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Modern CCD Observations of Moving Celestial Objects: Algorithms and Software for Interactive Processing

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Abstract. The problems of observing asteroids using CCDs are discussed. Their identifications and orbit determinations are considered. Also, a method for quality control of CCD observations is suggested.

1. Introduction

CCD observations of the Small Solar System bodies are rapidly progressing. Every month professional astronomers together with an increasing number of amateurs obtain several hundreds of thousands of asteroid positions and send them to the International Minor Planet Center. Everyone who observes a celestial object using a CCD detects moving celestial objects as a "by product". Usually, tests of such observations and identifications of moving objects are not produced by these observers.

Obviously, it would be advantageous for the MPC to receive observations of asteroids with their identifications. Thus, it is necessary to provide astronomers, especially amateurs, with a package for quick solutions to the control and identification problems immediately after CCD observations have been made.

The original algorithms and software were developed in the Pulkovo Astronomical Observatory to solve the following problems:

- test of any positional observations of celestial bodies, artificial and natural, by analyzing the first and second derivatives of the orbital or approximate coordinate (O-C) residuals,
- calculation of the apparent motion parameters (namely topocentric angular velocity, μ, angular acceleration, $\dot{\mu}$, positional angle, ψ, and curvature, C of the trajectory) by using the spherical coordinate approximation,
- preliminary orbit determination of a celestial body observed on a super short arc of its topocentric trajectory; we use the Classical Laplace Method and the new Apparent Motion Parameters Method created at Pulkovo Observatory for the calculation of the circular and the elliptic orbital elements,
- an identification of the observed celestial body using of known orbital catalogues or our own orbit determinations,
- our own ephemeris service for known and unknown celestial objects from artificial satellites up to the Kuiper Belt asteroids.

We have had much success with the practical applications of our algorithms and software. We use the "CERES Plus" package and "LAPLACE" software in our analysis of moving celestial bodies. The algorithms and major results were published in Russian (Bykov 1989, 1996; Kiselev & Bykov 1973, 1976). Several examples are given here in the Tables.

We hope that our investigations may be useful for near-Earth space control and also for searches of the moving celestial objects through analysis of old and new CCD frames obtained at any amateur or professional astronomical observatory.

2. Examples

Table 1. Accuracy of CCD Observations.

Observatory		Telescope (diameter, focus, field of view)	Detector, catalogue	Number of			Mean error of a single observation for		Int. or Ext. acc.
code	name, country			minor planets	dates	positions	α	δ	
1	2	3	4	5	6	7	8	9	10
801	Oak Ridge	1.5 rfl	CCD	14	27	72	0.34	0.36	ext.
	Obs., USA		GSC				0.05	0.06	
704	Lincoln	1.0 rfl	CCD	5	3	16	0.52	0.50	int.
	Lab., USA						0.14	0.09	
711	McDonald	0.76 rfl	CCD	4	4	22	0.32	0.13	int.
	Obs., USA	2.3 $46\times46'$	GSC				0.02	0.09	
				51	28	335	0.21	0.16	ext.
							0.03	0.02	
610	Pianoro,	0.26 rfl	CCD	55	19	204	0.46	0.51	int.
	Italy	1.0 $22\times15'$	GSC				0.05	0.07	
				4	8	29	0.61	1.29	ext.
							0.09	0.80	
689	Flagstaff,	0.20 tr.c	CCD	15	9	53	0.29	0.26	ext.
	USA		GSC				0.07	0.04	

A sample of accuracies of CCD observations of the numbered minor planets reported to International Minor Planets Center during 1995-1996.

The CERES software package, which was developed at the former Institute of Theoretical Astronomy (in Russia), was used to calculate (O-C)-differences for nearly 700 minor planets which were observed irregularly and quasi-simultaneously in 1995-96 using CCDs as well as photography at nearly 50 observatories. The accuracy of observations was estimated by means of dispersion of average (O-C) for each type of observations obtained by each telescope. Some results are given in Table 1. Here, the term "Internal accuracy" (int.) indicates that an estimation was derived from analysis of minor planet positions obtained in one night for each of them. "External accuracy" (ext.) indicates that observations made during several successive nights were used only. In the columns 8 and 9, where the main results of the accuracy investigations are presented, the values below accuracy values are the mean errors of our estimates.

3. Example of Accuracies of Modern CCD Observations.

Table 2. (O–C) residuals for the NMP 3035 Chambers.

Obs.	Date (DT) 1998 09	α $22^{\mathrm{h}}49^{\mathrm{m}}$	$O-C$ $''$	δ $-6°23'$	$O-C$ $''$	V	$Zen.$ $°$
704	18.25538	60.439	0.74	16.49	−0.92	17.7	40
	18.26829	59.860	0.85	20.89	−0.99	17.7	40
	18.28114	59.211	−0.13	25.30	−1.08	17.7	40
	18.30675	58.062	0.07	33.11	−0.31	17.7	43
Mean	18.27789	59.393	0.38	23.95	−0.82		
Error			±0.24		±0.18		
699	18.27145	59.725	0.98	19.79	1.18	17.4	28
	18.28938	58.936	1.35	25.79	1.18		28
	18.30800	58.068	1.01	32.31	0.91		31
Mean	18.28961	58.910	1.11	25.96	1.09		
Error			±0.12		±0.09		

(O–C) residuals for the NMP 3035 Chambers observed by two telescopes (obs. codes **699,704**) with a CCD during a single night.

Table 3. Error Estimation.

Obs.	Date 1998 09	j	$\dot{\alpha}$ s	O–C $''$	$\dot{\delta}$ $''$	O–C $''$	Err.$\dot{\alpha}$ %	Err. $\dot{\delta}$ %
610	10.89271	3	−45.072	57.40	−404.74	−47.95	7.8	13.4
704	14.28740	5	−48.696	−15.76	−353.99	−4.74	2.2	1.4
699	18.28961	3	−45.345	0.69	−342.64	−7.34	0.1	2.2
704	18.27789	4	−46.472	−17.87	−323.14	11.47	2.6	3.4
704	25.17234	5	−39.320	5.89	−303.09	−3.36	1.0	1.1
704	14 − 25	14						

The first derivatives and estimation of accuracy of data presented in Table 2.

Parameters $\dot{\alpha}$, $\dot{\delta}$, their accuracy characteristics (in percents) and differences (O − C) which may be obtained by linear approximation of the coordinate sets presented in Table 2 and by comparison with the exact values given by the CERES software.

Table 4. Apparent Motion Parameters.

NMP Dates	451 Patientia 1993 04 08.24614	1531 Hartmut 1993 07 23.99637	2302 Florya 1993 07 21.24017
codes	809 (*photo*)	801&587 (CCD)	801&587 (CCD)
positions	15	7	7
nights	5	3	3
topoc. arc	$0\overset{\circ}{.}5$	$0\overset{\circ}{.}6$	$1\overset{\circ}{.}3$
α calc.	$15^h43^m36\overset{s}{.}933$	$21^h15^m23\overset{s}{.}125$	$21^h05^m09\overset{s}{.}804$
obs.	$15^h43^m36\overset{s}{.}985$	$21^h15^m23\overset{s}{.}134$	$21^h05^m09\overset{s}{.}841$
δ calc.	$-4^\circ\ 27'\ 00\overset{''}{.}97$	$-4^\circ\ 31'\ 33\overset{''}{.}41$	$-16^\circ\ 55'\ 30\overset{''}{.}76$
calc uad obs.	$-4^\circ\ 27'\ 01\overset{''}{.}75$	$-4^\circ\ 31'\ 33\overset{''}{.}97$	$-16^\circ\ 55'\ 30\overset{''}{.}37$
μ calc.	$421\overset{''}{.}9944$	$774\overset{''}{.}6957$	$818\overset{''}{.}9019$
obs.	$421\overset{''}{.}8901$	$774\overset{''}{.}9191$	$817\overset{''}{.}7663$
$\dot{\mu}$ calc.	$16\overset{''}{.}6739$	$11\overset{''}{.}7524$	$15\overset{''}{.}2804$
obs.	$16\overset{''}{.}7164$	$12\overset{''}{.}5745$	$15\overset{''}{.}4006$
ψ.	$289^\circ.3509$	$276^\circ.9167$	$279^\circ.1318$
obs.	$289^\circ.3548$	$276^\circ.8532$	$279^\circ.1641$
c calc.	7.6302	3.4289	1.6596
obs.	7.6576	3.6675	1.6718

Calculation of the geocentric differential parameters for some numbered minor planets and comparison with the actual parameters obtained with a processing of positional observations.

Table 4 shows apparent motion parameters $\alpha, \delta, \mu, \dot{\mu}, \psi, C$ are reliable and can be calculated from the modern position observations. They allow us to obtain the preliminary orbit elements of asteroid.

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