Interferometric field of view measurements at the VLTI

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ABSTRACT

In August 2014 we performed technical observations at the VLTI with the AMBER and PIONIER beam combiners to measure the interferometric field of view (FOV). As targets we included binaries with component separations between 100 and 300 mas, for which orbits and/or interferometric speckle measurements are available from the Washington Double Star databases or from the literature. The analysis included effects such as bandwidth and time smearing of the interferograms, and photometric attenuation due to the seeing and image quality based on a new formalism of the ESO Exposure Time Calculators. We also consulted the literature for results of interferometric surveys such as the SMASH survey.[1] to estimate the effective FOV for these instruments. Based on our analysis, we conclude that emission outside a FOV diameter of 160 mas will be significantly supressed if not completely invisible. These results provide important information as to the size of the source structure to be included when modeling interferometric data obtained with these instruments.

Keywords: Interferometry:field of view

1. INTRODUCTION

From August 10 to 16, 2014, observations of a list of binaries with AMBER and PIONIER were performed to determine the field of view of VLTI through these instruments. This slot had been reserved for PRIMA commissioning, and had become available for technical time after the latter's cancellation.

The non-homothetic architecture of the VLTI implies that the field of view (FOV) is limited to the Airy disk of the on-axis source; the images of the off-axis sources do not coincide with the with-light fringe position. As a result, the fringe contrast decreases with the distance to the optical axis, but is also a function of spectral resolution R. The exact relation between the two quantities for the VLT-I instruments (as function of R) can be determined empirically using binary stars with known separation. For the astrophysical interpretation of the visibility measurements of extended sources (> 100 mas) the knowledge of the FOV is important.

The following strategy was adopted:

- observe binaries on 1 quadruplet (PIONIER) or 2 triplets (AMBER)
- observe only in low resolution and medium resolution (2.17 micron) with AMBER
- observe a CAL-SCI-CAL sequence

The field of view was measured during 6 nights and most time during this technical period was dedicated to this project. The available configuration (A1-J3-K0-G1) was not well suited for the observation of large separation, however.

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2. METHOD AND ANALYSIS

A list of binary stars was compiled from the Washington Double Star catalogs, providing astrometric measurements (WDS) or orbit solutions (ORB6[2]). Target stars were selected based on the following criteria: 16h < RA < 3h, Dec < 20°, $V < 7$, $K < 5$, $\Delta V < 3$, $D < 3$ mas, and 30 mas < R < 300 mas.

The AMBER data were reduced using amdlib 3.0,[3] selecting 20% of the best frames (in terms of S/N), after concatenating all five files per observation. The PIONIER data were reduced using pndrs.[4]

For the analysis, the main obstacle was finding reliable solutions for the relative positions of the binary components. Due to their often large separations, the Python script CANDID* usually failed in finding a good initial guess, but was more reliable at smaller separations (Fig. 4). The WDS orbit catalog† provided predictions based on (preliminary) orbits, which often led to good fits after performing a grid search. It must be emphasized that several PIONIER solutions may not be unique due to the closely spaced local minima of χ^2 related to the fairly narrow bandwidth of the spectrometer.

We assumed that IRIS[5] is tracking the photo center. The algorithm looks at a certain number of the brightest detector pixels and determines their center of gravity. If one has unbalanced stars, this center might be the brighter of the two. If they are balanced, it might be something resembling the photocenter To compute the image quality (IQ) on the IRIS detector, we used the new formalism encoded in ESO's instrument Exposure Time Calculators, as follows with seeing s, air mass x, wavelength λ, telescope diameter D[m], outer scale $L_0 = 23$ m, r_0 Fried parameter, telescope FWHM of Airy disk TEL, and $INS = 0.2$":

$$IQ = \sqrt{ATM^2 + TEL^2 + INS^2} \tag{1}$$

$$ATM = s\,x^{0.6}(\lambda/500\text{nm})^{-0.2}\sqrt{1 + F_{\text{Kolb}}2.183(r_0/L_0)^{0.356}} \tag{2}$$

$$r_0 = 0.976 \cdot 500 \cdot 10^{-9}\text{nm}/s \cdot (180/\pi \cdot 3600) \cdot (\lambda/500\text{nm})^{1.2}x^{-0.6} \tag{3}$$

$$F_{\text{Kolb}} = 1/(1 + 300D/L_0) - 1 \tag{4}$$

Depending on magnitude difference and seeing, the primary or a point on the line between it and the photo center would be tracked, and injected into the fibers. An attenuation of the secondary can be caused by it being too close or beyond the field of view. However, the overall fringe contrast will be less if seeing is worse as the turbulence is different between the two telescopes. Therefore situations appear where mainly the secondary is injected into the fiber of telescope A, and mainly the primary is injected into the fiber of telescope B. These two beams of light do not interfere however.

Orbital dynamics, grid and model fitting including bandwidth smearing computation was done using the OYSTER‡ package, based on IDL. The results are described in the follwing, in order of separation.

3. RESULTS

3.1 HD 208450 (WDS 21579-5500, $\rho = 41$ mas)

The relative component positions were found close to the one predicted by the WDS orbit. The value $\Delta V = 1.2$ quoted by the WDS reduces to $\Delta H = 0.5$ in the H-band, which is consistent with the spectral type of the secondary being F8 based on the ΔV, from which follows that its $(V - H)$ is redder than the primary by about 0.6 (Allen's Astrophysical Quantities, pages 151 and 388), yielding the ΔH given above. The separation of the components is well within the FOV, even if only the primary is centered in IRIS.

*https://github.com/amerand/CANDID
†http://ad.usno.navy.mil/wds/orb6/orb6frames.html
‡http://www.eso.org/∼chummel/oyster/oyster.html

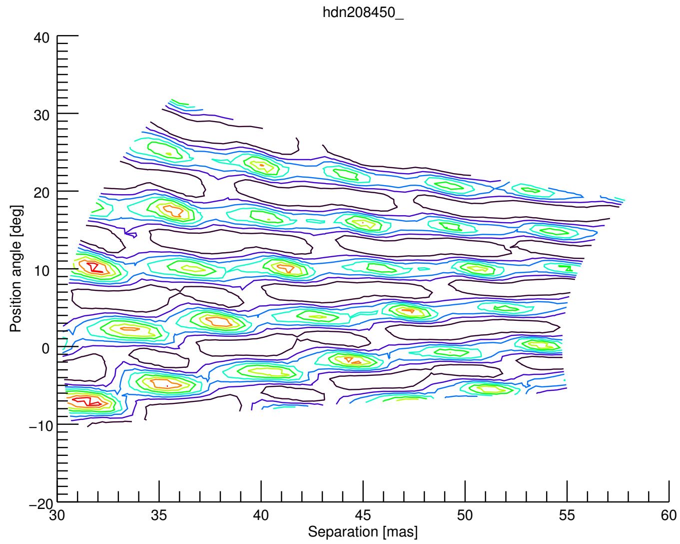

Figure 1. χ^2 surface for PIONIER observations of HD 208450 with A1-J3-K0-G1. The blue contour lines denote minima of χ^2.

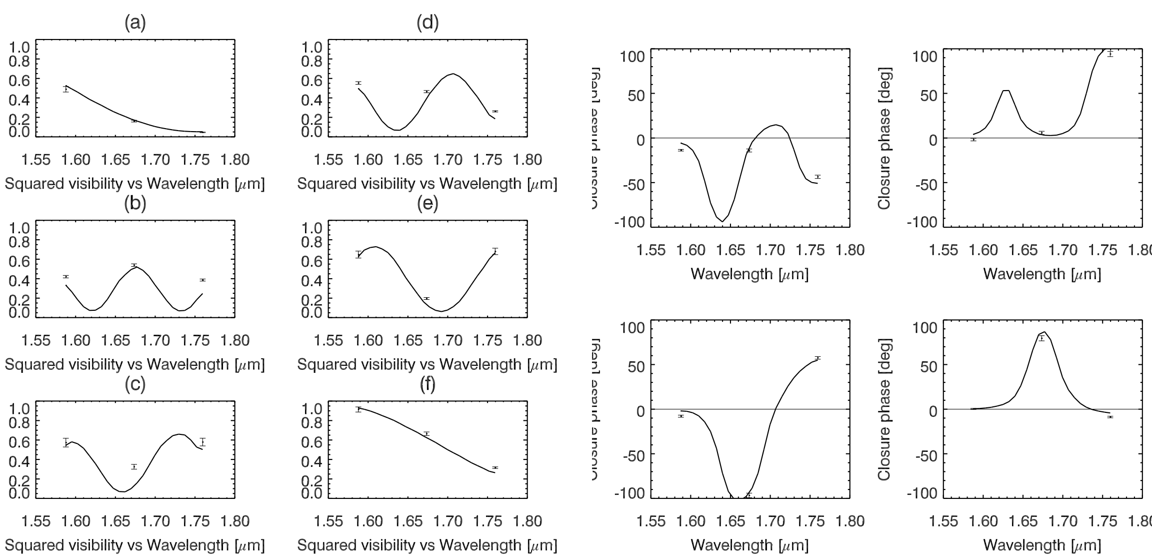

Figure 2. PIONIER V^2 and closure phases of HD 208450 on all baselines and triples of A1-J3-K0-G1. Solid lines correspond to fit with $\rho = 40.5$ mas and $\theta = 26.38°$.

3.2 HD 211088 ($\rho = 78$ mas)

According to the WDS, $\Delta V = 1.48$,[6] and with a total Simbad $V = 4.81$ we get $V_\mathrm{p} = 5.06$ and $V_\mathrm{s} = 6.54$ (letters p and s for primary and secondary). The primary is G8III, and should have $(V - H) = 2.07$ ($H_\mathrm{p} = 2.99$), but has 1.90. The secondary must therefore be bluer than the primary, based on the visual magnitude difference it is probably of type A7V, for which $(V - K) = 0.47$ and hence $H_\mathrm{s} = 6.07$. Thus we would predict a $(V - H) = 1.88$ for the binary G8III+A7V, compared to the observed value 1.90. The magnitude difference in H would be $\Delta K = 3.08$.

The ORB6 prediction is $\rho = 78.3$, $\theta = 120.02$, but based on a few measurements. The minimum we find is about 20 mas farther, but due to the fairly large magnitude difference we cannot tell for sure if this solution is unique.

The fits to the closure phases support tracking the photocenter in the seeing of about 0.92”.

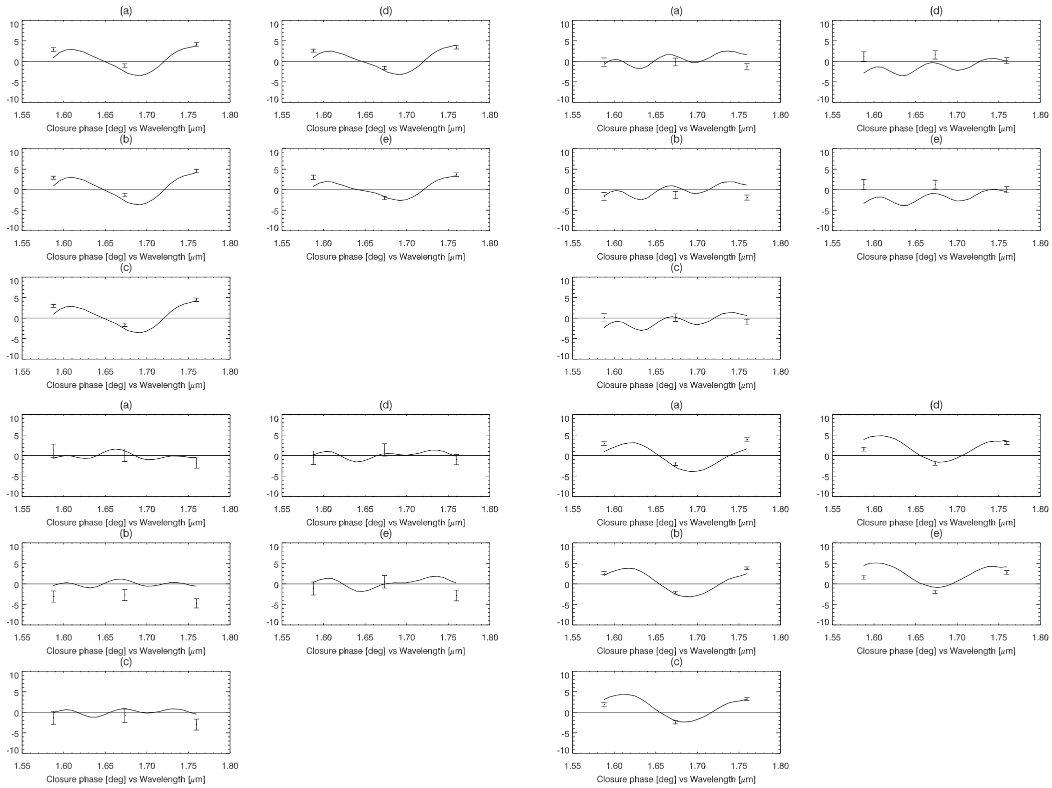

Figure 3. PIONIER closure phases of HD 211088 on (from left to right): AA1-AG1 AG1-AJ3 AA1-AJ3, AK0-AA1 AA1-AG1 AK0-AG1, AK0-AA1 AA1-AJ3 AK0-AJ3, AK0-AG1 AG1-AJ3 AK0-AJ3.

3.3 HD 203006 ($\rho = 97$ mas)

No orbit is available, just one measurement by the Hipparcos satellite which gave ρ = 142 mas, and $\theta = 1°$, for the epoch of 1991.25. The magnitude difference in the Hipparcos band was $\Delta H_p = 2.5$. The primary is of spectral type A2p, for which we would expect $(V - K) = 0.14$, while the observed one is $(V - K) = 0.11$. We can therefore assume the two components are nearly the same, and adopt the magnitude difference also as ΔH. CANDID finds a possible companion (Fig. 4) at ρ = 65.3 mas and $\theta = 357.6$, with a magnitude difference of $\Delta H = 2.1$ to the primary. A better model with about the same position angle, but larger separation of 97 mas is found with a search of the χ^2 surface. At this separation, sensitivity to tracking positions is not large, confirmed by the fact that the ΔH we measure is similar to our adopted $\Delta H = 2.5$.

3.4 HD 143275 (δ Sco, $\rho = 27 - 165$ mas)

The secondary of this binary is in a highly eccentric 11-year orbit and therefore spends most of its time at apastron nearly 200 mas away from the primary. The last periastron occurred in July of 2011. Since the data taken in 2014 see the binary at a large separation one does not therefore know the intrinsic magnitude differences, and so we looked for and found public archival data taken with AMBER and of April 2011, just a few months before periastron.

The magnitude differences in the visual have been determined[7] to be 1.87 +/- 0.17 and 2.24 +/- 0.26 at 550 nm and 850 nm, respectively. The fitted H and K magnitudes are given in the caption to Fig. 5.

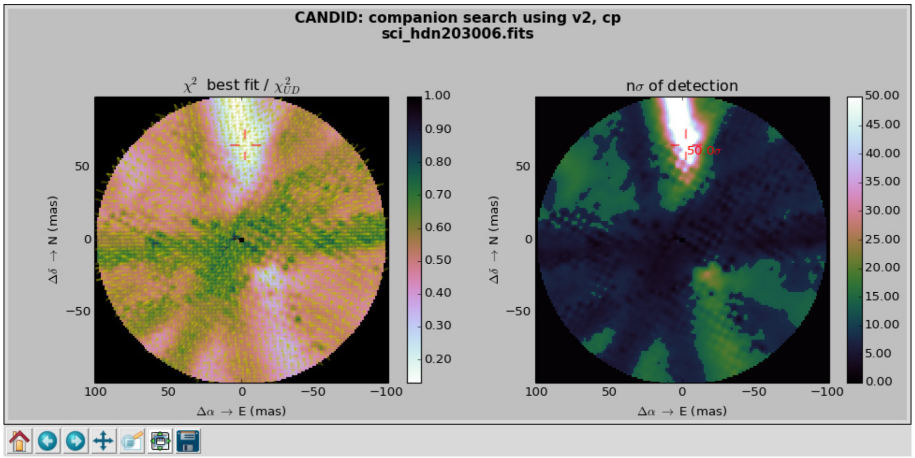

Figure 4. CANDID $\chi2$ surface map for HD 203006 The minimum χ^2 of 4.7 (compared to a single star of $\chi^2 = 37$ was found at $\rho = 65.3$ mas and $\theta = 357.6$, with a magnitude difference of $\Delta H = 2.1$ to the primary.

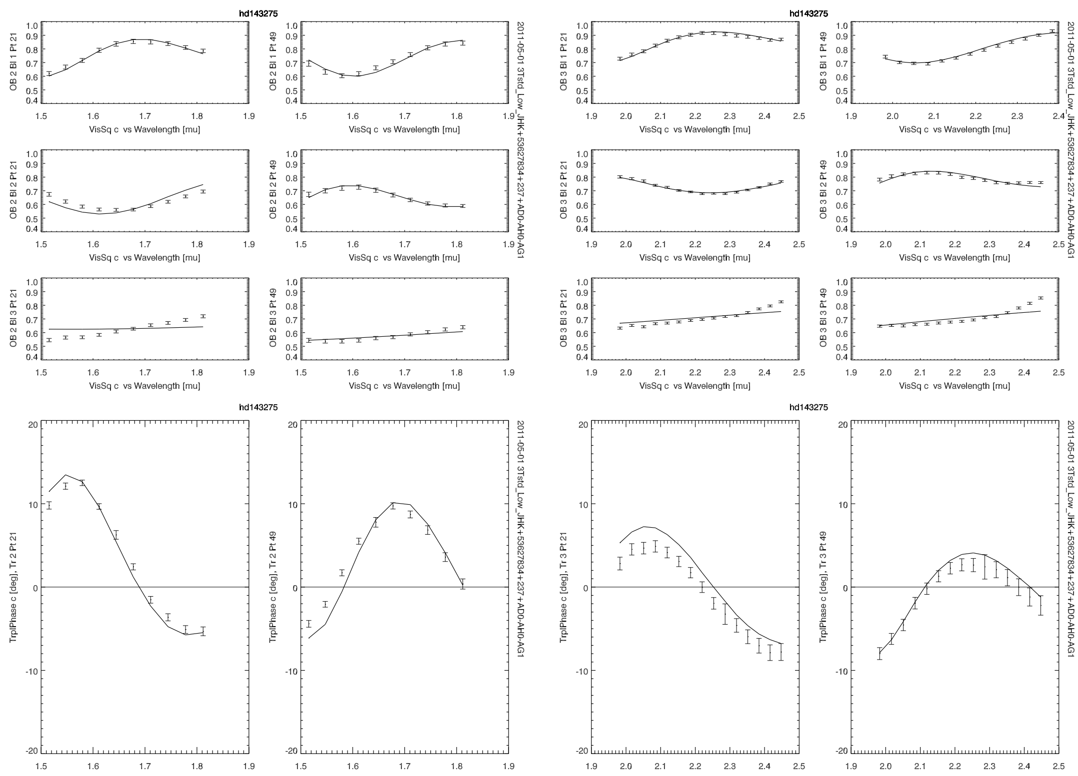

Figure 5. AMBER H (left column) and K (right column) low resolution observations April 30, 2011, of δ Sco on D0-H0-G1. Fit with $\rho = 27.1$ mas, $\theta = 40.5°$, $\Delta H = 2.86$, $\Delta K = 3.15$, $D = 1.64$ mas. The fitted diameter is consistent with the analysis presented in in Table 2 by A. Meilland.[8]

In Fig. 6 we show data from May 24, 2008, when the binary was again at large separations (166 mas). The H band magnitude difference has increased a bit (by about 0.4 mag), while ΔK has not changed. The attenuation computed (and therefore already included) is about 0.5 mag. This indicates that in the H band, the attenuation computed is not strong enough.

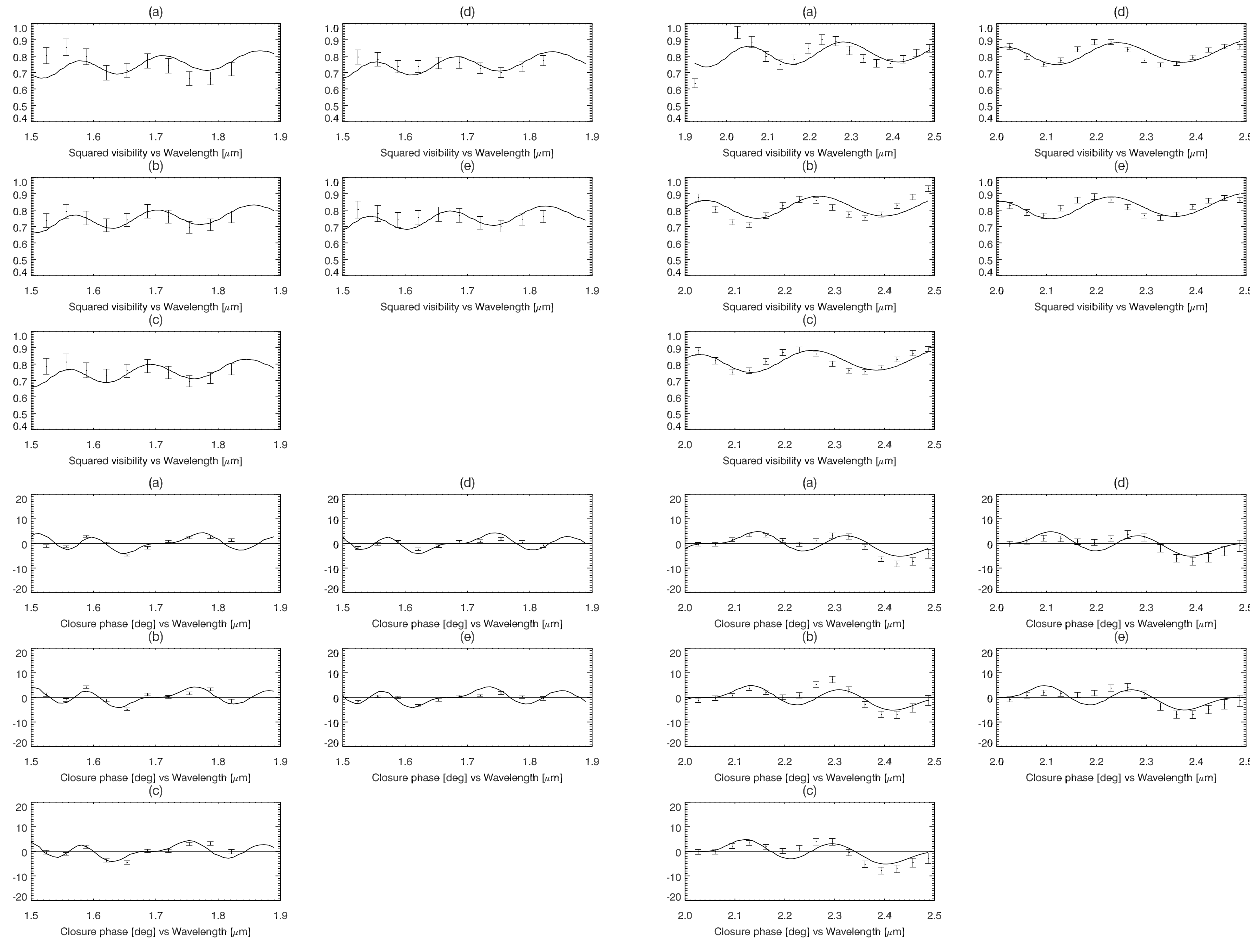

Figure 6. AMBER H (left column) and K (right column) low resolution observations May 24, 2008, of δ Sco on H0-D0. Fit with $\rho = 165.8$ mas, $\theta = 1.65°$, $\Delta H = 3.29$, $\Delta K = 3.12$, $D = 1.64$ mas.

3.5 HD 195330 (WDS 20311-1503, $\rho = 148$ mas)

This binary has a primary of type K1III (CDS, but the WDS gives G5III), ($M_V = 0.75$, $(V - H) = 2.40$), with $\Delta V = 1.1$.[9] we estimate the companion type A4V, ($M_V = 1.8$, $(V - H) = 0.36$), from which we get $\Delta H = 3.1$ (`print,dmag(6.121,1.1)-[2.4,0.36]`). The data quality does not allow verification of the correct position of the binary, and thus the magnitude difference is also uncertain.

3.6 HD 220759 ($\rho = 223$ mas)

According to the Hipparcos results, $\Delta V = 1.98$, and with a total $V = 6.47$ we get $V_{\rm p} = 6.63$ and $V_{\rm s} = 8.61$ (letters p and s for primary and secondary). The primary is K4III ($M_V = 0$), and should have $(V - K) = 3.26$, but has 3.65. Since this is redder, it could be caused by interstellar reddening. The companion, due to the significant magnitude difference, must be a main-sequence star and would have to have a type around A5 ($M_V = 1.95$). For this type, $(V - K) = 0.38$, and therefore I compute $K_{\rm p} = 3.37$ and $K_{\rm s} = 8.23$ and thus $\Delta K = 4.8$. This is rather large compared to the $\Delta K = 3.0$ derived from the AMBER data (and consistent with the PIONIER data), therefore we cannot obtain evidence that the companion is strongly attenuated. In fact, the attenuation of the secondary is estimated to be 0.5 mag at a seeing of 0.66".

3.7 HD 162587 (WDS17534-345, $\rho = 414$ mas)

The ORB6 orbit shown with the WDS measurements in Fig. 10 predicts $\rho = 414$ mas and $\theta = 205.92°$.

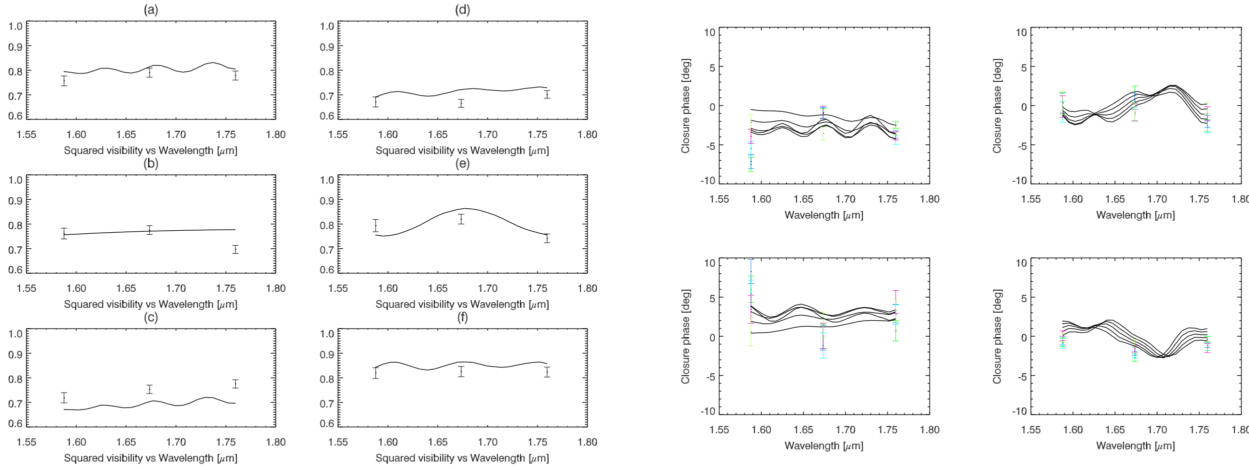

Figure 7. PIONIER V^2 and closure phases of HD 195330 with model parameters $\rho = 148.2$ mas, $\theta = 127.51°$, $D = 0.81$ mas, and $\Delta H = 3.1$. The five observations are plotted on top of each other, showing the drift due to Earth's rotation. Median seeing of 1.21".

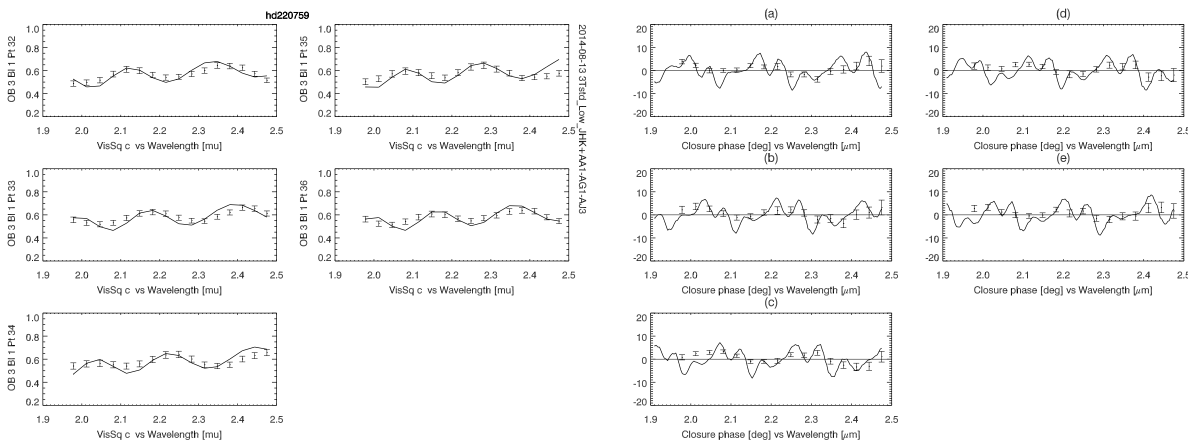

Figure 8. AMBER V^2 and closure phases of HD 220759 on baseline A1-G1 (80 m).

The WDS lists $\Delta V = 2.04$ and a spectrum of K3III for the primary. No good fits could be obtained, most likely because the primary is also a spectroscopic binary with a period of 458 days (SB9 data base).

3.8 Companions not detected ($\rho = 223$ mas)

A number of binaries were fit satisfactorily with a single star, in which cases also the closure phases were near zero. Three of them had ended up on the observing list due to single measurements with the Lunar occultation technique. Therefore, the companion may not be characterized well enough to conclude that we missed it.

In the case of HD 218240, the primary is a G8 giant, and the secondary 2.0 mag fainter (in V). Hipparcos measured $\rho = 255$ mas and $\theta = 299°$, a more recent measurement in 2013[10] results in $\rho = 204.3$ mas and $\theta = 345.13°$. This type of binary is similar to HD 220759 (see 3.6), and we estimate the companion type F0V, leading to $\Delta H = 3.4$. In the case of HD 220759, the companion was detected at $\rho = 98$ mas with $\Delta K = 3.0$, and thus, with HD 218240 being a binary with a significantly larger separation, we compute an additional $\Delta H = 0.42$ attenuation leading to the non-detection of the companion.

The situation is similar with HD 218434 (WDS 23084-2849), with a primary of type G9III and $\Delta V = 2.28$. A recent speckle measurement (epoch 2014.7686) is available from the WDS ($\rho = 223.6$ mas, $\theta = 115.5°$). The visibilities are best fit with a single star ($D = 0.9$ mas); a binary model would fit the data if the companion

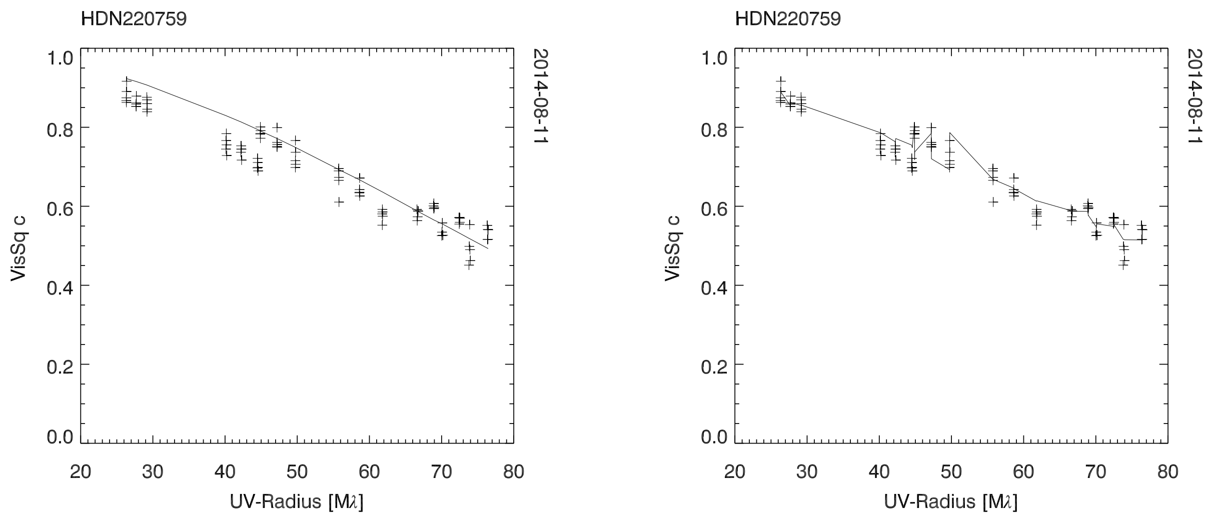

Figure 9. PIONIER V^2 of HD 220759 versus uv-radius for A1-J3-K0-G1. Left: single disk fit ($d = 1.4$ mas). Right: binary fit ($d = 1.24$ mas, $\Delta m = 3.1$ for median seeing $r0 = 0.88$).

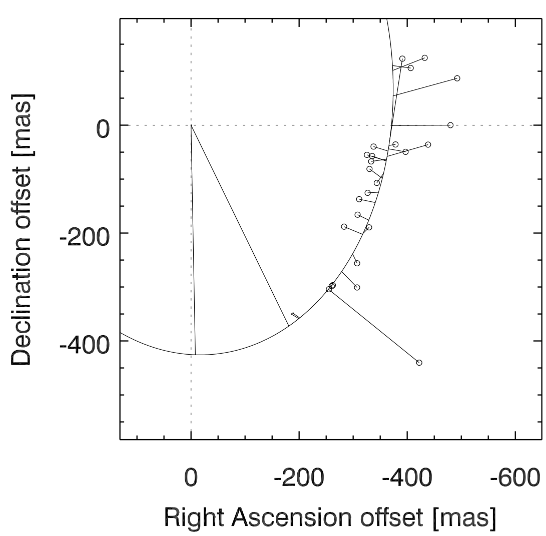

Figure 10. Orbit of HD 162587 and measurements from the WDS. North is at the top, East to the left. The line at $PA = 206°$ (E from N) denotes the position of the secondary for 2014, August 12.

$\Delta H = 4.4$. Only the closure phases show small deviations from a single star model, i.e. from zero phase, but they may not be real (see Fig. 11).

Finally, HD 219023 (WDS 23133-4937), has a primary of type G9III ($M_V = 0.75$, $(V - H) = 2.07$), with $\Delta V = 2.64$. We estimate the companion type F2V, ($M_V = 3.44$, $(V - H) = 0.78$), from which we get $\Delta H = 3.93$. A recent measurement (epoch 2014.8533) of the relative position is available in the WDS, $\rho = 180.7$ mas and $\theta = 332.9°$. Fitting the PIONIER data yields an estimate of $\Delta H = 3.9$, accounting for additional $\Delta H = 0.2$ due to FOV attenuation. The resulting model closure phases are less than $2°$, with the observed phase also near zero, even though the two do not correlate.

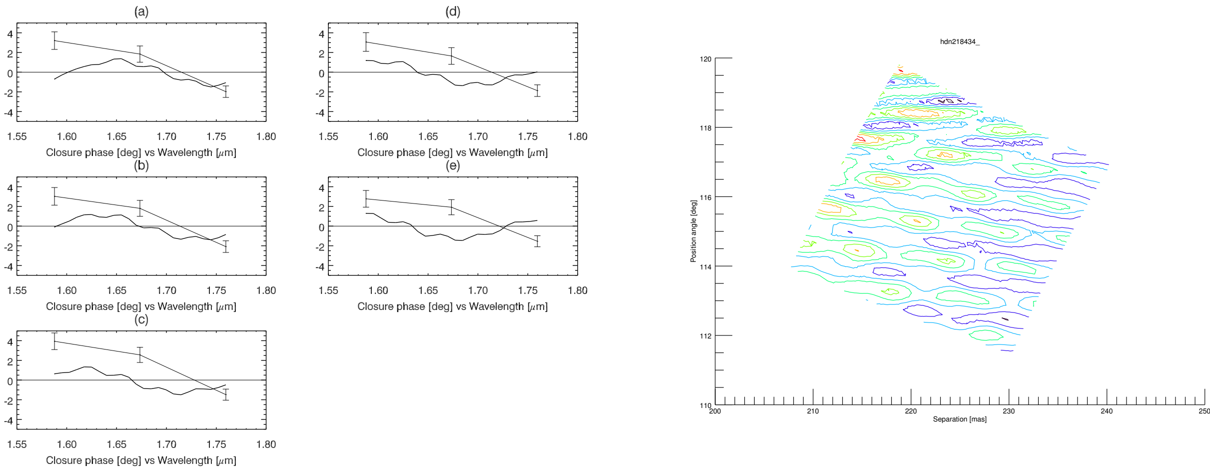

Figure 11. PIONIER A1-K0-G1 closure phases of HD 218434 (left) at the position (ρ = 223.6 mas,θ = 115.5°)[6] and shown in the middle of the χ^2 map (right). The drift of the closure phase with time can be seen clearly, but the measured data do not show it.

4. CONCLUSIONS

While this report is still incomplete (not all data are analyzed yet), I think one can say that corrections for flux attenuation of the secondary begin to be significant at separations of more than 160 mas. Hugues Sana concluded from his observations of a sample of O-star binaries[1] that "PIONIER/VLTI is hardly sensitive to any binaries with separations >120 mas". As shown in this report, that conclusion depends on the brightness ratio of the components which affects the track point. A clear case for the companion outside the field of view with significant attenuation is difficult to establish since the wider systems typically have a red giant primary which dominates the IR flux. The ideal binary would have two identical components at large separations.

The present report may help to design another technical test if the following can be prepared: two binaries with small measured magnitude differences with separations of about 150 and 300 mas, and a short baseline configuration.

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