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PHOTOGRAPHIC OBSERVATIONS OF MAJOR PLANETS AND THEIR MOONS DURING 1961-1990 AT THE MAO NAS OF UKRAINE

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ABSTRACT. We present the results of photographic observations' processing of Saturn's moons, Uranus, Neptune and their moons on the basis of MAO NAS of Ukraine photographic observational archive. The analysis of the results is given. Observations were obtained using 4 telescopes: Double Long-Focus Astrograph (DLFA, D/F = 400/5500), Zeiss Double Astrograph (DAZ, D/F= 400/3000), Reflector Zeiss-600 (D/F= 600/7500), Wide-angle Astrograph, (DWA, D/F= 400/2000). Observations were carried out during 1961 – 1990 (http://gua.db.ukr-vo.org). Digitizing of plates has been done by EPSON EXPRESSION 10000XL (EE) flatbed scanner in 16-bit gray color range with resolution 1200dpi.(Andruk et al.: 2005, 2012; Golovnja et al.: 2010;. Protsyuk et al. 2014a, 2014b). The reduction of plates was made using the software developed in MAO NASU in the enhanced LINUX-MIDAS software kit. (Andruk V. et al.: 2016a, 2016b). Tycho2 was used as a reference system. The internal accuracy of the reduction for the first three instruments is ±0.08 – ±0.13 arcsec for both coordinates. For the wide angle astrograph DWA, RMS errors appeared 2 – 2.5 times higher. The total amount of processed plates with images of Saturn's moons is **209 (511** frames**), 33** plates contain the images of Uranus and U1,U2,U3,U4 moons, **29** plates have images of Neptune and N1 moon (Yizhakevych et al., 2015, 2016, 2017; Protsyuk et al., 2015). The online comparison of calculated positions of objects with IMCCE ephemeris data was made (http://lnfm1.sai.msu.ru/neb/nss/nssephmf.htm).

Keywords: Catalogs, Solar System Bodies, Saturn, Uranus, Neptune.

1. Introduction

The current work is the continuation of the preceding publications (Ivanov et al., 2013; Izhakevich et al.,1991; Kaltygina et al., 1992; Kulyk et al., 2012; Pakuliak et al.,1997a, 1997b, 2012; Shatokhina et al., 2005; Yizhakevych et al., 2014, Yizhakevich et al., (http://gua.db.ukrvo.org/starcatalogs.php?whc=sat90) and comprises the discussion of major planets' photographic observations' processing results. Using the observed data we obtained **1385** astrometric positions and magnitudes of 8 Saturn's moons S2, S3, S4, S5, S6, S7, S8, S9, **58** positions of Uranus, **66** positions of U1, U2, U3, U4 satellites of Uranus, **51** positions of Neptune, **9** positions of N1 moon of Neptune. All of them are obtained in the Tycho-2 reference frame The analysis and the accuracy assessment of the obtained catalogs are considered.

2. Saturn's moons

From the total amount of photographic observations of Saturn, collected in MAO NASU (DATABASE of JOINT PLATE ARCHIVE (DBGPA V2.0), we selected about 250 plates with the best quality of images. Taking into account, that each plate contains several exposures of different duration (from some seconds to some minutes), the total volume of processed material consists of **511 digital images**. The division of digital plate image into exposure frames and their further processing were done using the special software package (Andruk et al., 2014; 2015; Kazantseva et al., 2015**).**

Table 1 gives the data of the internal accuracy of the reduction of Saturn's moons' observations for each of 4 telescopes. Columns contain the telescope scale ("/pix), the mean number of Tycho-2 reference stars, unit weight RMS errors of magnitudes and positions, and a number of positions N by each telescope.

Table 1. The internal accuracy of the reduction of Saturn's moons' observations.

Telesc.	Scale "/px	Ref. stars	rms_{mg}	rms_{α}	rms_{δ}	N posit.
DLFA	0.79	75	0.27	0.09	0.09	1017
DWA	**2.17**	**610**	**0.27**	**0.23**	**0.22**	**101**
DAZ	1.45	142	0.34	0.09	0.10	95
Z600	0.59	16	0.37	0.09	0.11	172

From the Table 1, it is obvious that DWA observations (field 8°x8°, scale 103"/mm) are the least suitable for such determinations because of internal errors which are more than twice higher than the other telescope ones**.** DWA observations (1978 – 1986, **13** nights) were not effective enough. Plates available for the processing are the ones containing mostly images of S5, S6, S8 moons. The possible reasons of the bad accuracy may be the poor resolution of images because of insufficient shift of telescope between the exposures and the telescope scale.

DLFA Saturn's moons observations occurred the most productive (1961- 1984, **57** nights) and durable. During the period, images of 7 main Saturn's moons S2-S8 were obtained.

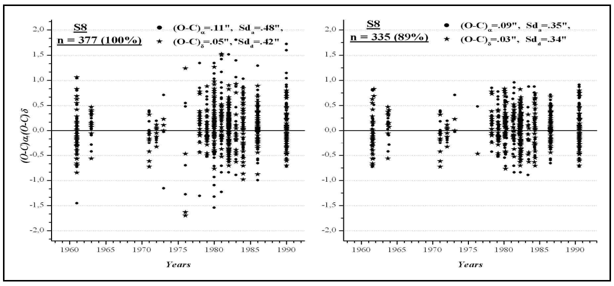

Figure 1: The distribution of S8 observations with dates and the dispersion of $(O\text{-}C)_i$ in respect to their mean values.

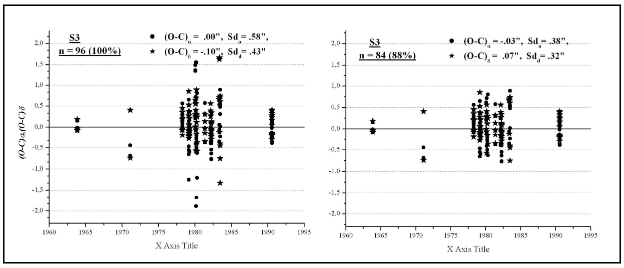

Figure 2: The distribution of S3 observations with dates and the dispersion of $(O\text{-}C)_i$ relatively to their mean values.

The brief series of observations were obtained in Uzbekistan in the field conditions with the two other telescopes: **DAZ** in 1986 (**7** nights) and **Z600** in 1990 (**9** nights). The astrometric observations with Z600 reflector are among the first on using the reflector for the purposes of positional astrometry (Kaltygina et al., 1992).

The dispersion of values of random $(O\text{-}C)_i$, the mean values of (O-C) and standard deviations Sd were derived using the IMCCE ephemeris data (http://lnfm1.sai.msu.ru/neb/nss/nssephmf.htm) separately for each set of satellite positions. For S4, S5, S6, S8 with the wide sample of observations the standard deviations Sd became in the limits 0.41" to 0.48". For the other satellites with the small set of observations, these values are significantly larger. Table 2 and 2a show the statistical data of reduction for each moon separately. Here, N is the number of obtained positions, **Bph** is a photographic stellar magnitude with the standard deviation $\mathbf{Sd_B}$, (O-C) is mean values of residual deviation and Sd is a standard deviation for α and δ coordinates. The last column contains the following notations for telescopes: 1 corresponds to DLFA, 2 – DWA, 3 – DAZ, 4 – Z600.

Fig. 1 and Fig. 2 show the dispersion of values of random $(O\text{-}C)_i$ in respect to their arithmetical mean value for two moons **S3** and **S8** on various volumes of samples**:** the left side shows the full sample, the right side – results after the elimination of observations with $(O\text{-}C)_i$ exceeding or equal to $2\boldsymbol{\sigma}''$. Dates of observations are given along the X-axis that helps to assess the intensity of observations during the 30 year period.

2.1. Application of $2\boldsymbol{\sigma}''$ criterion to all series of observations leads to the reduction of the sample volume by more than 10%-15% and to the mean decrease of the standard deviation Sd by 0.15". At the same time, the arithmetic mean values (O-C) for each satellite are reduced within the error of the mean, and the vast majority of (O-C) is clustered around their arithmetic mean of ± 1". Table 2a shows the differences of statistical characteristics when applying the $2\boldsymbol{\sigma}''$ criterion to the samples with significantly different volumes for **S3** and **S8** satellites.

Table 2. The results of the reduction of Saturn's moons' photographic observations.

Obj.	**N**	**(O-C)$_\alpha$**	**Sd$_\alpha$**	**(O-C)$_\delta$**	**Sd$_\delta$**	**Teles.**
S2	**12**	0.48	**.68**	0.16	.48	1
S3	**96**	0.00	**.58**	0.10	.43	1,4
S4	183	007	.44	0.07	.42	1-4
S5	269	0.15	.47	0.07	.42	1-4
S6	435	0.09	.47	-003	.43	1-4
S7	12	-0.04	.47	0.10	**.63**	1,4
S8	**377**	0.11	.48	0.04	.41	1-4
S9	1	0.44		-0.27		4

Table 2a. The comparison of the results of the S3 and S8 reduction before and after the application of 2σ″ criterion.

N, %	**(O-C)$_\alpha$″**	**Sd$_\alpha$″**	**(O-C)$_\delta$″**	**Sd$_\delta$″**
S3, Bph=10.6 ±.08				
96, 100	+0.00 ±0.06	.58	+0.10 ±0.04	.43
84, 88	-0.03 ±0.04	.38	+0.07 ±0.04	.32
S8, Bph=11.9 ±0.04				
377, 100	+0.11 ±0.02	.48	+0.04 ±0.02	.41
335, 89	+0.09 ±0.02	.35	+0.03 ±0.02	.34

2. 2. The next step in the evaluation of the satellite reduction quality was made by determining the differential coordinates in the sense of ″satellite minus satellite ″ and their comparison with theoretical data.

Table 3. The statistical characteristics of differential coordinates of Saturn's satellites by DLFA observations.

Si-Sj	**N**	**(O-C)$_\alpha$**	**Sd$_\alpha$**	**(O-C)$_\delta$**	**Sd$_\delta$**
S8-**S2**	6	-.05±.21	.52	.03±.08	.21
S6-**S2**	6	-.51±.18	.46	-.25±.13	.33
S5-**S2**	10	-.46±.25	.80	-.08±.09	.33
S4-**S2**	8	-.06±.29	.83	-.14±.10	.28
S3-**S2**	7	-.12±.20	.53	-.03±.08	.21
S8-S6	193	.01±.02	.28	.04±.02	.32
S5-S6	187	.02±.02	.24	-.06±.02	.25
S8-S3	43	.11±.05	.31	.02±.03	.22
S6-S3	68	.13±.04	.31	-.06±.03	.25
S5-S3	61	.10±.04	.29	.01±.03	.22
S8-S4	119	.00±.03	.31	.01±.03	.30
S6-S4	139	-.02±.02	.28	.00±.07	.17
S5-S4	125	.02±.02	.27	-.02±.02	.27
S3-S4	38	-.06±.04	.24	.11±.04	.25

Table 3 selectively for some pairs of satellites presents statistical characteristics of differential coordinates from observations at the **DLFA** telescope. First of all, these are the pairs formed by the combination of the **S2** satellite with other four ones. Positions of S2 (Enceladus) form the short-term observational series (n=12), obtained in 1979–1981 at DLFA. Here, the statistical data for other pairs of moons with the essentially larger number of observations

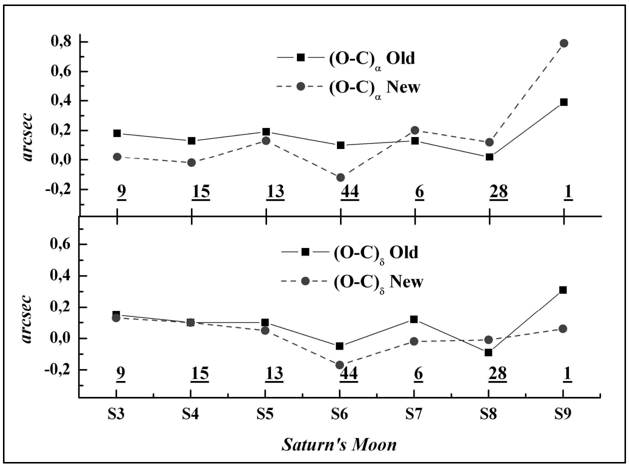

Figure 3: Matching of the mean values (O-C) obtained in the processing of Saturn's moons' observations using two techniques.

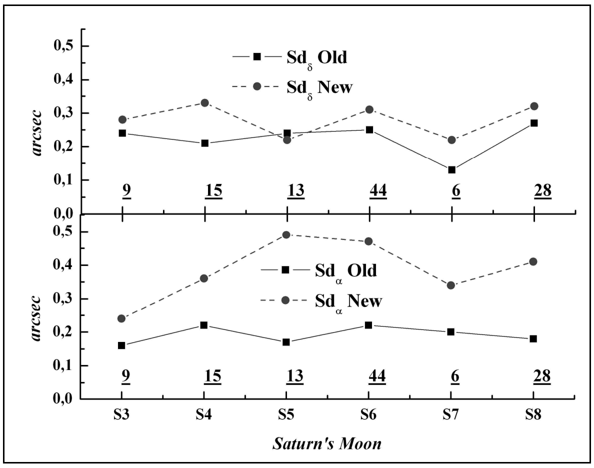

Figure 4: Matching of standard deviations Sdα and Sdδ obtained in the processing of Saturn's moons' observations using two techniques.

are given. For these pairs, values of Sd occurred two times lower than for pairs with S2. It may be due to small volumes of samples or the inaccuracy of S2 theoretical data. For the short-term observations and samples of small volumes, such type of analysis is not always unambiguous.

2. 3. One more step in the evaluation of the observation reduction quality was made by comparison of two techniques of processing the same series of photographic observations. We used the observations obtained by Z600 reflector in 1990. Both types of reduction are made in the same reference system of Tycho-2. In the first case we used the "classic" method of the reduction and in the last one the method of the reduction of digital plate images was applied**.**

It occurs that the number of positions of the same objects calculated with using two methods differs. The classic method gives 231 positions of 7 Saturn's satellites. The modern technique gives only 172 positions. But, only in 119 cases, a match is found on objects and their moments of observations.

Fig. 3 and 4 show the differences in statistical characteristics for two different techniques of plate processing. The discrepancies of mean values of (O-C)α and (O-C)δ (Fig.3) on each satellite are small within the error of the mean. As for the differences in standard deviations Sd (Fig.4) on α coordinate, they are more significant while Sd_δ doesn't show any differences. The number of satellite positions is shown along X-axis.

The quantitative and qualitative difference in the results of reduction by using two techniques exists for other telescopes too. For example, earlier we had obtained 5 positions of S1 satellite close to Saturn (1980, DLFA). But processing of the digital image does not provide them. For S2 satellite 42 positions were previously determined from the observations obtained by tree telescopes DLFA, DWA, Z600 (1978-1990).

The digital image processing procedure has fixed only 12 positions of S2 obtained by DLFA (1979-1981). The cause of this disagreement may lay in the imperfection of the algorithm which evaluates the center and the quality of the satellite image and eliminates "trash" images. It requires the further study and improvement.

3. Uranus, Neptune and their moons

We have completed the processing of photographic observations of Uranus, Neptune and their moons obtained with three telescopes: DLFA, DWA, Z600 during 1963-1990 (Protsyuk et al., 2015**;** Yizhakevych, 2017a in press). The observational technique, as well as reduction one, were the same as for Saturn's moons. We used **33** plates (or 20 observational nights) with Uranus images and **29** plates with Neptune (16 nights). Besides the images of major planets, we succeeded to identify and process 4 moons of Uranus , U1, U2, U3, U4 and one moon of the Neptune –N1. Finally, we obtained catalogs of astrometric positions of Uranus (**n=61**) , its 4 satellites (**n=56**), Neptune (**n=51**) and its satellite N1 (**n=9**).

Table 4 contains the assessment of the internal accuracy of the reduction for Uranus and Neptune observations – RMS errors for both coordinates **α**, **δ,** and photographic stellar magnitude Bph. Here, as the volume of treated observations significantly yields the Saturn's one, so the statistical parameters are determined less certain.

Table 4. The internal accuracy of the reduction of photographic plates with Uranus and Neptune images.

Tel..	Scale "/px	Ref. stars	Rms Bph	Rms α	Rms δ	N posit. Uran./ /Nept.
DLFA	0.79	97	.29	.06	.08	9 |/ 3
DWA	**2.17**	800	.32	.16	.20	29 / 33
Z600	0.59	16	.36	.09	.10	23 / 15
					Σ =	**61 / 51**

Tables 5 and 6 comprise differences $(O\text{-}C)_i$ between observed and theoretical positions (DE405) of planets and their moons, mean values of (O-C) and standard deviations Sd on both coordinates. All the estimations are obtained online using IMCCE data.

Table 5. The results of the reduction of photographic observations of Neptune and its satellite N1.

Object	N	$(O-C)_\alpha$	Sd_α	$(O-C)_\delta$	Sd_δ	Tel.
N1	8	0.14	.41	0.25	.49	4
N1	1	0.95	-	-0.01	-	1
Σ = 9		0.23	.46	0.23	.46	
Neptune.	3	0.23	.46	0.07	1	1
Neptune	33	0.20	.68	-0.32	.98	2
Neptune	15	-0.06	.38	0.00	.44	4
Σ = 51		0.12	.60	-0.20	.83	

Table 6. The results of the reduction of photographic observations of Uranus and its satellites U1-U4.

Obj.	N	$(O-C)_\alpha$	Sd_α	$(O-C)_\delta$	Sd_δ	Tel.
U1	3	-0.30	1.18	0 .78	.73	4
U2	8	-0.16	0.86	0 .31	.39	4
U3	22	0.04	0.52	0 .12	.31	4
U4	22	-0.09	0.56	0.10	.49	4
U4	1	0 .00	-	-0.61	-	2
Σ = 56						
Uranus	9	0.86	0.61	-0.23	.61	1
Uranus	29	0.13	0.80	-0.22	.75	2
Uranus	23	0.15	0.66	0.06	.69	4
Σ = 61		0.24	0.76	-0.12	.74	

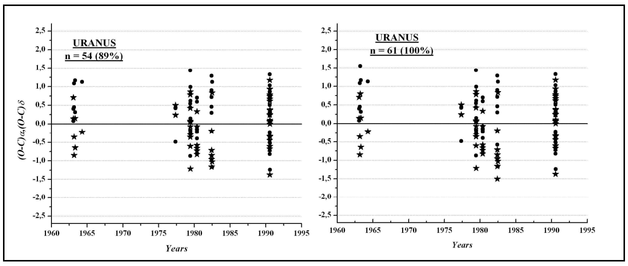

Figure 5: The distribution of Uranus observations with years and the dispersion of $(O-C)_i$ deviations

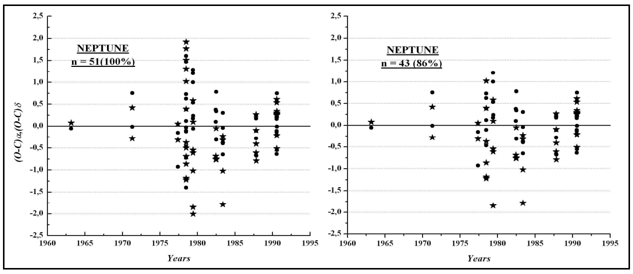

Figure 6: The distribution of Neptune observations with years and the dispersion of $(O-C)_i$ deviations

3.1. Fig. 5 and 6 demonstrate the distribution of observations of Uranus and Neptune during a 30-year observational period and the scatter of (O-C)i values relative to their arithmetic mean.

The (O-C)i scatter range is rather wide and is within ±2.0″. After the elimination of positions with (O-C)i ≥ **2σ″,** the total amount of Uranus and Neptune positions decrease by 10-16%, and the range of (O-C)i scatter around the mean value narrowed to ± 1.5″. Taking into account the paucity of samples (for Uranus number of positions n is 61, for Neptune n=51), such narrowing has a significant effect on statistical parameters of a reduction, mainly on the standard deviations. It also casts doubt on the reliability of the evaluation of the material.

3.2. As in the case of Saturn, we have made the comparison of two techniques of processing procedure for U1, U2, U3, U4, N1 satellites (Z600, 1990). Fig. 7 demonstrates the differences between the standard deviations Sd_α and Sd_δ obtained using different techniques of reduction.

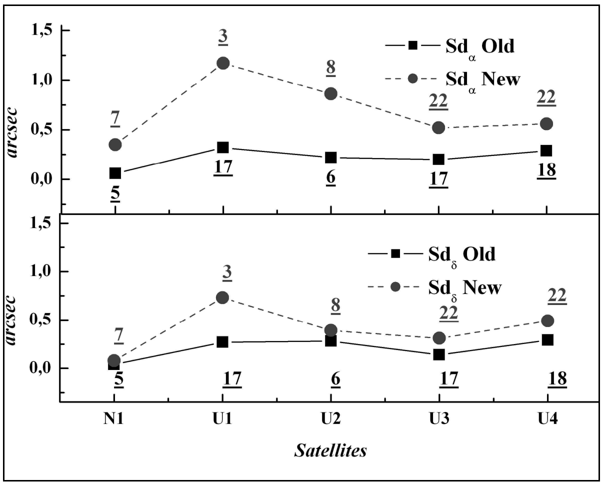

Figure 7: The comparison of reduction results made using two different processing procedures by comparison of standard deviations Sdα and Sdδ

Solid lines in Fig.7 represent the classic technique of the reduction, and the dashed ones describe the digital technique. Digits under the signs mark the number of positions. The remarkable divergence between two techniques on **α** coordinate may be the consequence of small volumes of samples.

4. Conclusions

1. Processing of photographic observations of major planets and their moons was performed in the framework of UkrVO project (Vavilova et al., 2012a; 2012b; 2014a; 2014b).

2. We obtained astrometric catalogs of Saturn's satellites (n=1385 positions), Uranus (n=61), Neptune (n=51), Uranus's satellites U1 (n=3), U2 (n=8), U3 (n=22), U4 (n=22), Neptune's moon N1 (n=9) in Tycho-2 reference system. The internal accuracy of reduction in both coordinates is in the range 0.06″-0.11″. For DWA telescope this accuracy is more than twice worse and is 0.16″- 0.23″. The accuracy of photographic magnitudes varies from 0.27 mg to 0.37mg for all 4 telescopes.

3. The comparison of calculated positions with theory DE405 shows that the scatter of $(O-C)_i$ values is ± 2". Elimination of positions with $(O-C)_i$ ≥ **2σ″** leads to the decrease of the sample volume by 10%-15% and to the reduction of standard deviation Sd approximately by 0.15". For narrow samples, the application of the $(O-C)_i$ ≥ 2σ″ criterion can produce the erroneous conclusions.

4. The comparison of results obtained by the two techniques, classic and digital, shows the difference in the number of calculated positions for all objects. The reasons for these discrepancies are studied.

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