What does a 10 cm s⁻¹ shift in velocity look like?

TEM image of silicon wafer lattice (typical CCD)
What does a 10 cm s\(^{-1}\) shift in velocity look like?

TEM image of silicon wafer lattice (typical CCD)
What does a 10 cm s\(^{-1}\) shift in velocity look like?

TEM image of silicon wafer lattice (typical CCD)
Deconstructing measurement precision
Deconstructing measurement precision
Deconstructing measurement precision

Radial Velocity [cm s$^{-1}$] vs Orbital phase

$\sigma_{RV}$
Deconstructing measurement precision

\[ \sigma_{RV} = \sigma_{\text{photon}} + \sigma_{\text{facility}} + \sigma_{\text{jitter}} \]
Deconstructing measurement precision

\[ \sigma_{\text{RV}} = \sigma_{\text{photon}} + \sigma_{\text{facility}} + \sigma_{\text{jitter}} \]

- Aperture
- Efficiency
- Information content
Deconstructing measurement precision

- Aperture
- Efficiency
- Information content

$\sigma_{\text{RV}}$

$\sigma_{\text{photon}}$

$\sigma_{\text{facility}}$

$\sigma_{\text{jitter}}$

KPF system efficiency model

Throughput vs. Wavelength [nm]
Deconstructing measurement precision

\[ \sigma_{\text{RV}} \]

\[ \sigma_{\text{photon}} \] \hspace{1cm} \sigma_{\text{facility}} \hspace{1cm} \sigma_{\text{jitter}} \]

Aperture
Efficiency
Information content

e.g. Bouchy+ 2001, Halverson+ 2016, Gibson+ 2018
Deconstructing measurement precision

\[ \sigma_{RV} \]

\[ \sigma_{\text{photon}} \]

\[ \sigma_{\text{facility}} \]

\[ \sigma_{\text{jitter}} \]

Aperture

Efficiency

Information content

SNR \sim 500
Deconstructing measurement precision

\[ \sigma_{RV} \]

\[ \sigma_{photon} \]

\[ \sigma_{facility} \]

\[ \sigma_{jitter} \]

Instrumental stability

Calibration ability

External errors, analysis

e.g. Avila+ 2008, Sturmer+ 2014, Halverson & Roy+ 2015
Deconstructing measurement precision

- $\sigma_{\text{RV}}$
- $\sigma_{\text{photon}}$
- $\sigma_{\text{facility}}$
- $\sigma_{\text{jitter}}$

Instrumental stability
Calibration ability
External errors, analysis

Sky fiber (A)
Calibration source (B)
Starlight (C)
Deconstructing measurement precision

\[ \sigma_{RV} \]

- \( \sigma_{\text{photon}} \)
- \( \sigma_{\text{facility}} \)
- \( \sigma_{\text{jitter}} \)

Instrumental stability
Calibration ability
External errors, analysis

Graph: Differential drift (cm s\(^{-1}\)) vs. Time (hour)

\( \sigma_{A-B} = 26 \text{ cm s}^{-1} \)
Deconstructing measurement precision

- $\sigma_{RV}$
- $\sigma_{\text{photon}}$
- $\sigma_{\text{facility}}$
- $\sigma_{\text{jitter}}$

Instrumental stability
Calibration ability
External errors, analysis

Spectrum
Mask
CCF
Deconstructing measurement precision

\[ \sigma_{RV} \]

\[ \sigma_{\text{photon}} \]

\[ \sigma_{\text{facility}} \]

\[ \sigma_{\text{jitter}} \]

Instrumental stability

Calibration ability

External errors, analysis

Roy+ 2018
Deconstructing measurement precision

Total NEID instrumental error budget: 27.0 cm s\(^{-1}\)

Instrument (uncalibratable): 15.1 cm s\(^{-1}\) (30.6%)
- Fiber & illumination: 8.7 cm s\(^{-1}\)
  - Calibration source modal noise: 2.5 cm s\(^{-1}\)
  - Continuum modal noise: 2.5 cm s\(^{-1}\)
  - Near-field scrambling: 3.5 cm s\(^{-1}\)
  - Far-field scrambling: 5.0 cm s\(^{-1}\)
  - Stray light: 5.0 cm s\(^{-1}\)
  - Polarization: 2.0 cm s\(^{-1}\)

Instrument (calibratable): 11.2 cm s\(^{-1}\) (11.1%)
- Thermo-mechanical: 7.8 cm s\(^{-1}\)
  - Thermal stability (grating): 3.5 cm s\(^{-1}\)
  - Thermal stability (cross-disp): 3.0 cm s\(^{-1}\)
  - Thermal stability (bench): 3.0 cm s\(^{-1}\)
  - Vibrational stability: 2.0 cm s\(^{-1}\)

Calibration source (uncalibratable): 11.5 cm s\(^{-1}\) (18.7%)
- Calibration accuracy: 5.7 cm s\(^{-1}\)
  - Stability: 4.0 cm s\(^{-1}\)
  - Photon noise: 4.0 cm s\(^{-1}\)

External errors (uncalibratable): 18.7 cm s\(^{-1}\) (49.6%)
- Calibration process: 10 cm s\(^{-1}\)
Deconstructing measurement precision

\[ \sigma_{RV} \]

\[ \sigma_{\text{photon}} \quad \sigma_{\text{facility}} \quad \sigma_{\text{jitter}} \]

estimated \( \sigma_{\text{jitter, Sun}} \)

Marchwinski et al. 2015
Now in the era where no single source of instrumental noise dominates.
Now in the era where no single source of instrumental noise dominates.

### Total NEID instrumental error budget: 27.0 cm s⁻¹

<table>
<thead>
<tr>
<th>Instrument (uncalibratable): 15.1 cm s⁻¹ (30.6%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber &amp; illumination: 8.7 cm s⁻¹</td>
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<td>Detector effects: 7.1 cm s⁻¹</td>
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<tr>
<td>Readout thermal change: 5.0 cm s⁻¹</td>
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<tr>
<td>Charge transfer inefficiency: 5.0 cm s⁻¹</td>
</tr>
<tr>
<td>Barycentric correction: 1.7 cm s⁻¹</td>
</tr>
<tr>
<td>Algorithms: 1.0 cm s⁻¹</td>
</tr>
<tr>
<td>Exposure midpoint time: 1.0 cm s⁻¹</td>
</tr>
<tr>
<td>Coordinates and proper motion: 1.0 cm s⁻¹</td>
</tr>
<tr>
<td>Reduction pipeline: 10 cm s⁻¹</td>
</tr>
<tr>
<td>Software algorithms: 10 cm s⁻¹</td>
</tr>
<tr>
<td>Instrument (calibratable): 11.2 cm s⁻¹ (1.1%)</td>
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<tr>
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<tr>
<td>Vibrational stability: 2.0 cm s⁻¹</td>
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<tr>
<td>Pressure stability: &lt;0.1 cm s⁻¹</td>
</tr>
<tr>
<td>LN2 fill transient: 1.0 cm s⁻¹</td>
</tr>
<tr>
<td>Zerodur phase change: 5.0 cm s⁻¹</td>
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<td>Pixel inhomogeneities: 1.0 cm s⁻¹</td>
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<td>Electronics noise: 1.0 cm s⁻¹</td>
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<td>Stitching error: 3.0 cm s⁻¹</td>
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<td>CCD thermal expansion: 2.0 cm s⁻¹</td>
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</tbody>
</table>

### Calibration source (uncalibratable): 11.5 cm s⁻¹ (18.7%)

| Calibration accuracy: 5.7 cm s⁻¹ |
| Stability: 4.0 cm s⁻¹ |
| Photon noise: 6.9 cm s⁻¹ |

### External errors (uncalibratable): 18.7 cm s⁻¹ (49.6%)

| Calibration process: 10 cm s⁻¹ |
| Software algorithms: 10 cm s⁻¹ |

### Telescope: 12.2 cm s⁻¹

| Guiding: scrambling |
| ADC: 6.9 cm s⁻¹ |
| Focus: 5.0 cm s⁻¹ |
| Windshake: 8.0 cm s⁻¹ |

### Atmospheric effects: 14.1 cm s⁻¹

| Micro-telluric contamination: 10 cm s⁻¹ |
| Sky fiber subtraction: 10 cm s⁻¹ |
Now in the era where no single source of instrumental noise dominates
Calibratable error examples

From telescope

White Light

Echelle Grating

Dispersed Light

To cross-disperser

800 mm
Thermal fluctuations on spectrometer optics

\[ \Delta v = \alpha_L c \Delta T, \]

\[ \Delta T = 10 \text{ mK} \]

\[ \Delta v = 15 \text{ cm s}^{-1} \]
Thermal fluctuations on spectrometer optics

KPF green / red cameras

Camera optical elements have measurable $dn/dT$, CTE
Thermal fluctuations on spectrometer optics

KPF green / red cameras

Camera optical elements have measurable $dn/dT$, CTE
Thermal fluctuations on spectrometer optics

KPF green / red cameras

Camera optical elements have measurable $dn/dT$, CTE
Examples of errors *not* tracked by calibration source

- Fundamentally, spectrometer records monochromatic images of entrance aperture

Spectrometer line profile

'Spectral' domain

Entrance slit

'Spatial' domain

6 km s\(^{-1}\)
Spectrometer PSF

Telescope pupil

Beam profile on grating, camera optics sets the aberration distribution, final PSF
Far-field variations impacting RV measurement performance

e.g. Stuermer + 2014, Halverson + 2016
Pupil variation within spectrometer lead to changes in effective aberrations.

1” shift on fiber face (near-field)

Near-field input  Far-field output

Input pupil shift (far-field)

Input pupil
Detector effects: Charge transfer *inefficiency*

Parallel transfer direction

Serial transfer direction

Serial transfer CTI (shifting and blurring of absorption features in the dispersion direction)

Parallel transfer CTI (shifting and blurring of orders in cross-dispersion direction)

Incident spectrum (pre-readout)

1-D extracted spectrum

Bouchy+ 2009, Blake+ 2017, Halverson+ 2018
CCD fringing can introduce systematic error

Example CCD flat, showing clear fringing structure

~1 m s$^{-1}$ precision not demonstrated at reddest (>800 nm) wavelengths on CCDs

Slide credit: Arpita Roy
The atmosphere contributes more than telluric absorption
You are only as precise as your calibration source
e.g. Bouchy+ 2001, Murphy+ 2007, Halverson+ 2014
Pushing to 10 cm s\(^{-1}\) will unveil a forest of new challenges

Total NEID instrumental error budget: 27.0 cm s\(^{-1}\)