New precise positions in 2013–2019 and a catalog of ground-based astrometric observations of 11 Neptunian satellites (1847–2019) based on *Gaia*-DR2

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ABSTRACT

Context. Developing high-precision ephemerides for Neptunian satellites requires not only the continuation of observing campaigns but also the collection and improvement of existing observations. So far, no complete catalogs of observations of Neptunian satellites are available.

Aims. We aim to provide new, precise positions, and to compile a catalog including all available ground-based astrometric observations of Neptunian satellites. The observations are tabulated in a single and consistent format and given in the same timescale, the Terrestrial Time (TT), and reference system, the International Celestial Reference System (ICRS), including necessary changes and corrections.

Methods. New CCD observations of Triton and Nereid were made at Lijiang 2.4-m and Yaoan 0.8-m telescopes in 2013–2019, and then reduced based on *Gaia*-DR2. Furthermore, a catalog called OCNS2019 (Observational Catalog of Neptunian Satellites (2019 version)) was compiled, after recognizing and correcting errors and omissions. Furthermore, in addition to what was considered for the COSS08 catalog for eight main Saturnian satellites, all observed absolute and relative coordinates were converted to the ICRS with corrections for star catalog biases with respect to *Gaia*-DR2. New debiasing tables for both the modern and old star catalogs, which were previously not provided based on *Gaia*-DR2, are developed and applied. Treatment of missing positions of comparison bodies in conversions of observed relative coordinates are proposed.

Results. OCNS2019 and the new debiasing tables are publicly available online. OCNS2019 includes 24996 observed coordinates of 11 Neptunian satellites obtained over 3741 nights from 1847 to 2019. All observations are given in TT and ICRS. The star catalog biases are removed, which are significant for Nereid and outer satellites. We obtained 880 (5% of total now available) new coordinates for Triton over 41 nights (1% of total observation nights so far), and 790 (14%) for Nereid over 47 nights (10%). The dispersions of these new positions are about 0''03 for Triton and 0''06 for Nereid.

Conclusions. OCNS2019 should be useful in improving ephemerides for the above-mentioned objects.

Key words. catalogs – astrometry – ephemerides – planets and satellites: individual: Neptune – methods: observational – methods: data analysis

1. Introduction

To support current and future scientific investigations of the Neptune system and relevant space exploration missions (e.g., NASA's Trident, [Mitchell et al. 2019](#); [Prockter et al. 2013](#)), high-precision ephemerides for Neptunian satellites are needed ([Jacobson 2009](#); [Brozović et al. 2011, 2020](#); [Emelyanov & Arlot 2011](#); [Jacobson et al. 2012](#); [Emelyanov & Samorodov 2015](#)). The precision of ephemerides and determined dynamical parameters depends both on the precision of observations and on the length of the time interval covered by observations ([Desmars et al. 2009a](#); [Emelyanov 2010](#); [Jacobson et al. 2012](#); [Arlot et al. 2012](#); [Emelyanov & Samorodov 2015](#); [Lainey 2016](#)). Therefore, not only the continuation of observing campaigns but also the collection and improvement of existing observations are required. In the present work, we provide new precise positions, and compile an observational catalog including all available ground-based astrometric observations of Neptunian satellites. So far, no complete catalog tabulating all observations of Neptunian satellites in a consistent format and in the same timescale and reference system is available. In fact, most of the available observations are presented

in formats which are specific to their respective publications, and are consequently in various formats of data type, timescale, coordinates, and so on.

New CCD observations of Triton and Nereid were made at Lijiang 2.4-m and Yaoan 0.8-m telescopes in 2013–2019, and then reduced based on *Gaia*-DR2 ([Gaia Collaboration 2018](#)). Among all the available observed coordinates of Triton, we obtained 880 (5% of total now available) new coordinates for Triton over 41 nights (1% of total observation nights so far), and 790 (14%) for Nereid over 47 nights (10%). Our analysis shows that the standard deviations of the residuals with respect to the ephemeris positions given with DE430/NEP081x1¹ are about 0''03 for Triton and 0''06 for Nereid.

For the compilation of the observational catalog, we extract most data from three databases: the Natural Satellite Data

¹ The planetary ephemerides DE438 ([Folkner & Park 2018](#)) and satellite ephemerides NEP081x1 ([Jacobson 2009](#)). They can be retrieved from the JPL Solar System Dynamics website <https://ssd.jpl.nasa.gov/>.

Center (NSDC²; Arlot & Emelyanov 2009), the Minor Planet Center (MPC³), and the JPL Solar System Dynamics Website (JPL-SSD⁴). Although these databases are frequently updated, a few errors and omissions can be recognized by using the SAO/NASA Astrophysics Data System (ADS).

Since the discovery of the first Neptunian satellite, Triton (more than 170 years ago), many observations of Neptunian satellites have been made and published in different formats. However, for convenience of use, it is preferable that all observations are tabulated in a single and consistent format, as done by Desmars et al. (2009b) for their COSS08, an observational catalog of eight main Saturnian satellites. Furthermore, we convert all the observed coordinates to the International Celestial Reference System (ICRS).

Each star catalog has its unique systematic relations with the ICRS (Schwan 2001). For absolute coordinates actually referenced to a star catalog, the biases induced by star position errors should be corrected. Considering the *Gaia*-DR2 catalog as an extremely accurate realization of the ICRS, Eggl et al. (2020) determined the biases with respect to the *Gaia*-DR2 for the 26 modern star catalogs commonly used as a reference for the ICRS. Here, we apply their provided debiasing tables⁵ to the Neptunian satellites for the first time. In addition, we also develop and apply debiasing tables to the currently used modern star catalog, *Tycho*-1 (ESA 1997), and the old ones, the Yale Zone Catalogs (Yale University 1997), which were not studied by Eggl et al. (2020).

Conversions of observed relative coordinates, except for the separations independent of coordinate systems, require complementary positions of comparison bodies. However, these positions are usually unavailable in observational data. Here, a treatment is proposed for this based on the ephemeris positions given with DE438/NEP081x1. Analytical estimations and test calculations show that the introduced error of $< \sim 5 \mu\text{as}$ is negligible.

The new precise positions are described in Sect. 2. The compilation procedure is described in Sect. 3. The final observational catalog is presented and analyzed in Sect. 4. We call this catalog OCNS2019, which stands for the Observational Catalog of Neptunian Satellites (2019 version). Conclusions are given in Sect. 5.

2. New precise positions of Triton and Nereid (2013–2019)

2.1. CCD observations

All CCD observations are made with the 0.8-m reflector at the Yaoan station (IAU observatory code, O49, assigned by MPC⁶) of Purple Mountain Observatory and the 2.4-m reflector at the Lijiang station (O44) of Yunnan Astronomical Observatory. For more instrumental details, for example of the used reflectors and CCD detectors, see Table 1. A total of 440 frames of CCD images (41 nights) were obtained for Triton and 395 frames (47 nights) for Nereid. The exposure time is about 0.2–2 min for Triton and 1–5 min for Nereid, depending on the settings of telescopes, the weather conditions, and the topocentric zenith

Table 1. Instrumental details for the used reflectors and CCD detectors.

Years	2013	2013, 2017	2018–2019
Site	O44	O44	O49
Diameter of primary mirror	2.4 m	2.4 m	0.8 m
CCD detector	PI VersArray	YFOSC	PIXIS
CCD field of view (effective)	5' × 5'	9' × 9'	11' × 11'
Size of CCD array (effective)	1340 × 1340	1900 × 1900	2048 × 2048
Size of pixel	20 μm	13.5 μm	13.5 μm
Angular extent per pixel	0''.215	0''.285	0''.346

Notes. The “Site” row provides the IAU observatory code.

Table 2. Details of the astrometric reduction.

Satellite site	Triton O44	O49	Nereid O44	O49
N_{m*}	19–87	7–118	40–87	30–124
Mean(N_{m*})	33	52	68	84
S/N	20–700	50–1800	14–123	10–55
Median(S/N)	370	380	70	27

Notes. The “Site” row gives the IAU observatory codes. N_{m*} is the number of matched *Gaia*-DR2 reference stars. S/N is the measured signal-to-noise ratio of a satellite.

distances. However, some frames can be used to provide both observed positions of Triton and Nereid. According to the standard procedure of astrometric observations, the flat-field, bias, and dark frames were also taken.

2.2. Astrometric reduction based on *Gaia*-DR2

A robust and stable astrometric reduction procedure was carried out according to Ofek (2019). The observed positions of Triton and Nereid were obtained with respect to the reference stars in the same fields of view. Here, following the advice of Arlot et al. (2012) and Ofek (2019), *Gaia*-DR2 is used as a reference catalog. After matching the reference stars with the positions in *Gaia*-DR2, a plate model was applied between the pixel and standard coordinates for each reference star as suggested by Ofek (2019). Specifically, the plate model is selected based on the number of matched stars (N_{m*}) by applying the following rules:

- $5 \leq N_{m*} < 10$: an affine transformation;
- $10 \leq N_{m*} < 75$: an affine transformation + tip/tilt terms;
- $75 \leq N_{m*} < 120$: an affine transformation + tip/tilt terms + 3rd order Chebyshev polynomials of the second kind;
- $N_{m*} \geq 120$: an affine transformation + tip/tilt terms + 3rd and 4th order Chebyshev polynomials of the second kind.

Finally, the observed astrometric positions of Triton and Nereid are easily obtained by the calibration of parameters involved in the plate models. For more details on the reduction procedure, see Table 2.

2.3. Analysis of the observational data

To check and analyze our new observed coordinates (O), we make a comparison with a theory (C). In the present paper, the ephemerides used in calculating C are DE438/NEP081x1. Finally, in Table 3, the statistics of the ($O - C$) residuals are given for each satellite at each observatory and each opposition.

² <http://nsdb.imcce.fr/obspos/obsindhe.htm>

³ <https://www.minorplanetcenter.net/iau/ECS/MPCAT-OBS/MPCAT-OBS.html>

⁴ https://ssd.jpl.nasa.gov/?eph_data

⁵ <ftp://ssd.jpl.nasa.gov/pub/ssd/debias/>

⁶ The MPC’s hosted list of IAU Observatory Codes is available at <https://www.minorplanetcenter.net/iau/lists/ObsCodesF.html>

Table 3. Statistics of $(O - C)$ residuals for our new observational data using the ephemerides DE438/NEP081x1.

Satellite	Site	Years	N_α	$\Delta\alpha \cos \delta$		N_δ	$\Delta\delta$		N_g
				Mean	SD		Mean	SD	
Triton	O44	2013	22	+0 ^h 00 ^m 09 ^s	0 ^h 00 ^m 24 ^s	22	-0 ^h 00 ^m 28 ^s	0 ^h 00 ^m 21 ^s	3
	O44	2017	62	-0 ^h 00 ^m 18 ^s	0 ^h 00 ^m 29 ^s	62	+0 ^h 00 ^m 15 ^s	0 ^h 00 ^m 31 ^s	7
	O49	2018–2019	356	+0 ^h 00 ^m 11 ^s	0 ^h 00 ^m 28 ^s	356	+0 ^h 00 ^m 20 ^s	0 ^h 00 ^m 34 ^s	31
Nereid	O44	2017	108	-0 ^h 00 ^m 51 ^s	0 ^h 00 ^m 52 ^s	108	+0 ^h 00 ^m 24 ^s	0 ^h 00 ^m 48 ^s	8
	O49	2018–2019	287	-0 ^h 00 ^m 43 ^s	0 ^h 00 ^m 61 ^s	287	+0 ^h 00 ^m 00 ^s	0 ^h 00 ^m 61 ^s	39

Notes. The statistics are given for each satellite at each observatory and each opposition. N_α , N_δ , and N_g are the numbers of observed Right Ascension (α), Declination (δ), and observation nights, respectively. SD is standard deviation.

Comparisons with previously published data were also made. In Sects. 4.2 and 4.3 we present statistics for all available ground-based astrometric observations. According to Table 7, our new observed coordinates account for 5% (=880/18626) of the total for Triton and 14% (=790/5508) for Nereid. Correspondingly, the observation nights account for 1% (=41/3446) of the total nights spent observing Triton and 10% (=47/480) of the total nights spent observing Nereid. As seen in Fig. 9 and Table A.1, our new observed coordinates have a small dispersion on the whole. In particular, the dispersion is significantly smaller than those not reduced with *Gaia* data.

Furthermore, the residuals of our new observed coordinates for Triton were checked for the significant trend due to the Triton ephemeris around Neptune. As the period of Triton orbiting around Neptune is about six days, a six-day periodic variation was checked. For this, we considered the Triton observations in $\text{obsTime} = 58438.5\text{--}58450.6$, which covers the 12 days with the highest observation frequency. For Right Ascension and Declination, respectively, the mean residuals per day were analyzed by applying a nonequispaced fast Fourier transform (NFFT; Keiner et al. 2009). Results show that there are no significant six-day (or other) periodic terms; that is, the amplitudes of these terms are much smaller than the standard deviations of residuals. This is probably because the Triton ephemeris around Neptune is sufficiently accurate. Indeed, it is generally believed that, on the basis of the accurate Triton ephemeris, the Neptune ephemeris around the Sun can be improved by observations of Triton (Poroshina 2013; Folkner et al. 2014; Pitjeva & Pitjeva 2014).

3. Compilation of ground-based astrometric observations of Neptunian satellites (1847–2019)

3.1. Items of data and useful information on observations

In order to use the observational data correctly and effectively, we require information about the instruments, the timescales and reference systems, and so on used by observers when they made reductions and published their results. The following list shows all the items useful for defining an observation consisting of at least one coordinate of an astronomical object. For each item, its label and type are on the left and right sides of an equal sign, respectively, followed by its description.

(1) Items for data source:

- **db** = <String>
The database from which the observation is extracted.
The values can be NSDC = NSDC, MPC = MPC, SSD = JPL-SSD, ADS = ADS, and so on.

Our new observational data derived in Sect. 2 are labeled with **db** = OCNS.

- **df** = <String>
The name of the file containing the observation in the database. The value **ref** signifies that the data are directly extracted from the original publication.
- **pubRef** = <String>
The reference to the publication that refers to the observations. For example, the Astrophysics Data System (ADS) reference, the Digital Object Identifier (DOI), the URL for the address of a resource on the internet, and so on.
- **pubSrc** = <String>
This specifies the origin of the reference. The values can be ADS, DOI, URL, and so on.
- (2) Items for instrument and technique:
 - **site** = <Enumeration (string)>
The IAU observatory code.
 - **inst** = <String>
Description of the instruments used, such as the observatory, detector, telescope, design, aperture, and/or focal length.
 - **type** = <Enumeration (character)>
Observation type. In the present study, the only one involved is 0 = optical.
 - **tech** = <Enumeration (character)>
Observation technology and the mode of instrumentation.
C = CCD; P = photographic; M = micrometer;
T = automatic meridian transit circle measures;
A = the observation is extracted and only available from MPC and has been converted to the FK5/J2000 system by rotating FK4/B1950 coordinates.
- (3) Items for timescale and reference system:
 - **ts** = <Enumeration (string)>
The timescale associated with the observation.
TT = Terrestrial Time (TT);
TDT = Terrestrial Dynamical Time (TDT);
ET = Ephemeris Time (ET);
UTC = Coordinated Universal Time (UTC);
UT = Universal Time (UT);
GMT = Greenwich Mean Time (GMT) = UT – 12h;
PMT = Paris Mean Time (PMT);
LMT = local mean time;
CST = Central Standard Time (CST);
PST = Pacific Standard Time (PST).
 - **rfs** = <String>
The reference system in which the observed coordinates are measured. If a star catalog is used in the astrometric reduction, it should be the fundamental reference system to which the star catalog is commonly used as a reference. In the present study, those involved are as follows.
ICRS = ICRS;
B<year> = the mean equator and equinox of the FK4 system at the Besselian epoch specified by <year>;
TOD = the true equator and equinox of date.
 - **rfsCnt** = <Enumeration (string)>
The center of **rfs**, which can be the observatory (for topocentric coordinates) or the center of the Earth (for geocentric coordinates). The corresponding IAU observatory code is used.
- (4) Items for observational coordinates:
 - **obs** = <Enumeration (string)>
The observables associated with the observation. In the present study, only angular observables used for an optical observation are involved. Such observables are absolute coordinates and four kinds of relative coordinates, namely:

ABS = absolute coordinates, (α, δ) , where α is the Right Ascension in hours and δ is the Declination in degrees;
 PAS = position angle and separation (p, s) for a relative position. Here, p is given in degrees and s in arc-seconds;
 TAN = tangential coordinates, $(\Delta X, \Delta Y)$, for a relative position measured in a plane tangent to the celestial sphere and referenced to the point of tangency, with ΔX towards east and ΔY towards north. Both coordinate components are given in arc-seconds;

DIF = differential coordinates $(\Delta\alpha \cos \delta_0, \Delta\delta)$ for a relative position measured from a given point (α_0, δ_0) on the celestial sphere, where $\Delta\alpha = \alpha - \alpha_0$ and $\Delta\delta = \delta - \delta_0$. Both coordinate components are given in arc-seconds;

DRD = observed differences between two absolute coordinates $(\Delta\alpha, \Delta\delta)$ for a relative position. $\Delta\alpha$ and $\Delta\delta$ are defined as DIF. Both coordinate components are given in arc-seconds.

- obsTime = $\langle \text{Decimal} \rangle$
Mid-time of the observation expressed in MJD (Modified Julian Day);
- obsCnt = $\langle \text{Integer} \rangle$
The origin of the measure of observed coordinates. For an absolute position, this is equal to zero; for a relative position, it is equal to the NAIF ID code⁷ for a Solar-System body.
- obsTrg = $\langle \text{Integer} \rangle$
The NAIF ID code of the measured target.
- obsCoord = $\langle \text{Array of decimals (length=2)} \rangle$
Observed coordinates. For a missing coordinate component (p or s), nan is used.

(5) Items for decimal precision

- dpTime = $\langle \text{Decimal} \rangle$
The decimal precision used in the timing of the observation, given in seconds;
- dpCoord = $\langle \text{Array of decimals (length=2)} \rangle$
The decimal precision used for measuring obsCoord. Both coordinate components are given in arc-seconds. For a missing component (p or s), nan is used.

(6) Items for reduction

- astCat = $\langle \text{Enumeration (string)} \rangle$
The star catalog of reference used in the astrometric reduction. The values are the corresponding catalog code assigned by the MPC⁸. In addition,
 + = known ephemerides are used to provide reference Solar-System bodies;
 ? = unknown star catalogs, unspecified or unavailable, are used.
 / = neither a star catalog nor ephemerides are used (e.g., for tech = P, rfs = TOD is easily found by the trail of a star obtained by stopping the telescope);
- aberr = $\langle \text{Enumeration (character)} \rangle$
Indicate whether the stellar aberration is excluded or included in obsCoord, and, if included, whether the aberration time is already corrected. Used indicators are
 E = excluded;
 I = included;
 T = aberration time is corrected;
 ? = unknown.

- refrac = $\langle \text{Enumeration (character)} \rangle$
Indicate whether the atmospheric refraction is excluded or included in obsCoord. Used indicators are E, I, and ? as aberr.

- phase = $\langle \text{Enumeration (character)} \rangle$
Indicate whether the phase effect is excluded or included in obsCoord. Used indicators are E, I, and ? as aberr.

In the following, we give the additional items defining the converted data in TT and ICRS (Sects. 3.3 and 3.5), additional corrections for star catalog biases (Sect. 3.4), and residuals with respect to theory (Sect. 3.6):

(7) Items for converted data and corrections.

- obsTt = $\langle \text{Decimal} \rangle$
Mid-time of the observation in TT, applying the conversions mentioned in Sect. 3.3.1, expressed in MJD;
- obsCoordIcrsB = $\langle \text{Array of decimals (length=2)} \rangle$
Observed coordinates resulting from the conversion of obsCoord from rfs to the ICRS mentioned in Sects. 3.3.2 and 3.5;
- catBias = $\langle \text{Array of decimals (length=2)} \rangle$
The star catalog bias corrections to be removed from obsCoordIcrsB as mentioned in Sect. 3.5. Each component corresponds to that of obsCoordIcrsB in the same position. If no corrections are needed, both components are zero.

(8) Items for residuals with respect to theory:

- aberrRsd = $\langle \text{Enumeration (character)} \rangle$
If aberr $\neq$?, the indicators, E, I, and T, are directly used as aberr. Otherwise, lowercase indicators are used, applying the rules mentioned in Sect. 3.6;
- refracRsd = $\langle \text{Enumeration (character)} \rangle$
If refrac $\neq$?, the indicators E and I are directly used as refrac. Otherwise, lowercase are used, applying the rules mentioned in Sect. 3.6;
- phaseRsd = $\langle \text{Enumeration (character)} \rangle$
If phase $\neq$?, the indicators E and I are directly used as phase. Otherwise, lowercase are used, applying the rules mentioned in Sect. 3.6;
- theoryRsd = $\langle \text{String} \rangle$
Theory used for computation of residuals;
- rsdIcrsB = $\langle \text{Array of decimals (length=2)} \rangle$
The $(O - C)$ residuals before removing catBias, namely the differences between obsCoordIcrsB and theoretical coordinates referenced to the ICRS. Both coordinate components are given in arc-seconds;
- rsdIcrsA = $\langle \text{Array of decimals (length=2)} \rangle$
The $(O - C)$ residuals after removing catBias, namely rsdIcrsB – catBias. Both coordinate components are given in arc-seconds.

3.2. Observational data collection

Nowadays, most ground-based astrometric observational data can be extracted from the following three databases:

- db = NSDC: NSDC provides large numbers of published raw observational data of natural satellites, together with information about the reference frame used by the observer, the reduction made, and the timescale needed to link all the data (Arlot & Emelyanov 2009).
- db = MPC: MPC provides observational data of natural outer irregular satellites of giant planets.
- db = SSD: JPL-SSD provides observational data that are currently being used in creation and improvement of modern

⁷ The ID code used in the JPL Solar System Dynamics Group catalog, which is available at https://naif.jpl.nasa.gov/pub/naif/toolkit_docs/FORTRAN/req/naif_ids.html

⁸ The MPC's hosted list of Catalog Codes is available at <https://minorplanetcenter.net/iau/info/CatalogueCodes.html>

planetary and lunar ephemerides as well as the planetary satellite ephemerides.

As a general selecting rule for collection, we favor and retain the data in their original format (similar to the publications), as in [Arlot & Emelyanov \(2009\)](#). For observations reduced twice or more times in several references, the most recently reduced ones are retained.

Although these databases are frequently updated, a few errors and omissions in them are recognized by using the ADS.

On one hand, the following additional published observational data missing in the above databases are found by searching in the ADS:

- [Soulié et al. \(1975\)](#): Three relative positions of Triton in 1970 were obtained, using the simultaneously observed Neptune as the comparison body.
- [van Biesbroeck et al. \(1976\)](#): 11 absolute positions of Nereid in 1967–1969;
- [Veiga et al. \(1996\)](#): 8 relative positions of Nereid with respect to Neptune in 1982–1985 and 53 of Triton in 1985–1988;
- [Dourneau et al. \(2015\)](#): 189 absolute positions of Triton in 2007–2013;
- [Maris et al. \(2018\)](#): 50 absolute positions of the outer satellite, Neso (obsTrg = 813).

On the other hand, verification of all the data and information in the above databases is carried out using the source information and references accessed via ADS:

- Data errors in original publications. For example, as mentioned in [van Biesbroeck et al. \(1976\)](#), the time given by [Rose \(1974\)](#) is incorrect (NSDC/nm1006); several data entries are repeated in NSDC/nm1024 ([Gomes-Júnior et al. 2015](#)).
- Incorrect information input. For example, the aberration times are already corrected (aberr = T≠I) for data in NSDC/nm0042 ([Hall 1900](#)), NSDC/nm0043 ([Hall 1911](#)), and NSDC/nm0044 ([Hall & Burton 1913](#)); the used star catalog is *Tycho-1* (astCat = f≠g) for data in NSDC/nm0017 ([Kiseleva et al. 2012](#)).
- Data loss. Six observed position angles are lost in NSDC/nm0035 ([Hussey 1899](#)).
- Incorrect data lines. One position angle and one separation observed at two adjacent points in time are combined as one point in NSDC/nm0055 ([Davis 1874](#)); one observed separation of NSDC/nm0040 ([Royal Observatory Greenwich 1908](#)) and two observed position angles of NSDC/nm0070 ([Neuĭmin & Pokrovskiĭ 1926](#)) are incorrect; calendar time formats of NSDC/nm0059 ([Royal Observatory Greenwich 1900](#)) and NSDC/nm0074 ([Wirtz 1905](#)) and values of calendar times of NSDC/nm0006 are incorrect.

Table A.1 shows the main items of information for each set of the collected observational data. Our new data derived in Sect. 2 are also included in the collection and labeled with db = OCNS. In addition, broken links are updated.

3.3. Converting to the Terrestrial Time and the International Celestial Reference System

Tables 4 and 5 show the various timescales and reference systems, respectively, originally used by the collected observational data. As these data are not referenced to the same space-time coordinate system, they are timed in TT and expressed in the ICRS.

Table 4. Statistics of timescales of observational data extracted from the sources.

Timescale	ts	<i>N</i>	<i>N</i> %	<i>N_g</i>	<i>N_g</i> %	Years
Central S.T.	CST	1928	7.71%	712	18.32%	1897–1922
Ephemeris Time	ET	76	0.30%	38	0.98%	1949–1982
Greenwich M.T.	GMT	1480	5.92%	488	12.56%	1847–1923
Local M.T.	LMT	1201	4.80%	480	12.35%	1847–1920
Paris M.T.	PMT	444	1.78%	144	3.71%	1883–1912
Pacific S.T.	PST	619	2.48%	118	3.04%	1892–1905
Terrestrial D.T.	TDT	12	0.05%	4	0.10%	1984–1985
U.T.	UT	226	0.90%	99	2.55%	1928–1970
Coordinated U.T.	UTC	19010	76.05%	1803	46.40%	1963–2019

Notes. ts is the item for timescale defined in OCNS2019. Here, S.T., M.T., U.T., and D.T. are Standard Time, Mean Time, Universal Time, and Dynamic Time, respectively. *N* and *N*% are the number and percentage of observed coordinates, respectively, and *N_g* and *N_g*% are those of observation nights.

3.3.1. Timescales

Table 4 shows the three kinds of timescales (ts) appearing in the data collection: the dynamical time (TDT/ET), UTC, and the time standards based on Earth’s rotation (UT, local mean times, or standard times).

As TT continues TDT, which in turn succeeded ET, we apply TT = TDT = ET. At present, most observers use UTC in timing observations. The relationship between UTC and TT is conventionally provided by the International Earth Rotation Service (IERS)⁹. For many old observations, standard times or local mean times were used. Their differences from GMT = UT – 12h are simply the longitudes of locally chosen meridians.

The relationship between UT (strictly speaking, UT1) and TT is conventionally provided by the IERS and on the *Long-term Delta T* page¹⁰ provided by the United States Naval Observatory (USNO).

3.3.2. Reference systems

Table 5 shows the three kinds of reference systems (rfs) appearing in the data collection: the mean equator and equinox of the FK4 system at a particular epoch, the ICRS, and the true equator and equinox of date. There are conventional procedures for converting the observed absolute coordinates from these reference systems to the ICRS:

- For the mean equator and equinox of FK4 system at a particular epoch, the classical procedure of transferring individual observations ([Seidelmann 1992](#) pp. 179–180) is applied. Specifically, absolute coordinates are transformed back to the epoch of the observation on the FK4 system converted to the FK5 system of J2000 (FK5/J2000), and corrections for E-terms (the elliptic terms of aberration) and the FK4 – FK5 equinox offset are applied. Finally, the FK5/J2000 coordinates are converted to the ICRS ([Mignard & Froeschlé 2000](#)).
- For the true equator and equinox of date, absolute coordinates are converted by applying sequential rotations for nutation, precession, and frame bias based on the IAU2006 model ([Wallace & Capitaine 2006](#)).

⁹ <http://hpiers.obspm.fr/>

¹⁰ <https://www.usno.navy.mil/USNO/earth-orientation/eo-products/long-term>

Table 5. Statistics of the reference systems of observational data extracted from the sources.

rfs	C	obs	N	N%	N _g	N _g %	Years
B1899	?	PAS	42	0.17%	21	0.52%	1899–1901
B1905	?	PAS	12	0.05%	6	0.15%	1905–1905
B1949	K	ABS	14	0.06%	3	0.07%	1949–1949
	+	DIF	972	3.89%	44	1.09%	1985–1994
	?	ABS	30	0.12%	12	0.30%	1967–1987
B1950		DIF	98	0.39%	47	1.16%	1949–1987
	I	DIF	34	0.14%	12	0.30%	1977–1984
	p	DIF	16	0.06%	6	0.15%	1982–1985
	+	DIF	150	0.60%	4	0.10%	1997–1997
	?	ABS	362	1.45%	32	0.79%	1990–2004
		DRD	6	0.02%	1	0.02%	1999–1999
	L	ABS	116	0.46%	13	0.32%	2013–2015
	U	ABS	1798	7.19%	29	0.72%	2012–2018
	V	ABS	2018	8.07%	76	1.88%	2006–2019
	c	ABS	86	0.34%	5	0.12%	2004–2009
	f	ABS	108	0.43%	53	1.31%	1986–1993
	g	ABS	3092	12.37%	1141	28.19%	1963–2014
ICRS	l	ABS	292	1.17%	145	3.58%	1998–2000
	m	ABS	6	0.02%	1	0.02%	2002–2002
	o	ABS	454	1.82%	77	1.90%	2002–2014
	p	ABS	460	1.84%	24	0.59%	1993–1998
		DIF	1866	7.47%	43	1.06%	1993–1998
	q	ABS	1950	7.80%	124	3.06%	1992–2018
	r	ABS	4550	18.20%	112	2.77%	1996–2013
	s	ABS	12	0.05%	2	0.05%	2004–2004
	u	ABS	170	0.68%	42	1.04%	2009–2012
	v	ABS	78	0.31%	20	0.49%	2008–2009
	/	DIF	414	1.66%	64	1.58%	1903–1991
		PAS	5620	22.48%	1813	44.79%	1847–1942
TOD	?	PAS	164	0.66%	75	1.85%	1902–1920
	C	DRD	6	0.02%	1	0.02%	1970–1970

Notes. rfs and obs are the items for reference systems and observables used in OCNS2019, respectively. C is the MPC code of the astrometric catalog, astCat. N and N% are the number and percentage of observed coordinates, respectively, and N_g and N_g% are those of observation nights.

Among these observed absolute coordinates, as seen in Table 5, many are deduced using reference star catalogs. Although each of the star catalogs are commonly used as the reference to the ICRS or the FK4 system, the deduced coordinates, strictly speaking, are referenced to the star catalog itself. It is reasonable to break the systematic relation between a star catalog and the ICRS into the two parts (e.g., Schwan 2001):

- The transformation between the reference system and the ICRS. This part models and eliminates the global transformation known a priori. Any residual corrections of zero point and equator are absorbed by the following bias correction.
- The bias correction for the removal of remaining global rotations and regional biases between the catalog and the ICRS. The treatment of the first part has been described in the previous paragraph. As for the second part, the procedure is developed and provided in Sect. 3.4.

Conversions of observed relative coordinates, except for the separations independent of coordinate systems, require the complementary positions of comparison bodies. However, these positions are usually unavailable in the observational data. A treatment is proposed and analyzed in Sect. 3.5.

3.4. Star-catalog bias corrections based on Gaia-DR2

3.4.1. Available debiasing tables based on Gaia-DR2

For the 26 modern star catalogs commonly used as a reference to the ICRS, Eggl et al. (2020) propose a treatment of the biases between them and the ICRS in absolute coordinates of minor planets. Considering the Gaia-DR2 catalog as an extremely accurate realization of the ICRS, Eggl et al. (2020) determine the biases by computing the median differences catalog–Gaia-DR2 in positions and proper motions at the comparison epoch $T_0 = \text{J2000.0}$ for the common stars in each of the divided tiles. The determined biases are contained in their provided debiasing tables.

The debiasing tables are applied for the first time to the absolute coordinates of Neptunian satellites. Table 6 provides the star catalogs used in the reduction of all the 15596 absolute coordinates. The catalogs can be identified for 15192 absolute coordinates (97.41%), in which 15070 (96.63%) use one of the catalogs studied in Eggl et al. (2020). In the present study, we use the finest debiasing table (NSIDE = 256)¹¹ containing 786432 HEALPix (Górski et al. 2005) tiles.

As seen in Table 6, the Tycho-1 catalog and Yale Zone Catalogs are not studied by Eggl et al. (2020). For these catalogs, we first need to determine the biases and make new debiasing tables.

3.4.2. Debiasing table extensions for the modern catalog: Tycho-1

The Tycho-1 catalog is similar to the star catalogs studied in Eggl et al. (2020), however we make the comparison with Gaia-DR2 at the mean epoch of the catalog, that is, $T_0 = \text{J1991.25}$, as the positions depend less on the proper motions at this epoch (Schwan 2001). After transforming the positions and proper motions of Tycho-1 and Gaia-DR2 to T_0 , the biases are determined as in Eggl et al. (2020). Figure 1 shows the bias values for the Tycho-1 catalog at J1991.25 in the new debiasing table containing 786432 HEALPix tiles. The biases of Tycho-1 with respect to Gaia-DR2 are significant in proper motions and obviously different from those biases of Tycho-2.

3.4.3. Debiasing table extensions for the old catalogs: Yale Zone Catalogs

Yale Zone Catalogs are old catalogs published preceding the FK5 catalog (Fricke et al. 1988). They are a collection of catalogs of independent zones, but, as mentioned in Pierce (1978), adjacent and homogeneous zones can be combined and treated as one subsystem. In the present paper, we focus on the subsystem covering the observations reduced with the catalogs, that is, the combination of Volumes 16 and 17 of Yale Zone Catalogs (approximately, the region of Declination between -10° and -2°).

The comparison is made at the mean epoch of the combined catalog, that is, $T_0 = \text{J1933.50}$. First, we applied the conversion for catalog positions and proper motions from the FK4 system to the ICRS (Seidelmann 1992, pp. 167–187), which is compatible with that applied to the observed coordinates referenced to this catalog (see Sect. 3.3.2). We then determined the biases between the converted catalog and Gaia-DR2 at T_0 as for Tycho-1. Figure 2 shows the HEALPix map of the bias values for the selected Yale zones at J1933.50 in the new debiasing table containing 786432 HEALPix tiles. There are significant biases in both positions and proper motions with respect to Gaia-DR2.

¹¹ ftp://ssd.jpl.nasa.gov/pub/ssd/debias/debias_hires2018.tgz

Table 6. Statistics on astrometric catalogs used for the reduction of *absolute* coordinates (obs = ABS) in OCNS2019.

Catalog	<i>C</i>	<i>N</i>	<i>N</i> %	<i>N_g</i>	<i>N_g</i> %	Years	Vizier CDS ID	Reference	Debiasing table
Unknown	?	404	2.59%	46	2.41%	1967–2004	N/A	N/A	N/A
Yale	K	14	0.09%	3	0.16%	1949–1949	I/141	Yale University (1997)	Present paper
2MASS	L	116	0.74%	13	0.68%	2013–2015	II/246	Cutri et al. (2003)	Eggl et al. (2020)
Gaia-DR1	U	1798	11.53%	29	1.52%	2012–2018	I/337	Lindgren et al. (2016)	ibid.
Gaia-DR2	V	2018	12.94%	76	3.98%	2006–2019	I/345	Gaia Collaboration (2018)	ibid.
USNO-A2.0	c	86	0.55%	5	0.26%	2004–2009	I/252	Monet (1998)	ibid.
Tycho-1	f	108	0.69%	53	2.77%	1986–1993	I/239	ESA (1997)	Present paper
Tycho-2	g	3092	19.83%	1141	59.71%	1963–2014	I/259	Høg et al. (2000)	Eggl et al. (2020)
ACT	l	292	1.87%	145	7.59%	1998–2000	I/246	Urban et al. (1998)	ibid.
GSC-ACT	m	6	0.04%	1	0.05%	2002–2002	I/255	Lasker et al. (1999)	ibid.
USNO-B1.0	o	454	2.91%	77	4.03%	2002–2014	I/284	Monet et al. (2003)	ibid.
PPM	p	460	2.95%	24	1.26%	1993–1998	I/146; I/193	Roeser & Bastian (1988); Bastian et al. (1991)	ibid.
UCAC-4	q	1950	12.50%	124	6.49%	1992–2018	I/322A	Zacharias et al. (2013)	ibid.
UCAC-2	r	4550	29.17%	112	5.86%	1996–2013	I/289	Zacharias et al. (2004)	ibid.
UCAC-3	u	170	1.09%	42	2.20%	2009–2012	I/315	Zacharias et al. (2010)	ibid.
NOMAD	v	78	0.50%	20	1.05%	2008–2009	I/297	Zacharias et al. (2005)	ibid.

Notes. *C* is the code of the astrometric catalog, astCat, similar to the MPC flag. *N* and *N*% are the number and percentage of observed coordinates, respectively, and *N_g* and *N_g*% are those of observation nights.

Fig. 1. Biases of the Tycho-1 catalog with respect to Gaia-DR2 at J1991.25. *Top panels:* local biases for positions along the directions of Right Ascension (*left*) and Declination (*right*), and *bottom panels:* biases for proper motions. The absolute value of color-bar limits for the *top panels* is the 99th percentile of $\sqrt{(\Delta\alpha \cos \delta)^2 + (\Delta\delta)^2}$, and, for the *bottom panels*, the 99th percentile of $\sqrt{(\Delta\mu_\alpha \cos \delta)^2 + (\Delta\mu_\delta)^2}$.

Fig. 2. Biases of Volumes 16 and 17 of Yale Zone Catalogs with respect to *Gaia*-DR2 at J1933.50, after having applied the conversion from the FK4 system to the ICRS. *Top panels:* local biases for positions along the directions of Right Ascension (*left*) and Declination (*right*), and *bottom panels:* biases for proper motions. The absolute value of the color-bar limits for the *top panels* is the 99th percentile of $\sqrt{(\Delta\alpha \cos \delta)^2 + (\Delta\delta)^2}$, and, for the *bottom panels*, the 99th percentile of $\sqrt{(\Delta\mu_\alpha \cos \delta)^2 + (\Delta\mu_\delta)^2}$.

Fig. 3. Geometry of the conversion of the given observed coordinates of a body, *A*, relative to a comparison body, *B*. The north poles of the original and target reference systems (ORS and ICRS) are *P* and *P'*, respectively. α'_B and α'_P are the Right Ascensions of *B* and *P* referenced to the ICRS, and δ_B and δ'_B are the Declinations of *B* referenced to the ORS and ICRS, respectively. $\theta = \angle PP'$, $s = \angle AB$, $p = \angle PBA$, and $p' = \angle P'BA$.

3.5. Converting observed relative coordinates to the International Celestial Reference System

Observationally, there are two different methods for measuring the position of body *A* with respect to body *B*. One uses a micrometer (tech = M) to directly measure either a separation, *s*, or a position angle, *p*, referenced to the true equator of date (rfs = TOD), while the other uses the measurements obtained with a CCD or photographic plate (tech = C/P) to derive a pair of coordinate differences. Geometrically speaking, *s* is independent of coordinate systems.

3.5.1. Converting *p*

The conversion formula of *p* from the original reference system (ORS) to the ICRS writes

¹¹ https://naif.jpl.nasa.gov/pub/naif/generic_kernels/spk/planets/a_old_versions/de721_full.bsp

Fig. 4. Differences in geocentric positions of the Neptune system barycenter between DE438 (Folkner & Park 2018) and other high-precision ephemerides: (1) DE430 (Folkner et al. 2014), the base of DE438; (2) DE721¹⁴, which is very similar to DE421 (Folkner et al. 2009) but covers a longer time span; (3) INPOP19a (Fienga et al. 2019), the latest INPOP ephemerides developed by IMCCE; and (4) EPM2017 (Pitjeva & Pitjev 2018), the latest EPM ephemerides developed by IAA RAS. The vertical span in gray shows the time span covering the observed relative coordinates referenced to non-ICRS reference systems in OCNS2019.

$$p' = p - \delta p, \quad (1)$$

where

$$\begin{aligned} \sin \delta p &= \sin \theta \sin \alpha'_B \sec \delta_B, \\ \cot \delta p &= -\cot \alpha'_B \sin \delta'_B + \csc \alpha'_B \cos \delta'_B \cot \theta, \\ \alpha'_B &= \alpha'_B - \alpha'_P, \end{aligned} \quad (2)$$

where *B* is the comparison body, *P* and *P'* are the north poles of the ORS and ICRS, respectively, α'_B and α'_P are the Right Ascensions of *B* and *P* referenced to the ICRS, respectively, δ_B and δ'_B the Declination of *B* referenced to the ORS and ICRS,

Fig. 5. Distribution of ground-based observations in OCNS2019 for Triton, Nereid, the set of inner satellites of Neptune (obsTrg = 805–808, i.e., Despina, Galatea, Larissa, and Proteus), and the set of outer satellites of Neptune (obsTrg = 809–813, i.e., Halimede, Psamathe, Sao, Laomedeia, and Neso). For each satellite or set of satellites, both the histogram of the number of observations, N , and the observation nights at each opposition, N_g , are presented.

respectively, and $\theta = \widehat{PP}'$ is the general precession and nutation in declination. The geometry of the conversion is also seen in Fig. 3.

Equation (1) shows that the conversion for p needs absolute positions of B , which are nevertheless usually unavailable in observational data. Fortunately, high-precision ephemerides can always provide sufficiently reliable theoretical estimates for absolute positions of B . In the present work, B can only be Neptune or Triton, and we use the DE438/NEP081xl ephemerides for them.

As DE438 is created based on DE430 (Folkner et al. 2014) with improved orbital data for Mercury, Mars, Jupiter, and Cassini (Folkner & Park 2018), the accuracy of DE438 for the Neptune system barycenter should be at the same level as DE430. Furthermore, Folkner et al. (2014) show that DE430 can provide positions of the Neptune system barycenter accurate to several thousand kilometers, or to several hundred milliarcseconds as observed from Earth. Indeed, as seen in Fig. 4, the maximum difference between the Neptune system barycenter positions as given by DE438 and another four high-precision planetary ephemerides developed by JPL (Folkner et al. 2014, 2009), IMCCE (Fienga et al. 2019), and IAA RAS (Pitjeva & Pitjev

Table 7. Number of observed coordinates (N) and observation nights (N_g) of observational data in OCNS2019 for each satellite.

Satellite	obsTrg	N	N_g	Years
Triton	801	18626	3446	1847–2019
Nereid	802	5508	480	1949–2019
Despina	805	12	3	1997–1997
Galatea	806	34	4	1997–1997
Larissa	807	26	4	1997–1997
Proteus	808	226	9	1991–2002
Halimede	809	126	20	1999–2015
Psamathe	810	72	14	2001–2009
Sao	811	90	16	2001–2009
Laomedeia	812	84	14	2001–2015
Neso	813	192	13	2002–2010

2018) is about 0".5 at the level of accuracy quantified by Folkner et al. (2014). In addition, Jacobson (2009) estimates that the error of relative positions between Triton and Neptune given with DE438/NEP081xl is within 0".2. Therefore, it is

Fig. 6. Star catalog bias corrections (*catBias*) of observed absolute coordinates (*obs* = *ABS*) in OCNS2019 with respect to *Gaia*-DR2. The four panels display the biases, respectively, for Triton, Nereid, the set of inner satellites (*obsTrg* = 805–808, i.e., Despina, Galatea, Larissa, and Proteus), and the set of outer satellites (*obsTrg* = 809–813, i.e., Halimede, Psamathe, Sao, Laomedeia, and Neso). $\Delta\alpha \cos \delta$ is the bias along the direction of Right Ascension and $\Delta\delta$ in Declination. The vertical dashed line in red denotes $\Delta\alpha \cos \delta = 0$ and the horizontal dashed line shows $\Delta\delta = 0$.

Fig. 7. Ratios of the star catalog bias corrections (*catBias*) to the standard deviations of the (*O* – *C*) residuals before removing *catBias* (*rsdIcrsB*). The four panels display the ratios, respectively, for Triton, Nereid, the set of inner satellites (*obsTrg* = 805–808, i.e., Despina, Galatea, Larissa, and Proteus), and the set of outer satellites (*obsTrg* = 809–813, i.e., Halimede, Psamathe, Sao, Laomedeia, and Neso). For each satellite/set, MEAN and SD indicate the mean and standard deviation, respectively, computed for each site and each opposition. The ephemerides used in calculating *C* are DE438/NEP081x1 for Triton and Nereid, DE438/NEP090 for inner satellites, and DE438/NEP086 for outer satellites. $\Delta\alpha \cos \delta$ is along the direction of Right Ascension and $\Delta\delta$ Declination.

reasonable to say that DE438/NEP081x1 can provide positions of *B* (Neptune or Triton) accurate to several hundred milliarcseconds. In the following discussions, the ephemeris error of *B*, ε_B , is taken as $\sim 0''.5$.

Neglecting nutation terms in θ , the following equation, to first order, gives the introduced error:

$$\begin{aligned} \varepsilon_p &= s \left\| \left(\frac{\partial \delta p}{\partial \alpha'_B} \varepsilon_{\alpha'_B}, \frac{\partial \delta p}{\partial \delta'_B} \varepsilon_{\delta'_B} \right) \right\|_2 \\ &= s \left\| \sin^2 \delta p \left(\frac{\partial \tan \delta p}{\partial \alpha'_B} \varepsilon_{\alpha'_B}, \frac{\partial \tan \delta p}{\partial \delta'_B} \varepsilon_{\delta'_B} \right) \right\|_2 \\ &\sim (n t \sec^2 \delta_B) \cdot s \cdot \varepsilon_B, \end{aligned} \quad (3)$$

where $\varepsilon_{\alpha'_B}$ and $\varepsilon_{\delta'_B}$ are the position error of *B* in α'_B and δ'_B , respectively, t is the time from the standard epoch, J2000.0, to the observation epoch, and n is the rate of general precession in declination. For all observed p , $s < 0.2$, $|t| < 153$ yr, and $|\delta_B| < 30^\circ$. Therefore, given $|n| \approx 20''.04 \text{ yr}^{-1}$ (Urban & Seidelmann 2014, p. 216), $\varepsilon_p \sim 10^{-6} \cdot \varepsilon_B \sim 0.5 \mu\text{as}$, which is much smaller than the observation error. That is to say, the influence of ephemeris use in the conversion is negligible.

3.5.2. Converting a pair of coordinate differences

As seen in Fig. 3, given *B* and the pair of coordinate differences (Δ) between *A* and *B*, the absolute position of *A* can be obtained. Therefore, to convert Δ to the ICRS, we turn Δ into the absolute coordinates of *A* and *B* and then, after converting these two abso-

lute coordinates to the ICRS (see Sect. 3.3.2), turn them back to a new pair of coordinate differences. Here also, as in Sect. 3.5.1, we use the high-precision ephemerides DE438/NEP081x1 to provide *B* accurate to several hundred milliarcseconds ($\varepsilon_B \sim 0''.5$). In this conversion, although the absolute coordinates of *A* and *B* are both affected by ε_B , the error of their differences, as is discussed below, is much smaller than $s \cdot \varepsilon_B$.

Specifically, the effect of ε_B on the conversion of Δ , ε_Δ , can be roughly broken into the following three parts: ε_1 for the differential corrections for E-terms, ε_2 for the differential precession (and nutation) from the observation epoch to J2000.0, and ε_3 for the differential equinox and bias corrections from the FK4 system to the ICRS. Test calculations show that, among these three parts, ε_2 is dominant. Also, analytical estimations are given as follows:

To analytically estimate ε_1 from the expressions for aberrational displacements due to E-terms (Smart & Green 1977, p. 186), we derive the conversion formula for differential corrections for E-terms, that is,

correction to $\Delta\lambda$ =

$$ek \sec \beta_B (\tan \beta_B \cos \bar{\lambda}_B \Delta\beta + \sin \bar{\lambda}_B \Delta\lambda),$$

correction to $\Delta\beta$ =

$$ek (\cos \beta_B \sin \bar{\lambda}_B \Delta\beta - \sin \beta_B \cos \bar{\lambda}_B \Delta\lambda), \quad (4)$$

where $\Delta\lambda = \lambda_A - \lambda_B$, $\Delta\beta = \beta_A - \beta_B$, $\bar{\lambda}_B = \omega - \lambda_B$, λ_A and λ_B are the ecliptic longitudes of *A* and *B*, respectively, β_A and

Fig. 8. Comparisons between *rsdIcrsB* and *rsdIcrsA*, the $(O - C)$ residuals, respectively, before and after removing the known catalog biases (*catBias*). Only the observational data which are corrected by more than half of the standard deviations of residuals are shown in this figure. The ephemerides used in calculating C are DE438/NEP081x1 for Triton and Nereid, and DE438/NEP086 for outer satellites (*obsTrg* = 809–813, i.e., Halimede, Psamathe, Sao, Laomedeia, and Neso). The *three columns from left to right* are the comparisons for Triton, Nereid, and outer satellites, respectively. The *first and last rows* are the comparisons along the directions of Right Ascension ($\Delta\alpha \cos \delta$) and Declination ($\Delta\delta$), respectively.

β_B are the ecliptic latitudes of A and B , respectively, κ is the constant of aberration, and e and ω are the eccentricity and the longitude of the perihelion of the Earth's orbit, respectively. Differentiating Eq. (4) with respect to λ_B and β_B , we find that $\varepsilon_1 \sim |(e \kappa \sec^2 \beta_B) \cdot s \cdot \varepsilon_B|$. The values of κ and e may be taken as $20''.496$ and 0.01673 (Seidelmann 1992, pp. 169–171), respectively. For all the observed coordinate differences, $|\beta_B| < 2'$ and $s < 6'$. Therefore, $\varepsilon_1 \sim 3 \times 10^{-9} \cdot \varepsilon_B$.

To analytically estimate ε_2 , we apply the approximate conversion formula for differential precession and nutation given in Seidelmann (1992, pp. 108–109), that is,

$$\begin{aligned} \text{correction to } \Delta\alpha &= e \tan \delta_B \Delta\alpha - f \sec^2 \delta_B \Delta\delta, \\ \text{correction to } \Delta\delta &= f \Delta\alpha, \end{aligned} \quad (5)$$

where $\Delta\alpha = \alpha_A - \alpha_B$, $\Delta\delta = \delta_A - \delta_B$,

$$\begin{aligned} e &= -\cos \alpha_B (nt + \sin \epsilon \Delta\psi) - \sin \alpha_B \Delta\epsilon, \\ f &= +\sin \alpha_B (nt + \sin \epsilon \Delta\psi) - \cos \alpha_B \Delta\epsilon, \\ \epsilon &= 23^\circ 44', \end{aligned} \quad (6)$$

where t is the time from the standard epoch, J2000.0, to the observation epoch, n is the rate of general precession in declination, and $\Delta\psi$ and $\Delta\epsilon$ are the nutations in longitude and obliquity at t . Differentiating Eq. (5) with respect to α_B and δ_B , we find

that $\varepsilon_2 \sim |(n t \sec^2 \delta_B) \cdot s \cdot \varepsilon_B|$. For all the observed coordinate differences, $|\delta_B| < 30^\circ$. If A is Triton, $s < 0.2$ and $|t| < 93$ yr; if A is Nereid, $s < 6'$ and $|t| < 51$ yr. Therefore, $\varepsilon_2 \sim 10^{-5} \cdot \varepsilon_B$. Here ε_3 contributes in a similar manner to the nutation terms in ε_2 but is much smaller. Therefore, generally speaking, the total error, $\varepsilon_A = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \sim 10^{-5} \cdot \varepsilon_B \sim 5 \mu\text{as}$, is much smaller than the observation error and so is negligible.

3.6. Computation of residuals between observed coordinates and theoretical ones

As presented in Sect. 2.3, residuals are purely indicative, and can be used to measure the accuracy of observed coordinates (O) in relation to theories (C). In the present paper, the ephemerides used in calculating C are DE438/NEP081x1 for Triton and Nereid, DE438/NEP090 (Brozović et al. 2020) for inner satellites, and DE438/NEP086 (Brozović et al. 2011; Jacobson et al. 2012) for outer satellites.

When computing $(O - C)$ residuals, some corrections like aberration, refraction, and phase effects have to be applied. Details on these corrections can be found in Desmars et al. (2009b). To deal with the observations missing information for corrections in the data publication, we apply the same rules as Desmars et al. (2009b).

Fig. 9. (O - C) residuals (rsdIcrsA) between observed coordinates in OCNS2019 and theoretical ones after removing the known catalog biases with respect to *Gaia*-DR2. The ephemerides used in calculating C are DE438/NEP081x1 for Triton and Nereid, DE438/NEP090 for inner satellites (obsTrg = 805–808, i.e., Despina, Galatea, Larissa, and Proteus), and DE438/NEP086 for outer satellites (obsTrg = 809–813, i.e., Halimede, Psamathe, Sao, Laomedea, and Neso). Our new observed coordinates derived in Sect. 2 are marked by red dots (db = OCNS).

4. The observational catalog: OCNS2019

4.1. Outputs

The OCNS2019 observations are tabulated in a consistent format. We generate an output for OCNS2019 with all observations sorted in ascending order by obsTt. The PSV (pipe-separated-values)

format is chosen as the output layout. The catalog is available in electronic form at NADC (see address in acknowledgements).

In addition, the complementary debiasing tables extended for *Tycho*-1 and Yale Zone Catalogs are publicly available together. The debiasing table containing 786432 HEALPix tiles is used for catalog bias corrections in OCNS2019.

4.2. Temporal histograms of observed coordinates

Figure 5 gives the temporal distributions of numbers of observed coordinates for Triton, Nereid, the set of inner satellites, and the set of outer satellites, respectively, at each opposition. The distributions are relatively inhomogeneous. As seen in Fig. 5, there are not only significant gaps but also years with many observations. Because of this heterogeneity, distributions of observation nights are also given in Fig. 5.

Table 7 gives the numbers of observed coordinates, the observation nights, and the covered years for each satellite. There are a total of 24996 observed coordinates obtained over 3741 nights.

4.3. Statistics of star catalog bias corrections and computed residuals

Figure 6 shows the star catalog bias corrections with respect to *Gaia*-DR2. The corrections can reach about 0".04 for inner satellites, 0".07 for Triton, and 0".4 for Nereid and outer satellites. Because of the long distances from Neptune to Nereid and outer satellites, usually only absolute positions can be obtained due to the small fields of view. Furthermore, due to their faintness, the used reference stars are generally fainter and therefore have greater position biases than those used by Triton.

Moreover, as shown in Fig. 7, for Triton, Nereid, and outer satellites, the star catalog bias corrections can reach the standard deviations of residuals (σ). More specifically, 143 (4%) nights of observational data for Triton, 151 (31%) for Nereid, and 8 (24%) for the outer satellites are corrected by more than 0.5σ . For these data, the comparisons of residuals with and without the catalog bias corrections are shown in Fig. 8. Systematic changes of residuals are noticeable, and in particular for outer satellites, after the catalog bias corrections, the data before 2012, which are used in the development of NEP086, have significant offsets from these ephemerides. Furthermore, when developing the ephemerides currently used in calculating C , the effect of star catalog biases is not systematically quantified and corrected. These catalog bias corrections can be used to improve the ephemerides.

Figure 9 shows the residuals of all the collected data after removing the known catalog biases. The last four columns of Table A.1 show the mean and standard derivation of these residuals for each reference. In general, the dispersion of the data reduced with *Gaia* data is significantly smaller than others.

5. Conclusions

The OCNS2019 catalog includes 24996 ground-based observed coordinates of 11 Neptunian satellites obtained over 3741 nights. All observations are tabulated in the same consistent format and given in the same timescale (TT) and reference system (ICRS). Biases induced by star position errors with respect to *Gaia*-DR2 are removed, which are significant for Nereid and outer satellites. Debiasing tables for the used catalogs, *Tycho*-1 and Yale Zone Catalogs, which are not studied in Eggl et al. (2020) are also developed and applied. We obtained 880 (5% of total now available) new coordinates for Triton over 41 nights (1% of total observation nights so far), and 790 (14%) for Nereid over 47 nights (10%). The dispersion of these new coordinates is small on the whole, and is significantly smaller than those not reduced with *Gaia* data. Therefore, this catalog should be useful in improving ephemerides for the above-mentioned objects. For the time being, the development of relevant ephemerides is ongoing.

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Appendix A: Ground-based astrometric observational data of Neptunian satellites collected in OCNS2019**Table A.1.** Sets of *ground-based* astrometric observational data for Neptunian satellites collected in OCNS2019.

Reference	db	df	<i>S</i>	site	ts	rfs	obs	<i>M</i>	<i>C</i>	<i>A</i>	<i>R</i>	<i>P</i>	<i>N</i>	<i>N_g</i>	Years	μ_1 mas	σ_1 mas	μ_2 mas	σ_2 mas
0 Lassell (1849a)	NSDC	nm0051; nm0050	T	503; 992	LMT; GMT	TOD	PAS	M	/	I	?	I	14	8	1847–1848	+233	666	+615	1587
1 Rümker (1849)	NSDC	nm0053	T	992	GMT	TOD	PAS	M	/	I	?	I	4	2	1849–1849	−62	744	+177	2409
2 Lassell (1849b)	NSDC	nm0052	T	992	GMT	TOD	PAS	M	/	I	?	I	5	3	1849–1849	+665	592	+803	504
3 Lassell (1850)	NSDC	nm0053	T	992	GMT	TOD	PAS	M	/	I	?	I	3	2	1849–1849	−310	58	+1101	–
4 Lassell (1851)	NSDC	nm0053	T	992	GMT	TOD	PAS	M	/	I	?	I	18	12	1850–1850	+162	548	−1193	1026
5 Lassell (1852a)	NSDC	nm0053	T	992	GMT	TOD	PAS	M	/	I	?	I	11	6	1851–1851	+367	261	−929	784
6 Lassell (1852b)	NSDC	nm0053	T	992	GMT	TOD	PAS	M	/	I	?	I	48	24	1852–1852	+134	531	−194	908
7 Lassell (1857)	NSDC	nm0053	T	992	GMT	TOD	PAS	M	/	I	?	I	8	5	1856–1856	−302	712	+892	672
8 Lassell (1864)	NSDC	nm0054	T	992	GMT	TOD	PAS	M	/	I	?	I	20	13	1863–1863	+54	327	+377	301
9 Davis (1874)	NSDC	nm0055	T	787	LMT	TOD	PAS	M	/	I	?	I	62	24	1873–1874	−64	360	−150	281
10 Hall (1876)	NSDC	nm0021	T	787	LMT	TOD	PAS	M	/	I	?	I	39	21	1876–1877	−50	190	+254	304
11 Hall (1877)	NSDC	nm0021	T	787	LMT	TOD	PAS	M	/	I	?	I	83	40	1875–1876	−24	375	+277	309
12 USNOM17Q-1881 (1881)	NSDC	nm0011	T	787	LMT	TOD	PAS	M	/	I	?	I	17	8	1877–1877	+80	266	+198	362
13 Henry (1884a)	NSDC	nm0071	T	007	PMT	TOD	PAS	M	/	I	?	I	16	8	1884–1884	+6	470	+295	622
14 Henry (1884b)	NSDC	nm0071	T	007	PMT	TOD	PAS	M	/	I	?	I	5	4	1884–1884	+144	–	+742	1113
15 Henry et al. (1886)	NSDC	nm0048	T	007	PMT	TOD	PAS	M	/	I	?	I	34	19	1883–1884	−12	713	+559	850
16 Perrotin (1887)	NSDC	nm0073	T	020	PMT	TOD	PAS	M	/	I	?	I	27	15	1886–1887	+193	196	+14	303
17 Lohse (1887)	NSDC	nm0057	T	968	GMT	TOD	PAS	M	/	I	?	I	6	3	1885–1886	+377	290	+412	1108
18 Young (1888)	NSDC	nm0028	T	H80	GMT	TOD	PAS	M	/	I	I	I	68	35	1883–1888	+172	440	−99	583
19 Winlock & Pickering (1888)	NSDC	nm0027	T	802	GMT	TOD	PAS	M	/	I	I	I	31	12	1866–1868	−59	573	+241	816
20 Parrish & Stone (1892)	NSDC	nm0029	T	780	LMT	TOD	PAS	M	/	I	?	I	18	11	1889–1891	+111	474	−373	905
21 Barnard (1893)	NSDC	nm0068	T	662	PST	TOD	PAS	M	/	I	?	I	76	8	1892–1893	−15	178	+46	352
22 Barnard (1894)	NSDC	nm0068	T	662	PST	TOD	PAS	M	/	I	?	I	102	10	1893–1894	+41	198	+1	350
23 Schaeberle (1895)	NSDC	nm0030	T	662	PST	TOD	PAS	M	/	I	?	I	35	12	1894–1895	−2	146	−63	212
24 Barnard (1895)	NSDC	nm0068	T	662	PST	TOD	PAS	M	/	I	?	I	142	14	1894–1895	+68	224	+20	370
25 Schaeberle (1897)	NSDC	nm0030	T	662	PST	TOD	PAS	M	/	I	?	I	59	22	1895–1897	−47	135	+28	144
26 Drew (1897)	NSDC	nm0031	T	690	GMT	TOD	PAS	M	/	I	?	I	85	46	1896–1897	+106	381	−40	395
27 Schaeberle (1898)	NSDC	nm0030	T	662	PST	TOD	PAS	M	/	I	?	I	39	14	1897–1897	−27	121	+99	135
28 Barnard (1898)	NSDC	nm0033	T	754	CST	TOD	PAS	M	/	I	?	I	161	51	1897–1898	+32	233	−37	271
29 Drew (1899)	NSDC	nm0032	T	690	GMT	TOD	PAS	M	/	I	?	I	36	12	1898–1898	−36	235	+176	266
30 Barnard (1899)	NSDC	nm0033	T	754	CST	TOD	PAS	M	/	I	?	I	165	51	1898–1899	+54	159	−20	245
31 Hussey (1899)	NSDC	nm0035	T	662	LMT	TOD	PAS	M	/	I	?	I	29	13	1898–1899	+22	233	+122	274
32 Aitken (1899)	NSDC	nm0034	T	662	PST	TOD	PAS	M	/	I	I	I	26	13	1898–1899	+46	238	−63	289
33 Royal Observatory Greenwich (1899)	NSDC	nm0058	T	000	GMT	TOD	PAS	P	/	I	?	I	24	11	1899–1899	+38	238	−221	275
34 Hall (1900)	NSDC	nm0042	T	802	GMT	TOD	PAS	M	/	T	?	I	46	17	1847–1848	−72	1007	−124	747
35 Kostinsky (1900)	NSDC	nm0022	T	084	LMT	B1899	PAS	P	?	?	E	I	18	9	1899–1899	−183	205	−194	225
36 Royal Observatory Greenwich (1900)	NSDC	nm0059	T	000	GMT	TOD	PAS	M	/	I	?	I	28	13	1896–1898	−244	913	+408	488
37 Barnard (1901)	NSDC	nm0069	T	754	CST	TOD	PAS	M	/	I	?	I	361	116	1899–1901	+11	227	+14	239
38 Christie (1901)	NSDC	nm0080	T	000	GMT	TOD	PAS	P	/	I	?	I	13	7	1899–1900	+92	433	+141	356
39 Kostinsky (1902)	NSDC	nm0022	T	084	LMT	B1899	PAS	P	?	?	E	I	24	12	1899–1901	+0	285	−290	313
40 Hussey (1902)	NSDC	nm0035	T	662	LMT	TOD	PAS	M	/	I	?	I	16	8	1899–1900	+145	86	+361	256
41 Barnard (1903)	NSDC	nm0076	T	754	CST	TOD	PAS	M	/	I	?	I	223	74	1901–1903	+23	167	+91	327
42 Perrine (1903)	NSDC	nm0072	T	662	PST	TOD	PAS	P	/	I	I	I	102	8	1902–1902	+80	334	−19	211
43 Royal Observatory Greenwich (1903)	NSDC	nm0040	T	000	GMT	TOD	PAS	P	/	I	?	I	130	36	1902–1903	+4	273	−54	264
44 Christie (1904)	NSDC	nm0080	T	000	GMT	TOD	PAS	P	/	I	?	I	102	24	1902–1902	−86	189	−58	197
45 Aitken (1904)	NSDC	nm0034	T	662	PST	TOD	PAS	M	/	I	I	I	26	13	1901–1902	−99	261	+9	197
46 Royal Observatory Greenwich (1904)	NSDC	nm0040	T	000	GMT	TOD	PAS	P	/	I	?	I	108	29	1903–1904	−37	151	−44	213
47 Hammond & Rice (1905)	NSDC	nm0037	T	786	LMT	TOD	PAS	M	/	I	E	I	16	9	1907–1908	−86	125	+129	262
48 Wirtz (1905)	ADS	ref	T	522	LMT	TOD	PAS; DIF	M	/	I	?	I	28	13	1903–1905	+462	591	−28	591
49 Royal Observatory Greenwich (1905)	NSDC	nm0040	T	000	GMT	TOD	PAS	P	/	I	?	I	114	27	1904–1905	−13	193	−78	233
50 Barnard (1906a)	NSDC	nm0041	T	754	CST	TOD	PAS	M	/	I	I	I	112	39	1903–1905	+23	208	+99	290
51 Hammond (1906)	NSDC	nm0037	T	786	LMT	TOD	PAS	M	/	I	E	I	9	5	1908–1908	+53	173	+114	130
52 Barnard (1906b)	NSDC	nm0060	T	754	CST	TOD	PAS	M	/	I	I	I	32	11	1905–1906	+40	252	+206	323
53 Royal Observatory Greenwich (1906)	NSDC	nm0040	T	000	GMT	TOD	PAS	P	/	I	?	I	126	24	1905–1906	−72	213	+10	240

Notes. The set of our new data derived in Sect. 2 is listed at the bottom of this table, which is labeled with db = OCNS. Here, db, df, site, ts, rfs, and obs are the items defined in OCNS2019. For each reference, *S* gives the list of involved satellites, where the characters T, N, I, and O denote Triton, Nereid, the set of inner satellites (obsTrg = 805–808, i.e., Despina, Galatea, Larissa, and Proteus), and the set of outer satellites (obsTrg = 809–813, i.e., Halimede, Psamathe, Sao, Laomedeia, and Neso), respectively. *C*, *A*, *R*, *P* are astCat, aberr, refrac, and phase, respectively. *N* and *N_g* are the number observed coordinates and observation nights, respectively. Statistics for (*O* − *C*) residuals (rsdIcrsA) after removing star catalog bias with respect to *Gaia*-DR2 are given in the last four columns. μ_1 and σ_1 are the mean and standard deviation, respectively, of the residuals in the first component of rsdIcrsA, and μ_2 and σ_2 the second component. The ephemerides used in calculating *C* are DE438/NEP081x1 for Triton and Nereid, DE438/NEP090 for inner satellites, and DE438/NEP086 for outer satellites.

Table A.1. continued.

Reference	db	df	S	site	ts	rfs	obs	M	C	A	R	P	N	N _g	Years	μ_1 mas	σ_1 mas	μ_2 mas	σ_2 mas
54 Barnard (1907)	NSDC	nm0041	T	754	CST	TOD	PAS	M	/	I	I	I	49	17	1906–1907	+12	137	+20	179
55 Royal Observatory Greenwich (1907)	NSDC	nm0040	T	000	GMT	TOD	PAS	P	/	I	?	I	56	14	1906–1907	−60	212	+28	175
56 Royal Observatory Greenwich (1908)	NSDC	nm0040	T	000	GMT	TOD	PAS	P	/	I	?	I	52	14	1907–1908	+29	280	−180	225
57 Barnard (1909)	NSDC	nm0041	T	754	CST	TOD	PAS	M	/	I	I	I	148	50	1907–1909	+56	213	+59	289
58 Christie (1909)	NSDC	nm0080	T	000	GMT	TOD	PAS	P	/	I	?	I	4	2	1907–1907	+28	2	−202	644
59 Albrecht & Smitil (1909)	NSDC	nm0061	T	662	PST	B1905	PAS	P	?	E	E	I	12	6	1905–1905	+182	157	−198	405
60 Barnard (1910)	NSDC	nm0041	T	754	CST	TOD	PAS	M	/	I	I	I	77	25	1909–1910	−3	244	−15	456
61 Hall (1911)	NSDC	nm0043	T	786	PMT	TOD	PAS	M	/	T	?	I	120	53	1908–1910	−17	311	+202	353
62 PUSNO6A-1911 (1911)	NSDC	nm0062	T	786	LMT	TOD	PAS	M	/	I	E	I	388	180	1894–1906	−37	276	+93	299
63 Barnard (1912)	NSDC	nm0041	T	754	CST	TOD	PAS	M	/	I	I	I	127	42	1910–1912	+33	214	+145	338
64 Barnard (1913)	NSDC	nm0041	T	754	CST	TOD	PAS	M	/	I	I	I	62	31	1912–1913	+49	188	+46	278
65 Hall & Burton (1913)	NSDC	nm0044	T	786	PMT	TOD	PAS	M	/	T	?	I	72	23	1911–1911	+24	250	+87	217
66 Burton (1913)	NSDC	nm0063	T	786	PMT	TOD	PAS	M	/	T	?	I	170	34	1911–1912	+18	165	+117	188
67 Royal Observatory Greenwich (1913)	NSDC	nm0064	T	000	GMT	TOD	PAS	P	/	I	?	I	80	11	1910–1910	−19	161	−35	161
68 Barnard (1915)	NSDC	nm0041	T	754	CST	TOD	PAS	M	/	I	I	I	34	15	1913–1914	−33	252	+93	255
69 Barnard (1916)	NSDC	nm0041	T	754	CST	TOD	PAS	M	/	I	I	I	62	32	1915–1916	+43	206	+95	289
70 Barnard (1917)	NSDC	nm0041	T	754	CST	TOD	PAS	M	/	I	I	I	72	36	1916–1917	−83	195	+23	354
71 Barnard (1919)	NSDC	nm0041	T	754	CST	TOD	PAS	M	/	I	I	I	92	47	1917–1919	−35	343	+131	288
72 Burton & Hall (1919)	NSDC	nm0045	T	786	LMT	TOD	PAS	M	/	I	?	I	282	64	1912–1919	+41	259	+127	316
73 Hall (1920)	NSDC	nm0046	T	786	GMT	TOD	PAS	M	/	I	?	I	48	17	1919–1920	−73	227	+196	302
74 Hall (1922)	NSDC	nm0047	T	786	GMT	TOD	PAS	M	/	I	?	I	46	23	1920–1921	−173	182	+245	326
75 Bower & Hall (1923)	NSDC	nm0046	T	786	GMT	TOD	PAS	M	/	I	?	I	36	18	1921–1923	−107	257	+172	306
76 Balanovskii (1923)	NSDC	nm0065	T	084	LMT	TOD	PAS	P	?	?	E	I	164	75	1902–1920	−8	336	−106	425
77 Neufmin & Pokrovskii (1926)	NSDC	nm0070	T	084	GMT	TOD	PAS	M	/	I	?	I	118	30	1923–1923	−51	319	+222	338
78 Barnard (1927)	NSDC	nm0041	T	754	CST	TOD	PAS	M	/	I	I	I	151	75	1919–1922	+87	238	+130	290
79 Crawford (1928)	NSDC	nm0075	T	662	UT	TOD	PAS	M	/	I	E	I	22	11	1928–1928	−46	192	−117	232
80 Alden (1940)	NSDC	nm0025	T	077	UT	TOD	PAS	P	/	I	I	I	60	30	1939–1939	+29	90	+15	77
81 Alden (1943)	NSDC	nm0026	T	077	UT	TOD	PAS	P	/	I	I	I	86	43	1940–1942	+23	77	−18	97
82 Harris & van Biesbroeck (1949)	NSDC	nm1005	N	711	UT	B1949	ABS	P	K	E	E	I	14	3	1949–1949	−338	1020	−969	950
83 Rose (1974)	ADS	ref	N	711; 693	ET; UT	B1950	DIF	P	?	E	E	I	88	44	1949–1969	+349	1008	+150	1119
84 Soulié et al. (1975)	ADS	ref	T	999	UT	TOD	DRD	P	C	I	?	I	6	1	1970–1970	−317	466	−29	82
85 van Biesbroeck et al. (1976)	ADS	ref	N	693	UT	B1950	ABS	P	?	E	E	I	22	11	1967–1969	+1827	737	−510	1923
86 Walker et al. (1978)	NSDC	nm0009	T	689	UTC	TOD	DIF	P	/	E	E	I	56	9	1975–1977	+19	62	−36	89
87 Veillet (1982)	NSDC	nm1007	N	711; 809	UTC	B1950	DIF	P	I	E	E	I	12	5	1977–1981	−27	175	−51	229
88 Harrington & Walker (1984)	NSDC	nm0010	T	689	UTC	TOD	DIF	P	/	E	E	I	228	38	1979–1983	+1	31	−21	71
89 Veillet & Bois (1988)	NSDC	nm1007	N	568; 809	UTC	B1950	DIF	P	I	E	E	I	22	7	1982–1984	+42	189	−99	186
90 Walker & Harrington (1988)	NSDC	nm0008	T	689	UTC	TOD	DIF	P	/	E	E	I	112	15	1984–1986	+3	17	−66	22
91 Landgraf (1988)	NSDC	nm1008	N	809	UTC	B1950	DIF	C; P	?	E	E	I	10	3	1987–1987	−101	547	−181	695
92 Schaefer & Schaefer (1988)	NSDC	nm1009	N	807	UTC	B1950	ABS	C	?	E	E	I	8	1	1987–1987	−40	137	−362	44
93 Colas & Buil (1992)	NSDC	ni0002	I	809	UTC	TOD	DIF	C	/	E	E	I	16	1	1991–1991	−6	83	−234	257
94 Veiga et al. (1996)	ADS	ref	TN	874	ET; TDT; UTC	B1950	DIF	P	p; +	E	E	I	122	18	1982–1988	−81	230	+34	211
95 Veiga & Vieira Martins (1996)	NSDC	nm0003	T	874	UTC	B1950	DIF	C	+	E	E	I	866	31	1989–1994	+75	454	+32	182
96 Veiga & Martins (1998)	NSDC	nm0004	T	874	UTC	ICRS	DIF	C	p	E	E	I	1518	35	1995–1997	−92	127	−87	193
97 Owen (1999a)	NSDC	nm0005	T	673	UTC	ICRS	ABS	C	?	E	E	I	6	1	1999–1999	−224	66	−158	73
98 Owen (1999b)	NSDC	nm0006	T	673	UTC	ICRS	DRD	C	?	E	E	I	6	1	1999–1999	+61	138	−20	41
99 Veiga et al. (1999)	NSDC	nm1001; nm1002	N	874	UTC	ICRS	DIF; ABS	C	p	E	E	I	808	24	1993–1998	−51	197	−97	210
100 Vieira Martins et al. (2004)	NSDC	ni0003; nm0013	TI	874	UTC	ICRS	ABS	C	g	E	E	I	264	4	2000–2002	−142	217	+23	252
101 Pascu et al. (2004)	NSDC	ni0001	I	250	UTC	ICRS	DIF	C	+	E	E	I	150	4	1997–1997	+0	12	+0	12
102 Qiao et al. (2007)	NSDC	nm0015	T	337	UTC	ICRS	ABS	C	r	E	E	I	1886	20	1996–2006	+73	54	−25	45
103 Dourneau et al. (2007)	NSDC	nm0018	T	999	UTC	ICRS	ABS	T	g	E	E	I	190	95	1999–2005	+0	207	−168	252
104 Kulyk et al. (2009)	NSDC	nm0016	T	188	UTC	ICRS	ABS	P	g	E	E	I	4	2	1990–1990	+126	60	+320	52
105 Emelyanov & Arlot (2011)	NSDC	nm1026	N	511	UTC	ICRS	ABS	C	r	E	E	I	280	13	2000–2010	+22	107	+87	141
106 Kiseleva et al. (2012)	NSDC	nm0017	T	119	UTC	ICRS	ABS	P	f	E	E	I	108	53	1986–1993	−61	420	−330	412
107 USNO (2013)	SSD	ccd1.nofs	T	689	UTC	ICRS	ABS	T	1; g	E	E	E	1946	971	1998–2013	−6	124	−15	144
108 TMO (2014)	SSD	ccd1.tmo	TN	673	UTC	ICRS	ABS	C	g	E	E	I	414	82	2001–2012	+16	168	−3	84
109 USNO (2014)	NSDC	nm0078	T	689	UTC	ICRS	ABS	T	g	E	E	E	168	84	2013–2014	−6	140	+0	136
110 Qiao et al. (2014)	NSDC	nm0019	T	327; 337	UTC	ICRS	ABS	C	r	E	E	I	2190	39	2007–2009	+21	63	−3	64
111 Gomes-Júnior et al. (2015)	NSDC	nm1024	N	874; 809	UTC	ICRS	ABS	C	q	E	E	I	1746	78	1992–2014	+19	117	−9	88
112 Dourneau et al. (2015)	ADS	ref	T	999	UTC	ICRS	ABS	T	g	E	E	I	378	189	2007–2013	−1	72	−74	86

Table A.1. continued.

Reference	db	df	S	site	ts	rfs	obs	M	C	A	R	P	N	N _g	Years	μ_1 mas	σ_1 mas	μ_2 mas	σ_2 mas
113 Yizhakevych et al. (2016)	NSDC	nm0083	T	083; 188	UTC	ICRS	ABS	P	g	E	E	I	20	6	1963–1990	+332	539	+269	471
114 Wang et al. (2017)	NSDC	nm0081	T	286	UTC	ICRS	ABS	C	U	E	E	I	1510	15	2014–2016	+58	12	−9	12
115 Yu et al. (2018)	NSDC	nm1025	N	327; 044	UTC	ICRS	ABS	C	U	E	E	I	272	10	2012–2017	−13	53	+52	67
116 Maris et al. (2018)	ADS	ref	O	309	UTC	ICRS	ABS	C	o	E	E	I	100	1	2010–2010	+175	286	−421	490
117 Yu et al. (2019)	NSDC	nm0082; nm1032	TN	327	UTC	ICRS	ABS	C	V	E	E	I	348	14	2006–2007	+18	67	+42	78
118 MPC38967	MPC	SatObs	N	568; 675	UTC	ICRS	ABS	C	?	E	E	I	12	2	1999–1999	−16	116	−151	215
119 MPC40913	MPC	SatObs	N	413	UTC	ICRS	ABS	A	?	E	E	I	6	3	1990–1990	−725	149	−890	35
120 MPC43261	MPC	SatObs	N	568	UTC	ICRS	ABS	C	?	E	E	I	6	1	2001–2001	−56	152	+275	7
121 MPC44182	MPC	SatObs	N	807	UTC	ICRS	ABS	C	?	E	E	I	6	1	2001–2001	−671	32	−5	88
122 MPC46216	MPC	SatObs	N	644	UTC	ICRS	ABS	C	m	E	E	I	6	1	2002–2002	+158	257	+180	89
123 MPC46508	MPC	SatObs	N	807	UTC	ICRS	ABS	C	?	E	E	I	6	1	2002–2002	−311	132	+45	159
124 MPC47500	MPC	SatObs	O	568; 807; 309	UTC	ICRS	ABS	C	?	E	E	I	46	6	2001–2002	−155	297	−99	534
125 MPC47501	MPC	SatObs	O	807; 309	UTC	ICRS	ABS	C	?	E	E	I	68	6	2001–2002	+86	245	+38	379
126 MPC49423	MPC	SatObs	O	807; 304; 568	UTC	ICRS	ABS	C	?	E	E	I	76	11	2001–2003	+106	447	+48	639
127 MPC49424	MPC	SatObs	NO	568	UTC	ICRS	ABS	C	?	E	E	I	6	2	2003–2003	+36	538	+457	159
128 MPC49767	MPC	SatObs	O	807; 309; 950; 568; 304	UTC	ICRS	ABS	C	?	E	E	I	86	10	2002–2003	+4	481	−110	571
129 MPC49878	MPC	SatObs	O	568	UTC	ICRS	ABS	C	?	E	E	I	6	1	1999–1999	−145	83	−194	67
130 MPC52312	MPC	SatObs	O	304	UTC	ICRS	ABS	C	o	E	E	I	10	1	2004–2004	−331	272	−165	75
131 MPC52313	MPC	SatObs	O	304	UTC	ICRS	ABS	C	o	E	E	I	26	1	2004–2004	+62	246	−63	353
132 MPC52492	MPC	SatObs	NO	568; 415	UTC	ICRS	ABS	C	c; r	E	E	I	40	5	2004–2004	+12	303	−208	224
133 MPC52493	MPC	SatObs	N	415	UTC	ICRS	ABS	C	r	E	E	I	6	1	2004–2004	−2	167	−245	262
134 MPC52887	MPC	SatObs	N	415	UTC	ICRS	ABS	C	r	E	E	I	8	2	2004–2004	+776	481	+265	467
135 MPC53171	MPC	SatObs	N	415	UTC	ICRS	ABS	C	r	E	E	I	6	1	2004–2004	−258	261	−446	252
136 MPC53948	MPC	SatObs	N	415	UTC	ICRS	ABS	C	s; r	E	E	I	18	3	2004–2004	−181	223	−130	160
137 MPC54343	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o	E	E	I	4	1	2005–2005	+561	212	−481	133
138 MPC54557	MPC	SatObs	N	415; 644	UTC	ICRS	ABS	C	o	E	E	I	16	3	2005–2005	−166	200	+139	296
139 MPC54697	MPC	SatObs	O	568; 309	UTC	ICRS	ABS	C	?	E	E	I	28	5	2004–2004	−114	205	+251	467
140 MPC54698	MPC	SatObs	N	568; 415	UTC	ICRS	ABS	C	?; o	E	E	I	18	4	2004–2005	+139	383	+101	301
141 MPC54823	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o	E	E	I	10	2	2005–2005	+41	224	−127	225
142 MPC54965	MPC	SatObs	N	644; 415	UTC	ICRS	ABS	C	o; r	E	E	I	20	4	2005–2005	+48	207	+30	274
143 MPC55508	MPC	SatObs	N	415	UTC	ICRS	ABS	C	r; o	E	E	I	10	3	2005–2005	+29	453	+87	356
144 MPC56794	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o	E	E	I	20	5	2006–2006	+123	510	−3	468
145 MPC57110	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o	E	E	I	12	3	2006–2006	+51	81	−53	228
146 MPC57416	MPC	SatObs	N	415; 213	UTC	ICRS	ABS	C	o; c	E	E	I	10	2	2006–2006	+254	254	+84	287
147 MPC57417	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o	E	E	I	20	5	2006–2006	+50	193	−55	167
148 MPC57573	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o	E	E	I	40	11	2006–2006	−14	458	−161	352
149 MPC57574	MPC	SatObs	N	415; D35	UTC	ICRS	ABS	C	o; r	E	E	I	12	3	2006–2006	+127	125	−247	308
150 MPC57792	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o	E	E	I	8	2	2006–2006	+465	275	−84	201
151 MPC57793	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o; r	E	E	I	44	12	2006–2006	+48	252	−26	245
152 MPC57947	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o	E	E	I	38	10	2006–2006	+30	271	−112	264
153 MPC58097	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o	E	E	I	4	2	2006–2006	+32	430	−593	107
154 MPC59029	MPC	SatObs	N	644	UTC	ICRS	ABS	C	o	E	E	I	22	4	2002–2002	−69	90	+39	100
155 MPC59581	MPC	SatObs	N	415	UTC	ICRS	ABS	C	r; o	E	E	I	4	2	2007–2007	+77	41	+0	220

Table A.1. continued.

Reference	db	df	S	site	ts	rfs	obs	M	C	A	R	P	N	N _g	Years	μ_1 mas	σ_1 mas	μ_2 mas	σ_2 mas
156 MPC59860	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o; r	E	E	I	18	5	2007–2007	−162	312	−70	299
157 MPC60086	MPC	SatObs	N	415	UTC	ICRS	ABS	C	r	E	E	I	20	5	2007–2007	−91	173	−112	209
158 MPC60268	MPC	SatObs	N	415	UTC	ICRS	ABS	C	r	E	E	I	20	5	2007–2007	−100	230	−111	170
159 MPC60451	MPC	SatObs	N	415	UTC	ICRS	ABS	C	o; r	E	E	I	10	3	2007–2007	+201	175	−170	320
160 MPC60647	MPC	SatObs	N	415	UTC	ICRS	ABS	C	r	E	E	I	24	6	2007–2007	+158	188	+14	427
161 MPC60906	MPC	SatObs	N	415	UTC	ICRS	ABS	C	r	E	E	I	16	4	2007–2007	+18	265	−280	255
162 MPC61163	MPC	SatObs	N	415	UTC	ICRS	ABS	C	r	E	E	I	12	3	2007–2007	−39	318	−95	252
163 MPC62864	MPC	SatObs	N	415	UTC	ICRS	ABS	C	v	E	E	I	4	1	2008–2008	+38	94	−748	132
164 MPC63123	MPC	SatObs	N	415	UTC	ICRS	ABS	C	v	E	E	I	8	2	2008–2008	+449	290	−453	344
165 MPC63363	MPC	SatObs	N	415	UTC	ICRS	ABS	C	v	E	E	I	12	3	2008–2008	+26	352	−40	260
166 MPC63584	MPC	SatObs	N	415	UTC	ICRS	ABS	C	v	E	E	I	6	2	2008–2008	−158	787	+31	626
167 MPC63806	MPC	SatObs	N	415	UTC	ICRS	ABS	C	v	E	E	I	4	1	2008–2008	−509	221	−211	113
168 MPC64093	MPC	SatObs	N	415	UTC	ICRS	ABS	C	v	E	E	I	12	3	2008–2008	+236	387	+98	267
169 MPC65920	MPC	SatObs	N	415	UTC	ICRS	ABS	C	v	E	E	I	4	1	2009–2009	+340	175	+73	153
170 MPC66450	MPC	SatObs	N	415	UTC	ICRS	ABS	C	v	E	E	I	4	1	2009–2009	+740	431	−497	297
171 MPC66686	MPC	SatObs	N	415	UTC	ICRS	ABS	C	v	E	E	I	12	3	2009–2009	+38	462	−126	178
172 MPC66905	MPC	SatObs	N	415; 673	UTC	ICRS	ABS	C	v; r	E	E	I	16	4	2009–2009	−18	122	+13	254
173 MPC67130	MPC	SatObs	N	673	UTC	ICRS	ABS	C	r	E	E	I	4	1	2009–2009	−101	17	−50	204
174 MPC67668	MPC	SatObs	N	415	UTC	ICRS	ABS	C	u	E	E	I	4	1	2009–2009	−213	352	−147	189
175 MPC70193	MPC	SatObs	N	415	UTC	ICRS	ABS	C	u	E	E	I	6	2	2010–2010	+1139	759	−39	264
176 MPC71528	MPC	SatObs	N	673	UTC	ICRS	ABS	C	r	E	E	I	4	1	2010–2010	+122	224	−267	194
177 MPC72437	MPC	SatObs	N	415	UTC	ICRS	ABS	C	u	E	E	I	4	1	2010–2010	+594	216	−264	34
178 MPC75593	MPC	SatObs	N	E07; 673	UTC	ICRS	ABS	C	u; r	E	E	I	34	7	2011–2011	+19	244	+56	136
179 MPC75849	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	u	E	E	I	28	7	2011–2011	−19	72	+22	121
180 MPC76329	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	u	E	E	I	12	3	2011–2011	−39	115	−20	153
181 MPC76732	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	u	E	E	I	32	8	2011–2011	−2	136	−64	143
182 MPC77162	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	u	E	E	I	4	1	2011–2011	+2263	8	+313	1
183 MPC78327	MPC	SatObs	O	568	UTC	ICRS	ABS	C	c	E	E	I	62	3	2009–2009	+141	227	−213	187
184 MPC79140	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	u	E	E	I	4	1	2011–2011	+50	30	+427	65
185 MPC79746	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	u	E	E	I	8	2	2012–2012	−337	217	−81	108
186 MPC79971	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	u	E	E	I	4	1	2012–2012	−90	21	+1	36
187 MPC80114	MPC	SatObs	N	673; E07	UTC	ICRS	ABS	C	r; u	E	E	I	6	2	2012–2012	−107	184	+435	320
188 MPC80452	MPC	SatObs	NO	309; E07	UTC	ICRS	ABS	C	o; u	E	E	I	48	8	2010–2012	+1	368	−109	171
189 MPC83713	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	q	E	E	I	4	1	2013–2013	−61	121	+99	121
190 MPC84214	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	q	E	E	I	8	2	2013–2013	−130	85	+54	25
191 MPC84512	MPC	SatObs	N	673; E07; C95	UTC	ICRS	ABS	C	r; q	E	E	I	26	6	2013–2013	+84	152	−108	298
192 MPC84739	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	q	E	E	I	20	5	2013–2013	+51	61	−62	92
193 MPC85079	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	q	E	E	I	24	6	2013–2013	−54	268	+39	132
194 MPC85502	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	q	E	E	I	20	5	2013–2013	−120	322	−130	261
195 MPC89137	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	q	E	E	I	4	1	2014–2014	+231	12	+113	63
196 MPC89456	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	q	E	E	I	8	2	2014–2014	−18	82	−37	95
197 MPC90446	MPC	SatObs	N	E07; G37	UTC	ICRS	ABS	C	q; o	E	E	I	32	7	2014–2014	+11	332	−72	139
198 MPC90966	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	q	E	E	I	4	1	2014–2014	+100	8	+28	68
199 MPC94830	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	q	E	E	I	14	3	2015–2015	−27	397	−5	179
200 MPC95374	MPC	SatObs	N	E07	UTC	ICRS	ABS	C	q	E	E	I	8	2	2015–2015	+171	183	−36	132
201 MPC97001	MPC	SatObs	N	G40; E07	UTC	ICRS	ABS	C	q	E	E	I	16	4	2015–2015	+90	108	+46	176
202 MPC99414	MPC	SatObs	NO	W84	UTC	ICRS	ABS	C	L	E	E	I	28	2	2015–2015	−442	684	+13	138
203 MPC100688	MPC	SatObs	N	F51	UTC	ICRS	ABS	C	L	E	E	I	76	10	2013–2014	−20	55	−25	78
204 MPC100689	MPC	SatObs	N	F51	UTC	ICRS	ABS	C	L	E	E	I	12	2	2014–2015	−10	35	+46	73
205 MPC101342	MPC	SatObs	N	G40	UTC	ICRS	ABS	C	q	E	E	I	6	1	2016–2016	−53	144	−41	220
206 MPC107170	MPC	SatObs	N	Z80	UTC	ICRS	ABS	C	U	E	E	I	4	1	2017–2017	−1081	669	+722	207
207 MPC110808	MPC	SatObs	N	D29; I41	UTC	ICRS	ABS	C	q; U	E	E	I	18	4	2018–2018	−82	123	+24	124
208 MPC115066	MPC	SatObs	N	G40	UTC	ICRS	ABS	C	q	E	E	I	4	1	2018–2018	+94	132	+108	356
209 MPC115989	MPC	SatObs	N	G40	UTC	ICRS	ABS	C	q	E	E	I	6	1	2018–2018	−69	295	+11	231
210 <i>Present paper (Sect. 2)</i>	OCNS	O44; O49	TN	O44; O49	UTC	ICRS	ABS	C	V	E	E	I	1670	62	2013–2019	−18	53	+13	48