Moire Effect Produces 10x Resolution Boost on Mt. Palomar NIR Spectrograph

LLNL-CONF-654774

David Erskine (LLNL)

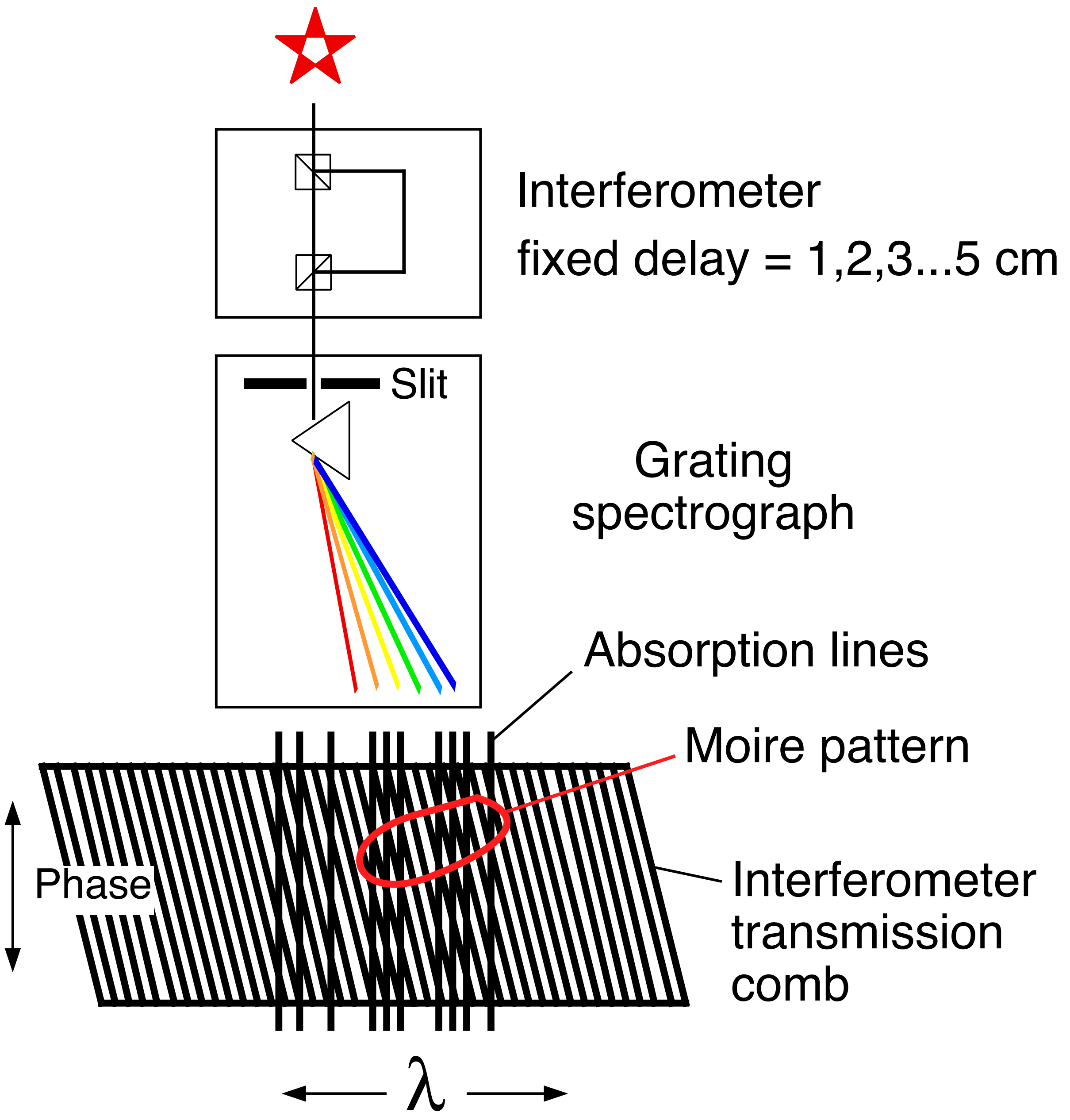
J. Edelstein (UC Berkeley)

erskine1@llnl.gov
jerrye@ssl.berkeley.edu

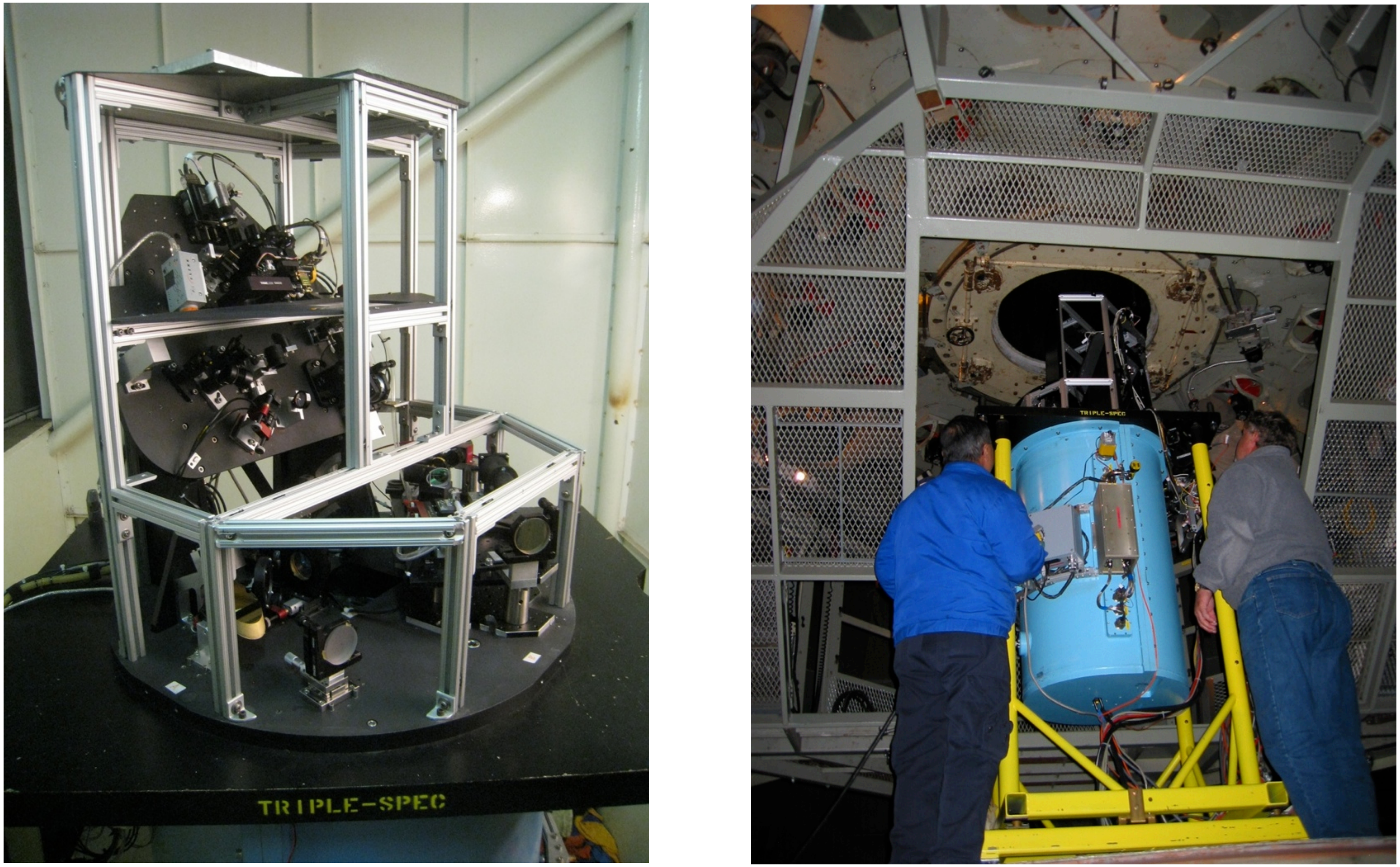
10x CASIS.key

CASIS Signal & Image Sciences Workshop, May 21, 2014

Externally Dispersed Interferometer Scheme

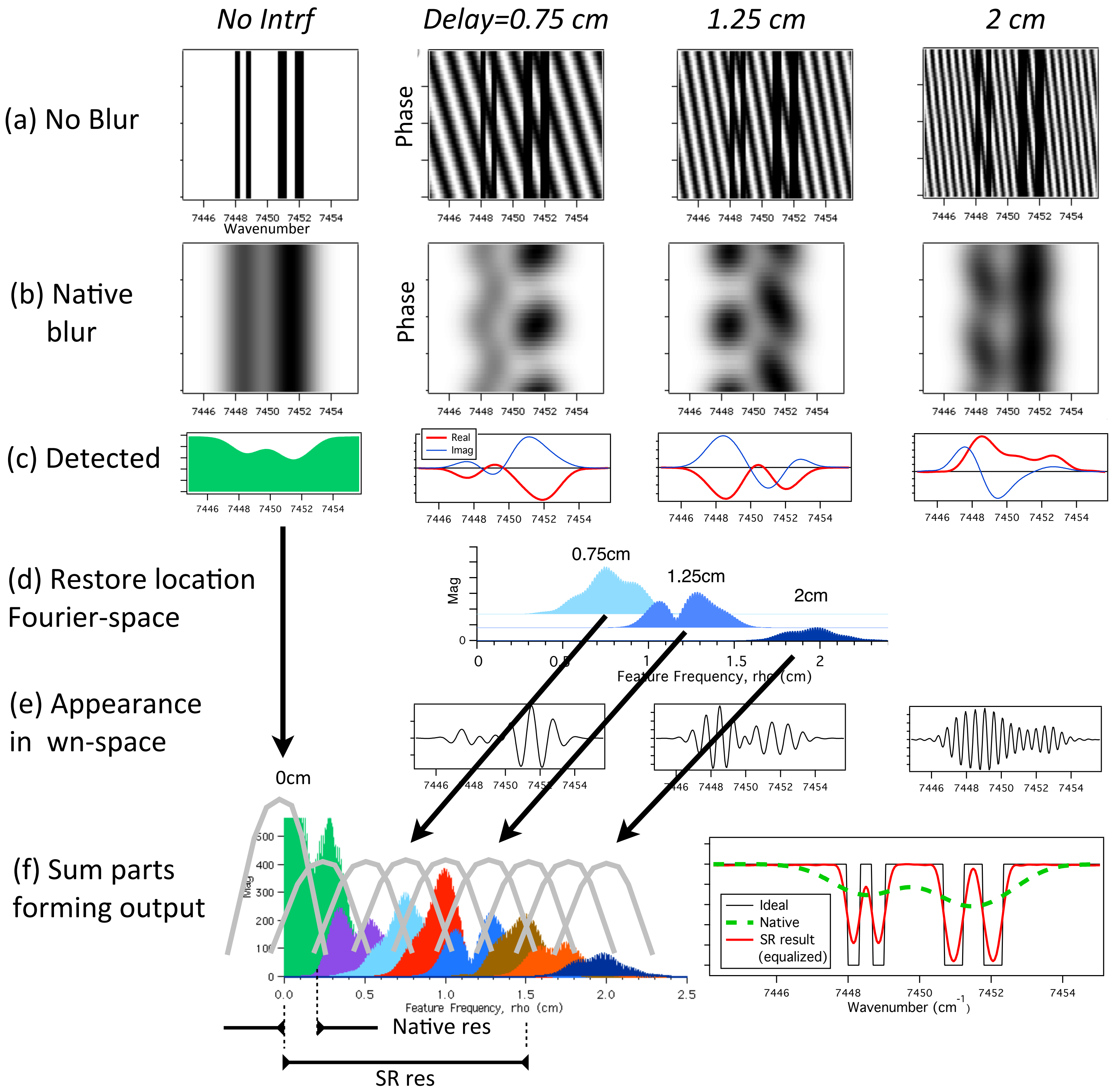


Externally Dispersed Interferometer (EDI) scheme. The sinusoidal transmission comb of the interferometer multiplies the stellar spectrum yielding a moiré pattern. This manifests high resolution spectral information (high feature frequency) heterodyned down to broad and detectable features (low feature frequency). The interferometer delay (optical path difference) is chosen from several fixed values, typically 1 to 5 cm, to sense different feature frequency regions. The overall moiré phase shifts in proportion to target Doppler velocity, and is the subject of other reports.[1,2] The *shape* of moiré pattern encodes the shape of the high resolution spectrum. The topic of this paper is to reverse the heterodyning process and deduce the original spectrum from a series of moiré patterns measured at different delays.



Photograph of the TEDI interferometer, which sits atop Cornell's TripleSpec spectrograph (blue cryogenic cylinder). The interferometer fits in the Cassegrain output cavity of the Mt. Palomar 200 inch mirror, while the TripleSpec is bolted to the bottom of the mirror. The TEDI unit captures the starlight, passes it through an interferometer, and then re-injects it to the spectrograph with a beam having same f/# and focus location as original beam. (The non-interference spectra displayed in this article are with the arm in place, by summing several fringing exposures to cancel the fringing components.)

Moire Effect



No Intrf

Delay=0.75 cm

1.25 cm

2 cm

(a) No Blur

(b) Native blur

(c) Detected

(d) Restore location Fourier-space

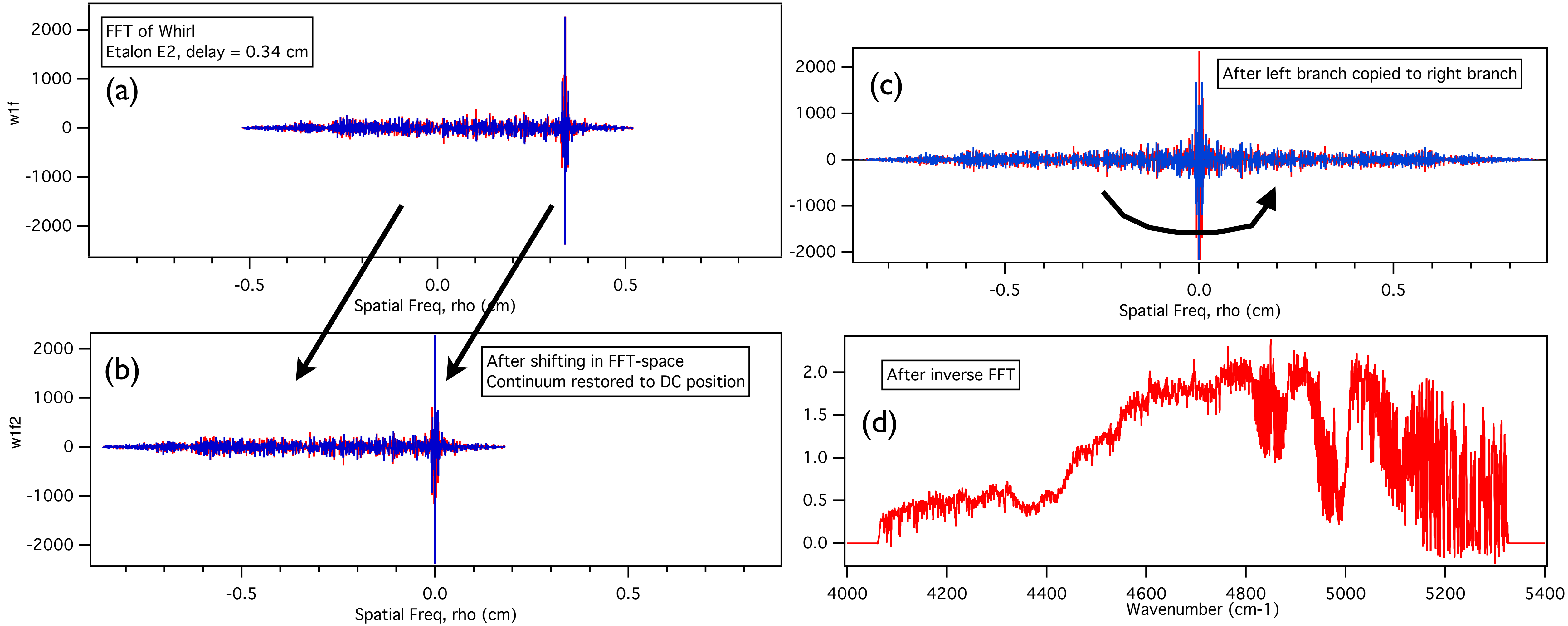
(e) Appearance in wn-space

(f) Sum parts forming output

Native res

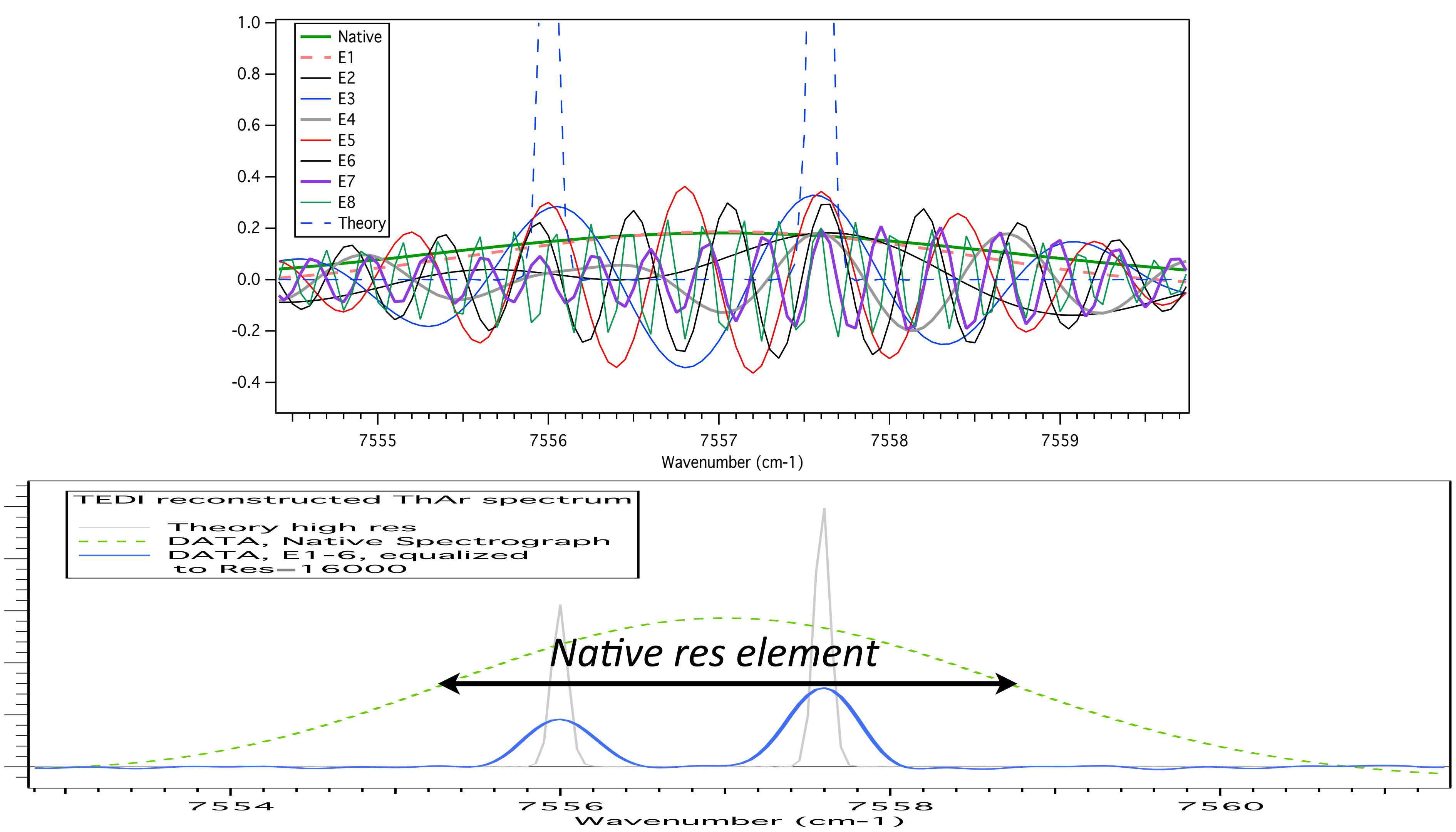
SR res

Reverse Heterodyning, Shift in Fourier Space



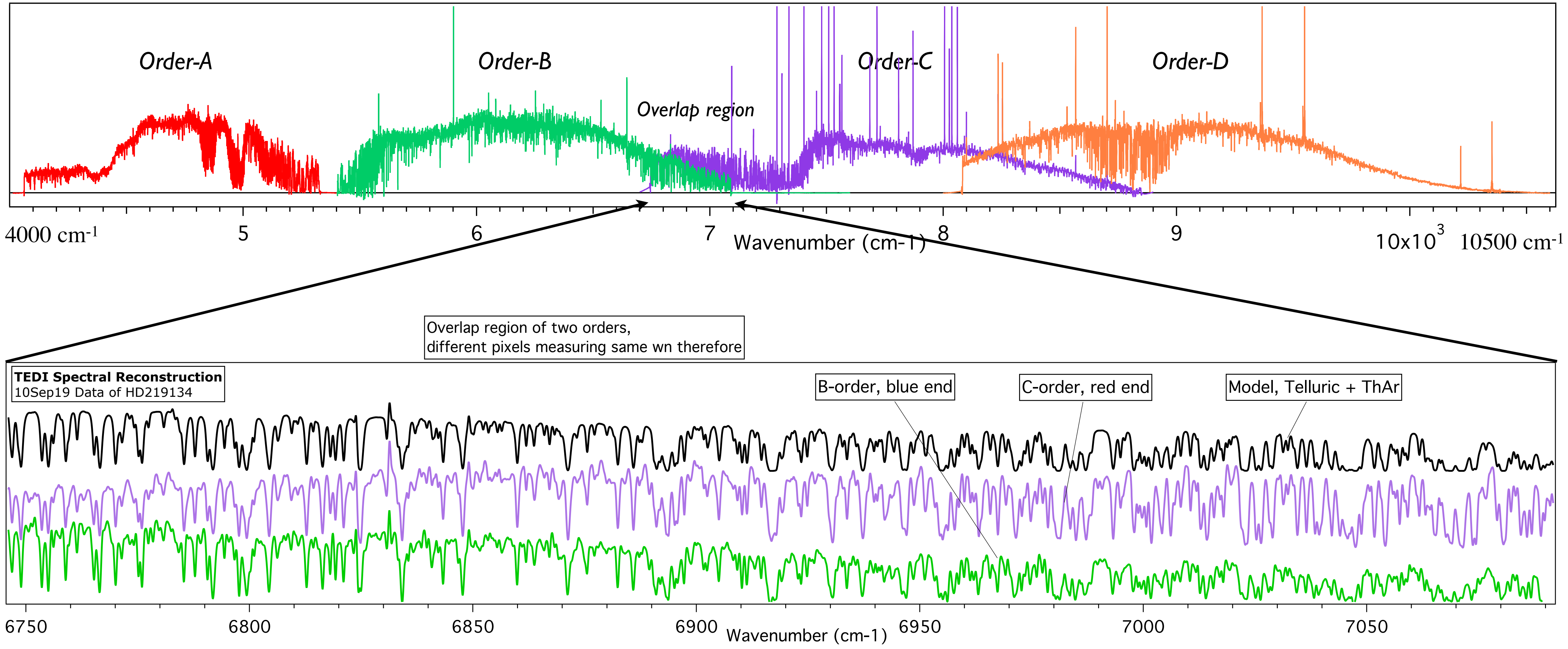
Stages of heterodyning reversal processing. (a) Fourier transform of whirl, here for etalon E2 having small delay of 0.33 cm. This puts continuum comb spike at 0.33 cm, which is within detectable range of native spectrograph ($-0.5 < \rho < 0.5$ cm^{-1}). (b) The Fourier transform is shifted by the etalon delay, which moves the comb spike to zero frequency, along with moving other signal energy to left. For larger delay etalons there may be no comb spike and the signal energy ends up even further to the left. (d) The inverse Fourier transform is applied and the imaginary part set to zero to form a purely real output spectrum. This has same effect as (c) adding the complex conjugate to making the right and left frequency branches mirror reflections. Since the E1 and E2 etalons are small enough to produce a resolvable continuum comb, the resulting spectra will have all the information of an ordinary spectrum plus additional higher resolution information. By adding higher delay components, even higher resolution is produced in the composite final spectrum.

Sum the wavelets



(Top) Reconstruction of an otherwise unresolvable ThAr doublet (7556, 7557.6 cm^{-1}) from wavelets derived from multiple etalons. (Bottom) Summed results. The native spectrograph (green dash) cannot resolve the doublet (gray, hi res theory). The EDI reconstructed spectrum (solid blue curve) equalized to res=16000 easily resolves the doublet. Since each channel's fringes are produced from the interferometer and not the disperser (except a broad 4 cm^{-1} envelope), the precision of the result is insensitive to the native spectrograph or details of its slit, focal blur, pixel spacing or beamshape.

Unlimited Simultaneous Bandwidth

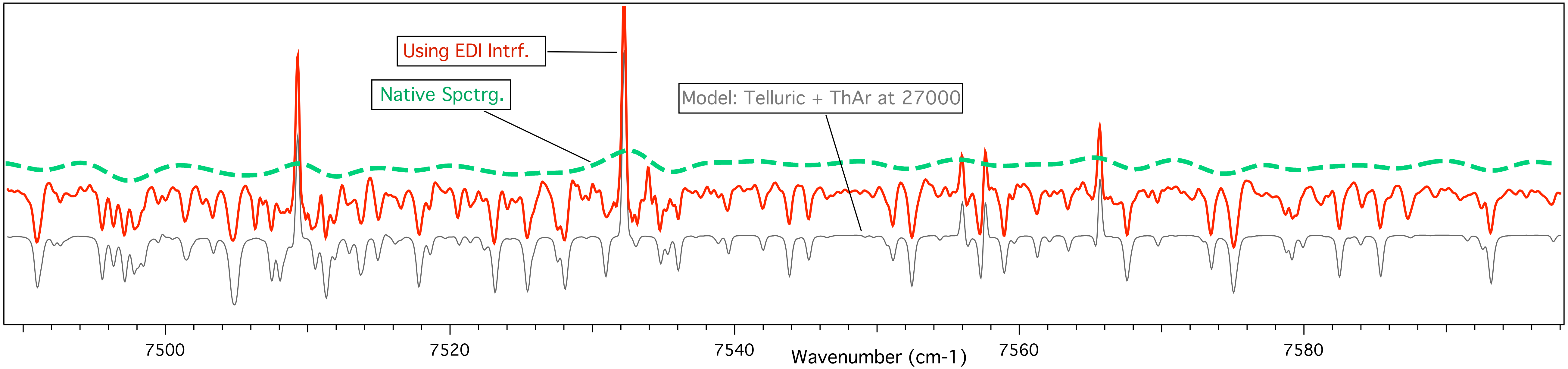


The TEDI reconstructed resolution boosted spectrum spans the 4 orders of TripleSpec spectrograph in NIR (4100-10500 cm^{-1}), here observing HD219134 on Sept 19, 2010. The lower graph is zoomed in region of overlapping orders B & C, showing agreement between two very unrelated groups of pixels (on opposite sides of detector), and with telluric model[14] (black curve).

10x Resolution Boost on Starlight

Native spectrograph cannot resolve the lines

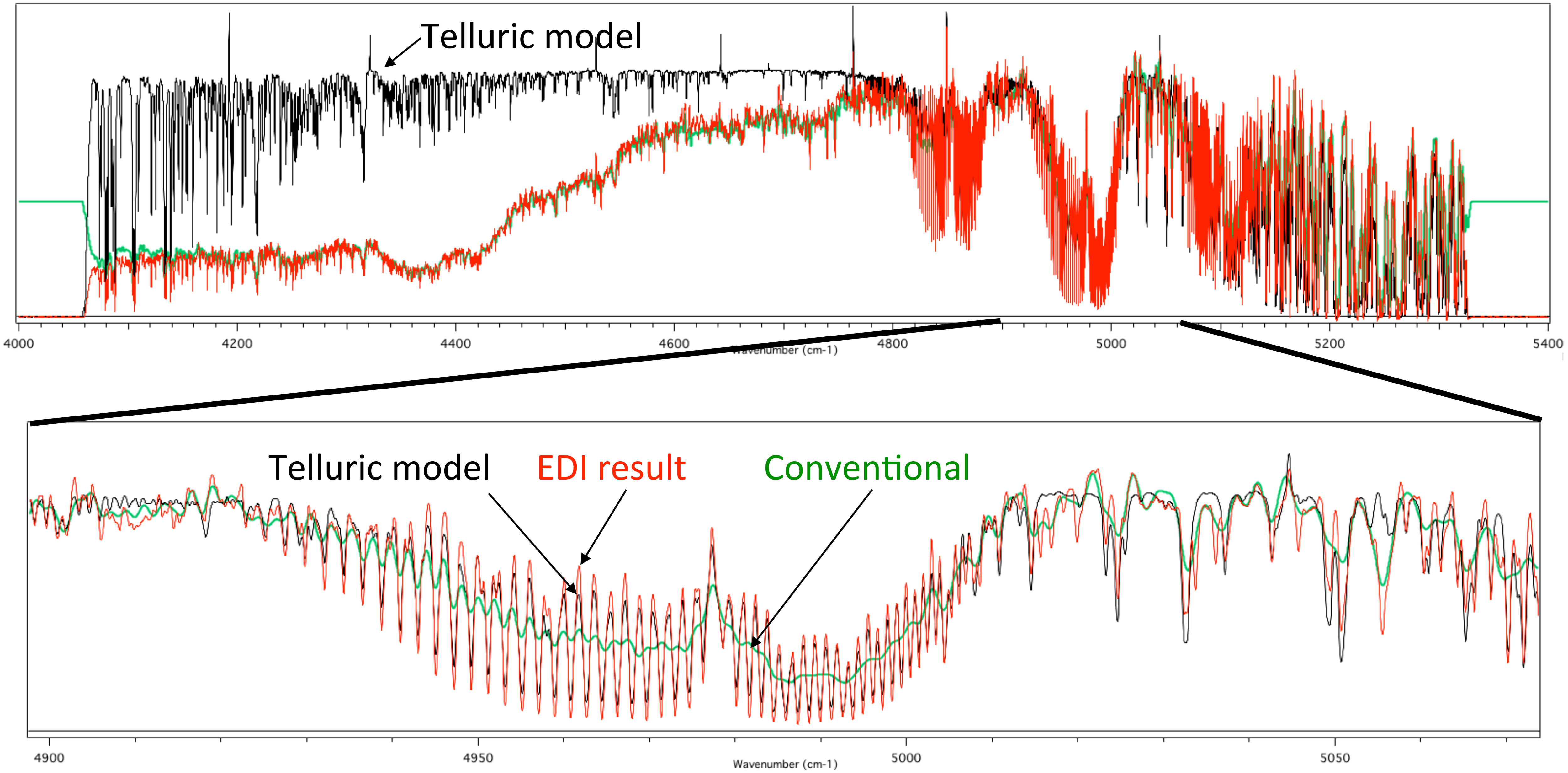
The EDI enabled spectrograph can



Demonstration of a 10-fold resolution boost observing telluric features mixed into spectrum of star κ CrB along with ThAr calibration lamp emission lines. The green dashed (top) curve is the “ordinary” spectrum measured without the interference, having native resolution 2,700. It cannot resolve any of the telluric features. The red (middle) curve is the EDI (TEDI) reconstructed spectrum measured with 7 contiguous delays, up to 3 cm, and equalized to a Gaussian resolution of 27,000. The gray (bottom) curve is a model of telluric[14] and ThAr[15] features blurred to resolution of 27,000, showing excellent agreement with ISR data. Resolution boosting occurs simultaneously across the full bandwidth (0.9-2.45 μm) of the native spectrograph (final resolution varies linearly with wavenumber times largest delay).

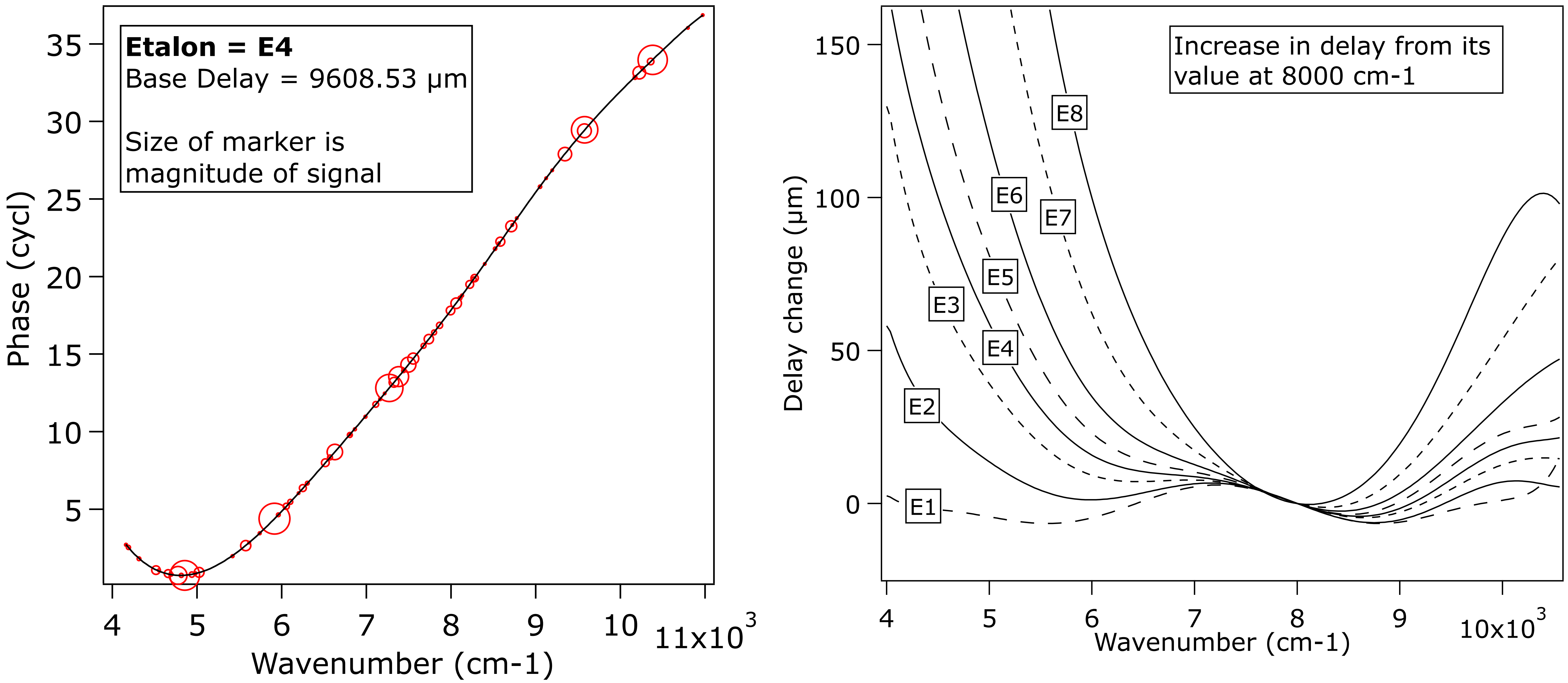
The end

Garage of candidate slides

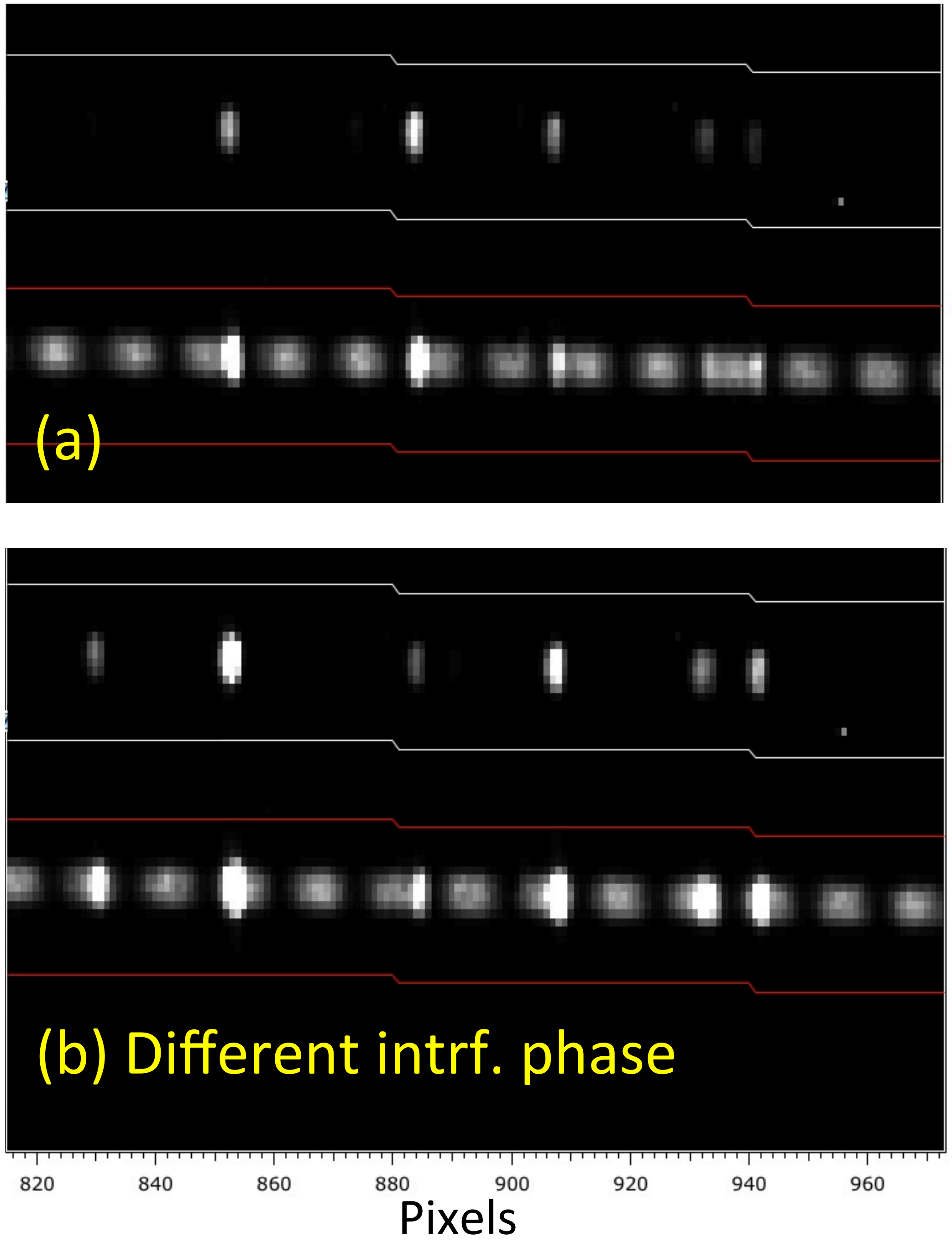


A-order spectral reconstruction (SR) results having 4x boost (11,000 resolution) for star HD219134+ThAr lamp, September 19, 2010. Black is telluric model, red is SR results, green is native ordinary spectrum. (Top) full order 4100-5300 cm^{-1}. The shape of the continuum is accurately reproduced (comparing red to green curves) in spite of the signal coming from two very different kinds of components, fringing vs nonfringing. The overall transmission of the spectrograph system is evident comparing red or green to black. (Bottom) zoom in on a telluric feature near ∼4980 cm^{-1}due to CO_2 molecule.

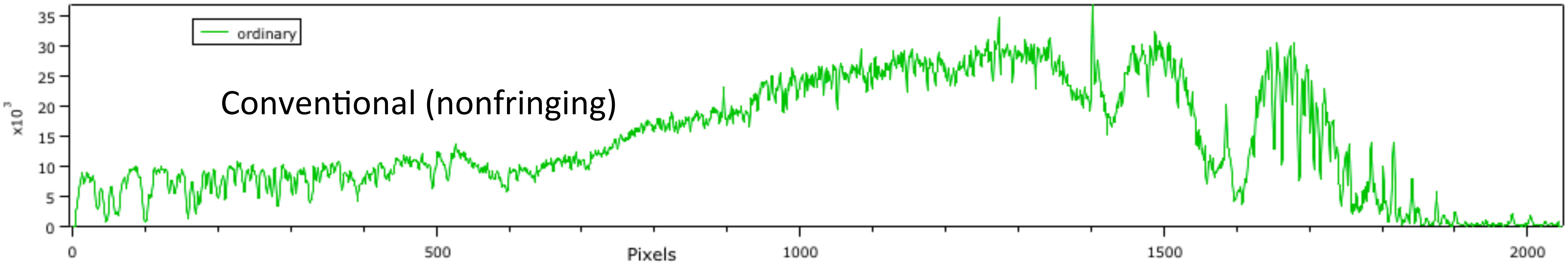
Glass Dispersion Phase Shift Removed



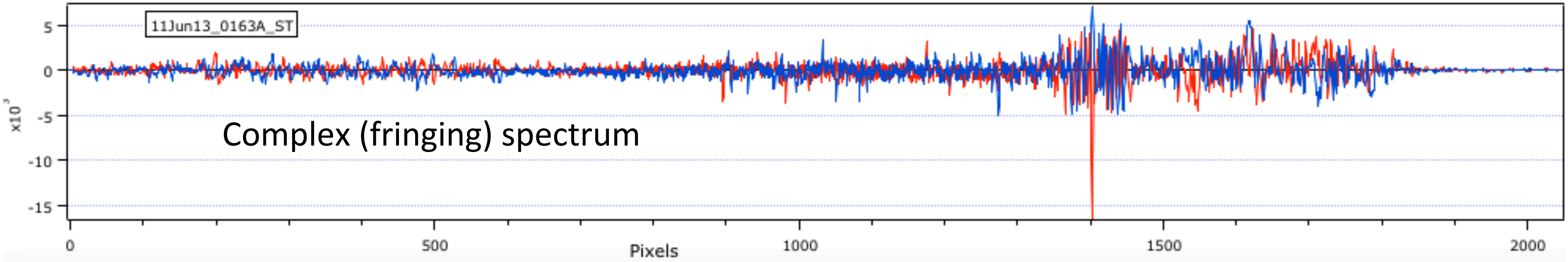
The dispersion characteristics of set of glass etalons are calibrated over a 4000-11000 cm^{-1} bandwidth by phase shift comparison with ThAr emission line model.[15] The resulting phase vs wavenumber curve (left), taken with a specific base delay value, is then used to "untwist" stellar fringing spectra so that a constant delay (the base value) can be used during reversal of heterodyning effect, in the processing prior to summing the individual channels to assemble the reconstructed spectra. The derivative of a 10th order polynomial fit to the phase data provides delay vs wavenumber curves (right). Only the phase curves, not the delay curves, are needed for the spectral reconstruction. But the family of delay curves are useful for detecting an integer fringe skip error in the phase shift measurement, by their common behavior. The dispersion characteristic of the beamsplitter substrate (most obvious in the smallest delay E1) is a common component of all. Delay values for E1-8 are ∼ 0.1, 0.3, 0.7, 1, 1.3, 1.7, 3 and 4.6 cm.



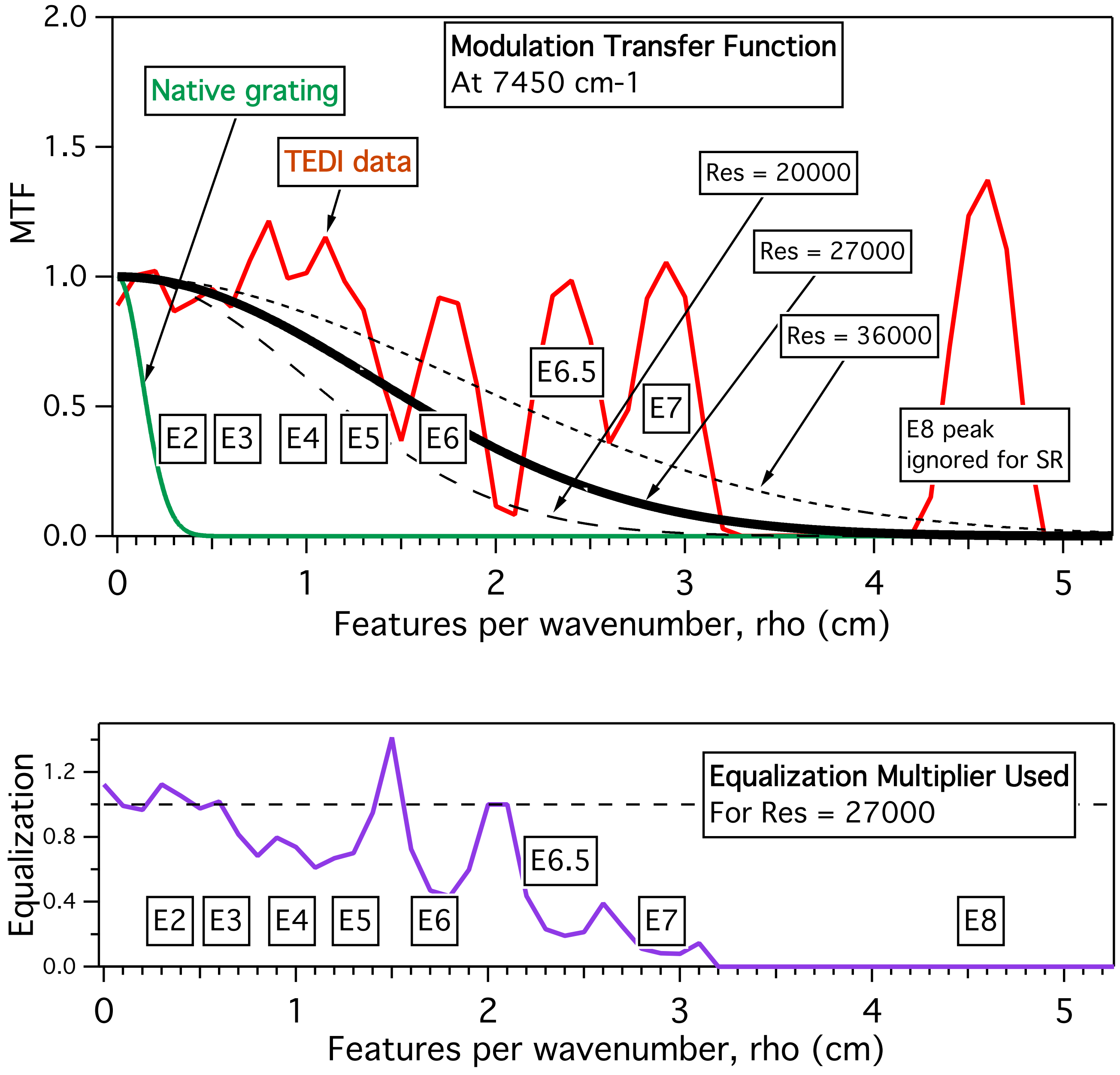
Closeup of two raw exposures (a) & (b) having different interferometer phases, showing a single echelle diffraction order (of four used). Each order has four fibers, A, B, and A_{sky} & B_{sky}. Thin pairs of white and red lines designate fiber A (white, top) or fiber B (red, lower). The adjacent sky fibers are not shown. Here, fiber A contains purely ThAr spectral lamp lines and fiber B a mixture of ThAr and stellar signals, but these roles are swapped in other exposures. Note that the phases of the ThAr lines, manifested by their modulated intensity, differ between exposures. The phase of the periodic stellar continuum also shifts by same amount, but it is perceived as a sideways translation rather than an intensity modulation.

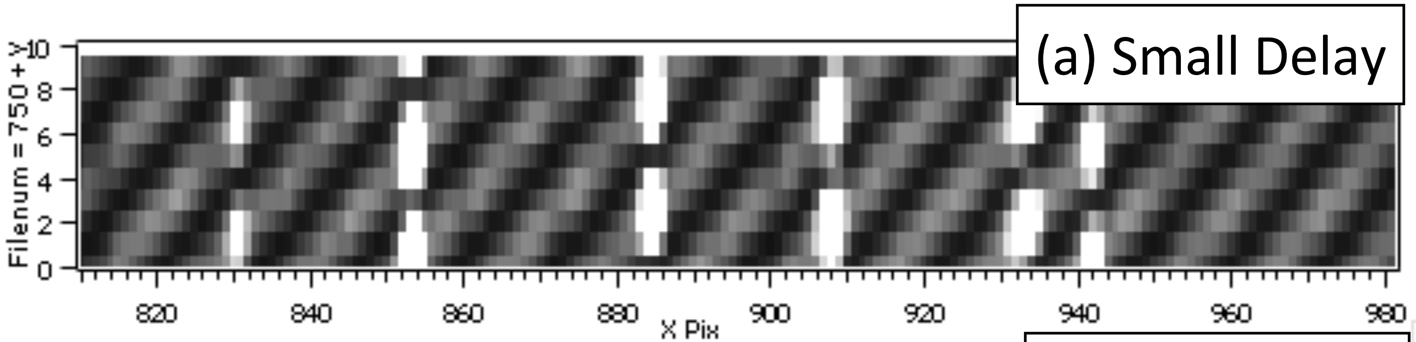


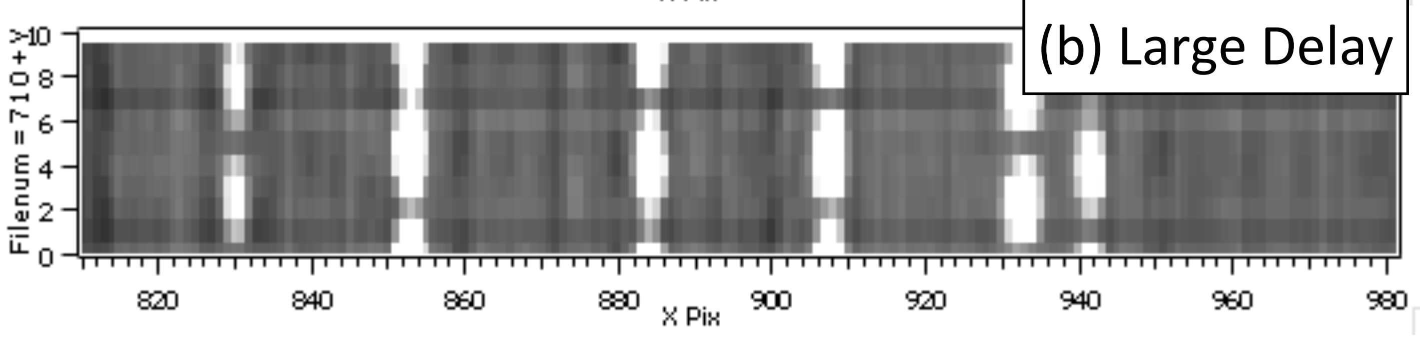
Conventional (nonfringing)

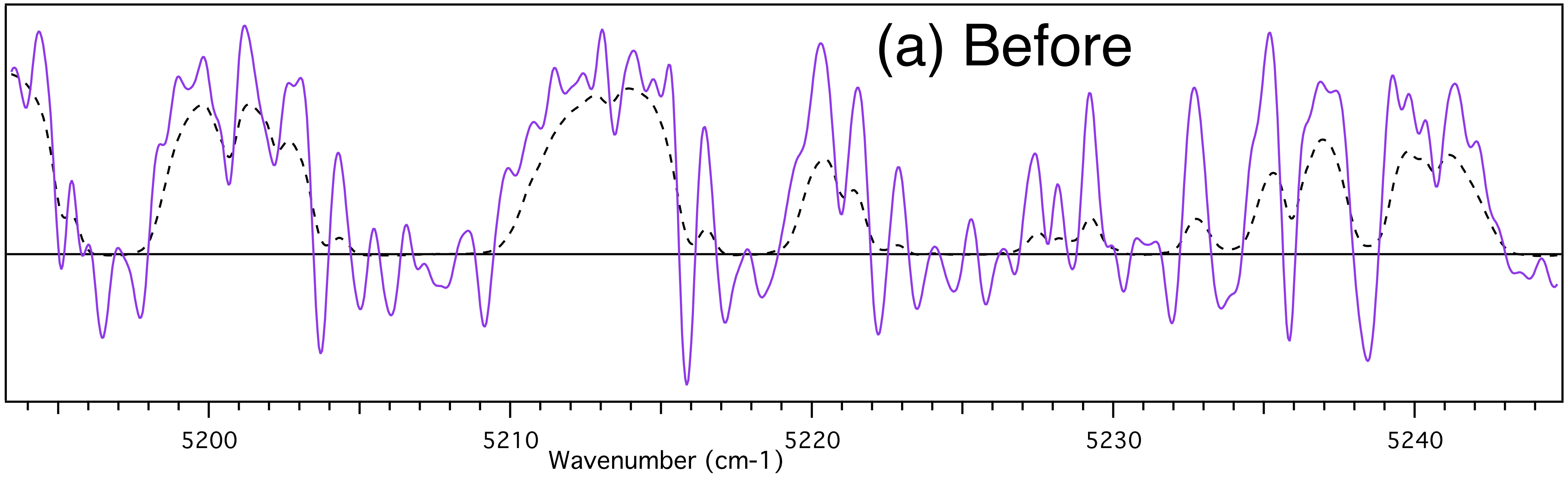


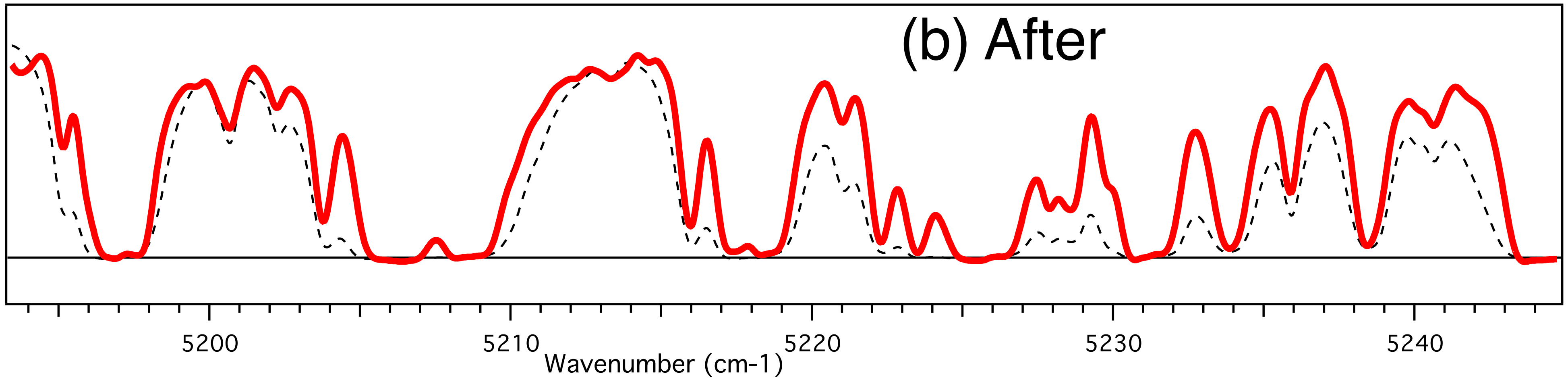
Complex (fringing) spectrum

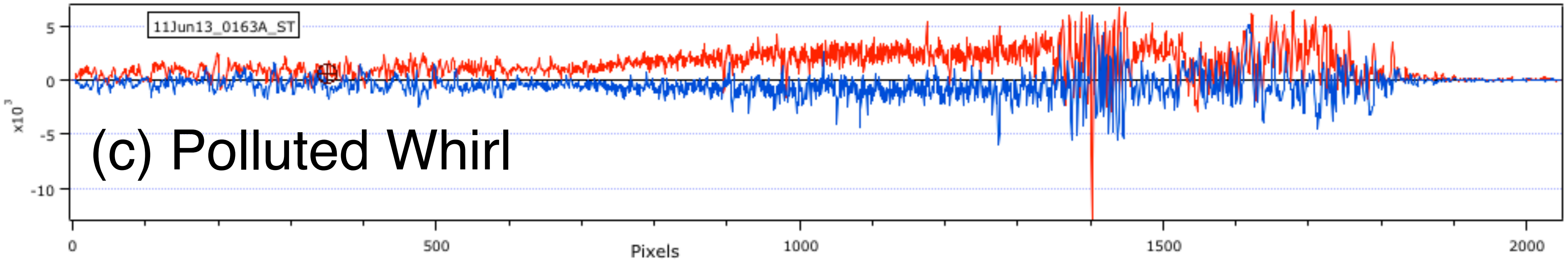

Modulation Transfer Function
At 7450 cm-1
Native grating
TEDI data
Res = 20000
Res = 27000
Res = 36000
E2
E3
E4
E5
E6
E6.5
E7
E8 peak
ignored for SR
MTF
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
Features per wavenumber, rho (cm)
Equalization Multiplier Used
For Res = 27000
Equalization
1.2
0.8
0.4
0.0
E2
E3
E4
E5
E6
E6.5
E7
E8
0
1
2
3
4
5
Features per wavenumber, rho (cm)

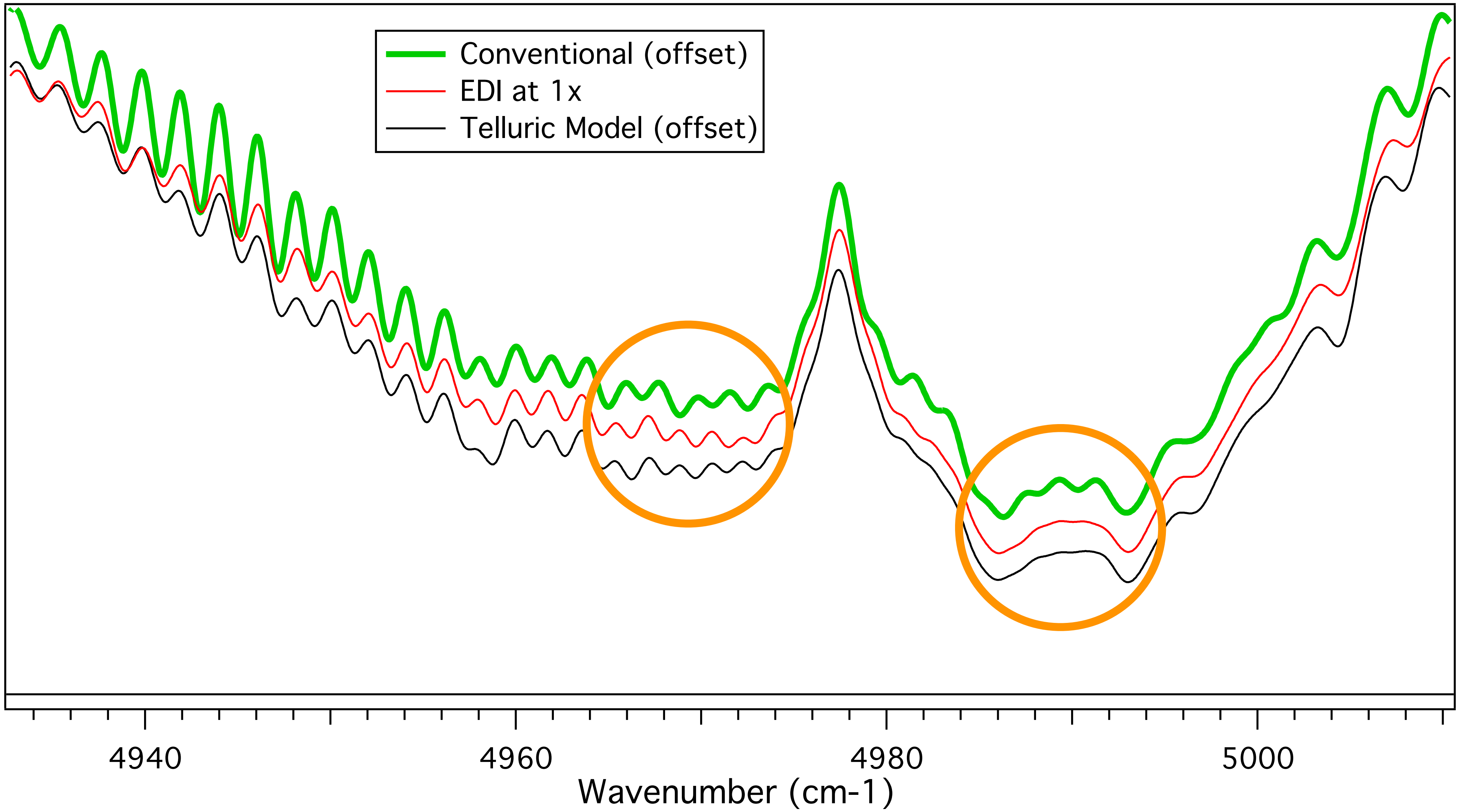

(a) Small Delay


(b) Large Delay

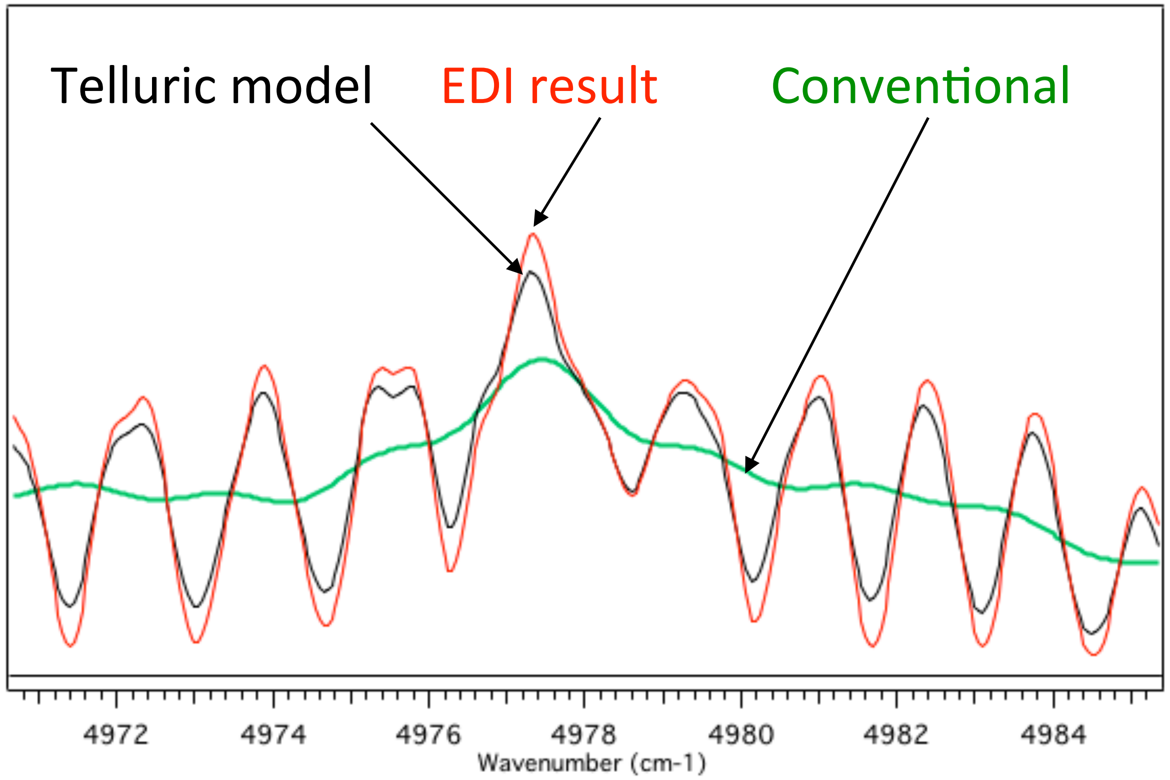

(a) Before
5200
5210
5220
5230
5240
Wavenumber (cm-1)

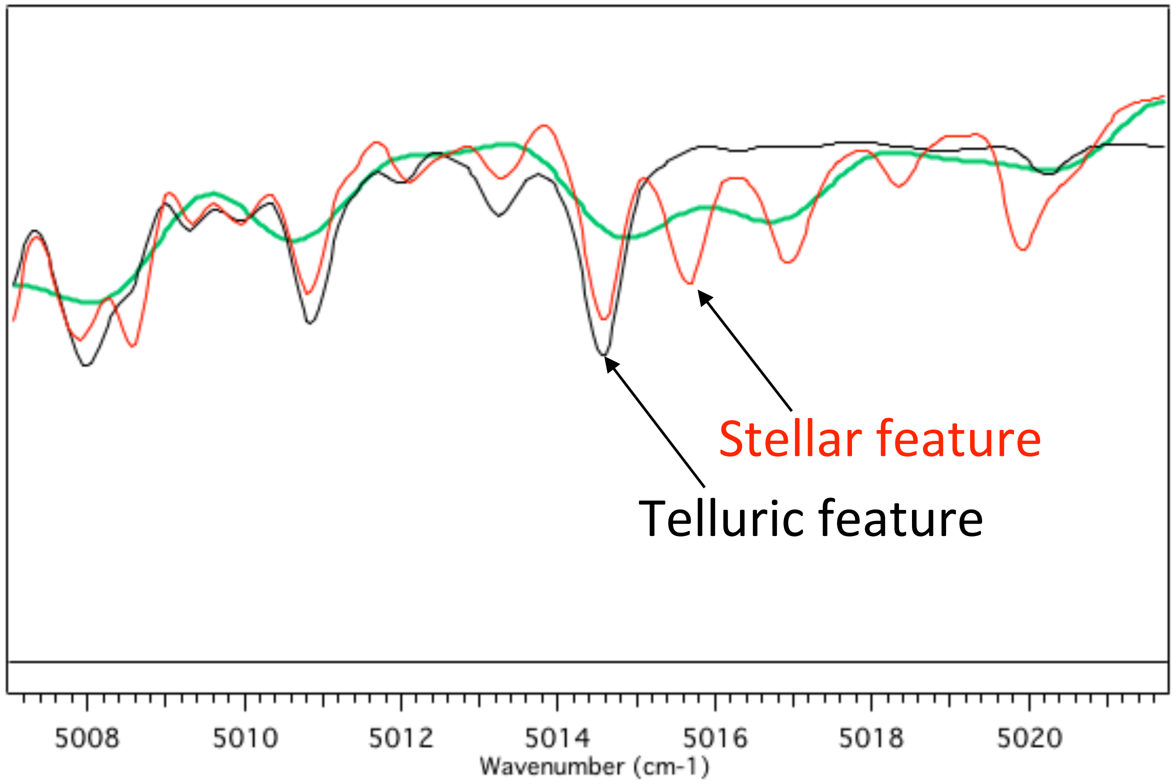

(b) After
5200
5210
5220
5230
5240
Wavenumber (cm-1)

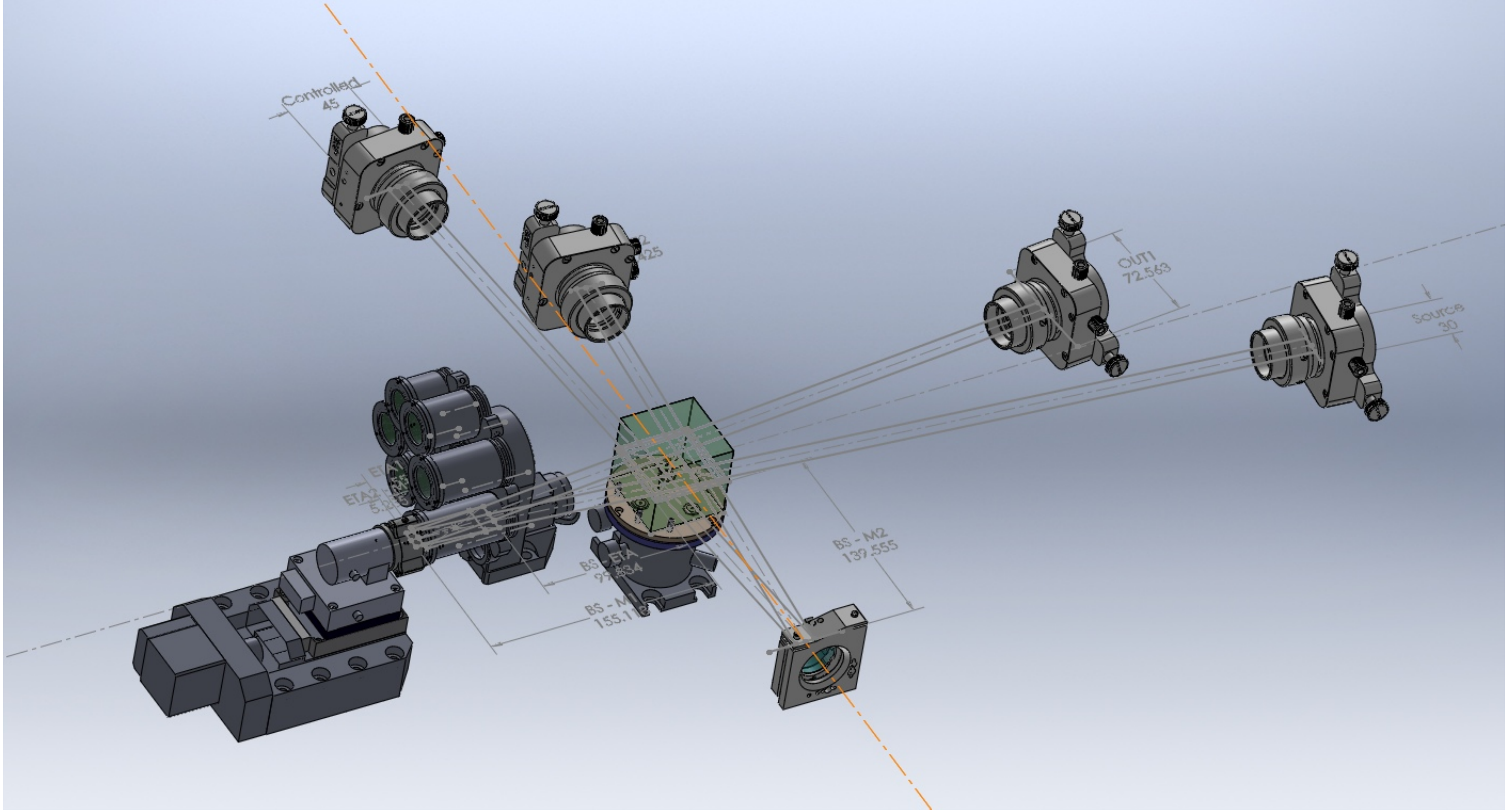

11Jun13_0163A_ST
(c) Polluted Whirl
5
0
-5
-10
x10³
0
500
1000
1500
2000
Pixels

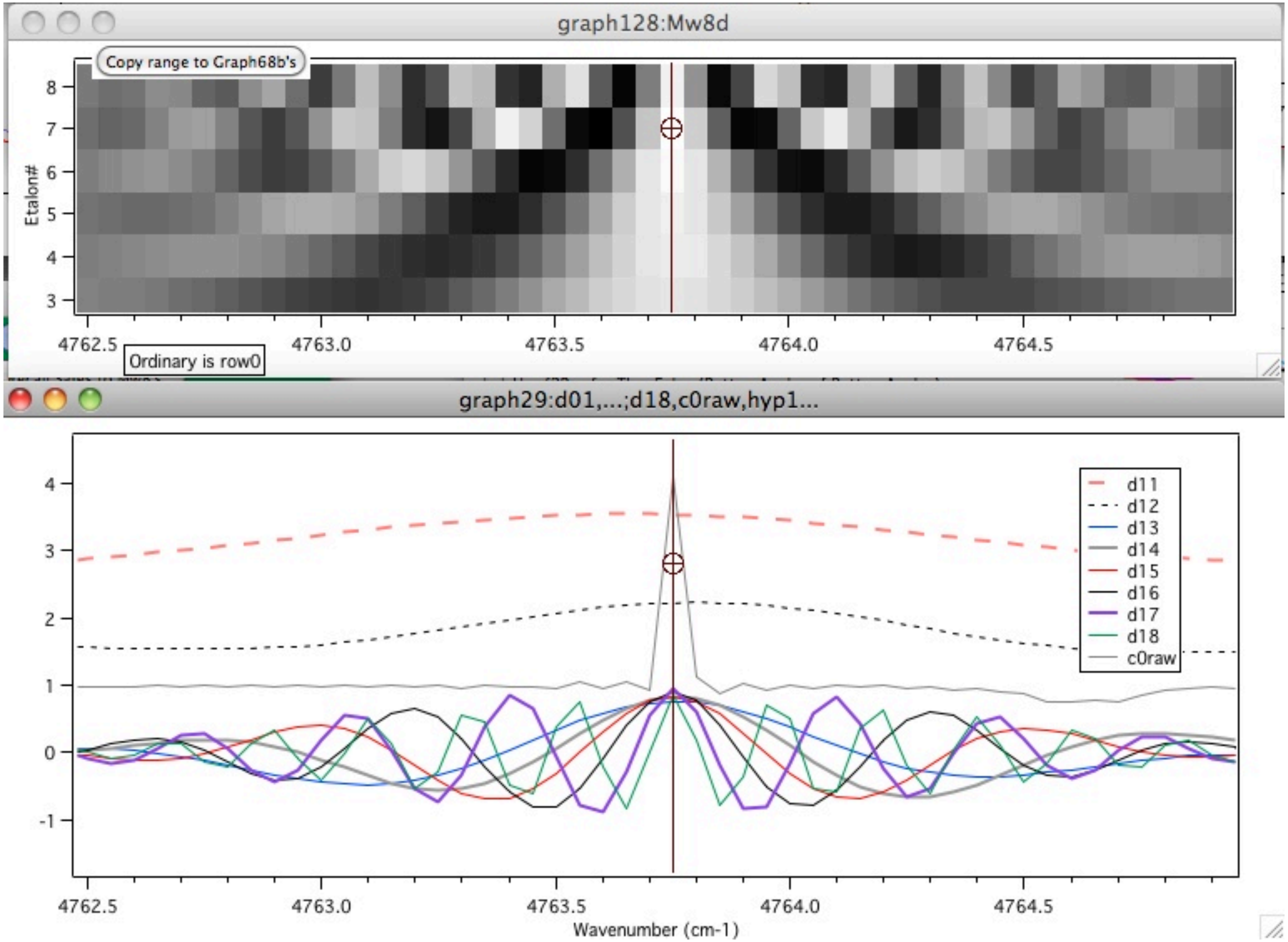


Zooms-ins of A-order SR result (red) of Fig. 5. (Left) subtle features of telluric model (black), such as the tiny dips and detailed shapes of the peaks of CO_2 feature at ∼4980 cm^{-1}, are beautifully reproduced. The ordinary spectrum (green) of native spectrograph cannot resolve these. (Right) The current model does not yet contain stellar features, such as at 5016-18 cm^{-1}, because of individuality of each star's Doppler velocity, elemental constituents, photosphere temperature and pressure broadening. (Bottom) The EDI result (red, "1x") using only fringing measurements and blurred to have the same resolution (2700) as native spectrograph, more accurately follows details of telluric model (thin black curve) than conventional spectrum (bold green) obtained from same exposures. (See conventional's wiggles at 4970 & 4990 cm^{-1} disagreeing with model.) Green and black curves offset vertically for clarity (bottom only). Target is star HD219134+ThAr lamp, September 19, 2010

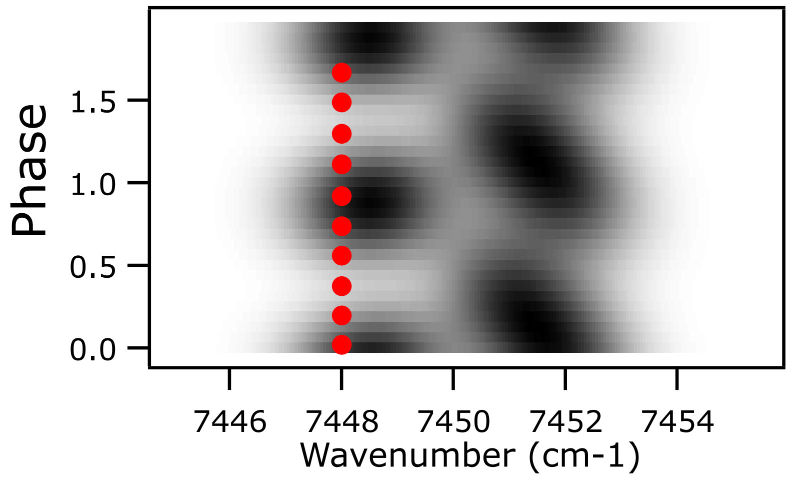

Telluric model
EDI result
Conventional
4972
4974
4976
4978
4980
4982
4984
Wavenumber (cm-1)


Stellar feature
Telluric feature
5008
5010
5012
5014
5016
5018
5020
Wavenumber (cm-1)

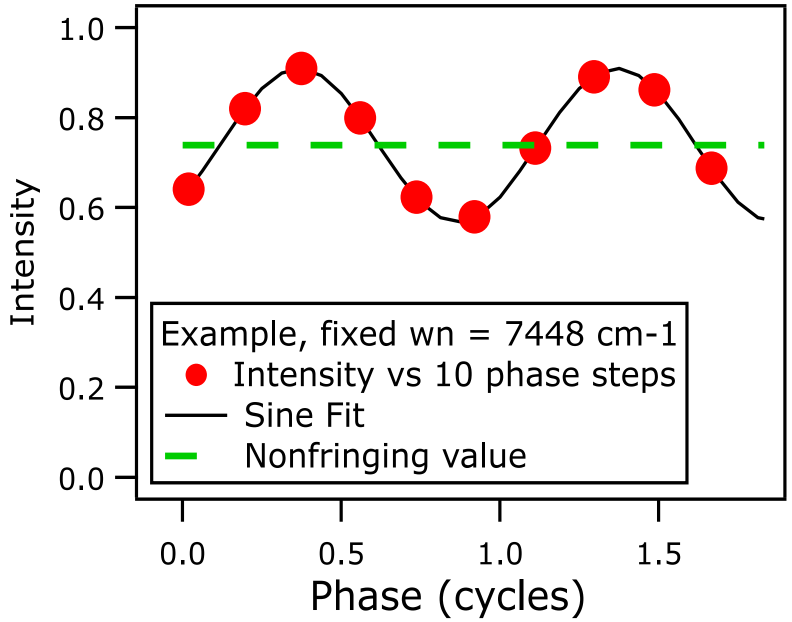

Controlled
45
2
425
OUT1
72.563
Source
30
ETA1
ETA2
5.2
BS - ETA
99.834
BS - M1
155.11
BS - M2
139.555


graph128:Mw8d
Copy range to Graph68b's
Etalon#
8
7
6
5
4
3
4762.5
4763.0
4763.5
4764.0
4764.5
Ordinary is row0
graph29:d01,...;d18,c0raw,hyp1...
4
3
2
1
0
-1
d11
d12
d13
d14
d15
d16
d17
d18
c0raw
4762.5
4763.0
4763.5
4764.0
4764.5
Wavenumber (cm-1)

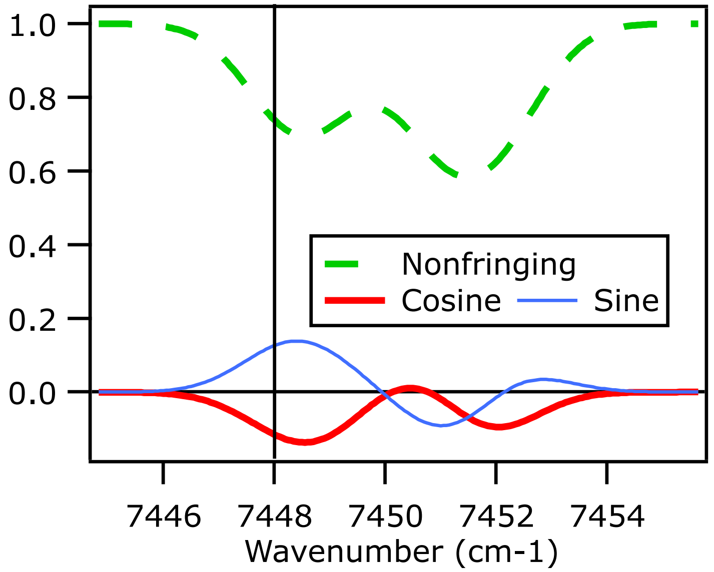
(a) Data source

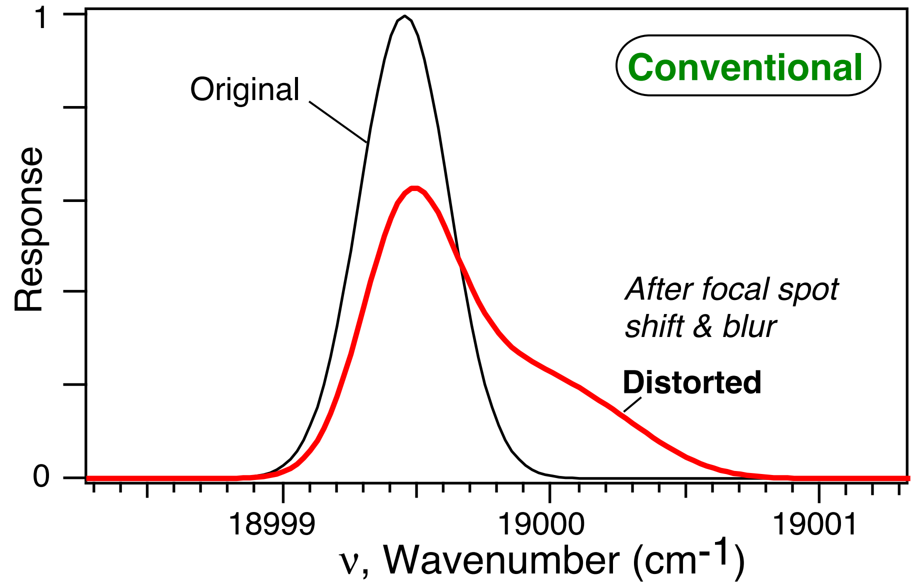


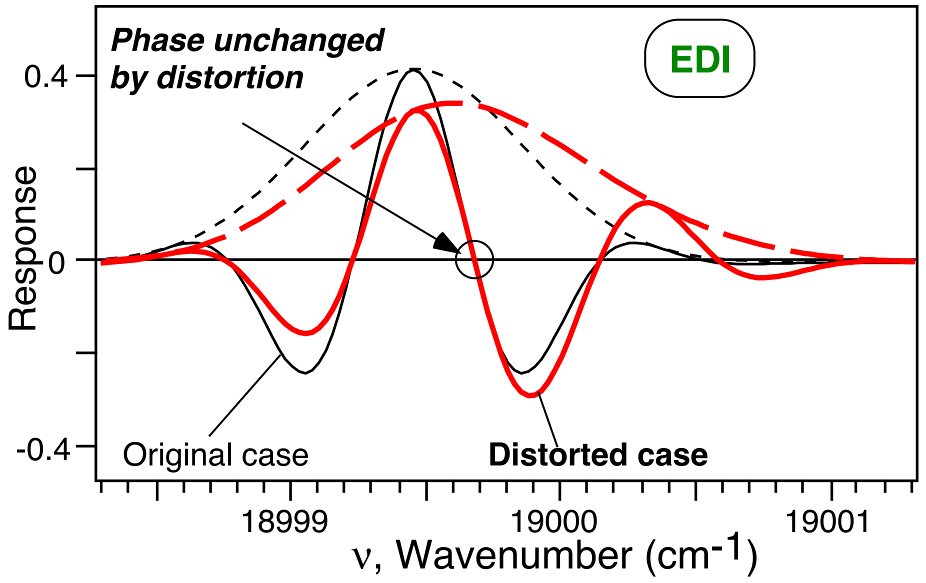
(b) Fitting example



(c) Complex representation




1
0
Response
Original
Conventional
After focal spot
shift & blur
Distorted
18999
19000
19001
ν, Wavenumber (cm-1)


Phase unchanged
by distortion
EDI
0.4
0
-0.4
Response
Original case
Distorted case
18999
19000
19001
ν, Wavenumber (cm-1)