The Human Element: Why Robotic Telescope Networks are not always Better, and Performing Backyard Research

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Abstract: In some cases, backyard astronomy with amateur-grade telescopes, mounts, and cameras can yield results on par, or even better, than research-grade robotic telescopes. The "human element" gives more control over variables such as gain, dark frames, camera cooling, and tracking. Furthermore, being able to adjust variables on-the-fly allows a much greater control of an otherwise limited setup. For purposes of comparison, I took exposures of the same double star with my telescope and robotic telescopes and compared the results. In the field, I found three additional WDS catalogue doubles, two of which I measured in addition to the original target. Also, I discovered a dim, approximately 1.3" separation new potential binary, which I was unable to measure but which warrants further study. After comparing the measurements between my 4-inch telescope and the 0.4 meter robotic telescopes, I concluded that my setup performed similarly despite having only one fourth the aperture.

Introduction

To perform research without access to major telescopes that are actively monitored by humans, researchers depend upon robotic telescopes to receive images. Such networks include Skynet and the Las Cumbres Observatory Network. The convenience of these robotic networks is due to their automation and ability to operate without a person, yet this also can lead to some issues. There is no "quality check", meaning images might be returned that are out of focus, misaligned, or have misshapen stars. Also, the exposure time cannot be dynamically checked. Because of this, excessive amounts of telescope time might be used by researchers submitting multiple exposures with 5s, 10s, 20s, and 30s exposure times.

One night, having recently acquired a telescope, mount, and camera designed for astrophotography, I was trying to take a picture of a Messier 103, an open star cluster in Cassiopeia. My mount did not "goto" properly, and when I took the image, it was only a random starfield. I was disappointed until I noticed a double star in the image. I measured its separation to be 6.49 arcseconds, and then looked up its coordinates in the Washington Double Star Catalog and on the Second Data Release of the European Space Agency's Gaia Collaboration. It turned out to be WDS 01210+5920 STI 1576, and my measurement agreed well with the Position Angle (PA) and separation (sep) listed in the WDS. Figure 1 shows this "fortuitous discovery", as I call it, that shows the possibility for research with backyard telescopes.

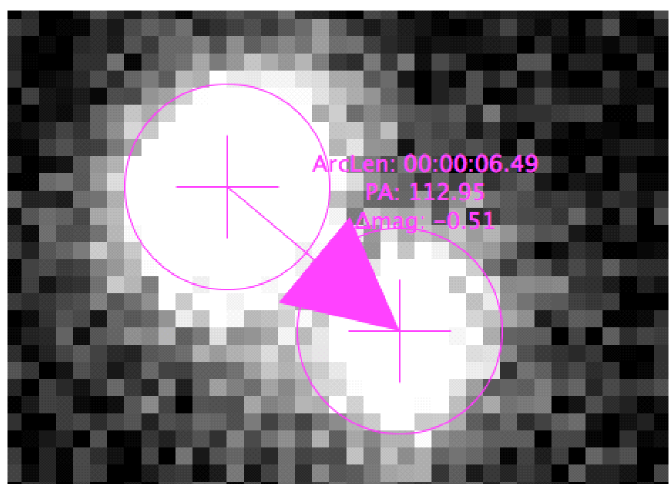

Figure 1. *Fortuitous discovery of WDS 01210+5920 STI 1576.*

Amateur telescopes can make significant contributions to research, as with the recent discovery of a 2.6-km Kuiper belt object (too dim for Hubble to image directly) by stellar occultation using an amateur telescope in Japan (Arimatsu, 2019). In this paper, I explore the prospect of performing research with my personal backyard setup. I selected a star by going to Stelledoppie and filtering the stars that are in Cassiopeia and have a separation of less than 6 arcseconds. I chose Cassiopeia because it was near zenith around midnight for my Texas location during late fall, and 6 arcseconds as the separation because I wanted to test the limits of my setup. I chose to image WDS 00057+4549 STT 547AB, taking images from my telescope, the Skynet Robotic Observatory Network (Skynet), and the Las Cumbres Observatory Network (LCO).

Double Stars

Double stars are important because some of them are binary, and measuring the separation and position angle allows researchers to calculate the orbits of those that are gravitationally bound. That allows a range of other values to be derived which can either provide new information or check other methods. Moreover, double stars are accessible and a good entry point into backyard research. However, oftentimes double stars are separated by only a few arcseconds, which makes measuring them very difficult. For telescopes, the phrase "bigger is better" usually applies, but there are many factors that influence the quality of an image that are not related to telescope size. These include mount tracking, camera noise, and seeing. With such tight tolerances, sometimes the "human element" is needed for quality-control and to apply changes on-the-spot.

Setup

My telescope is an Explore Scientific ED102 Apochromatic Refractor Essential Series, which has FCD1 series glass. The aperture is 102mm, and the focal ratio is $f/7$, giving the focal length to be 714mm. Refractors are well-known for having chromatic aberration, a type of optical aberration that results from different wavelengths of light refracting at different angles and therefore coming to focus at different focal lengths. However, the ED102 is a triplet lens, hence the "apochromatic" designation. The triplet lens system works to focus three wavelengths of light at the same focal point, unlike most normal refractors of today, which only focus two wavelengths (as most today are achromats, a doublet lens). The triplet lens reduces the chromatic aberration significantly to the point where it can barely be observed. Although my telescope has the slightest bit of chromatic aberration on the brightest stars such as Vega, it is very minimal and does not affect research.

My mount is a Skywatcher AZ-EQ5, one of the many variants of Skywatcher's EQ5 design. This mount is a German Equatorial Mount design, so once it is polar aligned, it can track the sky perfectly and long exposures can be taken. Otherwise, the stars will trail, and the images will be unusable. An alt-az mount, in contrast, has field rotation as it tracks the sky, so even if it tracks perfectly, a "de-rotater" is required to rotate the image exactly opposite to the amount the tracking incurs, which adds complexity and cost. Furthermore, a German equatorial mount only needs to rotate one axis to track the sky, and the rotation rate is always constant. No matter where in the sky the mount is pointed, the right ascension axis, as it is called, will track the sky perfectly rotating once every sidereal day. This is in contrast to an alt-az mount where both axes must rotate, and each must rotate at a different speed depending on where in the sky it is pointing. Overall, a German equatorial mount is much simpler, which means good images are easier to acquire.

My camera is a ZWO - ASI 1600mm cool, version 3. Contrary to most astronomical research cameras, it is not a CCD but a CMOS sensor. This type of sensor is what is found in smartphones and most consumer cameras. However, CMOS sensors in astronomical cameras are optimized to have an extremely low read noise, dark current, and almost no amp glow. Essentially, when the camera sees black, the sensor records a value extremely close to black even at long exposures, so that faint stars are able to be captured with a relatively high signal-to-noise ratio (SNR). The sensor is a 22mm diagonal, which means it has a large field of view. This is wonderful for finding targets. Also, unlike normal cameras, it has a Peltier-type cooler. This cooler is able to cool to 40 ^{o}C below ambient temperature, however I run it around 30 ^{o}C to save battery. The use of a cooler is absolutely essential for good images, because for every 7 - 8 ^{o}C of cooling, the noise level is reduced by half (Bracken, 2017). Therefore, the SNR is further increased. Combined with the sensor's already-low read noise, very dim stars can be observed with relatively short exposures. For example, the camera is able to record (although quite faintly) magnitude 14 stars with 30 second exposures in moderate light pollution.

The "optical train" is the accessories that come after the focuser. The optical train on my setup includes a 2x Barlow lens. This effectively doubles the focal length of my telescope, turning my $f/7$ into a $f/14$ telescope. If I had an $f/14$ refractor, I would certainly use it for the high magnification, but I currently do not, so a 2x Barlow lens is used for magnification purposes. The reason why a long focal length is needed is that double stars are very close together, and I need to be able to "split" the components. At $f/14$, my telescope and

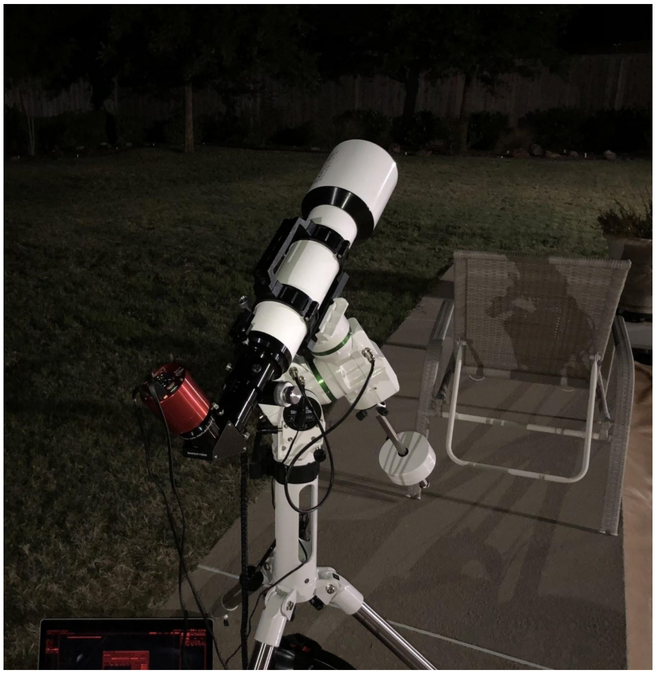

Figure 2. My setup for imaging.

camera combination have a true field of view of 0.71 x 0.54 degrees, with each pixel representing 0.55". The camera, Barlow lens, and telescope were chosen to optimize the pixel scale, specifically to prevent under sampling for my telescope's focal length (Buchheim 2007). Figure 2 shows my setup but without the Barlow lens in the optical train. Note that as of completing this project, several parts have been "polished" and improved. The diagonal has been removed and replaced with extenders, there is an Astronomik L-3 luminance filter located in front of the sensor, the polar alignment scope has been removed, a small counterweight to improve balance has been added directly onto the telescope, a guide scope and guide camera has been mounted to the top, and a regulated AC/DC power converter has replaced the battery.

Advantages of My Setup Relative to Robotic Telescopes

There are several advantages to using a backyard approach to gathering data. In conducting prior research using robotic telescopes, I had to wait for the images to come back. For LCO, this time was usually minimal, but for Skynet there sometimes were significant delays. Oftentimes I would request an image to be taken that night, but it would not come back for a week or two. When I use my own telescope, however, I have control over when my images will be taken.

Figure 3 shows the image I obtained of the target pair STT 547AB displayed in AstroImageJ, an astronomical image processing software (Collins, 2017). There is a slight asymmetry to the stars, but the bright region is significantly rounder than the stars' halos, meaning centroid measurements are not affected.

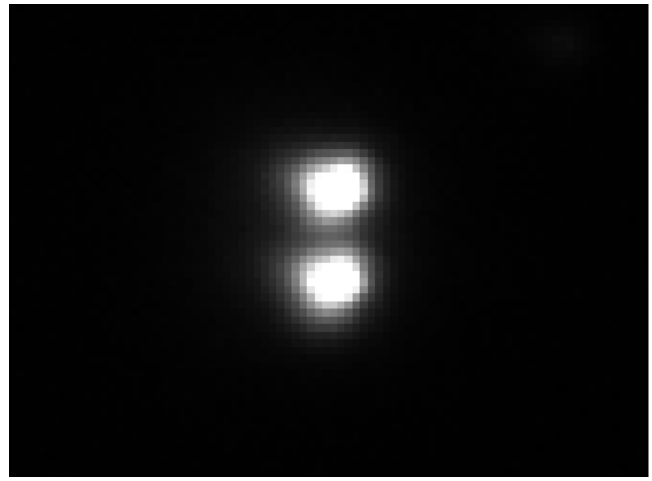

Figure 3: My best image of STT 547AB.

For comparison purposes, I took pictures of this starfield using Skynet on two telescopes, DSO-17 in North Carolina and AURT in Alberta, Canada. In both cases, the returned images were unusable. From AURT, the mount did not track properly, which resulted in the streaks shown in Figure 4.

For DSO-17, the mount did not track perfectly, and the stars were too bloated to perform accurate centroid measurements. This effect might occur if the target was low in the sky, but Skynet only takes images if the target is above thirty degrees. When DSO-17 imaged the double star (4 AM on October 30, 2018), it was 70 degrees above the horizon. It is possible that the atmosphere may have been unstable on the night the image was taken, but such conditions of bad seeing would not

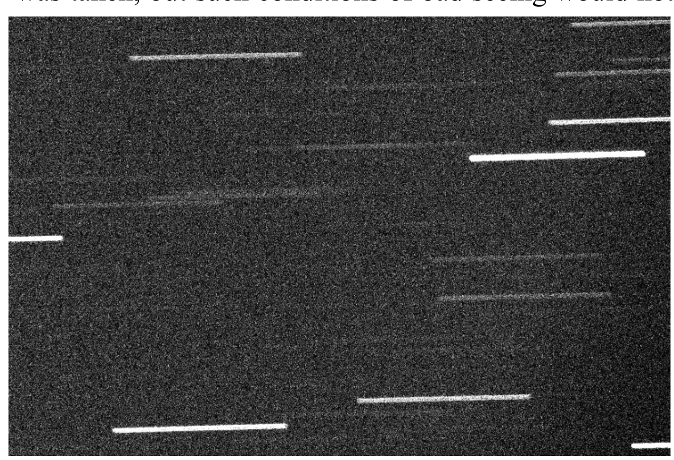

Figure 4. *AURT image showing incorrect tracking.*

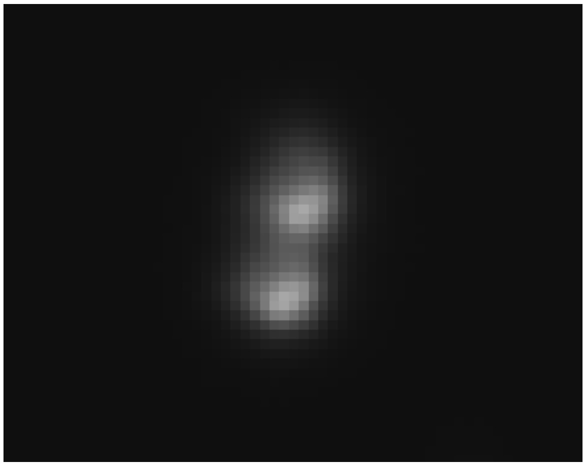

Figure 5: DSO-17 Bloated Stars with a slight drift along the NE/SW corners.

cause the stars to be asymmetric, just larger. The asymmetry of these stars indicates a problem with the mount that seeing could not have caused. Figure 5 shows a 30-second exposure taken by DSO-17.

The Las Cumbres Observatory telescopes gave much better results, and by visual inspection the stars appeared rounder than the ones that are in my images. One of the images was not focused or collimated properly and had donut shaped stars (due to the central obstruction), but the rest of the images were very high quality as shown in Figure 6.

Because the LCO telescopes are 0.4m in aperture and their mounts are much more advanced than mine, the images are expected to be better. Our first images from LCO, however, were overexposed with exposures of 30 seconds and 60 seconds. To perform accurate centroid measurements, the stars must not be too overexposed. After some trial-and-error, we found the optimal exposure time to be three seconds. This process of trial and error takes time on the researcher's part and wastes telescope time that other people could use. The ability to make adjustments to elements like gain, focus, and specific framing of the field during the course of an observation is possible for human but not robotic researchers. Despite this, LCO gave back impressive results, both in the quality of the image and the speed with which they were taken.

One extremely important necessity for high quality images is the "seeing," which is the measure of the stability of the atmosphere. The seeing is completely out of the control of the observer; it is simply a function of the weather and air currents that day. Seeing is the prime reason why large telescopes cannot achieve their maximum resolution because the atmosphere "smears" out the stars. On nights of bad seeing, imaging double stars is almost hopeless because the stars will be very bloated. For example, with excellent seeing, I can split doubles under an arcsecond visually, but on nights of terrible seeing, splitting doubles under seven arcseconds is a challenge. On an average night, anything under two arcseconds reduces to mush in the eyepiece. For robotic telescope networks, images are taken when the skies are clear but not necessarily when seeing is good. However, when I do the imaging myself, I am outside looking at the stars. Therefore, I can evaluate the seeing and whether imaging a target is feasible, taking into account the difficulty of resolving the double star and the local hour-to-hour conditions.

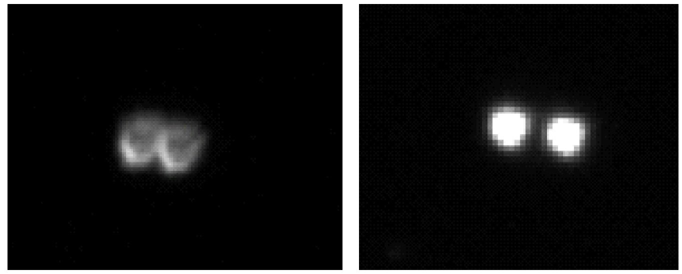

Figure 6: Bad LCO image, left; and good LCO image.

Limitations of my Setup Relative to Robotic Telescopes

There are some limitations to my telescope, mostly related to its small aperture. Since it is only 102mm (4 inches) in aperture, the diffraction limit is around 1.23 arcseconds (Nave, 2000). However, for practical reasons, stars separated by anything less than three arcseconds are too close to image accurately with a single exposure. For this reason, speckle interferometry is in increasingly common use for close doubles (Wasson, 2018). This limitation is not that restrictive, though, as there are plenty of double stars that have separations above three arcseconds.

I was also limited by my mount. At the time of imaging for this project, I did not have a guiding solution, either by an autoguider or an off-axis guider. Every mount experiences periodic and sinusoidal movement known as "periodic error" because of imperfections in the worm and drive gears (Saunders 2012). This means that no matter how well a mount is polar aligned, there will be back-and-forth drift in the right ascension direction as the mount tracks the sky. As a result, my mount could not do unguided images for longer than around 60 seconds, and I sometimes struggled to have round stars. The addition of an autoguider has fixed this problem.

My camera does not have any major limitations that

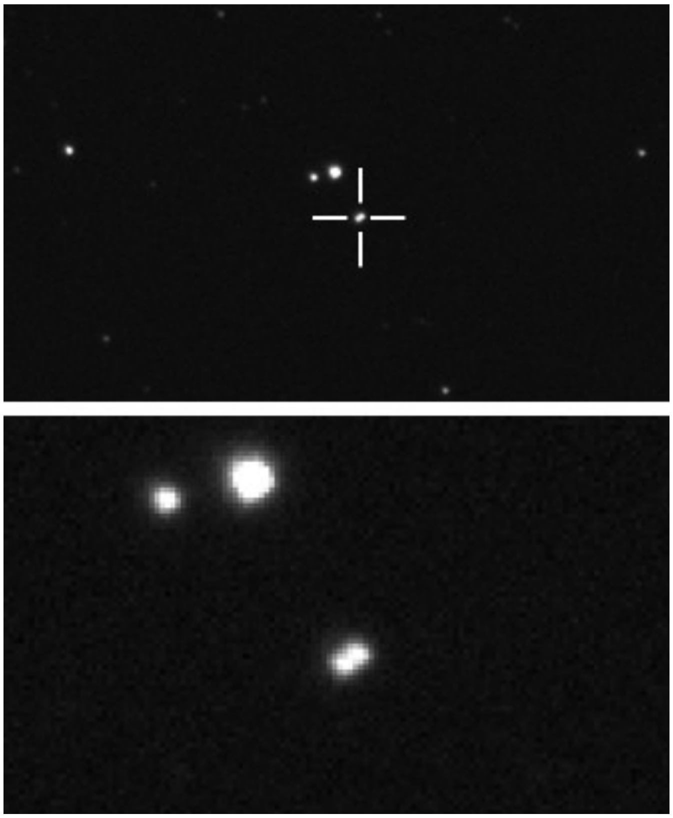

Figure 7. Fortuitously discovered potential binary at 00 06 32.31, +45 54 30.95, in a 60-second LCO exposure. Bottom image is zoomed in further.

are glaring problems. Certainly a more expensive sensor would give better results, as is the case for almost everything that is more expensive, but there is not a single main problem with the camera. Overall, my camera is the best piece of equipment in my setup.

Observations

The starfield of STT 547AB held some surprises. In addition to the target binary, I spotted several other known binaries and a potential binary by closely examining the image. Figure 7 shows one of these fortuitously-discovered doubles that has not been previously recorded in the WDS. This new double could potentially be gravitationally-bound because of its similar parallax and proper motion shown in Table 1 (Harshaw, 2018). In Figure 7, we zoom in on this double on a 60-second exposure from LCO. My telescope, while being able to capture these stars, only did so very faintly and the two stars cannot be resolved.

Image Analysis

The images were platesolved using Astrometry.net which produces a downloadable platesolved .fits file. The .fits files were then opened in AstroImageJ, which was used to find the position angle and separation of the stars. My images were not calibrated against a dark, bias, or flat frame, but the target star was bright enough not to need noise reduction. The LCO images are automatically calibrated using the network's calibration algorithm.

In Figure 8 and Table 1, all of the double stars - binary or not - that were found in the field are tabulated

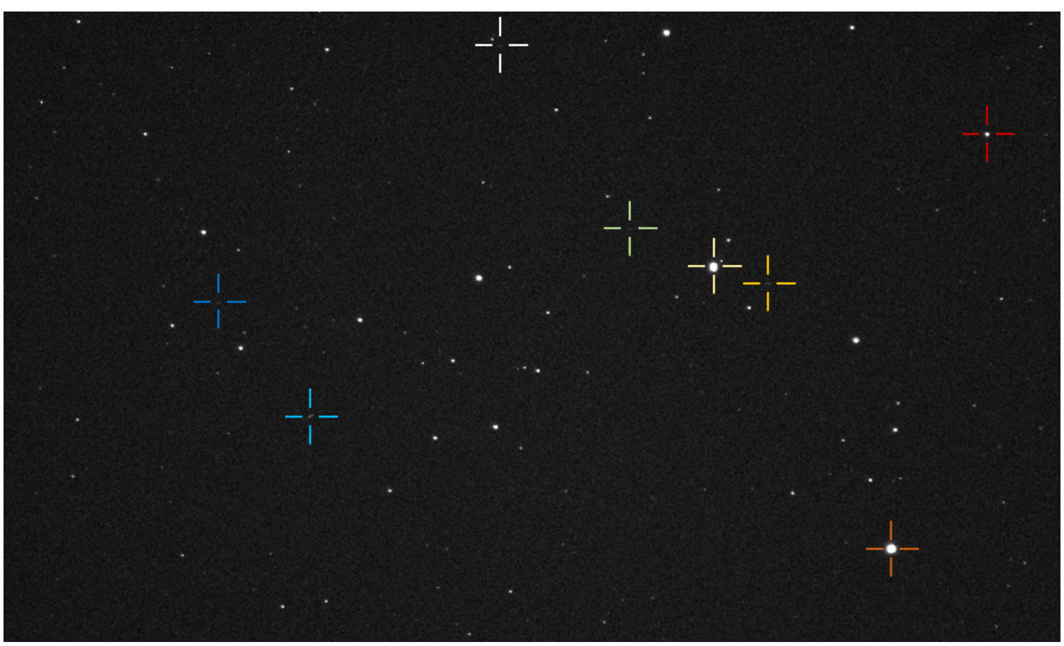

Figure 8. Starfield with double stars in Table 1 indicated.

Table 1. WDS and Gaia star data.

Coordinates	Name	Orbit in WDS?	Gaia Plxs	PM's (ra1, ra2; dec1, dec2)	Magnitudes	Measurable by my Telescope
00 04 55.317 +45 54 53.80	VYS 1	unsolved	4.1509, 4.3027	6.858, 6.547; -4.171, -4.013	10.5, 10.5	No
00:04:57.622+45:40:25.20	BU 997	unsolved	13.6562, 13.6018	18.385, 18.465; -65.374, -68.095	7.4, 9.5	No, high Δmag
00 05 31.350, +45 48 26.30	PAL 2	unsolved	0.9229, .9543	5.164, 5.362; -0.196, 0.144	13.9, 14.7	Yes
00 05 41.03 +45 48 43.3	**STT 547AB**	Yes	86.8735, 86.9402	888.615, 845.89; -162.47, -148.54	8.2, 8.3	Yes
00 06 00.27, +45 49 20.05	**POP 217YG**	Linear solution	0.7087, 0.7429	4.795, -3.695; -3.720, -4.805	14.8, 15.8	Optical
00 06 32.31, +45 54 30.95	**Potential binary!**	-	0.5394, 0.6123	-2.73, -2.707; 0.06, 0.064	14.9, 15.1	No, small sep
00:06:54.192 +45:40:52.95	-	-	0.6912, 1.1713	-0.653, -12.158; -0.602, 1.749	13.4, 14.2	Optical
00 07 15.96, +45 44 03.27-	-	-	0.8739, 1.4887	-3.004, 21.835; -2.610, 4.247	14.7, 14.9	Optical

along with their WDS Catalogue designations where applicable, corresponding data from the Gaia space telescope, and notes regarding whether it was possible to measure them in my images. The double stars were noted by visual inspection of the image, so there are some optical doubles that are not tabulated in the WDS and were not measured in the images. The white crosshair in Figure 8 is the same as in Figure 7; it gives a reference for the location of the new double in relation to the entire starfield.

Tables 2, 3, and 4 and the corresponding Figures 9, 10, and 11 show the various double stars and contain measurements of position angle and separation of each system. The measurements are made on both my images and the LCO images. The stars of WDS BU 997 have a delta mag too high to resolve in my images or the LCO images, so this system was not measured. Note that I only took 30 second images appropriate for a magnitude 8 star, as I did not anticipate measuring other, much dimmer stars, so the dimmer stars would be more accurate if the exposure had been adjusted for them. Although the original LCO images were overexposed for most of the stars in the field, they made possible the measurement of magnitude 14 stars. For each of the tables that follow, the last row is the average ± standard error of the mean.

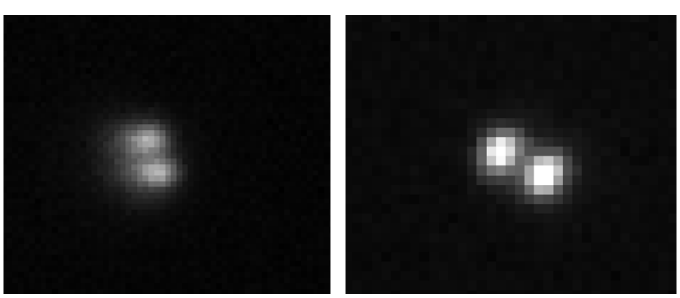

Figure 9: *VYS 1 through my telescope (left) and LCO (right).*

VYS 1

Although the nature of this double is uncertain, the parallaxes and proper motions are similar. The measurements of this system did not vary much, and my images gave essentially the same error as the LCO images. This star system is pushing what any telescope can resolve using a single exposure, and speckle interferometry is needed to give a reliable measurement. Still, the fact that my four-inch telescope can accurately record this double is impressive. Figure 9 shows my image and the LCO image. My image looks substantially less "sharp," as the stars are more smeared out, yet the measurements have low error. Table 2 shows the measurements of my images and the LCO images.

PAL 2

PAL 2 is a very dim star system, around magnitude

Table 2. Measurements made of VYS 1 from my images and LCO.

My Telescope		LCO (3 second exposures)	
Position Angle	Separation	Position Angle	Separation
26.21	2.78	25.83	2.78
27.98	2.74	28.66	2.88
25.73	2.89	28.80	2.84
25.02	2.91	26.58	3.00
		27.55	2.76
26.2 ± 0.63	**2.83 ± 0.041**	**27.5 ± 0.67**	**2.85 ± 0.042**

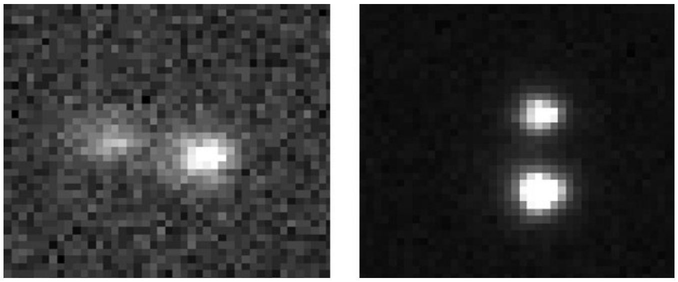

Figure 10. PAL 2 through my telescope (left) and LCO.

14, so my 30-second exposure is too short to record the stars with enough SNR to perform accurate measurements. The LCO images that I originally thought were horrendously overexposed turned out to be essential to measure this magnitude 14 double, so the LCO measurements have a very low error. My images are not good enough to be reliable. If I had taken a longer exposure, perhaps around two minutes, the stars would have been properly exposed. However, at this point, periodic error starts to creep in and the starfield will show drift, so a guiding solution is needed to measure this system accurately. Figure 10 shows the system through my telescope and LCO, and Table 3 lists the measurements from my images and LCO.

Table 3. Measurements made of PAL 2 from my images and LCO.

My Telescope		LCO (60 second exposures)	
Position Angle	Separation	Position Angle	Separation
90.99	5.77	91.61	6.06
92.43	6.11	91.66	6.07
90.32	5.54	91.12	6.02
91.33	5.75	91.64	6.06
		91.46	6.05
91.3 ± 0.44	**5.8 ± 0.118**	**91.5 ± 0.12**	**6.05 ± 0.010**

STT 547 AB

STT 547 AB was the original target for this project, and so the exposure was tuned for this double. My images were exceptionally accurate, with the separation having a standard mean error of 0.004. LCO, by comparison, was a very respectable 0.03 standard mean error for the separation, yet this is almost 10 times larger than mine. The position angle standard error of the mean also is much lower on my images, although the difference is not quite as dramatic as the separation. My images gave much more precise results despite the LCO image stars appearing rounder than mine. This shows that the quality of an image is based not only on its visual appearance, but also on factors that are much harder to readily observe. Figure 11 shows a comparison of this system in my images and LCO images, and Table 4 lists the measurements.

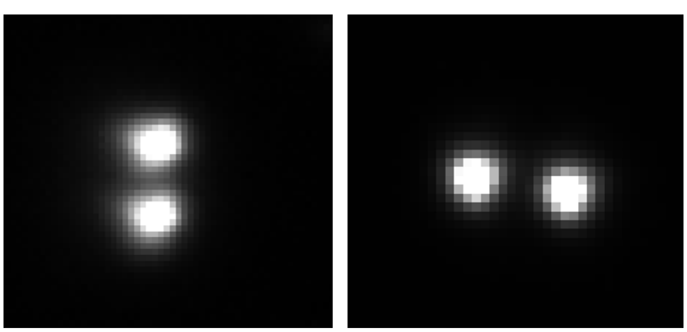

Figure 11. *STT 547 AB through my telescope (left) and LCO.*

Conclusion

Due to the greater control over real-time variables that impact observing, human-monitored telescope setups can perform quite well, even when limited in aperture compared to much larger robotic telescope networks. In comparing my four-inch telescope to 0.4-meter robotic telescopes on a three double stars in the same starfield, my setup performed similarly to LCO. The magnitude 14 star system, PAL 2, was the only double that I could not measure, but if I were able to take longer exposures, I am certain my setup would take images approaching the quality of the LCO images. In fact, as of completing this project, I have acquired more astrophotography gear, most importantly an autoguider. With this autoguider, I can take exposures in excess of several minutes, allowing me to push past the periodic error which was my limiting factor. Therefore, my future projects are likely to yield even better measurements, especially for the closer and dim-

Table 4. Measurements made of STT 547 from my images and LCO.

My Telescope		LCO (60 second exposures)	
Position Angle	Separation	Position Angle	Separation
189.59	5.99	189.55	6.07
189.38	6.01	189.14	5.95
189.62	5.99	188.94	6.02
189.77	6.00	190.04	6.07
		189.78	5.97
189.59 ± 0.080	**6.00 ± 0.004**	**189.5 ± 0.218**	**6.03 ± 0.03**

The Human Element: Why Robotic Telescope Networks are not always Better ...

mer double star targets. Furthermore, actually looking at the sky and being outside while the images are being taken is a refreshing break from astronomy of today, in which observations are either done remotely or by trained telescope operators, not the astronomers themselves. Observations such as this demonstrate that small aperture astrometry is a viable alternative to large robotic telescopes because the limitations of the small aperture are offset by the human element.

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Special thanks to my parents, who (with much persuasion) bought me an astrophotography setup and support such an expensive hobby.

This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory, Astrometry.net to plate solve image, and the AstroImageJ software written by Karen Collins and John Kielkopf at the University of Louisville, updated for double star astrometry by Karen Collins.

Special thanks to the Las Cumbres Observatory (LCO) network for time on the 0.4m telescopes.

This work has also made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

References

Arimatsu, K., K. Tsumura, F. Tsui, Y. Shinnaka, K. Ishikawa, T. Ootsubo, T. Kotani, T. Wada, K. Nahase, and J. Watanabe, 2019, "A kilometer-sized Kuiper belt object discovered by stellar occultation using amateur telescopes", *Nature Astronomy*, **3**, 301-306. https://www.nature.com/articles/s41550-018-0685-8.

Bracken, Charles, 2017, *The Deep Sky Imaging Primer, 2nd Edition*, Deep Sky Publishing. ISBN 978-0999470909.

Buchheim, Robert, 2007, *The Sky is Your Laboratory: Advanced Astronomy Projects for Amateurs*, Praxis Publishing, Chichester, UK. ISBN 978-0-387-73995-3.

Collins, Karen, John F. Kielkopf, Keivan G. Stassun, and Frederic V. Hessman, 2017, "AstroImageJ: Image Processing and Photometric Extraction for Ultra-Precise Astronomical Light Curves", *The Astronomical Journal*, 153:77.

Harshaw, Richard. "Gaia DR2 and the Washington Double Star Catalog: A Tale of Two Databases", *Journal of Double Star Observations*, **14**, 734 - 740.

Nave, Carl Rod. "The Rayleigh Limit." From the hyperphysics website: http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/Raylei.html . Described in "Doing It by the Numbers: JavaScript Calculations in Web-Based Physics Instructional Material: A presentation from the 121st AAPT National Meeting: Guelph, Ontario, Canada", 2000.

Saunders, Rick, 2012, "Gears and Periodic Errors," *Journal of the Royal Astronomical Society of Canada*, **106**, 162 - 164.

Wasson, Rick. "Speckle Interferometry with the OCA Kuhn 22" Telescope," *JDSO*, **14**, 223 - 241.