Measurement of atmospheric neutral wind and temperature from Fabry-Perot interferometer data using piloted deconvolution

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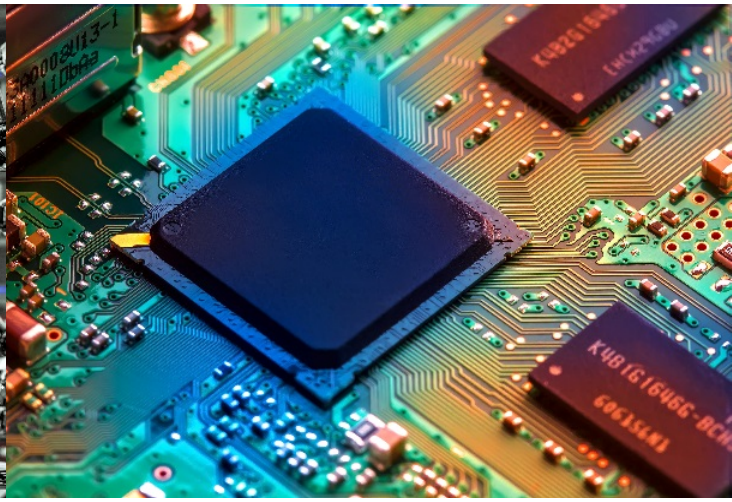

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Overview

- Fundamentals of Fabry-Perot interferometry and application in atmospheric neutral wind and temperature estimation

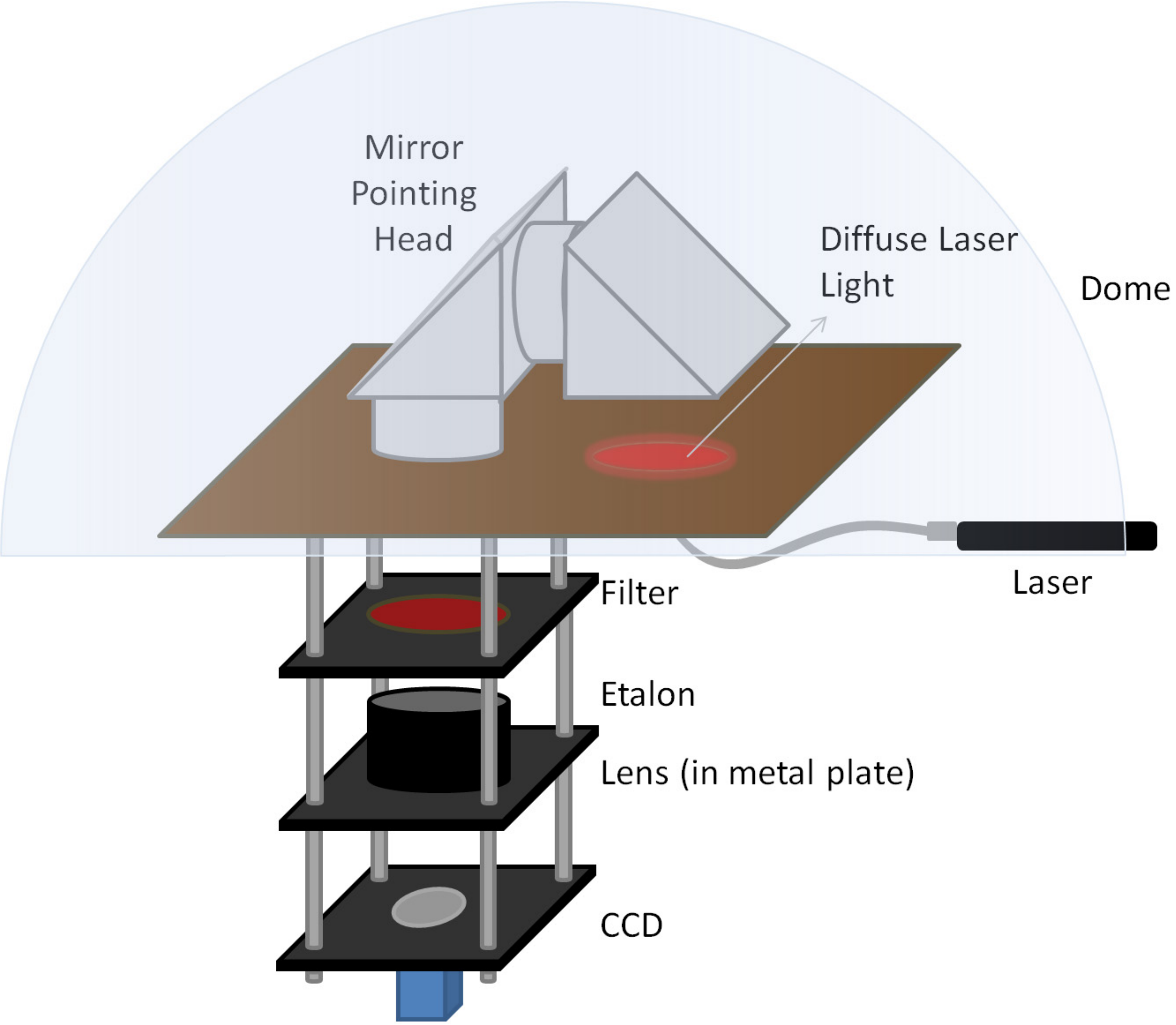
- Using a pilot signal to track instrument drift (comparisons, advantages)

- Generating a pilot signal pragmatically (results from field experiments at the Urbana Atmospheric Observatory)

Fabry-Perot Interferometers

- Commonly used to measure the spectrum of the 630.0-nm redline emission, enabling estimation of line-of-sight neutral wind and temperature.

- Requires a zero-wind reference, which often makes use of zenith observations and assumptions about the behavior of the vertical wind (typically “always zero” or “average zero”).



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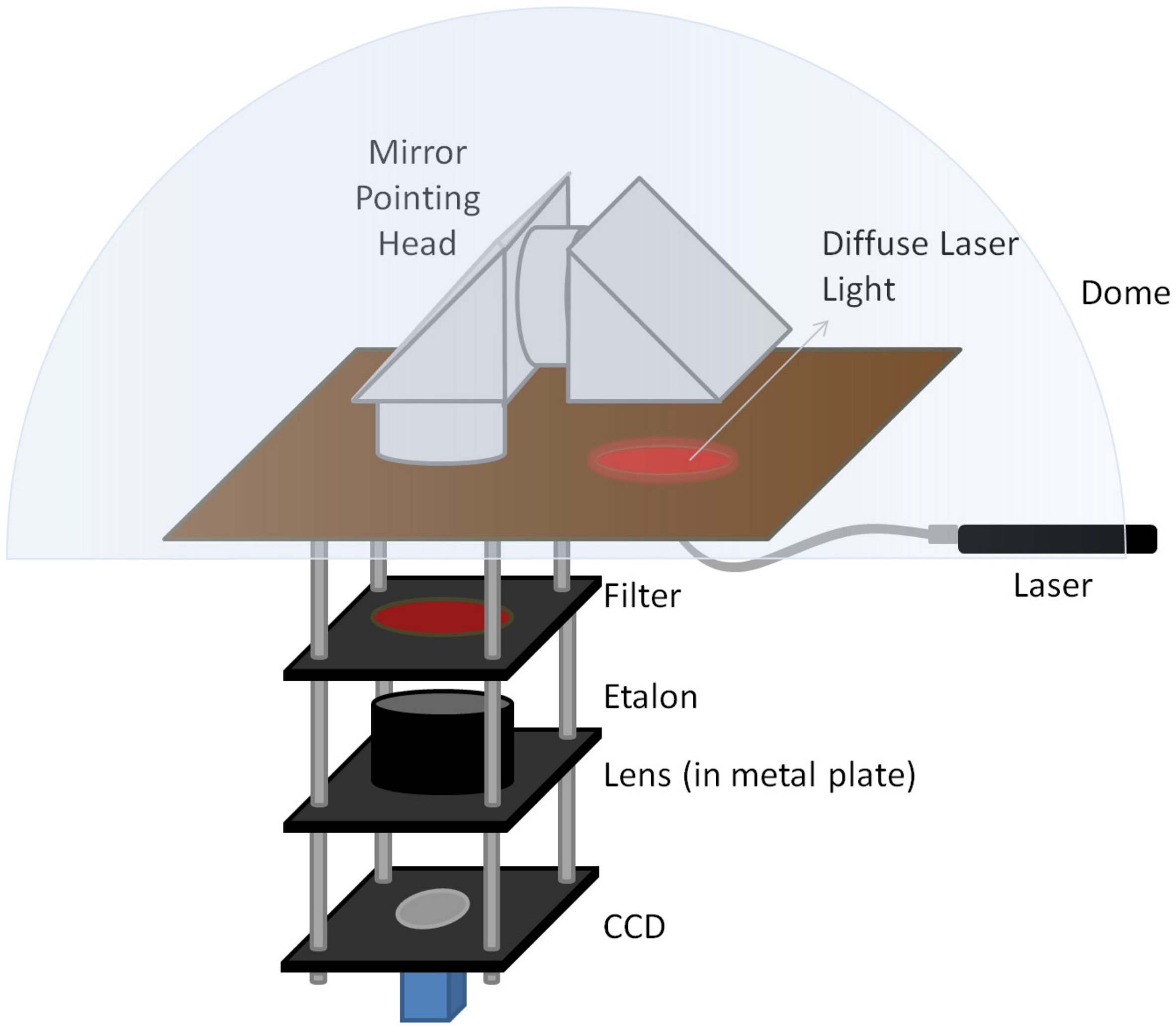
Fabry-Perot Interferometers

- Ambient temperature fluctuation in the instrument housing leads to a time-varying system function (“drift”)

- A method to track instrument drift and the appropriate vertical wind assumption enables estimation of instantaneous vertical wind.



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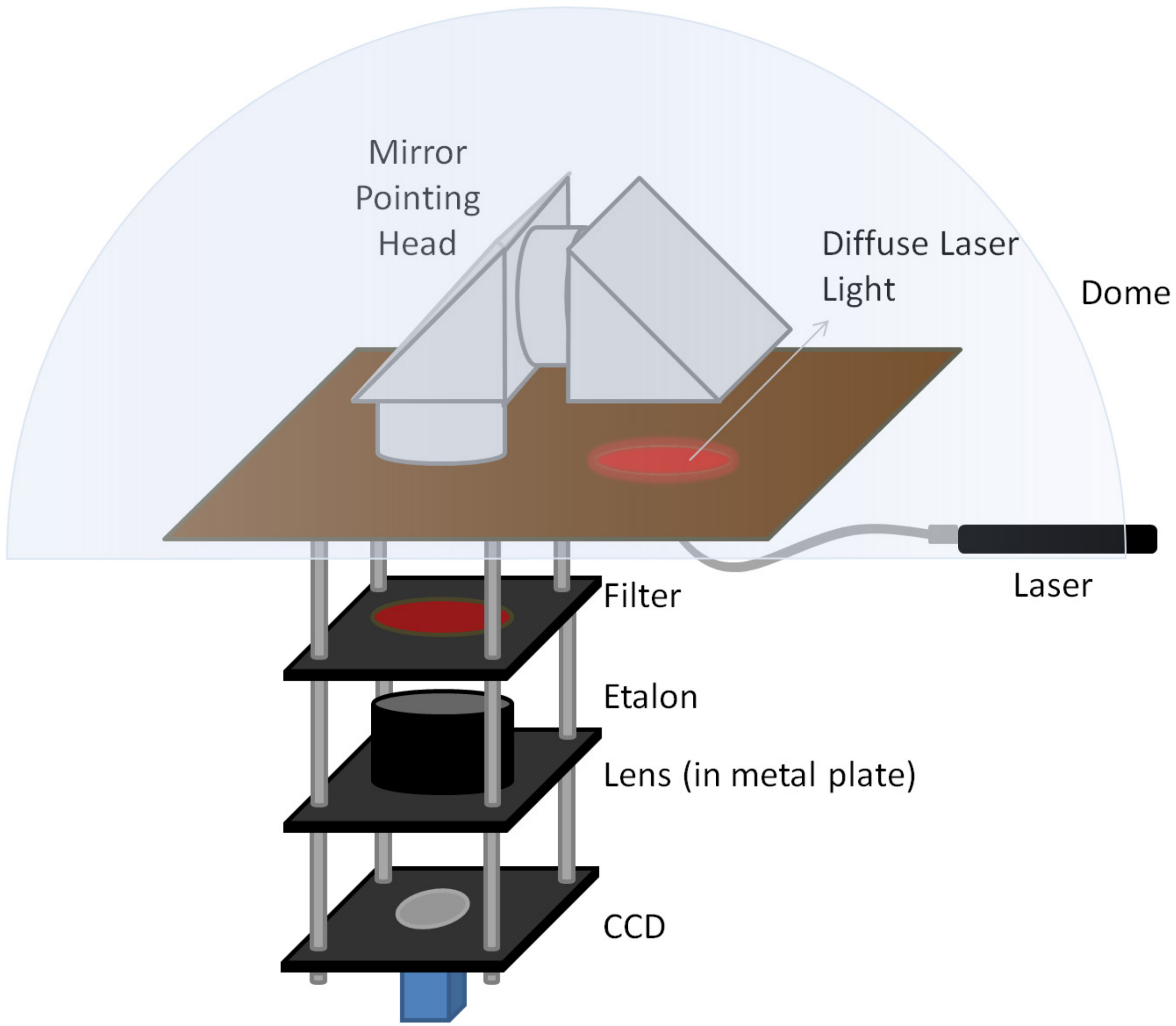
Tracking Instrument Drift

- Instrument drift is often tracked by estimating the system function using an “isolated” exposure from a frequency-stabilized HeNe laser ($\approx$ impulse input) after every sky exposure.

- Instrument parameters estimated from laser exposures are then linearly interpolated in time.



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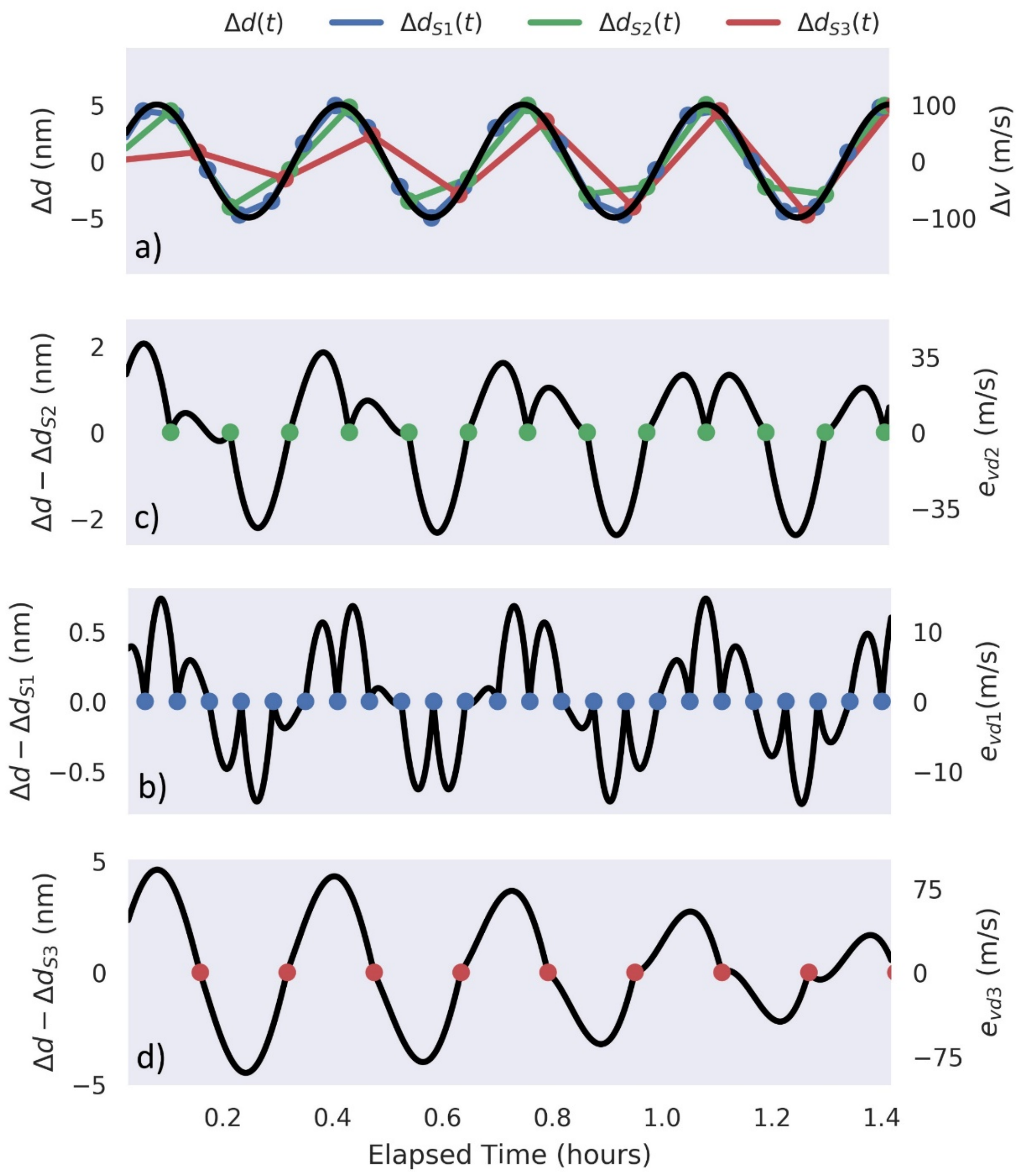
Tracking Instrument Drift

- Using linear interpolation introduces a component of error into the wind measurement.

- Can we track instrument drift and take sky exposures at the same time?
  - Eliminates linear interpolation error
  - Eliminates need for a laser exposure after every sky exposure



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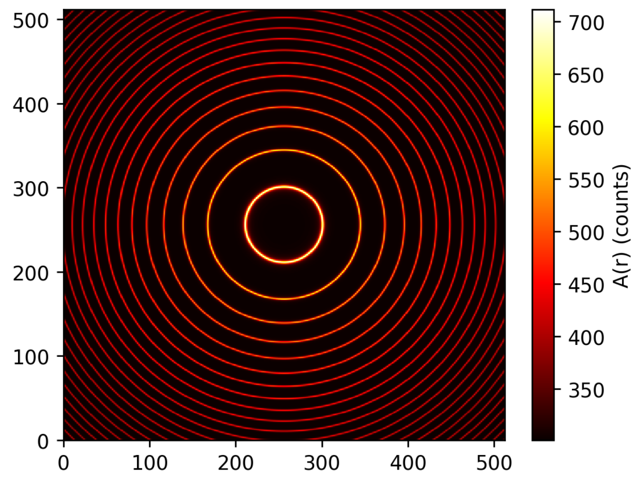
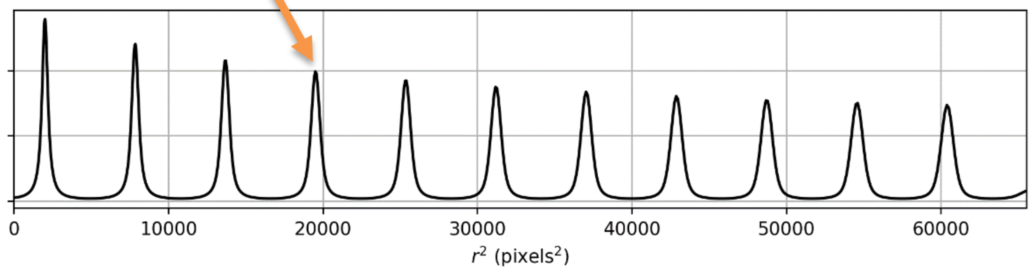
Forward Model (Traditional)

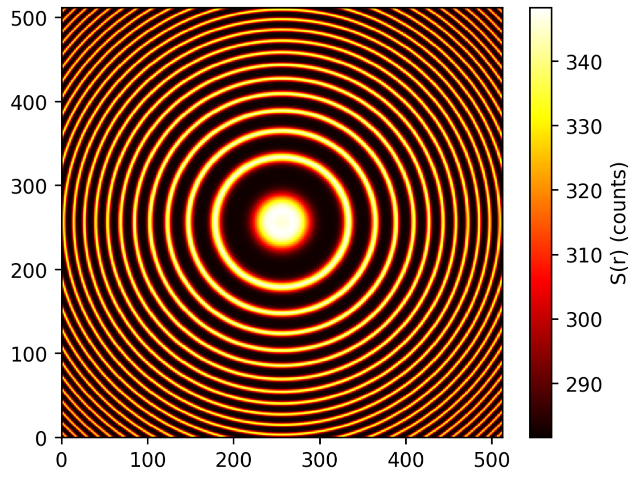
Laser Exposure



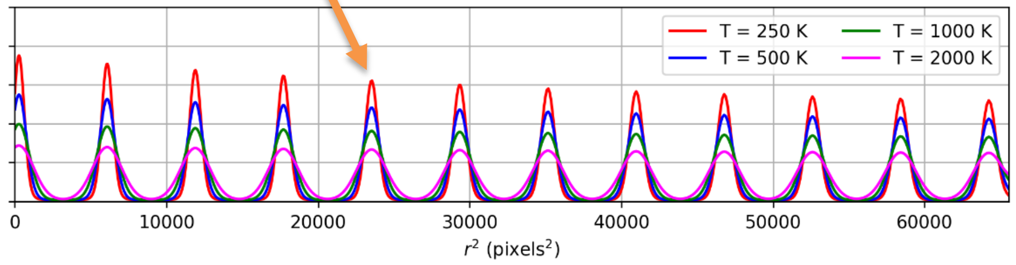
$$A(r, \lambda_p, t) = \int_{-\infty}^{\infty} A(r, \lambda, t)\delta(\lambda - \lambda_p)d\lambda$$



Sky Exposure



$$S(r, t) = \int_{-\infty}^{\infty} A(r, \lambda_p, t)Y(\lambda, t)d\lambda$$



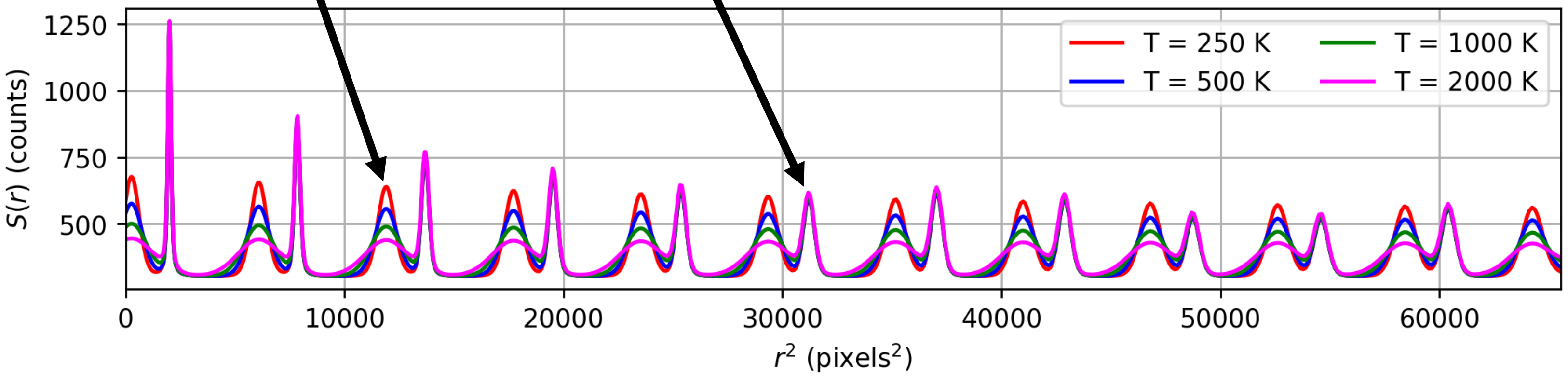
Forward Model ("Piloted")

- Allow laser light to enter the aperture of the instrument during sky exposures

"pilot" signal

$$\tilde{S}(r,t) = \int_{-\infty}^{\infty} A(r,\lambda,t)\,[Y(\lambda,t) + \delta(\lambda-\lambda_p)]\,d\lambda = \int_{-\infty}^{\infty} A(r,\lambda,t)Y(\lambda,t)d\lambda + A(r,\lambda_p,t)$$

convolved sky spectrum **laser**

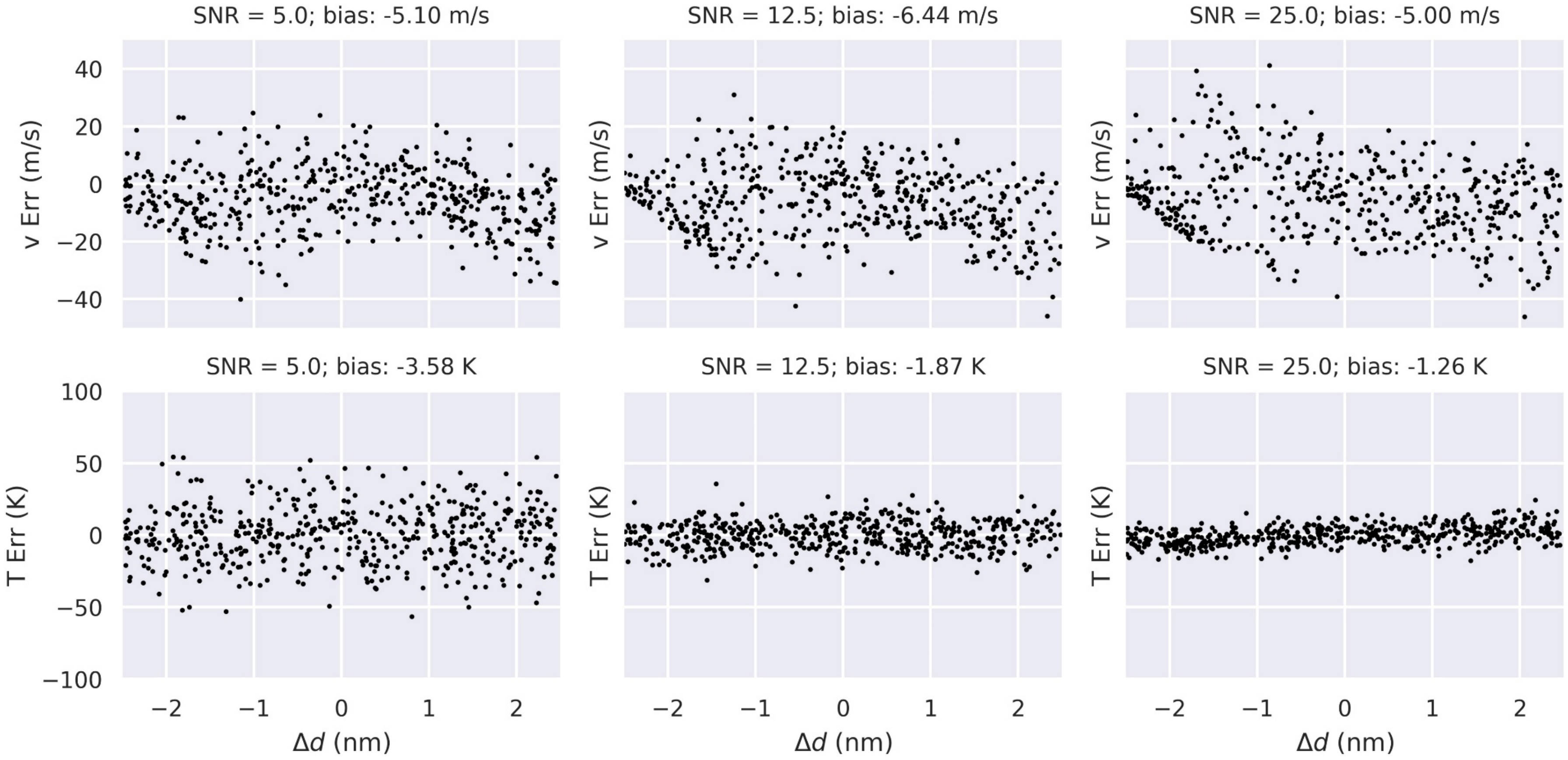


Assessing Invertibility

- Coordinate descent with system updates between stages (gradient-based and suboptimal even with convex cost, but computationally cheap).

- Monte Carlo Simulation:
  1. Perform a traditional laser + sky calibration on a noisy image with a random wind $\in [-300, 300]$ m/s and a random temperature $\in [200, 1200]$ K
  2. Apply a random perturbation to neutral wind/temperature and also “drift” the instrument (perturb the etalon gap and several instrument parameters) and generate a “piloted” fringe pattern
  3. Run a “piloted inversion” to recover the perturbed neutral wind and temperature

Assessing Invertibility



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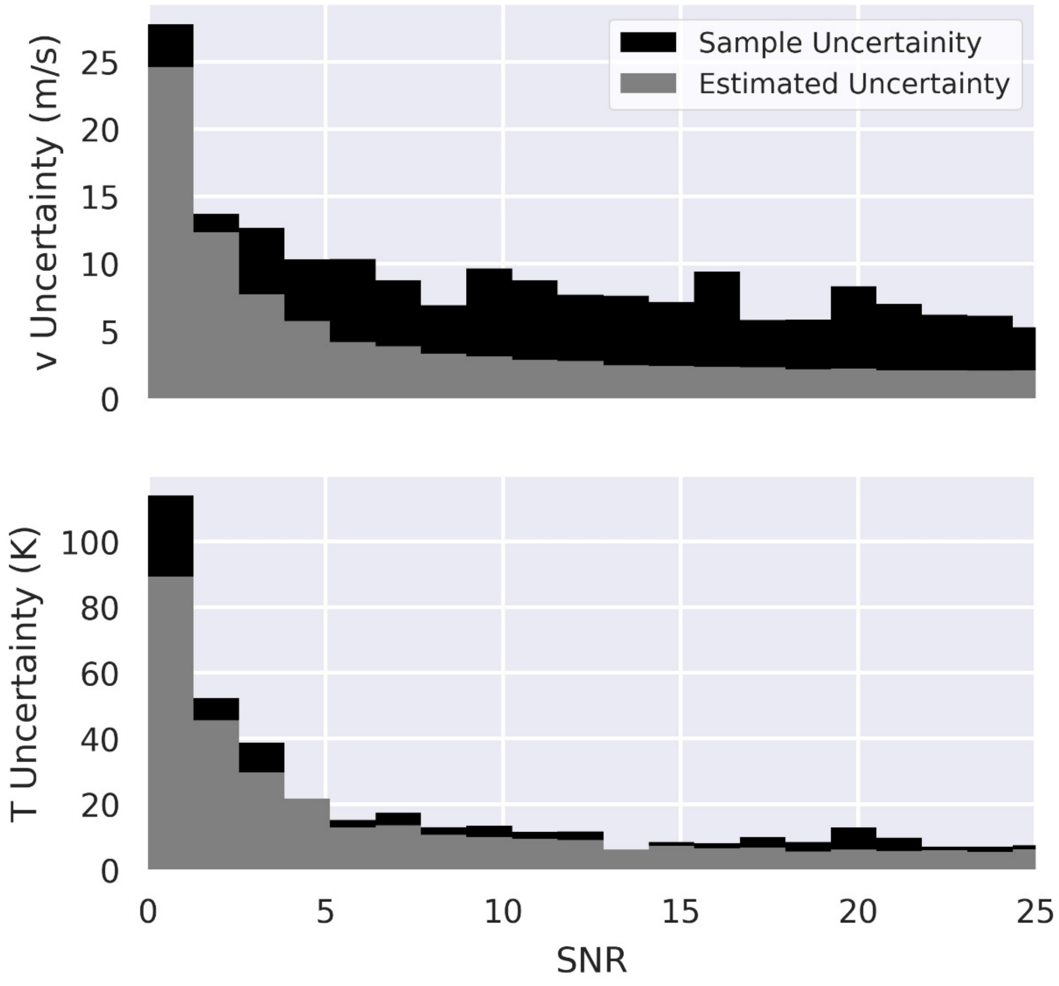
Wind precision does not tend to increase with SNR

Temperature precision tends to increase with SNR

Assessing Invertibility

- Uncertainties propagated through forward model using input covariance and numerically-calculated Jacobian
  - Propagated temperature uncertainties slightly underestimated
  - Propagated wind uncertainties underestimated by a factor of around 3 at high SNR



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Improvements over traditional deconvolution

- Inversion variance and variance of interpolation error are added in quadrature to form total wind uncertainty.

Total Velocity Uncertainty

Method	SNR	Δt_S (min)	σ_v (m/s)
standard	5	3 m	6.47 m/s
standard	5	6 m	**14.8 m/s**
standard	5	9 m	**27.23 m/s**
piloted	5	3/6/9 m	8.22 m/s
standard	12.5	3 m	4.89 m/s
standard	12.5	6 m	**14.2 m/s**
standard	12.5	9 m	**26.9 m/s**
piloted	12.5	3/6/9 m	6.31 m/s
standard	25	3 m	4.54 m/s
standard	25	6 m	**14.1 m/s**
standard	25	9 m	**26.8 m/s**
piloted	25	3/6/9 m	4.57 m/s

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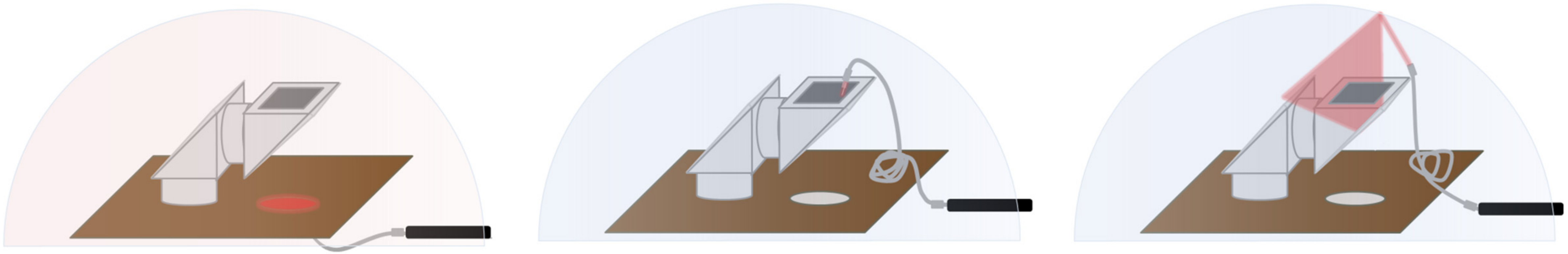
- Assumes gap fluctuation has a 5-nm amplitude and a 20-minute period

- Piloted method is the lower variance estimator for wind at longer exposure times (exceeding ~3 minutes) under these particular assumptions (~20% of observations across several existing FPIs)

Field Experiments

- We tested three potential methods for creating a HeNe pilot signal.



a) Dome Scattering Method

b) Direct Method

c) Specular Method

use a scattering chamber

directly point laser into instrument aperture

scatter laser into aperture using plastic dome

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Field Experiments

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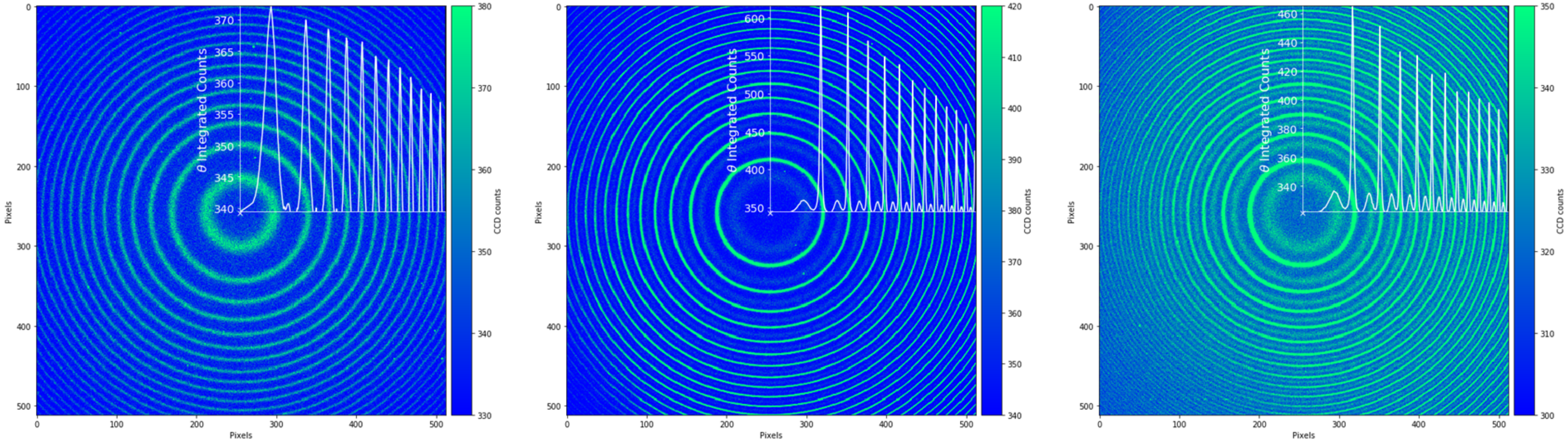
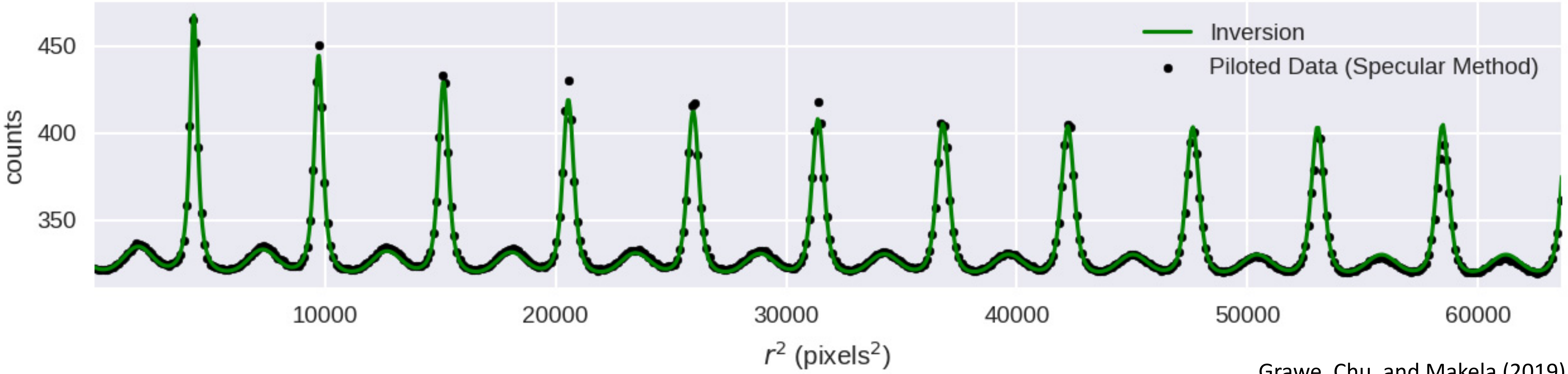


a) Dome Scattering Method　　b) Direct Method　　c) Specular Method

- The spectral method was the most pragmatic
  - Less prone to nonuniformity on the CCD, based on our tests
  - Laser light entering the aperture was strong enough for an inversion

Field Experiments



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- The spectral method was the most pragmatic
  - Less prone to nonuniformity on the CCD, based on our tests
  - Laser light entering the aperture was strong enough for an inversion

Conclusions

- Methods like piloted deconvolution can track instrument drift without performing an isolated laser exposure after each sky exposure.
- In many cases, piloted deconvolution leads to a lower variance wind estimator, especially in cases with longer exposure times and significant instrument drift.
- Field experiments suggest that it is possible to generate a pilot signal using dome-scattered laser light.

References

- M. A. Grawe, K. T. Chu, and J. J. Makela, "Measurement of atmospheric neutral wind and temperature from Fabry-Perot interferometer data using piloted deconvolution," Appl. Opt. 58, 3685-3695 (2019)

- B. J. Harding, T. W. Gehrels, and J. J. Makela, “Nonlinear regression method for estimating neutral wind and temperature from Fabry-Perot interferometer data,” Appl. Opt. 53, 666–673 (2014).