Spectral Interferometry
for Broadband UV / Optical Astronomy

Jerry Edelstein,
Space Sciences Lab, U. California, Berkeley
jerrye@ssl.berkeley

David Erskine
Lawrence Livermore National Laboratory
erskine1@llnl.gov

Concepts, Development & Analyses:
Michael Feurerstein, Pat Jelinsky
Eric Korpela, John Vallerga, Mario Marckwordt

Observations:
Barry Welsh, Kaoi Nishikida, Shauna Sallmen, Mark Bowen

Supported by NASA SARA, Calspace/Lockheed, LNLL LDRD

# UVO Next Generation Spectroscopy

**99’ UVWG**

*“Tracing the Cosmic Web”*

<table>
<thead>
<tr>
<th>Performance Requirement</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observational objective</strong></td>
<td>High resolution, point-source, absorption spectroscopy of ~1000 QSOs and galaxies with 17 – 20 mag</td>
</tr>
<tr>
<td><strong>Wavelength coverage</strong></td>
<td>1250-3200Å</td>
</tr>
<tr>
<td><strong>Spectral Resolution</strong></td>
<td>R = 20,000 - 30,000</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>SNR= 10 per resolution element for $F_\lambda=10^{-16}\text{ergs/s/cm}^2/\text Å$</td>
</tr>
</tbody>
</table>
| **Target Density @ 20.5 mag**            | One QSO per 10 arcmin
1 galaxy per 1 arcminute}
Spectroscopy with Externally Dispersed Interferometry (EDI)

§ Unequal path Interferometer ‘filter’ -feeds a grating spectrograph

(Applicable from the IR to the UV)

- The white-light interferometer causes a spectral fringe pattern
- The fringe pattern beats with the spectral pattern
- Heterodyne: a Moire beat pattern defeats the Nyquist Limit.
  High spatial frequency information on the detector
  (= high spectral resolution information)

Spectrograph Resolution improved several fold!
Externally Dispersed Interferometer (EDI)

Combine Interferometer and Grating in Series

Interferometer
\( \tau = 1 \text{ cm} \)
fixed delay

Grating spectrograph

Absorption lines

\( \tau \) slightly changed
Along Slit

Interferometer transmission spectrum

\( \lambda \)
EDI Apparatus used for Stellar Doppler Measurements

- Compact, small and inexpensive optics
- Phase stepping algorithm to extract moire fringes
Can apply interferometer fringes to an echelle spectrograph 2-d format

Use "Unslanted" fringe mode.
This mode has been demonstrated on sunlight.

**Slanted fringe mode**
Phases splayed vertically along slit.
Moire pattern determined in a single exposure.

**Unslanted fringe mode**
Phase uniform everywhere over slit.
Take 3 exposures to determine moire pattern.
Useful for echelle spectrographs or where astigmatism limits vertical resolution.

**Benefit to echelle:**
1) more light for same resolution (wider slit)
2) more stable PSF --> better accuracy
Uniphase operation allows use of imaging dimension

• EDI Multiphase measures all phases simultaneously
  Use slant-fringe and detector height

Multi-Phase
(Slanted Fringe)

(Straighten Fringe)

(Compress Fringe)

Uniphase

• EDI Uniphase measure one phase at a time

QuickTime™ and a GIF decompressor are needed to see this picture.
Interferometer phase-stepped in several exposures

Two styles of changing phase $\phi$

All phases at once

Phases done sequentially

Exposure 1, $\phi = 0^\circ$

$\varepsilon$-Leo on Lick echelle

Exposure 2, $\phi = 150^\circ$
Demo of Res. Boosting on Sunlight and a Linear Grating

R~20 k boosted to R ~50 k

Ordinary signal obtained by simple summation

\[ \text{Ordinary} = S_0 + S_{120} + S_{240} = \sum S_k \]

\[ S_{120} \]
\[ S_{240} \]
\[ S_0 \]

Therefore both fringing and nonfringing signals are obtained from same raw data

Fringing sideband isolated by phased-summation

\[ \text{Fringing} = S_0 e^{-i0^\circ} + S_{120} e^{-i120^\circ} + S_{240} e^{-i240^\circ} = \sum S_k e^{-i\phi_k} \]

Phase-stepping reversed

\[ S_{120} \]
\[ S_{240} \]
\[ S_0 \]
Relative Sensitivity
EDI / Standard
is Ratio of curves

Heterodyned and ordinary spectra are combined to produce higher resolution

EDI using $R=20k$ grating

Modulation Transfer Function

$R=50k$ grating alone

2.5x Res. boosting effect with 1 delay

"Bass"

"Treble"

$\rho$ (features per cm$^{-1}$)

Response

Science
EDI 'squared' Spectral Response

-Fringe / non-fringe are statistically independent components
-Squared combination represent 'S/N' within response.
-Response Profile is established by sine function, NOT grating

(Equalization in Fourier domain suppresses peak wings)
Sensitivity:
Fringe Phase Response to Resolution

Figure 4. Stages in construction of an EDI signal. a) The input absorption line $S_s(\nu)$. b) The interferometer transmission function $T(\nu, \gamma)$ alone, as if observing the continuum. c) The $S_s(\nu)T(\nu, \gamma)$ multiplied together but prior to the blurring. Panels d) through g) show simulated signals at the CCD after various amounts of applied blurring: 0.75, 1, 1.5 and 5 cm$^{-1}$ corresponding to $(\Delta \nu_0/\Delta \nu_\gamma)$ of 1.80, 2.24, 3.16 and 10.05, respectively.

Figure 5. Moiré fringe amplitude at center of line versus observed blurring $(\Delta \nu_0/\Delta \nu_\gamma)$. Our exact calculation is shown in dots. The reciprocal relation estimated by Ge$^3$ agrees with our calculation for blurring ratios above $\sim 2.5$. For less blurring the rhombus effect described in Fig. 6 causes phase interactions that deviate the behavior from the simple formula. The reciprocal relation in amplitude leads to a square root blurring dependence for the photon signal to noise ratio.
Heterodyning increases robustness to environmental insults

The peak of PSF(ρ) is most robust against focal spot changes
Heterodyning moves robust region to science area

Robust regions

Focal spot variations worse in wings

PSF(ρ)

Hybrid
Grating-only

Sensitivity to focal spot shift

Sums to large value
Grating-only

Hybrid

Sums to zero

ρ (features per cm⁻¹)
Radial Velocity Noise Calculations

- Exact treatment for Doppler velocimetry using actual stellar spectrum
- \( \sim \) Square Root dependence on spectrograph resolution

Figure 9. Calculated velocity noise for a single gaussian line receiving \( 10^6 \) photons/\( \AA \) in the continuum, for conventional and EDI spectroscopy. Thin curves assume constant noise set by continuum flux (constant noise case). Bold curves assume noise varying as square root of local intensity. Dotted line is estimate for EDI given by Ge.\(^2\) The EDI-net curve includes both fringing and nonfringing components and hence is always lower than the conventional technique. The EDI-fringing only curve has square root dependence on blurring, except at highest resolutions where the up-heterodyned signal component contributes (this component otherwise unresolved). Interferometer delay assumed to be 1 cm, intrinsic gaussian FWHM \( \Delta v_x = 0.5 \) cm\(^{-1}\), and average frequency of 20,000 cm\(^{-1}\).
EDI prototype has m/s Doppler precision, without environmental controls

Detection of the moon from the Doppler shift of sunlight
Using an Externally Dispersed Interferometer

Scatter due to heliostat pointing error acting on 4000 m/s velocity gradient across solar disk

Laboratory Unit in open air
Dime-store mirrors & heliostat
Fiber input dangling from roof
Observations, methods, Results

• Observations at Lick CAT Echelle
  Solar
  Stellar
  (α–Virgo, ε-Leo, η-Boo, t-Boo)

• Uniphase Operation

• Pre-slit configuration

• Post-slit configuration

• Resolution increase shown:
  • R @ 120k on 50k slit
Ultrawide Bandwidth Doppler Interferometer at Lick Echelle

Lick Echelle Spectrograph with a 1 cm delay interferometer at slit

Epsilon Leo (G0)

8000 Å

Isoce range

Interferometer creates intermediate fiducials having periodic spacing over all wavelengths.

This allows use of very wide bandwidth absolute fiducials from ThAr lamp. Wide bandwidth is key to better photon s/n.

4000 Å

ThAr range
Demonstration of Res. Boosting
R~50k boosted to R~100k
on telluric lines of α-Virgo

α-Virgo on Echelle with 3 cm delay

Intensity (Rel.)

Fringing
Ordinary (S/N~50)
Composite
Echelle without fringes
Echelle with fringes

Kitt Peak reference

diff(96k-53k)
R=53k
R=96k

Wavelength (Å)
EDI Spectrographs Compared

**EDI vs grating spectroscopy**
- Spectrograph resolution improved! (~2-3 X)
- Focal-blur & shift tolerance (~10X)
- Large Solid-angular acceptance (sensitivity gain)
- Equivalent simultaneous band-pass
- Comparable throughput & sensitivity
- Phase stepping (\(\lambda/3\)) can be used to obliterate fixed pattern noise

**EDI vs Spectral interferometers**
- FTS EDI sensitivity (100 X) (multiplex bandpass)
- Internally Dispersed Interferometers (e.g. SHS)
  - EDI Broad-band: No wavelength interferometer dependence
  - EDI Absorption Sensitivity; Dispersion of continuum noise

No l/10,000 needed here
EDI application to Spectroscopy

- **Imaging Spectroscopy:**
  - Slit imaging interferometric spectroscopy
  - Fiber-fed multi-object spectroscopy
  - Simultaneous bandpass echelle spectroscopy
  - Integral-field spectroscopy

- **Differential Spectroscopy**
  - Spectral Doppler spectroscopy (multi-wavelength differential)
  - *Spatial Differential* Target – Background
    - *E.g. relative velocities, turbulence,*
  - Spectral Differential Line – Reference
EDI UVO Spectrograph with Today’s Detectors

**FUV band 1150 - 1750 Å simultaneous**

*Existing Detector* COS MCP 170 x 10mm @ 25um (6800 pels)

- **R = 20 k** effective / EDI * R = 8.2 k Spectrograph
- **G = 3200 l/mm, R = 75 cm**
- Grating to *Slit width subtends 7”*

**NUV band 1700 - 3200 Å simultaneous**

*Existing Detector* Galex MCP 50 mm diam @ 20 um (2500 pels)

- **R = 20 k** effective / EDI * R = 8.2 k Spectrograph)
- **G = 3200 l/mm, R = 75 cm, 8 orders of dual phase**

**R = 30 k** effective (EDI * R = 12 k Spectrograph)

- **G = 3200 l/mm, R = 75 cm, 11 orders of dual phase**
Deep UVO Spectroscopy (Only) Mission

**Big Light Bucket**
- TRW Heritage Telescope
- 4.5m Deployable

**Sloppy Telescope**
- Static Primary, Active Secondary
- Existing deployment mechanism good to 5” imaging
- Graphite shell replicas
- 75 cm EDI @ R= 20 - 30k

Observatory quality to meet QSO and galaxy target confusion limit
Say 20”: focus/stability gives 10% chance of galaxy at 20.5 mag
Continue EDI Technology Development

- Analyses
  - Sensitivity of Spectroscopy versus Radial Velocity
  - Delay & equalization optimization of spectral profile
  - Sensitivity of external background vs phase stepping for spectroscopy
  - Simultaneous Differential Spectroscopy

- Elements
  - Monoliths
  - Beam splitters,
  - Gratings

- Technical NHST type optical layout & design

- Fly the dang thing
Silicon Etched Diffraction Gratings

Anisotropic etch → Atomically smooth planes → high efficiency/low scatter

Gratings Fabricated & Measured

<table>
<thead>
<tr>
<th>L / mm</th>
<th>blaze (°)</th>
<th>∅ (cm)</th>
<th>EFFICINCY Groove, peak (%)</th>
<th>SCATTER (1/arc-min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>55</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>3</td>
<td>1</td>
<td><strong>50 @ 834Å</strong></td>
<td>3x10^{-6}</td>
</tr>
<tr>
<td>150</td>
<td>3</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>3</td>
<td>10</td>
<td><strong>53 @ 1027Å</strong></td>
<td>2x10^{-6}</td>
</tr>
<tr>
<td>1000</td>
<td>3</td>
<td>10</td>
<td><strong>55 @ 1027Å</strong></td>
<td>6x10^{-6}</td>
</tr>
</tbody>
</table>

Grating Scatter:

<table>
<thead>
<tr>
<th>type</th>
<th>scatter (Is/Io/ arc-min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echelles</td>
<td>~10^{-3}</td>
</tr>
<tr>
<td>Mechanical</td>
<td>~10^{-4}</td>
</tr>
<tr>
<td>Holographic &amp; VLS</td>
<td>~10^{-5}</td>
</tr>
<tr>
<td>Silicon -Etched</td>
<td>~10^{-6}</td>
</tr>
</tbody>
</table>
EDI: Observatory Tolerance & Design Flexibility

**Breakthrough Spectroscopy Method**
- Factor of several increase in spectral resolution!
- Preserves imaging
- Wide field (etendue) interferometer
- Competitive Signal to Noise for emission or *absorption*

**Observatories Tolerance**
- Moderate focal quality
- Moderate stability (or poor seeing)
- Moderate resolution spectrographs
- Accommodate Changing pupil
Tradeoff of characteristics for instruments capable of $\lambda/\delta\lambda \sim 60,000$ over a wide bandwidth

- "Kitchen" 5 m
- Instrument Size
- "TV"
- "Toaster" 0.3 m

Grating-only

Keck, Lick

Externally Dispersed Interferometer (EDI)

Hybrid

FTS

Intrfmtr-only

Photon noise/sig (Relative)

1 100

EDI is an excellent compromise between size and low-light ability