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

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Introduction

- 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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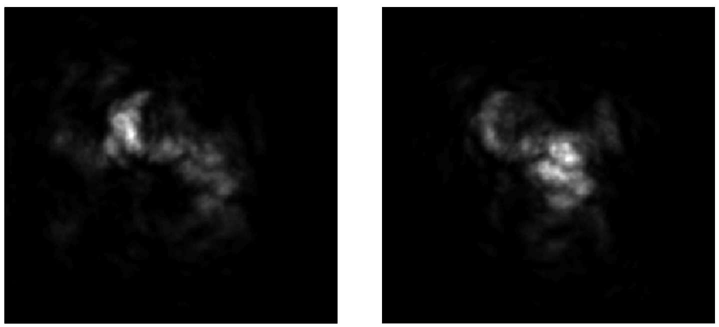
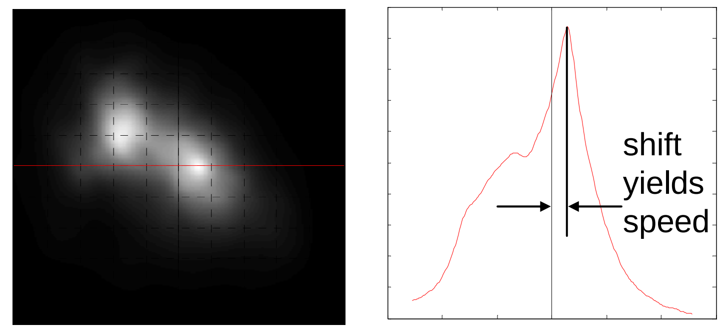
	Time domain	Space domain
Image plane	Temporal correlation	Target image motion
Pupil plane	Temporal correlation	Wavefront motion

Image-Plane Space-Domain Example

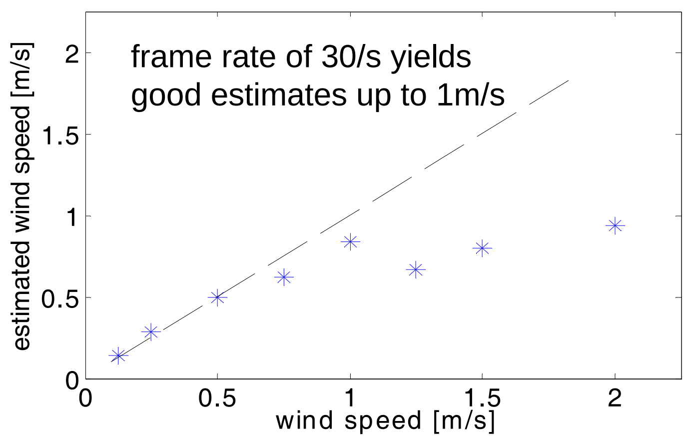
- **View A** – Two consecutive turbulence images separated by 30 ms.
- **View B** – Correlation of the two frames shown in View A: left image shows a 2-D correlation pattern and the right image shows a line scan through the correlation peak.
- **View C** – Initial results showing estimated wind speed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



(A)



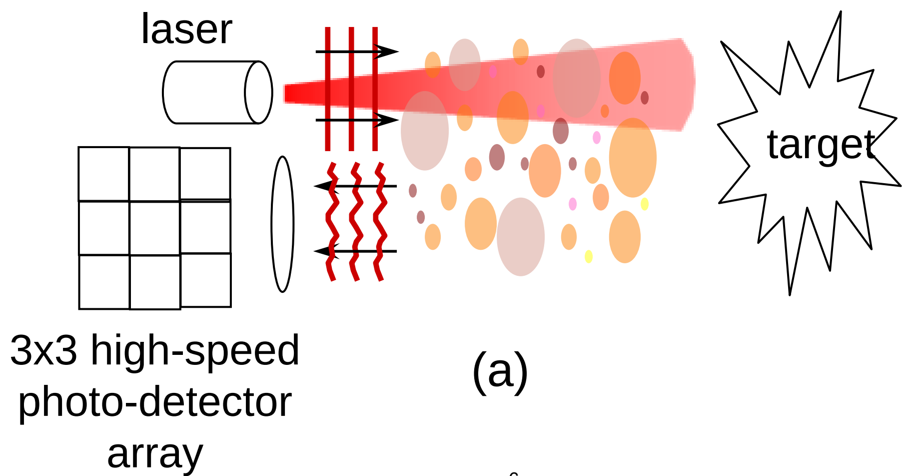
(B)



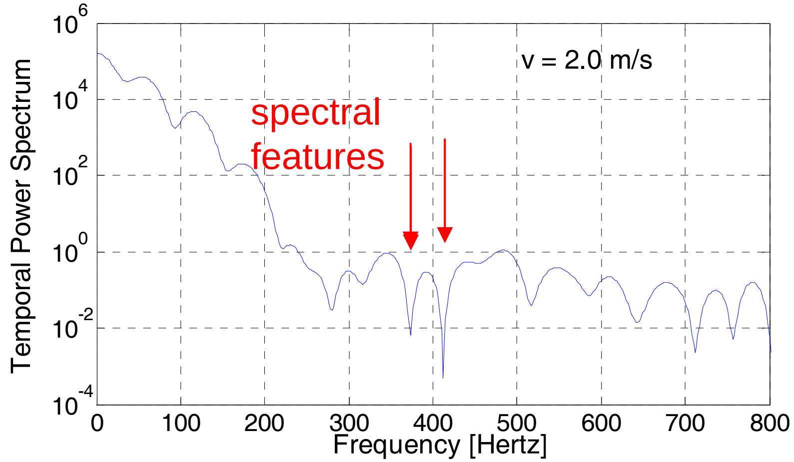
(C)

Image-Plane Temporal-Domain Example

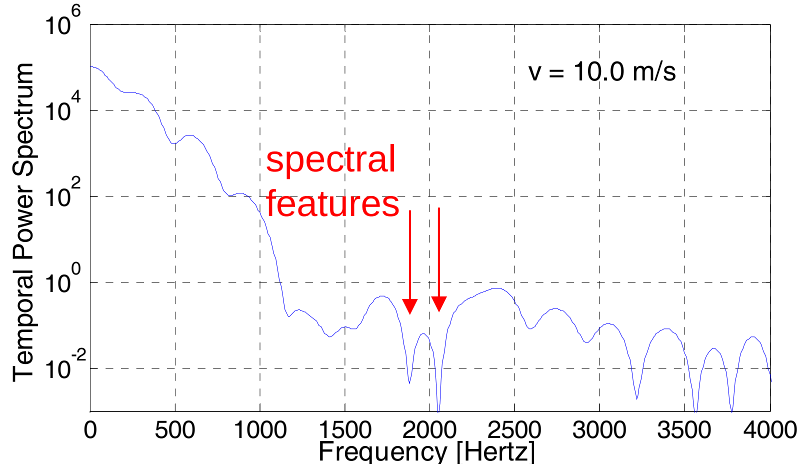
- **View A** – System utilizing small array of high-speed photo-detectors.
- **View B** – Power spectrum from central photo-detector for wind speed = 2 ms.
- **View C** – Power spectrum from central photo-detector for wind speed = 10 ms.



(a)



(b)



(c)

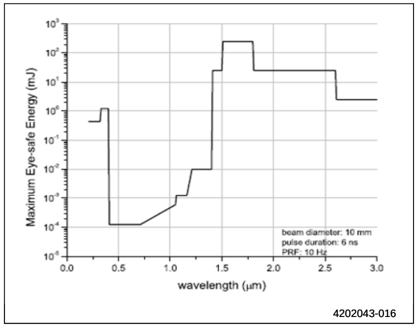
Pupil-Plane Space-Domain example

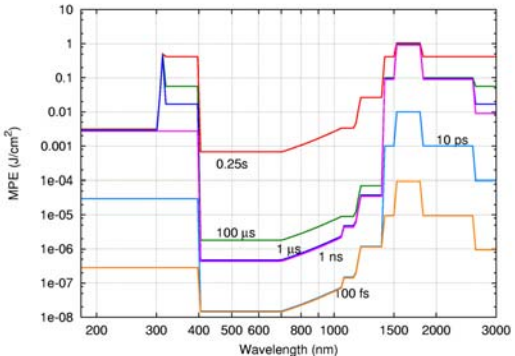
- Tracking wind displacement of atmospheric aberrations in a laser radar wavefront allows direct 2-D crosswind velocity vector measurement
- This example system considers a 0.355-μm wavelength, rather than the more common choice of 1.5 μm to measure crosswinds in each range bin [4].
  - This choice of 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.

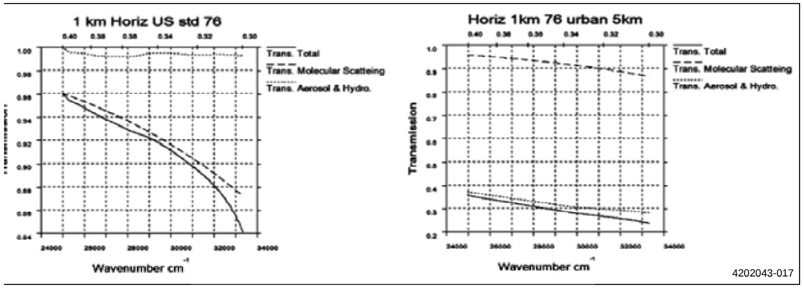
Choosing a Wavelength

- 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.

Wavelength (nm)	Advantages	Disadvantages
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

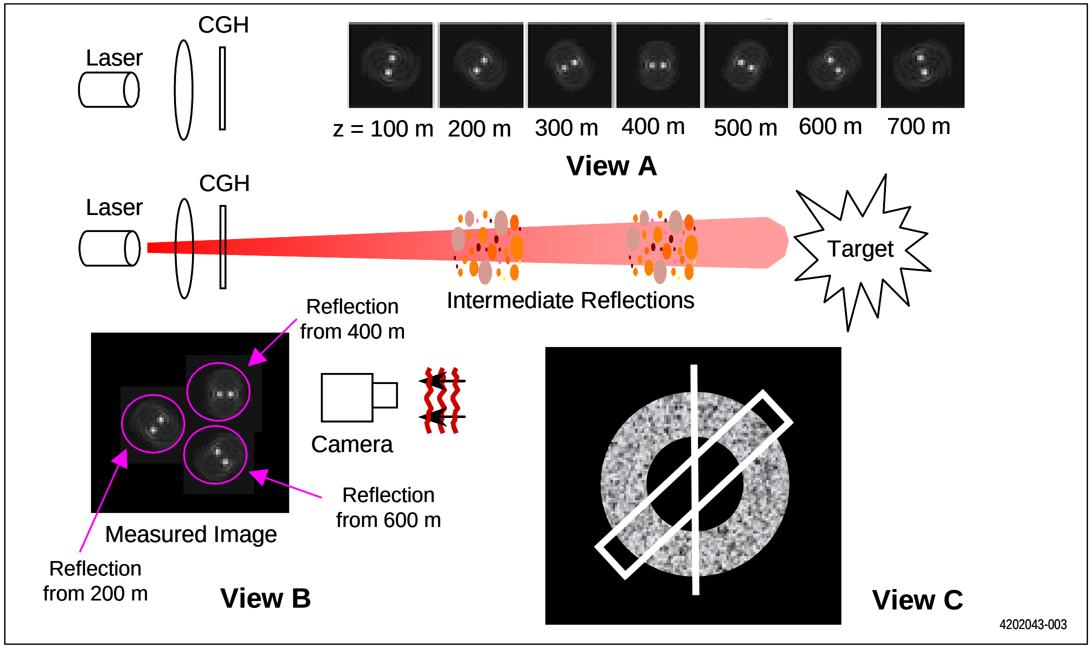




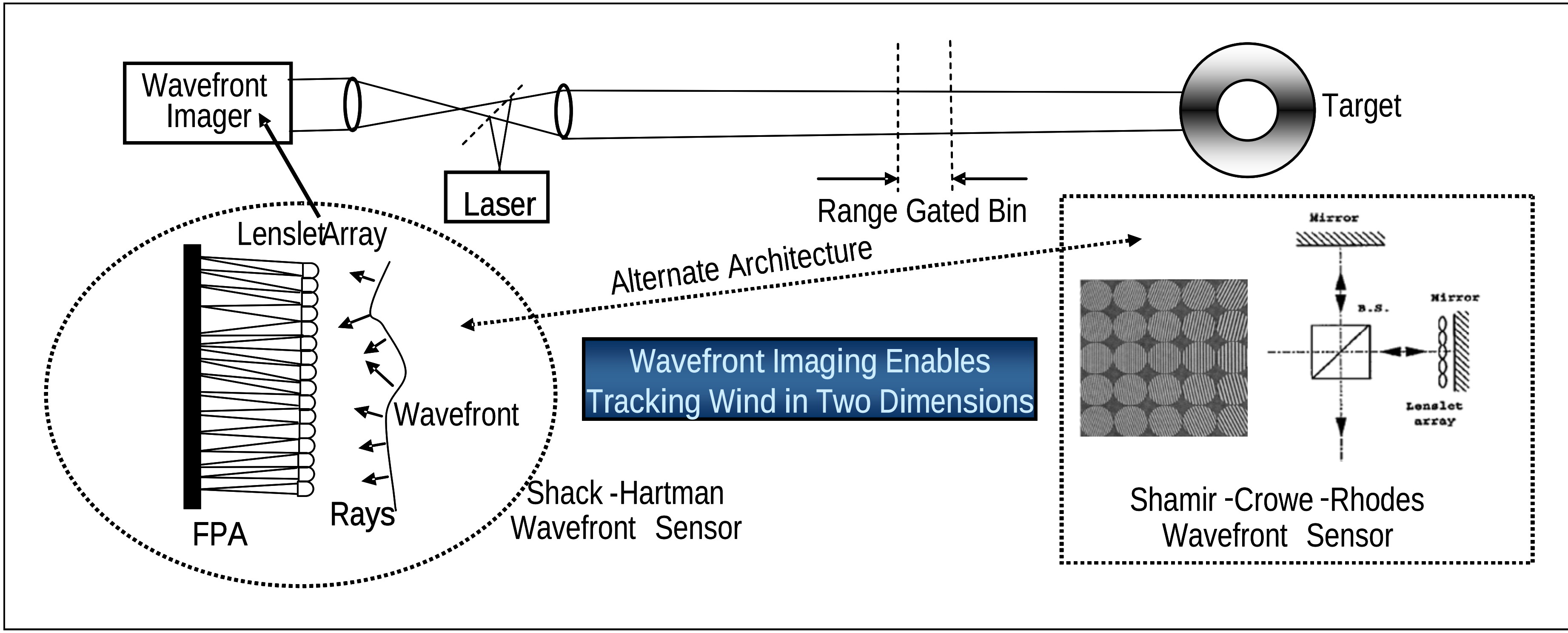


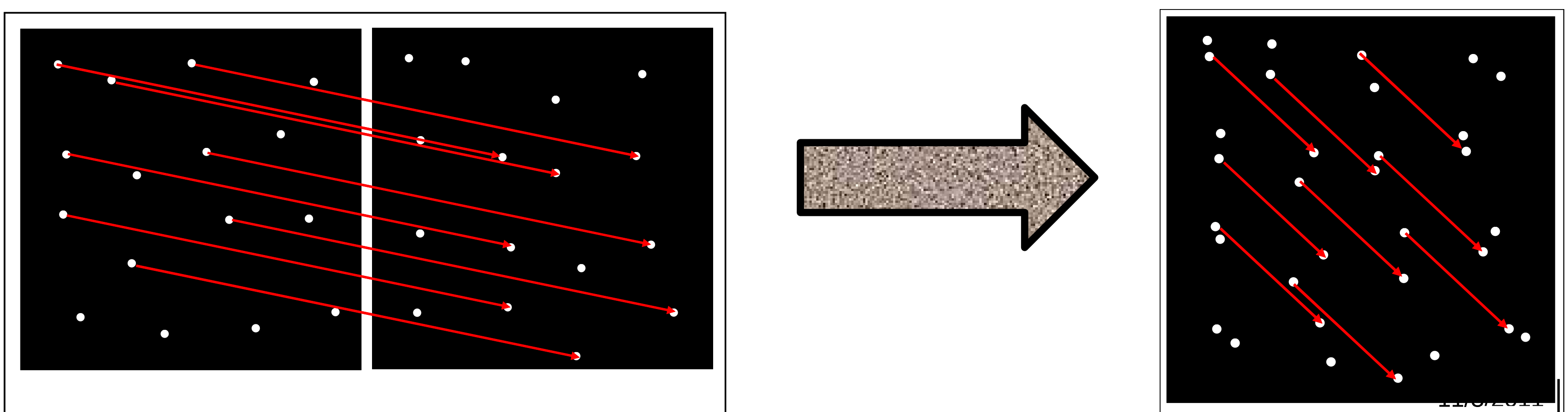
Optical Vortex Ranging

- 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





Summary

- Some applications of crosswind measurements are not amenable to multi-durectional-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 constratints for an example system were alleviated using optical vortex range resolution and the choice of a 355 nanometer wavelength

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