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

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* presenter
“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 \text{ mm} wavelength to accurately measure winds from aerosol backscatter \textit{when present} with a direct detection double-edge etalon DWL at 355 \text{ 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. \textit{Promising lower cost, mass, complexity}

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

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

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

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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
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)

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

Perform Ground Validations: TRL4
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): Velocity from OACF Phase:
\[ V = f * Df * C / (2 * (OPD)) \]

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-frequency operation

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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-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
Receivers and mounts instrumented with multiple accelerometers (blue wires) were used for vibration testing. WB-57 Taxi, takeoff and landing (TTOL) shock/vibe level testing (1.78 gRMS) showed that 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

![Graph showing average amplitude and contrast for audio and op-vibe tests](image)
Integrated Model Process Developed at BATC

- **Goals:**
  - <6 nm (0.11 rad phase error) vibration induced noise), 12 nm accp.
  - <5% visibility reduction due to thermoelastic distortions.

- **Main system modeling outputs**
  - Fringe visibility
  - Phase noise

References:


Code V  SolidWorks

Optical design  Mechanical design

Thermal sources

Thermoelastic response

6 DOF displacements for all 6 optical elements

To IM

NASTRAN

Aircraft PSD

Post processing modules

Integrated model (EOSyM-O)

Visibility

Outputs

Phase noise

Time window

Thermoelastic displacements

Inputs from subsystem models

Optical model

State space structural model

Disturbance PSD's

Isolation model

TOF delay

References:
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

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

<table>
<thead>
<tr>
<th>Vibe axis</th>
<th>OPD Standard Deviation (10/20 km)</th>
<th>Velocity precision - per shot</th>
<th>Precision w/ 1-second averaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>15/31 nm</td>
<td>2.3/4.6 m/s</td>
<td>16/33 cm/s</td>
</tr>
<tr>
<td>Y</td>
<td>19/38 nm</td>
<td>2.8/5.6 m/s</td>
<td>20/40 cm/s</td>
</tr>
<tr>
<td>Z</td>
<td>7/13 nm</td>
<td>1.0/2.0 m/s</td>
<td>7/14 cm/s</td>
</tr>
</tbody>
</table>
OAWL IIP System – Assembled 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

1. Laser Power Supply
2. Power Condition Unit
3. Data Acquisition Unit
4. Separate suspension system

Optic Bench
Receiver
Sub-Bench with Depolarization Detector
Telescope Primary Mirror
Telescope Secondary Mirror
Wire Rope Vibration Isolators
Laser
Chiller
Thermal Control Isolation
Double Window
Pallet Frame
Electronics Rack

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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

Double Window Reduces Astigmatism Due to bowing
IIP Optical System Exploded View

OAWL Optical System Integrated Into the WB-57 Pressurized Pallet

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Top Pallet Cover

Thermal Control Insulation Panels

Pallet Base

Chiller Electronics Rack

Thermal Control Insulation Panels
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.

![Graph showing hard target returns with t₀ pulse interfering with hard-target return inside receiver’s minimum range.](image-url)
Beam Expander

Micrograph of Optical damage on Expander secondary

The clearance on both sides is 0.02 in.
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