Multi-wavelength fringe measurement with a CCD spectrometer at COAST

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ABSTRACT

A low-resolution CCD spectrometer has been installed at COAST to provide multi-wavelength fringe measurements across the band 650-950 nm. The measurements are based on the analysis of time-series of channeled spectra. Laboratory tests and stellar observations are presented. The advantages and limitations of the system are discussed.

Keywords: astronomy, interferometry, optical, infrared

1. INTRODUCTION

The Cambridge Optical Aperture Synthesis Telescope[1] (COAST) is a stellar interferometer designed for synthesis imaging using measurements of visibility amplitude and closure phase. Its current status and most recent results are described elsewhere in these proceedings.[2] Four telescopes are used in the array and the beam combiners are designed so that four input beams are interfered to produce four separate output beams, each of which contains one quarter of the light from each telescope. The combined beams are passed through optical filters before being detected by avalanche photo-diodes (APDs). The optical filters used have central wavelengths between 600 and 1000 nm and typically have bandwidths from 10 to 40 nm. Only four different filters can be used at one time, because there are only four output beams and only one APD per beam. The light that enters the interferometer at other wavelengths is rejected by the filters and never reaches a detector. Clearly the performance of COAST would be greatly enhanced if it were possible to make simultaneous measurements of visibility and closure-phase across a much broader range of wavelengths.

To achieve this aim we are in the process of installing a CCD spectrometer that allows simultaneous visibility amplitude measurements to be made from 650 to 950 nm. Aspects of this work have been presented previously.[3,4] Here we describe the approach to data reduction we are using and present some of our preliminary results.

2. Channeled Spectrum

Our approach is to use the modulation in a channeled spectrum and the four-step method of phase-measurement interferometry[5] to allow visibility measurement at each pixel in the channeled spectrum. The beams of starlight that enter the beam-combiners are all tilt-corrected and combined with zero tilt and shear, and so the detected fringe pattern (for two-beam interference) can be expressed as the following function of wavelength λ:

$$I(\lambda) = I_0 \left[1 + |\gamma_{12}| \cos\left(\frac{2\pi x}{\lambda} + \phi_{12}\right)\right], \tag{1}$$

where I_0 is the intensity of the stellar spectrum, x is the optical path-difference, and $|\gamma_{12}|$ and ϕ_{12} are the modulus and phase of the complex fringe visibility. The spectrum of starlight is thus channeled with fringes, whose number is proportional to the optical path-difference (see for instance Ref. 6). If we know the calibration of our spectrometer and can count the number of fringes across a given bandwidth, we can estimate the optical path-difference. Once we know the spatial frequency of the fringes on the detector, we can estimate the fringe parameters $|\gamma_{12}|$ and ϕ_{12} at each pixel, i.e. at every recorded wavelength. All we need are four samples in the channeled spectrum spaced apart by one quarter of a fringe, as described in Section 6. Examples of channeled spectra obtained with an artificial star in the lab are shown in Fig. 1. A good example of channeled spectra from a real stellar target is shown in Fig. 2.

3. Design Considerations

For these experiments we did not want to make permanent changes to the optical layout of COAST and so the spectrometer was installed on the main beam-combining table so as not to interfere with normal operations. When experiments were performed light was diverted into the spectrometer simply by sliding a dispersing prism into one of the output beams of the beam-combiner.

The CCD camera, its controller, and the data-acquisition software were essentially identical to those used by our group for aperture masking experiments at the William Hershel Telescope.[7,8] At the WHT we had used the camera to vertically bin 10 ms frames of a greatly magnified image of a star that was modulated by fringes. Because the fringes were aligned vertically, parallel to the columns of the CCD, binning of the image into a single row of pixels introduced no loss in fringe visibility. This method of binning minimises the number of pixels used to record the fringes and thus vastly reduces the readout noise in the data, while at the same time allowing exposures of the fringes to be secured over timescales comparable to the atmospheric coherence time. At COAST we used the same CCD and software, but modified the control programs because it was no longer necessary to compress a large image in each frame. We aligned a stellar spectrum along one row of CCD pixels and changed the field-size and binning of the CCD to permit 5 ms frames.

Real-time fringe tracking was *not* implemented for these measurements. The delay line was set to follow the star at the appropriate sidereal rate and the fringe frequency in the channeled spectrum exhibited random fluctuations due to the time varying atmospheric OPD.

The prism glass was chosen so that the angular dispersion of the spectrometer was as close as possible to being a linear function of spectroscopic wavenumber, $1/\lambda$. A 60° prism of BK7 glass was found to be almost ideal for the wavelength range from 600 to 1000 nm.

Finally, the focal length of the spectrometer was chosen so that the diffraction limited image of starlight passing through a 10 mm diameter aperture (corresponding to a 16 cm aperture at the siderostats) would be approximately one pixel wide, or 26 μm at λ=800 nm. We also wanted to have $\sim$16 pixels across 40 nm (a typical filter bandwidth), and so a focal length of 400 mm was chosen as a compromise between the two criteria. This allowed individual pixels on the detector to sample $\sim$2 nm of each channeled spectrum.

4. CCD Spectrometer

The CCD camera we used contains an EEV CCD-1511 chip which has been thinned and is back illuminated. Its quantum efficiency is 85% at 500 nm and drops to 50% at 800 nm. The measured readout noise is 3.8 e^-. By comparison, the avalanche photo-diodes used at COAST have a quantum efficiency of 40%, but have a dark current of $\sim$1000 counts per second. Consequently one would expect that at high light levels where the noise is negligible, the CCD would have a slight advantage in signal-to-noise ratio over the APDs, but that at very low light levels the APDs would perform better. More detailed discussions of CCD noise and fringe detection are given by Nightingale[9] and ten Brummelaar.[10]

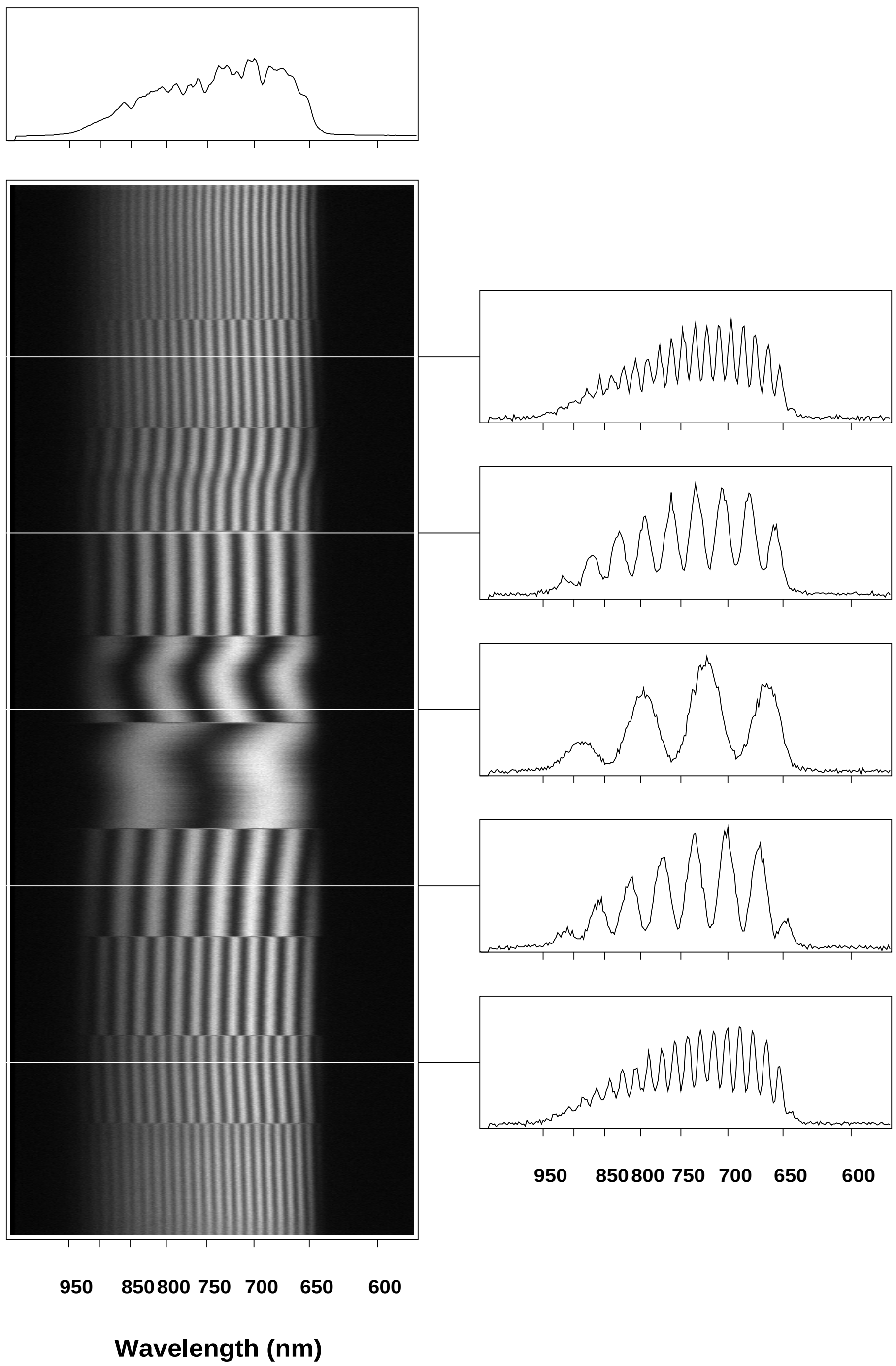


Figure 1: A time series of channeled spectra obtained with an artificial reference star at COAST. The time axis runs vertically, with each row in the image representing a 5 ms exposure of the channeled spectrum. In this figure the optical pathlength compensator has been moved in steps every second to change the path-difference x and move through the fringe envelope.

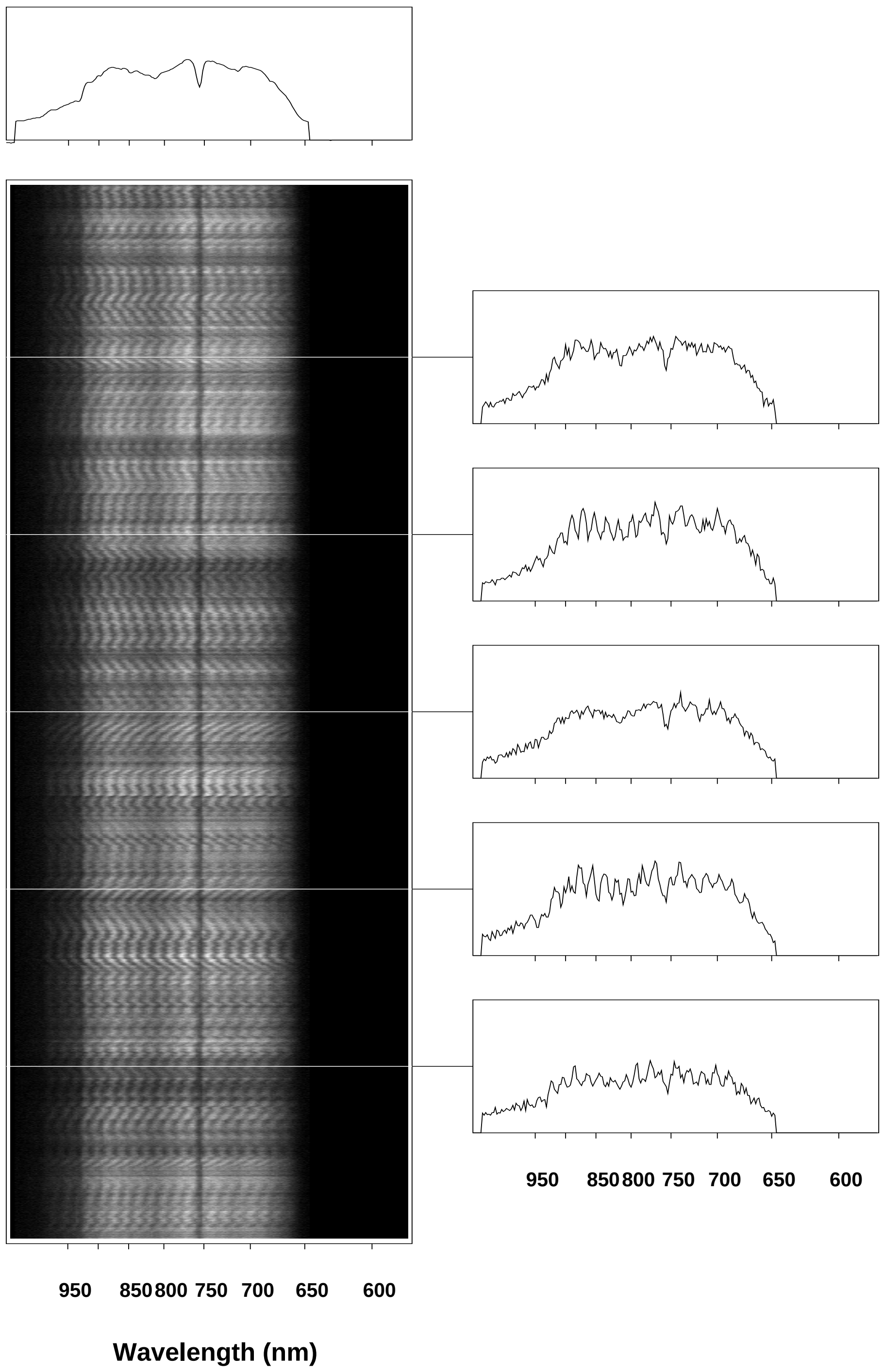


Figure 2: Channeled spectra obtained from the star α Boo. As in Fig. 1 each row in the image is a 5 ms snap-shot of the channeled spectrum. There are 1000 rows in this image representing 5 s of data. The plots on the right show the channeled spectrum at regular time intervals. Atmospheric phase fluctuations, intensity fluctuations, and visibility fluctuations are all evident in this data set. A strong atmospheric absorption feature at 760 nm can be clearly seen.

Because of the relatively slow readout rate of the CCD, it was not possible to use the CCD camera in the same way as the APDs are used at COAST. Normally the APDs record fringes with a 0.2 ms sampling interval during which time the fringe packet is swept past using a modulated delay. Typical modulation periods are 20–40 ms, and over this timescale the fringes are only moderately disturbed by atmospheric turbulence. By contrast the 5 ms readout rate for a 256 pixel line of data from the CCD camera makes it impossible to step through the fringe packet on a timescale comparable to the coherence time of the atmosphere. We would be forced to sweep through the fringe packet too slowly for the packet to remain "frozen". Our approach of using the channeled spectrum to provide the modulation was a necessary compromise.

5. Observing Routine

For the observations presented here, we used the following observing routine. Of the four available input beams only one pair is chosen (one baseline) with the light from the other telescopes being blocked. The fringes are acquired in the usual COAST manner by sweeping the appropriate delay trolley in a triangle wave back and forth through the fringe packet and listening to the amplified output of one of the APD detectors. For bright unresolved objects the fringes are easily identified in this way.

The sweeps are then turned off and the prism of the spectrometer is placed in the path of one of the output channels, diverting starlight into the spectrometer. Some preliminary observations are made of the channeled spectra and the delay-line offset is adjusted till there are approximately 10 to 15 fringes across the detected bandwidth. As mentioned above, no fringe tracking is used, and so the period of the fringes changes randomly with time.

When data recording begins, the shutter of the CCD is opened and at the same time the CCD starts reading out data. The CCD is continually illuminated by the stellar spectrum as the data is being read out. Each vertical bin reads out in frames of 5 ms, a total of 2000 being recorded. The shutter of the CCD is then closed and the readout stops. The software controlling the CCD then typically cycles to record 5 successive sequences of such data. Subsequently, two additional sequences of data are recorded, the first with a delay sweep turned *on* so as to blur out the fringes and provide a measure of the overall stellar spectrum, and the second taken with the input beams blocked to measure any background signals. This cycle is repeated for all baselines both for the source and calibrator.

6. Approach to Data Reduction

The mean background level as a function of pixel number is determined from the file that has only background counts. The mean stellar spectrum (with the background subtracted) is determined from the file that has the stellar spectrum but no fringes. The stellar spectrum is needed because unless we normalise the channeled spectra so that the mean intensity is independent of wavelength, our visibility calculations will be biased by features in the spectrum itself. This normalisation is only performed for the central part of the spectrum where the intensity is greater than one fifth of the mean value, otherwise noise at the edges of the spectrum would be amplified.

The mean spatial frequency of the fringes is then determined from the files containing the channeled spectra. If the signal-to-noise ratio of the fringes were very high we could in principle determine the fringe frequency from each 5 ms exposure in the data set. However, in practice most sources were found to be too faint for this to be feasible. The mean fringe frequency was determined from the incoherent sum of the power spectra of each line. To avoid confusing the fringe peak with low spatial frequency power in the stellar spectrum, the mean power spectrum of the file *without* fringes was first calculated and subtracted from the mean power spectrum of the file with fringes. The fringe frequency is stored for reference in the processing which follows.

The data files are now read in again and processed. Each file with fringes is processed in parallel with a file without fringes. For both files the data is read in one line at a time, the background is subtracted and the data is normalised by the mean stellar spectrum. Around each pixel, or a predetermined set of pixels, four points on the fringe are interpolated that are spaced one quarter of a fringe apart. The points are interpolated by smoothing the line of data with a Sinc function such that the highest frequency component corresponds to a spatial frequency slightly higher than the fringe frequency. From these four points the amplitude-squared of the fringe and the fringe phase are calculated using the 4-bucket method of phase-measurement

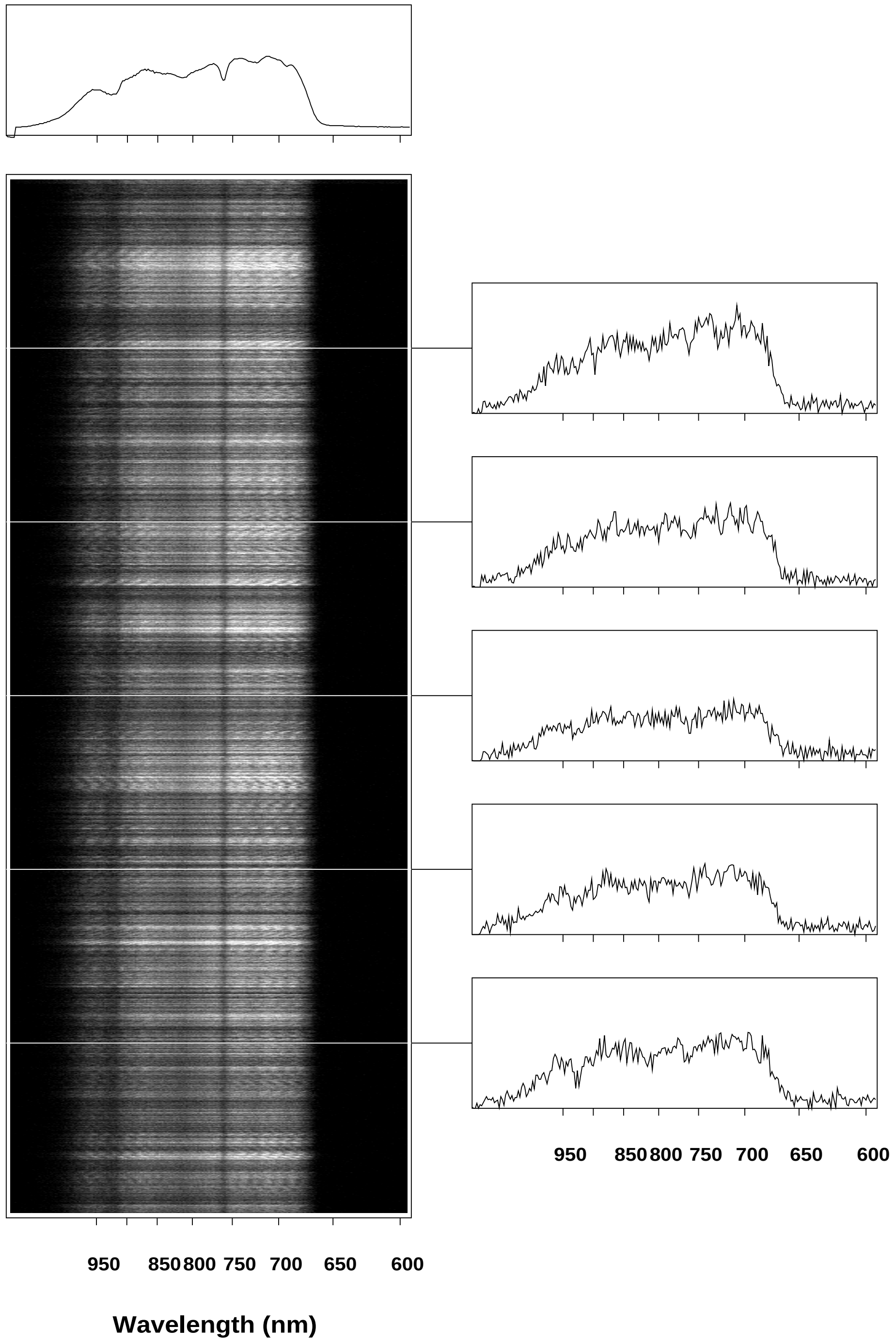


Figure 3: Channeled spectra obtained from the binary star Capella. The seeing conditions are noticeably poorer than in the previous example of α Boo. A drop in fringe visibility is evident near 810 nm.

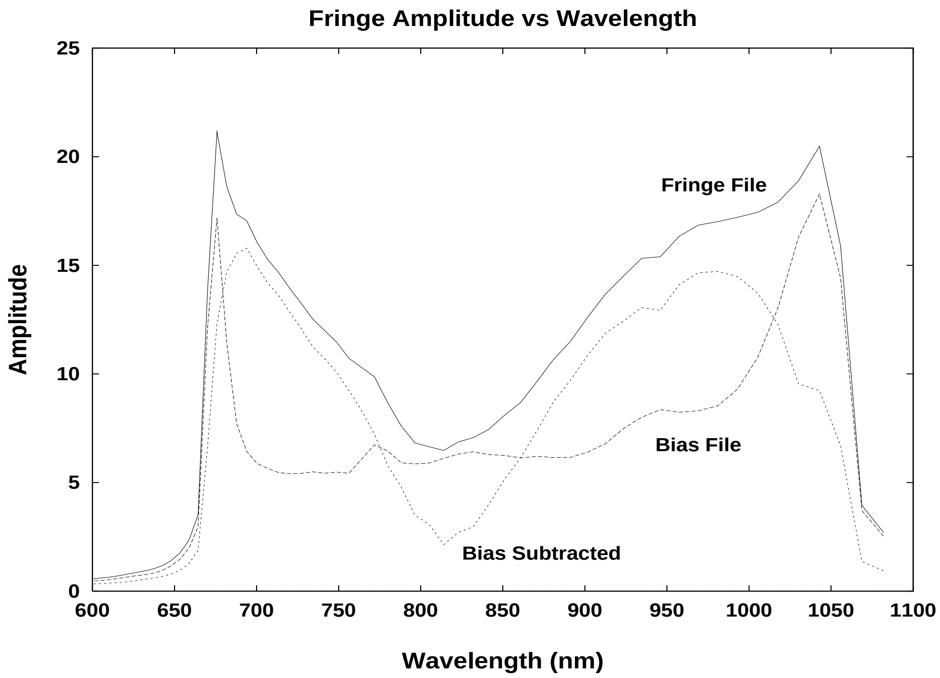


Figure 4: Illustration of bias subtraction for data from Capella (see text for details).

interferometry.[5] Although the first point lies at the pixel or wavelength for which the calculation is intended, the other points all lie at different wavelengths and so the resultant visibility estimate is an average over the wavelength range covered by the samples — which is to say the pixel range of one fringe.

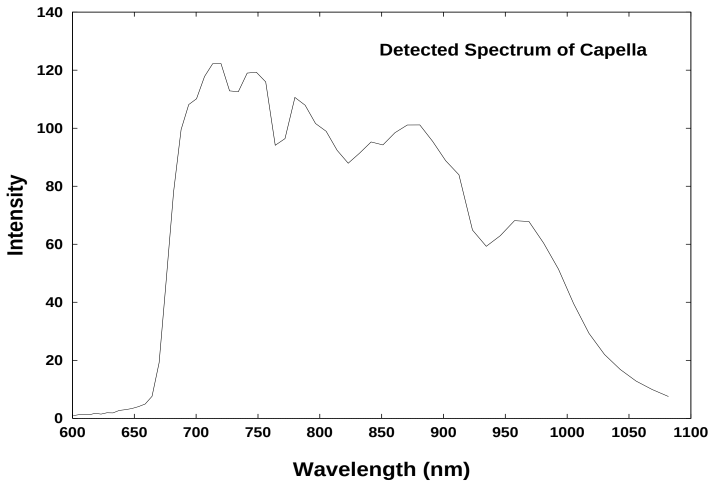
The amplitude-squared as a function of pixel number p is averaged for the file with fringes to yield $I_f^2(p)$. The file without fringes is similarly processed to yield an averaged amplitude-squared of $I_b^2(p)$, which is a measure of the bias in $I_f^2(p)$. We have also the mean intensity of the spectrum $I_s(p)$, which was calculated previously from the file without fringes. We can now write the visibility as a function of pixel number (wavelength) as

$$|\gamma_{12}(p)| = \frac{\left[I_f^2(p) - I_b^2(p)\right]^{1/2}}{I_s(p)}. \tag{2}$$

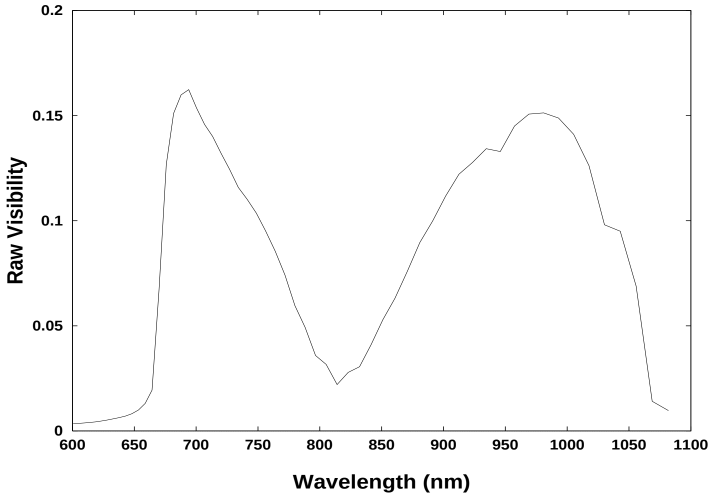
7. Results and Discussion

Our first stellar observations indicated that the observed raw visibility for an unresolved source was mostly featureless over the spectrum, with a mean visibility of $\sim$20%, which compared well (to within several percent) of the visibility measured by the APDs shortly afterwards.

We chose to then look at Capella as a test to see if we could detect the known changes predicted for this bright binary star. Capella is a well studied binary whose orbit is known precisely and whose components have an angular separation of $\sim$50 mas. Therefore when fringes are obtained, two sets of mutually incoherent channeled spectra are produced superimposed on each other in the spectrometer. However, since the binary system is not resolved by the spectrometer it appears as though only a single spectrum is present. Nevertheless, the two separate channeled spectra do differ, because the fringe frequency of each depends on the delay x, and this is different for each of the component stars. When the two fringe pat-



(a)



(b)

Figure 5: (a) The detected stellar spectrum of Capella and (b) the fringe visibility as a function of wavelength. The reduction in visibility at intermediate wavelengths is due to the binary nature of the source.

terns add together, what is seen is the beat between them — a single channeled spectrum with a visibility that is a periodic function of wavenumber. The depth of the modulation in the beat spectrum depends principally on the brightness ratio of the two components, which for Capella is approximately 1:1.

This modulation in visibility can be readily seen in the fringes. By choosing amongst the six available baselines at COAST we were able to select an example where the visibility approached zero midway through the observed spectral band, near 810 nm. It was interesting to note that as we repeated the experiment during the night it was evident that the minimum in visibility was slowly moving through the spectrum, as the rotation of the earth changed the projected baseline of COAST in the direction of the target star.

An example of a raw data file for Capella can be seen in Fig. 3. The process of bias-subtraction is illustrated in Fig. 4, and the uncalibrated visibility is shown in Fig. 5. Unfortunately not enough data were taken of calibration sources to allow accurate estimates of the absolute visibility amplitude to be recovered. Nonetheless, the change in visibility with wavelength predicted for the binary is very clear, and accurately reproduces the changes seen in the raw channeled spectra. Note that the drop in visibility at wavelengths shorter than 700 nm and greater than 1000 nm occurs because the bias subtraction performs poorly when the intensity of the spectrum drops to zero.

These results are encouraging and further work is in progress to investigate alternative methods of data reduction and to further quantify the performance of the system.

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