Direct measurement of crosswinds to remotely sense 3-D wind-velocity vectors

Devon G. Crowe*,1,3 Mark A. Neifeld,2,3 Jaime A. Anguita,4 and Anthony D. Gleckler5

1Raytheon Company, Space and Airborne Systems
El Segundo, CA 90245 USA
2Department of Electrical and Computer Engineering, University of Arizona
3College of Optical Sciences, University of Arizona,
Tucson, AZ 85721 USA
4College of Engineering and Applied Sciences
University of the Andes, Santiago 7620001, Chile
5GEOST, 7616 N La Cholla Blvd., Tucson, AZ 85741 USA

*Corresponding author: devon@raytheon.com

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We present a method for directly measuring the local 3-D wind-velocity vector using 1-D Doppler combined with a range-resolved 2-D crosswind measurement that is performed by tracking the displacement of atmospheric turbulence cells over time.

- Previous work on measuring crosswinds has either used modeling based solely on lidar Doppler wind measurement along the line of sight for multiple directions of regard [1], or provided passive path-integrated observations of crosswind [2, 3].

A pattern of Shack-Hartman spots that defines the signature of the atmospheric turbulence cells is used to determine its shift due to cross-wind [14], and the angle of rotation is used to determine range using a CGH vortex method [9].
## Choices for wind vector measurement using atmospheric turbulence characterization

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**Image-Plane Space-Domain Example**

- **View A** – Two consecutive turbulence images separated by 30 ms.
- **View B** – Correlation of the two frames shown in View A: left image shows a 2-D correlation pattern and the right image shows a line scan through the correlation peak.
- **View C** – Initial results showing estimated wind speed versus actual wind speed for 30ms frame time. All wind is horizontal for these examples.
Image-Plane Temporal-Domain Example

- **View A** – System utilizing small array of high-speed photo-detectors.
- **View B** – Power spectrum from central photo-detector for wind speed = 2 ms.
- **View C** – Power spectrum from central photo-detector for wind speed = 10 ms.
Pupil-Plane Space-Domain example

- Tracking wind displacement of atmospheric aberrations in a laser radar wavefront allows direct 2-D crosswind velocity vector measurement.
- This example system considers a 0.355-μm wavelength, rather than the more common choice of 1.5 μm to measure crosswinds in each range bin [4].
  - This choice of wavelength lies in an eyesafe region of the spectrum and offers a large increase in atmospheric return over the common choice mentioned above, as well as a much smaller atmospheric coherence length. These advantages allow using less laser power and smaller optics.
- An optical vortex (axial rotation) method for range binning is used [9], which reduces the computational requirements and reduces electronics cost, power and complexity.
Choosing a Wavelength

- For portable applications such as rifle sights, there are advantages to a short wavelength to reduce the size of the optics. A near-UV eye safe [4] wavelength of 0.355 micrometers is chosen in this example.

- Atmospheric transmission modeling indicates useful range can be obtained.

<table>
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<th>Wavelength (nm)</th>
<th>Advantages</th>
<th>Disadvantages</th>
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| 300 to 350      | 300× the molecular atmospheric return  
                 Much higher aerosol return  
                 6× smaller optics diameter can sample the atmospheric coherence length  |
|                 | Laser technology less mature  
                 Less penetration of dust and smoke  |
| 1500 to 1600    | More mature laser and FPA hardware  
                 Better penetration of dust and smoke  |
|                 | Very low atmospheric return  
                 Larger atmospheric coherence length requires larger aperture for spatial wavefront domain  |
Optical Vortex Ranging

- Piestun has demonstrated [9] rotation of an illumination pattern for ranging.
- For the intended application of this example fine range resolution is not required, which enables a very low hardware cost ranging method.
Wavefront Wind Drift Tracking

Wavefront Imaging Enables Tracking Wind in Two Dimensions

Alternate Architecture

Shamir-Crowe-Rhodes Wavefront Sensor
Summary

- Some applications of crosswind measurements are not amenable to multi-directional-look Doppler methods.
- Atmospheric turbulence perturbs optical wavefronts, which produces observables that characterize atmospheric motion [“wind”].
- Single directional-look measurement of range resolved 3-D wind vectors can be performed by combining atmospheric cell tracking from 2-D wavefront motions perpendicular to the line of sight with along-line-of-sight 1-D Doppler data.
- Hardware constraints for an example system were alleviated using optical vortex range resolution and the choice of a 355 nanometer wavelength.
REFERENCES