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New ephemerides of outer planetary satellites

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ABSTRACT
Ephemerides of planetary satellites require regular updates to take into account new observations of the satellites. Such revision has been all the more necessary in the case of outer planetary satellites, since a number of new moons have been discovered recently. Thus, we present updated versions of the ephemerides of the outer planetary satellites. The problem and the methodology for estimating ephemeris accuracy are discussed. Comparison with the Jet Propulsion Laboratory (JPL) ephemerides proves that the accuracy depends largely on the distribution of the observations. We give examples where, for a few satellites, the O−C residuals increase sharply at time intervals lying significantly beyond the time interval of observations used to generate the ephemerides. This fact alone indicates that there is an urgent need for new observations. Besides the ephemerides of moons, which can be accessed online via the MULTI-SAT server, we provide orbital parameters for the recently discovered faint satellites of Jupiter and Saturn. The problems discussed in this work are important for planning space observations of the outer satellites by future space missions like the European Space Agency (ESA) *JUpiter ICy moons Explorer* (*JUICE*) and National Aeronautics and Space Administration (NASA) *Europa Clipper* missions.

Key words: celestial mechanics – ephemerides – planets and satellites: general – planets and satellites: individual: Jupiter – planetary systems.

1 INTRODUCTION

With their easily recognizable orbits, the irregular (or faint) satellites of Jupiter, Saturn, Uranus, and Neptune are specific objects in the Solar System. Most of their current orbital peculiarities may be the consequence of their formation process from captured asteroids lying along heliocentric orbits. This resulted in high eccentricities of the satellite orbits, which can be as high as 0.75, as well as in great diversity of inclinations relative to planetary equators. Since irregular satellites are small in size, they are really faint in brightness, which is the reason why most of them were discovered only in recent decades. Hence, the observation interval is short for many of them and the number of observations is often low. Nevertheless, ephemerides of all these moons can be produced thanks to astrometric monitoring. As solar perturbations are very significant, the motion of irregular satellites can be modelled by numerical integration only.

We have already published ephemerides of irregular satellites (Emelyanov 2005; Emel'yanov & Kanter 2005), which can be accessed via the MULTI-SAT ephemeris server (Emel'yanov & Arlot 2008). Since these publications, new satellites have been discovered and the whole set of observations was significantly extended. This is why we decided to publish an updated version of our ephemerides (it should be noted, however, that they have been constantly updated as new observations emerged).

Up-to-date ephemerides of irregular satellites are available at the HORIZONS ephemeris server (Giorgini et al. 1996). Since updates at MULTI-SAT and HORIZONS do not occur simultaneously, different sets of observations are sometimes used, which can be easily deduced from the larger astrometric residuals during periods where new observations were not taken into account.

The precision of the ephemerides of irregular satellites is often poor. Using our methodology of estimating the ephemeris precision (Emelyanov 2010), we conclude that for some satellites the precision is so low that they are almost lost. In particular, despite some of them being retrieved previously (Brozovic & Jacobson 2017), they are such faint satellites that they need to be discovered again.

Since Brozovic & Jacobson (2017) published their ephemerides, new observations have been made. Moreover, a series of new faint satellites were discovered. This gives us the opportunity to update the models of motion of previously known satellites and determine the orbits of those newly discovered. An important part of the current work is to provide estimates of the precision of ephemerides. In particular, we compared the precision of different versions of the ephemerides generated with different sets of observations.

The question of the accuracy of outer-moon ephemerides is a key point for the space observation of these objects. In that respect, the *Gaia* mission will tie down the ephemerides of the brightest outer moons. These moons must have a magnitude below 20.9 and are just a small fraction of the whole outer-moon family. For the Jovian system, these moons are Himalia, Lysithea, Elara, Ananke, Carme, Pasiphae, Sinope, Leda, Themisto, and Callirhoe. For Saturn, there are Albiorix, Siarnaq, and Phoebe. Only Sycorax and Nereide are observable for the Uranian and Neptunian outer moon systems, respectively. Hence, the monitoring of all other outer moons will have to rely on essentially less accurate ground surveys.

In that respect, the present work will help analyse feasibility and the requirements associated with observations to be carried out by

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space missions like *JUpiter ICy moons Explorer* (*JUICE*) or *Europa Clipper* for the Jovian moons. Indeed, ephemeris accuracy has a direct impact on image windowing and, as a consequence, the data volume to be transferred from the spacecraft to the Earth. More generally, the current work will be useful for the preparation of any space mission or space project that plans to observe the outer moons of the giant planets.

Working with observations provided by the Minor Planet Center (MPC), we took the chance to update the photometric parameters of irregular satellites which, in turn, can be used to obtain estimates of satellite sizes and masses. Although the initial idea of updating photometric parameters of all irregular satellites was not implemented, estimates of radii and masses of some satellites were eventually obtained.

Before proceeding to the section describing our methodology, note that we do not consider the satellite S9 (Phoebe), since its high-precision ephemerides (available at MULTI-SAT) were elaborated by Desmars et al. (2013).

2 METHODOLOGY AND ALGORITHM OF DETERMINATION OF THE ORBITS

The orbits were determined by numerical integration based on a set of initial values of coordinates and velocities. Initial conditions were fitted to observations using the least-squares method (see the details of its application to the problem of natural planetary satellitesdynamics in chapter 6 of Emelyanov 2020). We did not assign weights to observations, since, according to our estimations, all the observations considered have roughly the same accuracy.

The dynamical model took into account perturbations caused by the Sun, the planets, and the non-sphericity of axisymmetric planets. The coordinates of the Sun, Earth, and planets were computed using the DE431 ephemeris (Folkner et al. 2014).

Attraction of the major satellites was modelled by considering them as rings with uniformly distributed masses. The radii of the rings were taken to be equal to the semi-major axes of the satellite orbits, the ring plane coinciding with that of the planet's equator. Gravitational fields of such rings were taken into account by correcting for both planetary masses and the coefficients J_2 and J_4 of expansion of the planet's gravitational potential. The accuracy of such representation of gravitational potentials turned out to be sufficient for solving our problem. Moreover, compared with the model where major satellites are considered as moving points, it provided us with better stability of the results of numerical integration.

Since such a replacement actually averages the influence of attraction of the satellites only, it can be expected that over long time intervals our approximation will not affect the global evolution of the orbits. The error introduced by replacing satellites with rings can be estimated by comparing our ephemeris with those of other authors. Such comparisons are shown below. As can be seen from the comparisons, differences in the set of the observations used change the ephemerides more significantly.

The values of the dynamical parameters *Gm* of the planets with satellites used in the model were taken from Jacobson, Riedel & Taylor (1991), Jacobson et al. (1992), and Jacobson (2000, 2004). The expansion of the force function corrected for the attraction of the main satellites can be found in Emel'yanov & Kanter (2005).

A specific algorithm was used for determining the orbits from observations. First, the equations of motion were integrated by Belikov's method (Belikov 1993), the rectangular coordinates of the satellite being developed as the coefficients of Chebyshev polynomials. Then, differential equations for the partial derivatives of measured values with respect to the initial conditions were solved by Everhart's method (Everhart 1974). These equations include the coordinates obtained earlier in the form of Chebyshev polynomial coefficients. After refinement of the orbital parameters, the segments of the series representing the satellite's coordinates were saved in a file. Such separation during the integration process made it possible to choose the integration step size of the equations optimally.

3 ESTIMATION OF EPHEMERIS PRECISION

When using ephemerides, it is important to know their precision. It is all the more important for the ephemerides of irregular satellites, since the number of observations is still small and they cover relatively short time intervals. Among other things, estimates of ephemeris precision are necessary when comparing ephemerides with those obtained by other researchers.

Emelyanov (2010) offered three methods for estimating the precision of the ephemerides of the outer planetary satellites. In this work, we choose the method of variating the orbital parameters using the covariance matrix of the parameters obtained in the process of fitting them to the observations. In particular, information about the precision of the observations is given implicitly by the covariance matrix.

The main idea of this method is as follows. A number of versions of each ephemeris are generated, where the fitted parameters are modified using a random-number generator and the covariance matrix. For each version, the satellite positions are computed for different given moments of time. Then, statistical evaluations of variations of the ephemerides can be considered as estimations of their precision. When estimating the precision, the time interval considered reaches from the first observation up to some moment in the future. At first, when doing preliminary calculations, this latter was set to 2022 December 31. However, as the ephemerides were updated, the time interval was expanded.

For each satellite, the ephemeris error was estimated using the root-mean-square (rms) value of the angular distances of the satellite's geocentric positions from the reference ephemeris obtained from the observations. Figs 1–3 give examples of the dependence of ephemeris precision over time for a few satellites. In those cases, there are many observations over a relatively large time interval. Estimates of precision are shown by solid lines. The horizontal line segments correspond to the interval of available observations. These segments are drawn at the level corresponding to the rms value of deviations of observed satellite positions from their calculated positions.

There are several reasons why ephemeris precision changes over time. One of them is that the satellite positions on the celestial sphere are obtained for different distances to the observer, so that, with the same precision of satellite positions in space, angular precision can vary. Moreover, previous studies (Emelyanov 2010) proved that the maximum error in satellite positions is reached along its trajectory. Hence, precision also depends on the direction of satellite motion relative to the sky plane. If the velocity vector is normal to the sky plane, the error in the satellite position is less compared with the case in which the velocity vector is normal to the line of sight.

For some satellites, the period of observations is very short. Figs 4 and 5 show estimates of ephemeris precision for such cases. It can be seen that the errors increase in time and the rate of degradation of precision is more significant when the intervals of observation are smaller. There are satellites for which the ephemeris error becomes so high by 2025 that their positions on the celestial sphere become indefinite and there is a risk of confusing such satellites with other objects.

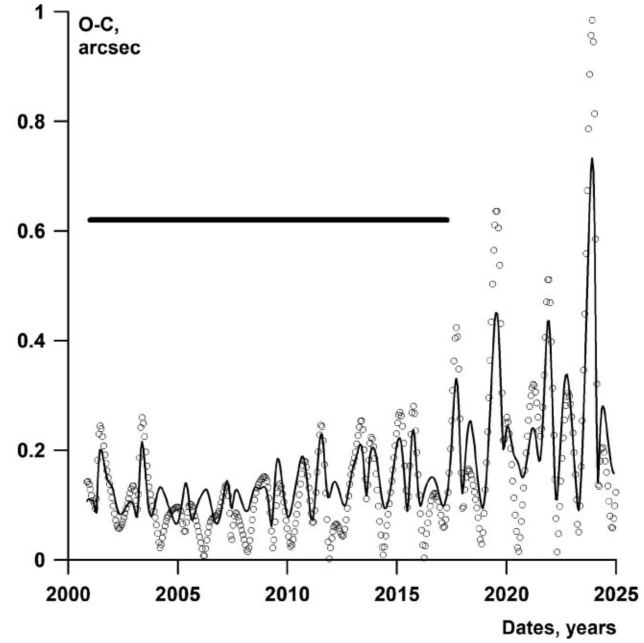

Figure 1. Estimates of ephemeris precision for the satellite J19 Megaclite (line) and differences of its positions relative to the JPL ephemerides (circles). This is the case of the large observation interval indicated by the horizontal line segment. The segment is drawn at the level corresponding to the rms value of deviations of observed satellite positions from their calculated positions. The mean orbital period of this satellite is 741 days (2.03 years).

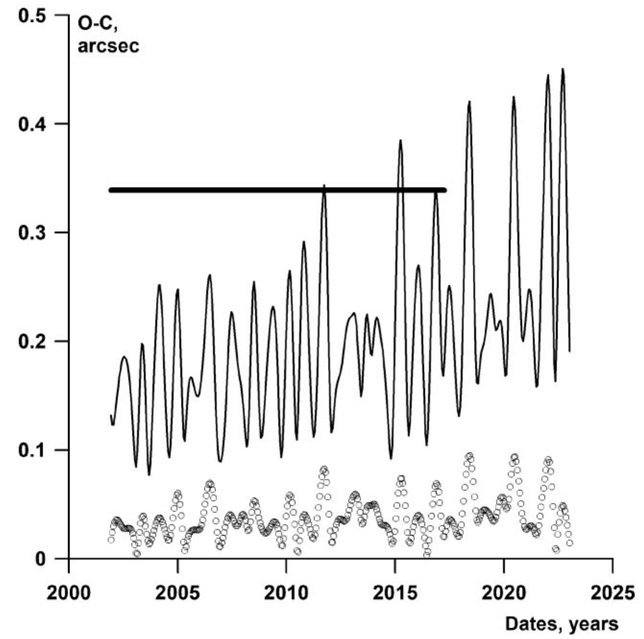

Figure 2. The same as in Fig. 1 but for the satellite J33 Euanthe. The mean orbital period of this satellite is 613 days (1.68 years).

4 COMPARISON WITH OTHER EPHEMERIDES

There are alternative sources for the ephemerides of outer planetary satellites. One of them, elaborated at the MPC, is available at https://minorplanetcenter.net/iau/NatSats/NaturalSatellites.html. Regrettably, we have no information about how the MPC ephemerides were developed. Obviously, these ephemerides are

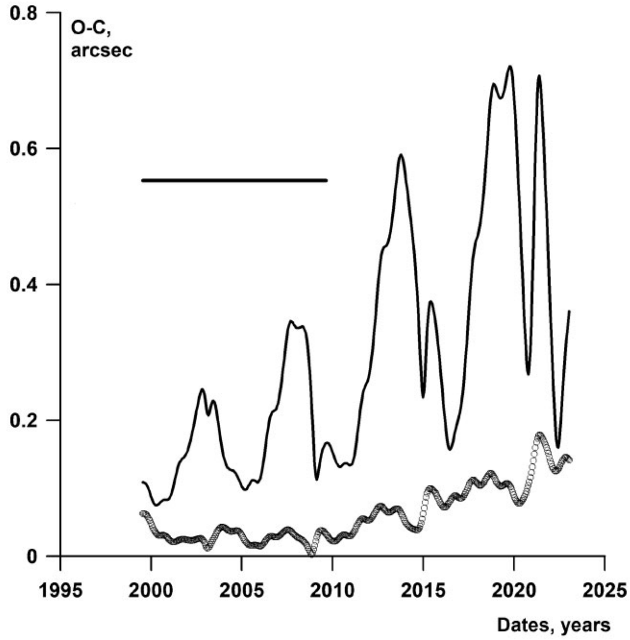

Figure 3. The same as in Fig. 1 but for the satellite U19 Setebos. The mean orbital period of this satellite is 2215 days (6.06 years).

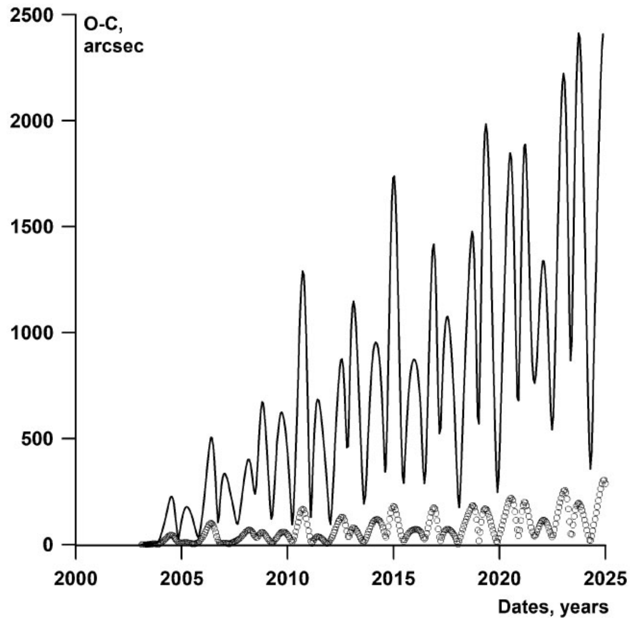

Figure 4. Estimates of ephemeris precision for the satellite S/2003 J10 observed at a short (80 days) time interval (2003.317–2003.537). See also the notes to Fig. 1. The mean orbital period of this satellite is 739 days (2.02 years).

based on numerical integration, however the MPC website provides us with no information about the dynamical model and methods of integration.

It should be noted that the output of the MPC ephemerides provides a limited number of decimal digits, sometimes corresponding to uncertainties of about 1 arcsec, which contributes to the differences observed between the ephemerides.

We compared our ephemerides with those provided by the MPC using the output of both ephemerides for the satellite J19 Megaclite.

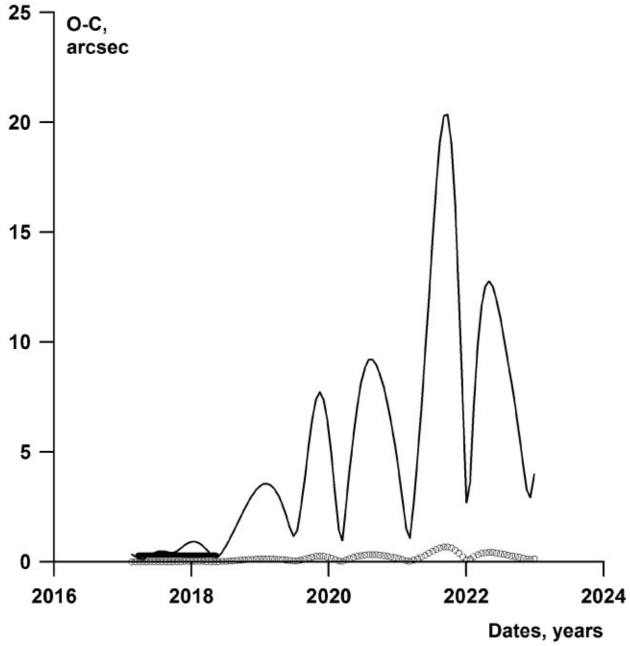

Figure 5. Estimates of ephemeris precision for the satellite J66 (S/2017 J5) observed at a 415-day time interval (2017.222–2018.359). See also the notes to Fig. 1. The mean orbital period of this satellite is 721 days (1.97 years).

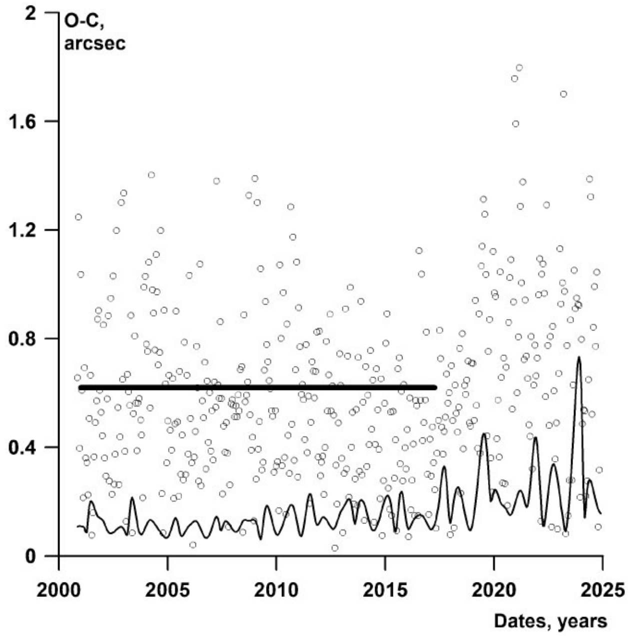

Figure 6. Comparison with the MPC ephemerides for the satellite J19 Megaclite. See also the notes to Fig. 1. Compare with the differences using JPL ephemerides for the same satellite in Fig. 1. The mean orbital period of this satellite is 741 days (2.03 years).

Positions of the satellite computed with the MPC ephemerides were used as input for the MULTI-SAT ephemeris server as if they were observations. We calculated O−C residuals as angular distances between the observed and predicted positions. The resulting O−C residuals (circles), as well as estimates of the ephemeris error (line), are given in Fig. 6. The plot proves that the differences between ephemerides exceed our precision estimates.

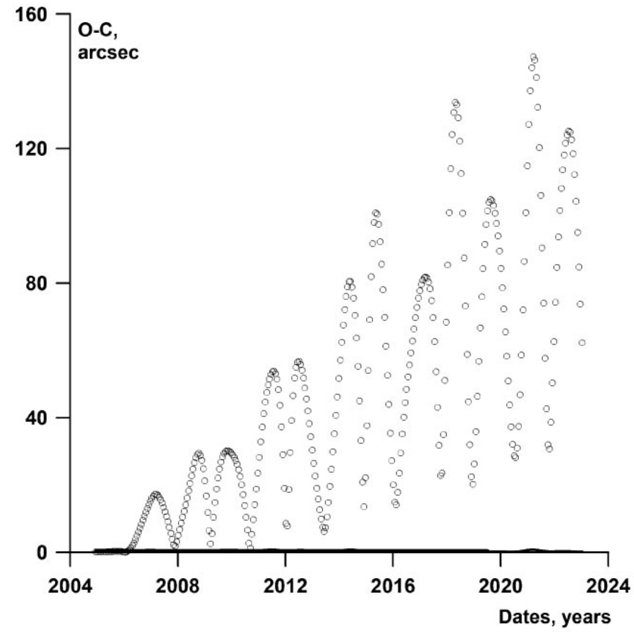

Figure 7. Comparison of our results with the JPL ephemerides for satellite S36 (Aegir). Observations made in 2019 are included. Empty circles are the differences between observations and positions obtained from the JPL ephemerides. The plot of precision estimates (line) merges with the *x*-axis. See also the notes relating to Fig. 1. The mean orbital period of this satellite is 1109 days (3.04 years).

We cannot tell for sure the reasons for such discrepancies. Assuming that the composition of observations used in the MPC ephemerides was close to ours, there might be two possible reasons: (1) lower precision of the MPC ephemerides and (2) low precision of the output data provided by the MPC website

From now on, we compare our ephemerides with those produced at the Jet Propulsion Laboratory (JPL) using the web interface for the Horizons system (https://ssd.jpl.nasa.gov/horizons.cgi). The JPL ephemerides proved to be closer to our ephemerides than those generated by MPC. Comparison was made in exactly the same way as described above. Celestial coordinates of satellites provided by JPL were treated as observations fed into MULTI-SAT to generate O−C values over a time interval. The time sampling was chosen to begin with the first observation of the satellite and continue up until 2025. Figs 1–5 show the results of such a comparison. As stated above, the plots also contain our estimates of ephemeris precision. The horizontal segment shows the interval of available observations, its level corresponding to the rms value of deviations from the observations. Figs 1–3 demonstrate that the differences between our results and the JPL ephemerides do not exceed our computed estimates of ephemeris precision. While this is true for almost all outer satellites, there are some exceptions.

Fig. 7 shows a comparison of our results with the JPL ephemerides for satellite S36 (Aegir). The differences are so high that, with the given scale, the plot of estimates of precision coincides with the *x*-axis.

Trying to understand the reasons for such differences in positions of Aegir, we found out that there were 20 observations of this satellite made in 2004–2006 and four more made in 2019. We used all 24 observations and found that astrometric residuals do not exceed 1.124 arcsec for the whole 15-yr interval of observations, the rms being equal to 0.462 arcsec. Having computed O−C values

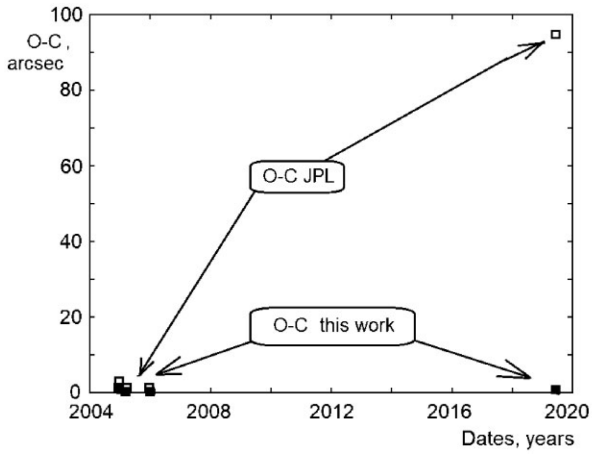

Figure 8. The astrometric residuals of S36 Aegir calculated with our ephemeris (filled squares) and the JPL ephemeris (empty squares). With both ephemerides, the residuals are small for the interval 2004–2006. For observations made in 2019, O−C values are small when using our ephemeris and reach up to 93 arcsec with the JPL ephemeris.

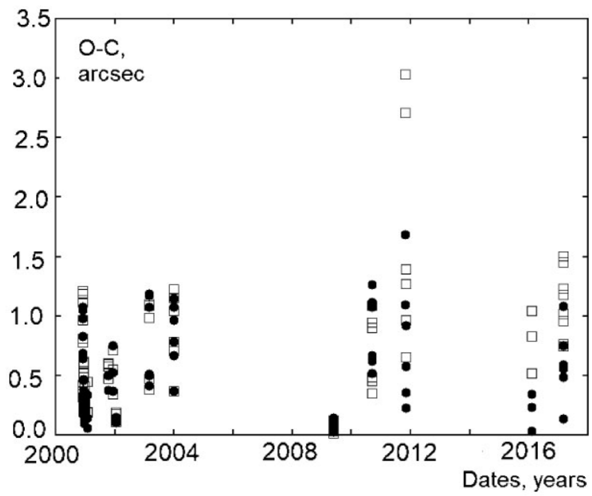

Figure 9. Astrometric residuals of J19 Megaclite with our ephemeris (bold points) and the JPL ephemeris (empty squares).

with the JPL ephemeris, we found that the JPL model for Aegir fits the observations made in 2004–2006 well, with residuals not exceeding 1.14 arcsec. However, for observations made in 2019, the residuals turned out to be about 93 arcsec. Fig. 8 provides O–Cs for Aegir obtained from both our ephemeris (filled squares) and the one generated by JPL (empty squares). Evidently, in determining Aegir's orbit, 2019 observations were not used by JPL. Surely, this is an inevitable aspect of the process of periodic updates of ephemerides, when some of the latest observations can be missed from consideration.

Our ephemeris is based on published observations that we have found up to 2021 March. In comparisons with the JPL and MPC ephemerides, we captured these ephemerides at about the same epoch.

We compared the residuals between observed positions and those obtained with both our and the JPL ephemerides for all irregular satellites. In most cases, O−C values were close for both ephemerides (see Fig. 9, where such residuals are given for J19 Megaclite).

Table 1. Orbital parameters of recently discovered Jovian satellites. The parameters were obtained using the MULTI-SAT server over a 25-yr interval, between 2000 January 1 and 2024 December 25.

Satellite	$a \times 10^{-6}$, km	*Min* e	*Max* e	*Min* i, deg	*Max* i, deg	Orbital period, days
J62	18.6962	0.127	0.137	23.46	46.74	521.912
J63	22.9492	0.143	0.399	150.13	173.44	709.372
J64	20.9370	0.075	0.248	136.84	165.72	618.586
J65	11.4788	0.135	0.216	17.40	29.38	251.239
J66	23.1953	0.140	0.385	142.64	163.77	720.756
J67	23.2470	0.169	0.558	152.06	175.08	723.233
J68	20.9608	0.096	0.443	139.62	163.96	619.598
J69	22.8184	0.134	0.399	141.23	151.06	703.339
J70	21.7707	0.098	0.341	139.84	167.11	655.731
J71	11.3984	0.078	0.142	28.98	39.54	248.606

However, a situation similar to that of S36 Aegir, when differing sets of observations were used, is repeated for another 10 satellites.

New observations are published regularly. Hence, we cannot guarantee that our ephemerides have taken into account all observations published recently. This is why we will definitely go on updating our ephemerides regularly.

5 ORBITAL PARAMETERS OF NEWLY DISCOVERED SATELLITES

Satellite orbital parameters are sometimes necessary when solving various problems in Solar system dynamics, like the question of the satellites' origin. Approximate values of orbital elements are usually given in reports of satellite discoveries. However, more precise values are published later, after the orbits are fitted to a significant number of observations. As shown by Brozovic & Jacobson (2017), the semi-major axis a, eccentricity e, and inclination to the Earth's ecliptic i vary within significantly broad limits. Brozovic & Jacobson (2017) determined the orbits for 59 irregular satellites of Jupiter by applying numerical integration over a 1000-year interval, which allowed them to compute mean, maximum, and minimum values for the satellites' osculating elements. As for the orbital parameters of other outer planetary satellites, a review can be found in the appendix of Emelyanov (2020).

The history of the discoveries of natural satellites of planets can be traced in Emelyanov (2020). There have been no recent discoveries of new moons of Uranus and Neptune. Ephemerides of the satellites of these planets have been developed for a long interval of time and have not been updated recently. Therefore, we have nothing to report about the satelites of Uranus and Neptune. A global overview of the orbital parameters for all four systems can also be found in Emelyanov (2020).

For some recently discovered irregular satellites (10 Jovian and 20 Saturnian), orbital parameters have not yet been published.

Our ephemeris service MULTI-SAT allows us to output the osculating elements on any date using the model of motion constructed from the observations. In this output we can have the mean, maximum, and minimum values. Thus, we calculated the mean values for the semi-major axis a, and the limits for the change of eccentricity e and inclination i of the orbits of new recently discovered irregular satellites (see Tables 1 and 2) for a 25-year interval, between 2000 January 1 and 2024 December 25. The inclination is measured relative to the Earth's equator for the J2000 epoch.

The tables also give the orbital periods defined from changes in the mean anomaly. Parameters are calculated using the MULTI-

Table 2. Orbital parameters of recently discovered Saturnian satellites. The parameters were obtained using the MULTI-SAT server for a 25-yr interval, between 2000 January 1 and 2024 December 25. The preliminary designation of the satellites is S/2004 Sat, where Sat is given in the table.

Sat.	$a \times 10^{-6}$, km	*Min* *e*	*Max* *e*	*Min* *i*, deg	*Max* *i*, deg	Orbital period, days
S20	19.2531	0.146	0.245	168.43	173.46	997.252
S21	23.1351	0.246	0.447	134.17	139.22	1313.200
S22	20.5906	0.157	0.284	156.78	156.94	1102.859
S23	21.4386	0.330	0.531	154.28	154.66	1171.494
S24	23.3361	0.005	0.107	56.10	60.09	1330.318
S25	20.9562	0.413	0.618	154.96	156.86	1132.201
S26	26.0993	0.078	0.238	163.81	165.41	1572.993
S27	19.8464	0.109	0.191	150.25	154.61	1043.684
S28	21.8313	0.100	0.212	147.27	149.40	1203.948
S29	17.0594	0.370	0.532	18.74	31.50	831.753
S30	20.7046	0.067	0.145	144.89	149.09	1112.081
S31	17.4958	0.158	0.270	55.54	59.26	863.935
S32	21.1514	0.186	0.327	154.83	162.99	1148.201
S33	23.5601	0.384	0.649	144.27	156.42	1349.270
S34	24.1495	0.180	0.352	157.70	162.85	1400.328
S35	21.9850	0.162	0.307	159.23	159.65	1216.644
S36	23.4172	0.516	0.759	124.45	142.96	1337.137
S37	15.9405	0.426	0.550	139.74	143.01	751.340
S38	22.2589	0.381	0.588	129.62	136.29	1239.285
S39	23.1924	0.054	0.155	143.10	144.66	1318.186

SAT server from the ephemerides, which are obtained by numerical integration based on observations.

Note that the semi-major axes and periods of orbital motion change insignificantly (by no more than 10 per cent). Therefore, we give average values only.

6 PHYSICAL PARAMETERS OF SOME SATELLITES

Astrometric data published by the MPC are sometimes accompanied by photometric data. Working with observations provided by the MPC, we could not help taking advantage of the possibility of updating the values of photometric parameters of irregular satellites and obtaining estimates of their sizes and masses. The necessary condition for obtaining such estimates is to know their apparent stellar magnitude in the *R*, *B*, or *V* bands. For the majority of irregular satellites, such estimates were obtained earlier by Emel'yanov & Ural'skaya (2011). Here, we made an attempt to update the results of this work. The methodology we used was the same as the one described in Emel'yanov & Ural'skaya (2011). Note that we excluded from consideration the satellites J06–13, S09, and N02, since their sizes and masses can be determined by more reliable methods.

It turned out, however, that for observations published after 2010 there were only rare cases when stellar magnitudes were given in the *R*, *B*, or *V* bands. Observations in the *B* band are exceptionally rare, so that they cannot be used to determine photometric parameters. New observations in the *R* band are available for the satellites S/2003 J12 and U17 (Sycorax), only. The number of satellites observed in the *V* band is a little higher. Tables 3 and 4 give values for the photometric parameters *H* and *G* of the satellites observed in the *R* and *V* bands, as well as estimates of their sizes and masses. The tables also give the number of observations of the satellite in the corresponding spectral band and the rms deviation of the measured absolute magnitude from its modelled value (σ).

Table 3. Photometric parameters H_R and G_R and estimates of sizes and masses for the satellites S/2003 J12 and U17. Here, *N* is the number of observations, *r* the estimate of the radius, *Gm* the estimate of the gravitational parameter.

Satellite	*N*	H_R	σ	G_R	*r*, km	*Gm*, $\mathrm{km^3\ s^{-2}}$
S/2003 J12	32	16.81	0.19	0.42	1.2	0.0000014
U17	70	7.77	0.38	3.38	79.5	0.2105656

Table 4. Photometric parameters H_V and G_V and estimates of sizes and masses for irregular satellites observed in the *V* band after 2010. Notations are the same as in Table 3.

Satellite	*N*	H_V	σ	G_V	*r*, km	*Gm*, $\mathrm{km^3\ s^{-2}}$
J17	74	14.11	0.42	1.11	5.1	0.0000944
J18	22	13.06	0.34	0.30	8.2	0.0004036
J41	6	14.11	0.42	-2.62	5.1	0.0000946
S20	23	11.38	0.26	-0.52	14.5	0.0019735
S26	96	10.86	0.47	-0.38	18.5	0.0040792
S29	198	10.52	0.51	0.25	21.6	0.0064741
U17	225	7.82	0.51	5.52	91.7	0.3234291

When obtaining estimates for sizes and masses, we made assumptions about the albedos (p) and densities (ρ) of the satellites similar to those made in Emel'yanov & Ural'skaya (2011), that is, for both *V* and *R* bands we took $p = 0.04$ and $\rho = 2.6\ \mathrm{g\,cm^{-3}}$, $p = 0.06$ and $\rho = 2.3\ \mathrm{g\,cm^{-3}}$, $p = 0.04$ and $\rho = 1.5\ \mathrm{g\,cm^{-3}}$, $p = 0.04$ and $\rho = 1.5\ \mathrm{g\,cm^{-3}}$ for the moons of Jupiter, Saturn, Uranus, and Neptune, respectively.

Certainly, the adopted values for albedos and densities are very approximate, which, in particular, results in differences between estimates for the radius of Sycorax in both tables. However, both estimates for the size of Sycorax are consistent with previous publications of its radius (Sheppard, Jewitt & Kleyna 2005; Lellouch et al. 2013).

In most cases, observations of the last decade published by the MPC have been accompanied with stellar magnitudes in the *r*, *i*, and *w* bands. However, even for the most 'popular' *r* band, available observations allow us to determine photometric parameters only for 60 irregular satellites, i.e. less than half of their total number. Since we do not know the models that could allow us to estimate the sizes of the bodies using their albedo and magnitude in *r*, *i*, or *w* bands, these observations turned out to be of no use for our purpose.

7 ACCESSIBILITY OF DATA AND EPHEMERIDES AT THE MULTI-SAT SERVER

All published observations of irregular satellites of Jupiter, Saturn, Uranus, and Neptune are available from the Natural Satellite DataBase (Arlot & Emelyanov 2009) and accessible at http://www.sai.msu.ru/neb/nss/html/obspos and http://nsdb.imcce.fr/obspos. The ephemerides are accessible via the MULTI-SAT server (Emel'yanov & Arlot 2008), available at both Sternberg Astronomical Institute (SAI: http://www.sai.msu.ru/neb/nss/html/multisat) and Institut de Mécanique Céleste et de Calcul des Ephémérides (IMCCE: http://nsdb.imcce.fr/multisat) web-sites. Both sites have user manuals (see http://www.sai.msu.ru/neb/nss/html/multisat/DephInse.htm or http://nsdb.imcce.fr/multisat/DephInse.htm). A description of the service is also given in chapter 12 of Emelyanov (2020). Here, we just note that the service allows us to obtain astrometric coordinates of satellites (right ascension and declination) as well as their barycentric coordinates, which can be used to compute osculating elements of Keplerian orbits.

8 CONCLUSION

In this work, we presented new data concerning the dynamics of almost all known irregular satellites of the giant planets, i.e. 71 satellites of Jupiter, 57 of Saturn, nine of Uranus, and six of Neptune. The only satellite excluded from consideration was Phoebe. Orbital parameters of these satellites were fitted to all published observations. An original methodology for determining the orbits and specific dynamical model was used. The orbital parameters obtained were then used to calculate the ephemerides that are accessible online via the MULTI-SAT service. Compared with earlier versions of the ephemerides available at MULTI-SAT, this version is based on extended sets of observations and provides positions of recently discovered irregular satellites.

We have estimated the precision of the ephemerides. These estimates can also be obtained using our ephemeris server. Ephemeris precision is shown to decrease rapidly over time. For some satellites, the errors in positions are comparable with the size of their orbits.

We also compared our ephemerides with those elaborated at the JPL. In general, the differences between the ephemerides turned out to be less than the estimated ephemeris precision.

For newly discovered satellites (10 Jovian and 20 Saturnian), orbital parameters are given.

For some satellites, we updated the values of their photometric parameters and estimates of their radii and masses.

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DATA AVAILABILITY

The data reported in this work are available at the MULTI-SAT service elaborated by SAI and IMCCE, accessible online at http://www.sai.msu.ru/neb/nss/multisat and http://nsdb.imcce.fr/multisat. The ephemerides can be used offline. Corresponding SPK binary kernel files can be provided on request.

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