THE FK5 EQUINOX AND EQUATOR FROM COMBINED RADAR AND OPTICAL DATA OF THE NEAR-EARTH ASTEROIDS

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1. Introduction

Minor planets optical observations have long been used for the purpose of establishing a Celestial reference frame. Being in existence since the early 1960s modern high-accuracy radar measurements of the so-called near-Earth asteroids (NEAs) have been widely extended to the orbit determination process and predicting of the next apparition of the asteroid. Even few radar measurements, when added to optical ones, significantly improve asteroid's ephemeris and reduce standard deviations of the orbital elements (Yeomans *et al.*, 1987). The idea to connect optical and radar data in the problem of the catalogue zero-point determination has been stated by several scientists (Boiko, 1975). And even the first attempt of the authors (Krivova *et al.*, 1994) with actual optical and radar observations of two NEAs: (4179) Toutatis and (1862) Apollo appears to have considerable promise. It was demonstrated the possibility of obtaining standard deviations of catalogue orientation parameters $1.5 - 2$ times better with radar data included.

In order to choose more suitable near-Earth asteroids for the purpose of the equinox and equator determination a numerical simulation has been developed. Using the results of numerical investigation and taking into account the first attempt with actual observations, we have selected the following near-Earth asteroids: (1620) Geographos, (3908) 1980 PA, (4769) 1989 PB, (1627) Ivar, along with the (1862) Apollo, and (4179) Toutatis.

S. Ferraz-Mello et al. (eds.), Dynamics, Ephemerides and Astrometry of the Solar System, 469–474.
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https://doi.org/10.1017/S0074180900127895 Published online by Cambridge University Press

The processing of both radar and optical observations of these minor planets makes it possible to determine not only a precise orbit for each asteroid, but tiny catalogue zero-point corrections as well. The results lend support to the validuty of the method used.

2. Numerical simulation: the uncertainty analysis

A numerical investigation was undertaken to choose more suitable near-Earth asteroids for the purpose of the equinox and equator determination. This simulating analysis is based on a well-known least-squares method. The three types of measurements presented in this study are optical right ascension and declination, radar time delay, and radar Doppler frequency shift. The standard deviation chosen for the optical observational noise is $1''$ in each coordinate. As for radar measurements, the standard deviation assumed to be about 20 μs in range and 5 Hz in Doppler case.

TABLE 1. 1991 JX type

i (deg)	0	10	20	30
Only optical data				
dA ($''$)	± 2.09	± 0.89	± 1.45	± 3.08
dD ($''$)	± 0.53	± 0.14	± 0.50	± 1.92
dE ($''$)	± 1.84	± 0.43	± 0.67	± 2.45
corr. coeff.(%)	95	91	97	92
normalized rms($''$)	1.029	0.986	1.010	0.960
number of obs.	362	364	366	366
Combined data (radar and optical)				
dA($''$)	± 0.67	± 0.46	± 0.51	± 0.39
dD($''$)	± 0.15	± 0.08	± 0.16	± 0.11
dE($''$)	± 0.24	± 0.14	± 0.21	± 0.15
corr. coeff.(%)	90	89	97	95
normalized rms($''$)	0.958	0.916	0.959	0.889
number of obs.	424	426	430	430

The primary purpose of this simulation was to examine the relationship between the length of optical observational history, the quantity of hypothetical radar measurements and uncertainties of the catalogue corrections. Of special interest is the question of how radar observation can decrease these uncertainties. That is why our strategy is to obtain standard deviations of the equator and equinox corrections as well as of corrections to the

https://doi.org/10.1017/S0074180900127895 Published online by Cambridge University Press

orbital elements derived from the processing of (1) optical observations, (2) combined optical and radar data covered several approaches to the Earth.

We have investigated two different types of asteroids. The first one is an asteroid with a short optical history (from half a year to 4 years) and with radar observations made during three of its approaches to the Earth: at the beginning, in the middle and at the end of the interval – we called it "1991 JX type". Another type is a near-Earth asteroid with a long (of more than 25-40 years) optical history and with radar data available during several approaches to the Earth – "Geographos type". In the "Geographos" case, there were simulated 5138 optical observations uniformly covering a time interval of about 35 years. As regards radar measurements, they were distributed according to the following schedule: each asteroid's approach to the Earth lasted for 2 months and repeated approximately every 2nd year. Each observation (both optical and radar) is considered to be made every 5th day.

TABLE 2. Geographos type

i (deg)	0	10	20	30
Only optical data				
dA ($''$)	± 0.11	± 0.11	± 0.12	± 0.12
dD ($''$)	± 0.03	± 0.03	± 0.03	± 0.03
dE ($''$)	± 0.04	± 0.04	± 0.04	± 0.05
corr. coeff.(%)	87	89	90	90
normalized rms($''$)	1.001	0.990	0.986	0.984
number of obs.	5138	5138	5138	5138
Combined data (radar and optical)				
dA ($''$)	± 0.10	± 0.10	± 0.10	±0.09
dD ($''$)	± 0.02	± 0.02	± 0.02	± 0.02
dE ($''$)	± 0.03	± 0.03	± 0.03	± 0.03
corr. coeff.(%)	91	91	88	86
normalized rms($''$)	0.951	0.941	0.937	0.936
number of obs.	5719	5719	5719	5719

In each case standard deviations for six orbital elements (derived from combined data) along with the uncertainties for parameters: dA – the FK5 equinox correction, $d\dot{A}$- its secular variation, dD – the FK5 equator correction, and dE – the correction to the mean longitude of the Earth (obtained from the optical data only) have been estimated. The numerical simulation was fulfilled within the ERA (Ephemerides Research in Astronomy) applied

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program package (Krasinsky *et al.*, 1995). All calculations were performed for each asteroid individually and for the combination of asteroids (the so-called global solution). Tables 1 and 2 demonstrate standard deviations of the parameters under consideration, maximum correlation coefficient, normalized root-mean squares residuals, and number of observations adopted, depending on the different values of the asteroid's inclination to the ecliptic plane.

As evident from the tables, parameters uncertainties do not depend to a large extent on the inclination of the asteroid's orbit. The influence of including radar data was expected to be significant for catalogue orientation parameters determination for asteroids with very short optical history (5–6 times), and only modest in the case when rich optical data exists (1.5–2 times). Obviously, asteroids with a long history of optical measurements and several approaches to the Earth covered with radar observations are preferable, but minor planets with a short optical and rich radar set, can be used too.

3. The FK5 equinox and equator from the processing of actual near-Earth asteroids

Using combined radar and optical observations for the set of NEAs, mentioned in the Introduction, several solutions for the zero-point corrections to the FK5 catalogue were obtained.

The orbits of asteroids are computed by numerical integration of the relativistic equations of motion of NEAs taking into account the perturbations from all major planets and Schwarzchild's terms due to the Sun. The Everhart 15th order method of integration was used. For calculations of the coordinates of perturbing planets and the Moon the DE200/LE200 ephemerides were used. The comparison of the measured values with the computed ones for optical and radar observations was made in barycentric coordinate system J2000.0. The O-C differences for radar observations were combined with those for optical ones in a linearized weighted least squares procedure to produce estimated corrections to non-singular orbital elements for a standard epoch and zero-point corrections (dA, $d\dot{A}$, dD and dE). This technique was applied to each NEA and for the combination of asteroids. To obtain these parameters the complete set of all available optical (they were mainly taken from the Minor Planet Catalogue) and radar data (Yeomans *et al.*, 1991) were used. Optical observations (which were taken not from the MPC) were transferred to the FK5 system using standard procedure adopted by IAU. It can be seen that we have chosen asteroids with various optical and radar observational histories. Some of NEAs have a long set of optical measurements but only 2 radar observations (Geographos, Ivar);

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Toutatis has also the long optical but sufficiently large radar history of about 55 observations; for 1980 PA there exist only short optical history and quite good set of radar data.

The processing of actual data provided support for the conclusion derived from the numerical simulation that standard deviations of the zero-point corrections are approximately two times better with radar data included. Table 5 demonstrates the preliminary results for the FK5 catalogue corrections and their standard deviations obtained from optical observations separately and from combined data for five (except Apollo) asteroids.

TABLE 3. The FK5 catalogue preliminary corrections

Only optical observations				Combined data			
dA(″)	dȦ(″/cy)	dD(″)	dE(″)	dA(″)	dȦ(″/cy)	dD(″)	dE(″)
0.568 ±0.078				0.294 ±0.052			
0.558 ±0.116	− 0.10 ±0.40			0.242 ±0.063	− 0.40 ±0.30		
0.525 ±0.119	− 0.10 ±0.40	0.109 ±0.045		0.242 ±0.060	− 0.35 ±0.30	0.057 ±0.042	
0.677 ±0.181	− 0.10 ±0.40	0.108 ±0.046	− 0.091 ±0.070	0.666 ±0.141	−0.35 ±0.30	0.062 ±0.041	− 0.166 ±0.049

Normalized rms for optical data : 1.035

Normalized rms for combined data : 1.039

Max. correlation coefficient between dA and dE for optical data: 89%

Max. correlation coefficient between dA and dE for combined data: 90%

4. Conclusion

1. The results confirm that the set of combined data of near-Earth asteroids is feasible for zero-point correction determination. The accuracy of zero-point corrections is about two times better in the case of processing combined photographic and radar data than in that of optical observations only. The preliminary corrections to equinox and equator of the FK5 were obtained. They are probable in comparison with other determinations (Branham *et al.*, 1994).

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2. As it could be expected, the equator correction is determined with confidence in every case.

3. Considering that the coefficient of correlation between the equinox correction and the correction to the longitude of the Earth is about 90-95%, one could obtain the linear combination of these parameters only. This correlation coefficient is reduced slightly (to 88-86%) for NEAs with a long optical history and radar observations available during several approaches to the Earth. An example of such an asteroid is just (1620) Geographos which was observed by radar technique second time.

4. It is desirable to observe NEA not only during its approach to the Earth, but before and after it. It should be recommended to observe NEAs with higher accuracy, as for asteroids from the main belt for example, "Selected minor planets", at least no more than 0.5″.

5. Now there exist more than 60 asteroids with available radar data (Ostro *et al.*, 1993). The inclusion of these observations will provide more conclusive and stable results.

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