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On the use of Hipparcos data for the determination of astrometric positions of outer planets

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Abstract. We investigated the improvement of observed astrometric positions of outer planets by use of Hipparcos Catalogue stars and satellite measurements. Positions of Jupiter from photographic plates were obtained, indirectly, from measurements of the Galilean satellites, using the G5 ephemerides of Bureau des Longitudes. The use of Hipparcos data in the astrometric reductions resulted in positions with an external rms error of 42 mas in right ascension, and 38 mas in declination, which is 5-10 times better than current or classical techniques. Furthermore, with such precision, poorly known instrumental characteristics can be studied, such as the anisotropy of the scale. Finally, an important impact on the fit of planetary ephemerides to the optical observations is expected.

Key words: astrometry – ephemerides – planets and satellites: general – planets and satellites: individual: Jupiter

1. Introduction

The spherical equatorial coordinates (RA, Dec) of the outer planets, such as Jupiter or Saturn, have not been well determined by the classical observational methods. The external mean error of such observations varied from about 200 to 500 milliarcsecond (mas) (Standish 1985, Kharin 1986, Pascu and Schmidt 1990). This error was due to a number of sources. The largest systematic error was called the "phase effect" and due to an augmentation of the geometric phase defect on the planets which was difficult to account for. But also contributing were a number of sources of accidental error, including the magnification of measurement errors by short-focus instruments and the limited accuracy of the astrometric catalogues used in the reduction process of the photographic or CCD images. However, the use of the Hipparcos Catalogue for CCD or photographic reductions, and the combination of satellite measurements with their very accurate relative ephemerides, appear to be good solutions to the problem. While Lindegren (1977) has had some success at reducing the phase effect in transit circle observations of the planets, he "..strongly recommended that the future series of observations of Jupiter are intermingled by observations of Galilean satellites and, eventually, perhaps even replaced by these..." This last method has been used for the first time by Sinclair (1974,1977) for Saturn and used successfully for other planets (Kisseleva et al 1989, Pascu and Schmidt 1980, 1987,1990, Morrison and Buotempo 1997). These studies confirm the interest in this method to obtain positional information of the planet independent of measures made on it. Furthermore, the Hipparcos Catalogue was used for new reductions of Schmidt plates (Robichon 1995) and meridian circle differential observations (Requieme, 1995), but it is not yet involved in photographic or CCD long focus reductions. In this paper we show how to use, in an optimal way, the possibilities of the Hipparcos Catalogue in this kind of reductions, in spite of the very small number of Hipparcos stars in the field of the long focus telescopes used for the available observations. Our aim is to improve the accuracy of the equatorial coordinates (RA, Dec) of the outer planets, especially Jupiter.

2. Use of the Galilean satellites for the determination of equatorial coordinates of Jupiter

The major source of systematic errors in the outer planet astrometry is the phase effect. Due to the lightening gradient and the law of scattering, the determination of the center of mass relative to the photocenter, is very difficult. Techniques based upon photographic emulsions and filters were developed (Pascu 1967,1972) as well as reduction and measurement methods using image analysis (Arlot 1981) or empirical corrections (Lindengren 1977). But, to obtain an astrometric accuracy of around 10 mas in position (RA, Dec), the displacement of the center of light relative to the center of mass of the planet is still a problem. Moreover, the dynamical theories of satellites were developed with the use of various observations - accurate long focus photographic plates, timing of occultations and eclipse phenomena of satellites with the planet, or timing of mutual events - and are more precise than the Jupiter ephemeris itself (Arlot 1981). The combination of accurate relative positions of satellites and observed RA. and Dec. of good quality allows us to obtain accurate equatorial coordinates of the planet. The problem of the phase effect of the planet is removed. For the computation of the planet- relative coordinates of the satellites, we use the G5 ephemerides (Arlot, 1982) which has an accuracy of 20 mas. This value is estimated by comparison with the mutual events (Vasundhara 1996). The algorithm of computation is then the following: first, after the reduction of the plates, we obtain equatorial coordinates (RA, Dec.) of the satellites. All the plates considered here contain more than 2 Galilean satellites. With the G5 ephemerides, we compute their positions relative to the planet. For each satellite, we can deduce from its equatorial coordinates and its planet-relative position, the equatorial coordinates of the planet. We obtain one position of the planet for each satellite. We can make the average of all these values but they are not equivalent. The external observational error can increase as a function of the position of the satellite against the reference stars on the plate. For example, a satellite which is far from the center of the plate or far from the area well covered by the reference stars, can have its coordinates altered, the plate constants being valid in or near the reference area (Van de Kamp, 1967). Furthermore, the dynamical theories of the satellites are also not equivalent and some of them are more precise than the other, in particular for the Saturnian system (Vienne, Private comm.). In consequence, the minimization of the observational and theoretical errors on the determination of the final position of the planet is realized by the choice of the satellites involved in the computation of the average value. The criteria of this selection are the position of the satellite on the plate relative to the reference stars and the accuracy of the theories. The final position is the mean of the positions of the planet deduced from the RA & Dec. of the chosen satellites. In this way, the equatorial positions of the planet are not affected by the phase effect, and we can estimate an external error of such positions as 50 mas.

3. Reduction model - ”Few stars” model

The photographic plates studied here (cf Sect. 4) have a field of 0.75 square degrees and the Hipparcos Catalogue has a density of 2.5 stars per square degree. Consequently, classical plate-reduction models, particularly a 6 constants model, cannot in most cases be applied. However, the scale and the orientation can be obtained independently, and accurate corrections made for refraction, thus, only the offsets in x and y need to be estimated. Separately, an original correction of refraction was applied based on mapping functions (Marini 1972, Yan 1996). In this way, a reduction with a very limited number of stars seems to be theoretically possible.

3.1. Statistical approach

Pascu and Schmidt (1990) proposed a relation between the total, single-image, external error e_t in the position of an object near the center of the plate and the reduction model.

$$e_t^2 = \frac{e_{cs}^2 + (Se_{ms})^2}{n-m} + (Se_{mo})^2 \quad (1)$$

where n is the number of stars, m the number of parameters used in the model, e_{cs}, the precision of the catalogue, e_{ms}, the precision of the measurements on stars, and e_{mo}, on the object. It is impossible with this relation to consider a reduction using only one star. Nevertheless, as we try to make an empirical estimation of the use of the Hipparcos Catalogue, it is possible to consider other laws of distribution of the external error relative to the number of available stars and to the number of parameters determined in the plate solution. It is not inconsistent, indeed, to consider that the external error due to the model, the precision of star catalogue, and the mesurements realized on the plate, could be written as a normal law, in particular as a Lorentz profile, of the number of stars used in the model. We applied these laws in the case of the determination of one parameter (offset in x and y) for 2 catalogues. Then:

$$e_t^2 = \frac{e_{cs}^2 + (Se_{ms})^2}{1+(n-m)^2} + (Se_{mo})^2 \quad (2)$$

We applied these two laws using two astrometric catalogues: the PPM, with an accuracy of about 250 mas and the Hipparcos Catalogue, with an accuracy of around 1 mas and a photocenter determination error of 3 μm (including atmospheric effects). The results are presented in Tables 1 and 2. We see that the use of one or two Hipparcos stars induces external errors better than those obtained with 2 or 5 PPM stars. In a first approximation, the choice of one parameter and ”one Hipparcos star” model is justified by the accuracy of the Hipparcos Catalogue.

Table 1. Single image external error (arcsec) for PPM

n-m	0	1	2	5	10	20
Law 1		0.265	0.192	0.131	0.103	0.085
Law 2	0.265	0.192	0.131	0.080	0.068	0.064

Table 2. Single image external error (arcsec) for Hipparcos

n-m	0	1	2	5	10	20
Law 1		0.088	0.076	0.068	0.065	0.064
Law 2	0.088	0.076	0.068	0.064	0.063	0.062

3.2. Practical approach

When we use long focus telescopes with a small field, only offsets have to be computed, by considering scale and orientation as known. But because of the important correlations between these parameters, it is necessary to improve the determination of the center of the gnomonic projection before setting scale and orientation values. In this way, errors on the position of the center and their propagation on the other parameters are minimized. For the observations reduced with trail and scale, we consider that, by this method, the real orientation of the plate relative to the equator of date is materialized on it, by a star trail. In this case, measurements were made relative to this trail and so the correction in orientation is equal to 0. Then, only offsets need to be determined. Furthermore, in a lot of cases, several exposures were made on the same plate. But only one trail was made, in general after the last exposure. In these cases, the first observations are without trail and the orientation parameters have to be computed. Their values are often near 0, because of insignificant rotation of the plate between the exposures. So in this case, if the orientation coefficient is properly chosen, the

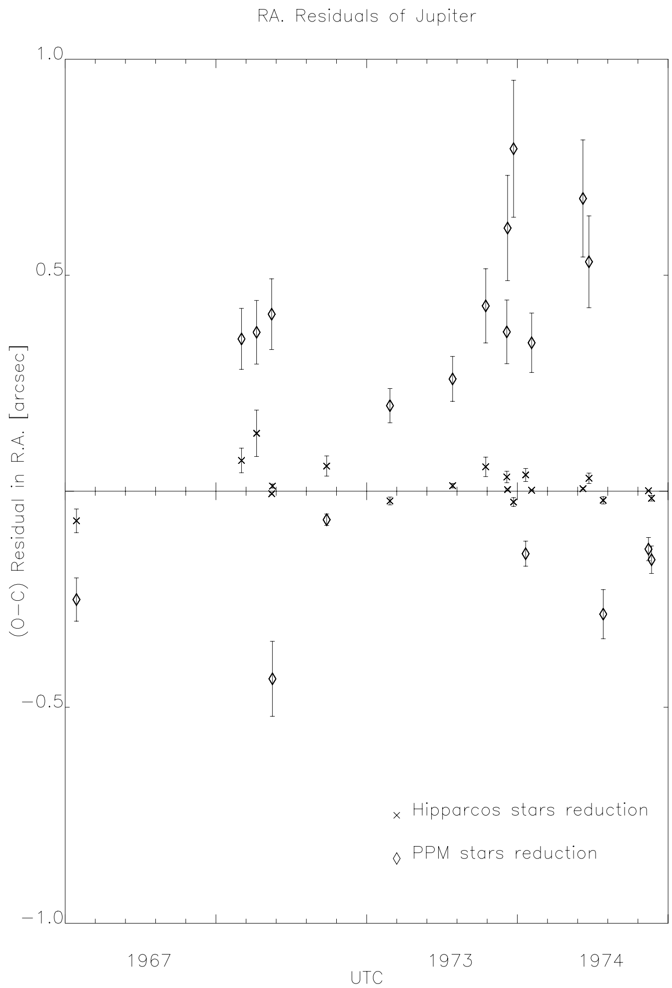

Fig. 1. (Observed -DE403) right ascension of Jupiter - The error bars for the Hipparcos star reduction (×) are multiplied by a factor 2. The plots materialized by ◇ represent the PPM star reduction.

χ^2 of the transformation standard coordinates/measured coordinates should be a minimum. It is possible, knowing the plate scale, to compute the value of the orientation correction with an iterative process on the χ^2 of the plate-to-plate transformation (Guo, 1993). A complementary approach is to consider 2 measured stars, even those not in the astrometric catalogues, but present on all exposures. We compute their inclination relative to the reference trail for each exposure, estimating, using this method, the correction of orientation for each of the exposures. In fact, we minimize the errors on the plate constants before the astrometric computation of the positions of the satellites.

4. Results and analysis

4.1. Global results

The plates that we used here, were taken with the McCormick 26-inch refractor, and its twin at the U.S. Naval Observatory (USNO) in Washington, DC. They were taken between 1967 and 1974 by D.Pascu (Pascu Private Comm. 1996) and partly measured by J.-E. Arlot (1981). The 5 X 7 plates cover a field equal to 0.75 square degrees. Kodak 103aG plates were used together with a yellow filter, Schott GG14. Of the 150 multiple-exposure plates taken, 41 were reduced here, 15 taken at the McCormick Observatory and 26 at USNO. A total of 137 exposures were reduced on these 41 plates. The results presented in this paper are issued from the comparaison between the observed equatorial coordinates of Jupiter obtained after astrometric reduction of the plates (using satellite positions computed from the G-5 ephemerides (Arlot 1982)), and those computed with JPL ephemeris, DE403 (Standish 1995). Figs. 1 and 2 represent the average nightly residuals of Jupiter, the error bars correspond to the standard deviations of several exposures averaged over one night. The improvement due to the use of Hipparcos data is obvious and is around a factor 10 in the average values and also in the standard deviations. These results have a considerable impact on the reduction and observational techniques and also on the planetary ephemerides. Since with this accuracy, small effects due to the reduction processes or dynamical theories can be detected. For instance, Pascu (1994), for the Galilean system, and Vienne (1997) for the Saturnian system, demonstrated respectively a difference between the observed plate scale and that of the satellite theory (with JPL and BdL ephemerides) and an anisotropy of this same parameter.

4.2. 1967 Series: Mc Cormick Observatory

The 48 observations obtained in 1967 have been reduced with at least three Hipparcos stars, permitting a full 6 constants reduction. In Table 3, we can see that the residuals obtained with Hipparcos stars seem to be of the expected order, but the errors in α and δ are slightly different. We can expect that the previous results are biased by a systematic error. The plate scales presented in Table 4 were computed by the least squares method during the reduction process, and then the values of the Table 4 did not include the zenith refraction. No significant offset can be detected.

4.3. 1973/1974 Series: U.S. Naval Observatory

These series are composed of 89 observations reduced with 1 or 2 Hipparcos stars per plate. A 6-constants model was used with 1 (or 2) Hipparcos star and 2 (or 1) PPM stars respectively. The aim here was to make a reduction in using the Hipparcos stars in priority. So, we made a new determination of the plate scales with the usual 6-constants model. The results given in Table 5 show a significant anisotropy of the plate scale, of around 4 mas/mm between x and y. The same plates have been re-reduced with these new values as plate scales and with a limited number of stars; we have only used the 1 or 2 Hipparcos stars considering the scale known. The obtained errors are not significantly different in α and δ. We can make the same comment on the average values. So, the systematic error detected in the 1967 series is neither a consequence of the model used in the reduction, nor in the correction of refraction, and is not due to the catalogues.

Table 3. Mean (O-C) for 1967/1973/1974 plates. N_H is the number of Hipparcos stars used in reduction and N_P, the number of PPM stars

Series	N_H	N_P	$\overline{(O-C)}_\alpha$(")	σ_α	$\overline{(O-C)}_\delta$(")	σ_δ
1967/68 48 observations	0	3	-0.041±0.172	±0.517	-0.431±0.174	±0.523
	3	0	0.028±0.023	±0.068	0.016±0.017	±0.053
1973/74 89 observations	1	2	0.167±0.099	±0.410	-0.050±0.103	±0.427
	1	0	0.010±0.007	±0.029	0.018±0.008	±0.030
Total			$\overline{(O-C)}_\alpha$(")	σ_α	$\overline{(O-C)}_\delta$(")	σ_δ
1967/74 137 observations	PPM		0.095±0.086	±0.429	-0.182±0.089	±0.412
	HIPP		0.016±0.009	±0.042	0.017±0.008	±0.038

Table 4. Plate Scales for 1967 and 1973/1974 Series (without refraction effects)

	X["/mm]	Y["/mm]
1967 Series	20.7590±0.0005	20.7590±0.0005
1973/1974 Series	20.842±0.001	20.846±0.002

4.4. Analysis of the results

The majority of the plates of the 1967 series, used in this paper, have no star trail, and so measurements were realized without any reference in orientation. We may surmise that effects detected in the 1967 series were due to a poor estimation of the plate rotation of the exposures despite the number of stars. Furthermore, correlations between plate constants are very important. So, if a parameter is larger (more than a factor 10) than the others, a poor determination of these latter values, in particular the offsets, will be made. In fact, the offset coefficient is clearly under-estimated compared to the orientation, particularly in x. A systematic error, more important in x, may be caused by this under-estimation and may be interpreted in the rms of the 1967 series. Moreover, several effects can explain the anisotropy of the scale. Among these, effects relative to meteorological conditions (unknown and supposed equal to the normal conditions) and differential temperatures can be dealt with. Studies about temperature dependence of scale for the McCormick refractor were made by McAlister et al (1974). In that work, the order of the correction was neglected but it will be useful to recompute this kind of estimation. In particular, the influence on the resulting positions, of the correlations between the expansion of the plate and the tube flexure with the differential temperature.

5. Discussion and future works

With DE403 (Standish, 1995), the JPL ephemerides begin to be based on the (J2000) reference frame of the International Earth Rotation Service (IERS), called ICRF. This means that the frame of the planetary ephemerides, based mainly on optical ground-based observations of the outer planets, and radar VLBI observations of inner planets, was linked with the ICRF, realized on the basis of catalogues of extragalactic radio sources (Arias et al, 1995). This link was in great part realized with lunar laser ranging, for the earth orbit, and VLBI observations of Mars and Venus, for the other planets. The observations of the outer planets being essentially optical, a direct tie in radio wavelength between their orbital planes and the ICRF is difficult. Furthermore the tie in optical wavelength is hard to realize, because there are very few optical observations of planets directly linked to the ICRF. In conclusion, an important part of the ephemerides is not directly aligned with the ICRF. There follows a disconnection of the outer planets orbits to the plane of the ICRF. But, an optical realisation of the ICRF exists: the Hipparcos Catalogue. The axes of the Hipparcos Catalogue have been linked with the ICRF with great precision (Kovalevsky, 1997). So, the use of the Hipparcos Catalogue in plate reductions allows us to connect directly the planet to the ICRF. The use of data, rereduced directly upon the ICRF, in a new adjustement of numerical or analytical ephemerides could reduce, to a great part, the misalignement between optical frame and ICRF. Fur-

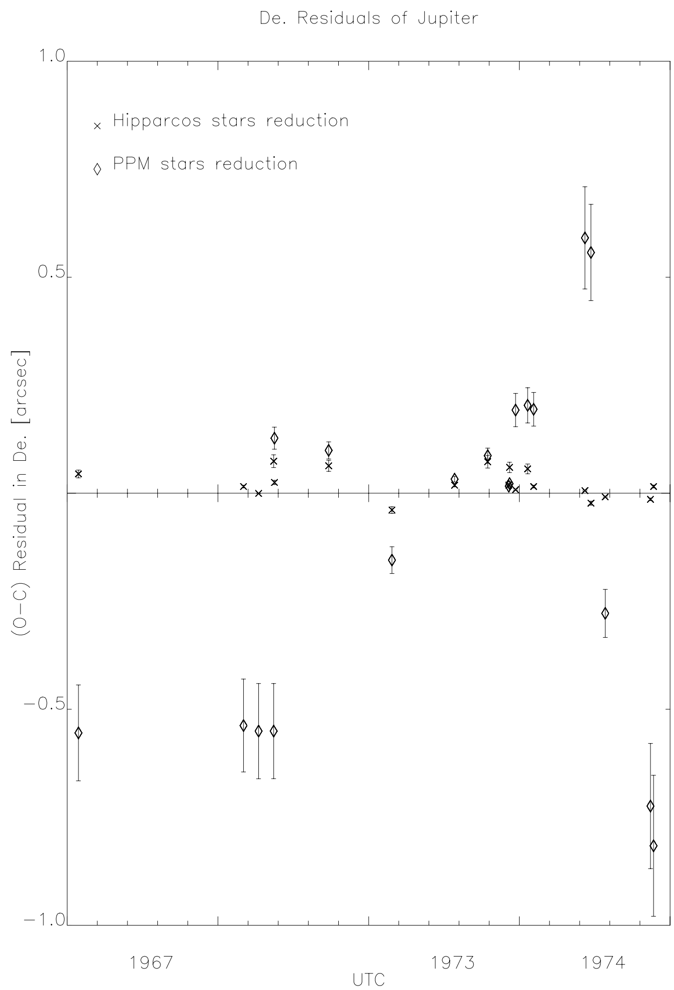

Fig. 2. (Observed -DE403) declination of Jupiter - The error bars for the Hipparcos star reduction (×) are multiplied by a factor 2. The plots materialized by ⋄ represent the PPM star reduction.

thermore, the Hipparcos Catalogue has no significant zonal or regional errors. These errors are the main causes, with the errors in the original reduction processes, of inadequacies still apparent in the optical data. From a more technical point of view, the use of Hipparcos makes possible the detection of poorly known instrumental characteristics. For instance, the problem of the plate scale for satellites/planet system is not resolved, as well as other instrumental implications.

6. Conclusion

Thanks to the Hipparcos mission, an improvement of around a factor 100 was obtained in the accuracy of stellar positions (Mignard, 1997). We have benefited from this improvement by deriving accurate planetary positions. The low density of stars seems to be a problem for its optimal use in CCD and photographic astrometric reduction, However, we have shown that a reduction with few stars is possible, and we obtained an accuracy of around 40 mas in the astrometric positions of Jupiter. Such precision has never been obtained with classic astrometric catalogues, and unknown effects due to neglected corrections were detected. For example, meteorological conditions often ignored should be taken into account if higher accuracy is expected. Finally, such advances should improve the ephemerides of the outer planets, and especially Jupiter, whose satellites have good ephemerides.

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