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Astrometric analysis of the field of AC +65°6955 from plates taken with the Sproul 24-inch refractor

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Positions of 12 stars on 423 plates taken from 1937 to 1969 with the Sproul 24-inch refractor are analyzed. Small changes are found in the astrometric field which are related to the history of the objective lens. An absolute parallax of +0.″1230.″002 for AC +65°6955 is determined.

INTRODUCTION

The nearby M3 dwarf, AC +65°6955 (Gliese 793, 1950: 20^h29^m8, +65°17′), has been on the Sproul astrometric program since 1937. The plate series was first measured from 1938 to 1947 (van de Kamp and Lippincott 1949) and later from 1947 to 1969 on the St. Clair-Kasten machine, using a reference frame of three stars. The residuals from a parallax solution for 30 yr of manual measurements suggested oscillatory behavior in both x and y, as may be seen in the first pair of residual series, I, in Fig. 1. In order to study the behavior of the star under greater measuring accuracy, the entire series was remeasured on the Strand Automated Measuring Machine (SAMM) at the US Naval Observatory.

I. MATERIAL, MEASUREMENTS, AND PRELIMINARY PLATE REDUCTIONS

The total number of plates and their distribution are shown in Table I. The plate-weighting system of the Sproul Observatory (van de Kamp 1945) was used throughout this study. A total of 12 stars, including AC +65°6955, which appeared consistently over the years, were measured on the SAMM. A 12th magnitude star noted by Worley (1962) at a distance of 35″ from AC +65°6955 shows no proper motion and thus is not a physical companion to the parallax star. The reference star positions and relative motions are given in Table II. A diagram of star positions on the plate is shown in Fig. 2. The plates were measured in a random sequence and in both direct and reverse orientation of the plate. All plates were first reduced by three linear plate constants, using all 11 reference stars, and by performing a separate reduction for each of typically four-exposure sets. All reference star residuals were printed and punched out for further study. Reference star No. 9 was occasionally too large for accurate measuring, and No. 7 was sometimes too faint as indicated by very large residuals for these stars. Mean positions of each star for each plate were formed and punched out for rapid plate reductions with various combinations of reference stars and plate constants.

II. ANALYSIS OF THE MEASUREMENTS

For the first comparison of the automated with manual measurements, the SAMM measurements of the original three reference stars (Nos. 3, 6, 11) were used in a three-constant reduction of all plates. The residuals from a linear motion and parallax solution are graphed in Fig. 1, Solution II, and they confirm the behavior of the manual measurements. A few adjacent years with low weight were combined into

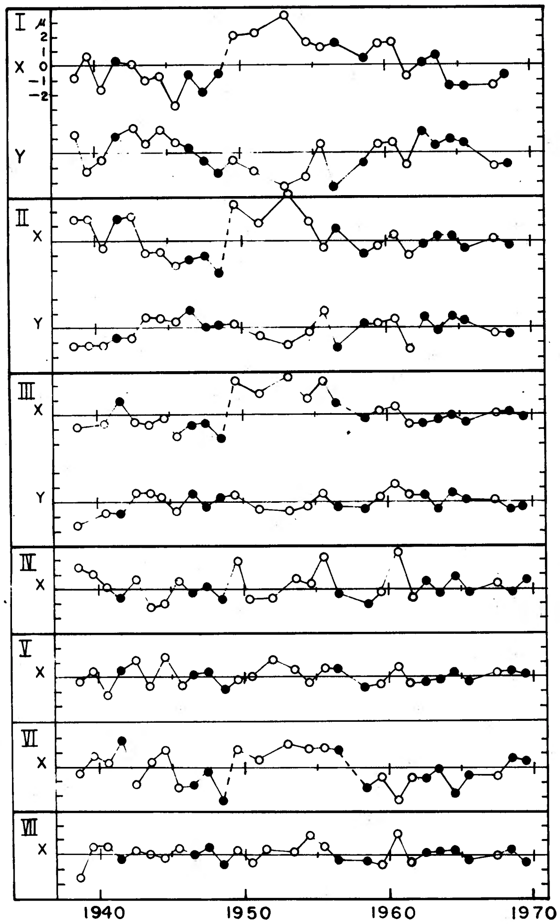

FIG. 1. Yearly mean residuals from several solutions. The source of each residual series is given in Table III and in the text. The weights of the points vary greatly. Points with weight less than 10 are shown as *open circles* ○, and points of weight 10 or greater are shown as *filled circles* ●. A few years of very low weight were combined into single points. The vertical scale is in microns; one $\mu=0\overset{''}{.}01887$ for the Sproul refractor.

single points in Fig. 1. The residuals from the parallax solution for AC +65°6955, referred to all 11 reference stars, also repeat the same long-term pattern, especially in x where the systematic runs are largest (Fig. 1, Solution III). Some plates, where star 7 was too faint, were eliminated from this solution. Table III identifies the series of residuals graphed in Fig. 1.

It is clear from the yearly means in Fig. 1 and also from the individual night means, that a discontinuity of about 3.5 μ is present in x at 1949. This coincides with the installation of a new cell for the 24-inch objective lens and a change in photographic emulsion in 1949.2. The less distinct break at 1957 coincides with adjustments of the objective lens from 1957.74 to 1958.03. An initial check on the instrumental origin of this behavior is the appearance of residuals from the plate reductions of reference star 4 which is the closest one to the center of the plate. The behavior in x of the yearly mean residuals of star 4, with linear motion and relative parallactic motion removed, is shown in Fig. 1, Solution VI. The pattern of the parallax star is repeated there with a somewhat smaller discontinuity in 1949, but a larger one in 1957.

In order to investigate the nature of the change in the astrometric field, the plates were reduced with different fourth terms in the equation of plate reduction. The various fourth terms tried were a magnitude term, a coma term, a color term, a quadratic term, and a radial term, $\rho=(x^2+y^2)^{\frac{1}{2}}$. The magnitude, color, and coma terms made no appreciable change in the behavior of the parallax star in 1949.2. The quadratic term reduced the 1949 discontinuity by about 25%. This is consistent with the results for the radial term which is described in detail below.

A study of the behavior of all 11 reference star residuals before and after 1949 shows a discontinuity in x which appears to be a function of the distance from the center of the plate. No discontinuity was found in y for the parallax star or the reference stars. Table IV gives the difference in x for each star and the radial distance, ρ, from the center of the plate. The differences were formed by subtracting the mean of the 10 night residuals in x preceding 1949.2 from the mean of 10

TABLE I. Yearly plate data.

Mean epoch	Number of nights	Number of plates	Total weight
1938.63	3	5	3
39.63	4	4	6
40.71	2	6	4
41.62	4	12	10
42.62	2	8	6
43.65	3	12	9
44.71	4	14	9
45.57	3	12	9
46.53	6	21	17
47.57	5	16	12
48.51	4	16	12
49.62	2	8	6
50.43	1	4	3
51.52	2	8	6
52.42	1	7	3
53.67	3	8	9
54.92	3	9	8
55.81	2	8	3
56.68	5	14	14
57.54	1	8	3
58.43	4	14	13
59.50	3	11	6
60.73	2	4	4
61.76	2	12	6
62.73	5	20	15
63.60	10	32	28
64.68	6	21	16
65.57	10	28	27
67.63	3	12	9
68.61	9	27	25
69.69	12	42	37
Totals	126	423	338

TABLE II. Reference star data, equator of 2000, epoch 1941.6.

No.	x mm	μ_x 0.001 mm/yr	y mm	μ_y 0.001 mm/yr	Mag[a]	Spectrum	Name
1	−67.709	+ 2.81	−56.912	+ 1.64	10.8	G0	AC +64°6803
2	−54.936	− 1.01	+31.935	− 2.40	10.0	G0	AC +65°6966
3	−47.483	+ 0.73	−10.749	+ 1.10	11.1	F5	AC +65°6951
4	−20.870	− 1.30	− 3.402	+ 0.30	9.0	F5	BD +65°1471 AC +65°6953
5	−11.609	− 0.63	+19.796	+ 0.36	10.9	G:	...
6	+ 0.716	− 0.44	+29.407	− 0.77	10.6	F8	AC +65°6963
7	+23.631	− 1.66	−10.749	− 1.91	11.3	G0	AC +64°6813
8	+24.207	− 4.71	+13.674	− 1.19	10.8	G0	AC +65°6962
9	+41.988	+ 2.57	+31.429	+ 0.98	8.6	F8	BD +65°1477 AC +65°6964
10	+48.844	− 4.20	+30.177	+ 2.66	10.2	F8	AC +65°6965
11	+63.219	− 0.46	−53.350	− 0.78	10.2	F2	AC +64°6806
π	+ 1.635	+23.09	−11.123	+15.11	10.43	dM3	AC +65°6955

[a] Approximate photovisual magnitude determined from image diameters.

nights following 1949.2. Differences formed in the same way for the apparent 1958 discontinuity show a shift for only the parallax star and for star 4, which is nearest the center. Since the differences around 1949.2 are approximately a linear function of ρ, all of the plates were reduced with a fourth term, ρ, in the equation of plate reduction. The value of ρ for the parallax star is zero, which results in a rather large extrapolation from the effect present in the reference stars. A study of the residuals of the parallax star showed that over-correction was present. The effect would not be expected to peak sharply at the plate center, and after several trials, the value of ρ for the parallax star was adopted as 1.2 cm. Also the positions and motions of the reference frame were refined so that differences between reference frame and current positions of reference stars were on the level of one micron or less and thus did not appreciably mix into the coefficient of ρ determined in the plate reductions. A graph of the coefficient of ρ across the 31 yr also reveals the change in the astrometric field. The introduction of the fourth constant in the plate reductions increases the probable error of unit weight of the parallax solution slightly because the fourth constant is not strongly determined relative to the accuracy of a single plate, and thus takes advantage of random errors of the reference stars. However, the dispersion of the normal points is greatly reduced (Table III, Col. 6), and the systematic displacement from 1949 to 1957 is removed as may be seen in Fig. 1, Solution IV. The appearance of these residuals gives no indication of an astrometric orbit.

Another approach to the problem is to determine the shift, in each segment of time, necessary to minimize the residuals. This was done by using the equation $x=c+\mu_x t+\pi P_\alpha+c_1\delta_1+c_2\delta_2$. Here $\delta_1=1$ for 1941.8 (when the objective was also adjusted) to 1949.2 and $\delta_1=0$ for all other time; and $\delta_2=1$ for 1949.2 to 1958.0 and $\delta_2=0$ for all other time. The solution yielded constants $c_1=-1.4\mu\pm0.2\mu$ (p.e.) and $c_2=+1.5\mu\pm0.2\mu$ (p.e.). The value of c_1 has the effect of removing the well determined color effect in 1941 (Lippincott 1957).

Both the p.e.1 and the dispersion of normal points were reduced as shown in Fig. 1, Solution V. The use of the δ terms gives a much lower probable error of unit weight than the four-plate constant method but it is not clear which is the best mathematical model of the behavior of the telescope.

III. INTERNAL ERRORS

The large amount of material and high measuring accuracy on this star field invite more discussion on the old subject of errors in the astrometric process. A solution for parallax, linear motion, and constant was made for the plate residuals of each of the 11 reference stars and in both coordinates. The diameter of star 9 was known in advance to be too large on many plates for good measurements and it gave a parallax effect of $+0''.060\pm0''.010$ in y but a slightly negative value in x, suggesting a seasonal effect in this very bright star. This effect is large enough to introduce appreciable parallax into the reference frame and thus a plate

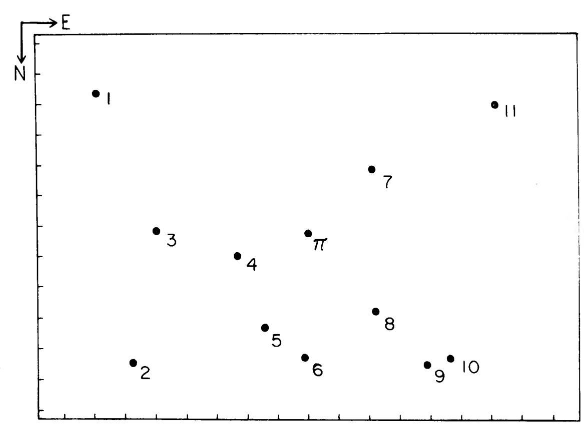

FIG. 2. Diagram of the star positions on the plate. The scale marks are cm; one cm = 188″.7.

TABLE III. Data for Fig. 1.

Solution	Measuring	Plate reduction	p.e.1 x unit 0.001 mm	p.e.1 y unit 0.001 mm	p.e. of a yearly normal point in x (average wt. 10) unit 0.001 mm
I	Manual	dependences 3 ref. stars	±2.15	±1.75	±1.00
II	SAMM	plate const. 3 ref. stars	1.63	1.35	0.81
III	SAMM	plate const. 11 ref. stars	1.42	1.12	0.99
IV	SAMM	4 plate const. 11 ref. stars	1.61	...	0.55
V	SAMM	3 plate const. 2 δ's in π sol.	1.07	...	0.39
VI	SAMM	Ref. star 4[a]	1.92	...	0.51
VII	SAMM	Ref. star 6[a]	0.81	...	0.28

[a] These entries refer to parallax solutions made on the residuals from plate reductions on reference stars 4 and 6.

reduction of three constants was done on eight reference stars eliminating star 9, star 1, which is also somewhat too bright, and star 7, which is too weak on many plates. The parallax solutions from the residuals of these eight stars yielded parallaxes which do not correlate with the expected values of the star parallaxes based on their magnitudes and spectral types. Two stars give "internal" parallaxes consistent in x and y of $+0''.008$ and $-0''.012$, which are three and four times their probable errors. Again this suggests the presence of small seasonal systematic errors for these stars which are comparable to the typical correction from relative to absolute parallax, and perhaps sets limits to the accuracy of parallax determinations, especially with few reference stars.

The relative parallax referred to the eight star frame is probably the best for AC $+65°6955$ and is $+0''.120 \pm 0''.002$ with $(\pi_x - \pi_y) = +0''.006 \pm 0''.005$. This agrees very well with all values determined at other observatories, and supersedes the earlier Sproul parallax. The absolute parallax is $0''.123 \pm 0''.002$ and the absolute visual magnitude is 10.88 ± 0.05, using $m_v = 10.43$ (Gliese 1969).

Comparisons of the p.e.1 from solutions using various combinations of reference stars are shown in Table V. These comparisons were made from plate reductions using three constants and restricted to the material from 1959 to 1969, where the coverage is good and the p.e.1 is not enlarged by the systematic shift in 1949. The precision of these probable errors is about 3%. The gain in accuracy is slow with increasing number of reference stars, but it must be remembered that the best stars were chosen for the three original reference stars and so increasingly poorer quality stars are being used as the number of reference stars increases.

The values for reference star 6, which are included in Table V, result from the eight star-reference frame and plates from 1959 to 1969. This reference star has an ideal diameter on the plates; it lies at the zero point of 1949 differences as may be seen in Table IV, and it is favorably situated relative to other reference stars. The probable error of the internal parallax for this star in x is $\pm 0''.0016$, smaller than most corrections from relative to absolute parallax, and normal points of weight 30 have a dispersion of only $0.1\,\mu$. This is further proof of the high accuracy of the SAMM measurements. The yearly mean residuals are shown in Fig. I, Solution VII.

The high measuring accuracy for this star field in the 1959–1969 interval provides good material for another check on the existence and size of the emulsion and "night" errors. Following the method of Land (1944), the emulsion shift was found to be $\pm 0.13\,\mu$ (p.e.) and the night error to be $\pm 0.30\,\mu$ (p.e.). A slightly simplified method, which uses equations involving only night error and emulsion shift yielded $\pm 0.27\,\mu$ (p.e.) for the night error and $\pm 0.19\,\mu$ (p.e.) for emulsion shift. This is a reduction of 30% to 50% in the same quantities determined by Land in 1944 with the same telescope. The reduction in the emulsion shift and night error may be due in part to the use of 11 reference stars which partly removes distortions. The reduction of emulsion shift may also be due to improved emulsion stability in plates of recent manufacture. The

TABLE IV. Residual differences around 1949.

	Parallax star	4	7	5	8	6	3	9	10	2	11	1
		Reference star number										
Difference (unit 0.001 mm)	+3.3	+2.3	+1.1	+1.7	+0.1	0.0	−0.3	−1.0	−0.8	−1.1	−0.4	−1.1
ρ (unit 1 cm)	(1.2)	2.5	3.2	3.4	3.5	4.2	5.2	5.9	6.3	7.2	7.6	8.3

TABLE V. Some error comparisons for plates from 1959 to 1969.

Reference stars	Measuring machine	micron unit		
		p.e.1_x	p.e.1_y	p.e.1_{xy}
3 ref. stars	Manual	±1.66	±1.12	±1.39
3 ref. stars	SAMM	1.00	0.95	0.98
8 ref. stars	SAMM	0.93	0.99	0.96
11 ref. stars	SAMM	0.87	0.95	0.91
Ref. star 6[a]	SAMM	0.66	0.86	0.76

[a] The p.e.1 values refer to a parallax solution on the residuals from plate reduction of reference star 6.

reduction in other accidental errors is almost certainly due to the better measuring technique.

IV. CONCLUDING COMMENTS

It is clear that the plate field of AC +65°6955 has experienced one or more sudden small changes in the x coordinate due to adjustment of the objective lens and change of emulsion. Good plate coverage and accurate measuring are necessary to reveal this effect clearly. The results presented here are not inconsistent with a study of residuals of all Sproul Observatory stars at high declination (Lippincott 1971). Also, there is no apparent discontinuity in some Sproul plate series where the plate coverage is strong and manual measurements would suffice to detect it. Furthermore, no effect is detectable in this or any other Sproul plate series for 1967 when the objective lens was removed from the cell for renovation of the telescope. It is difficult to ascribe any simple cause to these effects in the plate field since they appear to vary greatly through right ascension and declination and to occur only in the x coordinate. Factors such as figure of the lens, alignment of the components, flexure of lens and tube, changing amounts of coma and other seasonal effects, may all be involved. Accurate measurements of more star fields with good plate coverage in various declinations should clarify the history of the behavior of the lens, and maintain the continuity of the astrometric plate series.

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