Data Mining for Double Stars on VLT Survey Telescope Image Archive

Lucian Curelaru

Brasov Astronomy Club
Brasov, Romania
astroclubul.brasov@gmail.com

Abstract: The article presents a set of methods and tools used to identify and measure double stars on already existing images produced by the ESO VLT Survey Telescope in Paranal Chile. A precision analysis and a first set of measurements are included.

Introduction

Recently the idea of using existing telescope images to extract other data than what the telescope was targeting is having more and more success. This approach can be quite laborious sometimes, but also is encouraged by the fact that telescope time on big instruments has a big cost. I was involved in the last several years in different data-mining projects connected with asteroids, being part of the EURONEAR team [1] which has a lot of projects based on data mining. Starting from their ideas and having some previous experience in double star astronomy, I decided to apply this approach to the double star field as well. Using some already build scripts which I've adapted, I managed to start my first data mining project for neglected double stars. I think the idea can be a very succesful one on double star field maybe even much more than in asteroid field for many reasons. One, for measuring a double star even single isolated pictures are useful, but for asteroids you need in general three successive pictures from same sky region and same period of time. The second reason is that double stars are quite fixed, while for asteroids you need to have both the correct region of sky and the right timing to catch an object in the field by chance, as data mining projects tries to do. In addition, for double stars, the same field imaged multiple times at considerable time difference can generate multiple measurements, and also the historical data measurements can be extremely useful in some cases.

The Telescope and the Camera

I decided to use for this first project images taken with OmegaCAM from ESO VLT Survey Telescope [5]. I had already worked in the past with images from this telescope to recover some asteroids, so I had everything I needed. The instrument is really outstanding: a modified Ritchey-Chretien with a 2.61 meter primary mirror with active optics located at Cerro Paranal site at 2635m altitude, and a 256 Megapixel camera containing a 32 CCD mosaic covering one square degree of sky. The camera has also 4 supplemental CCDs used exclusively for autoguiding and field rotation corrections. The image is optically corrected and does not require any additional software corrections in order to provide very good astrometry, even near the edge of the field. With a resolution of 0.21 arcsec / pixel, the images are taken mostly in excellent sky conditions. Moreover, the telescope also provides data from the southern sky, which contains more unanalysed targets in double stars field than the northern hemisphere.

The Method

The idea of this project is to identify images, already produced in the past by a telescope, which might contain double stars and measure these found objects. Of course I addressed only images that are publicly available for research projects, but a lot of telescopes offer their images archives for free for such purposes. In most cases, there are some limitations only for new images, in general newer than six months to one year, depending by each observatory policy. At this time there are available probably millions of such images from hundreds of telescopes around the world.

It is clear than a lot of unmeasured double stars can be found on this huge amount of data, so I decided to try to focus on objects that lack measurements; and the primary search was targeted mainly on neglected double stars. On the other hand, even if I targeted first the images containing neglected stars, I decided to measure all doubles down to an established separation available on a selected image, because measuring more stars on an already downloaded image add only a little amount of supplemental effort and provides some extra measurements, even if not only on neglected objects. I might have occasionally skipped some doubles that already have a huge amount of measurements or some very close doubles. Even so, the amount of data is huge, so I decided to begin by analyzing images from a single instrument. I chose to start with the VLT Survey Telescope, which I already was familiar with. I also limited the first search to neglected objects with separation equal to or bigger than 3 arcseconds. I set this limit for the first set of analyzed neglected objects , but I'm quite sure that the limit can be easily lowered at least on OmegaCAM images which provide excellent quality.

For this purpose I needed first to search somehow automatically the neglected doubles on each OmegaCAM image archive. To do this I built a small java application which checks a list of WDS objects (in my case only 3 arcsec or higher separated neglected doubles) versus the list of freely available images from the targeted telescope archive. Here I used an already prepared image list from EURONEAR. At EURONEAR MegaArchieve[3] project, we have some crawlers which extract from different telescopes web-pages lists of available images containing basically the center of the field, names of images, and some other useful data. EURONEAR has an impressive collection of such references in the same unified format (text file with some position rules). I took the OmegaCAM reference file from this EURONEAR collection, wrote a small code to load the file data and, using the java app I've mentioned before, I produced a list OmegaCAM images which contains neglected doubles. Then for a part of the found images, I visited the ESO archive[4], downloaded the appropriate image, and started the measurement process. In addition, using another tool developed by me some years ago , named WDSFilter[8], I checked what other double stars different than the targeted one are contained in each downloaded image field, listing all doubles half a degree around the center of each image.

Having the images and the list of expected objects for each, I proceeded in the following way: I reduced the images with Astrometrica software[6] and measured the precise position of each targeted object component. These coordinates I inserted in a Google spreadsheet I built for a previous double star project described in a past JDSO article[9]. This spreadsheet parses the Astrometrica report output and computes the separation and position angle from the determined precise coordinates. In Astrometrica I've used the UCAC4 catalog[10] for field matching and sometimes the NOMAD catalog[11] when UCAC4 was not detailed enough (mostly on the fields close to south pole)

The OmegaCAM images came as FITS.FZ files containing 32 images each, one for each CCD of the instrument. To be able to work with them in Astrometrica, I used the Aladin software[7] to export FITS containing just one image each from the initial file (Astrometrica software is not able to work with FITS.FZ format).

I measured only a part of the candidates found by my java app stopping when I reached the limit of one hundred objects, but I intend to continue and present the next measurements in future articles. I intend to also reduce images from other instruments after the candidates from this instrument are finished. As I've mentioned before, there are hundreds of image sets available which might produce double stars measurements with this approach.

Even thought, I did not present in detail some of the tools which I built and used for this process, I am open to shareing them freely if anybody is interested in some similar research.

The Precision

Even though it seems quite obvious that the quality of images and resolution produced by the VLT Survey Telescope should provide excellent astrometry on close doubles, I wanted to also have a quantitative evaluation for the quality of my measurements. So I started the project with a set of test measurements and analyzed the results versus the already existing measurements. My first approach was to look for objects with a computed orbit of separation around 3 arcseconds range (±1 arcsecond), but unfortunately I was unable to find any OmegaCAM image containing such an object, at least in the archive analyzed in January 2016. So the next option was to try to measure some objects from images taken in the same year with other already published measurements. In addition, I tried to choose objects with as low movement as possible (deduced from the existing measurements). It is clear that this method is not as good as the first one because it is based on more presumptions like the precision of the comparing measurements, because that the comparing data is not produced by an orbital computation which is most pre-

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Table 1: Comparison Between my Measurements and WDS Values

Measured PA	Measured Sep	WDS PA	WDS Sep	PA O-C	Sep O-C
35.28538348	3.038154645	35.3	2.99	0.01	0.05
83.9355074	11.35849075	84.2	11.38	0.26	0.02
52.70710493	23.1725325	52.8	23.40	0.09	0.23
43.58756383	27.54301679	43.8	27.85	0.21	0.31
291.2291559	2.844526324	291.5	2.83	0.27	0.01
291.1967401	2.959303839	292.0	2.96	0.80	0.00
89.27862978	2.382852467	90.0	2.39	0.72	0.01

cise, and so on. But I considered that analyzing multiple objects in this manner could prove that the measurements produced by this method and from that source of images are in the accepted error range. I present the list of the measurements in Table 1.

For a better overview of the results, I also built two graphs presenting the PA differences (Figure 1) and separation differences (Figure 2)

As it can be seen in the presented data and graphs, the differences between my measurements and other measurements made in the same year for seven objects stays under one degree on PA and under 2% from the separation of measured star. I wasn't able to find a fully agreed criteria for maximum acceptable error in the double stars literature I've checked (the values varying from case to case), but in all criteria I saw the limit for PA is not smaller than one degree and the percent of accepted error on separation for close doubles can vary between a few to even ten percent. So I've concluded that the obtained values are good proof that the measurements have a good quality.

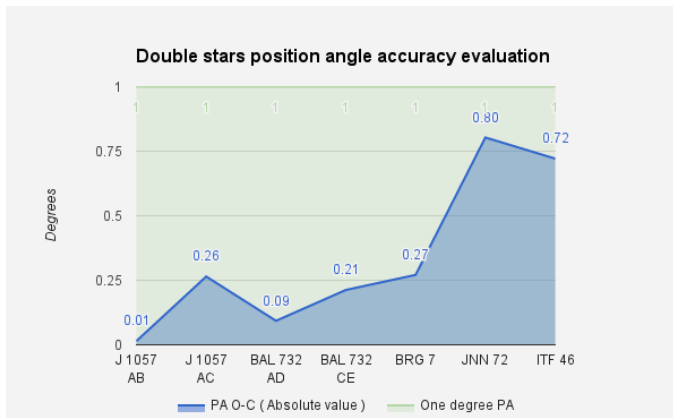

Figure 1: Position Angle differences for seven selected comparation objects

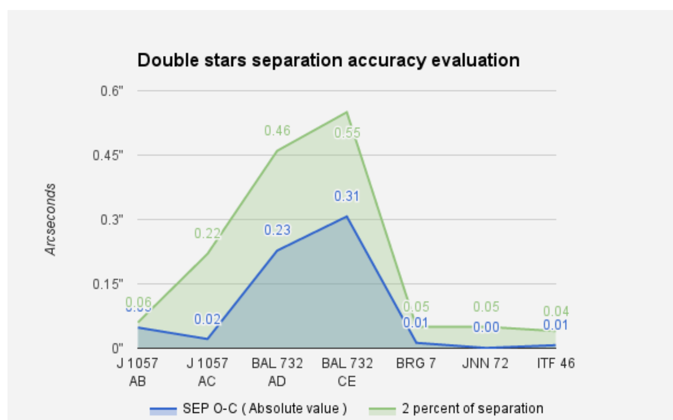

Figure 2: Separation differences for seven selected comparation objects

The Measurements

In the next tables I present the obtained measurements. All the magnitudes presented are taken from the WDS and not measured on images.

Even if I was targeting neglected doubles down to 3 arcsec separation, there were a few cases where I also found in the analyzed images not-targeted neglected doubles with a little smaller separation. Due to the good accuracy test results, I decided to also measure these objects down to 1.5 - 2 arcsec separation, even if not covered by the precision evaluation I presented earlier. I need to mention than the objects under 3 arcseconds separation were very clearly resolved by Astrometrica (Figure 3)

Neglected Measurements:

In Table 2 you will find a list of neglected double

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Table 2: Neglected Double Stars Measured on Analysed OmegaCAM Images

NAME	RA+DEC	MAGS	PA	SEP	DATE	N	NOTES
JSP 423	10430-5951	9.9,10.7	270.5	2.24	2015.084	1	
VOU 88	10434-6005	9.3,12.5	84.1	4.22	2015.084	1	
JSP 430	10458-6005	9.8,11.6	146.9	3.40	2015.084	1	
JSP 429	10453-6001	11.2,10.8	89.6	1.63	2015.084	1	
DAW 6AB	10440-6007	9.2,10.8	118.5	3.10	2012.124	1	
JSP 427	10442-6009	9.8,12.3	356.3	2.29	2012.124	1	1
DAW 8AC	10444-6000	8.1,13.5	92.5	8.40	2012.124	1	
HJ 4356BD	10440-5933	9.0,9.1	188.8	3.97	2013.301	1	
RUZ 2	12066-3137	16.8,19.4	6.4	5.52	2015.068	1	2
COO 70AB	08169-3452	10.8,11.0	137.8	2.25	2015.048	1	
RST5290	08171-3430	8.8,13.9	56.4	3.94	2015.048	1	
TDS6434	09161-4555	11.7,16.7	148.2	4.61	2015.026	1	3
RST5533	14204-3002	10.0,14.4	344.5	4.38	2015.024	1	4
B 268	14118-2954	11.6,13.0	84.9	2.35	2015.024	1	
BRT2673	07312-1215	10.4,12.3	111.5	55.51	2015.001	1	5
SLW 195	07305-1247	19.4,19.6	269.3	178.00	2015.001	1	
TDS4861	07296-1222	11.9,14.3	11.7	117.17	2015.001	1	6
RST3518	07284-1257	9.6,15.3	90.0	2.35	2015.001	1	
J 1049	06058+1652	12.3,12.4	118.3	3.02	2014.960	1	
TDS7204	10208-5408	12.5,14.6	80.9	6.73	2014.951	1	7
HJ1096	01550+1537	10.9,13.2	161.3	33.33	2014.799	1	8
TDS5111	07430-2337	12.2,14.0	256.5	1.67	2014.786	1	
TDS5158	07448-2250	12.3,16.1	190.6	5.34	2014.786	1	9
B144	07457-2331	10.5,14.2	179.3	3.54	2014.786	1	
RST4132	23460-1508	10.0,13.9	93.7	3.57	2014.752	1	

NOTES

1. Precise coordinates not available in WDS. From this measurement precise coordinates of the primary star are: 10 44 15.863 -60 09 04.33
2. There seems to be a small position difference of about 5 arcseconds.
3. Secondary magnitude is much fainter than WDS by about four magnitudes.
4. Very big movement in PA, but precise position fits, separation and magnitudes match very well. On the other hand, there are more than 60 years from last and only measurement. It might be also some quadrant identification mistake in the initial measurement.
5. There is a matching secondary by magnitude, but it is at 55 arcseconds distance. I presume there is a typo at the decimal separator of the separation. The PA is not exact, but is in a plausible range for more than one century of movement.
6. Primary star at precise coordinates, but secondary not found at expected position or neighborhood. Still a pretty good match could be a star which is not at two arcseconds, but at two arcminutes, having an appropriate PA and magnitude. Maybe the existing old measurement was incorrectly entered with arcseconds instead of arcminutes.
7. Quite big difference on PA and separation, but not impossible for 25 years period. Main star fits the catalog precise position. No other component in the close neighborhood, so the identification is probably correct. Maybe the initial measurement has low precision because the values are strangely rounded.
8. The objects do not have precise coordinates, but having a large imaged field around the star. I've studied the neighborhood as well and looked around with Aladin. The only nearly matching candidate is this one. The PA is plausible, but the difference in separation is quite big. The magnitudes are close. So In my opinion this could be the object in discussion, but the separation difference have to be explained or the object should be considered lost
9. Primary star at precise position. Most close match for secondary is the measured one but there are some big differences in PA and separation . Also the magnitude difference is big. Still no other candidate found in the field.

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Table 3: Two Potential Variants for the Secondary Component of SIN 56 AC

NAME	RA+DEC	MAGS	PA	SEP	DATE	N
SIN 56AC	10440-6005	8.6, 16.1	308.9	19.76	2012.124	1
SIN 56AC	10440-6005	8.6, 11.6	292.3	23.63	2012.124	1

(Continued from page 209)

stars measured with the presented methods.

Neglected with More Secondary Candidates

The object presented in Table 3 has two candidates for the secondary component and I was not able to determine which is the correct one, so I preferred to mention both objects. Maybe someone will be able to clarify this issue.

In both cases the stars are close enough to the expected position to explain the movement in 29 years. Unfortunately there is only one other observation in the past so the movement speed and direction are unknown.

Other Double Stars Measurements

In Table 4 you will find a list of double stars measured with the presented methods. This stars were not mainly targeted but they was on the same FITS with one of the targeted objects, so it could be measured with a minimal supplemental effort. A big part of them was also not measured for a considerable timeframe (more than 15 years), so the measurement is pretty useful even they do not exceeded the 20-years neglected condition.

Statistics

Coming back to neglected searchs in the OmegaCAM data, I want to also specify some numbers which might be interesting. The January 2016 OmegaCAM available images list from EURONEAR had 119,219 images. After the search, I found that there are 8,113 images that contain at least one neglected double with separation bigger than 3 arcseconds. Of course there are a lot of duplicates in that attempt because there are pictures taken at a different time which cover at least partially areas of sky already imaged in another observing session. After removing duplicates, I found that 423 different neglected doubles can be found in OmegaCAM images. For this article I've measured doubles only from 25 images obtaining measurements or information for 33 neglected (7 of them missing ones) and 67 other doubles.

More details: from the 67 other doubles found, I found that 52 had their last measurement within the 15 to 20 year range, so they are potential neglected candidates. I found none in 10 to 15 years range and 15 in the 0 to 10 years range. For the precision analysis, I used 4 other different images from which I've collected the 7 comparison objects. I have to mention that I also

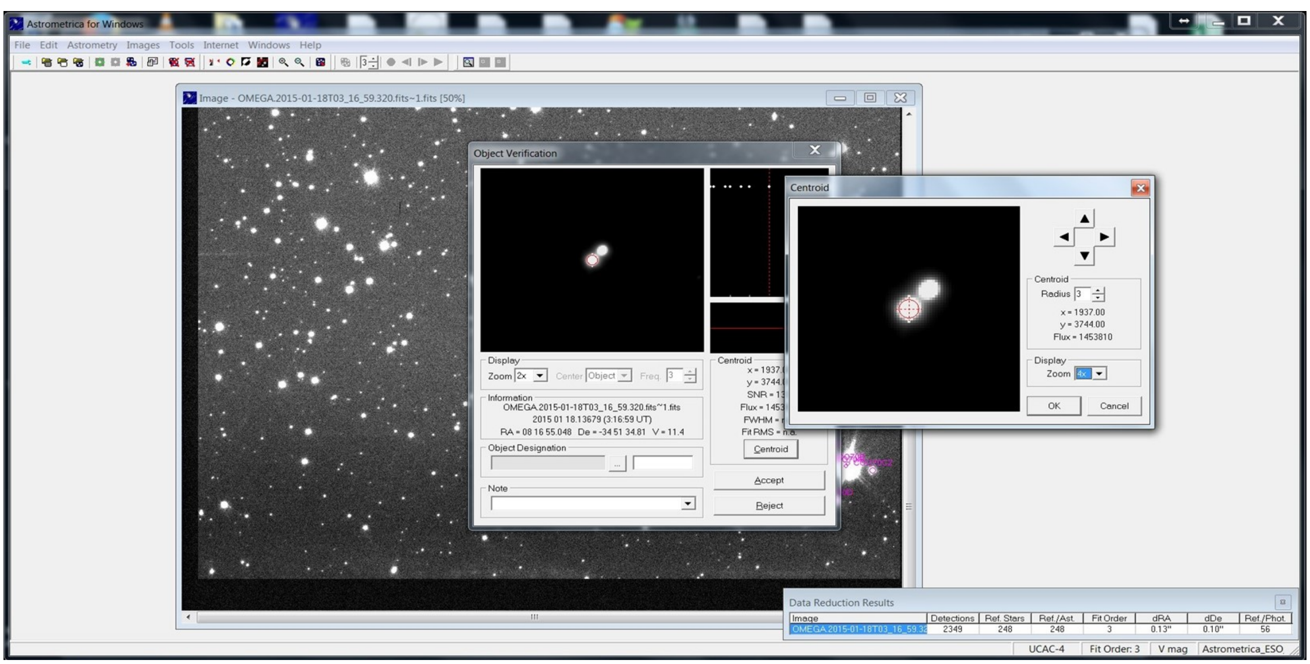

Figure 3: Measuring a close double star (COO 70 AB) on an OmegaCam image using Astrometrica. COO 70 AB is a 2.25 separated double with almost equal 9 magnitude components.

Table 4: Other Double Stars Found in Analysed OmegaCAM Images

Name	RA+DEC	Mags	PA	Sep	Date	N	Notes
BRT1993	12123-6444	11.3,10.1	151.9	2.61	2014.270	1	
HJ 4350	10432-5944	9.1,10.4	149.8	10.94	2015.084	1	
HJ 4354	10438-6005	9.6,10.4	214.9	10.09	2015.084	1	
HJ 4355	10438-5957	10.0,10.1	78.6	14.99	2015.084	1	
HJ 4353	10437-5935	11.0,10.5	181.1	4.96	2015.084	1	1
COO 112AB	10439-5933	9.8,10.1	240.4	6.46	2015.084	1	
SEE 123	10440-5932	10.4,11.1	307.0	3.90	2015.084	1	
HJ 4348AB	10421-5958	9.7,11.1	347.9	3.48	2015.084	1	
SEE 122AC	10421-5958	9.7,10.7	255.7	12.75	2015.084	1	
JSP 422AB	10428-6012	9.9,10.2	193.1	5.24	2015.084	1	
JSP 422AC	10428-6012	9.9,10.5	98.9	5.61	2015.084	1	
JSP 422AD	10428-6012	9.9,10.6	128.0	9.42	2015.084	1	
COO 113	10453-5945	10.0,9.9	195.1	14.63	2015.084	1	
DAW 7	10442-6008	10.4,10.6	359.4	3.83	2015.084	1	
HJ 4358AB	10440-6005	8.6,9.6	235.7	6.36	2012.124	1	
SIN 56AD	10440-6005	8.6,9.1	227.4	27.20	2012.124	1	
HJ 4359AC	10440-6007	9.2,9.7	195.5	7.98	2012.124	1	
DAW 8AB	10444-6000	8.1,10.6	276.8	7.03	2012.124	1	
HJ 4356AB	10440-5933	8.3,9.0	149.6	2.94	2013.301	1	
HJ 4356AC	10440-5933	8.3,10.7	268.8	4.86	2013.301	1	
SNA 12AF	10440-5933	8.3,12.5	8.1	3.67	2013.301	1	
SNA 12AG	10440-5933	8.3,12.3	337.3	5.05	2013.301	1	
J 2818	07267-1118	12.1,14.0	226.3	7.34	2015.078	1	
HJ 759AC	07273-1130	9.3,11.2	331.5	10.11	2015.078	1	
J 2476AB	07275-1145	11.4,11.8	304.2	5.36	2015.078	1	
J 2476AC	07275-1145	11.4,13.0	196.2	20.70	2015.078	1	
STF1097AC	07279-1133	7.6,9.6	312.8	19.91	2015.078	1	
BU 332AD	07279-1133	7.6,11.7	157.0	23.03	2015.078	1	
BU 332AE	07279-1133	7.6,13.2	43.3	32.32	2015.078	1	
BRT2672	07293-1128	13.1,12.8	39.8	4.59	2015.078	1	
BRT3198	07297-1125	11.4,12.0	5.9	3.55	2015.078	1	
LDS 407	12226-3103	13.0,12.1	38.9	9.86	2015.068	1	
SEE 152	12254-3108	9.8,12.0	84.8	2.54	2015.068	1	
RSS 281	12046-3111	8.5,13.5	160.3	8.57	2015.068	1	
HJ 4472	11464-2909	10.2,11.0	30.6	19.33	2015.067	1	

Table 4 concludes on next page.

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Table 4 (conclusion): Other Double Stars Found in Analysed OmegaCAM Images

Name	RA+DEC	Mags	PA	Sep	Date	N	Notes
HJ 4472	11464-2909	10.2,11.0	30.6	19.33	2015.067	1	
BRT1620	08198-3456	11.1,11.3	298.4	3.62	2015.048	1	
WFC 65	08171-3447	10.6,12.3	175.5	11.77	2015.048	1	
DAM 21AB_C	08169-3452	10.8,14.2	76.9	16.25	2015.048	1	
I 9009AB_D	08169-3452	10.8,13.4	343.9	24.59	2015.048	1	
DAM 21AB_F	08169-3452	10.8,13.3	225.1	28.32	2015.048	1	
DAM 21AB_E	08169-3452	10.8,15.8	238.9	17.84	2015.048	1	
DAM 21FG	08169-3452	13.3,15.6	0.0	3.45	2015.048	1	
HDS1184	08200-3425	9.2,10.7	79.4	25.04	2015.048	1	
SEE 202AB-C	14129-3000	9.9,13.4	136.2	30.57	2015.024	1	
XMI 63	07317-1300	10.3,10.5	340.6	18.39	2015.001	1	
J 2479	07310-1226	12.7,13.4	274.2	5.93	2015.001	1	
J 2480AC	07311-1227	10.9,13.1	315.8	5.78	2015.001	1	
J 2480AB	07311-1227	10.9,12.7	238.0	7.70	2015.001	1	
LDS 185	07288-1303	13.8,14.3	293.0	12.06	2015.001	1	
LDS 183	07285-1235	12.3,14.0	237.7	24.50	2015.001	1	
J 1260	06082+1653	12.0,14.0	286.4	4.58	2014.966	1	
GWP 756	06093+1636	15.0,16.3	290.3	52.02	2014.966	1	
GWP 742	06057+1657	11.9,17.6	333.8	59.22	2014.966	1	
FIN 406	10198-5430	11.4,10.7	136.5	3.53	2014.951	1	
HDS1490	10213-5404	9.2,10.0	96.8	20.62	2014.951	1	
CVR 403	01559+1559	17.1,17.3	287.6	8.38	2014.799	1	
CBL 11	01579+1614	16.1,15.8	90.6	12.16	2014.799	1	
DAM 996	01583+1550	11.0,15.1	44.9	7.32	2014.799	1	
DAM 998	01588+1551	12.7,15.2	244.3	3.44	2014.799	1	
B 143	07446-2328	10.1,13.6	139.2	5.84	2014.786	1	
ARA2070	07448-2332	12.7,12.5	145.6	12.94	2014.786	1	
DON1067	07451-2312	9.1,12.0	23.4	8.93	2014.786	1	
B 2151	07458-2336	10.0,13.4	33.1	5.85	2014.786	1	
ARA2072	07460-2338	10.4,12.9	79.0	10.56	2014.786	1	
ARA1708	07461-2255	12.7,13.2	25.0	8.67	2014.786	1	
FOX 277	23433-1505	11.4,11.5	228.9	5.28	2014.752	1	
LDS6059	23456-1412	18.0,17.3	148.3	113.12	2014.752	1	

Notes:

1. The secondary component is a little elliptic. It looks very alike with a close binary with a PA around 20 and probably a separation under one arcsecond. Unfortunatelly the components can not be distinguished more to perform an appropriate measurement.

used a few other images for different initial tests, and also there were images on which the targeted objects were too close to margin or into CCD gaps, but were recovered from other images which contained the searched object. This increased the number of images used from the archives from 25 to 37.

I've only analyzed a small fraction (5.83%) of the images. Considering that this analyzed part could be statistically relevant, I estimate that from the whole list of 423 selected OmegaCAM images I could extract about 1700 measurements of double stars with separation over the 2 - 3 arcsecond limit, from which around 567 are neglected doubles Of course the number will probably grow considerably if we lower the separation limit. Also, knowing that there are many image collections such as OmegaCAM only in EURONEAR MegaArchive[3], and probably hundreds of collections in the whole world, the idea of data mining becomes very attractive and offers a huge amount of data which waits to be processed.

Conclusions

Measuring double stars on archive images from big telescopes can be a very efficient way of getting good precision measurements for a lot of doubles. As shown, the precision seems to be very good on 3 arcseconds separated stars. Besides the quantitative evaluation, the appearance of the 2 - 3 arcsec doubles in the images (Figure 3), show that in most cases close doubles are clearly separated and the position can be precisely determined with Astrometrica, suggesting that good precision can be obtained on much closer doubles as well. This encourages me to continue this project in the future in more directions. Firstly I intend to measure the already identified neglected from OmegaCAM images. In this paper I've only analyzed the first 100 objects found on 25 images, but a total of 423 images that contains at least one neglected star, and probably other doubles, was identified, and this leaves a lot of work to do. A second approach is to repeat in the future the search under the 3 arcsec limit used here. Of course this needs also a new precision analysis to be done for closer separations. For sure, the next step is to extend the search to other image collections.

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This research has made use of the Washington Double Star catalog maintained at the U.S. Naval Observatory [2].

Data reduction was carried out using the Astrometrica software developed and maintained by Herbert Raab[6].

This research has also made use of "Aladin Sky Atlas" developed at CDS, Strasbourg Observatory, France (http://cdsads.u-strasbg.fr/cgi-bin/nph-bib_query?2000A%26AS..143...33B&db_key=AST&nosetcookie=1 and http://cdsads.u-strasbg.fr/cgi-bin/nph-bib_query?2014ASPC..485..277B&db_key=AST&nosetcookie=1) [7]

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