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Photometry and position observations of Saturnian satellites during their mutual eclipses and occultations in 1995 performed at the Observatories in Russia and Kazakhstan*

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Abstract. Photometry of mutual eclipses and occultations of planetary satellites is a powerful technique to explore these bodies. Observations of these rare events are a source of much precise information. In 1995 the Celestial Mechanics Department of the Sternberg Astronomical Institute (SAI) has organized the observations of mutual eclipses and occultations of Saturnian satellites on a number of observatories of the Commonwealth of Independent States (CIS) — the former Soviet Union (FSU). The ephemerides of satellites and their observing conditions have been computed beforehand and mailed these data to many observatories of CIS. The Crimean laboratory (CL) of the Sternberg Astronomical Institute, two observatories of the Fesenkov Astrophysical Institute of the Academy of Sciences of the Republic of Kazakhstan (FAI AS RK) in Almaty, and the Main Astronomical Observatory of Russian Academy of Sciences (MAO RAS) in Pulkovo took part in observations. A photoelectric photometer was used in CL of SAI, a CCD was employed to secure satellite images in FAI AS RK, and both CCD and photographic plates were used in MAO RAS. As a result of this observing campaign, photometric data and light curves were obtained for three mutual eclipses and occultations of Saturnian satellites. A number of position observations made allowed us to measure relative coordinates of satellites. Astrometric information has already been derived from photometric data. The mutual apparent positions of satellites were calculated with an accuracy of $0\farcs002 - 0\farcs003$. In this paper observations are described and the parameters characterizing the observed phenomena are given. The results of observations are available in electronic form.

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Key words: astrometry — occultations — eclipses — satellites of Saturn

1. Introduction

Accurate theories of motion of natural satellites are required to broaden our knowledge about the Solar System and to plan and realize space missions to other planets. In order to improve such theories it is necessary to make very accurate observations.

An efficient method for the study of planetary satellites are photometric observations of their mutual eclipses and occultations often referred to as mutual events. Observations of these rare phenomena provide a wealth of data. The surface characteristics and accurate astrometric data can be deduced from them (Mallama 1992; Descamps et al. 1992). The mutual positions of satellites as inferred from photometry of mutual events are several dozen and even several hundred times more accurate than those based on photographic observations. In the dynamics of natural satellites the effects are present that cannot be reliably interpreted on the basis of currently available observations. That is why we should take the maximum advantage of the "gift" offered by nature, the

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* Results of observations available in electronic form at CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

mutual events in satellite systems. Unfortunately, the mutual events are rare: they occur only when the Earth and the Sun cross the orbital planes of the satellites. A special effort must be made by the observers during these occurrences.

The first observations of a mutual event in Saturnian satellites were published in 1921 (Comrie 1921). These visual observations of the eclipse of Rhea by the shadow of Titan were made at five british observatories. The astrometric data derived from photometric observations of mutual occultations and eclipses of the Galilean satellites in 1973 and 1979 and four Saturnian satellites in 1980 were published in (Aksnes et al. 1984). The Bureau des Longitudes has been systematically launching international campaigns of observations of mutual phenomena in the system of the Galilean satellites (Arlot 1978; Arlot 1984; Arlot et al. 1990; Arlot 1996) and of the first eight Saturnian satellites (Arlot & Thuillot 1993).

Mutual events of major Saturn's satellites are confined to six-months epochs that occur once every 15 years. About 300 mutual events occur during each epoch. Each phenomenon typically lasts from 1 to 10 min and therefore it is accessible to observations at a specific group of observatories only. The last epoch of mutual events of Saturnian satellites took place in the second half of 1995. The worldwide distribution of events over observatories are discussed in Nasonova (1996). It was shown that part of all events is accessible to observation only at observatories of the FSU and nowhere else. It turns out that a failure to perform observations at these observatories may result in a loss of 20% of valuable observational data (Nasonova 1996).

In 1995 the observations has been organized on a number of observatories of the CIS (FSU) with the aim to observe mutual events in the system of Saturnian satellites. The goal of these observations was to make a contribution in the whole data base of observations of the major Saturnian satellites in order to improve the theory of their motion using the advantages of the rare events, mutual eclipses and occultations of the satellites.

Of interest are not only the photometry of mutual phenomena but also measurements of satellite positions at times close to such events. CCD observations of close apparent approaches are an opportunity to get more accurate measurements of the mutual positions of satellites. Photographic observations during these periods provide independent check on photometric results.

The staff of FAI AS RK had previous experience in this field gained during their photometric observations of mutual events of Galilean satellites in 1985. The results of their observations are published in (Grigorjeva et al. 1986a,b).

In the framework of the campaign of observatories of the CIS the only successful photometric observations turned out to be those made at CL SAI and at two observatories – in Assy and Almaty – of FAI AS RK. In addition, CCD position observations were performed at MAO RAS in Pulkovo and at two observatories of FAI AS RK. Within the framework of this campaign MAO RAS also performed photographic observations of Saturnian satellites.

During a mutual occultation of two satellites the combined flux decreases due to partial or complete screening of one satellite by the disk of the other satellite. Photometric observations with high time resolution make it possible to obtain the light curve of the combined flux of both satellites during their mutual occultation. This light curve depends on a number of factors: the mutual position of satellites (i.e., their coordinates), reflective properties of satellite surfaces, sizes and shapes of their bodies. During a mutual eclipse one of the satellites enters the umbra or penumbra of another satellite resulting in a decrease of the flux of the former. This decrease, in turn, is reflected in the measured light curve. During a mutual eclipse the combined light of the two satellites is measured. In some cases, when the angular separation between the two satellites is sufficiently large, it is possible to separately measure the magnitude of the eclipsed satellite. In the case of mutual eclipse, like in that of mutual occultation, the flux from satellites depends on their coordinates, sizes, shapes, and reflective properties.

The light curves of mutual events can be used to solve the inverse problem – to determine the differences of apparent coordinates of satellites at certain instants of time. Thus, photometry of mutual events of natural satellites provides an opportunity to obtain high-precision astrometric information. Given sufficient number of photometric observations, it is also possible to determine the sizes and shapes of satellites and the distribution of albedo on their surfaces.

Mutual events in the system of major Saturnian satellites occurred from April, 1995 to February, 1996. The period of possible observations of these events at the observatories mentioned above was much shorter – from July to December, 1995. Each event lasted several minutes. Up to 50 mutual events could be observed at each observatory. However, for various reasons (weather conditions and limited technical potential of observatories) photometric observations were performed only for 12 events of which only three proved to be successful. The ephemerides were computed at the Celestial Mechanics Department of the SAI by an original technique using a special software (Emel'yanov 1996) and have been published before (Emel'yanov et al. 1994).

In this paper we describe the results of observations of Saturnian satellites made within the framework of the campaign. The files with results available in electronic form are given in:
ftp cdsarc.u-strasbg.fr
username: anonymous
password: (type your e-mail adress here)
cd /pub/A+AS/[this volume number]/[this page number]
or

ftp ftp.sai.msu.ru
username: anonymous
password: (type your e-mail adress here)
cd /pub/PEOPLE/emelia/phemurus.
The file names are given below. The data can also be obtained on a request submitted to the first author of this paper at the following address: emelia@sai.msu.ru.

The authors would like to acknowledge the use of the data by making a reference to this paper. Below we describe the results subdividing the observations into the following groups:

– photoelectric photometry of single mutual events made at CL of SAI;
– CCD photometry of two mutual events made at observatories of FAI AS RK;
– CCD measurements of mutual satellite positions made at observatories of FAI AS RK;
– CCD measurements of satellite positions made at MAO RAS;
– photographic measurements of satellite positions made at MAO RAS.

2. Photoelectric observations of a mutual occultation of Saturnian satellites made at CL SAI

The observatory of CL SAI is located in Nauchnyi settlement at an altitude of 600 m. Its geographic coordinates are: east longitude $2^h16^m04^s$, north latitude $44°43'37''$.

The observations were made with a single-channel WBVR photoelectric photometer in a photon-counting mode. The satellite images were projected into the photomultiplier. The photoelectric photometer was mounted on a Zeiss-600 reflector with an aperture of 600 mm and focal length of 7500 mm. An interface counter mounted on an IMB PC compatible was used to count the pulses coming from the photoelectric photometer during the adopted exposure time. The number of these pulses is proportional to the incident flux on the cathode of the photomultiplier. The flux measured during the adopted exposure time was then read by a special interface software and stored in the computer memory. The interface and the corresponding software were developed by V.G. Kornilov (SAI).

The light curve was visualized on a display monitor in real-time mode thereby substantially facilitating the tracking of the event under study. The time signals were transmitted from a synchronometer, which we manually referred to the UTC scale to an accuracy of 0.1 seconds using radio time signals.

We began the photometry of satellite pair beforehand so that the duration of the event proper would be about 20% of the total observing time.

When observing Saturnian satellites the background contamination due to scattered light from both the Saturn and its ring poses a considerable challenge. The background brightness depends on the satellite position and relative fluctuations of this background due to imperfect telescope tracking can reach several tenths of magnitude. Thus, background measurements made with a $20''$ diaphragm in the immediate vicinity of rings show quasiperiodic flux fluctuations with an amplitude of about 0.1 of the flux itself. As a result, satellite light variations during mutual events observed at angular separations less $15''$ from the planetary disk are simply lost in the background fluctuations. Photometric data for mutual events in a pair of satellites at a sufficiently large separation from the Saturn's limb (where the ring background can be neglected) show a uniform trend on the light curve. Guiding attempts result in abrupt changes of the level of this trend. At the Crimean laboratory of Sternberg Astronomical Institute we performed photoelectric photometry of ten mutual occultations and eclipses of Saturnian satellites and only for two of these events the data proved to be free from unaccountable scattered light fluctuations. In this paper we present the results only for one completely successful photometric observing set.

This observing set had the following characteristics:

Date	1995 August 6
Event	occultation of Dione by Rhea
Observer	T.R. Irsmambetova
Angular altitude of Saturn	28°
Sun under horizon	30°
Angular altitude of the Moon	8°
Phase of the Moon	0.8
The angular separation of Saturn from the Moon	90°
Combined brightness of the satellites	9.3^m
The apparent distance to the edge of Saturn	$27''$

The exposure was 0.128 second resulting in a large number of data points for each mutual event. Our analysis showed that photometric data points can be combined into 1-second intervals without loss of accuracy. We actually averaged each eight consecutive counts. We considered the time of each such combined measurement to be the midtime of the fourth and fifth count. It is well to bear in mind that during such observations we measure the combined flux of both satellites, sky background, and the light scattered in the optical elements of the telescope.

The results of the set of observations described above can be found in file t0806o54.pmr. Each record in this file has a form of a simple sequence of integers equal to the numbers of pulses counted corresponding to the average number of photons crossing the photometer diaphragm a 0.128-second time interval. The time of the first count is $21^h31^m40\overset{s}{.}766$ (UTC scale) and the following counts are spaced at 1.024-s intervals. Figure 1 shows the resulting light curve with the flux given in relative units.

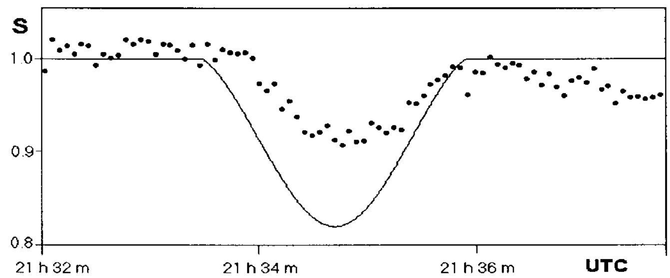

Fig. 1. Photometric observations of occultation of Diona by Rhea performed from CL SAI on August 6, 1995. The total flux, S, is given in relative units. The line is a preliminary ephemeride

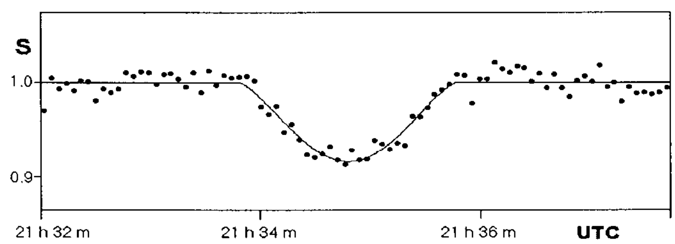

Fig. 2. The calculated (line) and observed (dots) total brightness curves of the satellites for the occultation of Diona by Rhea performed from CL SAI on August 6, 1995. The calculated curve is based on adjusted event parameters. The observations have been corrected for scale, zero point and secular trend effects

This observing set has been reduced in order to extract astrometric information (Emel'yanov et al. 1997). In particular, the apparent angular coordinate differences of satellites x_0, y_0 have been derived for a certain instant t_0 of time within the occultation observed. The measured quantity E as a function of time t is determined by the formula

$$E(t) = K\ S(t, x_0, y_0) + P + L\ (t - t_0), \qquad (1)$$

where the empirical parameters K, P, L were derived from the observations themselves, while the function $S(t, x_0, y_0)$ is the total light flux of the satellite pair normalized to the light of the two satellites outside the event. The adopted dependence of S on t, x_0, y_0 is described in (Emel'yanov 1995; Emel'yanov et al. 1997). This observing set allowed us to determine the satellite coordinate differences with an accuracy of $0\overset{''}{.}003$ and $0\overset{''}{.}005$ in right ascension and declination, respectively. The values of the refined parameters are published in (Emel'yanov et al. 1997). In Fig. 2 we compare observations with the theoretical satellite light curve computed after adjusting the above parameters. The flux is normalized to the combined light of the two satellites outside the event.

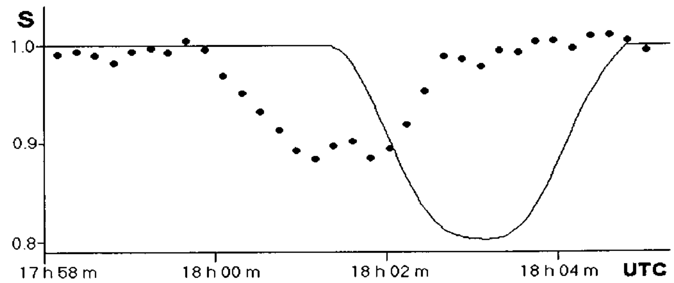

Fig. 3. Photometric observations of occultation and simultaneous eclipse of Enceladus by Tethys performed from Assy on September 14, 1995. The total flux, S, is given in relative units. The line is a preliminary ephemeris

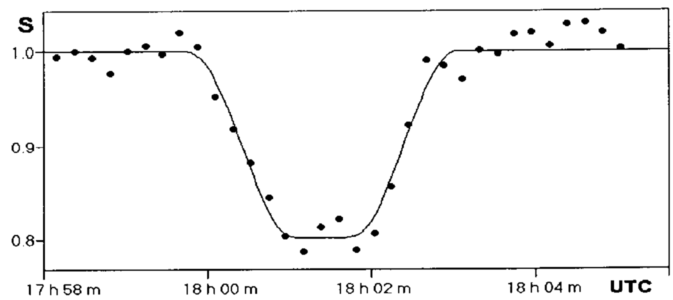

Fig. 4. The calculated (line) and observed (dots) total brightness curves of the satellites for the occultation and simultaneous eclipse of Enceladus by Tethys performed from Assy on September 14, 1995. The calculated curve is based on adjusted event parameters. The observations have been corrected for scale, zero point and secular trend effects

3. Photoelectric observations of a mutual occultation of CCD photometry of mutual events of satellites at FAI AS RK

At FAI AS RK the observations were performed at two observatories. The Assy observatory is located at an altitude of 2750 m at east longitude $5^{h}11^{m}31^{s}$, north latitude $43°13'20''$. The Almaty observatory (Kamenskoe Plato) has an altitude of 1450 m and is located at east longitude $5^{h}07^{m}49^{s}$, north latitude $43°11'10''$.

At the Assy observatory the observations were made with a 1-meter Zeiss telescope and at the Almaty observatory, with a 0.6-meter Zeiss telescope. On both telescopes photometric observations were made using cameras with image-magnification resulting in focal lengths of 12381 and 21474 mm for Zeiss-600 and Zeiss-1000, respectively.

The images were projected onto a ST-6V CCD thermoelectrically cooled to $-20°$C. The exposure times were always equal to 10 s and no filters were used. To avoid the scattered-light halo of the planet (which was not always possible), only a small CCD area containing the satellites to be observed was measured. The CCD was operated in the automatic image-file recording mode. The combined brightness of the two satellites was computed as the average over 11×11 pixels square region using standard CCD OPS software for CCD operation and reduction of frames.

A total of 15 mutual events of Saturnian satellites were observed and photometric data were secured for two of them.

The results of the first observing set can be found in file a0914e32.pmr. Each line in this file corresponds to one measurement and consists of four numbers. The first three numbers (hours, minutes, and seconds) give the time of observation – the average exposure midtime in the UTC scale. The last, fourth number gives the combined brightness (flux) of the two satellites in arbitrary relative units.

Figure 3 shows the resulting light curve (the flux is in arbitrary units). Here are the characteristics of the first event:

Date	1995 September 14
Event	Occultation and eclipse of Enceladus by Tethys
Observatory	Assy, FAI AS RK
Observer	V.G. Tejfel
Telescope	Zeiss-1000
Angular altitude of Saturn	40°
Sun under horizon	42°
Angular altitude of the Moon	26°
Phase of the Moon	0.7
The angular separation of Saturn from the Moon	63°
Combined brightness of the satellites	$9.9^{\rm m}$
The apparent distance to the edge of Saturn	28″

This observing set was also analyzed in (Emel'yanov et al. 1997). The reduction procedure was similar to that employed in the previous case. We obtained the apparent angular coordinate differences for satellites at a certain instant of time within the observing period. The accuracy of the satellite coordinate difference turned out to be $0\farcs002$ and $0\farcs008$ in the right ascension and declination, respectively. The values of the refined parameters are given in (Emel'yanov et al. 1997). In Fig. 4 we compare observations with the theoretical light curve computed after refining the parameters. The flux is normalized to the total light of the two satellites outside the event.

The second successful photometric observing set had the following characteristics:

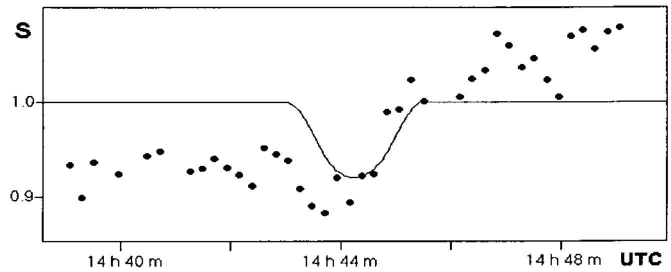

Fig. 5. Photometric observations of eclipse of Rhea by Enceladus performed from Almaty on November 25, 1995. The Rhea' flux, S, is given in relative units. The line is a preliminary ephemeris

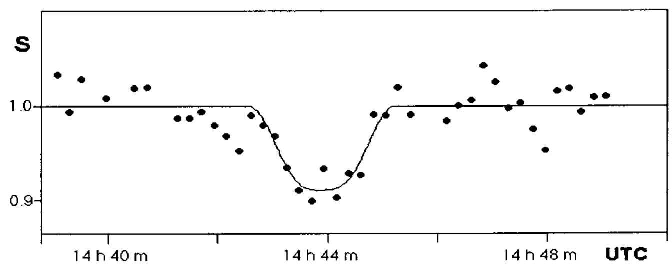

Fig. 6. The calculated (line) and observed (dots) brightness curves of Rhea for the eclipse of Rhea by Enceladus performed from Almaty on November 25, 1995. The calculated curve is based on adjusted event parameters. The observations have been corrected for scale, zero point and secular trend effects

Date	1995 November 25
Event	Eclipse of Rheas by Enceladus
Observatory	Almaty, FAI AS RK
Observers	V.G. Tejfel, G.A. Charitonova
Telescope	Zeiss-600
Angular altitude of Saturn	39°
Sun under horizon	37°
Angular altitude of the Moon	under horizon
Combined brightness of satellites	$9.7^{\rm m}$
The apparent distance to the edge of Saturn	15″

The results of the second set can be found in file a1125e25.pmr. The format of measurements is similar to that used for the previous observing set. Figure 5 shows the resulting light curve and Fig. 6, the same light curve with a fit involving parameters based on the analysis performed in (Emel'yanov et al. 1997). The accuracy of the satellite coordinate difference turned out to be $0\farcs009$ and $0\farcs029$ in the right ascension and declination, respectively. The values of the parameters are given in (Emel'yanov et al. 1997).

4. CCD measurements of positions of Saturnian satellites performed at FAI AS RK

The equipment of the FAI AS RK observatories was also used to perform CCD position observations of Saturnian satellites.

These observations were made with the same telescopes described above, only the focal length of the Assy telescope was set equal to 12909 mm.

During observations the CCD field always contained two or more satellites thereby allowing determination of their mutual positions.

We used standard ST-6V software to determine the angular separations between the satellites. After pointing the cross cursor on the maximum-brightness pixel interpolation is performed between the neighboring pixels in order to refine the position of maximum-brightness point (zero point). After pointing the cursor on the other satellite the program displays the angular separation between the satellites and the position angle.

The dates and times of observations were chosen so as to determine the mutual distances between the satellites during their approaches.

We performed a total of 11 observing sets to determine mutual apparent separations between Saturnian satellites. The duration of each such set was several tens of minutes. Table 1 gives the characteristics of these observing sets. It lists satellite numbers in the measured pairs in accordance with the notation generally accepted for saturnian satellites: 1 – Mimas, 2 – Enceladus, 3 – Tethys, 4 – Dione, 5 – Rhea, 6 – Titan, 7 – Hyperion, 8 – Iapetus. All observations were performed in 1995 and therefore the observing dates are given without years.

Angular separations between the satellites are measured directly with the CCD software. The scale of the observed field is determined from the images of binary stars.

The results are presented without correction for differential refraction. These corrections would be negligible since the angular altitude of the satellites was significant and the apparent separations between the satellites were very small.

To our regret the orientation of the CCD was set only approximately. Because of this and the fact that the angular separations between the satellites were very small the position angle was not a subject of our observations and we did not write the position angles in the files. To furnish the results with satellites configurations we only give in Table 1 the range of position angle values for each observing set. The position angles are determined for the first satellite in each pair (i.e., the one whose number is goes the first). The second number refers to the satellite with respect to which the position angles were determined. In the cases where we did not measure position angle at all the value in Table 1 is based on the ephemeris and is marked by an asterisk.

The results of observations can be found in files listed in Table 1. The data in these files are written in the following format. Each line contains the results of a single measurement. The first column gives the time of observation (the midtime of exposure) measured in minutes from the initial time given in the Table 1. The time is in the UTC scale. The second column gives the measured angular separation between the satellites in arcseconds.

The observing sets of 28 July and 14 September were performed at the Assy observatory and the remaining ones, at the Almaty observatory.

During one of the observing sets (August, 25) we measured the angular separation between the Tethys and an unidentified star. In Table 1 in this case an asterisk is used instead of the number of the second satellite. The magnitude of the star is of about 9.9. We hope this star could be identified with the precise ephemerides of Saturn and its satellite. Subsequently the measured angular separation between the satellite and the star could be used as one of measured values to refine the planet and satellite theories.

During the last observing set (November, 23) the satellites were observed both before their approach and during their separation. To distinguish the distances measured before and after the approach the latter are given as negative numbers. This allows us to fit a linear function to the observed data points over the entire observing set.

The results of observations described in this paper are shown graphically in Figs. 7–17. The observation time measured in minutes from the starting time is laid off along the x-axis and the mutual separation between the satellites in arcseconds, along the y-axis. The line is a linear least squares fit to the observed data points. The rms scatter of the observed separations about this linear fit (σ) is given in Table 1. The starting time used in Figs. 7–17 differs from the initial time used in the files and Table 1.

Substantial sigmas determined from these results concern the scale of the observed field and the pixel dimension. The discrete values in Figs. 7–17 confirm these conditions which could not be improved with the available telescope.

5. Position observations of Saturnian satellites made in MAO RAS

In MAO RAS the position observations of the main Saturnian satellites were performed on a 26-inch refractor with a focal length of 10.4 m. The images were obtained on an ST-6-type CCD during some of the observing sets and photographic plates during the other sets. Another name of MAO RAS is Pulkovo observatory. Its coordinates are: east longitude $2^h01^m19^s$, north latitude $59°46'18''$, an altitude of 75 m.

We reduced the CCD frames to determine the angular separations between the satellites and the corresponding position angles. If a frame contained more than two

Table 1. Some parameters of CCD position observations of the Saturnian satellites performed in FAI AS RK. Column σ is the rms scatter of the observed separations about the corresponding linear function of time. Column N gives the number of measurements in the observing set

Date, 1995	Satellites	Initial time	Position angle, °	σ, $''$	N	File name
28 July	$5-2$	$21^{\rm h}00^{\rm m}$	$270-279$	0.16	102	a0728d52.dat
16 Aug.	$4-5$	$21^{\rm h}00^{\rm m}$	$89-91$	0.23	67	a0816d45.dat
21 Aug.	$2-3$	$19^{\rm h}00^{\rm m}$	$77-82$	0.21	129	a0821d23.dat
25 Aug.	$3-*$	$21^{\rm h}00^{\rm m}$	$89-91$	0.17	383	a0825d3s.dat
14 Sep.	$4-2$	$17^{\rm h}00^{\rm m}$	$96-97*$	0.09	102	a0914d42.dat
14 Sep.	$4-3$	$17^{\rm h}00^{\rm m}$	$96-97*$	0.07	125	a0914d43.dat
28 Oct.	$1-3$	$15^{\rm h}00^{\rm m}$	$41-71$	0.13	113	a1028d13.dat
31 Oct.	$3-5$	$15^{\rm h}00^{\rm m}$	$34-55$	0.15	135	a1031d35.dat
06 Nov.	$2-4$	$15^{\rm h}00^{\rm m}$	$72-75$	0.17	120	a1106d24.dat
23 Nov.	$1-3$	$13^{\rm h}00^{\rm m}$	$265-271$	0.26	257	a1123d13.dat
23 Nov.	$2-3$	$13^{\rm h}00^{\rm m}$	$47-297$	0.17	204	a1123d23.dat

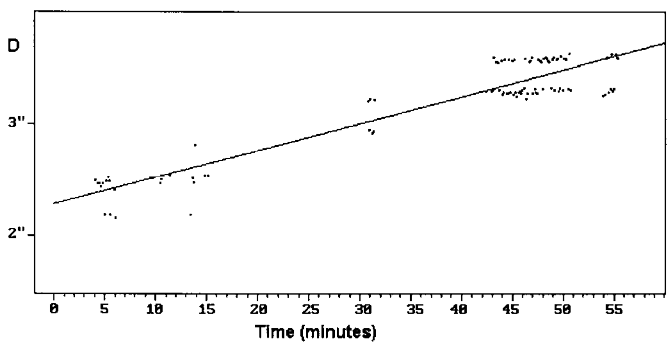

Fig. 7. The observed apparent distances D between the satellites. Observatory – Assy, Satellites – Rhea(5), Enceladus(2). Date – July 28, 1995, the starting time (UTC) – $21^{\rm h}50^{\rm m}$, $\sigma = 0\overset{''}{.}16$

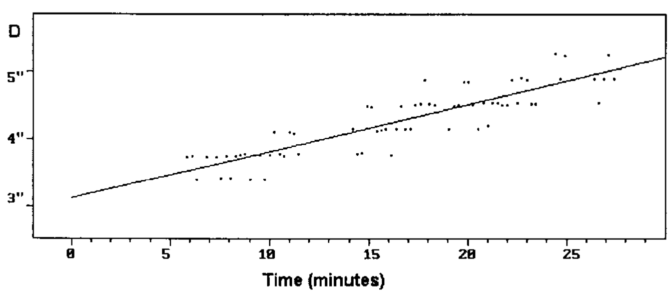

Fig. 8. The observed apparent distances D between the satellites. Observatory – Almaty, Satellites – Dione(4), Rhea(5). Date – August 16, 1995, the starting time (UTC) – $21^{\rm h}00^{\rm m}$, $\sigma = 0\overset{''}{.}23$

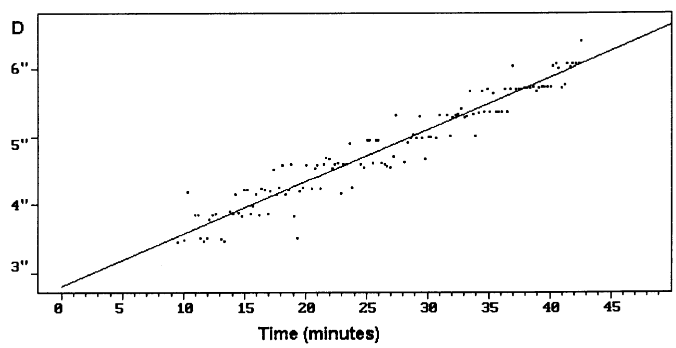

Fig. 9. The observed apparent distances D between the satellites. Observatory – Almaty, Satellites – Enceladus(2), Tethys (3). Date – August 21, 1995, the starting time (UTC) – $19^{\rm h}40^{\rm m}$, $\sigma = 0\overset{''}{.}21$

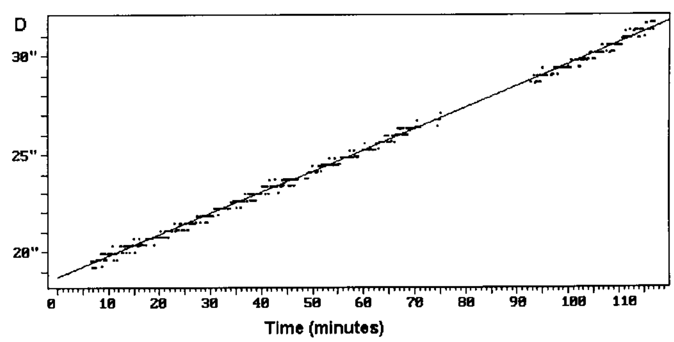

Fig. 10. The observed apparent distances D between the satellite Tethys(3) and some unidentified star. Observatory – Almaty, Date – August 25, 1995, the starting time (UTC) – $21^{\rm h}00^{\rm m}$, $\sigma = 0\overset{''}{.}17$

satellite images the relative coordinates were computed for each satellite pair and each set of such coordinates constituted a separate measurement consisting of a separation s and position angle p.

The orientation of the CCD frames determined from traces of the satellites in their diurnal motion. The frame scale follows from the comparison between the images of star clusters on the photographic plate and on the CCD frame.

The position angles are determined for the first satellite in each pair (i.e., the one whose number is goes the first). The second number refers to the satellite with respect to which the position angles were determined.

Table 2. Results of CCD position observations of the Saturnian satellites performed in MAO RAS

Date	Moment h m s	Satell. pair	s, $''$	p, $^\circ$	σ_s, $''$	σ_p, $^\circ$
1995 08 05	23 45 59	6 5	24.639	278.359	0.067	0.092
1995 08 05	23 45 59	3 5	36.171	277.055	0.063	0.022
1995 08 05	23 45 59	3 6	11.552	274.273	0.021	0.129
1995 08 05	23 45 59	4 5	139.616	275.019	0.032	0.007
1995 08 05	23 45 59	4 6	115.027	274.304	0.047	0.019
1995 08 05	23 45 59	4 3	103.476	274.308	0.052	0.007
1995 08 21	00 14 18	4 6	56.643	274.527	0.096	0.266
1995 08 21	00 14 18	3 6	69.629	275.400	0.190	0.274
1995 08 21	00 14 18	3 4	13.022	279.200	0.101	0.401
1995 08 21	00 21 18	4 6	56.940	274.901	0.147	0.350
1995 08 21	00 21 18	3 6	69.950	275.572	0.158	0.292
1995 08 21	00 21 18	3 4	13.031	278.507	0.060	0.348
1995 08 25	22 04 21	5 6	119.149	94.300	0.236	0.096
1995 09 01	22 03 06	5 6	82.484	272.937	0.167	0.085
1995 09 01	22 08 55	5 6	82.665	272.915	0.180	0.112

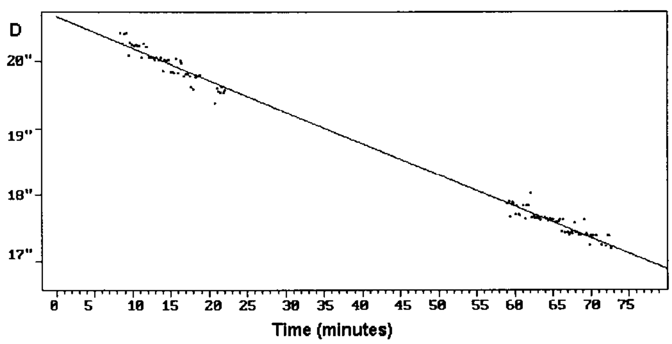

Fig. 11. The observed apparent distances D between the satellites. Observatory – Assy, Satellites – Dione(4), Enceladus(2). Date – September 14, 1995, the starting time (UTC) – 17^h20^m, $\sigma = 0.''09$

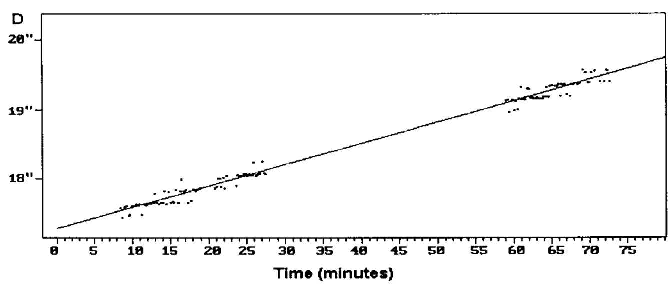

Fig. 12. The observed apparent distances D between the satellites. Observatory – Assy, Satellites – Dione(4), Tethys(3). Date – September 14, 1995, the starting time (UTC) – 17^h20^m, $\sigma = 0.''07$

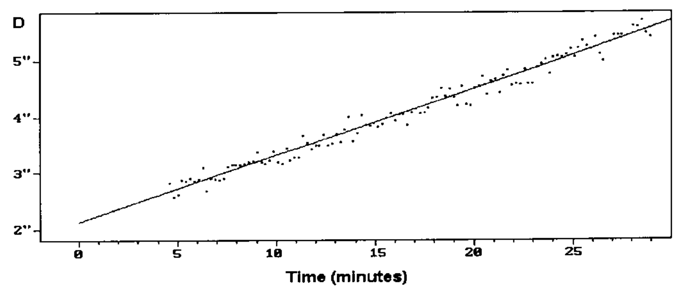

Fig. 13. The observed apparent distances D between the satellites. Observatory – Almaty, Satellites – Mimas(1), Tethys(3). Date – October 28, 1995, the starting time (UTC) – 15^h20^m, $\sigma = 0.''13$

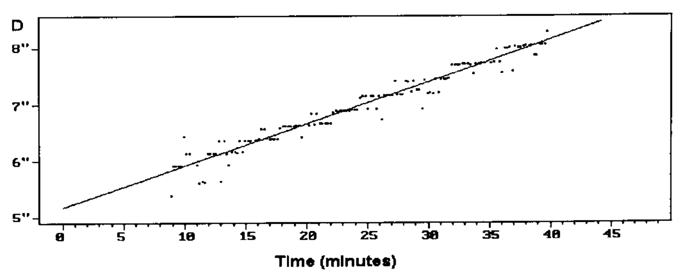

Fig. 14. The observed apparent distances D between the satellites. Observatory – Almaty, Satellites – Tethys(3), Rhea(5). Date – October 31, 1995, the starting time (UTC) – 15^h10^m, $\sigma = 0.''15$

Position angle is measured from the North direction in the equatorial reference frame for the epoch of observation. The time is on the UTC scale.

The results have been corrected for differential refraction. The rms errors σ_s, σ_p of measured coordinates s, p were inferred from repeatability of measurements based on a set of CCD observations. Each set consisted of 4–10 images. The result file contains a total of 15 measurements.

Table 2 gives results of the described CCD observations.

The results of these observations can be found in file *kccdb.dat*. Each line in this file represents a separate measurement and consists of 12 numbers:

1 – year,
2 – month,

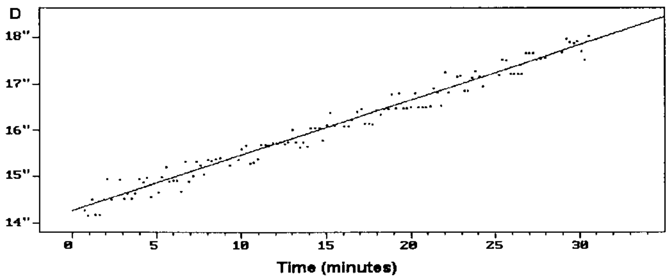

Fig. 15. The observed apparent distances D between the satellites. Observatory – Almaty, Satellites – Enceladus(2), Dione(4). Date – November 06, 1995, the starting time (UTC) – $15^{\mathrm{h}}30^{\mathrm{m}}$, $\sigma = 0\farcs17$

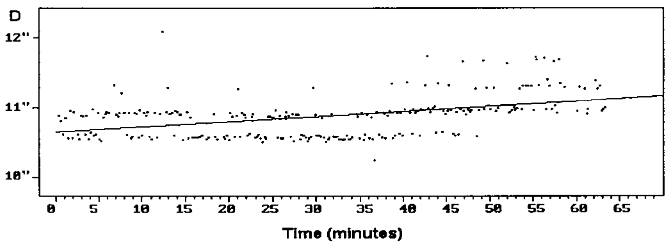

Fig. 16. The observed apparent distances D between the satellites. Observatory – Almaty, Satellites – Mimas(1), Tethys(3). Date – November 23, 1995, the starting time (UTC) – $13^{\mathrm{h}}40^{\mathrm{m}}$, $\sigma = 0\farcs26$

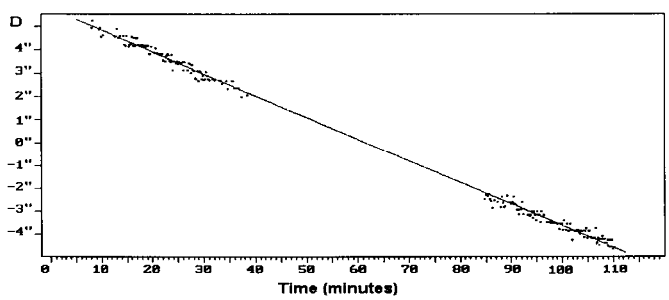

Fig. 17. The observed apparent distances D between the satellites. Observatory – Almaty, Satellites – Enceladus(2), Tethys(3). Date – November 23, 1995, the starting time (UTC) – $13^{\mathrm{h}}20^{\mathrm{m}}$, $\sigma = 0\farcs17$

3 – number (dates observ.),
4 – hour,
5 – min,
6 – second (moment observ.),
7 – number of first satellite,
8 – number of second satellite,
9 – angular distance between satellites s (arcsecond),
10 – position angle p (degree),
11 – the rms errors of angular distance between satellites σ_{s} (arcsecond),
12 – the rms errors of position angle σ_{p} (degree).

We now describe the results of photographic observations of the major Saturnian satellites. We used the plates to measure the satellite coordinates relative to both the center of the planet and that of satellite Titan. The measurements yielded relative coordinates $x = (\alpha_i - \alpha_j)\cos\delta_j$, $y = \delta_i - \delta_j$, where α and δ – right ascension and declination, respectively, indices i and j denote the number of the satellite and that of the body relative to which the coordinates have been measured, respectively: $j = 0$ for Saturn and $j = 6$ for Titan. The coordinates are referred to the equatorial reference frame for the epoch of observation and have been computed with correction for differential refraction.

The center of Saturn's image has been determined by measuring two points of the polar diameter of the planet and two points of the equatorial diameter with rings on the photoplates. The astrometric reduction of the relative coordinates of satellites was carried out by the formulas of "scale-trail" method worked out by Kisselev (1993).

The results of photographic observations are written in a separate file *kphot.dat*. The following format is used. Each line contains full data for a single measurement of relative satellite coordinates x, y, represented by a sequence of 10 numbers:

1 – year,
2 – month,
3 – number with part of day (moment of observ.),
4 – conditional number of photographic plates,
5 – satellite number (i),
6 – number of main body ($j = 0$ – planet, $j = 6$ – Titan),
7 – coordinate x (arcsecond),
8 – coordinate y (arcsecond),
9 – rms coordinate x (arcsecond),
10 – rms coordinate y (arcsecond).

The times of photographic observations are in the UTC scale. The measurement errors were computed from the repeatability of measurements based on several exposures taken on the same plate. There were usually 6 – 7 exposures per plate. The file contains a total of 237 lines (measurements) of which 128 are satellite coordinates relative to the planet and 109 are satellite coordinates relative to Titan satellite.

6. Conclusions

For the first time the major satellites of Saturn were observed by observatories in Russia and Kazakhstan within a framework of a coordinated observing campaign. This has been for us the first work of this type. Wide experience has been gained in performing such observations and reduction of their results. The main results of this work are a number of photometry sets of three mutual events of Saturnian satellites. Preliminary reduction of these observations (Emel'yanov et al. 1997) showed that they can be used to infer relative astrometric coordinates of satellites with an accuracy from $0\farcs002$ to $0\farcs03$. Photoelectric and CCD photometry yielded positional data of approximately the same accuracy.

Another result of the observing campaign are CCD measurements of positions of the major Saturnian satellites. A total of more than 1500 relative coordinates of satellites were obtained. The accuracy of position observations, as inferred from repeatability of measurements, varies from $0.''05$ to $0.''3$. We also performed photographic observations to determine a total of 237 relative positions of Saturnian satellites.

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