Binary Star Measurements with a 17th Century, Long-Focal, Non-Achromatic Refractor

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Abstract: As part of the evaluation of my long-focal, non-achromatic refractor of the type developed during the first century, i.e., the 17th century, of optical astronomy, I have observed 175 double and multiple stars. After having observed most of these binary stars visually, I decided to see if it would be possible to measure their position angles and separations. Thus, I built a micrometer and began a program to determine if - and how accurately - I could measure the characteristics of these binaries. To my great surprise, the average error of the measured position angles is only 2 degrees and that of the separations is only 1 arc-second - values that are almost a good as modern measurements. These results further indicate that these very early and relatively primitive telescopes were much better that modern astronomical historians believe.

Introduction

As a lunar and planetary scientist whose background is astronomy, I have had lifelong interests in making telescopes and observing with them, interests that were, in part, sparked by my having been born and having grown up about 20 miles from Yerkes Observatory, home of the Yerkes 40-inch refractor – the world's largest. I have also had a similar interest in historical astronomy and King's excellent book, *The History of the Telescope,* served to further this passion. I was, and still am, particularly interested in the long-focal, non-achromatic refractors of the second half of the 17th century, despite what King and, later, Watson (in his book, *Star Gazer*) disparagingly wrote about these early telescopes. King and Watson refer to the optical defects, ungainly lengths, crude altazimuth mountings of these telescopes (they were generally hoisted on a tall mast by a rope and pulley system) and conclude that they were, at best, difficult to use. However, most of the historical attention paid to these telescopes is given to those with the very longest lengths, such as Huygens' 123-foot telescope, Hevelius' 150-foot telescope (Figure 1) and Auzout's 300- and 600-foot telescopes. What these authors seem to ignore is

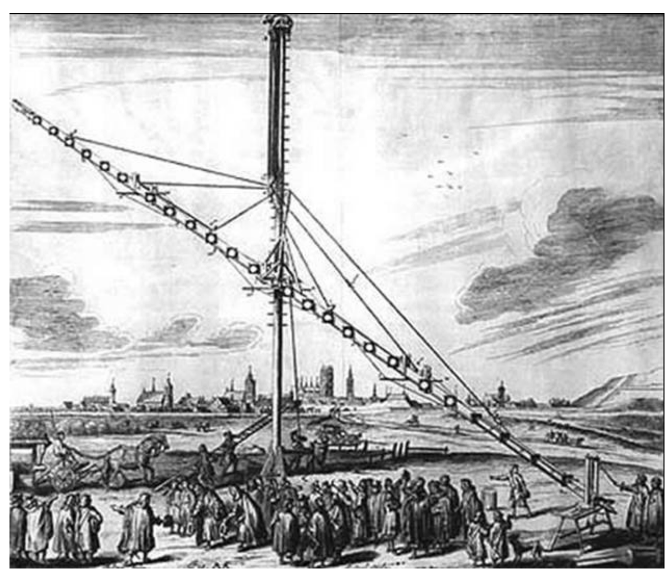

Figure 1: Hevelius' 150-foot, long-focal, non-achromatic refractor.

the fact that most of the discoveries of the 17th century were made with telescopes of modest lengths of 5 to 34 feet and, hence, their conclusion might not be valid.

My observing career began as a teenager with a small refractor and then with a series of 4¼-inch, homemade reflectors. As an undergraduate student, I was fortunate to have a summer job at Yerkes and observed the Moon and planets with the 40-inch and, later, with other large reflecting telescopes, e.g., the McDonald's 82" Cassegrain. My experiences observing with these telescopes, especially the Yerkes 40-inch, f/19 refractor and my 4¼-inch, f/22.5 Dall-Kirkham Cassegrain clearly demonstrated the well-known advantages of long-focal systems to me. That made me think that the more modest of the 17th century, long-focal, non-achromatic refractors might have been fairly good, despite what has been written about them. Thus, I made a long-focal, non-achromatic refractor in the late sixties to see just how well or how poorly the 17th century telescopes performed.

Since 1969 I have conducted systematic observing programs of the Moon, planets, galactic star clusters, globular clusters, galaxies and, of course, binary stars to determine how well my historical telescope performs and what could have been done with similar 17th century telescopes had the astronomers of that era pushed their telescopes to their observational limits.

A complete description of the telescope and the interim results of my observing programs are given in the April, 1992, issue of *Sky and Telescope* (Binder, 1992) and issue No. 31, Winter 2010, of the *Journal of the Antique Telescope Society* (Binder 2010). The purpose of this article is to report more extensively on the observations and measurements of binary stars I have made with this telescope.

My Long-Focal, Non-Achromatic Refractor

The main component of my telescope is a 3-inch (2.8 inch clear aperture) diameter, 17-foot (206 inches) focal length, single element, plano-convex lens and 3 Huygens eyepieces (Figure 2) with effective focal lengths of 4-inch, 2-inch and 1¹/₃-inch, yielding 50x, 100x and 150x, respectively, and a micrometer described below. The optical and mechanical construction of the telescope and its characteristics are given in detail in the articles cited above.

The telescope (Figure 3) was designed using pictures of various 17th century refractors, especially

Figure 2: The 2.8 inch, clear aperture lens of the Hevelius and the 150x, 100x and 50x Huygens eyepieces of the Hevelius.

Figure 3: The "Hevelius", the author's 17-foot, long-focal, non-achromatic refractor and its mounting.

those in King's *The History of the Telescope* (King 1955), as a guide. In particular, I wanted my telescope to resemble Hevelius' 150-foot telescope, hence the name of my telescope.

In order to use the Hevelius, it is hoisted up a pole by a rope, pulley and ratchet wheel system to the appropriate altitude and the eye-end is held in the vertical frame of an observing table that is modeled after its 17th century counterparts (Figure 4). An object is followed in altitude using a crank and cord system to move the frame up or down. Azimuth control is achieved by a crank and cord system which pulls the sliding, upper table top along the horizontal direction. Fine control is achieved by sliding the telescope along the bottom of the frame by hand and pushing the frame up or down by hand, against the tension of the cord holding the frame.

Figure 4: The details of the mounting table of the Hevelius and its eyepiece end.

Binary Stars – Visual Observations

Only two binary stars were discovered using the long-focal, non-achromatic refractors of the 17th century. Mizar was found to be double by Castelli in 1617 and rediscovered by Riccioli in 1643 and Hooke discovered that γ Aries was double in 1664.

I have always enjoyed double star observing and it is a good way to test the limits of any telescope. Thus, I have spent a lot of time looking at doubles in my evaluation of the Hevelius.

The closest stars the Hevelius has resolved are β BC Monoceros (2.9"), 1 ε Lyra (2.3") and 2 ε Lyra (2.4") – the latter two are split only under the very best conditions, but I have never resolved the somewhat dimmer, 2.3" pair (CD) in the quadruple system of ν Scorpii. I conclude that Hevelius' resolution is about 2.3" under the very best conditions (equal to that of a 2-inch achromat), and about 2.5" under normal observing conditions. The latter value is only 50% poorer than Dawes' theoretical limit of 1.7", a value that is very good for a non-achromatic refractor.

Despite Hevelius' non-achromatic objective, I can easily detect the colors of many of the brighter doubles. Albeiro's and γ Andromeda's yellow primaries and blue secondaries are nearly as attractive with the Hevelius as with my 4¼-inch Newtonians. Similarly, α Hercules' red and blue stars and Mizar's white and blue stars are quite striking.

When I began observing doubles with the Hevelius, I looked at most of my favorites and then decided to make a systematic study of double and multiple stars. I culled through *Burnham's Celestial Handbook* (Burnham, 1966) and made a list of 215 double and multiple stars down to the 5th magnitude that might be observable with the Hevelius. Of these, I split 130 pairs of stars in double and multiple star systems as documented in Binder, 2010. However, Burnham's magnitude data are given with an accuracy of ½ of a magnitude, so many of the stars I observed are as faint as magnitude 5.5 when checked against the values given in Hass' *Double Stars for Small Telescopes* (Haas, 2006). Thus, after that article was written, I went through Hass' book and, to a lesser extent, the *Washington Double Star Catalog* (ad.usno.navy.mill/wds/) and added all the stars down to magnitude 5.5 to my observing list, of which 45 pairs were split for a total of 175 pairs (Table 1).

Initially, I just observed the stars, noted their color, if possible, and estimated their Position Angle (PA) to an average accuracy of about 10° with respect to the published values. But, as I was finishing up observing the doubles and multiples on my original list, I asked myself if it would be possible to make micrometer measurements of the pairs using the Hevelius, since micrometers were made and used by Gascoigne as early as 1639. Given that question, I built a Filer Micrometer for the Hevelius in my basement machine shop.

The Micrometer

As luck would have it, the number of arc seconds in a radian, i.e., 206,265", is almost exactly 1000 times the 206-inch (+/-½-inch) focal length of Hevelius' objective. Thus, the plate scale is within about 0.1% of 3.6 inches/degree or 1000"/inch and hence a ¼ x 20 screw yields a scale of 50"/turn.

The micrometer (Figure 5) is made from brass, wood, plastic and a ¼ x 20 steel screw. It has a 1.7-inch focal length, bi-convex, Kepler eyepiece giving 120x, red light emitting diodes (LEDs) with batteries for illumination and human hair (my wife's) is used for the stationary and movable crosshairs, as was done in the 17th century. The sliding plate carrying the movable crosshair is driven by the screw against springs, so there is no backlash. The scale on the 3¾-inch diameter PA circle is graduated in increments of 1-degree (essentially $^1/_{30}$ of an inch) and is read to 1-degree accuracy. The scale on the $^{15}/_{16}$-inch diameter dial on the drive screw is graduated in increments of 1" (essentially $^1/_{12}$ of an inch) and is read to 0.1".

While 17th century machinists apparently could make the mechanical parts of a micrometer similar to mine, they certainly did not have LEDs and batteries to illuminate the crosshairs. Although there are vague references to the illumination of crosshairs in King, 1955, it is not clear to me how this was accomplished in the 17th century.

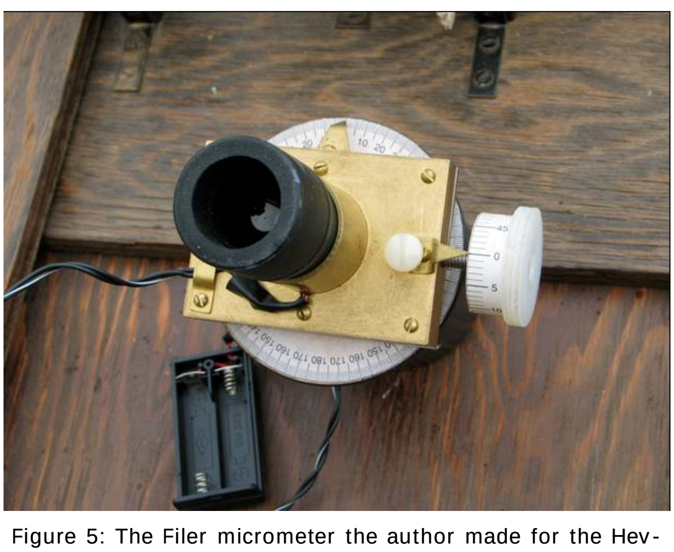

Figure 5: The Filer micrometer the author made for the Hevelius to measure double stars.

Binary Stars – The Micrometer Measurements

Of all the surprises the Hevelius has afforded me, the results of my double star, micrometer measurement program are by far the most surprising and gratifying.

Before I started the micrometer measurements, I thought I might be able to measure the PA and the separation (Sep) with accuracies of only several degrees and a few arc seconds, respectively. This pessimistic view was based on the facts that the Hevelius 1) is hung by ropes on a pole with the eye-end sitting in a sliding vertical frame on a sliding, horizontal table top that together form an alti-azimuth mount, whose motions are controlled by cranks, pulleys and cords and by being pushed and pulled by hand, 2) sways in any breeze, 3) cannot automatically follow the stars as is the case in a "clock" driven, equatorial mounted telescope and, hence, I cannot "set" the crosshairs on the stars while making the measurements and because 4) the Airy Disks of the stars are 2.5" in diameter and the crosshairs have apparent thicknesses of about 2" and because 5) I can see faint secondaries only by averted vision while making the measurements.

However, when I made my first set of micrometer measurements on five pairs of stars on Sept. 19, 2008, I was astounded by the results and became even more so as I progressed with the program.

It takes 15 to 20 minutes to measure a single pair, during which the stars (if they are near the celestial equator) move 4° to 5°. As a result, I often have to reposition the Hevelius in altitude via the rope and pulley on the pole once or twice during the measurements of a pair of stars.

The first step in the measuring process is to align the micrometer east-west by turning the entire body of the micrometer in the drawtube until the primary star moves along the east-west crosshair due to the star's diurnal motion. This step takes several minutes or more, especially when the seeing is poor or the Hevelius is swaying in the breeze by several arc seconds. The field-of-view of the micrometer eyepiece is about ¼° and I usually let the star drift ½ to ¾ of that. Since the apparent diameter of the Airy Disk of the star and the apparent width of the crosshair are about 2½" and 2", respectively, I can align the micrometer along the east-west direction to an accuracy of 3" or better, which translates to about 0.3° in PA.

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During this step, I also note where the secondary star is (in PA) with respect to one of the cardinal directions, i.e., whether the secondary is to the north of west, or to the east of south, etc., since I have found it is easiest to measure the PA differentially from the closest of the four major directions.

The second step is measuring the PA differentially from the closest cardinal direction. This is done by rotating the micrometer in its casing and noting the number of degrees of rotation on the PA circle. Because the stars are drifting to the west all the time, I make a measurement by trying to get the star pair to be parallel to the reference crosshair and, when possible, catch them as they quickly cross the crosshair. However, the visible Airy Disk of a bright star is about 2.5″ in diameter and that for a very faint star is around 1″. Thus, when the stars appears to be parallel to the crosshair before crossing the crosshair, they may no longer appears to lie parallel to it after crossing the crosshair. For apparent Airy Disks of 2.5″ and 1″ for the primary and secondary stars, respectively, and a separation of 10″, the difference in the apparent "parallel" PA before and after crossing could be up to 9°, while that of 60″ pair could be up to 1.4°. I compensate for this effect by pushing the Hevelius, by hand, back and forth so the stars across the crosshair several times during each measurement. Depending on circumstances, each PA measurement reading is some variable combination of the "parallel" parts of the step and the "crosshair crossing" parts. I generally make seven such measurements per pair (sometimes as few as five and as many as nine), per night and average the results for that night. Typically, the spread of the seven measurements is 5° to 10°. I also measure each pair on three (sometime more) different nights and the final PA value in Table 1 is the average of those three nights. The typical night-to-night variations in PA are 2° to 4°. So each determination of a pair's PA in Table 1 is generally based on 21 individual sets of measurements and the resulting, average difference between my measurements and the published values of the PAs for all of the measured pairs is just under 2.0° (Table 1).

Since I often have to reposition the Hevelius in altitude using the crank and pulley on the main pole, I do so after finishing the PA measurements, since the separation (Sep) measurements do not require that the micrometer be accurately aligned along the east-west direction and the original alignment may be lost during the repositioning.

The next step is the measurement of the pair's separation. In addition to the sources of error cited immediately above, there are two additional ones in the measurements of the Sep.

First, I do not attempt to align the micrometer so the movable crosshair and the parallel stationary one are exactly perpendicular to the line joining the two stars using the PA measurements, because I have not reduced those measurements at that point in time and because I can align the micrometer to within better than 5°. Even if the alignment error were as large as 10° (for close pairs and even less for wide pairs), the measured Sep error would be a negligible +1.5%, or 0.15" for a pair whose separation is 10" and <1.5" for a pair whose separation is 100".

Second, because the apparent diameter of the Airy Disk of a bright primary is 2½", that of a very faint secondary is, perhaps, 1" and the crosshairs are each about 2" in apparent width, the error in the measured Sep could be as much as +/-6", since I cannot really set the stars exactly on the crosshairs and have to estimate when they are crossing as they move across the crosshairs. As with the measurements of the PA, this effect is minimized by pushing the Hevelius back and forth by hand so the stars move across the crosshair several times during each measurement.

Finally, because it is nearly impossible to simultaneously see both stars cross their respective crosshairs, I have found that for close pairs, the best measurements are made by having the stars close to the crosshairs and adjusting the latter so they appear to have the same separation as pair of stars.

Like the PA measurements, I generally make seven separate measurements (but sometimes from five to nine) per night and measure the stars' Sep on three (sometimes more) different nights. The typical spread of the seven measurements is 1" to 2" for close pairs and 5" to 10" for very wide (around 100") pairs. The typical night-to-night variations in Sep are <1" for close pairs and 2" to 4" for very wide pairs. Each determination of a pair's Sep in Table 1 is generally based on 21 individual sets of measurements. The resulting, average difference between my measurements and the published values of the Sep for all the measured pairs is just over 1.0" (Table 1).

As seen in Table 1, I did not measure the PAs and Seps for eleven pairs. First, the micrometer's maximum travel is about 120", so I can't measure stars with larger Seps (α Aquila, 14 AC Canis Minor, α Capricornus, α Leo, ε 1,2 Lyra and α Ursa Major). I cannot measure δ Crovus and γ AD Vela, since I can barely see the faint secondaries without the microme-

(Continued on page 290)

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Table 1: Double and Multiple Stars Observed with the Hevelius.

Const.	Star	Date	N	RA	Dec	PA	Sep	M1	M2	M2-M1	Per.	PA-H	Sep-H	DPA	DSep
And	π	2008.814	3	0h 37m	34	173	36.0	4.3	7.1	2.8		175	36.7	2	0.7
	γ	2008.767	6	2h 4m	42	63	9.7	2.3	5.0	2.7		67	11.8	4	2.1
Aqr	ψ	2009.403	3	23h16m	-9	313	49.4	4.4	9.9	5.5		313	50.3	0	0.9
	94	2009.403	3	23h 19m	-13	351	12.3	5.3	7.0	1.7		356	12.2	5	-0.1
Aql	15	2009.816	3	19h 5m	-4	210	39.1	5.5	7.0	1.5		209	40.5	-1	1.4
	28	2009.865	3	19h 20m	12	176	59.7	5.5	9.0	3.5		174	60.7	-2	1.0
	α		0	19h 51m	9	287	192.0	0.9	9.8	8.9				0	0.0
	57	2009.233	3	19h 55m	-8	171	35.9	5.7	6.3	0.6		169	37.4	-2	1.5
Ari	γ	2008.773	4	1h 53m	19	0	7.5	4.5	4.6	0.1		3	9.2	3	1.7
	λ	2008.811	4	1h 58m	24	47	36.7	4.8	6.7	1.9		46	38.7	-1	2.0
	14 AC	2009.712	3	2h 9m	26	278	106.7	5.0	8.0	3.0		279	104.5	1	-2.2
	33	2009.813	3	2h 41m	27	2	28.6	5.3	9.6	4.3		356	23.6	-6	-5.0
Aur	14	2008.830	3	5h 15m	33	225	14.1	5.0	7.3	2.3		226	14.5	1	0.4
	41	2008.836	3	6h 12m	49	357	7.6	6.2	6.9	0.7		360	8.2	3	0.6
	ψ 5 or 56	2009.876	3	6h 47m	44	40	30.1	5.3	8.7	3.4		45	28.4	5	-1.7
Boo	κ	2008.863	3	14h 13m	52	235	13.5	4.5	6.6	2.1		235	14.7	0	1.2
	ι	2009.142	3	14h 16m	51	32	38.7	4.8	7.4	2.6		35	36.1	3	-2.6
	S 1835	2009.156	3	14h 23m	8	194	6.2	5.0	6.8	1.8		192	5.9	-2	-0.3
	π	2009.156	3	14h 41m	16	111	5.5	4.9	5.8	0.9		110	5.3	-1	-0.2
	ξ	2009.156	3	14h 51m	19	315	6.3	4.8	7.0	2.2	152	312	7.1	-3	0.8
	δ	2009.153	3	15h 15m	33	78	103.8	3.6	7.9	4.3		80	107.1	2	3.3
	μ	2009.153	3	15h 24m	37	170	107.1	4.3	7.1	2.8		172	108.6	2	1.5
Cam	1	2008.847	3	4h 32m	54	309	10.5	5.8	6.8	1.0		307	11.8	-2	1.3
	β	2008.841	3	5h 3m	60	210	83.0	4.1	7.4	3.3		211	81.2	1	-1.8
	19	2008.852	3	5h 23m	79	135	25.8	5.0	9.2	4.2		133	27.0	-2	1.2
	32	2008.847	3	12h 49m	83	328	21.5	5.3	5.7	0.4		326	21.0	-2	-0.5
Cnc	ζ	2009.104	3	8h 12m	18	72	5.9	5.1	6.2	1.1		72	6.0	0	0.1
	ι	2008.951	3	8h 47m	29	308	30.7	4.1	6.0	1.9		307	30.6	-1	-0.1
CVn	α	2008.858	3	12h 56m	38	229	19.3	2.9	5.5	2.6		230	19.3	1	0.0
CMa	FN	2009.950	3	7h 7m	-11	350	17.5	5.4	9.0	3.6		350	19.5	0	2.0
	h 3945	2008.858	3	7h 17m	-23	52	26.8	5.0	5.8	0.8		52	26.4	0	-0.4
	D 47	2009.816	3	7h 25m	-32	343	98.5	5.4	7.6	2.2		342	97.6	-1	-0.9
CMi	14 AB	2009.950	3	7h 58m	2	84	98.8	5.4	9.4	4.0		85	100.2	1	1.4
	14 AC		0			148	133.3	5.4	9.9	4.5				0	0.0
Cap	α		0	20h 18m	-13	292	381.2	3.7	4.3	0.6				0	0.0
	σ	2009.813	3	20h 19m	-19	180	56.3	5.4	9.4	4.0		175	59.2	-5	2.9
	ο	2009.282	3	20h 30m	-19	238	21.6	5.9	6.7	0.8		237	23.2	-1	1.6

Table 1 continued on next page.

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Table 1 (continued): Double and Multiple Stars Observed with the Hevelius.

Const.	Star	yy/mm/dd	N	RA	Dec	PA	Sep	M1	M2	M2-M1	Per.	PA-H	Sep-H	DPA	DSep
Cas	SHJ 355 AC	2009.107	3	23h 30m	59	268	75.8	4.9	7.2	2.3		268	76.1	0	0.3
	α	2009.137	3	0h 40m	57	282	69.5	2.4	9.0	6.6		281	64.9	-1	-4.6
	η	2009.118	3	0h 49m	58	319	13.0	3.5	7.4	3.9	480	319	13.0	0	0.0
Cen	BrsO 6	2009.980	3	11h 29m	-43	168	13.1	5.1	7.4	2.3		164	13.9	-4	0.8
	3	2009.183	3	13h 52m	-33	106	7.9	4.5	6.0	1.5		105	8.4	-1	0.5
	4	2009.197	3	13h 53m	-32	185	14.8	4.7	8.5	3.8		185	15.4	0	0.6
Cep	β	2009.038	4	21h 29m	71	248	13.2	3.2	8.6	5.4		250	14.1	2	0.9
	ξ	2009.038	4	22h 4m	65	275	7.9	4.4	6.4	2.0	3800	271	8.8	-4	0.9
	δ	2009.038	4	22h 29m	58	191	40.6	4.2	6.1	1.9		191	38.9	0	-1.7
Cet	37	2008.836	4	1h 14m	-8	331	48.4	5.2	7.8	2.6		330	49.6	-1	1.2
Com	12	2009.142	3	12h 23m	26	168	65.2	4.9	8.9	4.0		168	63.6	0	-1.6
	24	2009.142	3	12h 35m	18	270	20.1	5.1	6.3	1.2		268	21.4	-2	1.3
	35 AC	2009.575	3	12h 53m	21	127	27.9	5.0	9.8	4.8		126	26.6	-1	-1.3
CrA	BrsO 14	2009.334	3	19h 1m	-37	280	12.8	6.3	6.6	0.3		278	13.2	-2	0.4
CrB	ζ	2009.156	3	15h 39m	37	306	6.3	5.0	5.9	0.9		305	7.0	-1	0.7
	σ	2009.156	3	16h 15m	34	236	7.0	5.6	6.5	0.9		240	7.7	4	0.7
Crv	δ		0	12h 30m	17	217	24.9	3.0	8.5	5.5				0	0.0
Cyg	β	2009.318	3	19h 31m	28	55	34.7	3.4	4.7	1.3		55	34.6	0	-0.1
	16	2009.370	3	19h 42m	51	134	39.1	6.0	6.2	0.2		133	39.9	-1	0.8
	17	2009.370	3	19h 46m	34	67	26.3	5.1	9.3	4.2		69	26.4	2	0.1
	26	2009.370	3	20h 1m	50	150	41.4	5.2	8.9	3.7		146	39.9	-4	-1.5
	61	2009.370	3	21h 7m	39	151	31.1	5.3	6.1	0.8	659	152	30.7	1	-0.4
Del	γ	2009.233	3	20h 46m	16	266	9.1	4.4	5.0	0.6	3249	267	9.8	1	0.7
Dra	16-17	2009.884	3	16h 36m	53	193	89.4	5.4	5.5	0.1		195	89.0	2	-0.4
	17	2009.884	3			106	3.0	5.4	6.4	1.0		109	3.3	3	0.3
	ν	2009.203	3	17h 32m	55	311	63.4	4.9	4.9	0.0		312	62.7	1	-0.7
	S 2348	2009.884	3	18h 34m	52	271	26.2	5.5	8.7	3.2		263	24.7	-8	-1.5
	ψ	2009.058	3	17h 42m	72	15	30.0	4.6	5.6	1.0		17	31.2	2	1.2
	39	2009.203	3	18h 24m	59	21	89.0	5.1	7.5	2.4		20	89.3	-1	0.3
	ο	2009.203	3	18h 51m	59	319	36.5	4.8	8.3	3.5		317	36.1	-2	-0.4
Equ	ε	2009.233	3	20h 59m	4	67	10.5	5.3	7.1	1.8		72	10.1	5	-0.4
Eri	θ	2009.000	3	2h 58m	-40	90	8.4	3.2	4.1	0.9		90	9.0	0	0.6
	h 3565	2008.992	3	3h 19m	-19	121	7.8	5.9	8.2	2.3		120	8.4	-1	0.6
	f	2009.000	3	3h 49m	-38	217	8.4	4.7	5.3	0.6		212	8.6	-5	0.2
	32	2008.934	3	3h 54m	-3	348	6.8	4.8	5.9	1.1		353	7.2	5	0.4
	39	2008.997	3	4h 14m	-10	141	6.3	5.0	8.5	3.5		146	6.7	5	0.4
	ο2	2008.986	3	4h 15m	-8	104	83.0	4.4	9.7	5.3		104	83.8	0	0.8
	62	2009.904	3	4h 56m	-5	75	66.2	5.5	8.9	3.4		77	63.8	2	-2.4
For	ω	2008.992	3	2h 34m	-28	245	10.6	5.0	7.7	2.7		243	11.2	-2	0.6

Table 1 continued on next page.

Binary Star Measurements with a 17th Century, Long-Focal, Non-Achromatic Refractor

Table 1 (continued): Double and Multiple Stars Observed with the Hevelius.

Const.	Star	yy/mm/dd	N	RA	Dec	PA	Sep	M1	M2	M2-M1	Per.	PA-H	Sep-H	DPA	DSep
Gem	α	2008.995	3	7h 35m	32	57	4.6	1.9	3.0	1.1	445	57	5.0	0	0.4
Her	κ	2009.208	3	16h 8m	17	13	27.4	5.1	6.2	1.1		15	27.7	2	0.3
	α	2009.222	4	17h 15m	14	104	4.8	3.5	5.4	1.9	3600	100	4.6	-4	-0.2
	ρ	2009.203	3	17h 24m	37	319	4.1	4.5	5.4	0.9		320	4.5	1	0.4
	95	2009.225	3	18h 2m	22	257	6.3	4.9	5.2	0.3		259	6.6	2	0.3
Hya	F	2009.088	3	8h 44m	-7	311	79.0	4.7	8.2	3.5		309	77.1	-2	-1.9
	τ1	2009.088	3	9h 29m	-3	5	66.2	4.6	7.3	2.7		6	65.6	1	-0.6
	h 4465	2009.972	3	11h 42m	-32	44	66.1	5.4	8.3	2.9		43	67.2	-1	1.1
	H N 69	2009.183	3	13h 37m	-26	191	10.2	5.7	6.6	0.9		189	10.1	-2	-0.1
	54	2009.183	3	14h 46m	-25	124	8.1	5.1	7.3	2.2		121	8.3	-3	0.2
Leo	α		0	10h 8m	12	308	176.0	1.4	8.2	6.8				0	0.0
	γ	2008.852	3	10h 20m	20	126	4.6	2.4	3.6	1.2	619	123	4.6	-3	0.0
	54	2008.858	3	10h 56m	25	111	6.3	4.5	6.3	1.8		114	6.1	3	-0.2
	83	2009.137	3	11h 27m	3	150	28.6	6.6	7.5	0.9		146	29.1	-4	0.5
	τ1	2009.137	3	11h 28m	3	181	88.9	5.1	7.5	2.4		183	87.1	2	-1.8
	93	2008.858	3	11h 48m	20	357	74.1	4.6	9.0	4.4		356	76.8	-1	2.7
Lep	h 3752 AB	2009.947	3	5h 22m	-25	97	3.4	5.4	6.6	1.2		99	3.5	2	0.1
	h 3752 AC	2009.947	3			104	62.7	5.4	9.2	3.8		105	61.3	1	-1.4
	γ	2008.901	3	5h 44m	-22	350	96.9	3.6	6.3	2.7		348	95.6	-2	-1.3
Lup	κ	2009.455	3	15h 12m	-49	143	26.5	3.8	5.5	1.7		143	26.2	0	-0.3
	ζ	2009.455	3	15h 12m	-52	249	71.8	3.5	6.7	3.2		252	71.2	3	-0.6
	μ	2009.457	3	15h 18m	-48	129	23.2	5.0	6.3	1.3		130	23.1	1	-0.1
	ξ	2010.040	3	15h 57m	-34	49	10.3	5.1	5.6	0.5		47	10.6	-2	0.3
Lyn	5 AC	2009.865	3	6h 27m	58	272	95.8	5.4	7.9	2.5		273	92.3	1	-3.5
	12 AC	2009.865	3	6h 46m	59	309	8.7	5.4	7.0	1.6		308	8.9	-1	0.2
Lyr	ε 1,2		0	18h 44m	40	174	210.5	5.0	5.3	0.3				0	0.0
	ε 1		0			349	2.3	5.2	6.1	0.9	1725			0	0.0
	ε 2		0			81	2.4	5.3	5.4	0.1	724			0	0.0
	ζ	2009.350	3	18m 45m	38	150	43.8	4.3	5.6	1.3		148	42.2	-2	-1.6
	β AB	2009.350	3	18h 50m	33	150	45.4	3.6	6.7	3.1		147	45.1	-3	-0.3
	β AE	2009.356	3			317	67.2	3.6	10.1	6.5		314	71.4	-3	4.2
	β AF	2009.356	3			18	85.9	3.6	10.6	7.0		19	85.8	1	-0.1
	SHJ 282	2009.350	3	18h 55m	34	349	45.1	6.1	7.6	1.5		350	45.1	1	0.0
	η	2009.356	3	19m 14m	39	80	28.1	4.4	8.6	4.2		80	25.9	0	-2.2
Mon	8	2009.058	3	6h 24m	5	29	12.1	4.4	6.6	2.2		32	12.4	3	0.3
	β AB	2009.022	3	6h 29m	-7	133	7.1	4.6	5.0	0.4		127	6.6	-6	-0.5
	β BC	2009.022	3			108	2.9	5.0	5.3	0.3		100	2.9	-8	0.0
	ζ	2009.058	3	8h 9m	-3	247	64.7	4.4	9.7	5.3		247	61.2	0	-3.5

Table 1 continued on next page.

Table 1 (continued): Double and Multiple Stars Observed with the Hevelius.

Const.	Star	yy/mm/dd	N	RA	Dec	PA	Sep	M1	M2	M2-M1	Per.	PA-H	Sep-H	DPA	DSep
Oph	ρ	2009.225	3	16h 26m	-23	337	3.3	5.1	5.7	0.6		334	3.3	-3	0.0
	36	2009.205	3	17h 15m	-27	146	4.7	5.1	5.1	0.0		143	5.2	-3	0.5
	39	2010.073	3	17h 18m	-24	355	10.0	5.2	6.6	1.4		353	10.3	-2	0.3
	67	2009.235	3	18h 1m	3	142	54.3	4.0	8.1	4.1		139	55.9	-3	1.6
	70	2009.241	3	18h 6m	2	132	5.7	4.2	6.2	2.0	88.4	131	5.3	-1	-0.4
Ori	23	2009.586	3	5h 23m	4	29	31.6	5.0	6.8	1.8		30	31.5	1	-0.1
	δ	2008.989	3	5h 32m	0	0	52.8	2.4	6.8	4.4		359	52.8	-1	0.0
	θ_2	2009.589	3	5h 35m	-5	93	52.2	5.0	6.2	1.2		95	51.6	2	-0.6
	λ	2008.986	3	5h 35m	10	44	4.3	3.5	5.5	2.0		50	4.9	6	0.6
	θ_1 AB	2009.008	3	5h 35m	-5	31	8.8	6.6	7.5	0.9		30	7.8	-1	-1.0
	θ_1 AC	2009.008	3			132	12.7	6.6	5.1	1.5		132	12.3	0	-0.4
	θ_1 CD	2009.008	3			61	13.3	5.1	6.4	1.3		58	12.6	-3	-0.7
	I	2009.019	3	5h 35m	-6	141	11.3	2.9	7.0	4.1		135	10.2	-6	-1.1
	S 747	2009.008	3	5h 35m	-6	224	36.0	4.7	5.5	0.8		224	36.0	0	0.0
	σ AB-D	2008.995	3	5h 39m	-3	84	12.7	3.8	6.6	2.8		85	12.1	1	-0.6
	σ AB-E	2008.995	3			62	41.5	3.8	6.3	2.5		62	42.2	0	0.7
Peg	1	2009.312	3	21h 22m	20	312	35.9	4.2	7.6	3.4		308	40.3	-4	4.4
	η	2009.370	3	22h 43m	30	339	93.8	3.0	9.9	6.9		338	94.6	-1	0.8
Per	η	2008.817	3	2h 51m	56	301	28.5	3.8	8.5	4.7		295	31.2	-6	2.7
	S 331	2009.816	3	3h 1m	52	85	11.9	5.2	6.2	1.0		84	12.3	-1	0.4
Psc	ψ_1	2009.181	3	1h 6m	21	161	30.0	5.3	5.5	0.2		158	29.6	-3	-0.4
	ζ	2009.173	3	1h 14m	8	62	22.8	5.2	6.2	1.0		63	25.5	1	2.7
PsA	β	2008.814	3	22h 32m	-32	173	30.4	4.3	7.1	2.8		170	34.9	-3	4.5
	D 241	2008.819	3	22h 37m	-32	31	93.3	5.9	7.6	1.7		31	91.8	0	-1.5
Pup	D 31	2009.824	3	6h 39m	-48	320	12.9	5.1	7.4	2.3		319	13.7	-1	0.8
	π	2009.088	3	7h 17m	-37	213	68.9	2.9	7.9	5.0		213	66.5	0	-2.4
	P AB	2009.731	3	7h 35m	-28	150	38.3	4.6	9.1	4.5		141	36.9	-9	-1.4
	κ	2009.088	3	7h 39m	-27	318	9.8	4.4	4.6	0.2		317	10.2	-1	0.4
	h 4038	2009.986	3	8h 3m	-41	347	24.3	5.5	9.0	3.5		343	26.5	-4	2.2
	19 AE/ AD	2009.715	3	8h 11m	-13	257	69.2	4.8	8.4	3.6		257	67.3	0	-1.9
	D 67	2009.794	3	8h 14m	-36	176	66.9	5.0	6.0	1.0		174	65.5	-2	-1.4
	S 568	2009.824	3	8h 25m	-24	90	42.2	5.5	8.4	2.9		89	40.9	-1	-1.3
Pyx	ζ	2009.794	3	8h 40m	-30	61	52.4	5.0	9.6	4.6		59	51.3	-2	-1.1
Sgr	Pz 6	2009.252	3	17h 59m	-30	107	5.8	5.4	7.0	1.6		100	5.6	-7	-0.2
	μ AD	2009.255	3	18h 14m	-21	312	48.7	3.9	10.0	6.1		314	51.0	2	2.3
	μ AE	2009.255	3			115	50.6	3.9	9.2	5.3		112	49.4	-3	-1.2
	β	2009.334	3	19h 23m	-44	76	28.6	4.0	7.2	3.2		77	26.0	1	-2.6
	54	2009.813	3	19h 41m	-16	42	44.7	5.4	7.7	2.3		41	45.6	-1	0.9

Table 1 continued on next page.

Binary Star Measurements with a 17th Century, Long-Focal, Non-Achromatic Refractor

Table 1 (conclusion): Double and Multiple Stars Observed with the Hevelius.

Const.	Star	yy/mm/dd	N	RA	Dec	PA	Sep	M1	M2	M2-M1	Per.	PA-H	Sep-H	DPA	DSep
Sco	ξ	2009.219	3	16h 4m	-11	48	7.5	4.9	7.3	2.4		48	8.0	0	0.5
	S 1999	2009.219	3	16h 4m	-11	98	11.8	7.5	8.1	0.6		101	13.3	3	1.5
	β	2008.756	3	16h 5m	-20	20	13.6	2.6	4.5	1.9		21	14.2	1	0.6
	ν Aa-C	2008.726	3	16h 12m	-19	337	40.8	4.2	6.6	2.4		336	39.4	-1	-1.4
Scl	δ	2008.828	3	23h 49m	-28	296	74.7	4.6	9.4	4.8		294	74.0	-2	-0.7
Ser	δ	2008.751	3	15h 35m	11	174	4.0	4.4	5.2	0.8	1038	173	4.6	-1	0.6
	ν or 53	2009.235	3	17h 21m	-13	26	45.9	4.3	9.4	5.1		25	44.5	-1	-1.4
	h 4964	2010.073	3	17h 35m	-11	225	54.3	5.5	9.9	4.4		223	53.2	-2	-1.1
	θ	2009.235	3	18h 56m	4	104	22.3	4.6	4.9	0.3		103	23.0	-1	0.7
Tau	φ	2008.808	3	4h 20m	27	256	49.2	5.1	7.5	2.4		261	49.1	5	-0.1
	χ or 59	2009.876	3	4h 23m	26	24	19.8	5.4	8.5	3.1		20	20.2	-4	0.4
	88	2008.852	3	4h 36m	10	300	69.1	4.3	7.8	3.5		300	70.5	0	1.4
	τ	2008.811	3	4h 42m	23	214	63.0	4.2	7.0	2.8		215	62.0	1	-1.0
Tri	ι	2008.830	3	2h 12m	30	69	3.9	5.3	6.7	1.4		67	3.9	-2	0.0
UMa	41	2009.923	3	9h 29m	46	161	71.8	5.5	7.8	2.3		162	71.1	1	-0.7
	α		0	11h 4m	62	204	381.0	2.0	7.0	5.0				0	0.0
	ζ (Mizar)	2008.797	3	13h 24m	55	153	14.3	2.2	3.9	1.7		153	16.2	0	1.9
Vel	γ AB	2009.800	3	8h 9m	-47	219	41.0	1.8	4.1	2.3		221	40.3	2	-0.7
	γ AC	2009.800	3			152	62.6	1.8	7.3	5.5		152	61.5	0	-1.1
	γ AD		0			142	93.9	1.8	9.4	7.6				0	0.0
	α AC	2009.986	3	8h 29m	-48	40	18.9	5.5	9.2	3.7		40	19.6	0	0.7
Vir	γ		0	12h 42m	-1	var	Var	3.5	3.5	0.0	169			0	0.0
	τ	2009.575	3	14h 2m	2	290	81.0	4.3	9.5	5.2		291	80	1	-1.0

Table 2: Additional Measurements of Relatively Short Period Binary Stars

Star	Date	# Obs.	PA	Sep.
Xi Bootes	2010.287	3	310	5.9
Alpha Gemini	2009.950	3	68*	4.6
Gamma Leo	2010.098	3	120	4.0
36 Ophiuchus	2010.364	3	140	5.3
70 Ophiuchus	2010.350	3	128	5.6

* Questionable

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(Continued from page 284)

ter and when the light from the crosshairs is added, I cannot see them at all. Also, ε Lyra 1 and 2 are so close (2.3 and 2.4", respectively) that I generally cannot split them (the closest pair I have successfully measures is β BC Monocerus at 2.9"). Finally, γ Virgo has just passed its periastron and will not be resolvable again for a few more years. Thus the total number of pairs I have measured with the Hevelius is 164.

There are some informative trends observed in the data set regarding the differences between my measurements with the Hevelius and the published values. Assuming for simplicity that the published values are absolutely correct and the differences between the published values and my values for the PAs (ΔPA) and Seps (ΔSep) are solely due to errors in my measurements, then the data show the following:

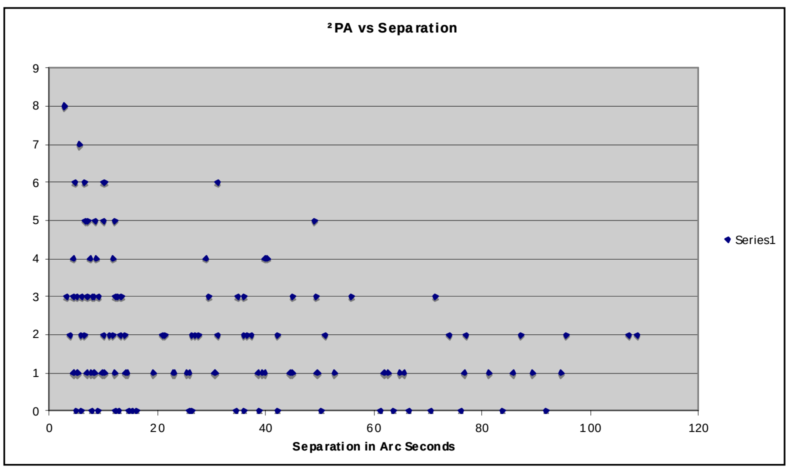

Figure 6: The dependency of the absolute value of DPA on the separation of a double star pair.

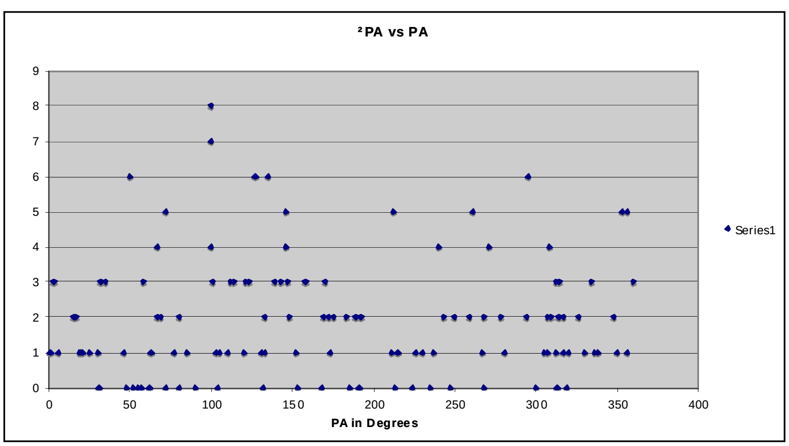

Figure 7: The dependency of the absolute value of DPA on PA of a double star pair.

First, as shown in Figure 6, ΔPA decreases with increasing Sep of the stars. This is expected because of the line joining the two stars is much more accurately estimated for wider pairs.

Second, while observing, I noticed that the difficulty in measuring the PA depends on the angle of the stars' westward motion with respect to the crosshairs. As seen in Figure 7, there is a tendency for the ΔPAs to be greatest at PAs of 90° and 270°and smallest at 0° and 180.

Third, Figure 8 shows that ΔSep tends to increase with increasing Sep, as I expected.

Fourth, ΔSep tends to increase with increasing differences (ΔM) in the magnitudes of the primary (M1) and secondary (M2) star, as I expected (Figure 9).

Fifth, like the measurement of the PA, the measurements of Sep vs. PA show a slight dependency on the PA, in that ΔSep tends to be greatest at 90° and 270° degrees and smallest at 0° and 180° (Figure 10).

Regarding the real values of ΔPA and ΔSep given in the 15th and 16th columns in Table 1: if all the differences between my measurements and those given in the double star lists were due to random errors in my measurements, then the sum of all data in each column would be zero, i.e., the negative and positive values would cancel each other out and this is not the case. The sum of the real values of ΔPA is -85° for the 164 stars measured. Thus there is an insignificant -0.52° bias in my measurements of the PA. Similarly, the sum of the real values of ΔSep is +7.5", yielding an insignificant +0.05" bias in my measurements of the stars' Seps.

From the data on the absolute values of ΔPA and ΔSep in Table 1, the sum of the absolute values of ΔPA is 327° for the 164 stars, which yield an average ΔPA of just under 2.0°. Similarly, the sum of the absolute values of Δ Sep is 172.5" for the 164 stars, which yield an average ΔSep of just over 1.0".

As amazing as these results were to me, I was even more pleased when Dr. William Hartkopf of the Naval Observatory e-mailed me after I sent him a copy of the article I published in the *Journal of the Antique Telescope Society*. Dr. Hartkopf had added my Hevelius measurements to the *Washington Double Star Catalog* (!) and had matched my measurements against their orbit and recti-

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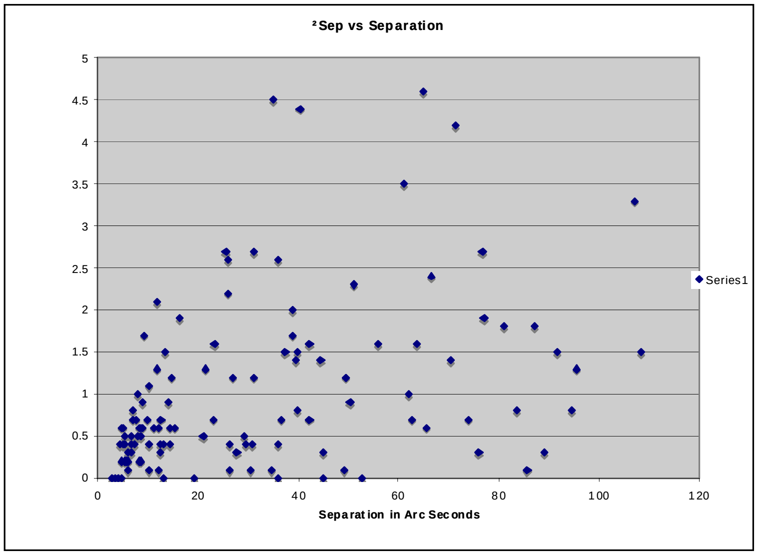

Figure 8: The dependency of the absolute value of DSep on the separation of a double star pair.

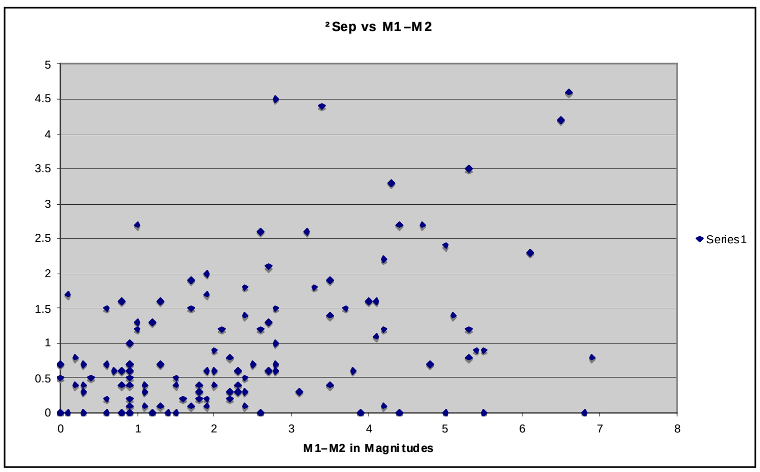

Figure 9: The dependency of the absolute value of DSep on the difference between the magnitudes of the primary (M1) and secondary (M2) stars of a double star pair.

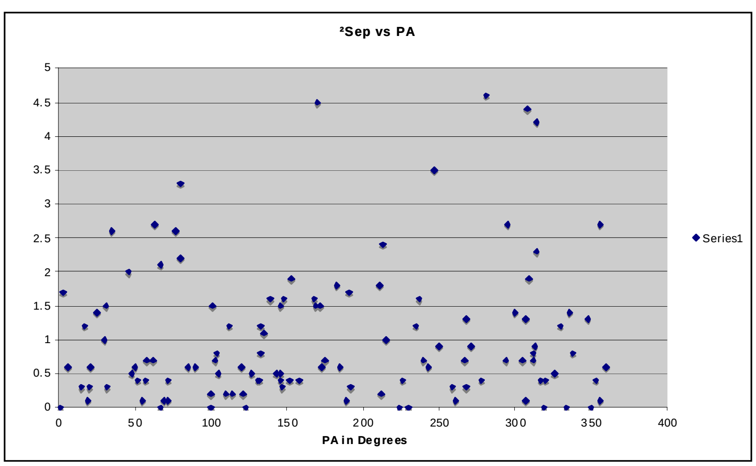

Figure 10: The dependency of the absolute value of ΔSep on the PA of a double star pair.

linear elements catalogs to determine the actual residuals. Of the 121 Hevelius measured pairs, 29 have either a published orbit - or a set of rectilinear elements, from which accurate calculations of the PAs and Seps were made for the dates on which I make the Hevelius measurements. Dr. Hartkopf found that the mean PA residual between the observed and calculated PAs for those 29 pairs is a negligible 0.12° (23% of that given in Table 1) and the mean absolute PA error is 1.57° (79% of that given in Table 1). The mean absolute Sep residual is only 0.63" (60% of that given in Table 1). However, he considers that the more appropriate measure of the quality of the Sep measures is the ratio of observed Sep to calculated Sep. He found a mean value of Sep(obs)/Sep(cal) of 0.9973 - i.e., the measurements are good to 0.3%. A similar calculation for all the data given in Table 1 yields a ratio of 0.9846 – i.e., the Hevelius measurements are good to 1.54% when compared to published (not calculated) values, much larger than for the 29 calculated pairs, but still very small. Dr. Hartkopf's comparisons suggest that the Hevelius measurements are even better than I found from my comparisons with the data given in Hass' book.

Given all the sources of observational errors discussed above and the "primitive" nature of the Hevelius, I find these errors and biases remarkably small. Further, if I were to measure these stars every year for a few years, as a 17th century astronomer probably would have done, the "errors" is my measurements would decrease significantly for the vast majority of the pairs since their periods are very long.

"Short Period" Binary Measurements

There are eight pairs of stars in Table 1, whose orbital periods are between 88 years (70 Ophiuchus) and 659 years (61 Cygnus). Thus, I expect to be able to note changes in their PAs and Seps within a few years to a decade or two, as would have a 17th century astronomer. So I have started to re-measure these "short period" binaries, the current measurements of which are given in Table 2 – though it is too early to have detected any conclusive orbital motion in these systems.

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Conclusions

My experience with the Hevelius and its micrometer clearly shows that there are at least 175 pairs of stars in double and multiple star systems brighter than 5.5 magnitude within the reach of a typical 17th century, non-achromatic, long-focal, non-achromatic refractors. Had any of the early astronomers made a systematic investigation of even the stars brighter than the 5th magnitude, they would have discovered well over 100 binary pairs - depending on just what they considered to be a double star (i.e., how close did they have to be and what would their relative brightness have to be to be considered a double star) and what the observer's latitude was compared to my 32° north latitude. Further, they could have made micrometer measurements with accuracies of 1° to 2° in PA and 1" or better in Sep and in doing so, they would have detected the orbital motions of at least a few of these binaries and provided an extra 100 years of baseline data for studying the orbital motions of all binaries. Unfortunately, this was not done in the 17th century and double star astronomy did not really get started until Herschel's time a century later.

Further, though the data reported here were made with a very simple and very primitive telescope, the measurements are on par with those made with modern telescopes and advanced measuring equipment. Thus, I hope my experience with the Hevelius will encourage observers with even modest telescopes to start observing and measuring binary stars and publishing these data for inclusion in the catalogs.

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