A Pixel Correlation Technique for Smaller Telescopes to Measure Doubles

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Abstract: Pixel correlation uses the same reduction techniques as speckle imaging but relies on autocorrelation among captured pixel hits rather than true speckles. A video camera operating at speeds (8-66 milliseconds) similar to lucky imaging to capture 400-1,000 video frames. The AVI files are converted to bitmap images and analyzed using the interferometric algorithms in REDUC using all frames. This results in a series of corellograms from which theta and rho can be measured. Results using a 20 cm (8") Dall-Kirkham working at f22.5 are presented for doubles with separations between 1" to 5.7" under average seeing conditions. I conclude that this form of visualizing and analyzing visual double stars is a viable alternative to lucky imaging that can be employed by telescopes that are too small in aperture to capture a sufficient number of speckles for true speckle interferometry.

Most astrophysically interesting visual doubles are less than 5" in separation. Imaging such doubles under less than ideal conditions at many locations is a challenge with smaller telescopes because the number of nights of good seeing is rare and the seeing disc can be large, negating our efforts to obtain clear separation between close pairs. There are two common strategies for beating average to poor seeing conditions. Lucky imaging uses short integration times to freeze seeing. If the investigator takes hundreds or even thousands of frames, there are bound to be a few frames that capture the double under good transient conditions (see Anton, 2012, for a review). Success depends on searching through the available frames, making a judgment as to quality, stacking the best frames in order to measure the resulting seeing disc and using an appropriate technique of finding the centroids of each component (i.e. "centroiding"). There are more automated methods of finding lucky imaging. For example, one could use the REDUC feature "Bestof (Max)" and select some percentage of the best frames. Anton (2012) prefers a more manual technique to pick the best images.

Speckle imaging beats the seeing by taking advantage of the seeing itself. Speckle imaging depends on sampling atmospheric cells that contain an image of the double. The smaller the aperture the fewer the atmospheric cells sampled and thus fewer speckles are captured. Turner et al. (1992) calculates that a 204mm aperture telescope will only gather about 4 speckles and the number of binaries available to measure is rather small (Turner lists only 4 known if a V-filter is used). Florent Losse (pers. comm.) suggests that apertures under 300mm may not collect a sufficient number of speckles to make speckle imaging feasible and that the situation is more optimal with scopes 400mm or more in aperture. This seemed to preclude true speckle imaging from my programs as I am aperture-limited.

I wondered, however, if an approach using lucky imaging camera speeds and autocorrelation might be viable. In 2010 Losse added an interferometric analysis package to his REDUC reduction program (http://www.astrosurf.com/hfosaf/index.htm) that permits reduction of speckle images. His observing program demonstrates that speckle interferometry is quite within the capabilities of astronomers with relatively modest telescopes (Losse, 2010; English summary at http://www.astrosurf.com/hfosaf/uk/speckle10.htm). Could the interferometric subprograms in REDUC could be used with smaller telescopes, perhaps without true speckles but using high speed integrations to capture pixels? Would the pixels captured carry enough information that autocorrelation of the available pixels might yield a measureable autocorrelogram using the autocorrelation subprograms in REDUC? If so, what pairs might I be able to image and measure on an average eastern Kansas night with seeing in the 2/5-3/5 range with a 204mm telescope? And, if results can be obtained, how accurate are those measures? If successful the pixel technique would allow many more nights of measuring astrophysically interesting pairs and I could move on to testing more exotic optical configurations that would increase the effective focal length of my optical train.

Methods

The telescope is a 204mm Dall-Kirkham with a native focal ratio of F/22.5. The cameras used include both the older and newer Image Source DMK21 video cameras, the difference being that the newer version has an upgraded and slightly more sensitive chip. Both cameras have 640x640 chips with 5.6μm square pixels. The optical train was fitted to a Vixen flip mirror to aid in image acquisition. Imaging was performed at prime focus with an effective focal length of 4590mm and a plate scale of 0.250 seconds/pixels without a filter. Integrations ranged from 8ms to 33ms, depending on the magnitude of the pair. The integration time of any one pair was eclectic: I simply reduced the integration time until the stars began "dancing" (the seeing disc began to break up) and then continued to reduce the integration time until the pair (or oblong blob) was barely visible. I then took a minimum of four video files of 400 frames/file of each double. As a safety precaution I then increased the integration time two steps, capturing eight more files. So a typical run might consist of 12 files, four each at 8ms, 11ms, and 16 ms (or 11, 16 and 33 ms) to insure that at least one run would have a sufficient number of pixels to analyze. Two pairs of known theta and rho were imaged at the beginning and end of each observing session. These are relatively wide pairs (8-16arcsec) acquired by normal integrations of 0.25 to 1 second. Four files of 25-50 images each were collected for the calibration pairs. In addition a minimum of two star trails were captured by the drift method.

The uncompressed video files (avi files, Y800 codec) were converted to bitmap images using the open source program VirtualDub (http://www.virtualdub.org/). At faster integration times I did not observe any hot pixels and thus I made no attempt to calibrate the images with darks, flats or bias frames. I did dark, subtract on calibration pairs with longer integration times. Camera orientation was determined by analyzing star trails using subroutines in REDUC. Plate scale is rather constant, but was checked each night using reductions of the angle and separation of rectilinear calibration pairs as detailed in Wiley (2012).

For each pair I began with the set of bitmap images of the shortest integration time. Each file of bitmap images was analyzed using the autocorrelation option in the interferometry menu of REDUC. All frames were included in the analysis regardless of quality. In other words, I made no attempt to sort "lucky images." The analysis result is a series of autocorrelograms (S0-S9). S0 is the unmasked result and while S1-S9 apply a series of masks (kernels of 3x3, 5x5 etc.) to separate the peaks. In general, the smaller the disc, the lower the number of the mask employed. This can be estimated by the measuring aperture; smaller apertures (e.g. 5x5) would call for S1-S2 autocorrelograms, as is the usual case for pairs reported herein. The largest aperture possible was used to insure successful centroiding. As the quadrant of the secondary was known; the relative position of the secondary was unambiguous. Theta and rho were harvested from the autocorrelogram. Each of the total of N=4 (occasionally 5) sets of results were combined to produce an overall average and error for that particular pair. The single exception was 20548+3242STT 418, the closest pair measured where one run resulted in a very different angle and only three measures are reported. Calibration pairs were handled in a similar manner except the images were stacked, then measured by centroiding using the standard REDUC subroutines. A spot check of single runs for selected calibration pairs taken at the end of each session was also made using 40-50 individual frames processed using the automatic reduction routine in REDUC.

Accuracy of the results was judged by comparing

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the results to the entire histories of observation of each pair and O-C calculations for three pairs with orbits and one rectilinear pair not used for calibration. The O-C calculations for the three pairs with orbits were performed using the Excel® program by Workman. (http://www.saguaroastro.org/content/db/binaries_6th_Excel97.zip) with more recent data from the Sixth Catalog of Orbits of Visual Binary Stars (Hartkopf and Mason, 2001 et seq.). The O-C calculation of the rectilinear pairs (including the calibration pairs) were performed using methods in Wiley (2012) derived directly from WDS equations (Mason et al., 2010). An Excel® sheet with worked examples is available on request. Since all doubles measures were STF (F. Struve) and STT (O. Struve) doubles , the history of observations were quite extensive, reaching to the 18th Century. I requested these data from USNO (Mason, 2006). Theta and rho of all historical records were converted to Cartesian (rectangular) coordinates using an Excel spreadsheet provided by Francisco Rica, as detailed in Wiley (2010). I did not weight the observations. I then compared the long-term history to my measure visually and by means of informal line fitting (for example, Figure 1) as implemented in Excel.

Results

Pairs and their measures and errors harvested in this are shown in Table 1. Included in this table are O-C calculations for five pairs with either orbital of rectilinear. Table 2 shows examples of the fit of the cali-

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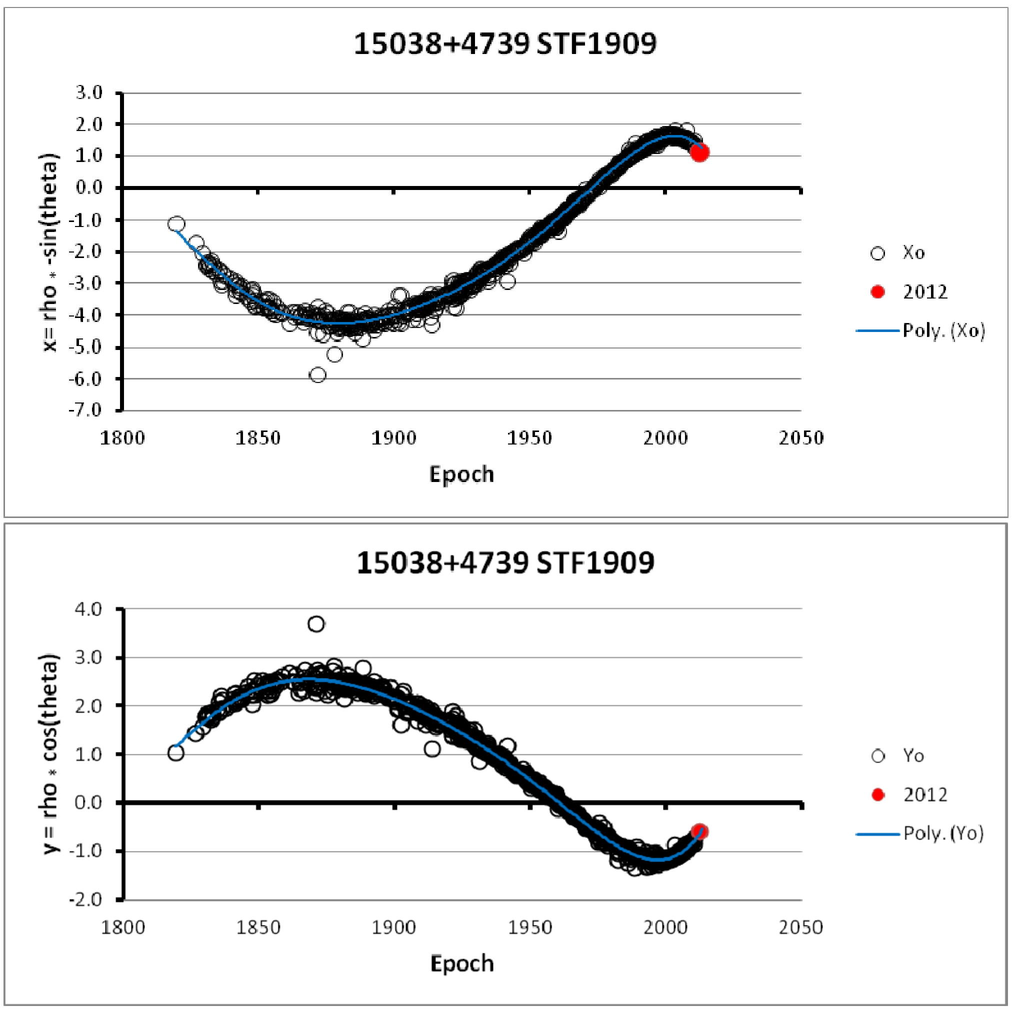

Figure 1: A higher resolution plot of the relative motion of 15038+4739STF1909. Upper: relative motion of the secondary along the x-axis as a function of Epoch. Lower: relative motion of the secondary along the y-axis as a function of Epoch. The blue line is a 6th order polynomial fitted in Excel® to the historical measures, extended to the date of measure herein. The y-axis scale is in arcseconds. Compare to the same pair in low resolution in Plate 2.

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Table 1. Measures reported and O-C analyses in this paper. WDS, Washington Double Star Catalog Number; Disc, discover code; PA(O), reported theta; Sep (O), reported rho; err PA (O) and errSep(O), standard error of theta and rho; Date, epoch of observation reported; N, the number of imaging runs, all taken on the same night; PA(C) and Sep(C),, theta and rho calculated from orbital elements or rectilinear elements; O-C observed versus calculated PA/Sep; O-C reference, author/s of orbital or rectilinear elements. All measures taken with a 204mm F/22.5 Dall-Kirham with a plate scale of 0.25 seconds/pixel.

WDS	Disc	PA (O)	Sep (O)	errPA (O)	errSEP (O)	Date	N	PA (C)	Sep (C)	O-C	O-C Reference
14497+4843	STF1890	45.9	2.55	0.03	0.002	2012.516	4	45.8	2.61	+0.1°/ -0.06"	Hartkopf & Mason, 2011b
15038+4739	STF1909	62.7	1.28	0.13	0.004	2012.516	5	62.5	1.266	0.2°/ -0.04"	Zirm, 2011
16289+1825	STF2052AB	120.3	2.24	0.34	0.042	2012.516	4	119.8	2.47	+0.5°/ -0.03"	Soderhjelm, 1999
16442+2331	STF2094AB	72.5	1.12	0.17	0.001	2012.516	4	72.8	1.16	*	
17237+3709	STF2161AB	320.8	4.14	0.02	0.004	2012.516	5	319.6	4.14	*	*
17564+1820	STF2245AB	290.4	2.59	0.07	0.004	2012.516	4	291.8	2.58	*	*
18101+1629	STF2289	226.2	1.23	0.16	0.001	2012.516	4	218.7	1.23	*	*
19487+1149	STF2583AB	103.2	1.45	0.07	0.017	2012.729	5	104.8	1.41	*	*
20093+3529	STF2639AB	300.9	5.73	0.02	0.011	2012.617	4	300.3	5.73	*	*
20126+0052	STF2644	205.2	2.54	0.05	0.021	2012.729	4	205.8	2.64	*	*
20184+5524	STF2671AB	336.6	3.762	0.26	0.025	2012.617	5	337.2	3.71	*	*
20377+3322	STF2705AB	262.21	3.13	0.49	0.086	2012.617	4	262.3	3.1	*	*
20585+5028	STF2741AB	26.4	1.93	0.05	0.004	2012.617	4	24.7	1.95	*	*
21068+3408	STF2760AB	33.1	4.77	0.21	0.037	2012.617	4	33.2	4.89	-0.1°/ +0.12"	Hartkopf & Mason, 2011b
20548+3242	STT 418	285.0	0.94	1.32	0.013	2012.729	4	284.6	1.12	*	*
21208+3227	STT437AB	20.2	2.38	0.02	0.003	2012.617	4	19.2	2.42	+1°/- 0.04"	Hartkopf & Mason, 2011a

Table 2. Measures reported and O-C analyses of four collimation pairs. WDS, Washington Double Star Catalog Number; Disc, discover code; PA(O), reported theta; Sep (O), reported rho; err PA (O) and err Sep (O), standard error of theta and rho; Date, epoch of observation reported; N, the number of imaging runs, single night; PA(C) and Sep(C),, theta and rho calculated from orbital elements or rectilinear elements; O-C observed versus calculated PA/Sep; O-C reference, authors of rectilinear elements. All measures taken with a 204mm F/22.5 Dall-Kirham with a plate scale of 0.25 seconds/pixel.

WDS	Disc	PA (O)	Sep (O)	errPA (O)	errSEP (O)	Date	N	PA (C)	Sep (C)	O-C	O-C Reference	Notes
15346+4331	STF1961AB	20.09	28.334	0.15	0.165	2012.516	25	20.1894	28.4496	-0.1°/-0.12"	Hartkopf & Mason, 2011b	1
20425+4916	ARG39AB	181.96	14.656	0.37	0.162	2012.6169	42	181.924	14.704	0.036/-0.044	Hartkopf & Mason, 2011b	2
15174+4348	STF1934AB	13.14	9.73	0.32	0.054	2012.516	40	13.185	9.731	-0.05/-.001	Hartkopf & Mason, 2011b	2
20425+4916	ARG39AB	181.86	14.724	0.14	0.011	2012.729	50	181.924	14.704	-.06/+0.02	Hartkopf & Mason, 2011b	2

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bration pairs taken at the end of observations and not used to calculate camera angle and resolution relative to predicted theta and rho derived from The Catalog of Rectilinear Elements (Hartkopf and Mason, 2011b). One example of fitting my observations to previous observations is shown in Figure 1 in high resolution. Example images of raw frames, stacked frames and autocorrelograms are shown in Plate 1 for two of the closer doubles analyzed. The third pair in Plate 1 illustrates some of the challenges to implementing this technique. Comparisons of the histories of observations and my measures as functions of x-values and y-values over Epoch are shown for all pairs reported in Table 1 in Plates 2-4 (in low resolution).

Discussion

The autocorrelogram is the sum result of analyzing all images and no effort was made to select better (or worse) images to analyze. This is because no one image sufficiently samples the seeing disk, making centroiding impossible or highly ambiguous; the use of all images is needed to produce a successful autocorrelation. The fact that I did not calibrate images requires some discussion. Autocorrelation should reject any positive pixel hits caused by random noise given that they are not correlated with pixels in other frames. In fact, in some frames one can see the autocorrelation select random noisy pixels inside the selection window, but those data never appear in the autocorrelogram. I observed no "hot" pixels at high integration speeds that would bias the results with the few darks I took. Never-the-less, it would be prudent to employ darks at all integration times. They are easy to acquire and apply in REDUC.

Figure 1 and Plates 2-4 suggest that this method of analyzing double star data in the 1-5 arcseconds of range of separation is comparable to other methods of measuring doubles as evidenced by the observation that the reported measures fall in line with the histories of observations along both the x-axis/Epoch and y -axis/Epoch plots. The extent to which the overall sum of previous observations portrays something accurate about the actual separation and distance of the pairs at any one time is the extent to which observations reported here can be judged as accurate as most measures and more accurate than some measures. For the four pairs that I could calculate observed versus calculated theta and rho, the O-C differences varied between 0.1° to 1° in theta and 0.12-.03" in rho. The most deviant O-C in theta was the pair 21208+3227STT437AB which had an O-C in theta of 1°. However, the last measure by Cvetkovic et al. (2011: PA=20.19°, Sep=2.381") and my measure differ by only 0.03° in theta and are identical in rho. The history of this pair suggests quite a bit of variation in recent measures. The most deviant O-C in rho was the rectilinear pair 21068+3408STF2760AB which also had the lowest O-C in theta.

The results in Table 2 are an indication of the fit of the camera angle and plate scale to predictions of position and angle derived from the Catalog of Rectilinear Elements. Each of the runs was withheld from modeling camera angle and plate scale and used as a check on O-C calibration fit and to insure that the camera was not moved during the session. Note the higher errors typical of analyzing single frames as compared to errors when the results of pooled runs are averaged (e.g. errors in Table 2 average about twice those in Table 1).

The methods reported herein suggest that this form of autocorrelation using a modest scope of 204mm aperture is quite successful in accurately measuring doubles in the 1.2"-2.0" (and greater) range of separation under seeing that would preclude harvesting measures using other techniques. This vastly increases the number of nights available to measure doubles with a 204mm aperture telescope working at a modest effective focal length, the equivalent of imaging with a 204mm SCT and a 2x-2.5x Barlow. On some nights seeing might be excellent. In such cases autocorrelation techniques may not be needed for many pairs.

There are several challenges to use of this technique. (1) Lack of critical focus, atmospheric dispersion, or collimation can cause distortion of images in the autocorrelogram; they will appear elongated and thus centroiding may be less accurate. How inaccurate is not addressed in this study and would require additional experiments. (2) Imaging at too slow an integration speed will result in an undersampled image. The autocorrelogram may not clearly separate the primary and secondary in the masked images (i.e. the REDUC in all of the S1-S9 autocorrelograms) or the Airy disc may be undersampled. (3) An insufficient number of frames may lead to ambiguous results. I would suggest at least 400 and now take a minimum of 500 frames; 1,000 frames might be better as one reaches the limits imposed by aperture and seeing. (4) Difference in magnitude may result in failure due to not imaging the secondary or saturating the primary. The limits imposed by this challenge are

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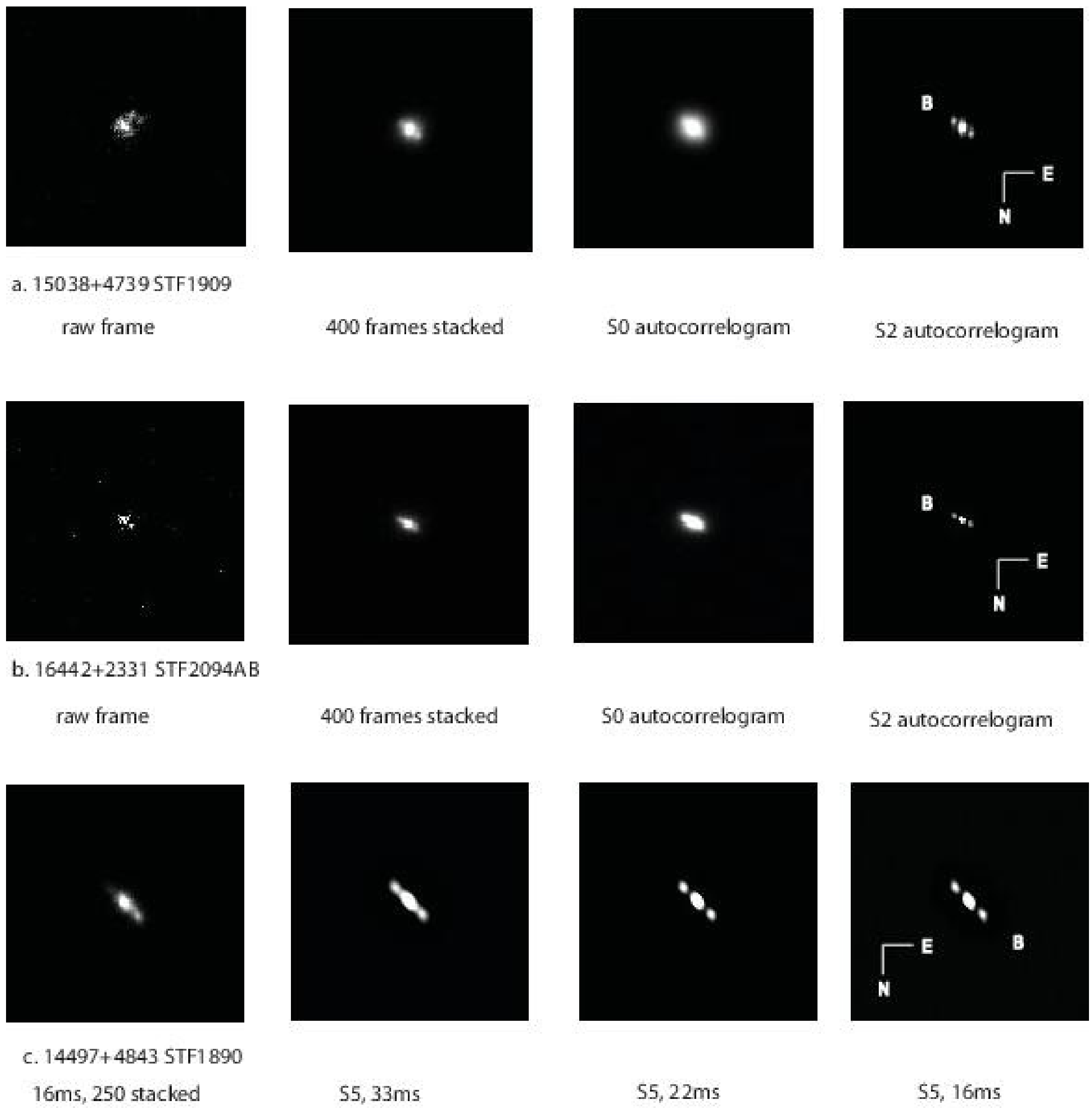

Plate 1. Images of three doubles. The upper two rows (a, b) are examples of two doubles measured in this study. Left to right are: a random raw frame, the entire stack of 400 frames, the unmasked (S0) autocorrelogram and a masked (S2) autocorrelogram. The lower row (c) illustrates the effects of integration time on the quality of the autocorrelogram on a pair not reported; Left to right are: a stack of 250 images of 16ms and S5 autocorrelogram of 250 images at three integration times. Note elongation cause either by miscollimation, lack of critical focus or atmospheric dispersion.

Plates 2-5 (following pages). History of observations of sets of STF and STT pairs as a function of relative motion on the x-axis (right) and y-axis (left) over the history of observations in low resolution. The black circles are previous measures, the solid red dot is the measure reported herein. Blue lines are fitted trend lines. Most are linear, but for orbital pairs STF1909 and STF2052 (Plate 2) lines are 6th-order polynomials and for orbital pairs STT 418 and STT 437.(Plate 5) lines are 2nd-order polynomials. The y-axis scale is in arcseconds. An example in high resolution is shown in Fig. 1.

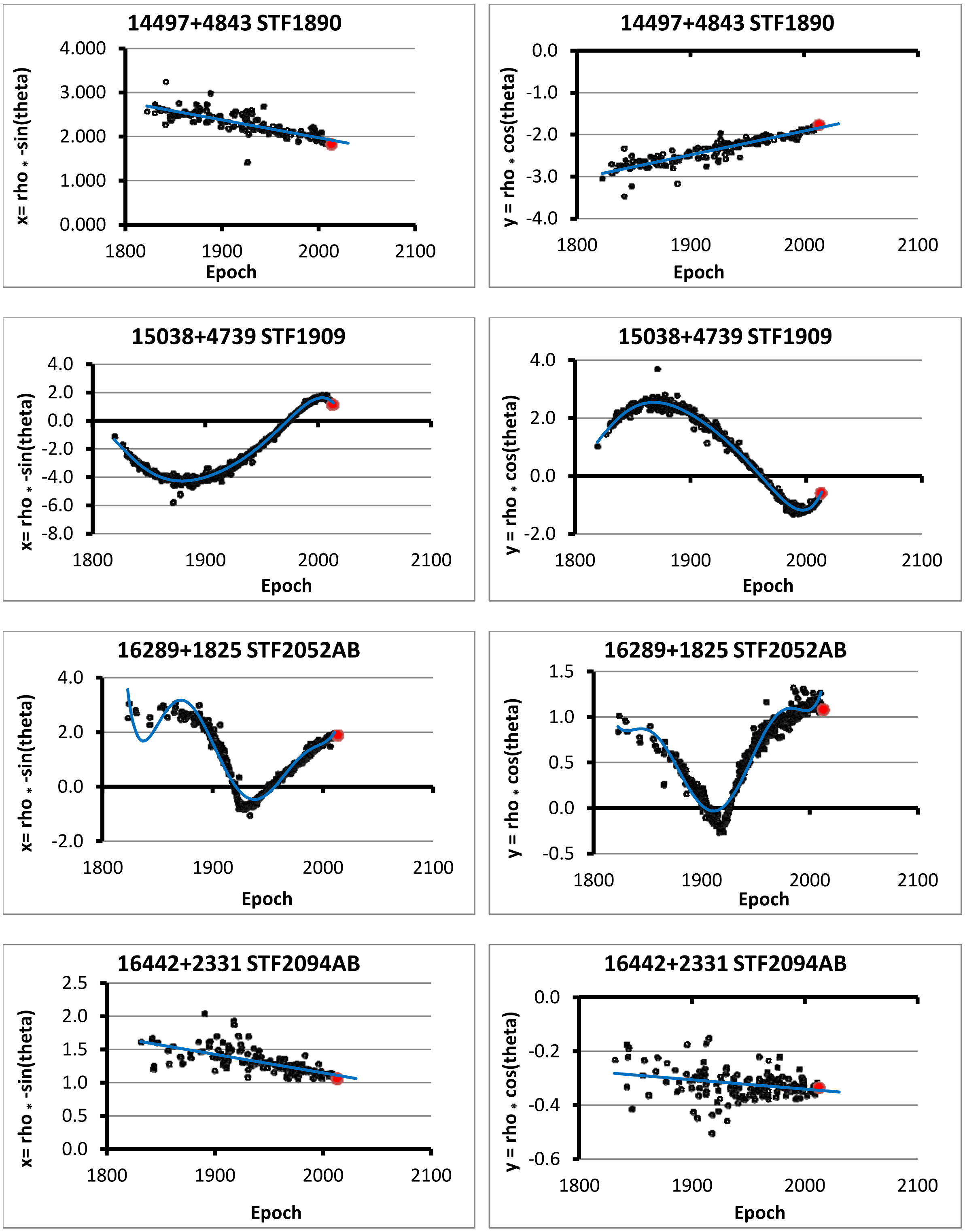
14497+4843 STF1890
x= rho * -sin(theta)
4.000
3.000
2.000
1.000
0.000
1800
1900
2000
2100
Epoch
14497+4843 STF1890
y = rho * cos(theta)
0.0
-1.0
-2.0
-3.0
-4.0
1800
1900
2000
2100
Epoch
15038+4739 STF1909
x= rho * -sin(theta)
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
1800
1900
2000
2100
Epoch
15038+4739 STF1909
y = rho * cos(theta)
4.0
2.0
0.0
-2.0
1800
1900
2000
2100
Epoch
16289+1825 STF2052AB
x= rho * -sin(theta)
4.0
2.0
0.0
-2.0
1800
1900
2000
2100
Epoch
16289+1825 STF2052AB
y = rho * cos(theta)
1.5
1.0
0.5
0.0
-0.5
1800
1900
2000
2100
Epoch
16442+2331 STF2094AB
x= rho * -sin(theta)
2.5
2.0
1.5
1.0
0.5
0.0
1800
1900
2000
2100
Epoch
16442+2331 STF2094AB
y = rho * cos(theta)
0.0
-0.2
-0.4
-0.6
1800
1900
2000
2100
Epoch

Plate 2.

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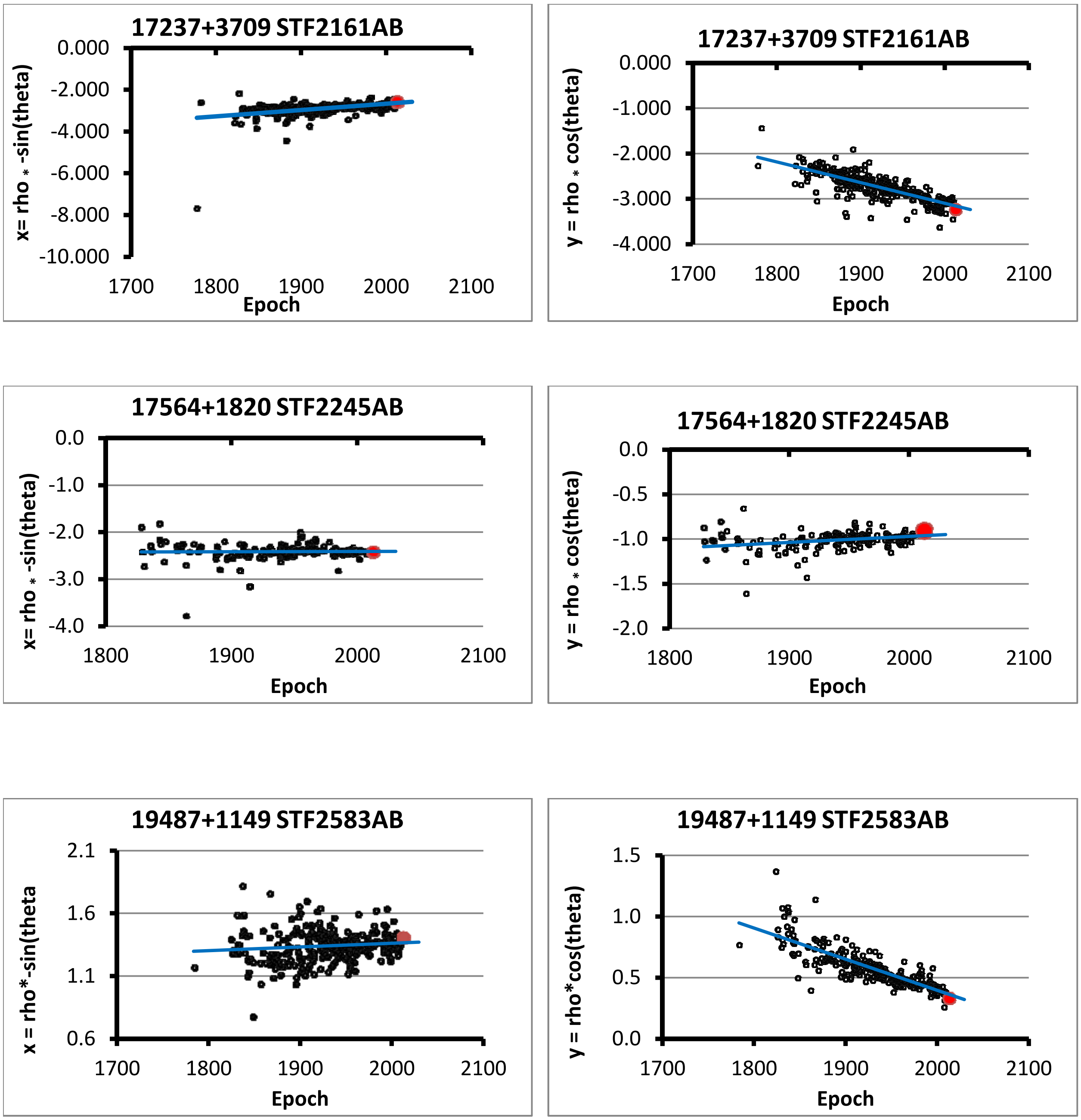
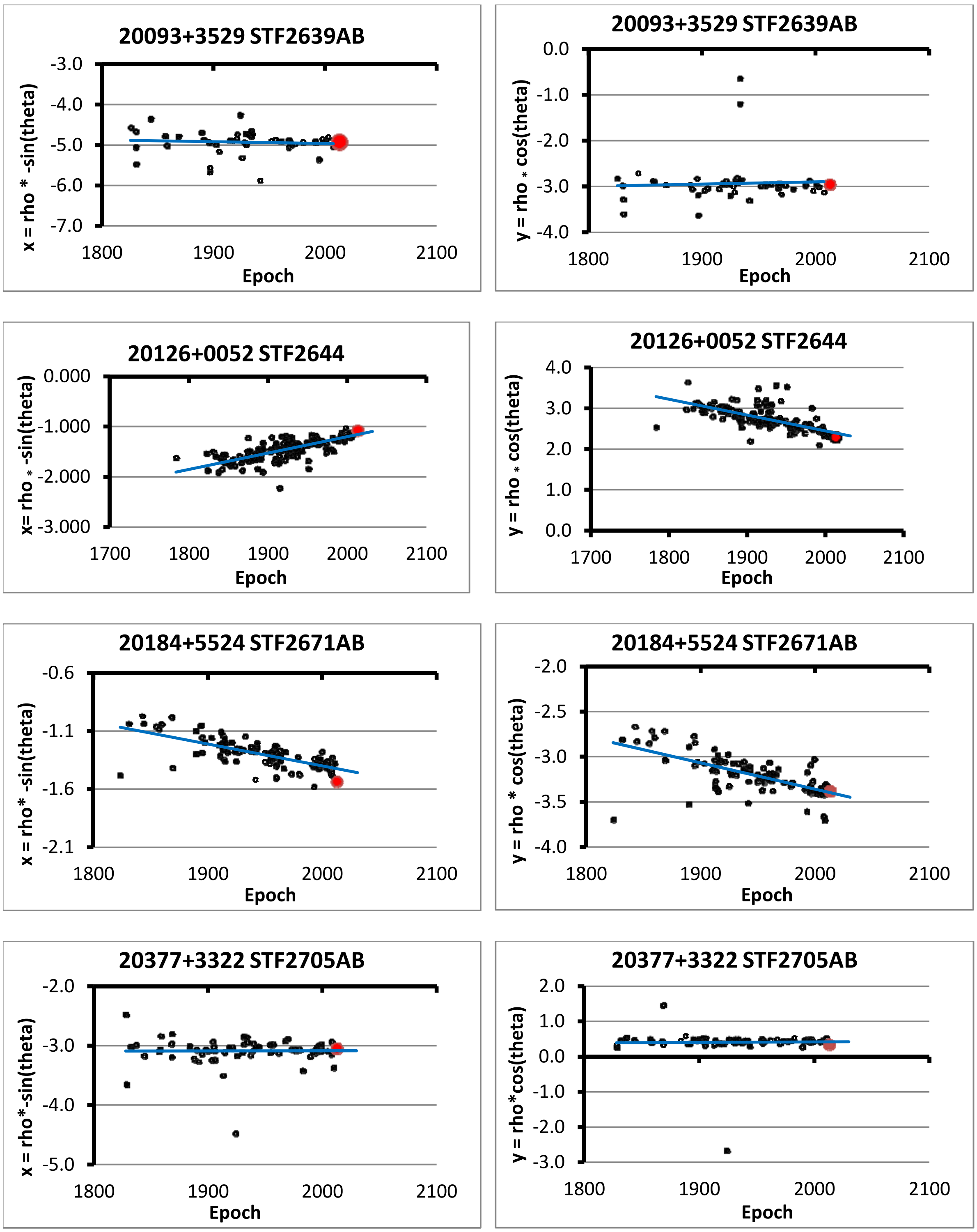


Plate 3.


20093+3529 STF2639AB
x = rho * -sin(theta)
Epoch
20093+3529 STF2639AB
y = rho * cos(theta)
Epoch
20126+0052 STF2644
x= rho * -sin(theta)
Epoch
20126+0052 STF2644
y = rho * cos(theta)
Epoch
20184+5524 STF2671AB
x = rho* -sin(theta)
Epoch
20184+5524 STF2671AB
y = rho * cos(theta)
Epoch
20377+3322 STF2705AB
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Epoch
20377+3322 STF2705AB
y = rho*cos(theta)
Epoch

Plate 4.

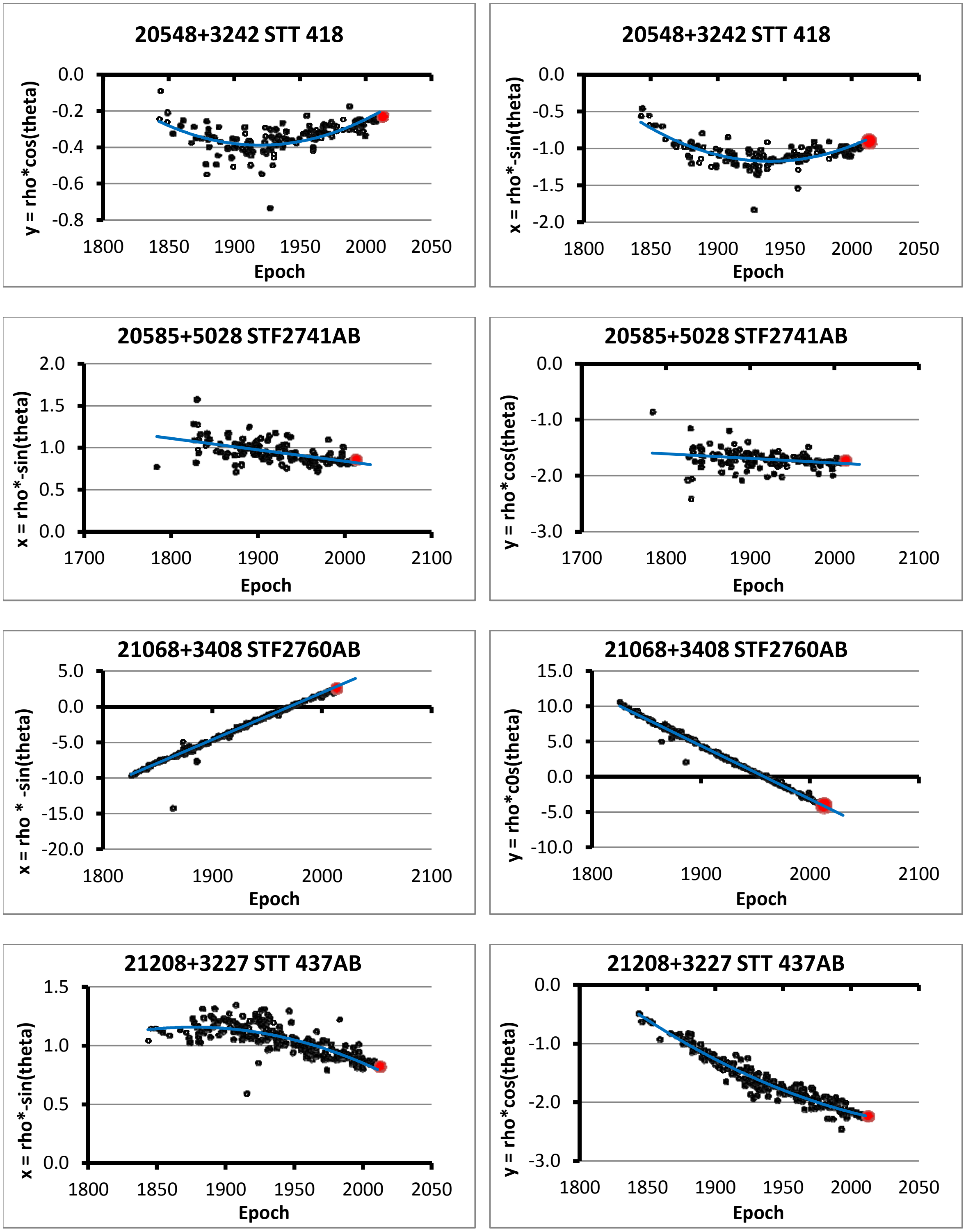
20548+3242 STT 418
y = rho*cos(theta)
Epoch
20548+3242 STT 418
x = rho*-sin(theta)
Epoch
20585+5028 STF2741AB
x = rho*-sin(theta)
Epoch
20585+5028 STF2741AB
y = rho*cos(theta)
Epoch
21068+3408 STF2760AB
x = rho * -sin(theta)
Epoch
21068+3408 STF2760AB
y = rho*c0s(theta)
Epoch
21208+3227 STT 437AB
x = rho*-sin(theta)
Epoch
21208+3227 STT 437AB
y = rho*cos(theta)
Epoch

Plate 5.

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not clear and further work is needed. (5) Use of too small a measuring aperture may fail to produce good centroiding of the autocorrelated images. (6) Darks should be employed to guard against hot pixels. One might think that using the smallest aperture (3x3) would really center the position, but this may not be the case; REDUC may have insufficient information to determine a good centroid. This was determined by trial and error during the project. This challenge puts the limits of my 204mm F/22.5 system at about 1.2" using an aperture of 5x5.

An early series of images of STF1890 (39 Boo) shown in Plate 1 row c demonstrates challenges (1) and (2). I chose not to report the measure of this pair because of the small number of frames (imaging done early in the project) and elongation of the image, probably caused either by a slight problem in collimation or uncritical focus. Additionally, we can see the effects of different integration times. From left to right we see the stacked image of 250 frames and autocorrelograms using the same mask (S5) but with three different exposures. Note that the shorter the integration time, the more distinct the separation.

This study suggests that pixel autocorrelation may be a viable approach to imaging and measuring doubles with smaller aperture telescopes. However, this study is just a first step showing the possibility and limits of the technique. Future work includes assessing repeatability, accuracy and precision over multiple nights and different seeing conditions, the effect of using a Barlow to increase focal length and additional tests of the effect of integration time on autocorrelogram quality.

Finally, because this technique does not require true speckles, it might be applicable to even smaller telescopes than mine. It would be interesting to see results with smaller refractors in the 100-180mm range and 180mm reflectors and I encourage others to try this technique.

Acknowledgements

My thanks to Florent Losse for his many emails commenting on interferometric techniques and my attempts to use autocorrelation to measure doubles and for sharing his version of the Workman Excel spread sheet. Thanks to Russ Genet for stimulating discussion of speckle imaging. Thanks to Francisco Rica for sharing his spreadsheets that efficiently converts theta and rho to the Cartesian system using Excel® macros. To these colleagues and the anonymous reviewer my thanks for comments that resulted in substantiate improvements. Thanks to Dr. Brian Mason for answering requests for data in a timely fashion and for his support of our research community. This paper made extensive use of the Washington Double Star Catalog, the Catalog of Rectilinear Elements and the Sixth Catalog of Orbits of Visual Binary Stars, all maintained by the U. S. Naval Observatory Astrometry Department by Drs. Brian Mason and Bill Hartkopf.

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