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Astrometric Observations of the Second, Third, and Fourth Satellites of Uranus

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Abstract—The results of astrometric observations of three Uranian satellites, performed at the Ka-Dar observatory from August to October 2005, are presented. In total, 20 satellite positions in the equatorial frame and 14 "satellite minus satellite" relative positions were obtained.

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INTRODUCTION

It is known that regular observations of planetary satellites are necessary to maintain and refine the theories of their motion. The theories of motion are used to study the physical parameters of satellites, to calculate the circumstances of occultations, and to maintain space research. In this paper, we present the results of the observations of Uranus's satellites.

OBSERVATIONS

Uranian satellites were observed at the Ka-Dar observatory, located in the Moscow region at 37°52′59″ E, 55°14′52″ N. A 356-mm Schmidt–Cassegrain telescope with a 3325-mm focal length was used, equipped with a SBIG STL 6303E CCD camera. The main CCD specifications are as follows (see www.sbig.com):

Total pixels: 3072 × 2048

Pixel size: 0.009 × 0.009 mm

Field of view (when installed in the reflector focus): 28.6 × 19.1 arcmin

Dark current: 0.3 *e*/pixel/s

Read noise: 13.5 *e*

Peak sensitivity wavelength: 5800 Å

Peak quantum efficiency: 68%

During nine nights in August–October 2005, we obtained 146 processable CCD images of the Uranian system. The exposure times varied between 10 and 60 s, depending on the observing conditions. The images were taken using a series of 5–10 exposures. They harbor the second (Umbriel), the third (Titania), and the fourth (Oberon) Uranian satellites; they also usually harbor several dozen field stars of up to stellar magnitude 17, making it possible to use reference stars for reduction. This is an advantage of our study over a number of works performed in the previous decade (Veiga and Vieira, 1995; Harper et al., 1997, 1999), in which this technique could not be applied because of the small fields of view. Our images of Uranus are heavily saturated and cannot be measured.

DATA REDUCTION

In our opinion, one of the main problems in the reduction of CCD observations of planetary satellites is the presence of a halo of scattered light from the planet. To account for this effect, we approximated the halo in rings around the images of satellites with second-order polynomials (Izmailov et al., 1998) and then subtracted the polynomial value for each element relevant to a satellite image.

Images of both the satellites and reference stars were processed assuming the Lorentz profiles (Franz, 1973):

$$I(x, y) = \frac{C}{(1 + Ar)^{\alpha}} + D; \quad (1)$$

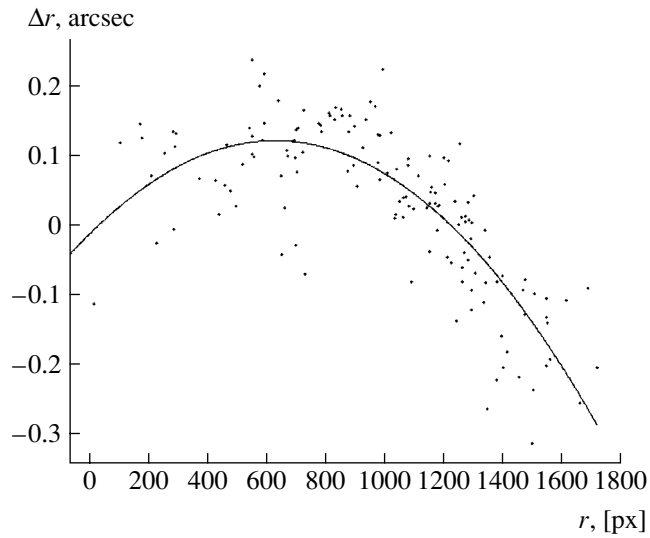
$$r^2 = (x_j - x_0)^2 + (1 + B)(y_j - y_0)^2 + E(x_j - x_0)(y_j - y_0); \quad (2)$$

where $I(x, y)$ is the brightness count for the element with coordinates x and y; x_0 and y_0 are the coordinates of the image center; and α, A, B, C, D, and E are the model parameters.

To determine the center coordinates and other parameters of a satellite or a star image, we solved a redundant system with the nonlinear least-squares method. In this way, we determined the CCD image center coordinates of both the Uranian satellites and the field stars.

Note that the standard reduction procedure suggests a subsequent application of the method of six constants. However, analysis of reference star residuals revealed radial shifts of the measured coordinates towards the centers of the field of view, a so-called generalized distortion (Kiselev, 1989), which may be as large as several tenths of an arcsecond depending on the distance from the center of the field of view.

The figure demonstrates the dependence of this radial shift (Δr) on the distance from the distortion center (r). The distance was calculated by applying a formula analogous to Eq. (2). In this case, the lines with an equal distortion may be ellipses with arbitrary orientations.



Distortion: the dependence of the radial shift of a star (Δr) on the distance from the distortion center (r).

Therefore, before applying the method of six constants for the calculation of equatorial coordinates, allowance for the generalized distortion was made, resulting in a significant decrease in the reference star residuals. We chose UCAC2 (Zacharias et al., 2004) as a reference catalog, because it is the most accurate catalog today and has a sufficient star density. The processing was performed with the Izmccd package (Izmailov, 2005). The typical error of unit weight, which is one of the results of the six-constant method and characterizes the quality of measurements and that of the catalog star coordinates, is approximately equal to 0.05, which is a satisfactory value. If more than one satellite fell into the field of view, then at the last stage of data reduction we calculated the differences in right ascension and declination for pairs of satellites. Finally, the observations were compared with theory by means of (O-C) calculations. For this purpose, we used the theory of motion by Laskar et al., 1987), coded by N. V. Emel'yanov (http://lnfm.sai. msu.ru/neb/nss/nsso-c0hr.htm).

OBSERVATIONAL RESULTS

The results of the observations are presented in Tables 1 and 2. Table 1 presents the J2000 topocentric equatorial coordinates of the satellites, and Table 2 demonstrates the "satellite minus satellite" coordinate differences.

The tables provide the mean moments of the observations (month and day with a fractional part) on the UTC scale; the satellite number (in Table 2, the numbers of the satellites for which the coordinate differences are determined); α, the right ascension (h, min, s) in Table 1 or $\Delta X = \Delta\alpha\cos\delta$, arcsec, in Table 2; δ, the declination (degrees, arcmin, arcsec) in Table 1 or $\Delta Y = \Delta\delta$, arcsec, in Table 2; K, the number of used CCD images; $(O–C)_x$ and $(O–C)_y$, arcsec, the differences between the observed and ephemeris positions, averaged over a series of CCD images; and σ_x and σ_y, the errors calculated from the convergence of (O–C) in the series (arcsec; internal errors).

The tables show that the mean intrinsic accuracy of our observations is about 0.03″. The mean (O–C) of equatorial coordinates are equal to

$$(O–C)_x = +0''.042 + 0.017,$$

$$(O–C)_y = –0''.027 + 0.034.$$

The error of a single observation, calculated from the (O–C) convergence in the series of observations, i.e., the external error averaged over X and Y, equals 0".12. Its value is determined by the accuracy of measurements of star and satellite positions, by the accuracy of the reference star coordinates, by the accuracy of the reduction, and by the accuracy of the theory of motion for satellites. The facts that the intrinsic error is mostly determined by the accuracy of measurements, the accuracy of star coordinates is significantly better than the external error, and the external error is larger than the intrinsic error by a factor of nearly four indicate that the reduction technique and the theory of satellite motion should be refined. The authors will continue observing the Uranian satellites and developing the data reduction technique.

Table 1. Topocentric equatorial coordinates of the satellites of Uranus, derived from the observations

Date (UTC), 2005		No.	α, h, min, s			δ, degree, arcmin, arcsec			K	$(O–C)_x$, arcsec	$(O–C)_y$, arcsec	σ_x, arcsec	σ_y, arcsec
8	15.952333	3	22	44	53.0484	–8	49	26.103	10	0.095	0.143	0.005	0.018
8	29.847666	3	22	42	49.6434	–9	0	58.294	5	0.117	–0.106	0.049	0.018
9	5.848575	2	22	41	46.8433	–9	7	28.032	6	0.049	–0.206	0.027	0.043
9	7.877994	2	22	41	29.4075	–9	9	50.638	10	0.158	–0.223	0.040	0.042
9	7.877994	3	22	41	28.5246	–9	9	2.956	10	0.100	–0.099	0.013	0.018
9	7.877994	4	22	41	28.2176	–9	8	57.450	10	–0.033	0.075	0.014	0.021
9	10.858932	3	22	41	3.0907	–9	12	26.957	9	0.014	0.122	0.023	0.022
9	10.858932	4	22	41	2.4856	–9	11	45.280	9	0.081	–0.056	0.014	0.015
9	10.869320	2	22	41	2.4366	–9	12	0.508	5	–0.016	0.196	0.075	0.094
9	10.869320	3	22	41	2.9988	–9	12	27.712	5	0.004	0.105	0.055	0.054
9	10.869320	4	22	41	2.3868	–9	11	45.902	5	–0.065	0.022	0.022	0.046
9	30.797414	2	22	38	17.6730	–9	27	55.492	8	0.184	–0.426	0.019	0.032
9	30.797414	3	22	38	18.0732	–9	28	34.012	8	–0.045	–0.014	0.028	0.019
9	30.797414	4	22	38	18.1253	–9	28	42.353	8	–0.007	–0.004	0.017	0.028
10	6.794935	4	22	37	35.0488	–9	31	40.221	10	0.044	–0.109	0.067	0.046
10	10.847958	2	22	37	9.5102	–9	34	59.747	6	–0.015	0.251	0.021	0.028
10	10.847958	3	22	37	8.6522	–9	34	39.865	6	–0.065	–0.031	0.027	0.021
10	10.847958	4	22	37	9.9480	–9	35	13.803	6	–0.003	–0.020	0.018	0.019
10	12.841250	3	22	36	56.5544	–9	35	24.260	5	0.040	–0.062	0.036	0.026
10	12.841250	4	22	36	57.6000	–9	36	34.836	5	0.208	–0.100	0.029	0.020

Table 2. Relative positions of the Uranian satellites derived from the observations

Date (UTC), 2005		No.		ΔX, arcsec	ΔY, arcsec	K	$(O–C)_x$, arcsec	$(O–C)_y$, arcsec	σ_x, arcsec	σ_y, arcsec
9	7.877994	3	2	–13.075	47.682	10	–0.058	0.124	0.034	0.043
9	7.877994	3	4	4.547	–5.506	10	0.131	–0.173	0.012	0.017
9	7.877994	4	2	–17.621	53.188	10	–0.174	0.263	0.040	0.062
9	10.858932	4	3	–8.960	41.677	9	0.066	–0.177	0.016	0.024
9	10.869320	2	3	–8.324	27.204	5	–0.020	0.091	0.044	0.089
9	10.869320	2	4	0.737	–14.606	5	0.048	0.174	0.072	0.053
9	10.869320	4	3	–9.062	41.810	5	–0.068	–0.083	0.045	0.063
9	30.797414	2	3	–5.922	38.520	8	0.226	–0.411	0.030	0.042
9	30.797414	2	4	–6.691	46.860	8	0.188	–0.421	0.021	0.047
9	30.797414	3	4	–0.769	8.340	8	–0.038	–0.010	0.032	0.017
10	10.847958	2	4	–6.476	14.057	6	–0.011	0.271	0.015	0.020
10	10.847958	3	2	–12.691	19.882	6	–0.049	–0.282	0.025	0.025
10	10.847958	3	4	–19.166	33.938	6	–0.061	–0.011	0.019	0.020
10	12.841250	3	4	–15.464	70.576	5	–0.034	0.010	0.009	0.009

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