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ACCURATE POSITIONS OF THE PLANET PLUTO FROM 1974 TO 1978

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ABSTRACT

Seventy-one geocentric positions of the planet Pluto in the years 1974 to 1978 are given with reference to AGK3 stars. Comparison of these positions with the Ephemeris of Kaplan *et al.* (1972) shows a clear epoch dependent systematic difference in both Right Ascension and Declination.

I. INTRODUCTION

A long-term program to measure the positions of the planet Pluto started at Asiago Observatory ten years ago. During this period we tried to keep as constant as possible the several factors leading to the determination of the celestial coordinates of the planet, from the emulsion type to the computer programs, the most notable exception being the measuring machine. With the present third paper (the previous two have been published by Barbieri *et al.* in 1972 and 1975) approximately 4% of the orbit of the planet is covered by our set of measurements. The astrometric positions of the planet are referred to AGK3 stars whose equatorial coordinates and proper motions were taken from a magnetic tape kindly supplied by U.S. Naval Observatory.

II. PLATE MATERIAL AND MEASUREMENT PROCEDURE

All plates, unfiltered Eastman Kodak 103a-0 with an exposure time of 15 min, were obtained with the Asiago 67/92 cm Schmidt telescope, which has a scale of 95.8 arcsec/mm. The apparent motion of the planet during the exposure time is not entirely negligible, in some cases amounting to almost two seconds of arc per hour in both coordinates. The calculated positions are therefore referred to the mid-exposure epoch. To obtain an estimate of the internal errors of our method, namely of the accuracy with which the faint image of the planet can be attached to the system of the bright stars, we have used the apparent displacement of Pluto over short times. On 20 nights, two consecutive plates were obtained; all the variables (set of reference stars, Zenith distance, quality of sky etc.) remaining nearly constant, the comparison of the measured displacement in R.A. and Dec. with that calculated from the Ephemerides should provide a reliable figure for our internal error. The results of this test are the following: in R.A. the average of the observed minus the calculated displacement is $0''.03 \pm 0''.19$, in declination it is $0''.04 \pm 0''.29$. The worst figure for the Declination is entirely due to plate 8456, which gives a very high residual of $-0''.96$ in Dec.; this value cannot be attributed to the quality of the plate, which is good, and remains difficult to explain. If we discard it, the average for declination comes down to $0''.01 \pm 0''.21$. Therefore, we take $0''.20$ to represent the internal errors of the positions of Pluto. The evaluation of the external errors is discussed below. In general the 71 plates measured were of good quality; the few plates below the standard are noted in Table I, which gives the astrometric positions. The measurement of the (x,y) coordinates of the reference stars and of the planet were performed with the Astroscan machine at Leiden Observatory. The Astroscan is basically a David Mann Comparator model 422 with two perpendicular screws driven by steppermotors. The densitometer part of the instrument consists of an optical system that illuminates a rectangular area of the plate and focuses that part of the plate onto a Reticon 128 elements photodiodes array (RL128EC). The enlargement of the projection system gives the photodiodes a spacing of 10 μ. The on-line software gives the possibilities to scan a matrix around a certain position on a photographic plate and write the digitized output data onto a magnetic tape. Some calibrated neutral density filters are measured together with the star plate, so it is possible to convert the digital output of the photodiodes into densities in an off-line computer. Optimally finding the position of a stellar image would be done by fitting the true image profile to the measured densities. As this profile is unknown, we used as a "best guess" the measured densities themselves, but rotated around a given position by 180°. Finding the position of the star then consists of finding the maximum of correlation between both direct and rotated densities as a function of the rotation origin. Thanks to the fully automated procedure a large number of AGK3 stars were

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TABLE I. Geocentric position of the planet Pluto.

Plate No.	Epoch (U.T.)			n(AGK3)	R.A. (1950.0)			Dec[a]			(O-C)$_\alpha\cos\delta$	(O-C)$_\delta$[b]	(O-C)$_\alpha\cos\delta$	(O-C)$_\delta$[c]
7688d	1974	DEC	15.0378	12	12	58	18.955	11	48	24.25	1.91	−1.91	1.13	−2.93
7720	1974	DEC	18.0628	54	12	58	31.473	11	48	56.05	1.81	0.22	1.06	−0.80
7731	1974	DEC	19.0833	60	12	58	35.413	11	49	7.31	1.10	−0.45	0.37	−1.46
7750	1974	DEC	21.1417	57	12	58	43.107	11	49	34.56	1.42	−0.17	0.71	−1.18
7811d	1975	JAN	14.0028	67	12	59	34.124	11	59	14.00	1.61	0.08	1.01	−0.86
7822	1975	JAN	15.0285	68	12	59	34.656	11	59	49.24	1.03	0.34	0.42	−0.59
7840	1975	FEB	6.9861	62	12	59	12.938	12	15	34.65	1.20	−0.28	0.52	−1.05
7862	1975	FEB	9.0243	58	12	59	7.920	12	17	10.87	0.81	0.16	0.12	−0.60
7877	1975	FEB	18.1000	55	12	58	40.183	12	24	30.61	0.94	−0.10	0.18	−0.78
7886	1975	APR	8.8639	45	12	54	21.135	13	1	58.67	2.06	−0.63	0.66	−0.94
7900	1975	APR	12.0264	34	12	54	2.282	13	3	41.73	2.38	−0.77	0.92	−1.07
7913	1975	APR	16.9535	42	12	53	33.227	13	6	7.40	2.60	−0.67	1.06	−0.94
7930	1975	MAY	2.8868	58	12	52	5.101	13	11	38.91	2.78	−0.63	1.02	−0.83
7931	1975	MAY	2.9021	57	12	52	5.011	13	11	39.50	2.60	−0.25	0.85	−0.45
7938	1975	MAY	8.9083	60	12	51	35.341	13	12	44.84	2.76	−0.38	0.95	−0.57
7939	1975	MAY	8.9222	60	12	51	35.268	13	12	44.80	2.64	−0.53	0.85	−0.73
7955	1975	MAY	17.9479	62	12	50	55.693	13	13	18.43	2.59	−0.45	0.71	−0.64
7956	1975	MAY	17.9597	61	12	50	55.655	13	13	18.24	2.72	−0.63	0.81	−0.82
7966	1975	JUN	4.8736	55	12	49	59.106	13	10	33.65	2.72	−0.95	0.68	−1.16
7967	1975	JUN	4.8872	55	12	49	59.066	13	10	33.68	2.57	−0.69	0.54	−0.89
7981	1975	JUN	13.8701	64	12	49	43.443	13	7	19.34	2.89	−0.30	0.82	−0.56
7982	1975	JUN	13.8840	64	12	49	43.433	13	7	18.79	3.00	−0.50	0.92	−0.75
7991	1975	JUL	2.9139	64	12	49	41.275	12	56	42.68	2.41	−0.61	0.35	−0.96
7992	1975	JUL	2.9285	64	12	49	41.279	12	56	42.14	2.25	−0.56	0.19	−0.91
8299	1976	JAN	9.0833	52	13	8	23.391	11	6	51.21	0.34	0.45	1.03	−1.00
8300	1976	JAN	9.0993	57	13	8	23.403	11	6	51.80	0.15	0.59	0.83	−0.86
8310	1976	JAN	10.1042	55	13	8	24.976	11	7	20.46	0.63	0.52	1.33	−0.92
8311	1976	JAN	10.1201	55	13	8	24.977	11	7	20.80	0.31	0.40	1.00	−1.05
8341	1976	JAN	27.0278	61	13	8	31.415	11	17	12.13	−0.41	0.26	0.31	−1.09
8364	1976	FEB	8.1069	58	13	8	14.064	11	25	56.54	0.28	0.22	0.97	−1.05
8365	1976	FEB	8.1222	60	13	8	14.027	11	25	57.46	0.22	0.44	0.91	−0.83
8373	1976	FEB	20.9590	64	13	7	37.090	11	36	11.36	0.28	0.68	0.87	−0.48
8374	1976	FEB	20.9750	64	13	7	37.031	11	36	12.65	0.25	0.61	0.84	−0.55
8407	1976	FEB	26.0028	61	13	7	17.954	11	40	20.94	0.60	0.22	1.14	−0.90
8408	1976	FEB	26.0181	56	13	7	17.877	11	40	21.80	0.37	0.32	0.92	−0.80
8427	1976	FEB	28.0049	60	13	7	9.690	11	42	0.38	0.57	0.24	1.11	−0.87
8428	1976	FEB	28.0208	61	13	7	9.629	11	42	1.17	0.68	0.24	1.20	−0.88
8449	1976	MAR	1.0132	61	13	7	1.049	11	43	40.39	0.63	0.52	1.13	−0.57
8450	1976	MAR	1.0285	61	13	7	0.992	11	43	41.15	0.78	0.53	1.28	−0.57
8455	1976	MAR	26.0194	56	13	4	50.511	12	3	18.19	1.42	0.38	1.59	−0.50
8456	1976	MAR	26.0354	57	13	4	50.415	12	3	17.93	1.39	−0.56	1.55	−1.44
8469	1976	MAR	29.9139	58	13	4	27.588	12	6	0.52	1.26	0.18	1.37	−0.67
8470	1976	MAR	29.9313	55	13	4	27.473	12	6	1.05	1.09	0.00	1.19	−0.85
8491	1976	MAR	31.9694	56	13	4	15.350	12	7	23.42	1.10	0.65	1.17	−0.18
8512	1976	APR	3.0458	53	13	4	2.939	12	8	43.21	1.16	−0.27	1.19	−1.09
8513	1976	APR	3.0597	59	13	4	2.868	12	8	44.00	1.33	−0.01	1.37	−0.83
8539	1976	APR	30.9750	60	13	1	20.347	12	21	44.87	1.28	0.27	0.89	−0.40
8540	1976	APR	30.9875	60	13	1	20.289	12	21	44.71	1.41	−0.09	1.02	−0.77
8547	1976	MAY	2.9188	53	13	1	10.017	12	22	14.61	0.97	−0.04	0.57	−0.71
8548	1976	MAY	2.9340	56	13	1	9.952	12	22	14.92	1.20	0.05	0.79	−0.62
8559	1976	MAY	5.0438	58	13	0	58.994	12	22	43.77	0.91	0.26	0.47	−0.40
8560	1976	MAY	5.0576	60	13	0	58.895	12	22	44.03	0.50	0.34	0.06	−0.32
8574	1976	MAY	7.0688	59	13	0	48.788	12	23	7.37	1.38	0.27	0.91	−0.38
8575	1976	MAY	7.0847	58	13	0	48.727	12	23	7.87	1.66	0.60	1.18	−0.05
8576	1976	MAY	23.9896	53	12	59	35.185	12	23	52.37	1.23	0.24	0.57	−0.41
8577	1976	MAY	24.0049	62	12	59	35.128	12	23	51.98	1.22	−0.07	0.55	−0.71
8588	1976	MAY	27.9306	60	12	59	21.535	12	23	33.85	0.22	−0.34	−0.47	−0.99
8937	1977	FEB	26.0701	40	13	16	23.755	10	48	57.88	−0.84	0.51	1.23	−1.18
8946	1977	MAR	14.0243	40	13	15	10.827	11	1	57.18	−0.97	0.51	0.90	−1.03
8953	1977	MAR	24.0438	51	13	14	16.327	11	9	39.81	−0.46	0.54	1.27	−0.92
8975	1977	APR	12.9799	54	13	12	18.174	11	22	38.01	−0.46	0.67	0.96	−0.64
8987	1977	APR	16.9882	57	13	11	54.150	11	24	43.21	−0.31	0.39	1.03	−0.90
8998	1977	APR	22.0160	26	13	11	24.387	11	27	3.20	−0.50	0.55	0.75	−0.72
9004	1977	APR	26.0465	39	13	11	1.084	11	28	39.81	−0.02	0.01	1.17	−1.23
9433	1978	JAN	8.0854	63	13	26	14.423	9	23	8.83	−2.26	1.92	1.47	−0.73
9465	1978	FEB	5.0292	61	13	26	28.208	9	39	1.23	−3.52	1.18	0.33	−1.33
9476	1978	FEB	15.9708	56	13	26	6.933	9	47	11.55	−3.31	1.33	0.49	−1.10
9489	1978	MAY	2.9743	30	13	19	37.676	10	37	56.10	−1.98	1.08	0.77	−0.77
9498d	1978	MAY	28.9132	32	13	17	35.063	10	40	31.84	−1.22	1.07	1.16	−0.73
9508d	1978	JUN	3.8979	30	13	17	14.609	10	39	36.49	−1.34	0.48	0.97	−1.31
9527d	1978	JUN	6.9563	30	13	17	5.563	10	38	56.45	−1.02	1.55	1.27	−0.25

[a] Results corrected for geocentric parallax: *Asiago Astrophysical Observatory*: $\phi = +45°51'45''$, $\lambda = -11°35'.7$, altitude 1045 m.
[b] Residuals formed by the astrometric ephemeris, interpolated to the epoch (E.T.) of the plate, taken from *The Astronomical Ephemeris.*
[c] Residuals formed as above: from the Ephemeris published by Kaplan *et al.* (1972)
[d] Denotes a plate below the standard.

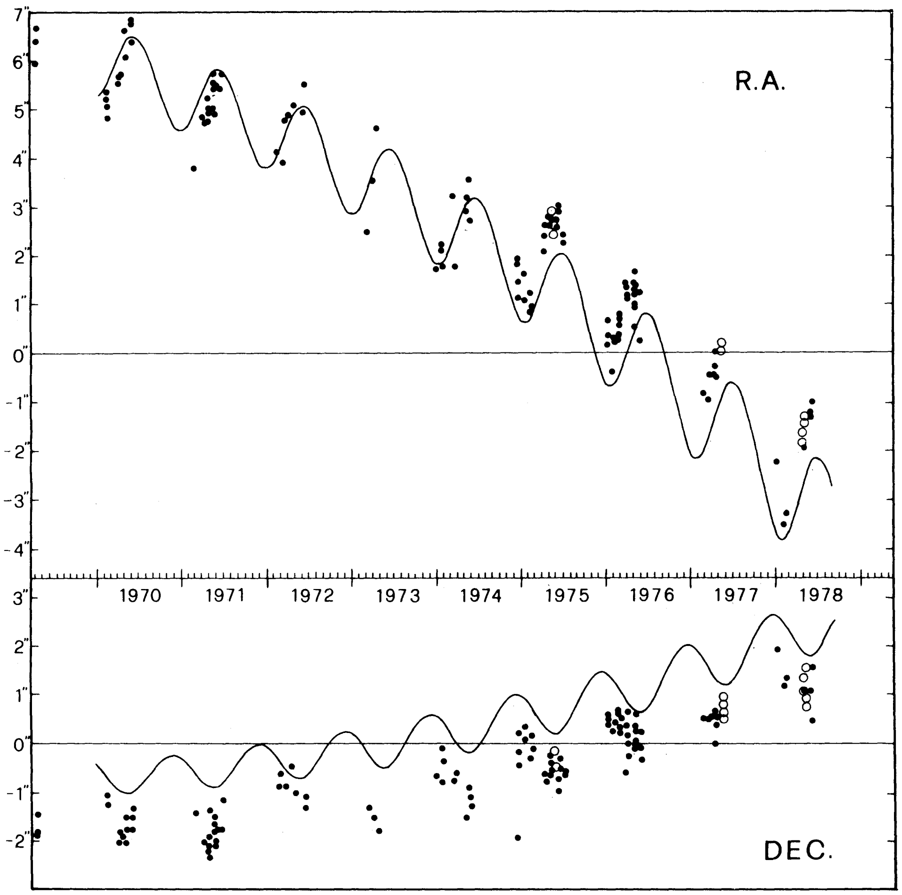

FIG. 1. Differences between the Asiago positions (paper I, paper II and this paper, filled circles) and those published in *The Astronomical Ephemeris* (taken as zero point) and in Kaplan *et al.* (1972) (solid sinusoid). Data from Jensen (1979) are plotted with open circles. Upper part: differences in right ascension; lower part: differences in declination.

measured on each plate. The area to be measured was a priori defined as a circle of 2.0° radius centered on the planet, and every AGK3 star present in this field was measured irrespective of its magnitude. The average number of these was 57; in the transformation from the rectangular to the celestial coordinates all badly fitting stars were discarded and the reduction repeated. In some cases the bright apparent magnitude was responsible for the displacement, but most of the discrepant stars show a systematic residual from plate to plate, suggesting the possibility of an error of the position in the catalog. The rejection level was finally set to 1.0 arcsec; this step however affects only a few stars, the average used in the final solution being 54. In total 3866 measures were obtained of 317 different AGK3 stars. The rms deviation of a single AGK3 star from the final fitting surface is 0″ .394 in R.A. and 0″ .371 in Dec. Regarding the reference surface itself, its uncertainty is very small thanks to the high number of reference stars; the worst case is plate n. 7688 with only 12 AGK3 stars, but this is an exception as shown by Col. 3 of Table I. On average, if the catalog error of an AGK3 star at epoch 1976 is 0.30 arcsec in both coordinates the reference surface is uncertain at the level of 0.05 arcsec. Formally we therefore assign a value of $0.21 = (0.20^2 + 0.05^2)^{1/2}$ arcsec to the rms error of the position of the planet in both coordinates.

III. DISCUSSION

The astrometric positions derived in our papers can be confronted with those published in the Astronomical Ephemeris and with those computed by Kaplan *et al.* (1972). The results of the comparison are shown in Fig. 1, where the data of the A.E. are taken as zero point. The few points available from a recent paper by Jensen (1979) (which are in good agreement with ours) have also been added to the figure for completeness. The first result of this comparison is that indeed the scatter of points around a smooth line parallel to that of Kaplan *et al.* (1972) is consistent with the total error quoted before; there are only two cases of large residuals (plates n. 8456 and n. 8588), not easy to understand because of the good quality of both plates. Second, it can be seen that the orbit used by Kaplan *et al.* (1972) gives a much better fit to the observed positions, as already known (see for instance Fig. 1 of our second paper); nevertheless, a systematic difference both in R.A. and Dec. is present which is clearly a function of epoch. We have fitted the residuals between our position and the orbit used by Kaplan *et al.* (1972) with a regression line. We found an angular coefficient in the $(O\text{-}C)_{\alpha\cos\delta}$ vs Epoch plane of $(5.66 \pm 0.30)\cdot 10^{-4}$ arcsec/day and of (-0.44 ± 0.30)-

$\cdot 10^{-4}$ arcsec/day in the $(O\text{-}C)_\delta$ vs Epoch plane. Therefore the trend of the residuals versus epoch in Dec. is nearly parallel to the epoch axis, but shifted of a quantity $\simeq -0.8$ arcsec, while in R.A. the regression line has a well determined slope (0.21 arcsec per year). Therefore we may say that although the orbit of Kaplan *et al.* (1972) agrees much better with the observations of these ten years than that of the A.E., nevertheless, a revision is needed that takes into account a time interval (and a number of observations) greater than that used in 1972. It is for this reason that our observations will continue in the forthcoming years.

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