Development and Demonstration of an Optical Autocovariance Direct Detection Wind Lidar (OAWL)

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OAWL Addresses the Decadal Survey 3D Winds Mission

- “Tropospheric winds are the #1 unmet measurement objective for improving weather forecasts”
- “Proper specification and analysis of tropospheric winds are prerequisites for accurate NWP”
- Doppler wind lidar (DWL) in space allows global profiling of winds, especially over oceans where large data gaps prevail
- Improved severe and tropical storm prediction and tracking
- Winds power mass flow of aerosols, pollutants, and moisture affecting health and resources
- Long-term atmospheric studies for climate change

- Current baseline sensor: Hybrid DWL (HDWL) combining a *coherent detection DWL at 2 mm* wavelength to accurately measure winds from aerosol backscatter *when present* with a *direct detection* double-edge *etalon DWL at 355 nm* wavelength to measure *lower precision winds from ever-present molecular backscatter* winds, particularly in clean air regions.

- OAWL measures *winds from aerosol backscatter with precision* similar to the HDWL coherent detection component *using light rejected from the molecular backscatter etalon* system resulting in a *single 355nm wavelength laser and optical system* measuring *winds from both aerosol and molecular backscatter* with high efficiency. *Promising lower cost, mass, complexity*

- *Other relevance: Multiwavelength* High Spectral Resolution Lidar (HSRL) (*ACE mission*)

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The Ball OAWL Development Team

Rick Battistelli – Software Engineering

Scott Edfers – FPGA code

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

Teri Hanson – Business analyst

Jim Howell – Systems Engineer, Aircraft lidar specialist, field work specialist

Kelly Kanizay – Custom electronics

Paul Kaptchen – Opto-mechanical technician

Mike Lieber – Integrated system modeling

Miro Ostaszewski – Mechanical Engineering

Bob Pierce – Optical Engineering

Jennifer Sheehan - Contracts

Sara Tucker – Technical Manager, Signal Processing, Algorithms

Carl Weimer – Space Lidar Consultant

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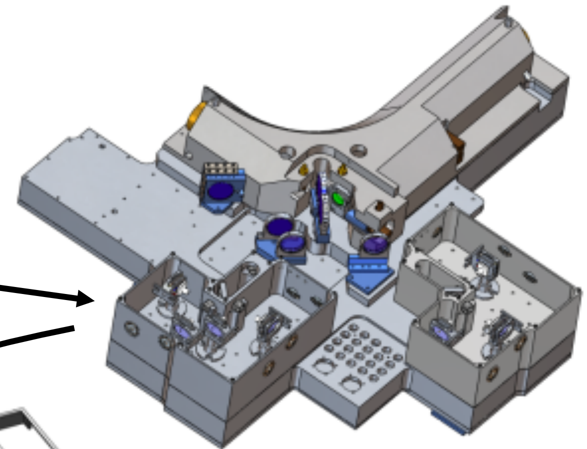
OAWL IIP Objectives

- 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 IIP Development Process

Take the OAWL Receiver (Ball IRAD)

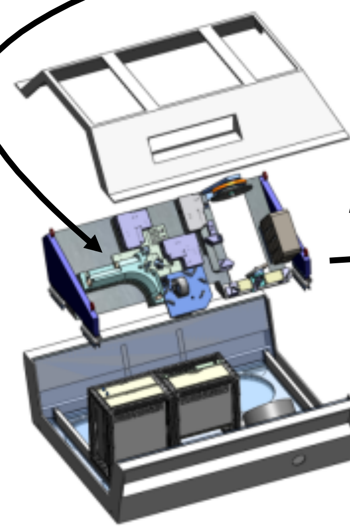
(entry TRL 3 (or 2.5 since the POC receiver uses same principles but is of a different architecture)



Shake & Bake to validate system design

Integrate into a lidar system fitting into a WB-57 pallet

(add laser, telescope, frame, data system, isolation, and autonomous control software in an environmental box)



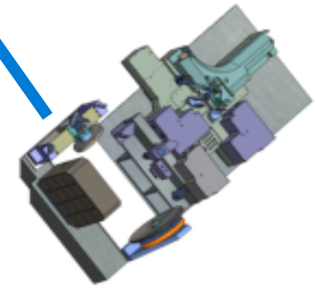
Perform Ground Validations: TRL4

Validate Concept, Design, and Wind Precision Performance Models from the NASA WB-57 aircraft: enter at TRL 3, exit at TRL 5

OAWL Validation Field Experiments

NOAA Mini-MOPA
Coherent Doppler Lidar

OAWL System



1. Ground-based-looking up

Side-by-side with the NOAA Mini-MOPA
Doppler Wind Lidar

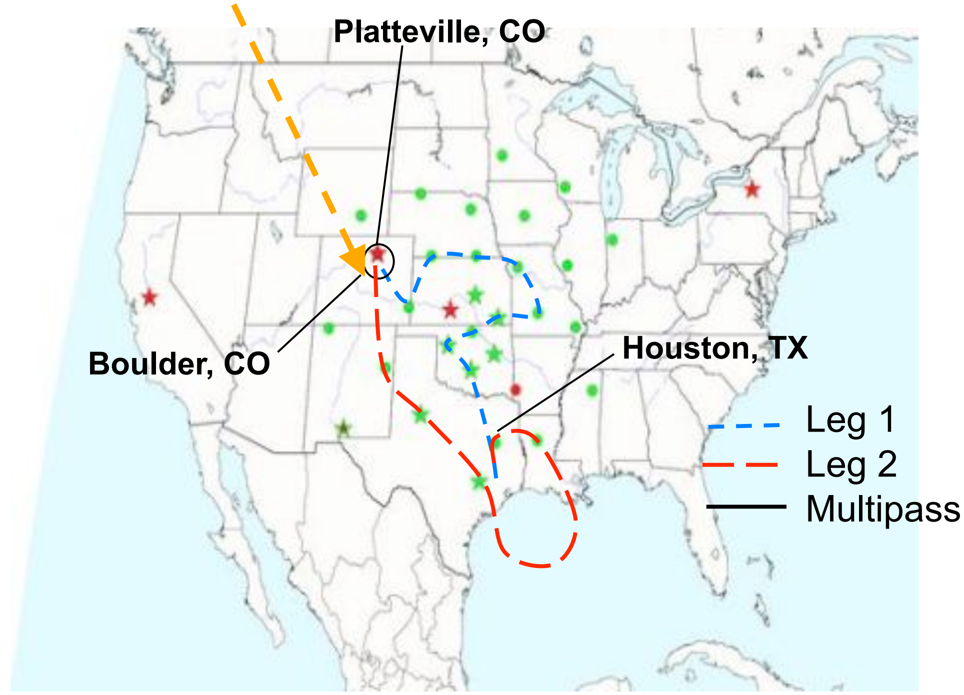
July 2010

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

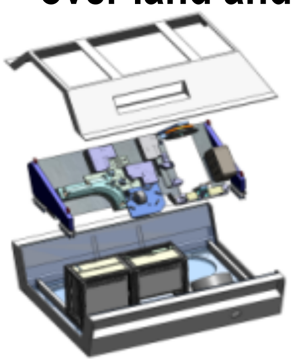
(15 km altitude looking down along 45° slant path (to inside of turns).

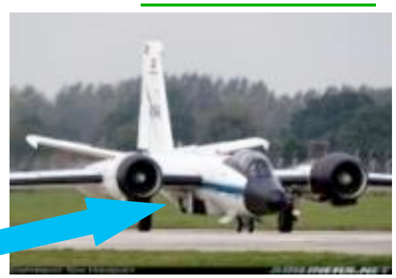
Many meteorological and cloud conditions over land and water)

Oct. 2010



** Wind profilers in NOAA operational network

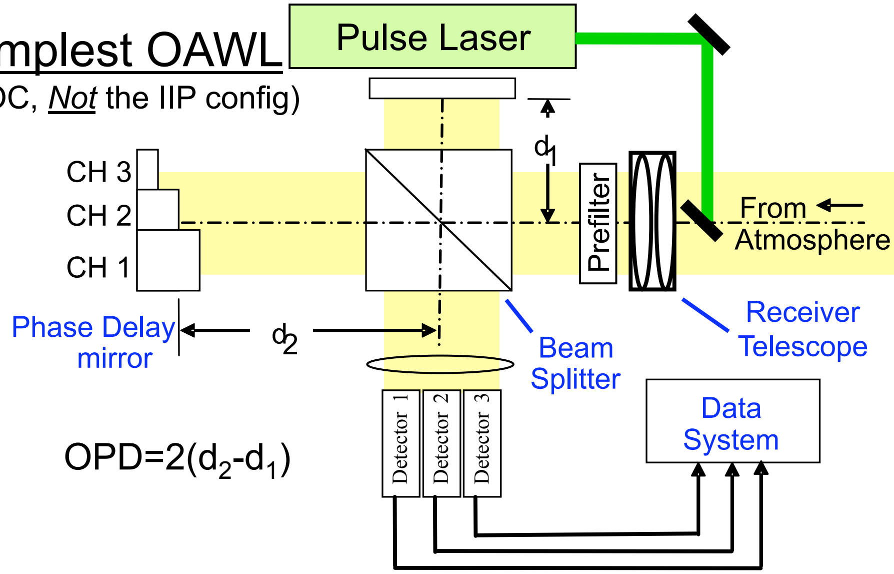




Optical Autocovariance Wind lidar (OAWL) approach

Simplest OAWL

(POC, *Not* the IIP config)



Optical Autocovariance Wind Lidar (OAWL):

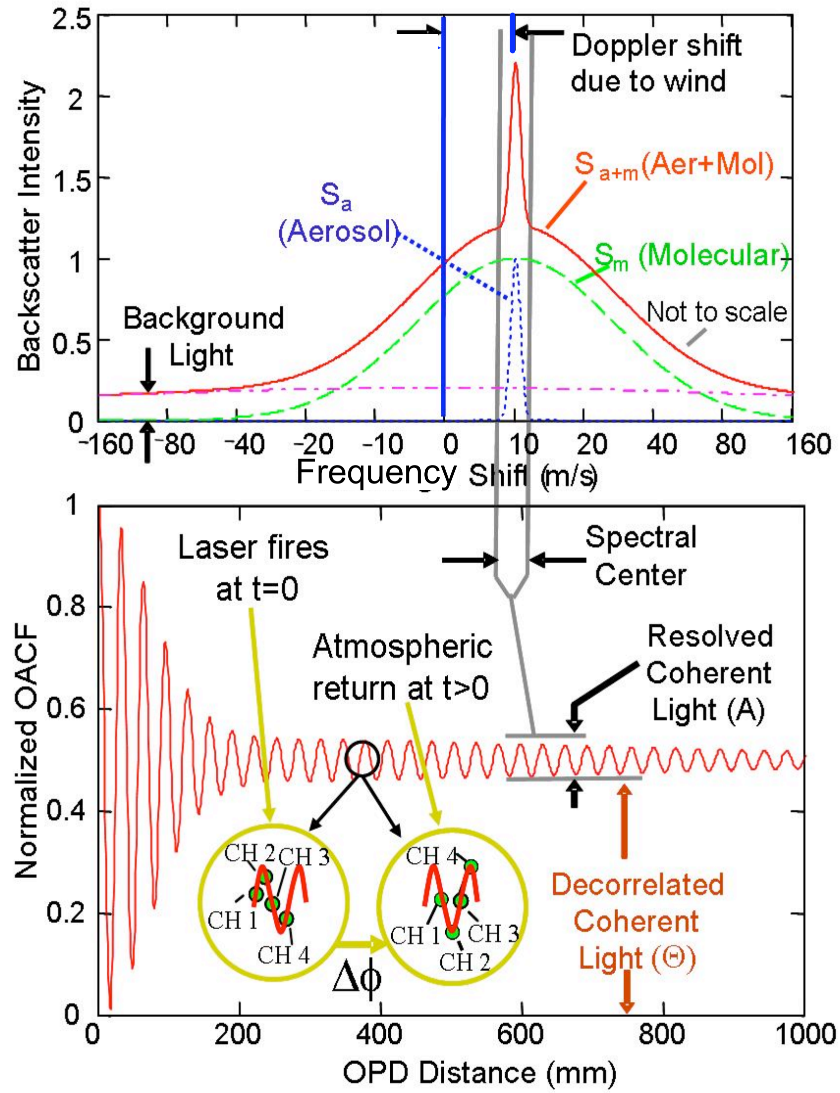
Velocity from OACF Phase: *V = l *Df * c / (2 * (OPD))*

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

$A = S_a * C_{aA} + S_m * C_{mA}$, $Q = S_a * C_{aQ} + S_m * C_{mQ}$

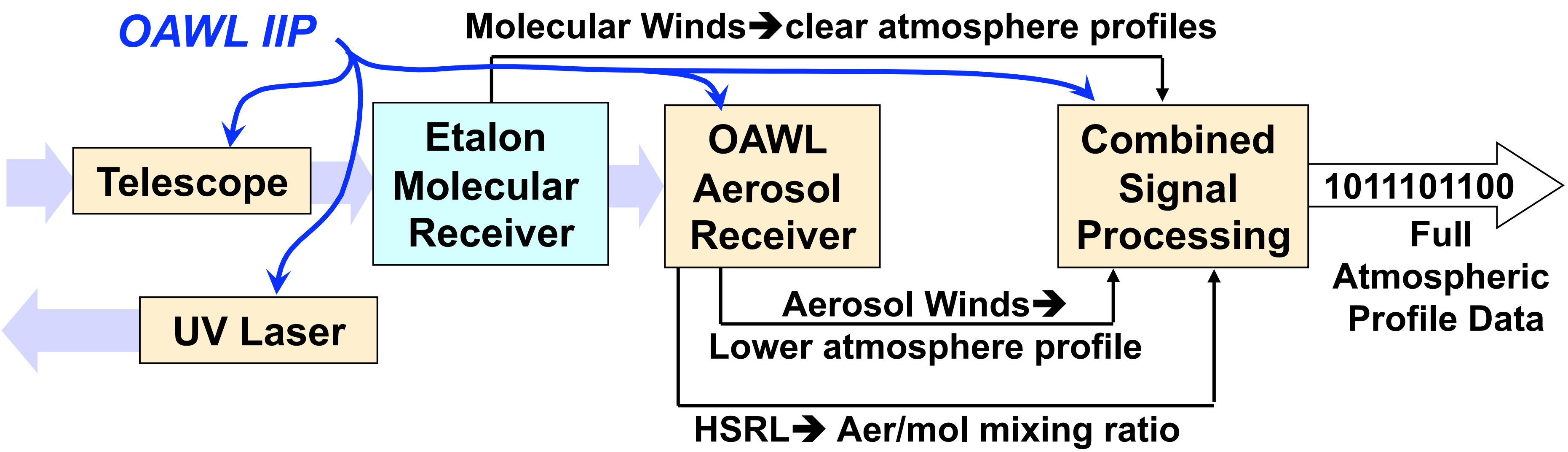
Yields: **Volume extinction cross section, Backscatter phase function, Volume Backscatter Cross section, from OACF Amplitude**

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



Df = phase shift as fraction of OACF cycle

Addressing the FULL Decadal Survey 3D-Winds Mission with an Efficient *Single-laser All Direct Detection Solution*



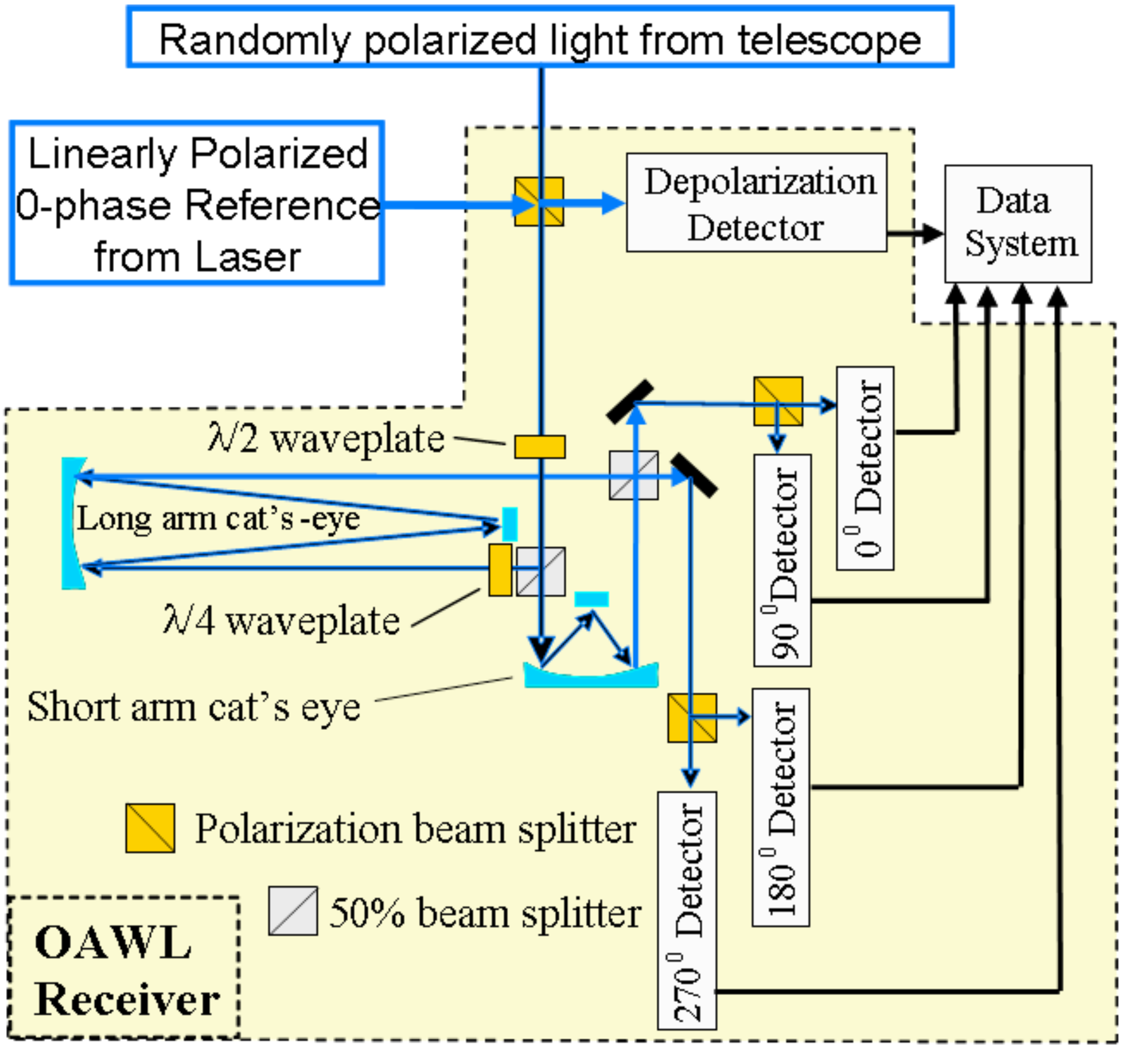
Integrated Direct Detection (IDD) wind lidar approach:

- **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**
- **OAWL 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

Ball IRAD Receiver Design Uses Polarization Multiplexing to Create 4 Interferometers in the Same space

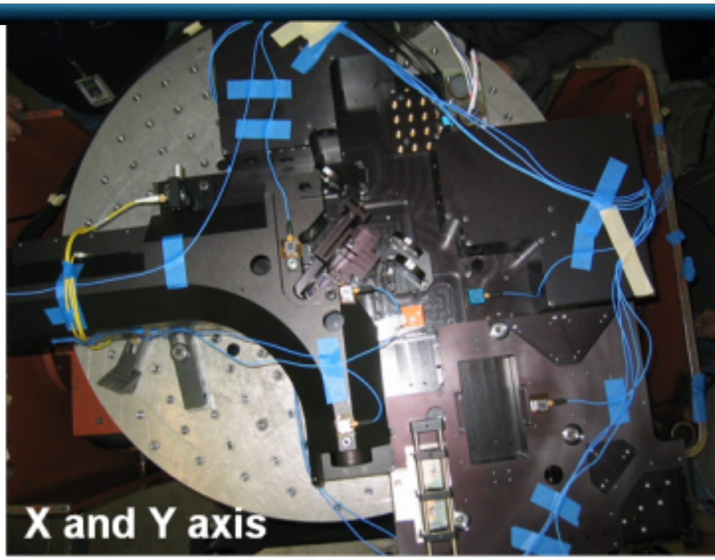
Integrated into the OAWL IIP System

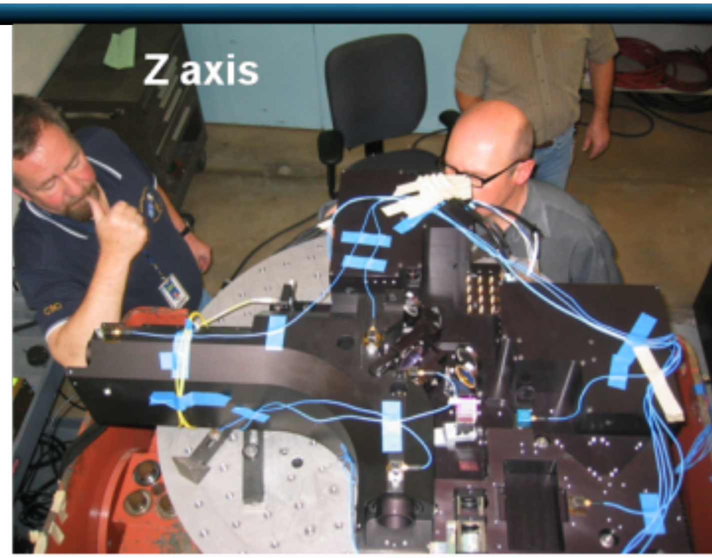


- Mach-Zehnder-like interferometer allows 100% light detection on 4 detectors
- Cat's-eyes field-widen and preserve interference parity allowing *wide alignment tolerance, practical simple telescope optics*
- Receiver is achromatic, facilitating simultaneous multi-l operations (multi-mission capable: 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 pending

IIP Task 1: Receiver Vibration Testing





Receiver and mounts instrumented with multiple accelerometers (blue wires)

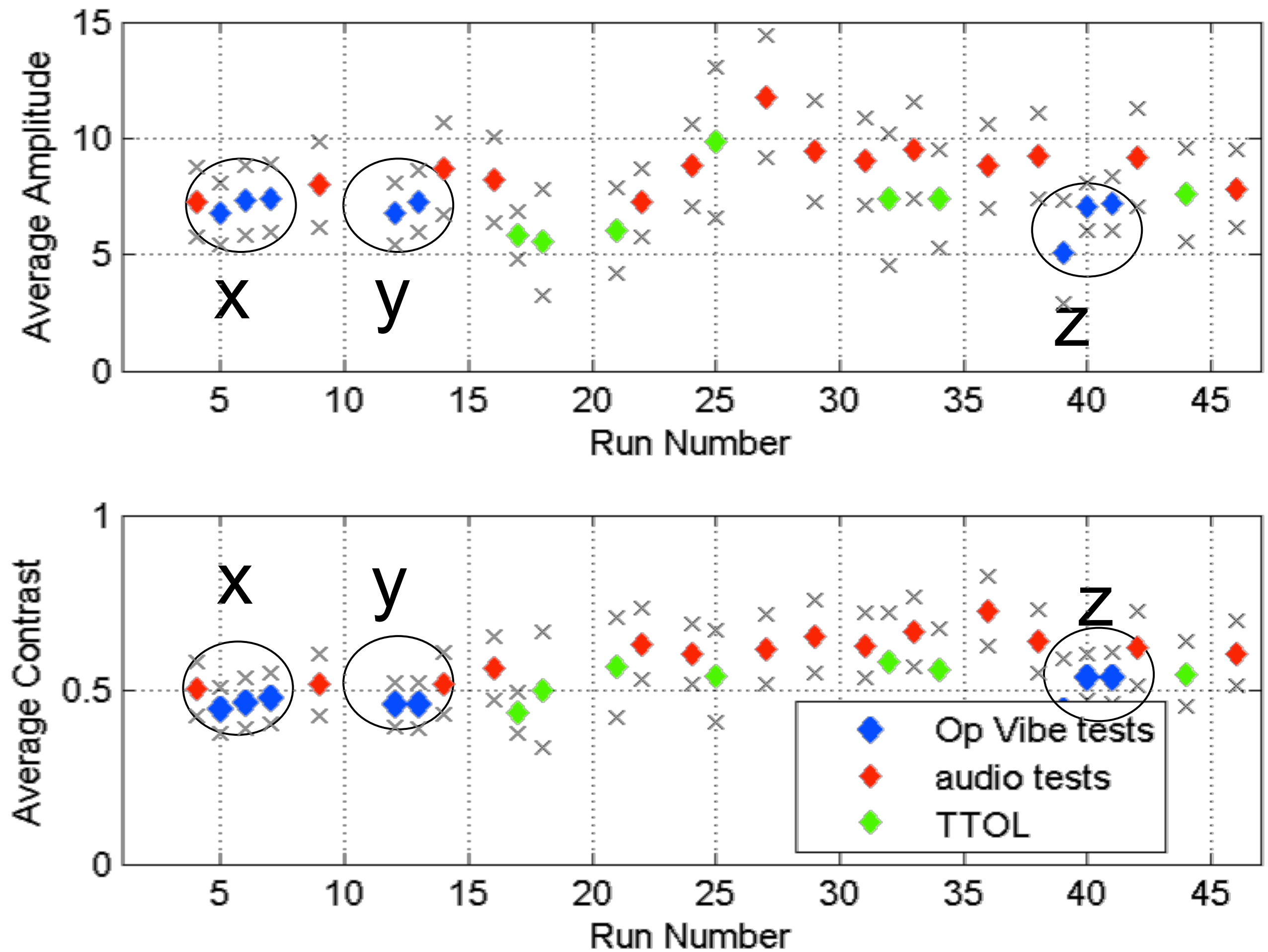
WB-57 Taxi, takeoff and landing (TTOL) shock/vibe level testing (1.78 gRMS) showed the adjustable beamsplitter needed staking to prevent alignment drifts, but the permanent interferometer alignment potting method is stable at these levels.

Operational vibe (0.08 gRMS) effects are within expectations; not expected to affect WB-57 wind measurement performance

Audio speaker used to excite on organ pipe mode within the interferometer to repeatedly sample the whole phase space between vibe tests.

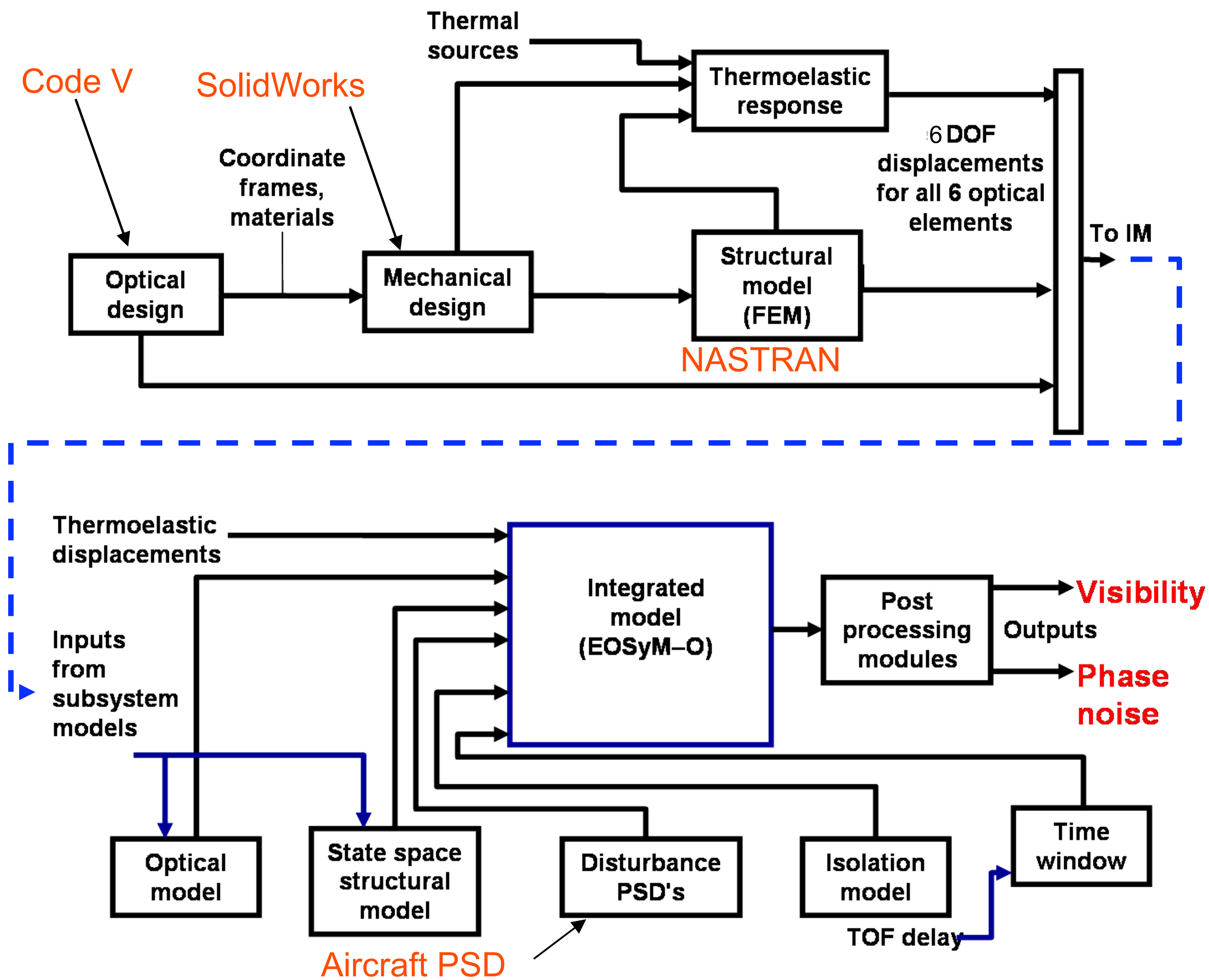
Results Summary

Average amplitude and contrast for audio and op-vibe tests, versus test number



Integrated Model Process Developed at BATC

- **Goals:**
  - <6 nm (0.11 rad phase error) vibration induced noise), 12 nm accep.
  - <5% visibility reduction due to thermoelastic distortions.
- **Main system modeling outputs**
  - Fringe visibility
  - Phase noise



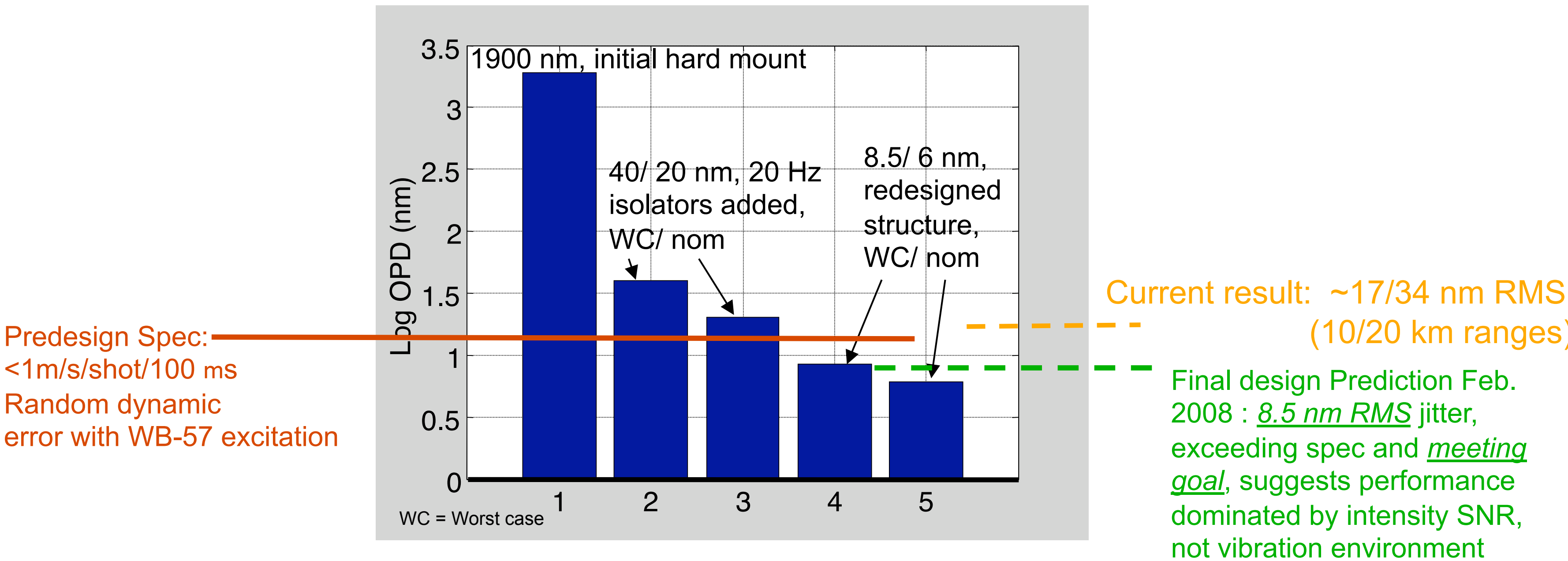
References:

M. Lieber, C. Weimer, M. Stephens, R. Demara, “Development of a validated end-to-end model for space-based lidar systems”, in SPIE vol 6681, U.N.Singh, Lidar Remote Sensing for Environmental Monitoring VIII, Aug 2007.

M. Lieber, C. Randall, L. Ayari, N. Schneider, T. Holden, S. Osterman, L. Arboneaux, "System verification of the JMEX mission residual motion requirements with integrated modeling", SPIE 5899, Aug 2005.

M. Lieber, C. Noecker, S. Kilston, “Integrated system modeling for evaluating the coronagraph approach to planet detection”, SPIE V4860, Aug 2002

Integrated Model – Design Iteration: Vibration-Induced Phase Noise Convergence on Specification



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 not quite validated.

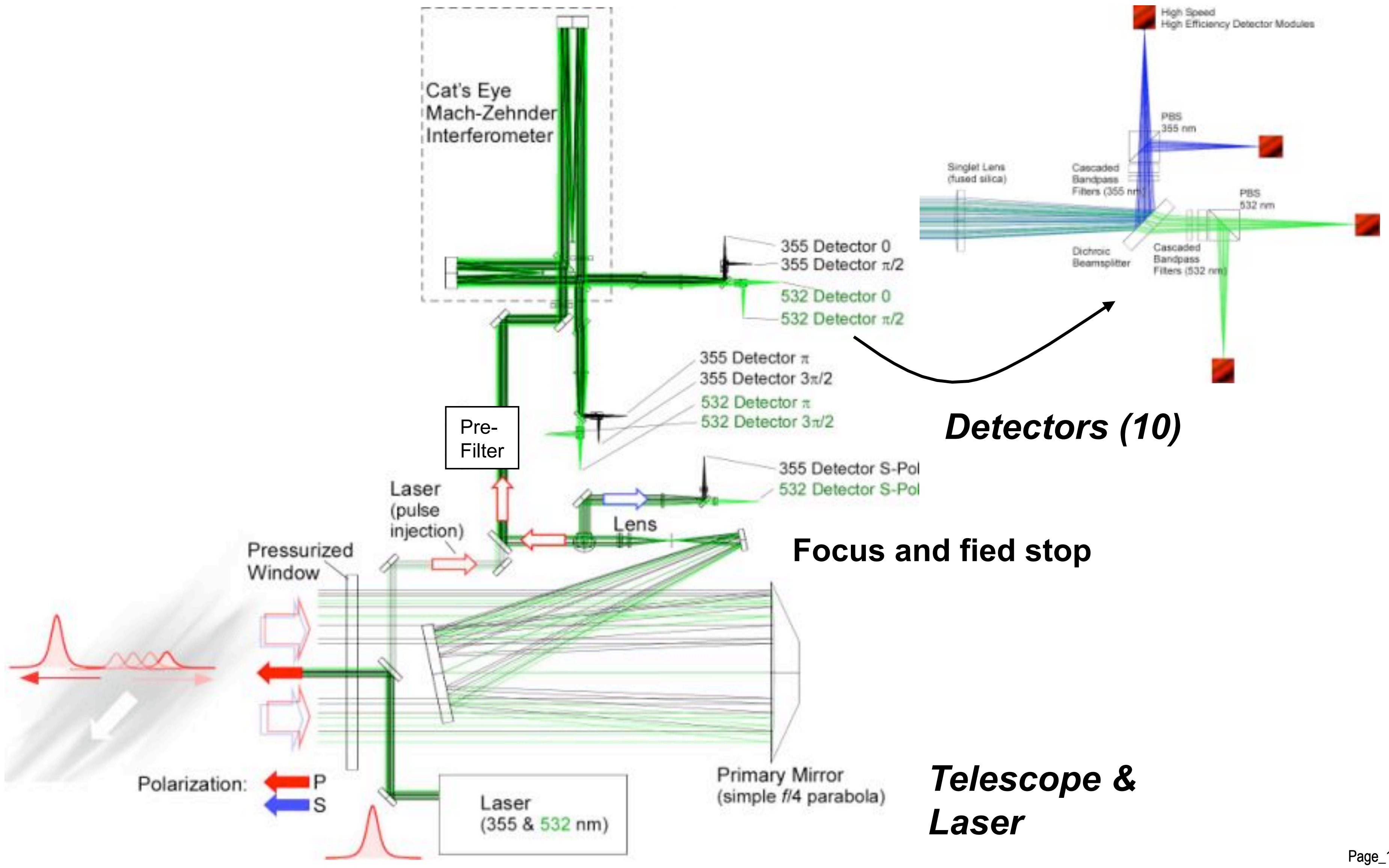
IIP Upshot: >4000 pulse returns will be averaged per wind profile suggesting the operational vibe induced errors will be ~0.07 m/s (10 km) per profile (insignificant)

Summary of vibration effects on precision

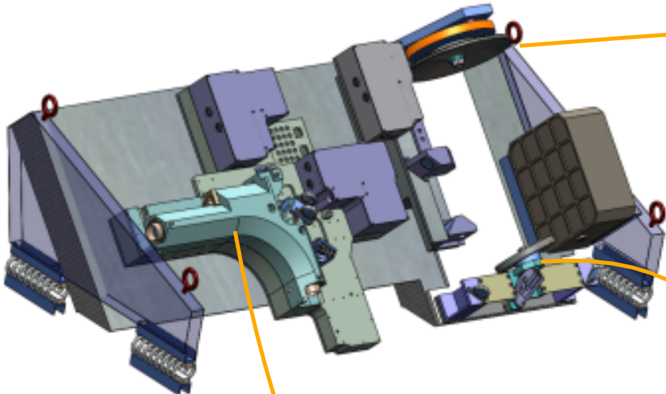
Vibe axis	OPD Standard Deviation (10/20 km)	Velocity precision - per shot	Precision w/ 1-second averaging
X	15/31 nm	2.3/4.6 m/s	16/33 cm/s
Y	19/38 nm	2.8/5.6 m/s	20/40 cm/s
Z	7/13 nm	1.0/2.0 m/s	7/14 cm/s

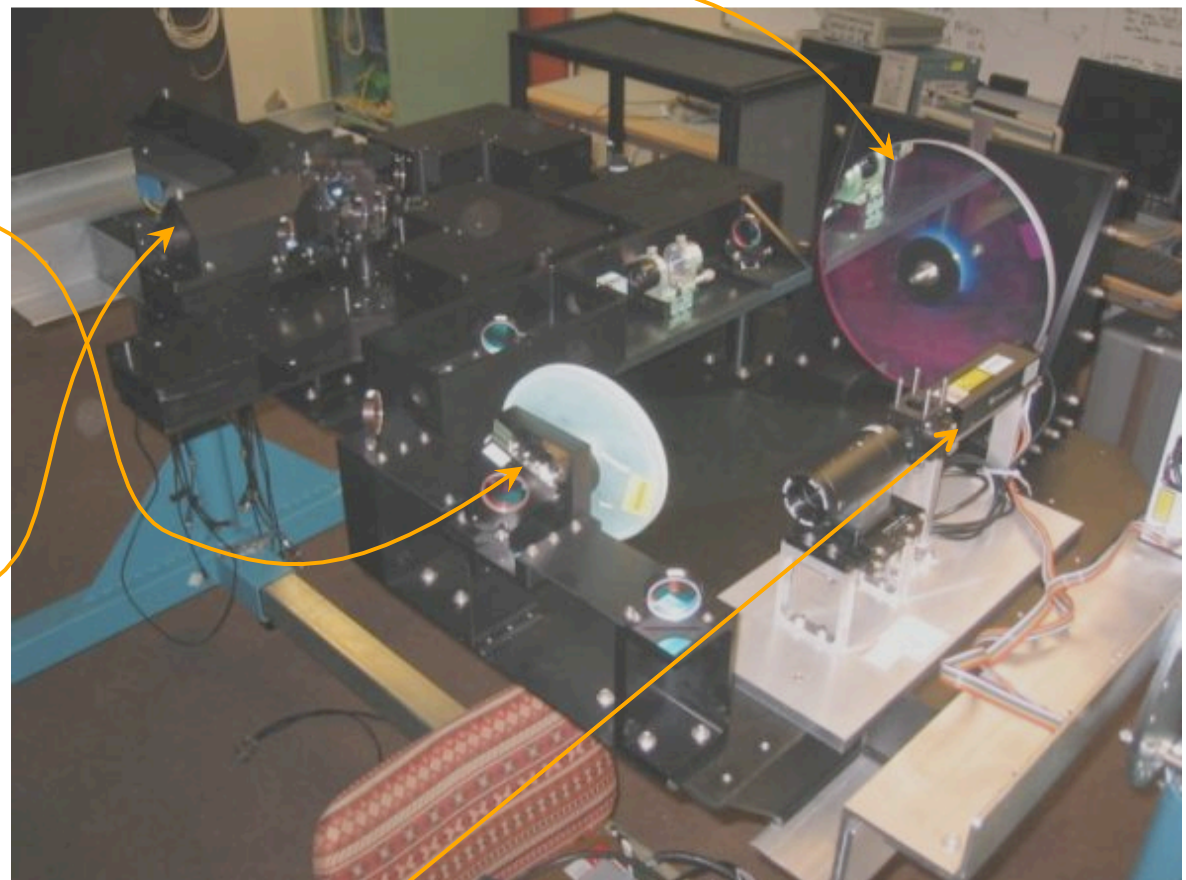
We have up to 20 seconds to average each profile and need to demonstrate <0.5 m/s precisionWe see s < 0.09 m/s due to vibe: ***Good to go!***

OAWL IIP Optical System Schematic



OAWL IIP System – Asssembled and Aligned, Ready for Ground Tests and Validations (except for laser!)



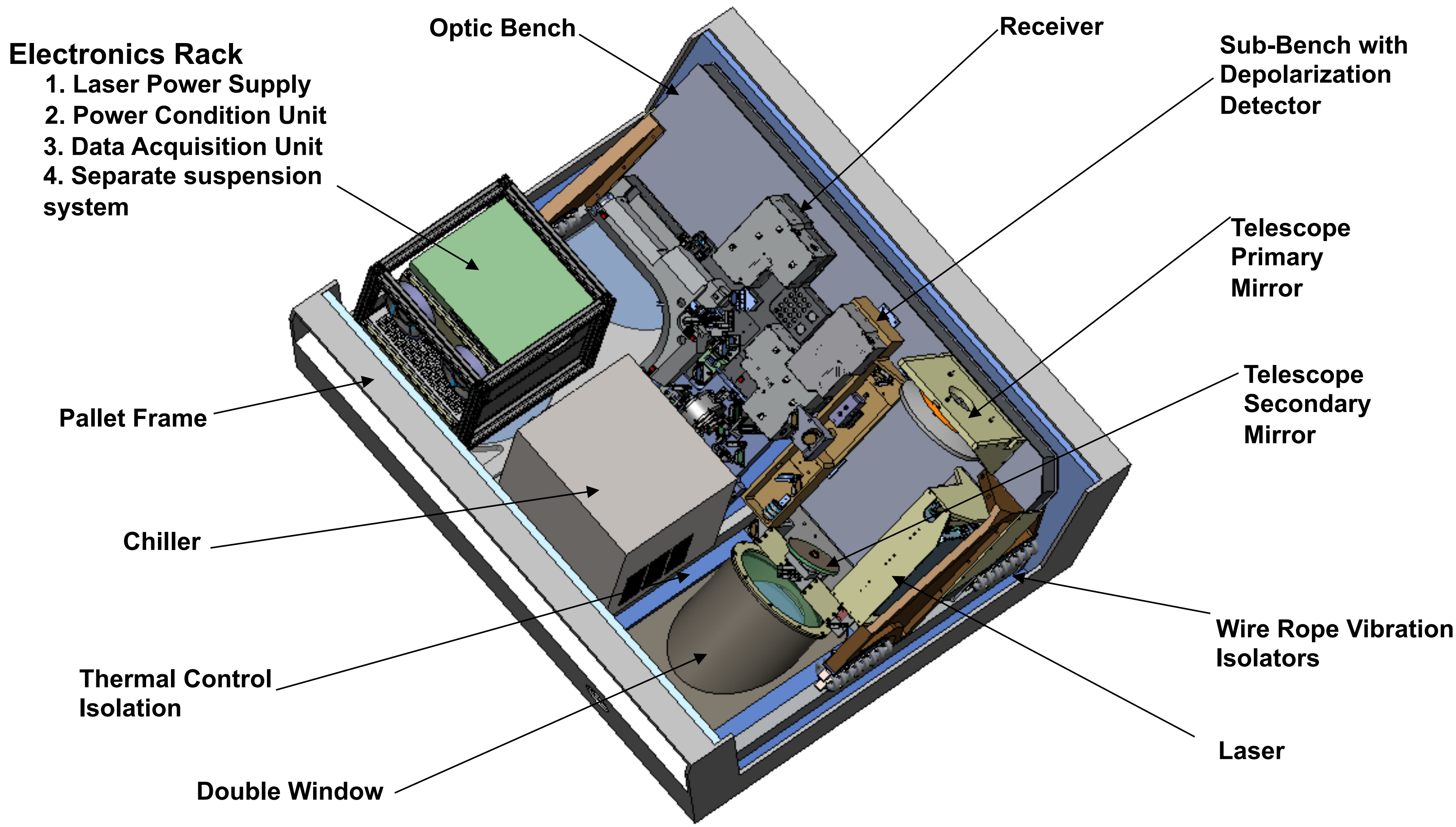


Waiting on Fibertek laser
(~6 mos late, expect within weeks)

Surrogate Laser 1
(50 mJ/pulse, 523 nm)
11 ns wide

Surrogate Laser 2
(2.5 mJ/pulse, 532 nm)
3 ns wide➔ *5X bandwidth*

OAWL IIP System in WB-57 Pallet



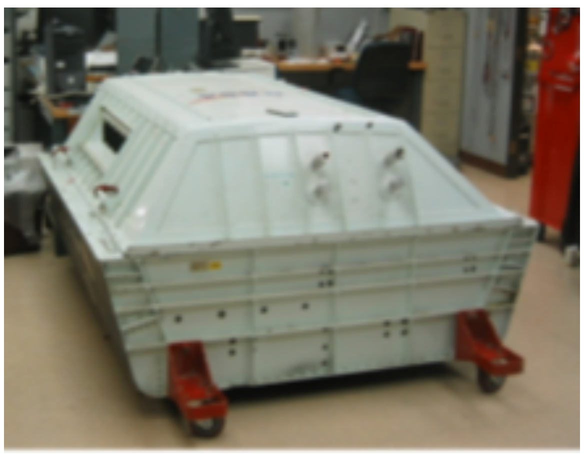
OAWL IIP System Parameters

- The OAWL optical system fits inside the pressurized pallet mounted with wire rope isolators to the pallet frame.
- The optical system is mounted 45 deg to the base of the pallet.
- The double window approach provides symmetric wave front distortion

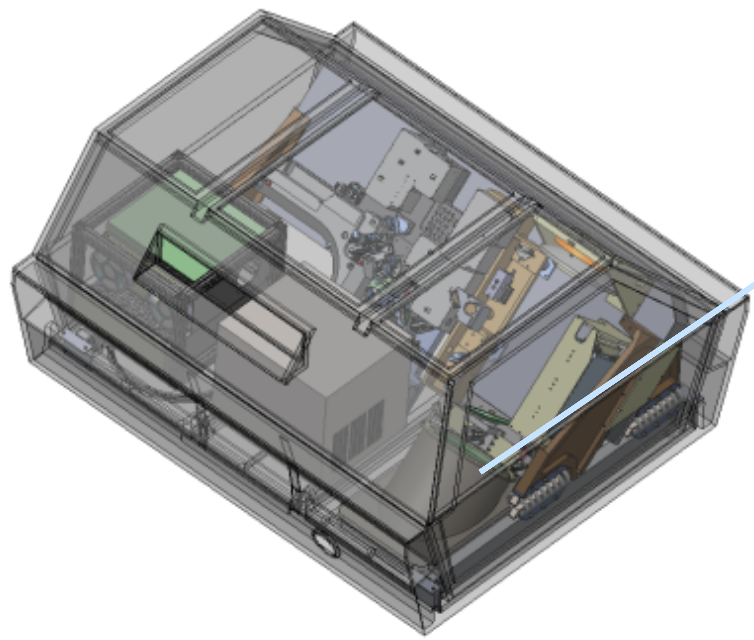
- OAWL System Mass – 202 kg
- Electronics Mass – 111 kg
- Thermal Control Enclosure – 10 kg
- Laser – 10 kg
- Telescope – 27 kg
- Sub-Bench – 17.7 kg
- Miscellaneous (10 % of Total) - 38kg

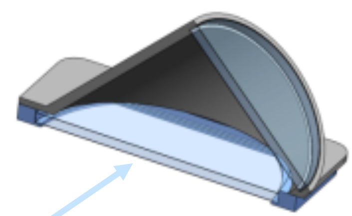
- Total – 415 kg

- Total (With 20% Uncertainty Factor Applied) - 500 kg



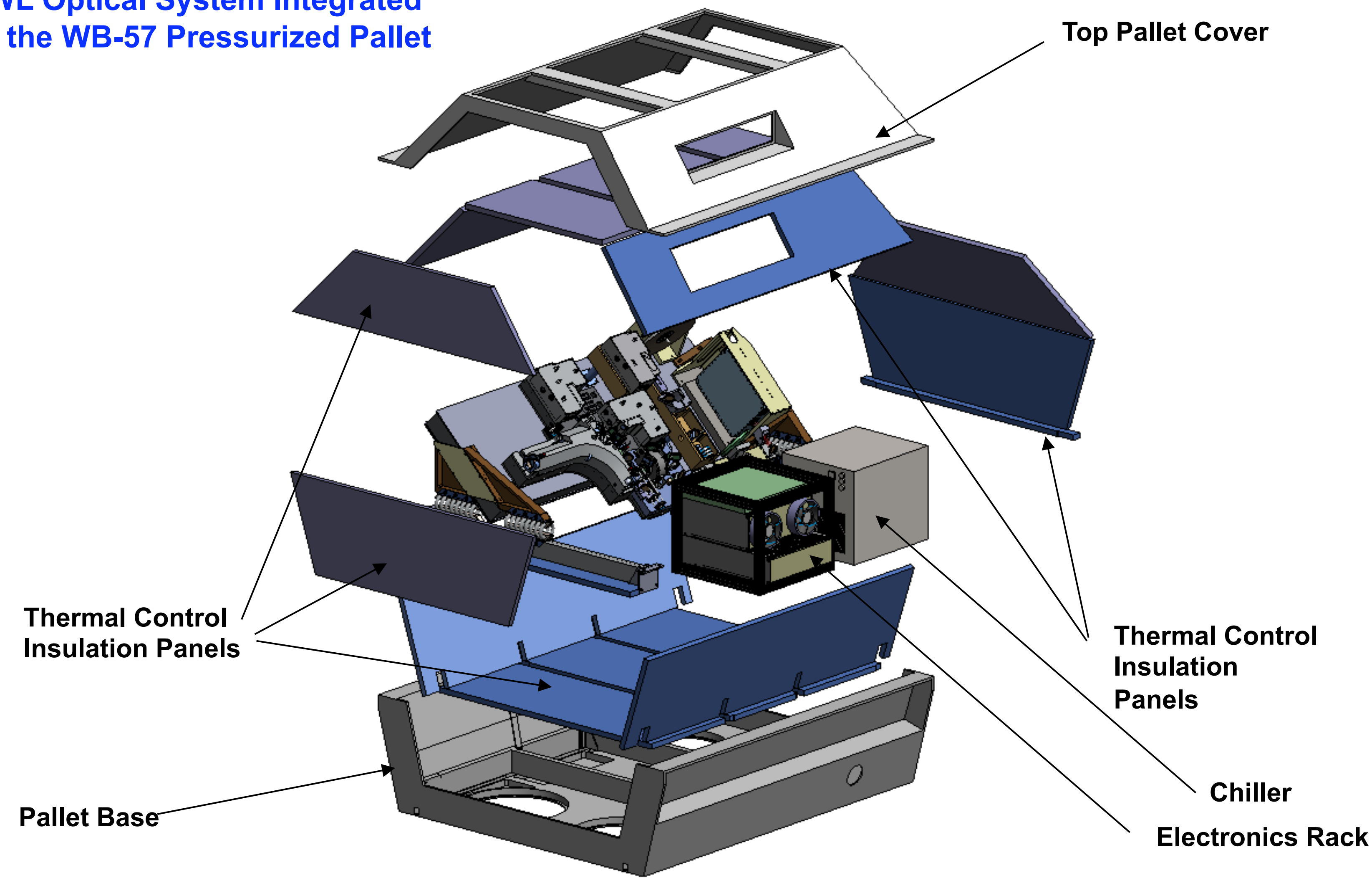
6' pressurized WB-57 pallet





IIP Optical System Exploded View

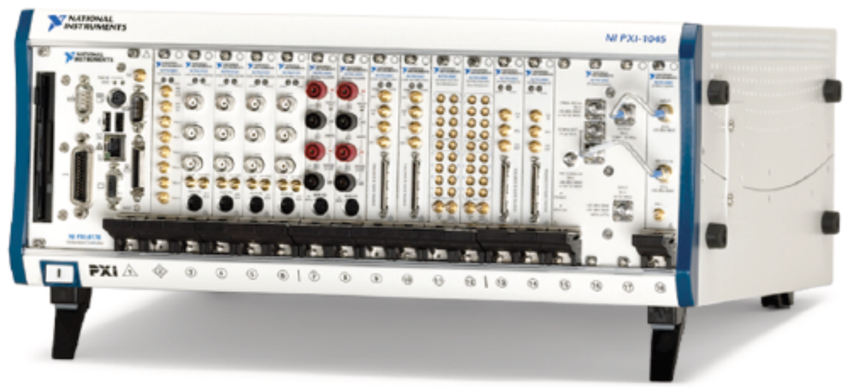
OAWL Optical System Integrated Into the WB-57 Pressurized Pallet



OAWL Data System

Data acquisition system cards:

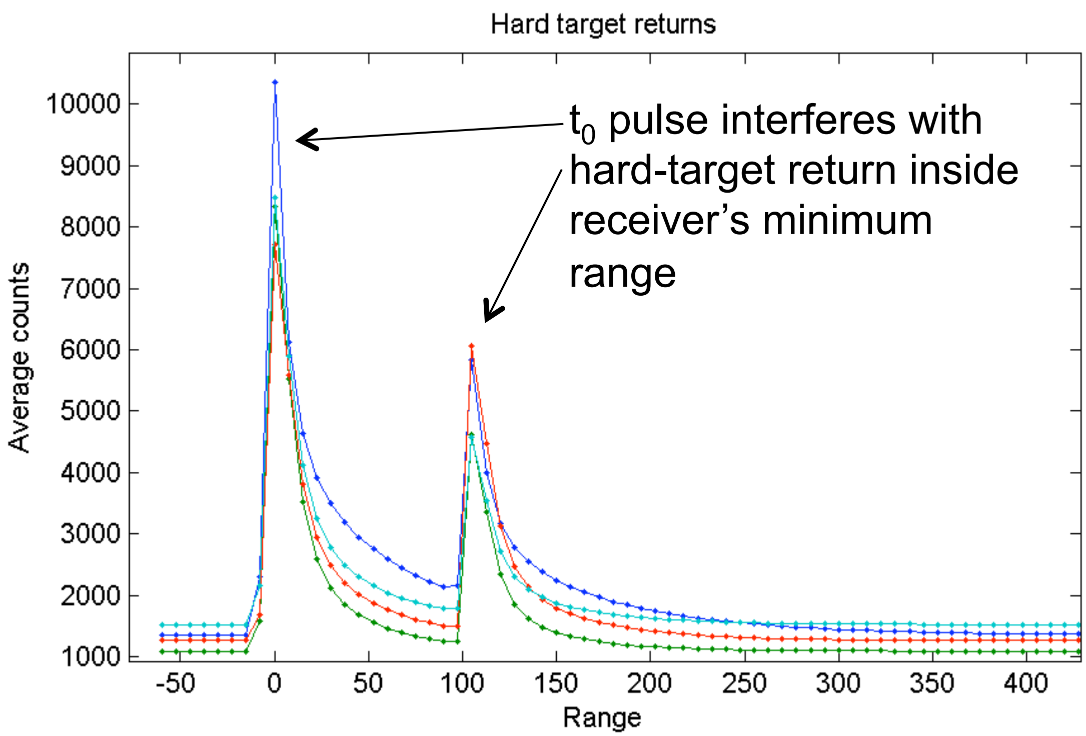
- National Instruments
  - Processor
    - Processing and data storage
      - Solid state hard drive
  - DMM Card
    - Measures housekeeping data
  - Switch Matrix Card
    - Switches through housekeeping sensors
  - Firewire Card
    - Acquires images from camera
  - DAQ
    - Acquires real-time accel data
    - Provides status bits to cockpit switches
- AIM
  - ARINC 429 Card
    - Ingests aircraft IMU and GPS data
- Custom
  - *Photon Counting* - 10 channels
    - Acquires data from detectors
  - *Analog digitizers* - 10 channels
    - Acquires data from detectors



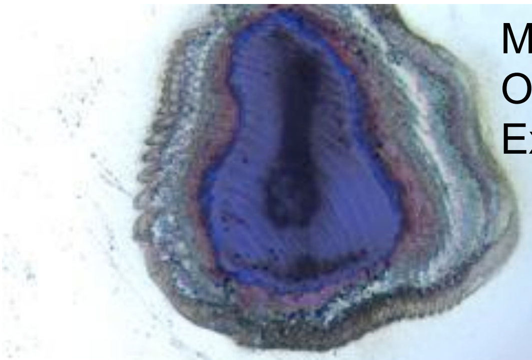
- + extra booster fans for 5 PSI ops
- Plan to test in environmental chamber

Preliminary Data: It's a lidar, winds in progress

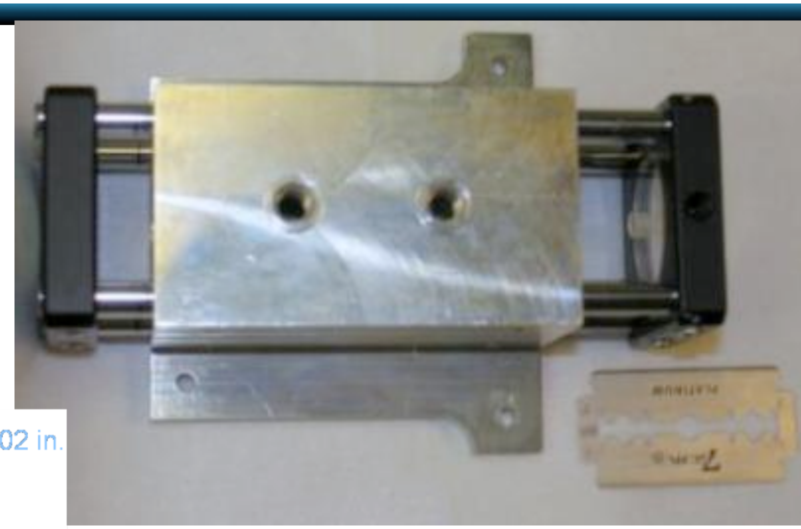
- Using temporary 532 nm laser with 3.1 ns pulses (>7X bandwidth → 8-10X lower SNR)
- ~2.5 μJ pulses (vs. 20-30 mJ) 100X lower SNR
- Hard target returns observed - allowing full testing of the data system – but low SNR with this laser bandwidth severely reduces the contrast of system.

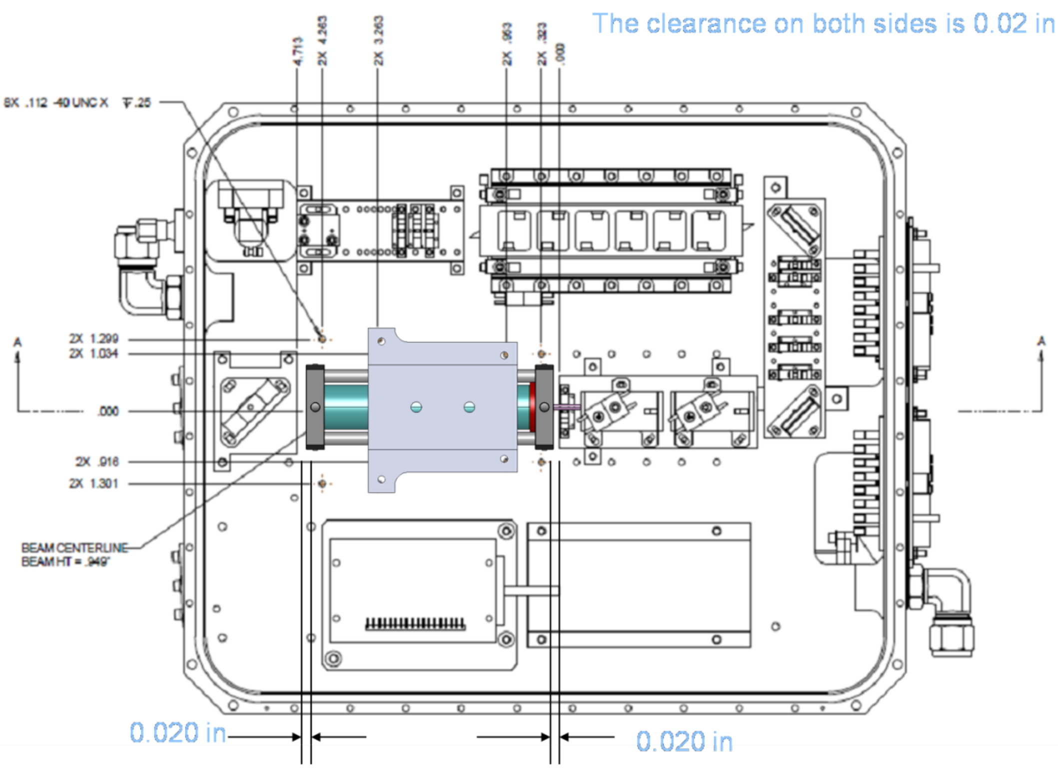


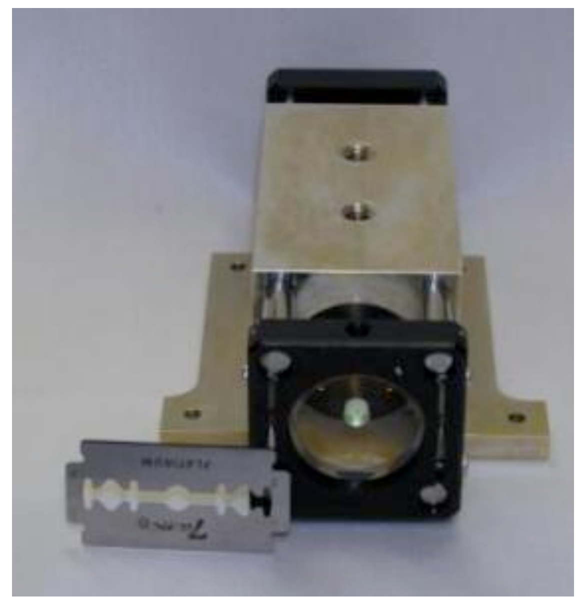
Beam Expander



Micrograph of
Optical damage on
Expander secondary







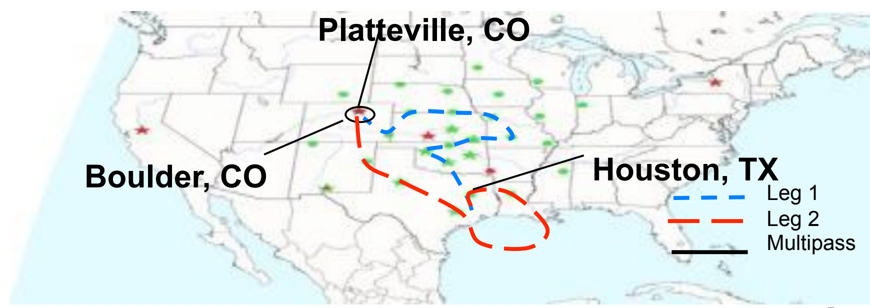
OAWL and NOAA's mini-MOPA comparison

General plan:

- LOS comparisons between OAWL and NOAA's mini-MOPA Coherent Detection Doppler lidar.
- OAWL
  - Will be located inside the NOAA Table Mountain T2 building
  - Enclosed facility with 2 windows providing eastern and northern/northeastern views
- mini-MOPA
  - Container on trailer parked outside.
  - LOS pointing may be interspersed with VAD scans to provide contextual wind information

Airborne Deployment Plan

- Pre-ship
  - Pallet shipped from Boulder, fully integrated
    - Shipped via air-ride motor carrier
- Pre-flight Day 1 (Monday, 18 October):
  - Hardware (via motor freight) & personnel arrive at Ellington. Unpack equipment and prep for functional pre-integration operational tests in lab
- Pre Flight Day 2 (Tuesday 19 Oct):
  - Ball conducts functional pre-integration operational tests in lab
- Pre-Flight Day 3 (Wednesday, 20 Oct):
  - Integrate pallet onto WB-57. Perform ground operational tests.
- Pre-Flight Day 4 (Thursday, 21 Oct):
  - Conduct TRR. Finalize flight plans
- Pre-Flight Day 5 (Friday, 22 Oct):
  - Slack day/ travel day for select personnel to allow meeting plane in Colorado.
- Flight Day 1 (Monday, 25 October):
  - Depart Ellington, conduct data flight, @ FL 500 land Denver area. Total flight time: 6 hours
- Flight Day 2 (Tuesday, 26 October):
  - Denver local data flight @ FL 500. Total flight time: 6 hours
- Flight Day 3 (Wednesday, 27 October):
  - Depart Denver area, conduct data flight @ FL 500, land Ellington. Total flight time: 6 hours
- Post-flight day 1 (Thursday, 28 Oct):
  - Offload pallet from WB-57. Pack equipment and ready for shipment to Boulder, CO.
- Post flight day 2 (Friday, 29 Oct):
  - Ship equipment. Ball personnel depart home.



Conclusions

- *An Optical Autocovariance wind lidar (OAWL) 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 OAWL system has been designed fabricated and integrated*
- *First light is achieved but winds are awaiting final laser delivery (expected within weeks)*
- *Plans/logistics for ground validations against a NOAA Coherent Doppler Wind Lidar are in place, expected in the next few months*
- *Components are designed that support installation of the OAWL system in a WB-57 aircraft and autonomous operation*
- *Flight tests from the WB-57 are planned for October 2010*