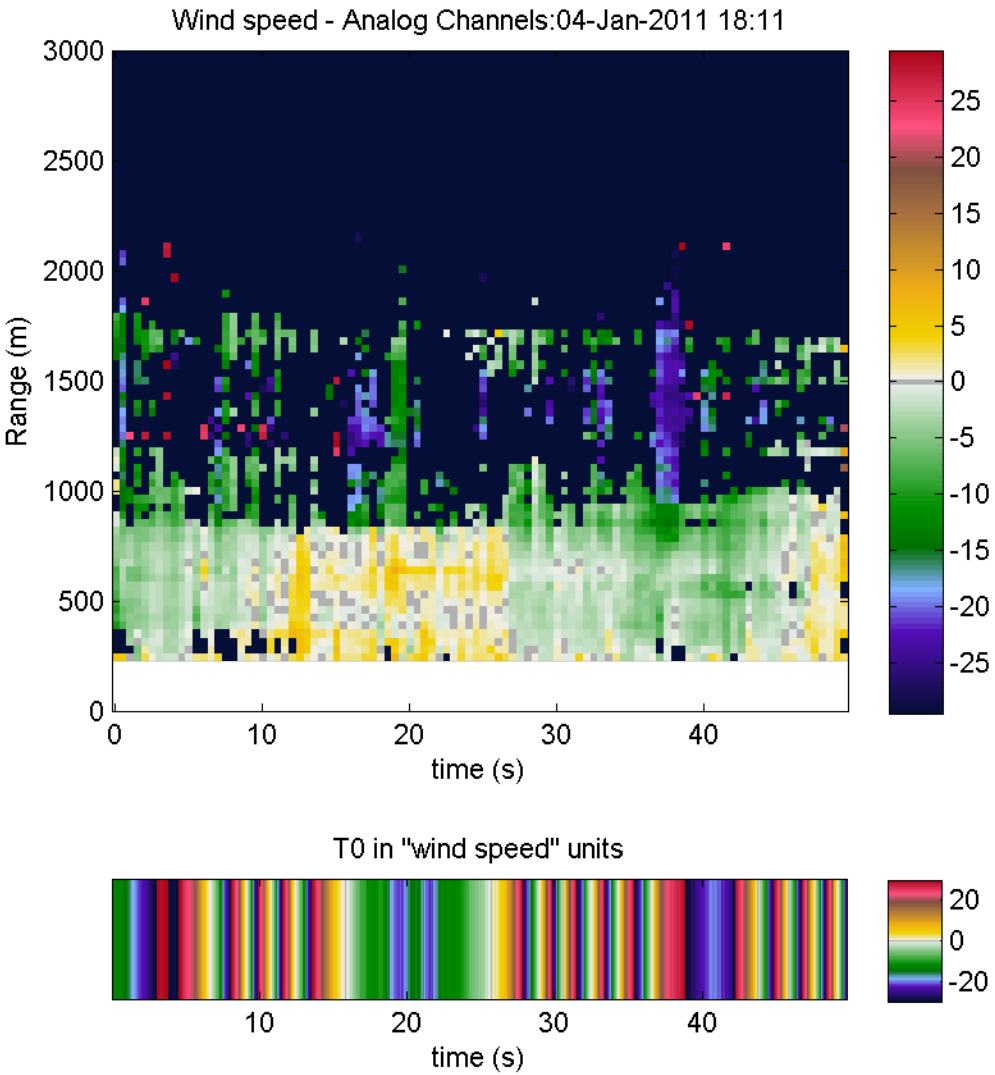
- A shift in performance was noted during the first TTOL level vibe test that was corrected by adjusting the output beamsplitter (the only adjustable element in the interferometer). This worked well for the vibe tests because the source had no field. However the test *results are still valid because they show the fast phase response to vibration.*

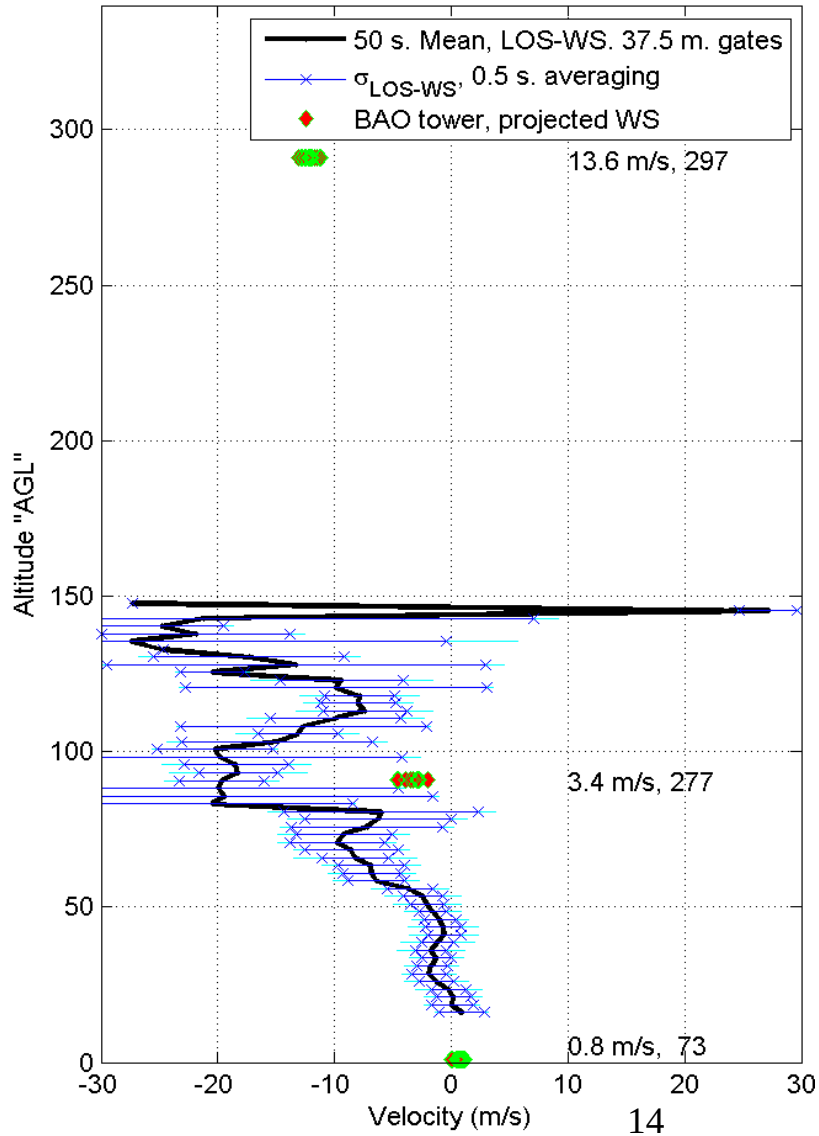
- *We believe that the construction method and materials developed for obviating the need for active control systems for high resolution interferometers (not just OAWL) are valid and suitable for flight path instrumentation because all other intra-interferometer components appear to have held alignment over time (~10^9 resolution is feasible without active control)*

- We now know that field widening is lost when the beams are sheared. Our initial instrument model did not predict the field widening sensitivity to alignment shearing. *We have incorporated corrections in the model that perfectly predict the observed behavior..*

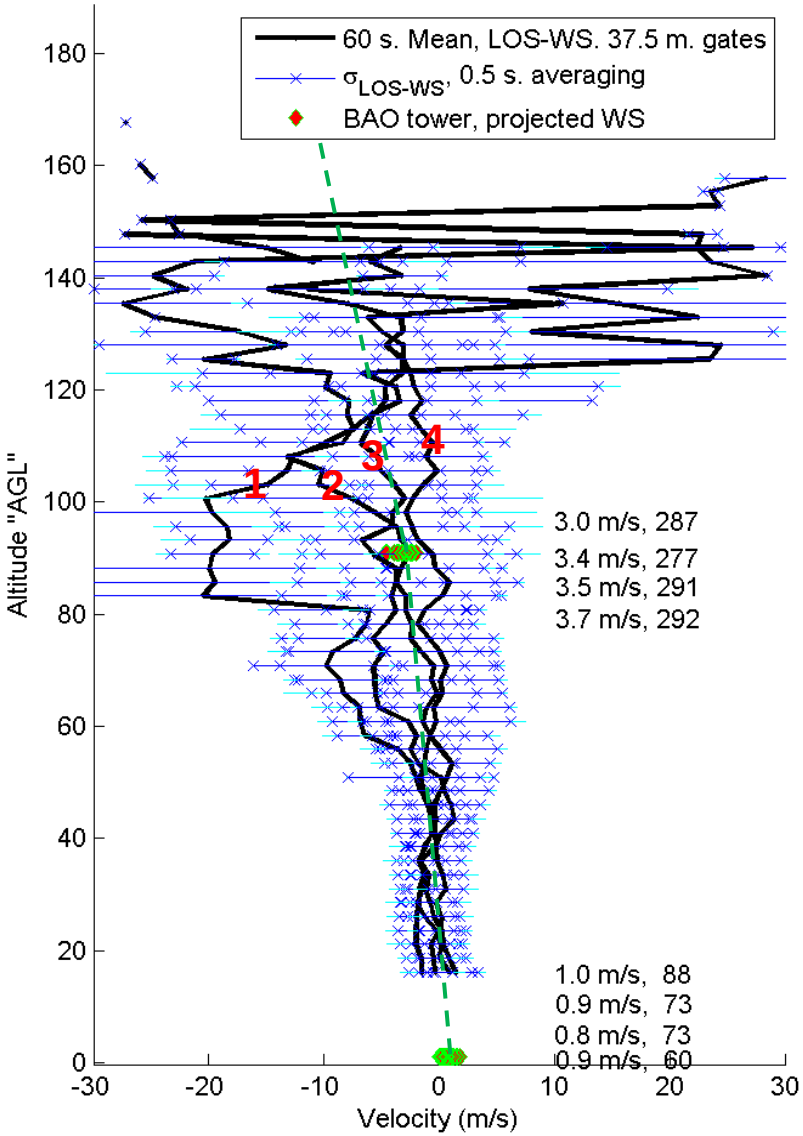
Preliminary Test Data: 04-Jan-2011 18:11
Threshold t_0 contrast > 0.4, atmos contrast > 0.04

Analog channels only



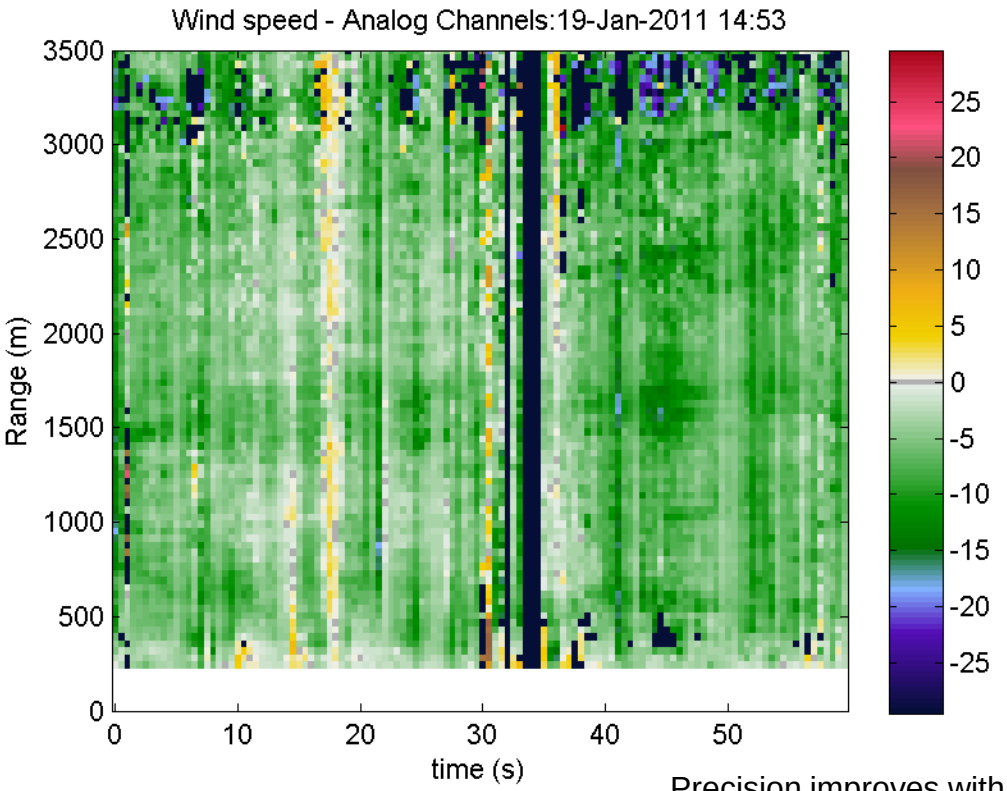


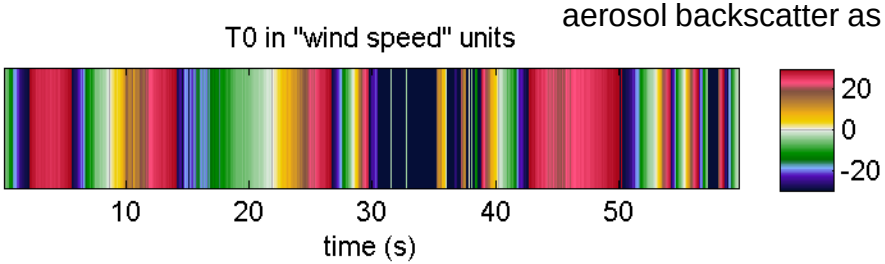
Preliminary data summary: 4 Jan 2011 – 18:11-18:31



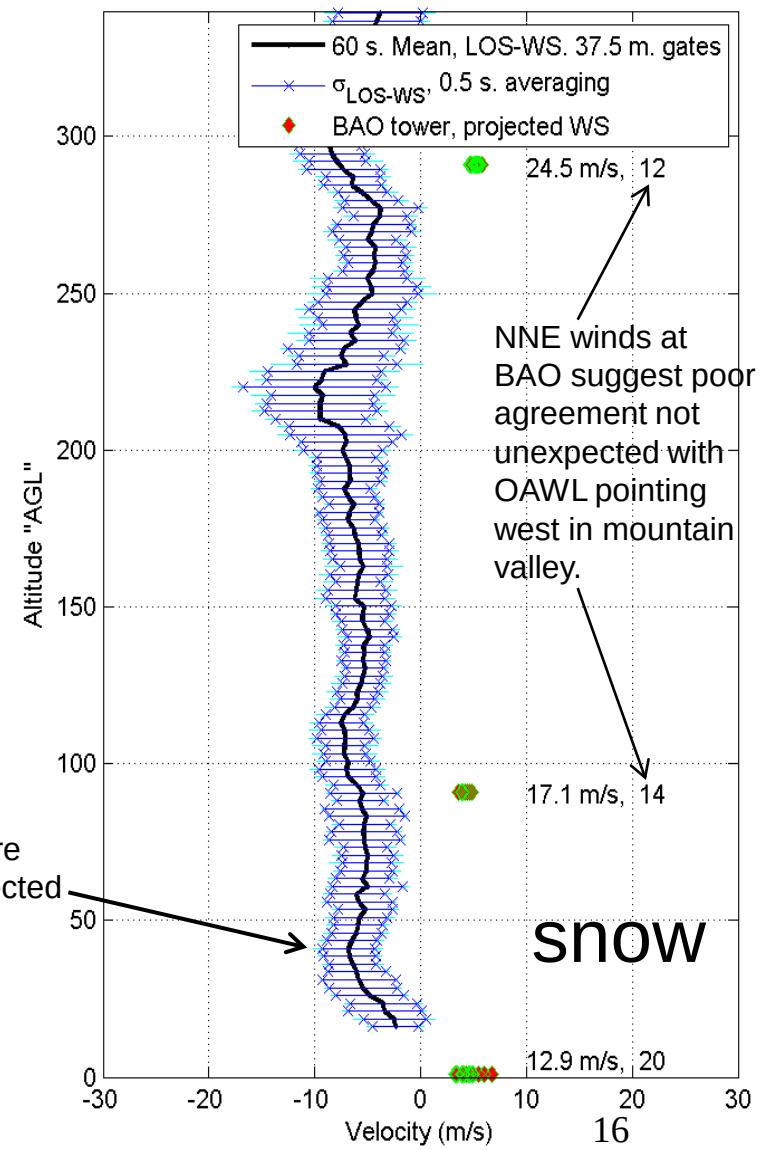
Jet-like feature at 100m could be real as it diminishes systematically in time (red sequence) while surrounding profiles track closely

Preliminary Test Data: 19-Jan-2011 14:53
More aerosol backscatter, but potential wind bias noted





Precision improves with more aerosol backscatter as expected

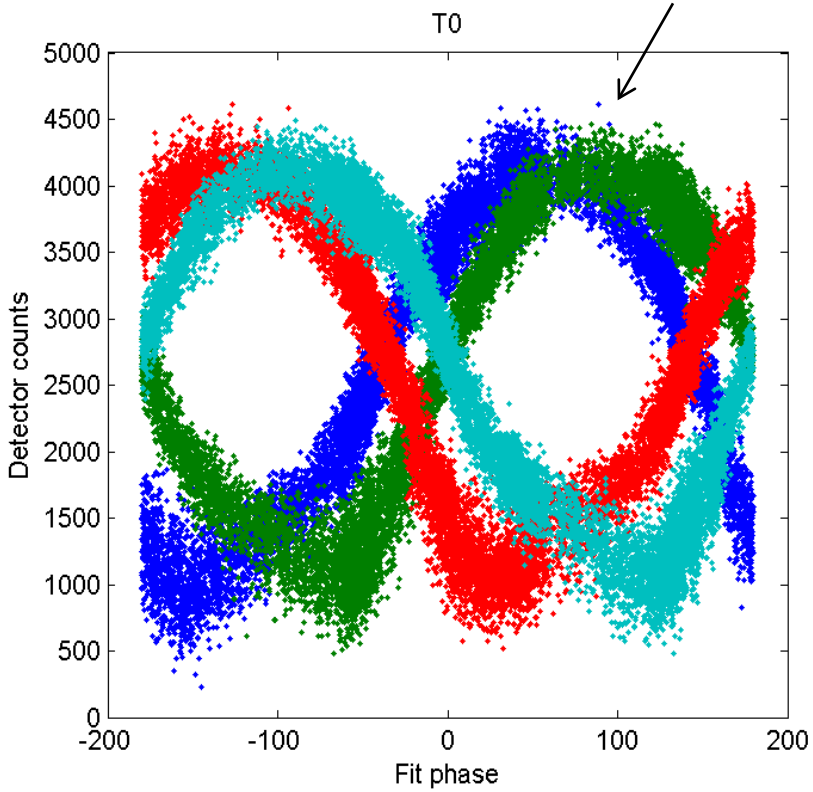


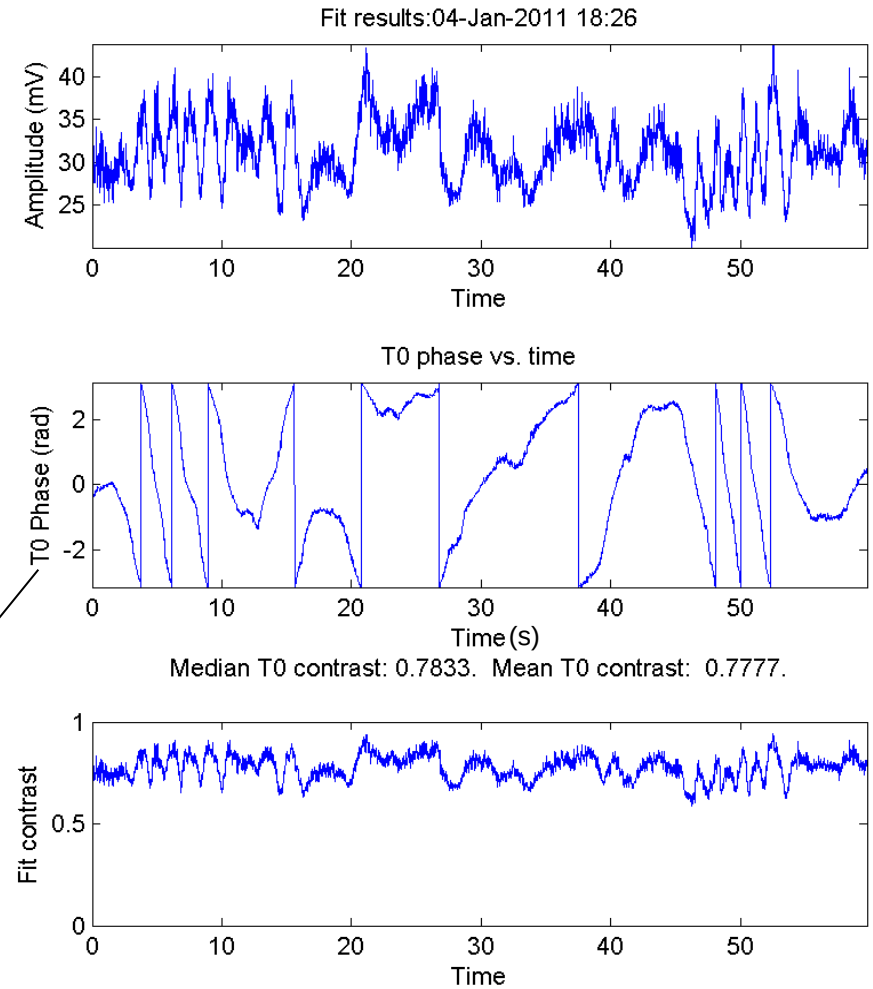
NNE winds at BAO suggest poor agreement not unexpected with OAWL pointing west in mountain valley.

snow

Problem #2: Imperfect Quadrature (355nm)
(Resolved with 355nm only waveplate May 2011)

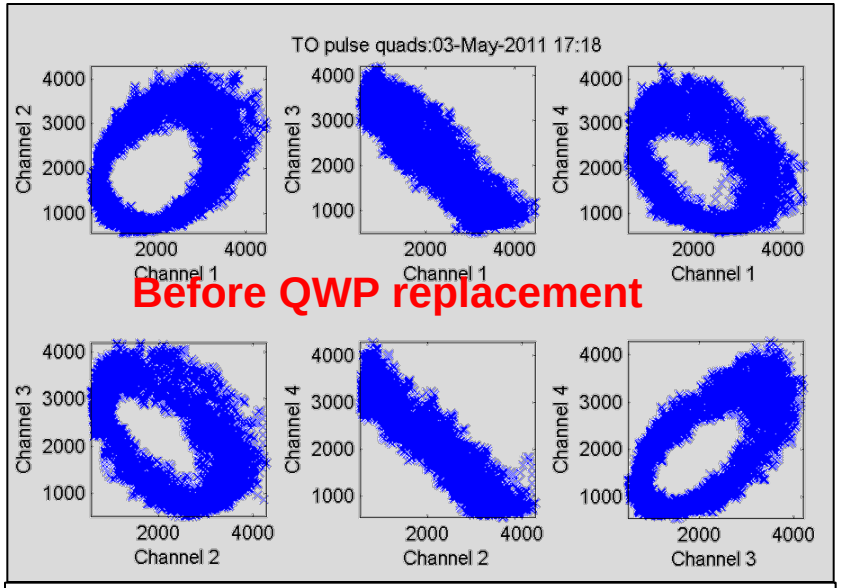
355nm/532nm λ/4 waveplate *NOT* λ/4 at 355nm : Replaced with 355nm only waveplate for now

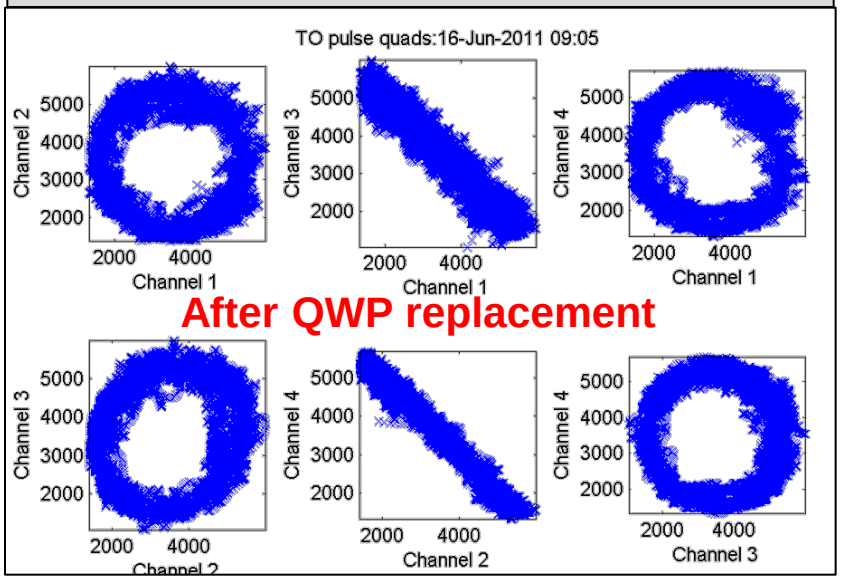




The entire autocovariance phase space rapidly scans over time due to random thermal variations, laser frequency drift, and platform vibration. T_0 phase is measured and subtracted from atmospheric return OA phase eliminating the need for precision environmental controls and complex laser-receiver lock loops.

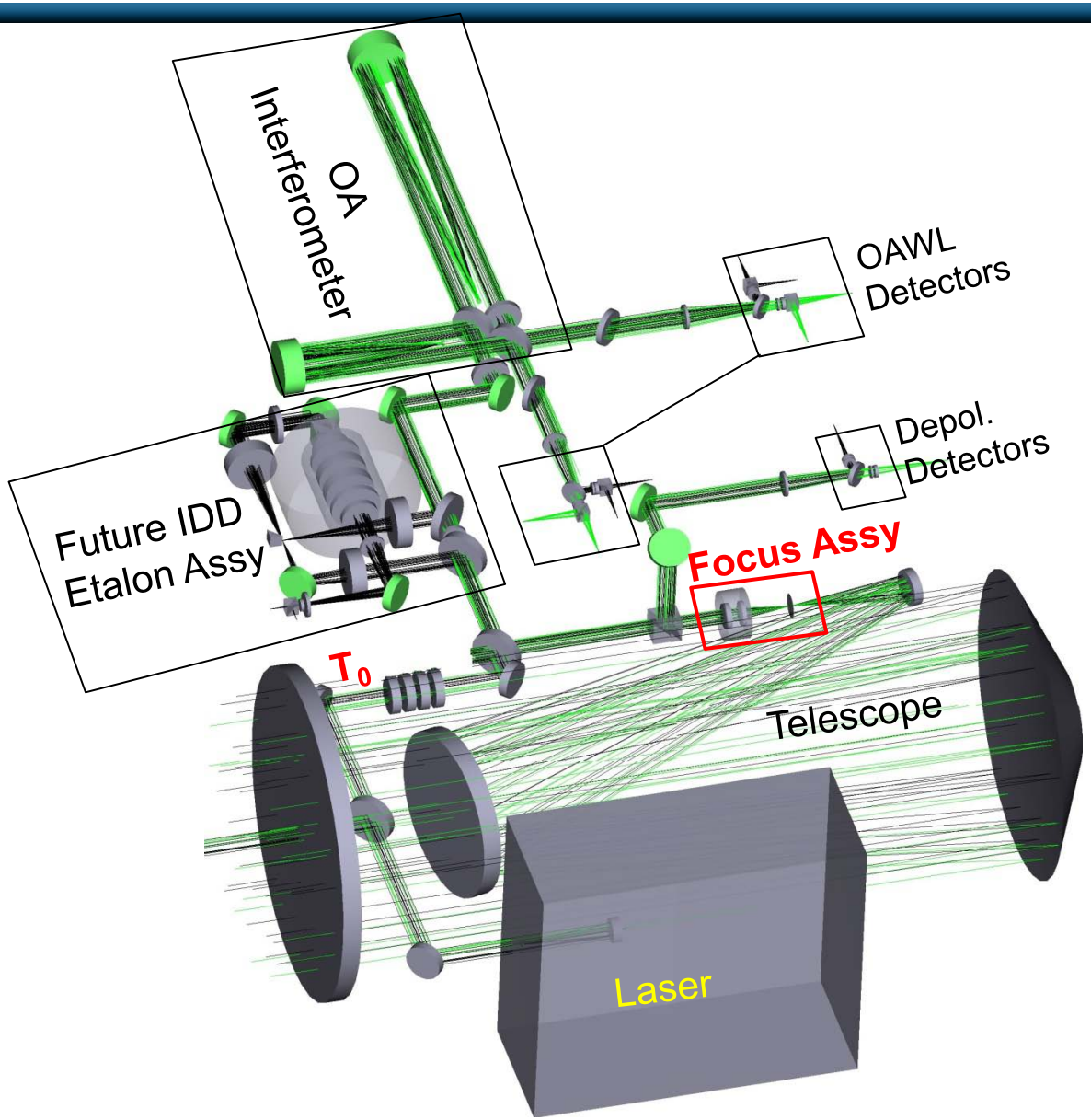
Optical Quadrature Restored – QWP at 355 nm





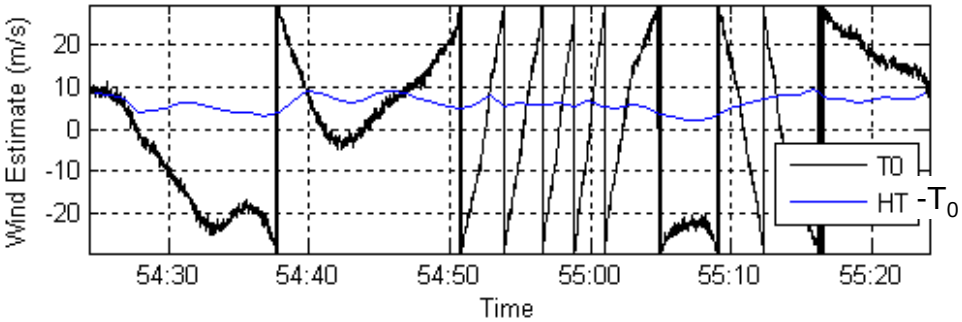
- Original quarter wave plate (QWP) was "dual wavelength" for 355 and 532 → but could not achieve quadrature at 355.
- External testing demonstrated this was not QWP at 355 (closer to 112° than 90°)
- New 355-only QWP purchased and installed. Issue Resolved for winds, but future dual wavelength HSRL applications will require better components

Problem #3: Uncertainty in Alignment of T_0 path relative to the Atmospheric Return Path Causes Wind Bias Error (Resolution in progress)

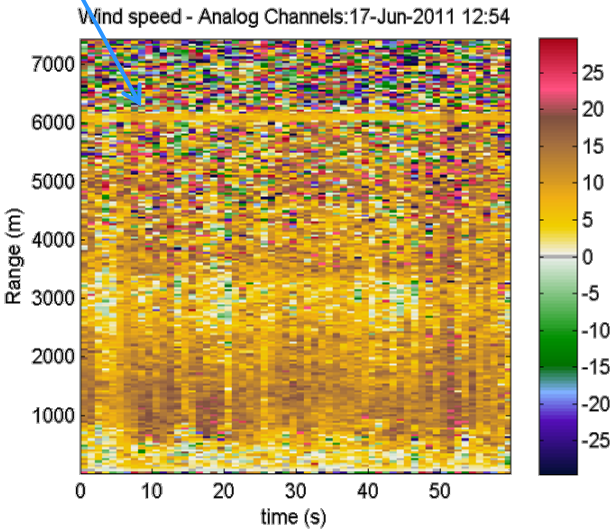


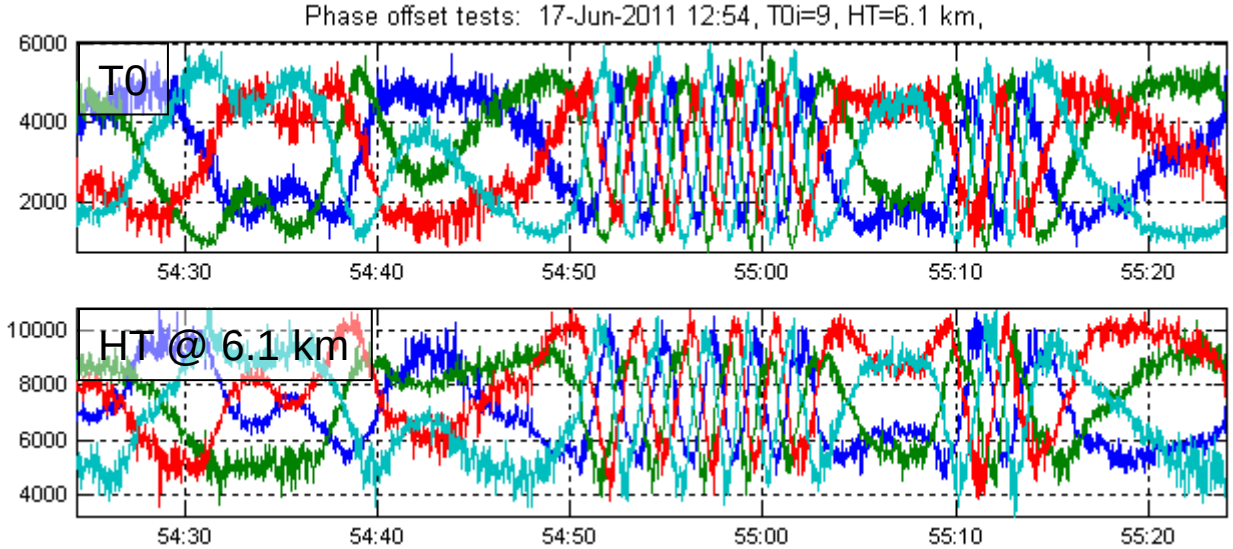
Observed Bias Due to T0 Alignment Uncertainty

- Due to current T0/pinhole alignment, a 100 um fiber coupled beam at "center" of pinhole/entrance pupil, for current T0 alignment, demonstrated a ~6-9m/s offset (fiber was difficult to position exactly) with **σ**<1m/s/pulse.
  - Real "HT" tests at 6.1 km showed an average speed of ~6.3 m/s (σ=1.8 m/s, 1sec).
  - Additional HT testing planned after an improved T0 alignment setup is installed & T0 is aligned.



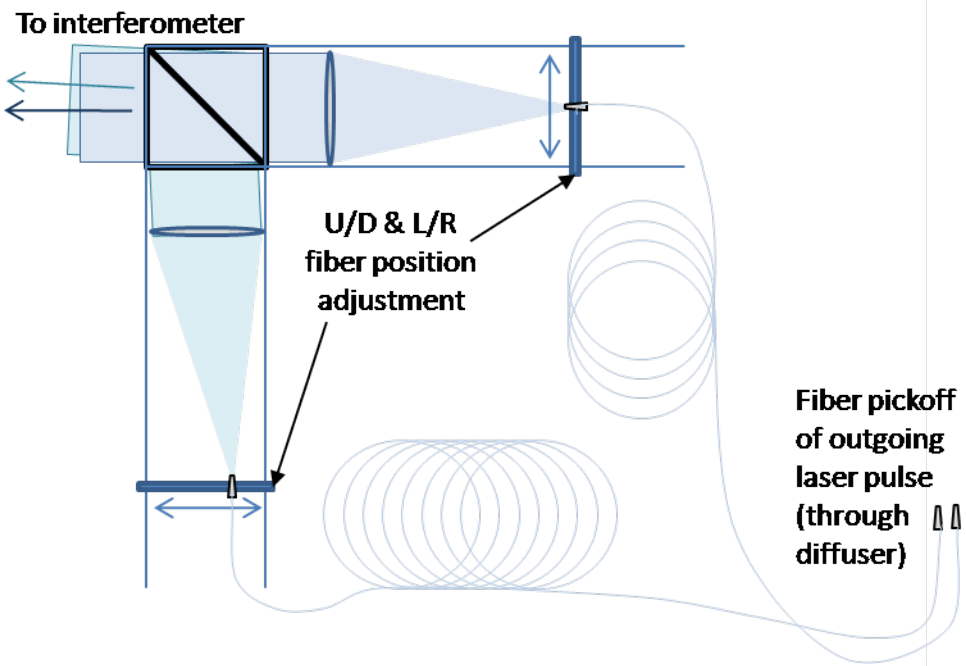
Perspective: Unwrapped phase ranges over equivalent 250-300m/s per minute

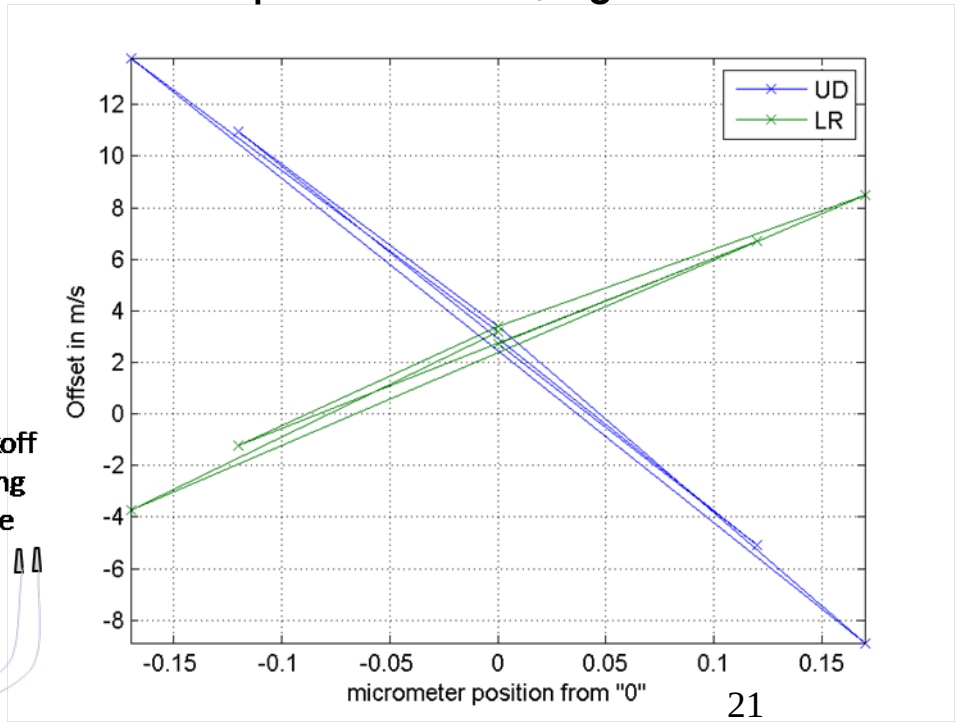




Verification of T_0 alignment angle as the cause of the wind bias

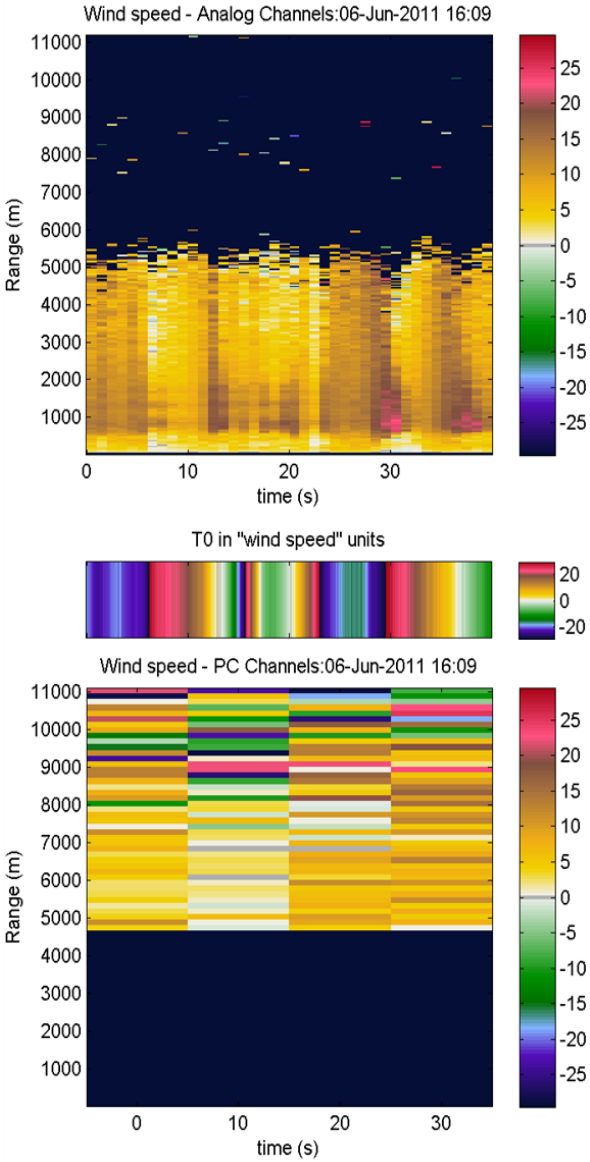
- Deliberately fed IFO with two collimated beams, separated by angles up to 1.2 mrad (receiver FOV), achieved by moving the input fibers up/down (UD) or left/right (LR) relative to the collimating lenses.
- Each beam was from a separate fiber, which sampled the same portion of the laser beam, but delayed the pulse by differing amounts.
- The resulting phase offsets, translated into m/s are plotted below, right.





Analog & PC Profiles on hazy day

(prior to QWP tuning)

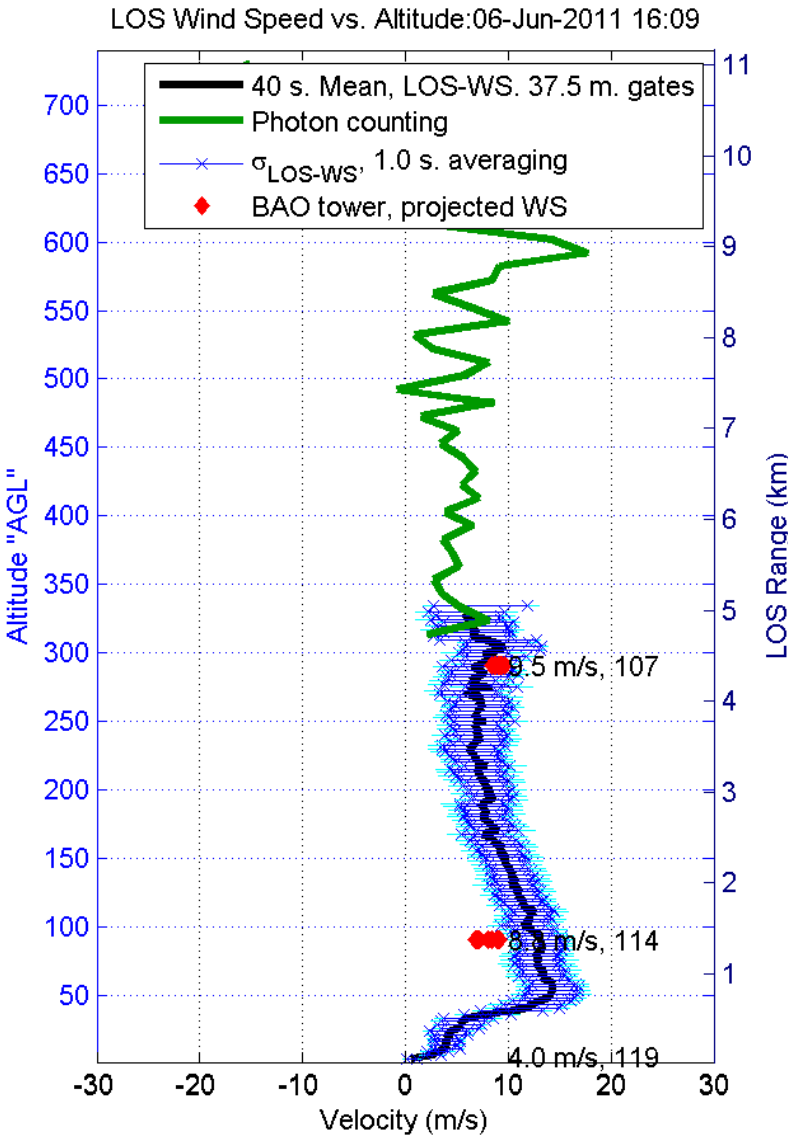


PC channels provide about 2 km more range on this day.

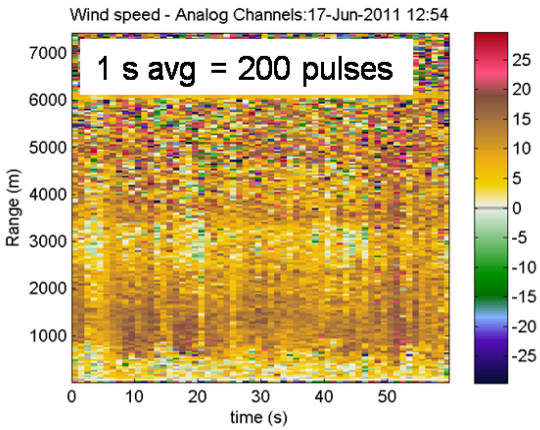
"Striations" (changes vs. time) are mainly due to poor optical quadrature (since been fixed via QWP tuning)

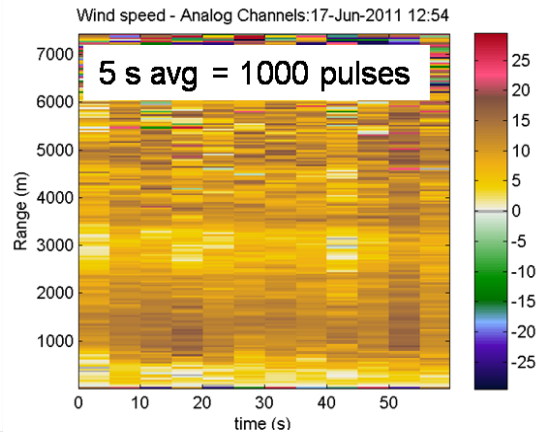
Changes vs. range between 600 m and 1500 m range are believed to be due to overlap alignment issues

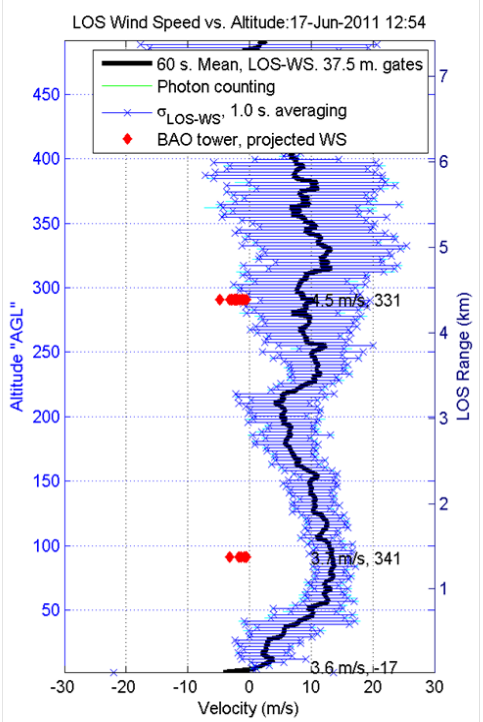
Horizontal features after overlap are actual wind features.

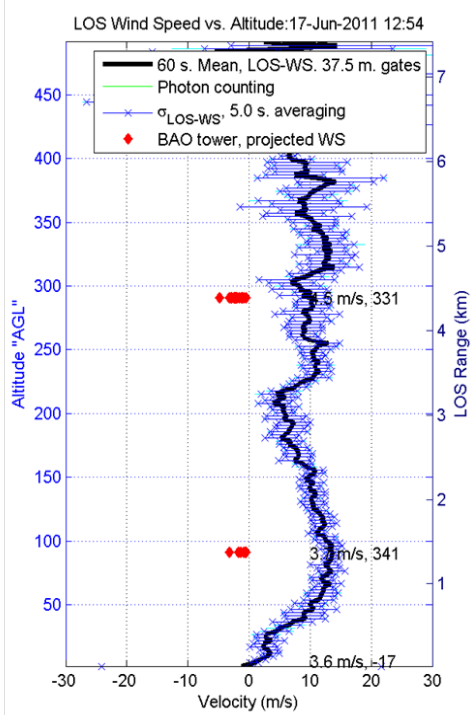


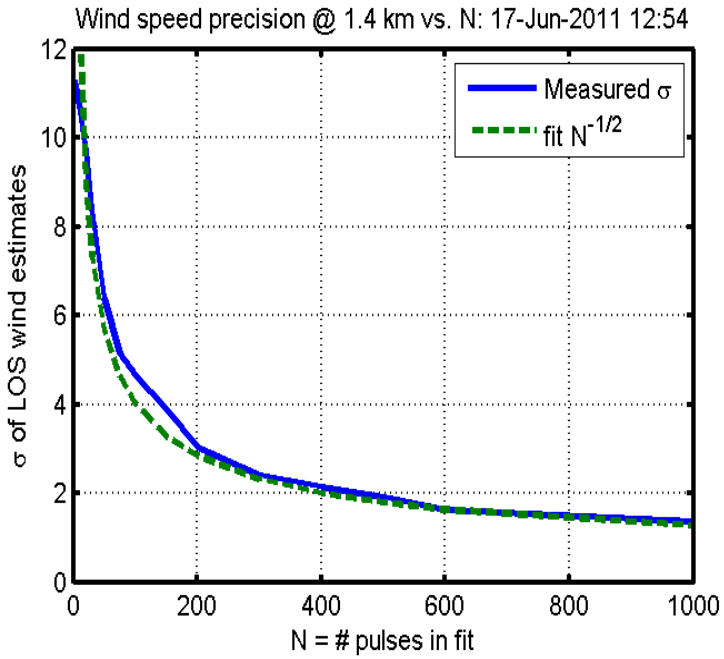
Wind Precision Improves with √N





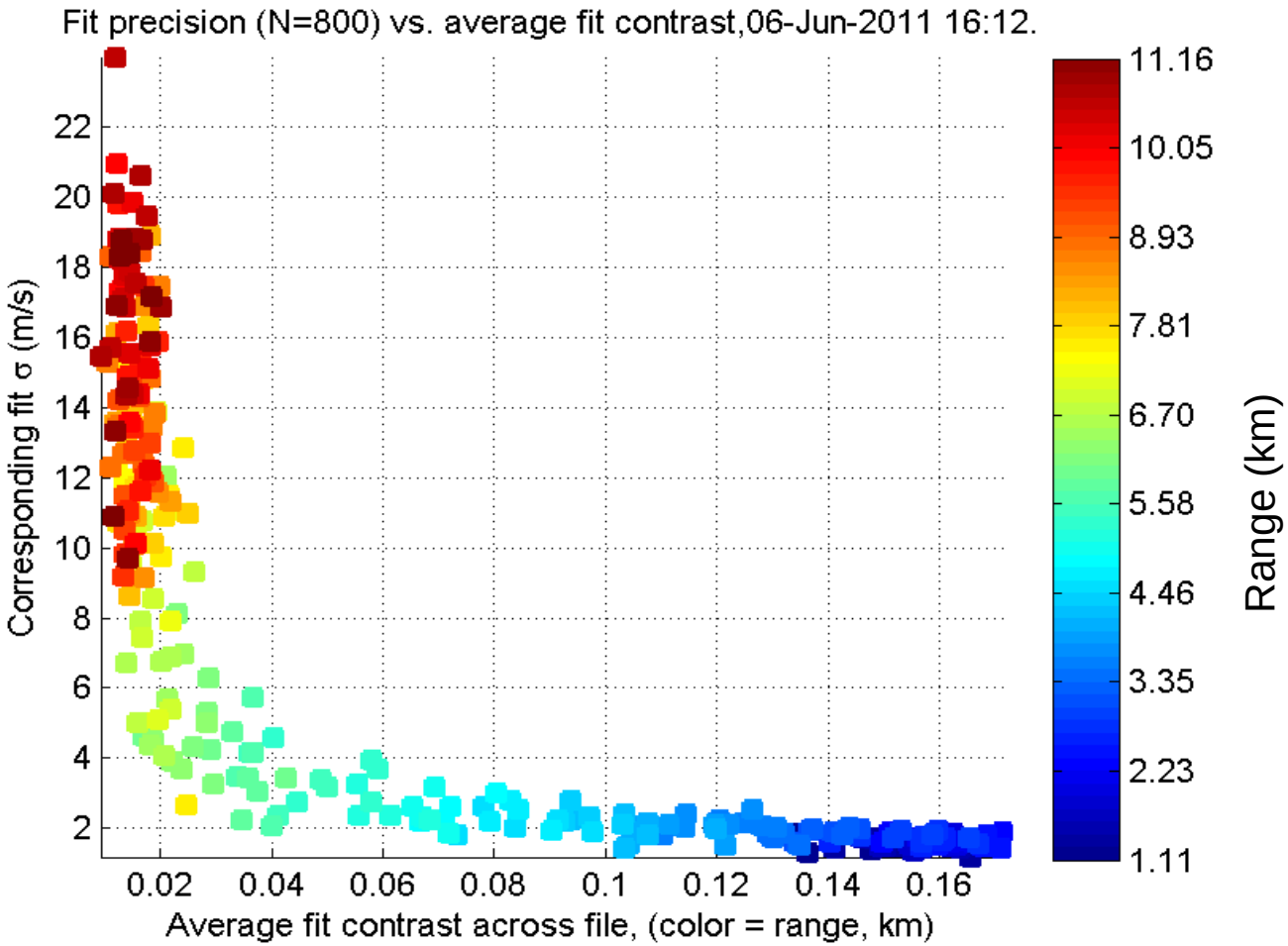






low backscatter/low contrast day
(17 Jun 2011)

Performance Scales as Expected with Contrast



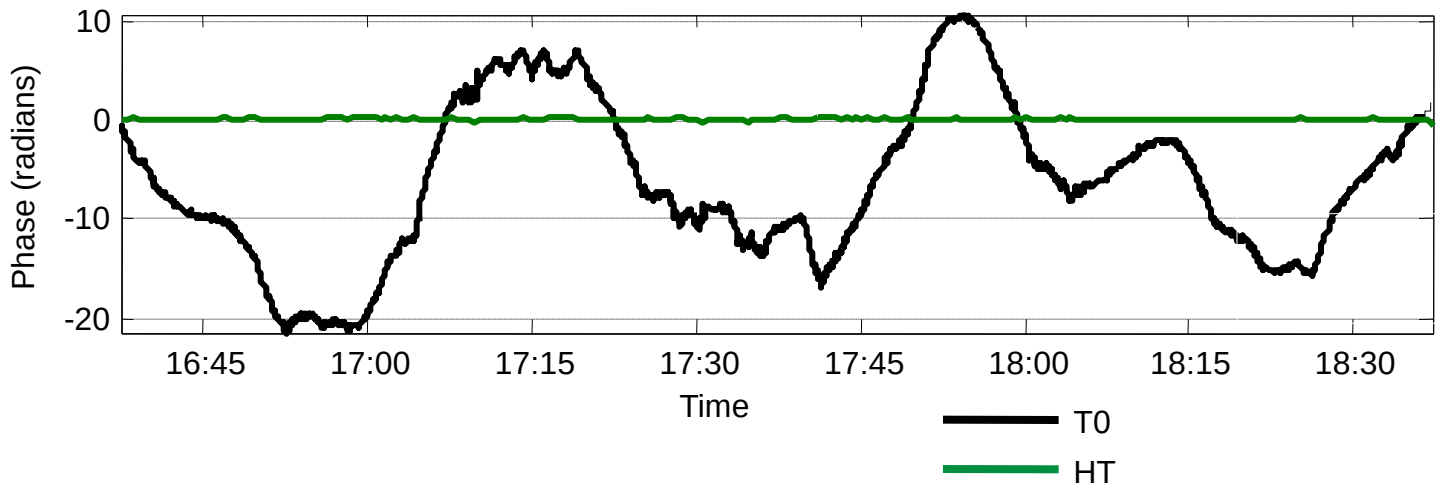
Conclusions / Plans

- *An Integrated Direct Detection approach using an Optical Autocovariance wind lidar (OAWL) to measure the winds from aerosol backscatter promises to greatly simplify the sensor and reduce cost for the 3D-Winds mission by reducing the system requirement to a single direct-detection lidar at one wavelength (355nm) using one laser and common optical elements with relaxed wave front requirements.*
- *A complete 10^9 resolution OAWL system has been designed fabricated and integrated*
- *Preliminary measurements demonstrating atmospheric wind profiles have been acquired . Bias uncertainties have been traced to poorly performing waveplate (resolved) and underspec mechanical stage (fix in progress)*
- *Plans/logistics for ground validations against a NOAA Coherent Doppler Wind Lidar are in place, expected execution in July 2011*
- *Installation of the OAWL system in a WB-57 aircraft pallet in progress to support autonomous operation after ground validations*
- *Flight tests from the WB-57 are planned for October 2011 (pending aircraft availability)*
- *Once validated, we plan to fly the system in support of atmospheric science missions, demonstrate OA-HSRL, and add an etalon to demonstrate a complete IDD solution for 3D-Winds*

Backups

Scaling the Issue

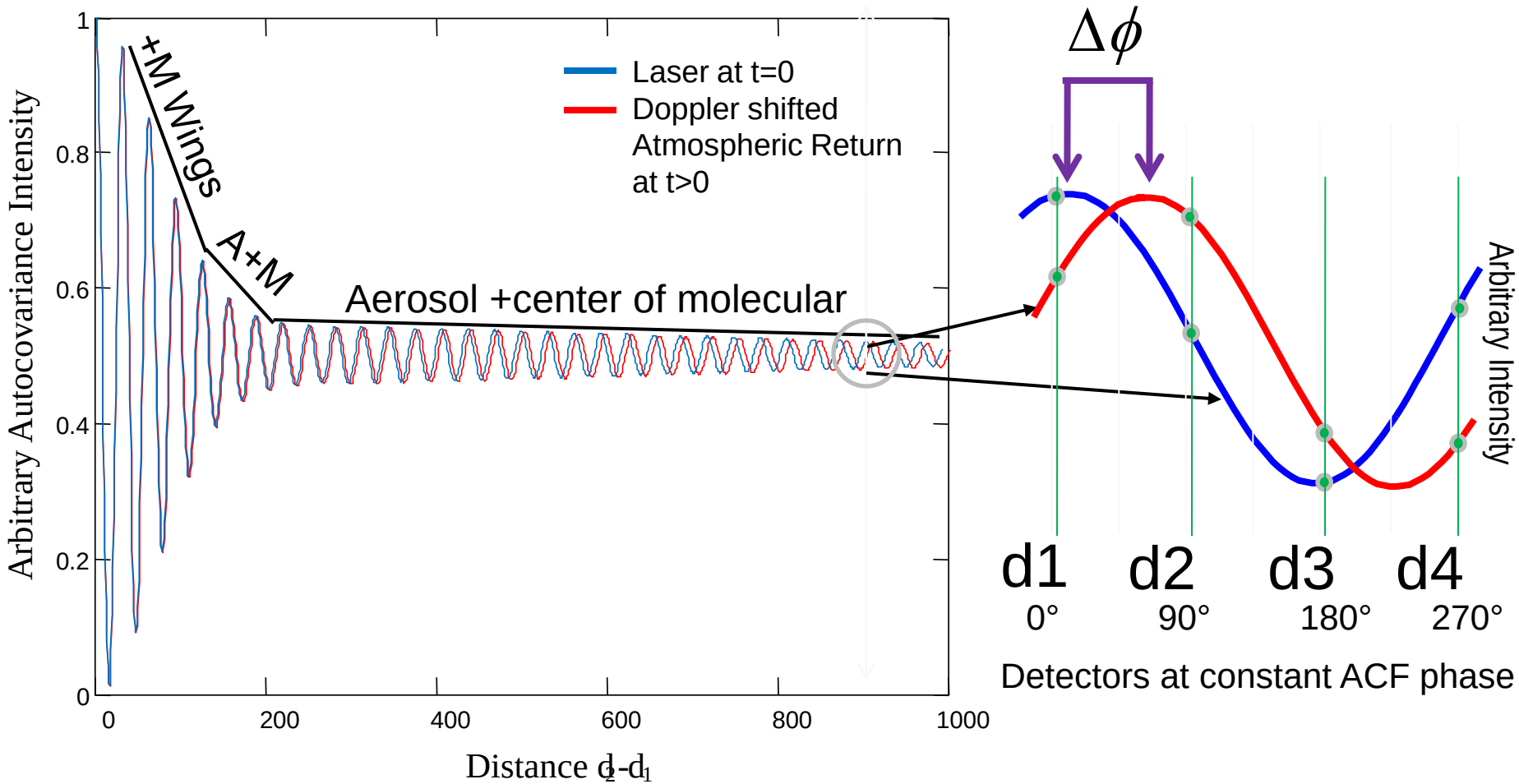
- We are searching for a 0 to ±π radian differences in signals that are varying over large ranges of up to 30 radians over 1-minute.
- Modeling (& experience) has demonstrated that careful alignment is required – because as system phase changes dramatically, so does the error in the estimate if alignment, or quadrature are off.



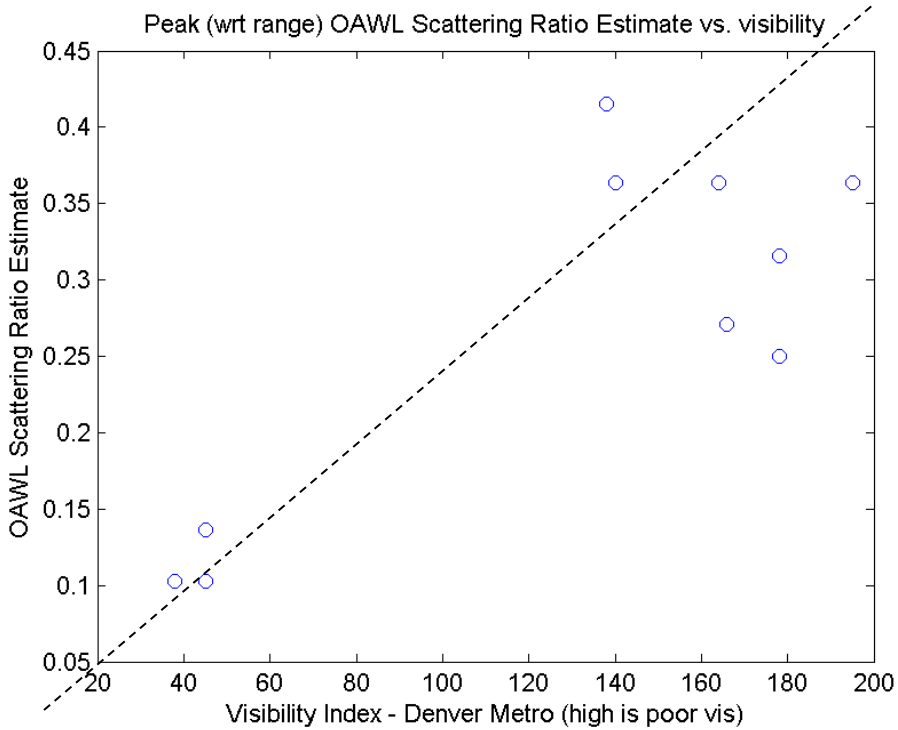
A Brief Optical Autocovariance History

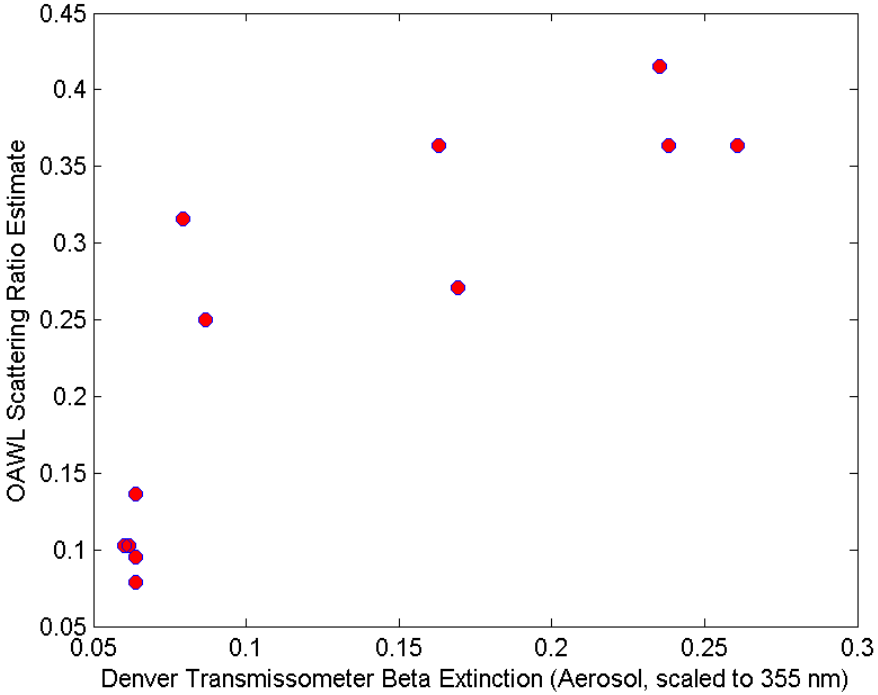
- 1995 Schwiesow and Mayor, NCAR: Paper describing the use of Optical Autocovariance for Wind Measurement- Coherent Optical Signal Processing for a Doppler Lidar Using a Michelson Interferometer., 1995 Coherent Laser Radar Conference (Keystone, CO). OSA Technical Digest Series 19, WA5-1 through WA5-4.
- 1996 Liu and Kobayashi Fukui U. Japan: defined Mach-Zehnder with 4-channel polarization multiplexing, and a T_0 sample, analyzed for Doppler wind measurement. Opt. Rev. V3, 47-52.
- 2001 Bruneau, CNRS Analysis of Mach-Zehnder, with 4-channel polarization multiplexing for Doppler Wind Lidar (Discriminator using channel ratios, *NOT* Autocovariance, wind measurement sensitive to aerosol/molecular backscatter ratio and temerature)
- 2004 Bruneau, et al: Relative (*NOT* absolute) wind profiles with a M-Z discriminator (*NOT* Autocovariance)
- 2004 Schweisow, Ball Aerospace: Started development at Ball in 2004 with IR&D funds, patent issued 2008.
- 2006 Grund – built and demonstrated absolute wind measurement with Optical Autocovariance DWL proof of concept based with 3 parallel step interferometer;
- 2007 Grund and Pierce designed a practical, absolute-referenced, field-widened, multi-λ receiver in 2007, built in 2008,9 with IR&D funds. Method and apparatus patent issued 2011.
- 2008-2011 Grund and Tucker, Ball under NASA IIP: Complete, practical optical autocovariance, field-widened, absolute referenced, DWL built and validation on ground and in air, *in progress*.

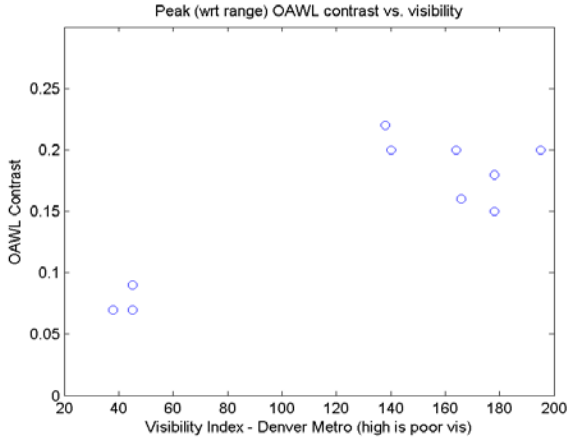
OAWL Frequency Measurement Principles



OA-HSRL Scattering Ratio Signal Also Observed



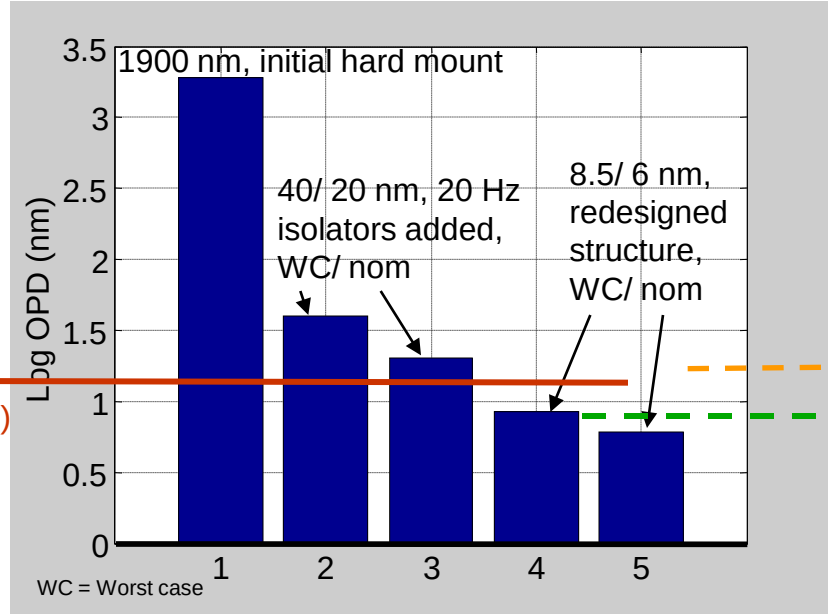




- Denver transmissometer data (~20mi away) scaled to 355nm (from 510nm) by subtracting ~molecular extinction and assuming linear scaling in λ for aerosol extinction cross section.

- *No attempt at instrument corrections or true HSRL calibrated retrieval*- this is preliminary raw data meant to show that the HSRL molecular signal is present and is observed (now TRL3?) can be used per theory presented previously in papers.

Integrated System Model – Design Iteration Convergences on Vibration-Induced Phase Noise Specification



Predesign Spec:
<1m/s/shot/100 μs (11nm RMS)
Random dynamic
error with WB-57 excitation

Vibe test result: ~13/34 nm RMS
(7.5 (100 μs) / 20 km ranges)

Final design Prediction Feb. 2008 : *8.5 nm RMS* jitter, exceeding spec and *meeting goal*, suggests performance dominated by intensity SNR, not vibration environment

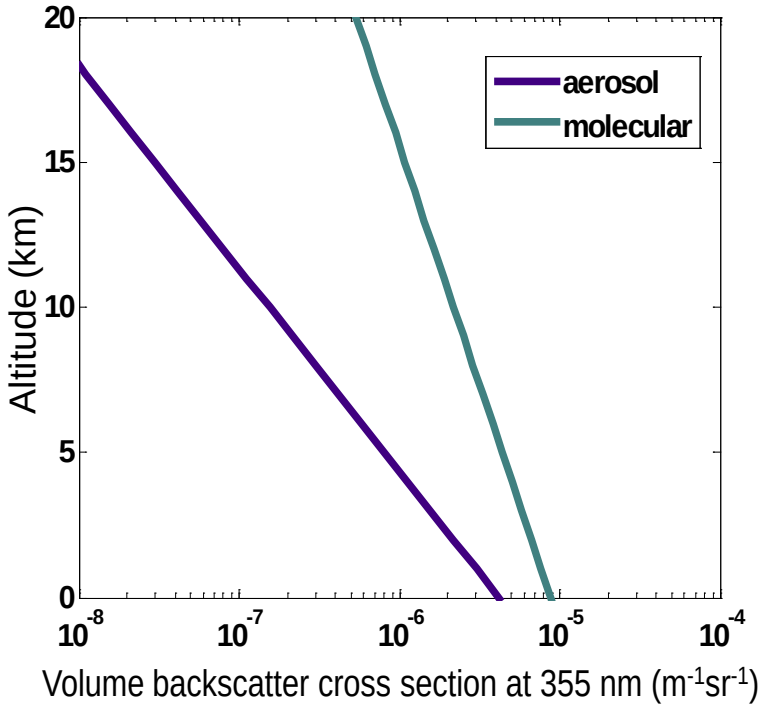
While current result does not exactly match the original model predictions, the receiver was modified to include the plate beamsplitter, and the FEM has not yet been integrated into the model – this is *in progress*.

Real measurements have a small amount of measurement noise that is not accounted in the model. Model validated within uncertainties for dynamic models and for test conditions.

IIP Upshot: >4000 pulse returns will be averaged per wind profile suggesting the operational vibe induced errors will be ~0.07 m/s (10 km) per profile (insignificant)

Ball Space-based OA Radiometric Performance Model – Model Parameters Using : Realistic Components and Atmosphere

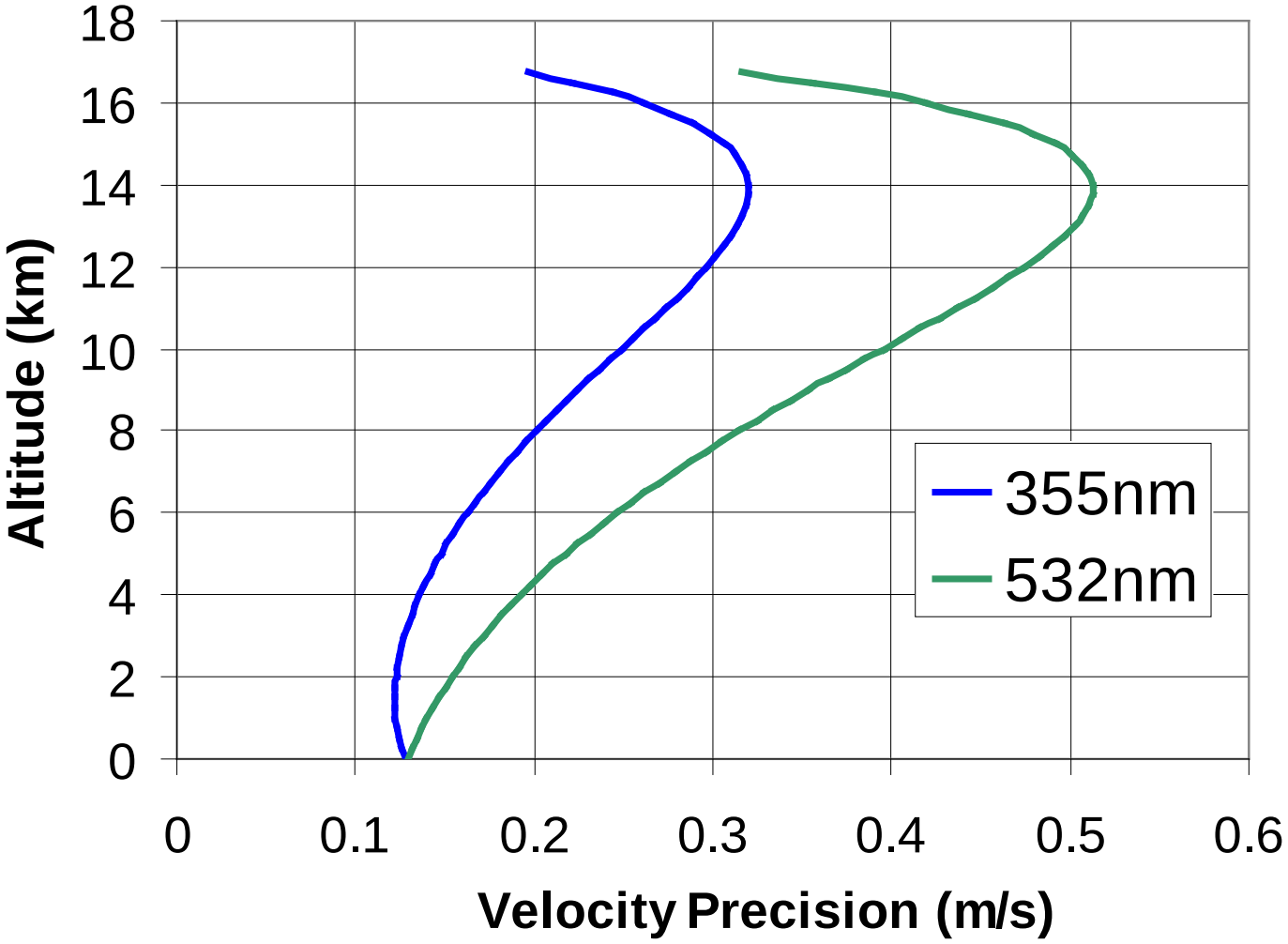
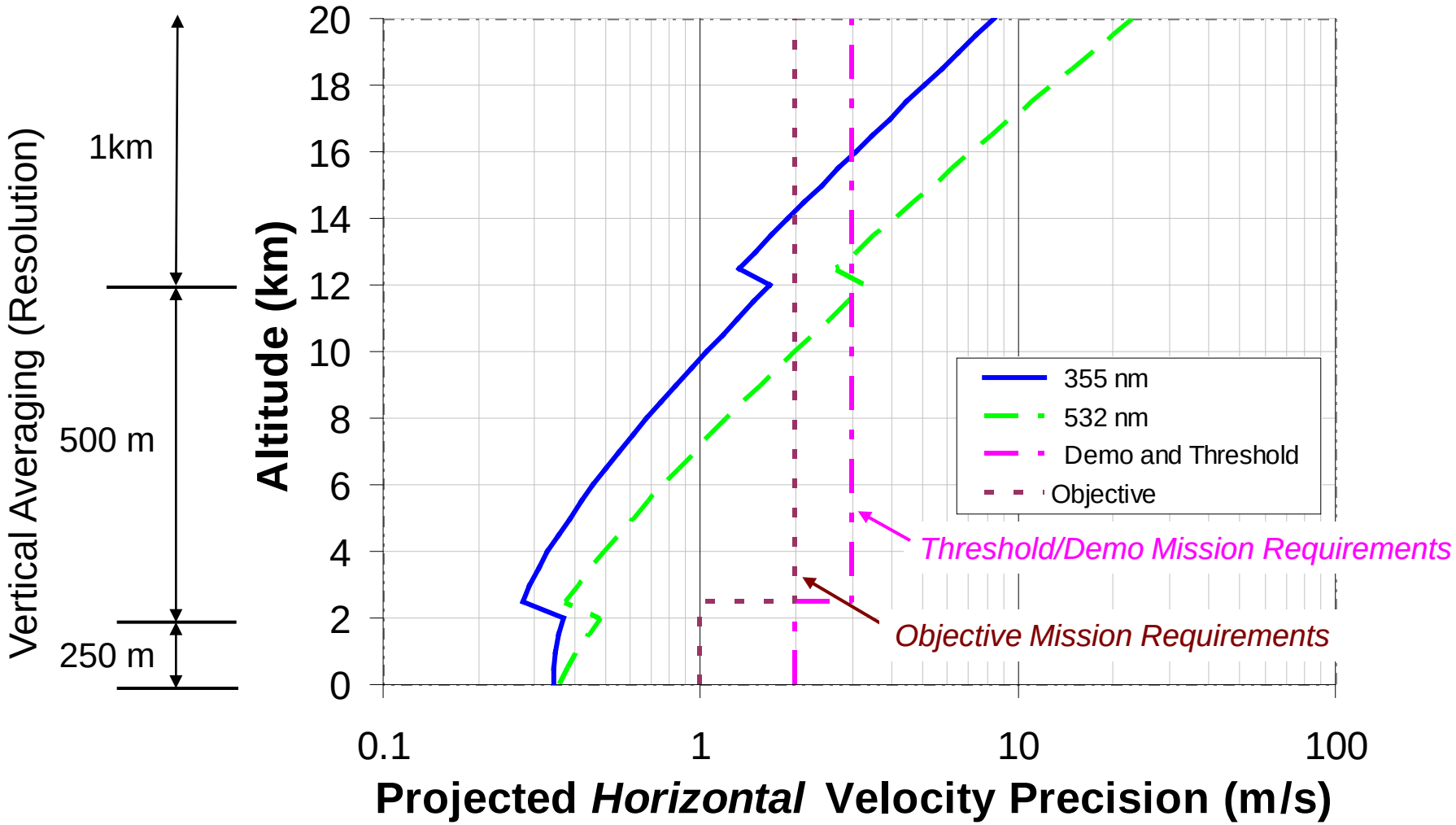
	LEO Parameters	*WB-57 Parameters*
Wavelength	355 nm, 532 nm	355 nm, 532 nm
Pulse Energy	550 mJ	30 mJ, 20 mJ
Pulse rate	50 Hz	200 Hz
Receiver diameter	1m (single beam)	310 mm
LOS angle with vertical	45^0	45°
Vector crossing angle	90^0	single LOS
Horizontal resolution*	70 km (500 shots)	~10 km (33 s, 6600 shots)
System transmission	0.35	0.35
Alignment error 5 μR average	15 μR	20 μR
Background bandwidth	35 pm	50 pm
System altitude	400 km	top of plot profile
Vertical resolution	0-2 km, 250m 2-12 km, 500m 12-20 km, 1 km	100m (7.5m recorded)
Phenomenology	CALIPSO model	CALIPSO model



λ-scaled validated CALIPSO Backscatter model used. (λ^{-4} molecular, $\lambda^{-1.2}$ aerosol)

Model calculations validated against short range POC measurements.

Expected Performance from the WB-57
(Daytime, 45°, 33s avg, 6600 shots)



OAWL – Space-based Performance:
Daytime, OPD 1m, aerosol backscatter component, cloud free LOS