COAST in the near-infrared: solutions for infrared interferometry

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ABSTRACT

There are difficult problems involved in building a near-infrared interferometer which uses more than two elements simultaneously. These problems have been overcome at the Cambridge Optical Aperture Synthesis Telescope (COAST). This has allowed us to make the first closure phase measurements on an astronomical source in the infrared. We describe a scheme for fast, low noise readout of an infrared focal-plane array detector, capable of adequately sampling pupil plane fringes on three simultaneous baselines, as well as a procedure for aligning a many-component beam-combiner in the infrared. Finally, the performance of the working COAST infrared system is discussed.

Keywords: interferometry, detectors, infrared, closure phase, imaging

1. INTRODUCTION

The Cambridge Optical Aperture Synthesis Telescope (COAST) (see Ref. 1, in these proceedings, and references therein) was designed to operate at wavelengths between 650 and 950nm, with the intention to add near-infrared capability later. We have now installed a beam-combiner and detector operating in the range 1.2–2.4μm.

Near-infrared (i.e. at wavelengths longer than one micron) stellar interferometry has been performed successfully with IRMA[2],[3] I2T,[4] IOTA[5] and PTI.[6] Until now, no group has combined the signals from three telescopes simultaneously to measure a closure phase. Closure phase measurements, together with measurements of visibility amplitude, allow an image of the source to be reconstructed.[7] The problems specific to infrared interferometry with three or more telescopes, and our solutions to them, are described below.

2. PROBLEM 1: SAMPLING THE FRINGE PATTERN

The first problem with doing infrared interferometry on three or more baselines simultaneously is to sample a non-redundant fringe pattern containing three of more sets of fringes effectively. If beam-combination is done in the image plane, the fringe pattern must be spread across many pixels of a detector. With the NICMOS III detector we obtained for use at COAST, the resulting high read noise and long readout time would have been unacceptable.

Consequently the COAST infrared system uses a pupil-plane beam combiner, which is an analogue of that used at COAST for visible light.[8] The beam-combiner accepts four input beams, one from each of four telescopes, and gives four output beams. Each output beam contains equal amounts of light from the four telescopes. The advantage of a pupil-plane beam-combiner is that only the total intensity of each combined (output) beam is measured, and so only four pixels must be read out, one for each of the four combined beams.

In order to record the fringes between the beams from two telescopes, the path delay of one of the beams is swept backwards and forwards through the white-light fringe position. The resulting fringe pattern is the intensity of a combined beam plotted against time. An example of such a temporal fringe pattern is shown in Figure 3.

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This can be extended to fringes on three simultaneous baselines by modulating the path delays for the three input beams at different speeds, such that the fringes between each pair of beams appear at a different temporal frequency. The widths of the fringe peaks in the frequency domain are increased by atmospheric turbulence, which also gives rise to low-frequency scintillation. The fringe frequencies must be set high enough for the fringe peaks to be well separated from each other and from the scintillation (see Figure 1 for an example power spectrum). Thus the minimum detector sampling rate is set by the atmosphere — at least 2kHz is required to measure a closure phase at a wavelength of 1.3μm in reasonable conditions.

3. SOLUTION 1: FAST READOUT OF NICMOS III

As stated in Sec. 2, each of the four combined beams from the beam-combiner is focused onto a single pixel of a NICMOS III detector. Only these four single pixels, widely separated on the detector, are read out when recording fringes. The NICMOS III multiplexor does not allow addressing of a chosen pixel, so all the other pixels in the array are skipped without being read.

The operations performed on the array are as follows: all pixels up to the first target pixel are skipped, then the first target pixel is read, then reset, then immediately read again. More pixels are then skipped until the second target pixel is reached, then the same read, reset, read sequence is performed on this pixel. The same operations follow for the third and fourth pixels. The entire sequence is repeated after a short pause to allow each pixel the desired total integration time. Note that each of the four target pixels continues to accumulate signal while the others are being read out. The read immediately after each reset is needed in order to subtract the reset level, which would otherwise be the dominant noise source.

Each read of a pixel uses the principles of double-correlated sampling (DCS) to reduce noise.[9] The resulting read noise decreases with increasing DCS integration time until it reaches a threshold value. We use a pixel read time of 45μs, which gives the minimum read noise of 16 electrons. Since two reads are needed for each sample, the overall read noise is 22e^-.

The multiplexor is driven by a 6MHz RISC microprocessor. The time required to skip over unused columns and rows of the NICMOS device is thus insignificant compared with the time taken to read out the target pixels.

The sequence of operations listed above is performed in a tight loop, the timing of which is tied to reference signals at 1Hz and 5kHz. These reference signals are also used by the path compensation trolleys and avalanche photodiode detectors at COAST, and thus detector reads and trolley sweeps are kept synchronised.

The sampling rates achieved by the method described here are 1.25kHz when reading four pixels, and 2.5kHz when reading just two pixels. As illustrated by Figure 1, the latter rate is fast enough to make closure phase measurements under most atmospheric conditions in which COAST is operated.

4. PROBLEM 2: ALIGNMENT OF PUPIL PLANE BEAM COMBINER

A pupil plane beam-combiner must precisely superpose the input beams from the telescopes. For high visibility fringes the beam angles must be matched to $\lambda/4$ across the pupil diameter. At COAST in the infrared, this angle is 2.7 seconds of arc (for a wavelength of 1.3μm and a 25mm pupil). The pupil positions must be matched to a few percent of the pupil diameter.

The beam-combiner contains beam-splitter units (see Figure 2) consisting of a glass plate with a 50% reflective dielectric multilayer coating on one face. This beam-splitting plate is used with a compensating plate of the same thickness, which ensures that all routes through the system pass through the same thickness of glass. The three surfaces which are not intended to be reflective are anti-reflection coated. A 10 degree angle of incidence is used so that the two principal planes of polarisation behave in the same way.

It is impossible to make dielectric multilayer coatings which are 50% reflective from visible wavelengths out to the edge of the K band at 2.4μm. It is similarly impossible to make anti-reflection coatings which work over such a wide band. Thus all four faces of a beam-splitter unit optimised for the infrared can have comparable reflectivity at visible wavelengths.

A beam-combiner which contains four such beam-splitter units cannot be aligned using visible light, as it is very easy to make the mistake of co-aligning beams which have been reflected from the wrong faces. Such a beam-combiner must be aligned in the infrared.

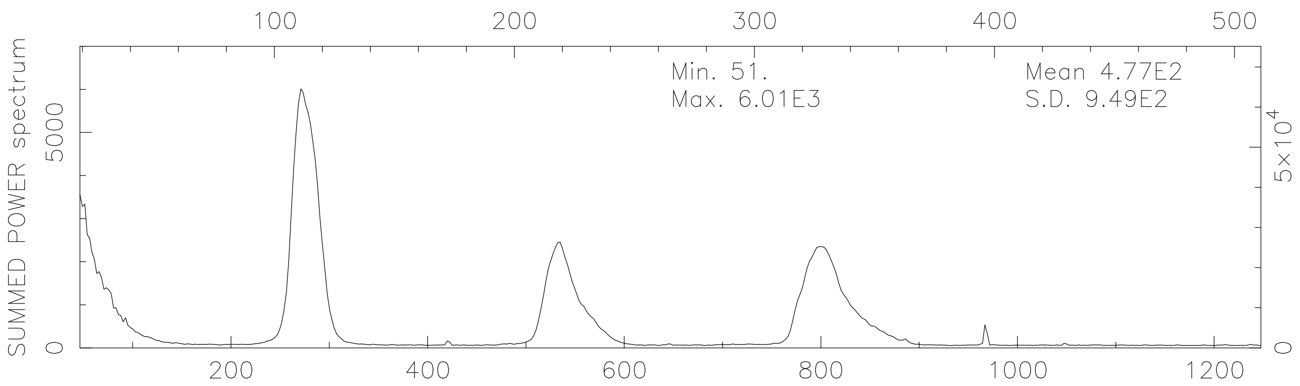

Figure 1. Power spectrum of three-baseline data on α Aurigae (Capella). The lower horizontal axis is temporal frequency in Hertz. The bandpass is the entire J-band. The spectrum contains fringe peaks at 270, 540 and 810 Hz, and a further peak due to scintillation below 150 Hz. The natural width of each fringe peak is inversely proportional to the time taken to sweep through the fringe packet. The number of fringes in the packet is the same in each case (set by the fractional bandwidth, 20% for these data) and so higher frequency fringe peaks are wider. The fringe peaks are further broadened by the atmosphere. On the night these data were taken we measured coherence times at 1.3μm of $\sim$16ms, so conditions were good, but not exceptional.

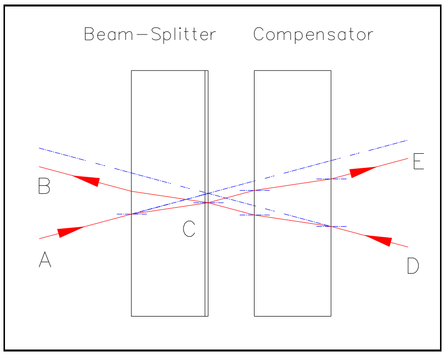

Figure 2. Beam-splitter unit. The unit combines two input beams A and D, to give two combined beams B and E, each of which contains equal fractions of A and D. The 50% reflective dielectric multilayer coating is labelled C. The angles of incidence of beams A and D on this surface are 10 degrees, to avoid polarisation effects.

There are problems associated with performing the alignment in the infrared. The most important of these is that it would be very difficult to measure the position of the pupil at many positions within the beam-combiner.

An infrared detector is required. We have elected to use the same NICMOS III intended for fringe measurement. A single reference source is used for alignment, which injects a collimated beam of white light into the beam-combiner at one of the outputs. The beam-combiner works in reverse to produce light at each of the inputs, where flat mirrors are placed to reflect the beams back into the combiner, where they are recombined and then imaged onto the detector. This double pass through the beam-combiner makes the logic of the alignment procedure more complicated. Also, the path length from the reference source to the detector is inevitably long (20 metres or more), thus a misalignment of 10 seconds of arc will cause a significant 1mm pupil shift, which will be confused with an angular displacement unless both the reference source and the detector are well focused *in the infrared.*

5. SOLUTION 2: ALIGNMENT PROCEDURE

The following is a summary of the alignment procedure used for the COAST infrared system:

1. Use beam-splitters/compensating plates with coatings optimised for visible wavelengths, in kinematic mounts
2. Align in visible, get pupil positions correct
3. Swap plates for IR versions. Minimise effect of different wedge angles
4. Apply fine adjustment scheme
    - Use relative angles of input beams measured at detector
    - Treat beam-combiner as several sub-units, each of which combines two beams
    - Tilt of single component fixes each sub-unit

To avoid having to measure the pupil positions through the beam-combiner in the infrared, the beam-splitter and compensating plates are kinematically replaced by plates optimised for visible wavelengths. The system can now be aligned using visible light. The pupil position at a particular point is measured by placing a target there and looking at the target through a theodolite focused on that point.

The beam-splitter and compensating plates cannot be made perfectly parallel-sided. The scatter in the wedge angles of our plates is five seconds of arc. There are eight plates in the beam-combiner, and so exchanging the visible plates for the infrared ones introduces misalignments greater than the required angular accuracy of 2.7 arcsec. We measure the wedge angles and choose replacement plates and their orientations (within constraints) in order to minimise the changes, but significant misalignments will inevitably remain.

The relative angles of the four beams (each corresponding to a different telescope) which make up each combined beam must now be made equal. This is done by means of a fine adjustment scheme. To measure the relative angles, each input beam in turn is allowed to enter the beam-combiner (the others being blocked), and the position of the image at the pixel which corresponds to the desired *output* beam is measured.

The optics feeding the detector are designed to give a coarse pixel scale, so that all the light from a beam falls into a single pixel, to minimise read noise when recording fringes. The image positions must be measured to a small fraction of a pixel, so a 5mm diameter aperture is introduced which diffracts the light over several pixels. The centroid of the large image gives the angle of the beam to two seconds of arc.

The beam-combiner combines four beams in a pair-wise fashion (beam 1 is combined with beam 3 at one beam-splitter, beam 2 is combined with beam 4 at another, and then the mixture of beams 1 and 3 is combined with the mixture of beams 2 and 4 at each of two further beam-splitters), and can be divided up into four sub-units, each of which consists of a beam-splitter unit (as in Figure 2) with one or more of the input beams relayed off a mirror. Each sub-unit combines two beams. A misalignment in the form of a small tilt of any component in the sub-unit can be corrected by tilting a relay mirror on either of the input beams, to equalise their angles of incidence on the beam-splitter. A further tilt of the same mirror can also compensate for either the beam-splitter or compensating plate not being parallel-sided.

The fine adjustment scheme is a sequence which corrects the alignment of the four sub-units in turn, by tilting one component in each. Each such adjustment superposes a pair of input beams at one or more of the outputs of the beam-combiner. A 20 arcsecond tilt causes a pupil shift of only 0.5mm (a small fraction of the 25mm pupil diameter) at the detector on a single pass through the beam-combiner. Similar adjustment schemes can be devised for pair-wise beam-combiners which combine more than four beams.

The relative angles of beams at the outputs of the beam-combiner are stable to six seconds of arc over timescales of a week, and so the only realignment which needs to be done regularly is the fine adjustment scheme, which takes a few minutes. The entire alignment procedure shown above can be performed in a day.

6. PERFORMANCE OF THE COAST IR SYSTEM

6.1. Visibilities and Coherence Times

Using a white light source, visibility amplitudes of 85% are obtained internally (see Figure 3), with a double pass through the beam-combiner. On an unresolved star, typical visibilities are 35–45% at 1.3μm using the full 40cm telescope apertures with tip-tilt correction (see Figure 4 for an example of stellar fringes). If the only visibility loss is due to atmospheric turbulence, the expected value for $2r_0$ apertures with perfect tip-tilt correction is 65%.[10] With

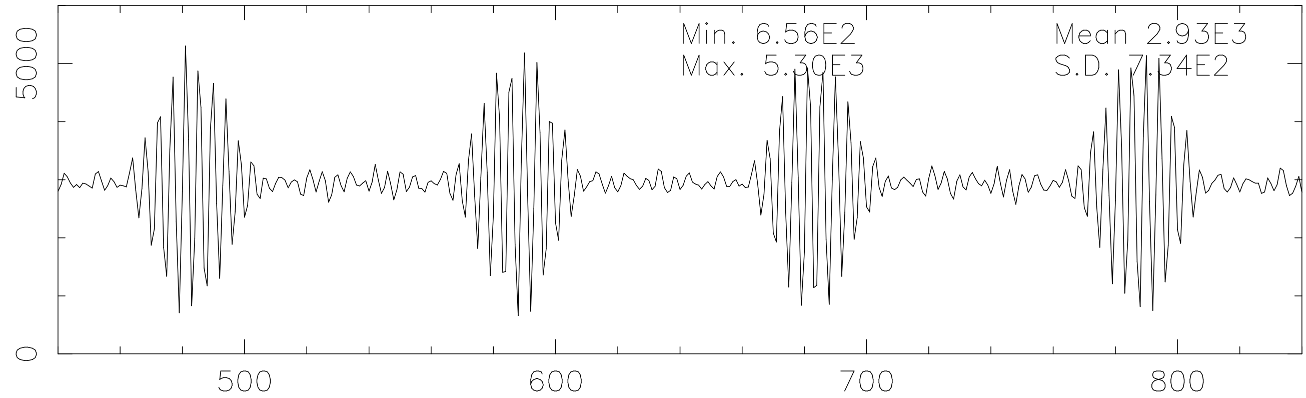

Figure 3. Internal 1.3μm fringes from COAST IR system, using white-light source. The horizontal axis is time in milliseconds, and the vertical axis is proportional to the number of photons detected in each one millisecond integration. In the time interval plotted, the path delay was swept through the fringe packet four times.

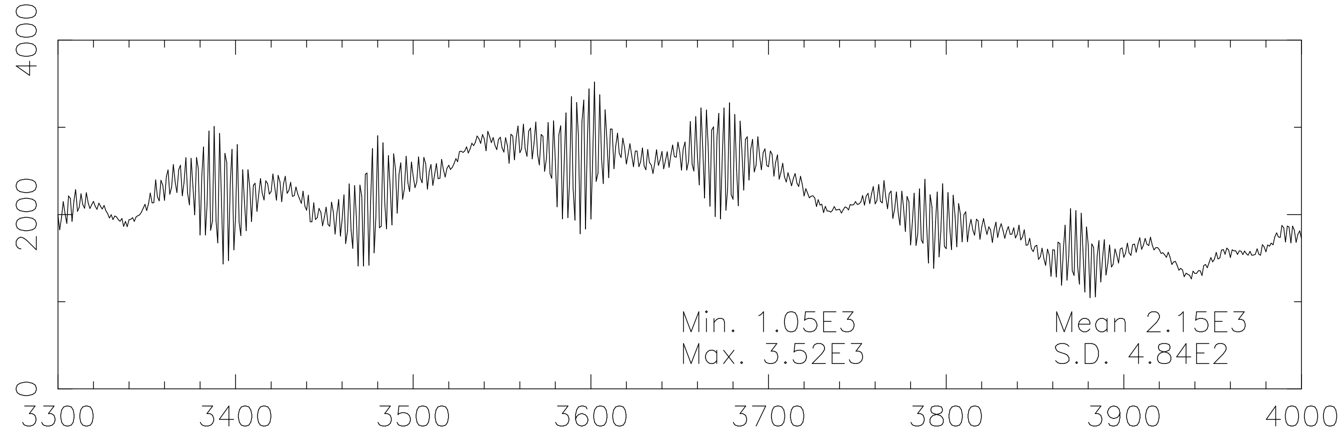

Figure 4. Stellar fringes (on α Bootis). The full 40cm telescope apertures were used. The bandpass is the entire J-band. The source is slightly resolved — the visibility amplitude is 25%

no tip-tilt the theoretical visibility is 30%. Due to slightly coarse sampling of the temporal fringe pattern, we would only expect to measure 57% and 26% respectively.

A comparison of near-contemporaneous COAST visible and infrared stellar data is given in Table 1. The increase in coherence time (derived from the width of the fringe peak in the power spectrum) going from 905nm to 1.3μm is about that expected for a $\lambda^{6/5}$ dependence.

6.2. Closure Phase

Figure 5 shows COAST infrared measurements of closure phase and visibility amplitude for the M supergiant star Betelgeuse. All four of the telescopes in the array were used for these observations. We used the standard COAST data reduction procedures.[11] The closure phase changes from $\sim$0 to $\sim$180 degrees at the same baseline as the visibility amplitude goes through a zero, as expected for a symmetric disc. Typical uncertainties in the closure phases are five degrees. We have made an image from these data, which will be published together with other data on Betelgeuse.[12] The results presented here demonstrate that COAST can successfully measure closure phases in the infrared.

λ/nm	$\Delta\lambda/\lambda$	Aperture/cm	Visibility	Coherence Time/ms
1290	20%	40	0.41	14
905	5%	16	0.25	8

Table 1. Comparison of near-contemporaneous COAST visible and IR data on an unresolved star (α Lyrae). The two data sets were taken within 30 minutes of each other. The aperture sizes and bandpasses are those normally used. The visibility amplitudes and coherence times are typical of those measured at COAST.

Figure 5 also illustrates that the scatter in the measured visibility amplitudes increases with visibility. This is to be expected when the uncertainty in the visibility amplitude is dominated by calibration error, caused by the seeing having changed between the observations of the source and the unresolved calibrator star.

7. CONCLUSIONS

We have implemented a scheme for fast, low noise readout of a NICMOS III near-infrared detector, and devised a procedure for aligning a pupil-plane four-beam-combiner in the infrared. Both are used in the working COAST infrared system.

The visibility amplitudes and coherence times measured with COAST in the infrared have the values we would expect, given the atmospheric conditions at the site. We measure closure phases which have the expected values, and thus we can conclude that COAST now operates successfully in the near-infrared.

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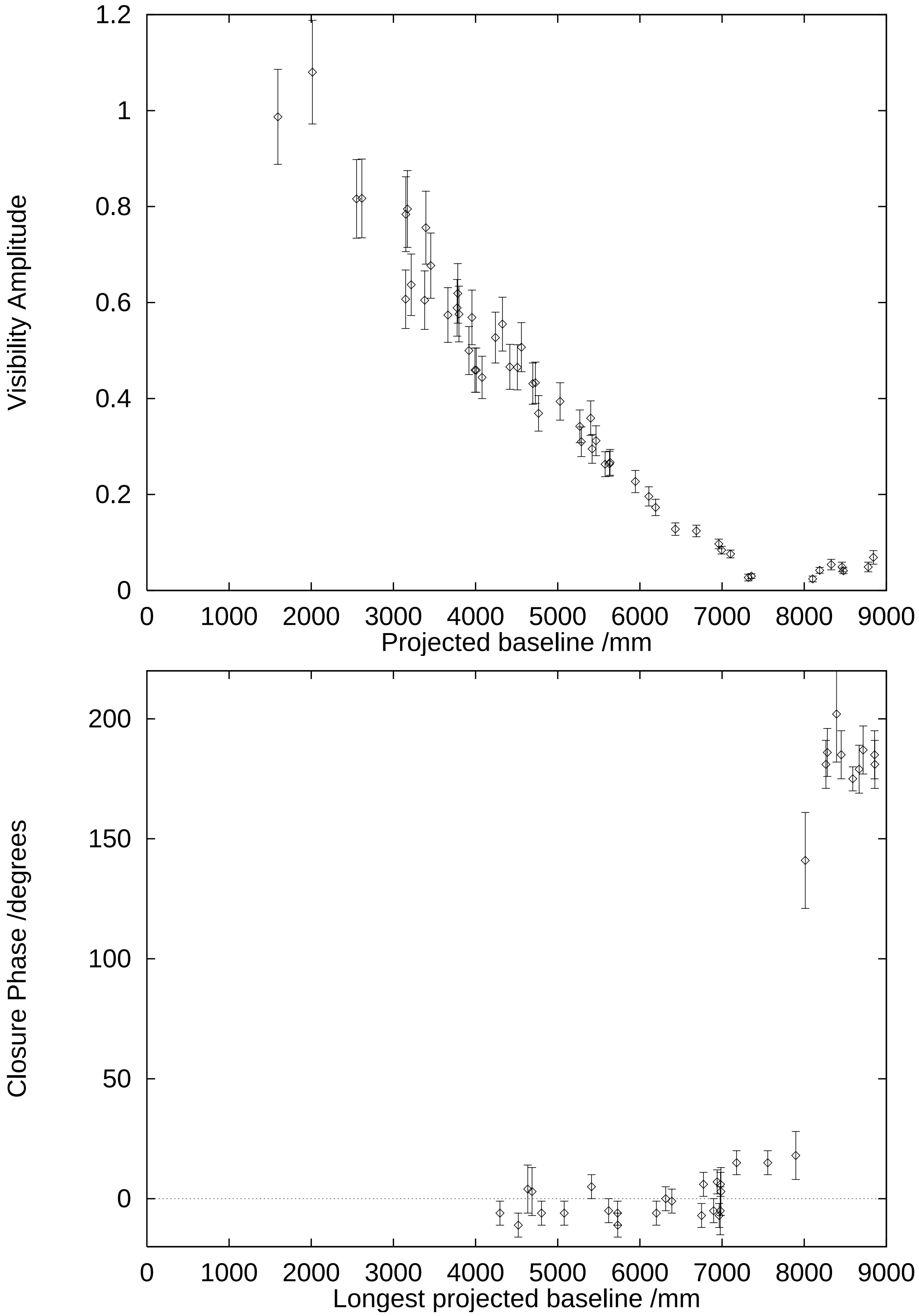

Figure 5. COAST IR (1.3μm) data on α Orionis (Betelgeuse). The top plot shows visibility amplitude plotted against the projected interferometer baseline. The bottom plot shows closure phase against the longest projected baseline in the triangle. Note that the closure phase changes from $\sim$0 to $\sim$180 degrees at the same baseline as the visibility amplitude goes through a zero, as expected for a symmetric disc.