A Prototype Single-Mode Fiber Beam Combiner for the CHARA Array

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ABSTRACT

Traditional methods of data collection in active fringe tracking Michelson stellar interferometers involve logging and analyzing the signals within the fringe tracking system for the scientific information about the object being observed. While these methods are robust and have produced excellent scientific results, they become more problematic as next-generation Michelson stellar interferometers are built with more telescopes and the aim of performing routine imaging.

The Center for High Angular Resolution Astronomy (CHARA) Array is one such next-generation instrument presently under construction on Mount Wilson, north of Los Angeles, California. The CHARA Array will feature a separation of the tasks of active fringe tracking and imaging. In anticipation of the advantages afforded by the task separation, a prototype imager was developed. The prototype imager employs single-mode fiber optic strands to convey the light from simulated telescopes to a smaller, non-redundant, remapped pupil plane, which in turn feeds a low resolution prism spectrograph. The spectrograph features two cylindrical optical elements whose net effect is to focus the light to a smaller plate scale in the spectral dimension than in the orthogonal spatial dimension.

Keywords: Interferometry, Imagers, Single-Mode Fiber Optics, Non-Redundant Mapping

1. INTRODUCTION

The Center for High Angular Resolution Astronomy (CHARA) Array is a five telescope, two-dimensional Michelson stellar interferometer currently under construction on Mount Wilson, north of Los Angeles, California.[1] The project is jointly funded by the National Science Foundation (NSF) and Georgia State University. Progress on the Array is monitored in a series of technical reports that are published quarterly, and immediately upon publication are available through the World Wide Web at http://www.chara.gsu.edu/chara/.

The Array features custom-designed one-meter aperture telescopes (actually *beam reducing* telescopes) located in a Y-shaped configuration within a 400 m diameter circle. Light incident upon the telescopes is reduced to a beam 12.5 cm in diameter (an 8:1 reduction) and conveyed to a central Beam Synthesis Facility (BSF) by means of a vacuum pipe. Once inside the BSF, the light from each telescope, while still in vacuum, is fed into a constant path length offset system and then into an Optical Path Length Equalizer (OPLE). Upon exit from the OPLE, the light is sent through another beam reducer to reduce the beam to 25 mm (a 5:1 reduction), a visible/IR dichroic split, and a beam "switchyard" (allowing a given telescope beam to be located at any channel of the fringe tracker). The emerging light is split by polarization, one for fringe tracking, and the other for tip-tilt correction and imaging.

2. ENCODING: TEMPORAL VS. SPATIAL

In order to use a Michelson interferometer for imaging, one must have at least three baselines. As a result, some planning must be done to be able to differentiate between the baselines. The methods fall into one of two general classes – temporal encoding and spatial encoding. Temporal encoding methods are a popular option when the fringe tracking detectors are single-pixel in nature. In this case, the path length difference about the phase center of each baseline is varied at a different frequency. Analysis of the time behavior of this composite signal gives visibilities and phase closures. The COAST[2] instrument uses temporal encoding for imaging. A schematic diagram, not too unlike the COAST instrument and expanded to eight channels, is shown in figure 1.

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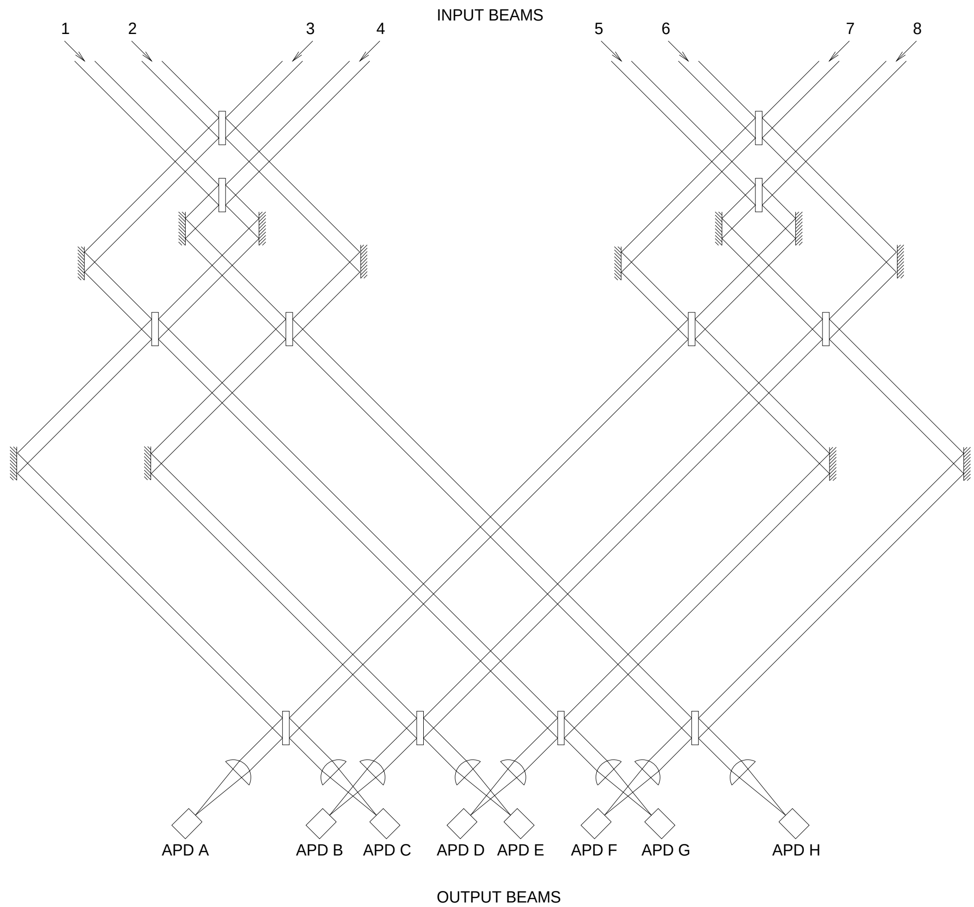

Figure 1. A schematic layout of an all beam combination system.

With the availability of two-dimensional detectors, spatial encoding becomes a possibility. The telescope beams are remapped non-redundantly to a configuration of known physical spacing, and hence each baseline has its own unique fringe spacing from which the visibilities and phase closures are measured. A hypothetical example of a spatially encoded imaging system is shown in figure 2.

The temporal encoding example in figure 1 suffers from a number of drawbacks. Note the large number of optical surfaces. Note further that some of the beam paths have different numbers of optical surfaces. In addition, the beam paths have reflections in different orders, which must be carefully planned to prevent polarization effects from reducing the raw visibilities. The spatial encoding example shown in figure 2 has a number of drawbacks as well. Chief among them is the large number of optical surfaces. The other main drawback addresses the issue of practicality. The focusing objective is quite large and would become unmanageable and/or expensive as more beams were added. These drawbacks can be overcome through the use of single-mode fiber optic strands.

3. THE CHARA ARRAY IMAGER

In the prototype design, three beams from “telescopes” are launched into single-mode fiber optic strands. The output of each strand is recollimated and rearranged into a non-redundant linear mapping pattern to spatially encode the visibility and raw phase of each baseline. The linear array is then fed through a prism to disperse the light in a direction orthogonal to the linear array spacing. Then the encoded and dispersed light is focused with a long focal length achromat. Prior to coming to a complete focus, a long focal length negative cylindrical element is inserted into the beam. It is oriented with its non-curved axis aligned parallel to the linear array. This is shown in figure 3. To first order, the negative cylindrical element “recollimates” the light, but only in the spectral dimension. A short focal length positive cylindrical element, oriented the same as the negative element, is then inserted into the beam

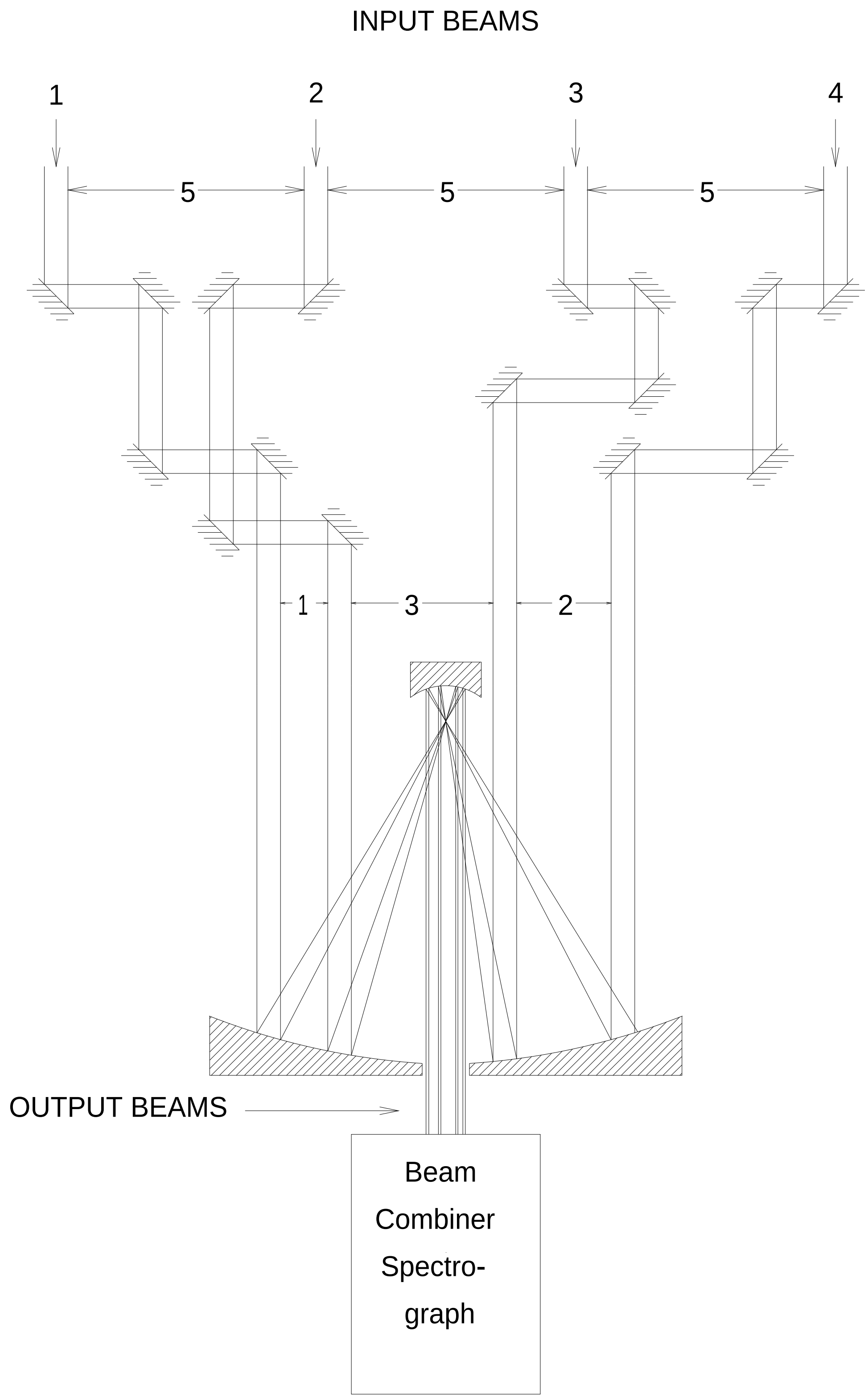

Figure 2. A schematic layout of a remapped one-dimensional non-redundant mapping combiner using a large objective. Note the many reflections required.

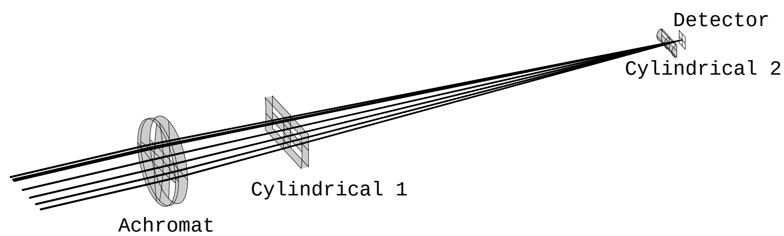

Figure 3. An optical ray trace of the Spectrograph Beam Combiner. This was drawn using *Beam 4* (Stellar Software, P.O. Box 10183, Berkeley, California 94709).

to bring the light to a focus in the spectral dimension. The end effect is to have the spatial frequency dimension (containing the fringe pattern) be brought to a focus with a larger focal length than the spectral dimension. One then gets high magnification along the spatial frequency dimension and low magnification (large spectral coverage) along the spectral dimension. This technique was succesfully demonstrated in the MAPPIT[3] experiment.

The fiber launching apparatus of the prototype is shown in figure 4, while the fiber output collimation apparatus is shown in figure 5, and finally, the spectrograph is shown in figure 6.

4. CONCLUSION

After acquiring the mutual phase center for two of the three baselines, data were taken using helium-neon laser light (to verify the existence of fringes at all three baselines) and tungsten filament white light. The fringes and corresponding power spectrum of the laser light is shown in figure 7. The fringes and corresponding power spectrum of the white light is shown in figure 8.

Note from the power spectrum in figure 7 that all three baselines are visible. Note further that the power spectrum in figure 8 is missing the highest frequency (longest spatially) baseline. Differential dispersion due to differing fiber optic strand lengths has been determined to be the culprit.[4]

To make the prototype useful in the CHARA Array, the lengths of the fiber optic strands need to be equalized (that is to say rebuilt) and a method for intensity calibration[5] be incorporated.

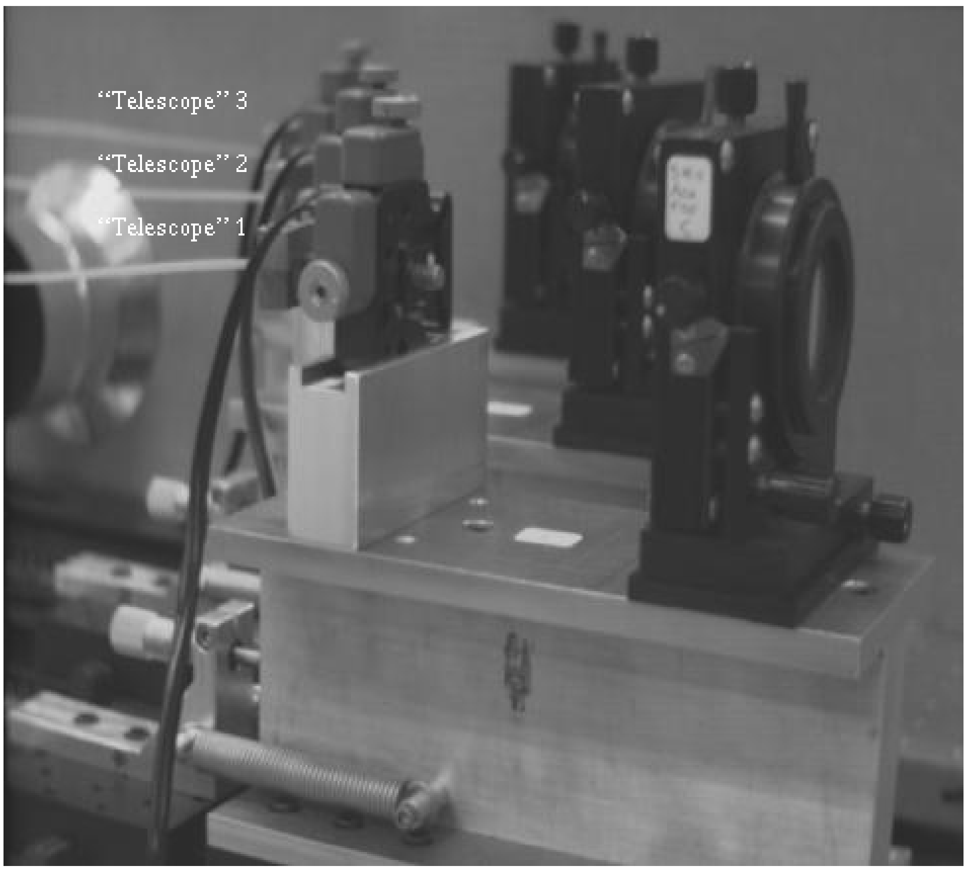

Figure 4. A view of the Fiber Launcher system from slightly above the optical axis height. Note that the three input beams are labelled as "Telescope" 3, "Telescope" 2, and "Telescope" 1.

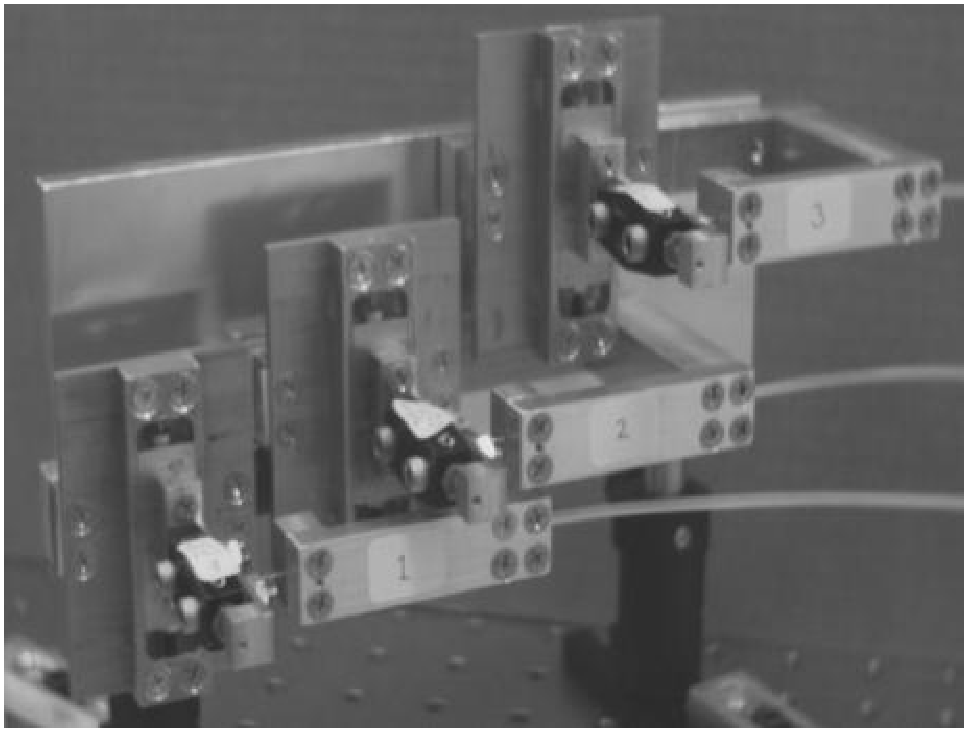

Figure 5. The Fiber Collimator System. The "Output" numbers on each system correspond to the "Telescope" numbers in Figure 4. "Output" 1 is at the bottom, "Output" 2 in the middle, and "Output" 3 at the top.

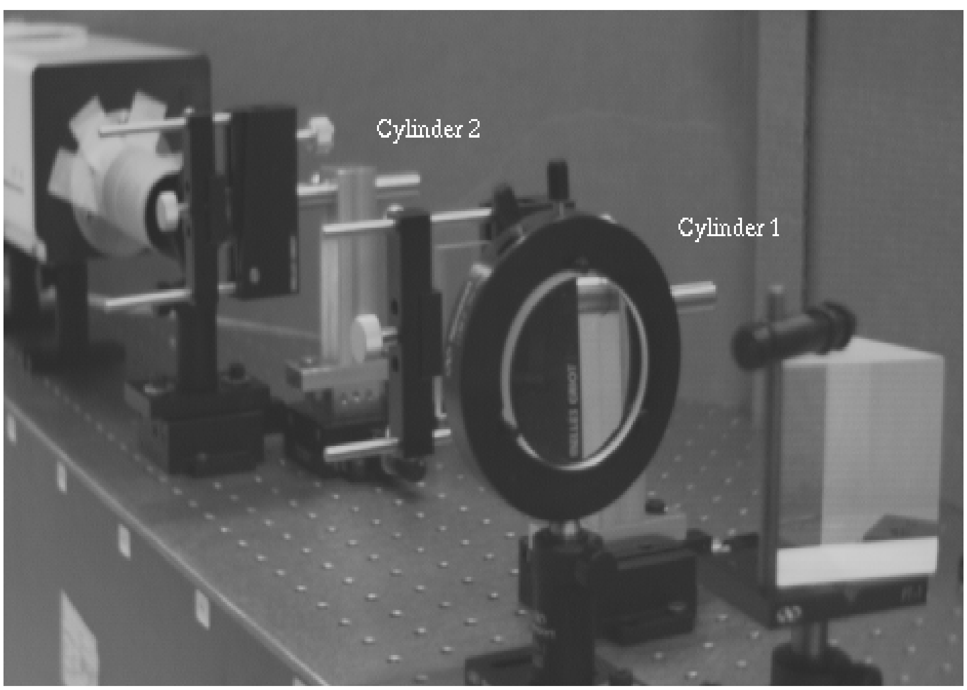

Figure 6. The Spectrograph System. Cylinder 1 is a negative element while Cylinder 2 is a positive element. This is the realization of figure 3.

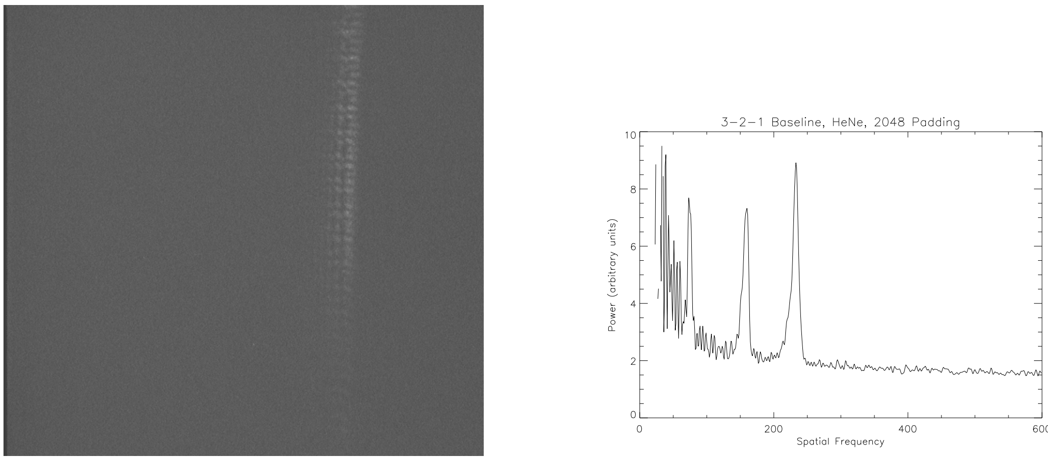

Figure 7. *Left:* A typical data frame of the HeNe laser, before applying the bias and flat frames. *Right:* The power spectrum of the HeNe laser data. The relevent data (480 points) was imbedded within a data string 2048 data points long, where the extra padding was set to the average of the data set. Note the three peaks at about 75, 160, and 230.

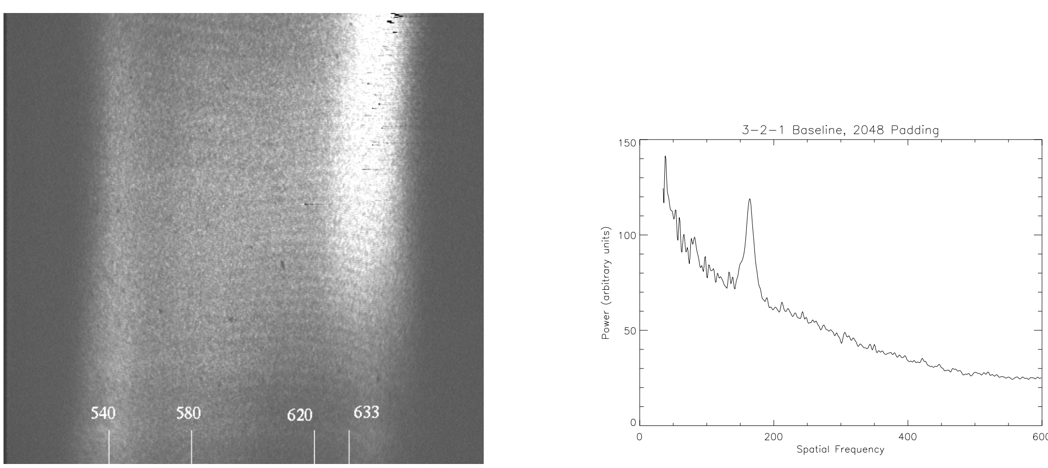

Figure 8. *Left:* A typical data frame, unfiltered, before applying the bias and flat frames. The numbers along the bottom are approximate wavelength values in nm – no effort was made to calibrate the non-linear dispersion characteristics of the prism. The dark few columns on the far left are residual sync errors between the ISIT output and the frame digitizer. The horizontal dark streaks within the bright area in the upper right are artifacts of the ISIT intensification method at saturation. The baseline 2-3 fringes can be seen best at about 620 nm, halfway down in the frame. *Right:* The power spectrum of the unfiltered white light data. The padding technique is described in the caption to figure 7. Note that even though the detector has light illuminating it from each of the "telescopes", only the two lowest frequency baselines show up above the noise.

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