Method for enhanced exoplanet biosignature detection using a small interferometric addition to a low resolution spectrograph

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Ersatz proceedings for poster "sciencesconf.org:758908" to Habitable Worlds Observatory (HWO2026) conference, 30 Nov. - 4 Dec, 2026, Paris, France.
Session: Life Detection & habitability - Biosignatures

Abstract. We theoretically explored the spectroscopic benefits of inserting one or more small fixed-delay Michelson interferometers into the beam of a low resolution spectrograph such as slitless imaging instruments similar to that in the James Webb Space Telescope, or integral field spectrograph of ground-based Gemini Planet Imager. For observing telluric features at 2 micron (5000 cm^{-1}) at native resolution R=70, the interferometer delay is optimally set to the periodicity of molecular signature fine structure, in this case, a range of delays centered at 0.58 cm. This is easily accomplished by a one or several small monolithic interferometer prisms inserted into the beam. The interferometrically boosted photon-limited sensitivity to detecting 2 cm^{-1} fine structure was calculated to be similar to a R=3850 native spectrograph. The signal to noise ratio was thus boosted by many orders of magnitude relative to the infinitesimally small ability of a $\sim$71 cm^{-1} wide point spread function to detect $\sim$2 cm^{-1} molecular fine structure. The fixed-delay nature of interferometer allows conventional long exposure staring mode for low flux sources– the delay is not scanned as in a Fourier Transform spectrometer. However, net exposure time is distributed into several phase stepping exposures to allow separation of nonfringing and fringing spectra. Nonfringing spectra provide a conventional output. Fringing spectra detect presence of molecular fine structure signal with boosted sensitivity.

Keywords: High resolution spectroscopy, Externally Dispersed Interferometry, Resolution Boosting, Exoplanets, Atmosphere, Molecules, Biosignature .

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1 References to cite

1.1 Method: Externally Dispersed Interferometry

We introduce externally dispersed interferometry (EDI)[1–15] as a solution to increasing the resolution of any spectrograph, by placing a fixed delay interferometer into the native spectrograph beam. This technology has been demonstrated on other linear and echelle spectrographs in the visible and near infrared. We conjecture that it would be advantageous to include an interferometer filter in a spaceborne spectrograph.

EDI can measure Doppler velocities[1,4,9,10] with a much smaller native resolution spectrograph than otherwise practical. The EDI technique has been used by other researchers to discover exoplanets[16,17] around HD102195 and HD87646, as well as confirmation of 51 Peg.[18]

EDI can boost the spectral resolution[5,6,11,12,14,15] of a spectrograph by a factor of several to an order of magnitude. The maximum resolution is limited only by the highest delay of a contiguous

range of delays used. It uses staring style of data collection familiar to astronomers observing weak sources, not using a scanning delay such as in a Fourier Transform Spectrometer (FTS).

1.2 Monolithic interferometer references

Reference 19 from 1995 describes using monolithic interferometers (photo in Fig. 8) used to measure solar photospheric Doppler oscillations in a Michelson Doppler Imager.

References 20–23 from 2008-12 describe thermally stable monolithic interferometers constructed advantageously using two glasses (BK7 and LAK7) having different thermal responses to cancel net drift.[24] These stable monolithic interferometers have been used as an EDI[3] to measure Doppler velocities, and in a white light illuminated calibration source in MARVELS (Multi-object Apache Point Observatory Radial Velocity Exoplanet Large-area Survey of Sloan Digital Sky Survey).[25]

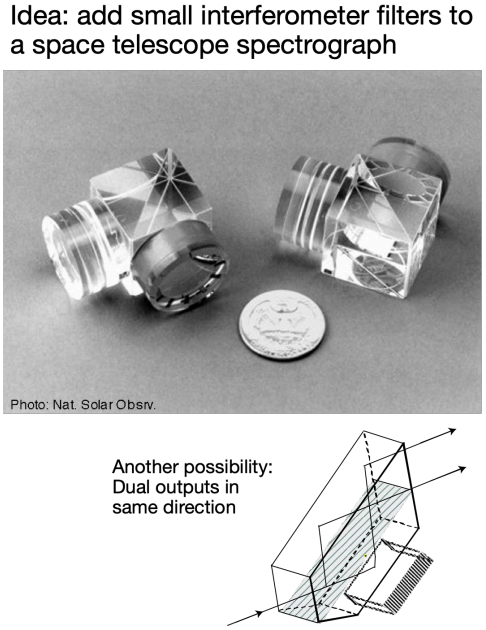


Fig 1 Idea: add small monolithic interferometer filters[19–23] to a space telescope spectrograph, and explore the benefits. For the design shown in the photograph, based on a beamsplitting cube, one output emerges 90 degrees to the input (which is easy to access), and a complementary output returns almost 180 degrees back toward the source (which is more difficult to access). A possible solution[7] to this awkwardness is the prism shown in drawing which directs both main and complementary outputs in the same direction, while displaced from each other.

2 Synopsis/Summary

We theoretically explored [Figs. 10-12] the spectroscopic benefits of inserting one or more small fixed-delay Michelson interferometers into the beam of a low resolution spectrograph similar to that in the James Webb Space Telescope, or integral field spectrograph of ground-based Gemini Planet Imager. This forms an Externally Dispersed Interferometer (EDI) [Figs. 1-6]. An EDI measured the CO_2 telluric feature using this resolution boosting technique [Fig. 7-9] at the Hale telescope using R$\sim$2700 TripleSpec in NIR. We believe EDI will also benefit lower resolution

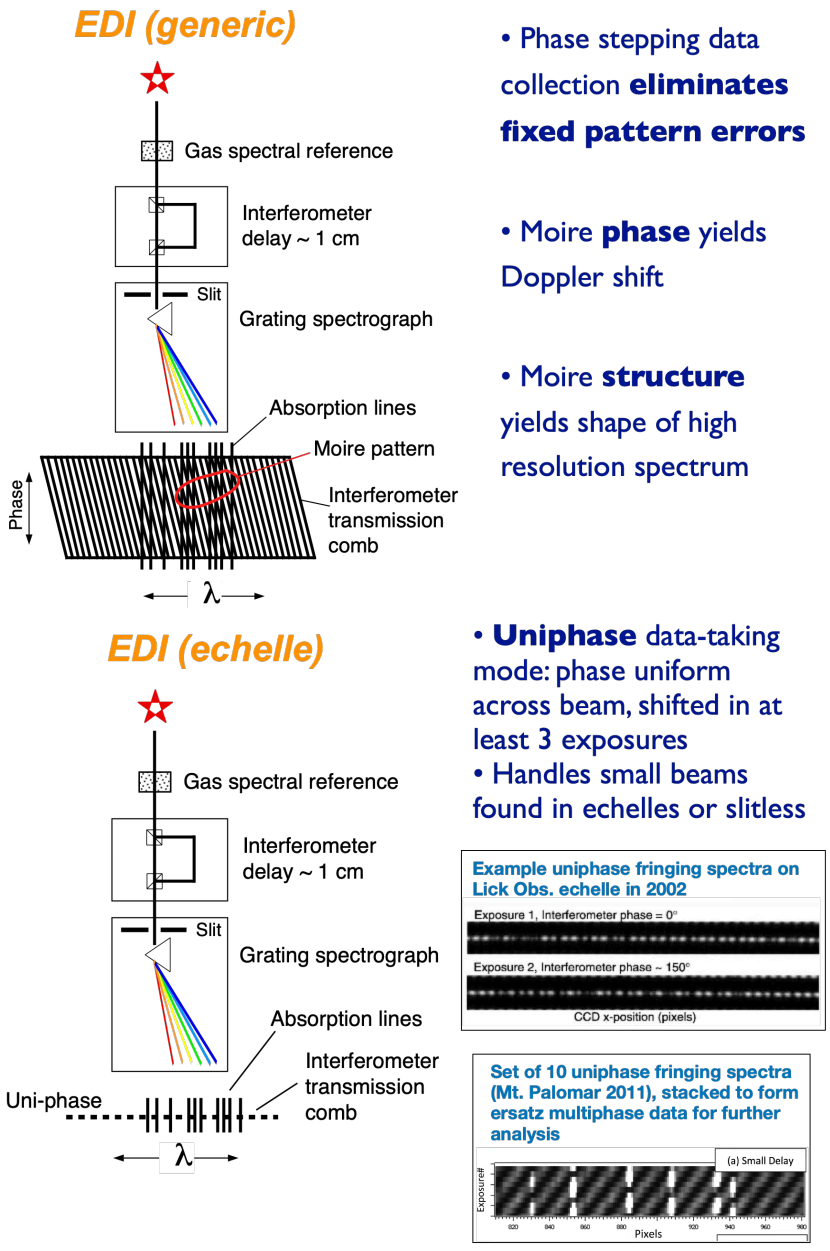


Fig 2 (a) Generic EDI scheme using multiphase or phase-slanted[4] mode where interferometer phase varies linearly along a tall slit of a linear spectrograph, which is also convenient for displaying generation of moiré patterns. (b) Uniphase mode of taking data has been demonstrated,[5,11] appropriate for narrow beams of an echelle spectrograph. In this mode (phase-stepping), interferometer phase is uniform across the beam and incremented in at least three separate exposures.

spectrographs. For observing telluric features at 2 micron (5000 cm^{-1}) at native resolution R=300 [Fig. 10], or R=70 [Fig. 11-12], the interferometer delay is optimally set to the periodicity of molecular signature fine structure, in this case delays near 0.58 cm. This is easily accomplished by a one or several small monolithic interferometer prisms inserted into the beam. The interferometrically boosted photon-limited sensitivity to detecting 2 cm^{-1}fine structure was shown [Fig. 12]

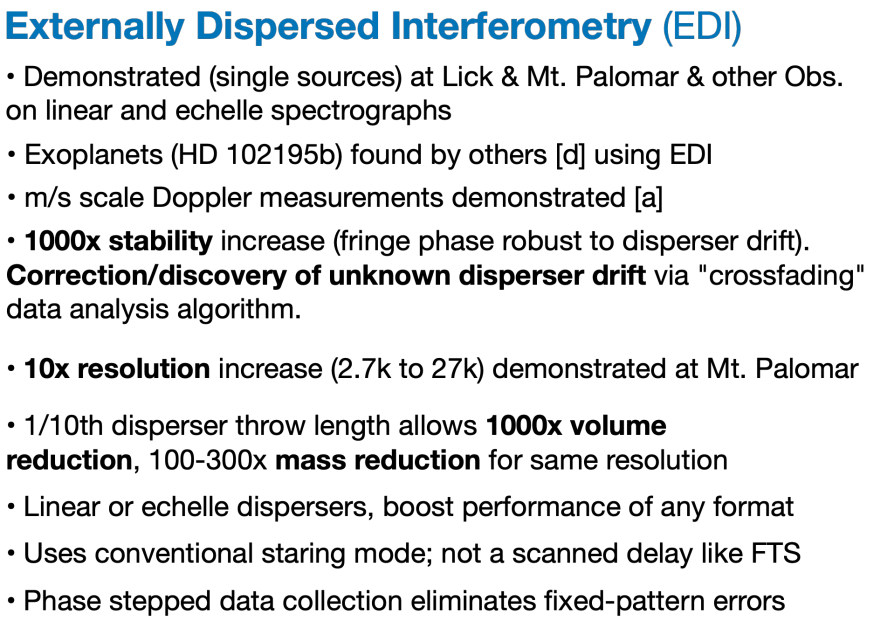


Fig 3 Externally dispersed interferometry (EDI)[3] has been demonstrated at Lick Obs. Hamilton echelle,[5] and Mt. Palomar Obs. Hale telescope[10–12] on TripleSpec NIR echelle[26] on starlight, as well as on linear grating spectrographs.[1,2,4,6] Exoplanets measured[18] and discovered[16,17] by others using EDI. Meter per sec scale Doppler reproducibility described in Ref. 1, 4. Dramatic stability increase against disperser drift achieved by strategic weighting and filtering of fringing and nonfringing components during data analysis using a "crossfading" algorithm, for both multiple[14] and single delays.[15,27] This allows discovery and correction of an unknown disperser wavelength drift. A 10x resolution (2.7k to 27k) has been demonstrated on the Hale Telescope and TripleSpec NIR echelle spectrograph.[11] Such a resolution boost could allow for a 10x reduction in throw length (for a linear grating) while achieving the same net resolution (with a mild worsening of photon signal to noise). That could allow for a 1000x volume reduction and commensurately large mass reduction, useful for a spaceborne instrument. EDI uses familiar conventional staring mode to collect data with long time exposures for weak sources, unlike a Fourier Transform Spectrometer which scans the delay and requires high frequency readouts. Phase-stepped data collection eliminates detector bias and fixed pattern errors for the fringing signals (since only the portion changing synchronous to the phase stepping survives).

to be similar in magnitude to a R=3850 native spectrograph. The signal to noise ratio was thus boosted by many orders of magnitude relative to the infinitesimally small ability of a $\sim$71 cm^{-1} wide point spread function to detect $\sim$2 cm^{-1} molecular fine structure. The fixed-delay nature of interferometer allows conventional long exposure staring mode for low flux sources– the delay is not scanned as in a Fourier Transform spectrometer. However, net exposure time is distributed into several phase stepping exposures to allow separation of nonfringing and fringing spectra. Nonfringing spectra provide a conventional output. Fringing spectra detect presence of molecular fine structure signal with boosted sensitivity.

Acknowledgments

We are shocked by the untimely passing of Professor James Lloyd (Cornell University), who was a key instigator of the TEDI project at Mt. Palomar Observatory that produced data and shaped ideas in this paper. He will be greatly missed. Thanks to recent discussions with UC Berkeley col-

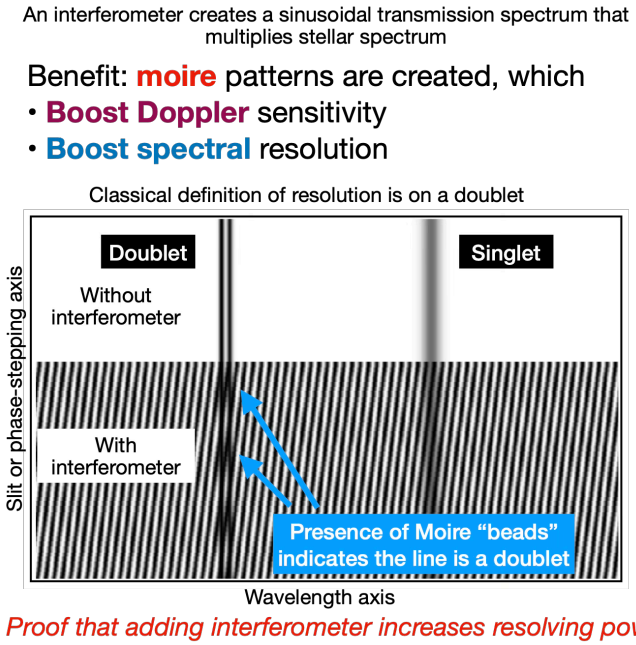


Fig 4 Graphical production of a moiré for the doublet (bottom of left feature), but not for the singlet (right feature), proves that including a periodic interferometer transmission comb in series with a disperser increases resolving power, since the classic definition of resolution is the ability to distinguish a doublet from a singlet. Without the interferometer comb (top portion) the two features would look similar when view from across the room. The two features were created to have equal net grayscale weight. Graphic is similar to Fig. 3 of Ref. 6.

league Micah Allard. This material is based upon previous work supported by the National Science Foundation under Grant No. AST-0505366, AST-096064, PAARE AST-1059158, NASA Grant NNX09AB38G, and portions under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

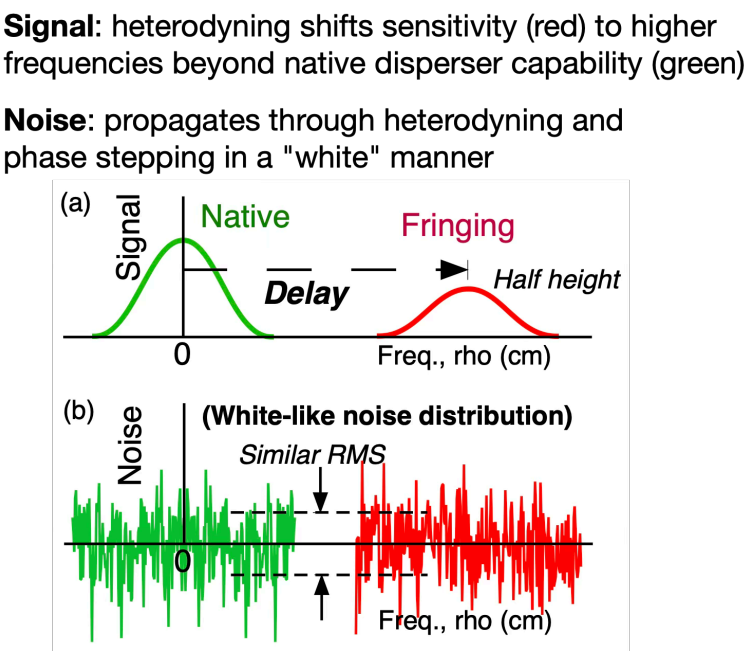


Fig 5 How photon and detector noises propagate through the EDI analysis is explored in Ref. 12. It shows that the noise propagates in a white manner through the heterodyning and phase stepping, ie. the root mean square (RMS) noise is about the same for the fringing signal as for the native (conventional) spectrograph. The fringing signal is reduced by a factor of 2x compared to the native sensitivity peak, due to the heterodyning effect producing both a positive and negative frequency shift of the input spectrum when multiplied by the sinusoid interferometer transmission, but only one of these produces the low frequency detectable moiré patterns. (Consider the 0.5 prefactor and the positive and negative arguments in the identity $\cos x = (0.5) * (e^{ix} + e^{-ix})$).

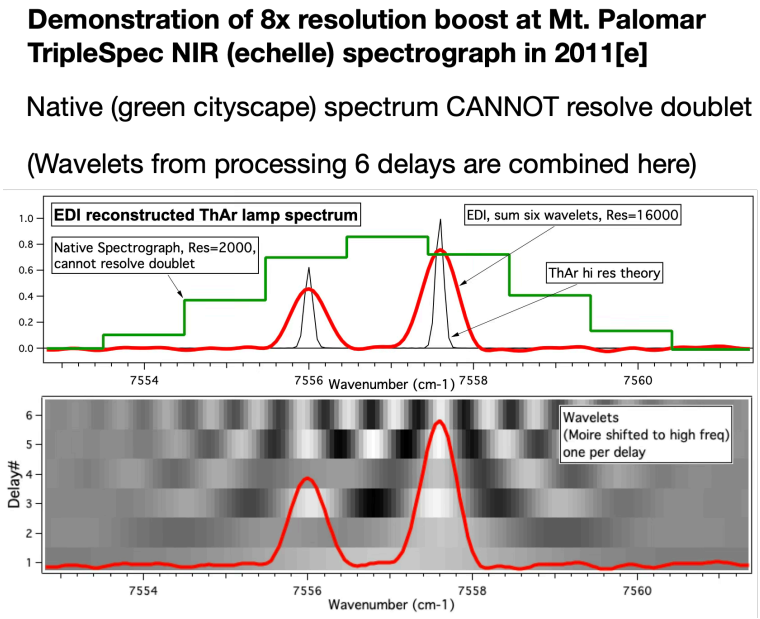


Fig 6 Demonstration[11] of 8x resolution boost at Mt. Palomar Observatory Hale telescope TripleSpec NIR (echelle) spectrograph[26] in 2011. Here the doublet of a ThAr spectral lamp is unresolved by the native disperser (green cityscape) having R ∼2000. Each of 6 delays used produce wavelets when the detected moiré are frequency up-shifted through data analysis to their original frequencies (shifted by the interferometer delay values). The wavelets are summed and then equalized to minimize ringing, with a final resolution of 16,000. The maximum resolution is set by the highest available delay value. Purchase of more and longer delays, and filter wheels on which to mount them, would have enabled higher resolutions. By using fixed delays, rather than a scanning delay (as in a Fourier Transform Spectrograph), the data is taken in long exposures as conventionally done for weak starlight, minimizing detector readout noise.

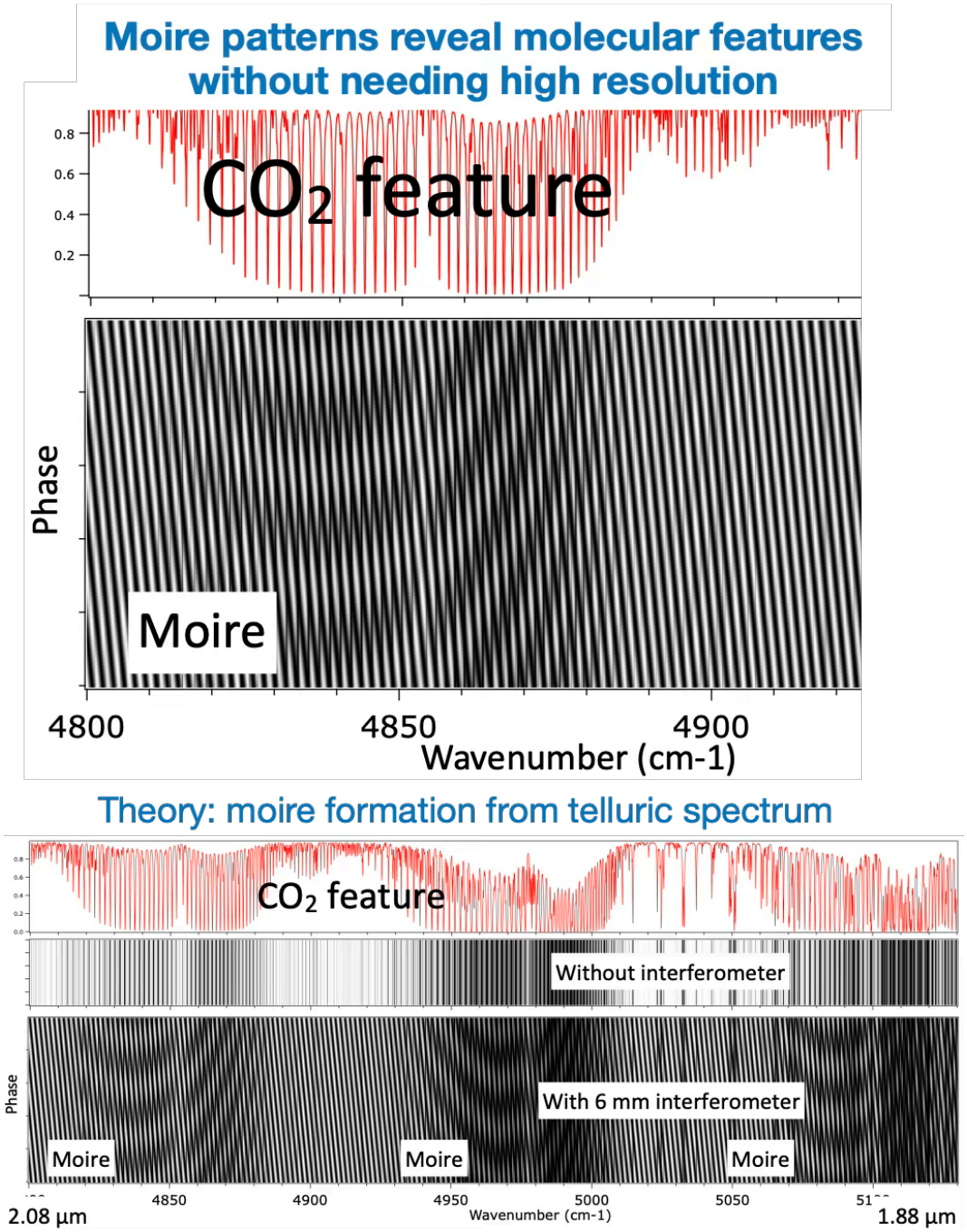


Fig 7 Graphical illustration of how moiré patterns can reveal molecular features without needing a high resolution disperser. (Upper) Closeup of moiré of a CO_2 feature near 4850 cm^{-1} shown in lower panel. (Lower) The theoretical telluric spectrum (red) vs intensity, and also as a grayscale panel labeled "Without interferometer". The lowest panel has overlayed on it a periodic grid of spacing made by a 6 mm delay interferometer, which creates the moiré patterns. Due to the physics of molecular rotation and vibration, the spacing of the fine molecular lines is quasi-periodic and in places exactly matches the interferometer periodicity, making broad moiré that is detectable by a much lower resolution disperser than without the interferometer. If using an echelle spectrograph, the phase would be uniform across the beam and at least three exposures would be taken, stepping the phase by about a third of a cycle for each. This allows separation of the fringing (moiré) from nonfringing (native or ordinary) spectral during data analysis. Both fringing and nonfringing data are useful in reconstructing the original high resolution spectrum. Graphic from Ref. 13.

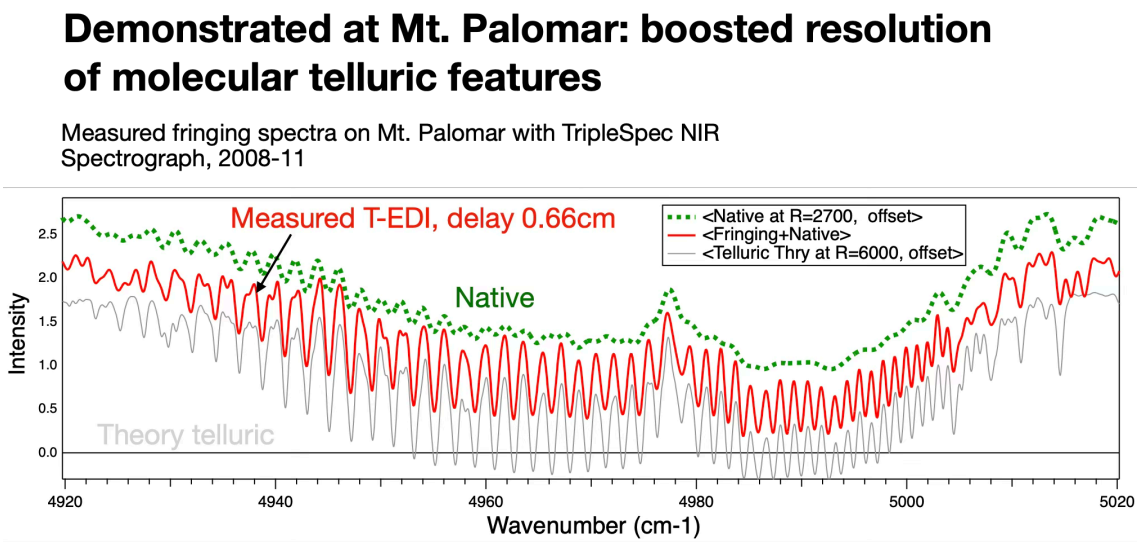


Fig 8 Similar to Fig. 24(b) of Reference 11, but re-analyzed using only a single delay of 0.66 cm, not several delays. Note that a theoretical model (gray curve) of the telluric[28] spectrum blurred to R=6000 has a similar magnitude. Hence the effective resolution has been approximately boosted 2x by the single delay, similar to performance shown in other stellar experiments.[5]

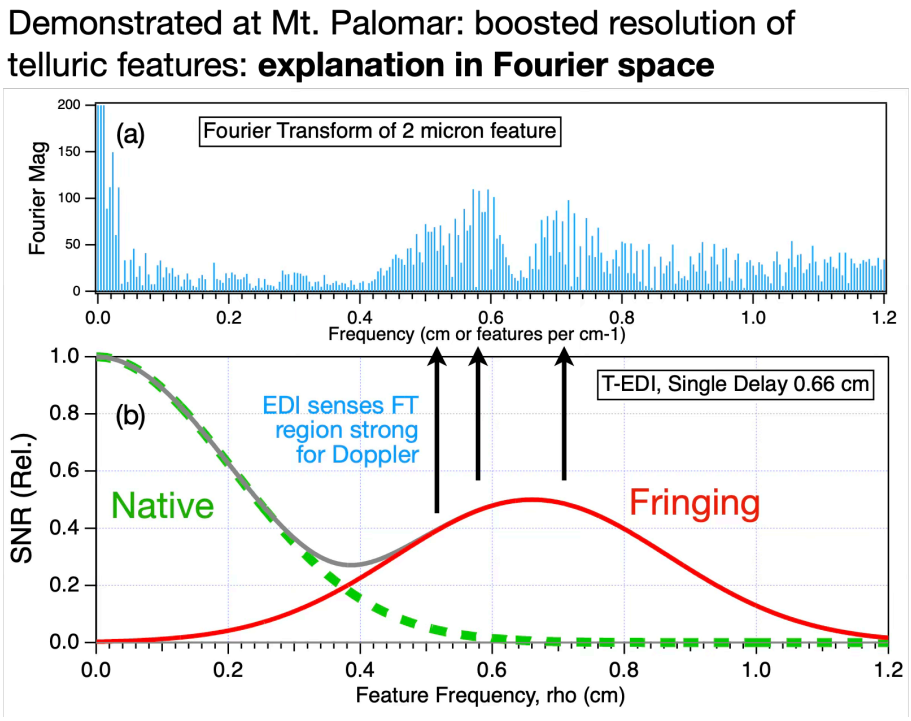


Fig 9 Fourier space behavior associated with the single delay 0.66 cm measurement of spectrum shown in Fig. 8. For this disperser resolution of R ∼2700, having a single peak (red curve, single delay) centered at 0.66 cm in (b) is optimally placed to measure the strong Fourier energy from 0.4 to 0.8 cm shown in (a). The native sensitivity (green dashes) is also ideally placed to measure the very low frequencies which define the broad W-shape of the spectrum (green dots in Fig. 8).

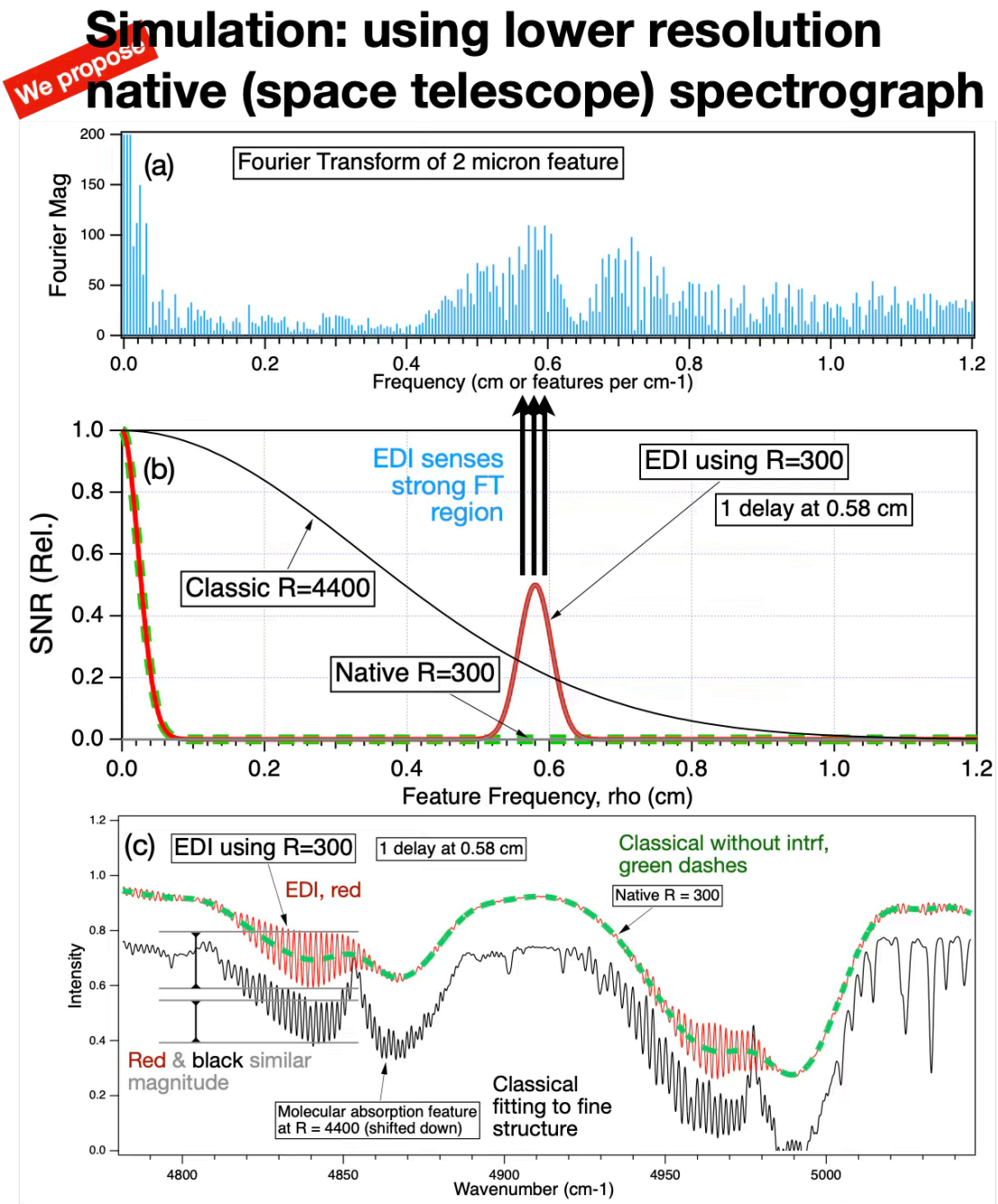


Fig 10 An analysis is done of what the measured spectrum would look like for the same single delay of 0.66 cm, but lower resolution or R=300. In (c) the conventionally measured curve (green dashes) at R=300 cannot resolve the fine structure– it can only map out the slowly varying dips. But note that the amplitude of a conventionally theory curve (black) fine features blurred to R=4400, is similar to that of the (red curve) EDI using R=300. Hence if one is constrained to use a R=300 disperser, using EDI dramatically increases the magnitude of the fine structure sensed, from essentially zero (green dashes), to a strong level similar to a R=4400 disperser.

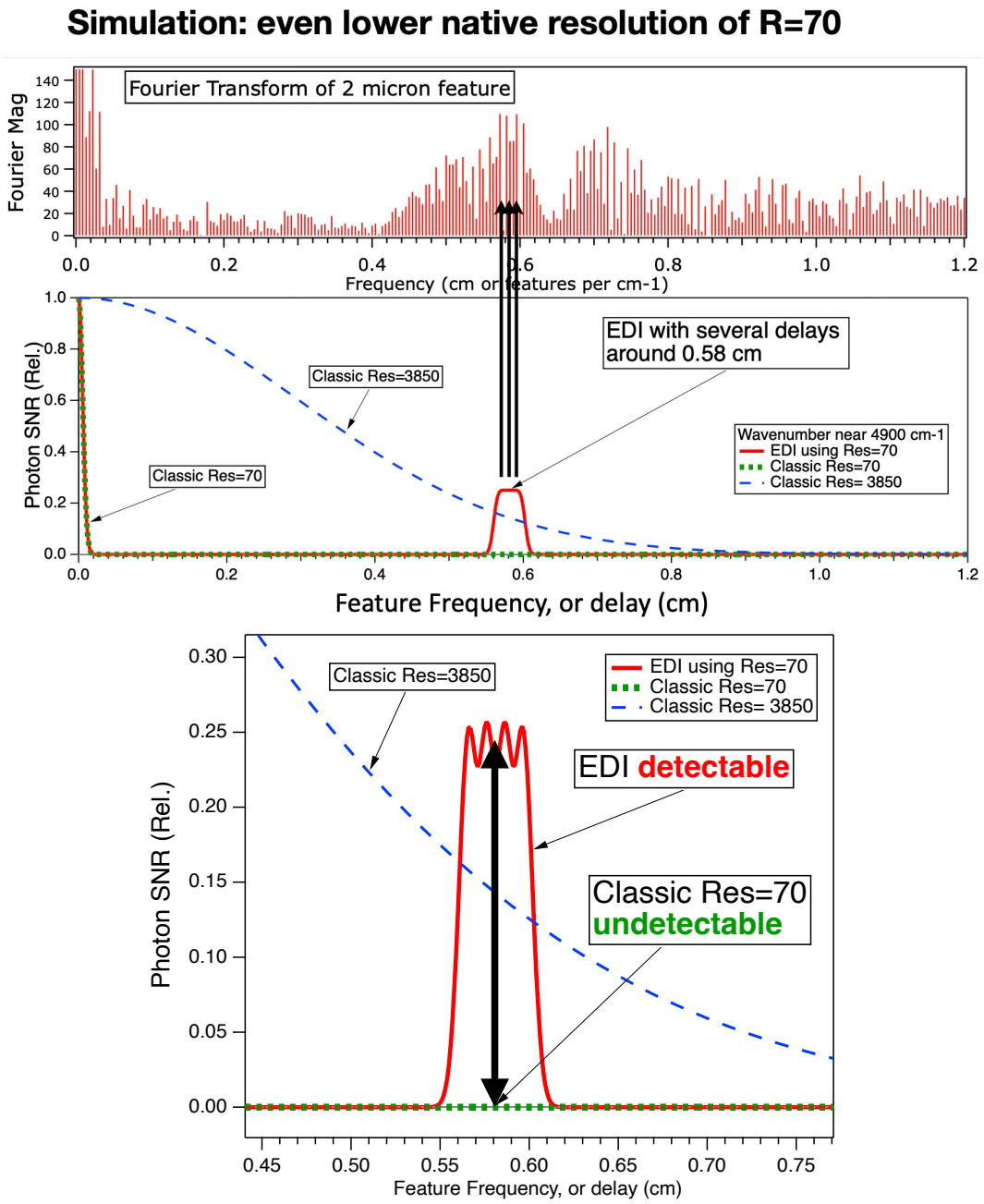


Fig 11 Fourier space situation if the disperser resolution is further reduced to 70. We suggest using several slightly different delays in the neighborhood of 0.58 cm, that sense a small region in delay space, making a plateau shape near 0.58 cm. The calculated results are shown in Fig. 12.

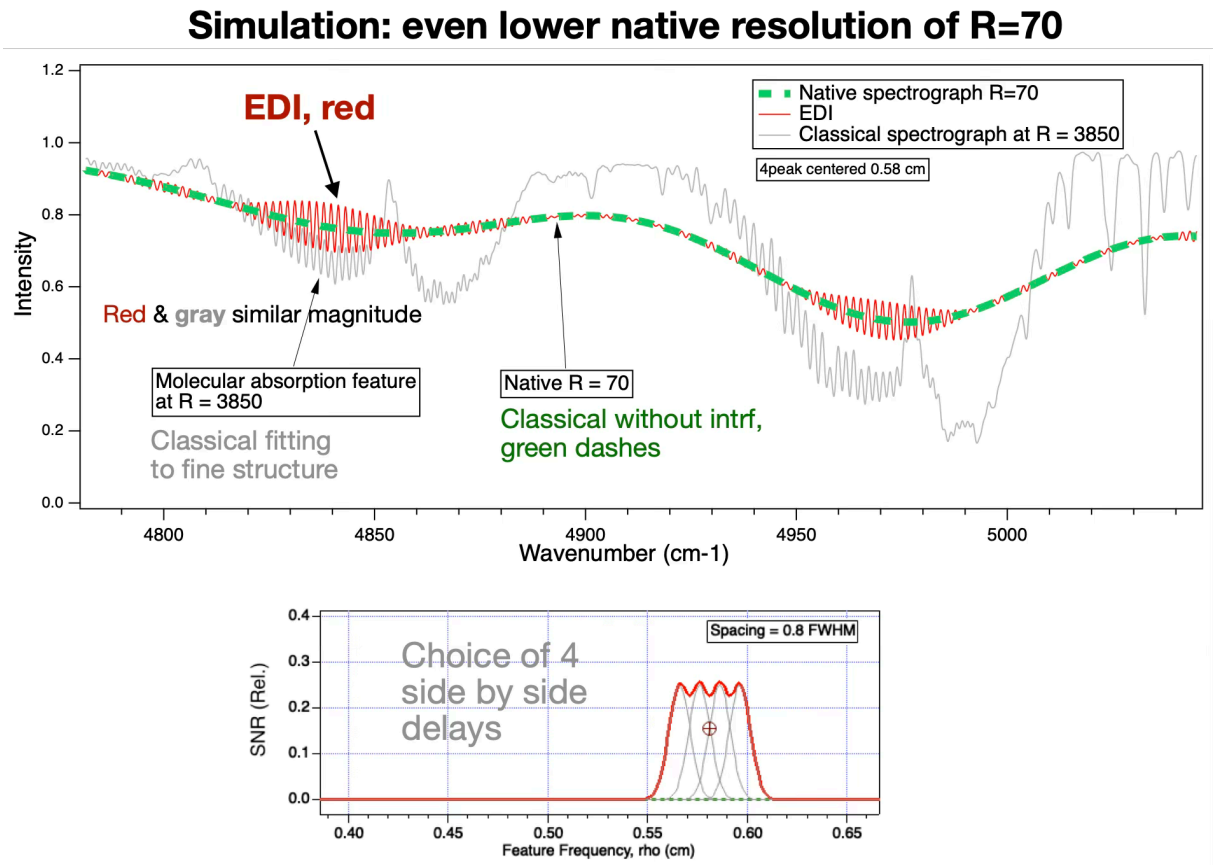


Fig 12 Results if the disperser resolution is further reduced to 70 and we use several slightly different delays in the neighborhood of 0.58 cm, that sense a small region in delay space (lower panel) making a plateau shape near 0.58 cm. The upper panel shows calculated results in wavenumber space. Green curve shows the conventional results for R=70. None of the fine structure is resolved. The red curve shows the EDI results for R=70. Note that the magnitude of the fine structure in the theory curve (gray) for R=3850 is similar to the EDI results. Hence the performance has been boosted dramatically from R=70 to something similar to R=3850.

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David J Erskine, orcid.org/0000-0002-7094-458X , received his PhD from Cornell in 1984. He retired in October 2024 from a career as an experimental physicist at Lawrence Livermore National Laboratory with experience in femtosecond lasers, semiconductor physics, superconductivity, diamond anvil cell high pressure physics, shock physics, high speed recording techniques, Doppler interferometry, white light interferometry, digital holography, Fourier signal processing, image reconstruction, and phase stepping algorithms for interferogram analysis. He continues to collaborate with astronomers on interferometric techniques for the Doppler planet search and high-resolution spectroscopy. He is a member of SPIE.

Biographies for the other authors are not available.

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