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Abstract:

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Contents

Acronyms and Abbreviations

Orbital elements	
a	Semimajor axis
e	Eccentricity
i	Inclination
Ω	Longitude of ascending node
ω	Argument of periapsis
M	Mean anomaly
$\varpi = \Omega + \omega$	Longitude of periapsis
Equinoctial elements	
$\lambda_0 = \Omega + \omega + M$	Mean longitude
$h = e \sin(\varpi)$	
$k = e \cos(\varpi)$	
$p = \tan(i/2) \sin(\Omega)$	
$q = \tan(i/2) \cos(\Omega)$	

Introduction

DynAstVO is a new orbital asteroid database. For each Near-Earth asteroid, the database provides orbital elements and their uncertainty, the state-vector, information about the observations, MOID, and the covariance matrix of the system.

The database is daily updated in an automatic process for objects with new observations. The observations comes from the Minor Planet Center.

This documents presents a state-of-the-art of the orbital asteroid databases and proposes an analysis of the different databases (Part I). The parameters provided in the database are fully described in Part II and the global processing of the database is presented in Part III. Additional databases of DynAstVO are presented in Part IV. Finally a comparison with existing database is proposed in Part V.

Part I

State of the art of orbital asteroid databases

1 Introduction

In this part, we present the state of the art of the orbital asteroid databases. Orbital elements of asteroids can be found in several databases such as Astorb (Bowell), MPCORB (Minor Planet Center), AstDyS/NEODyS (AstDyS), etc. Astorb, MPCORB, and AstDyS provide a full file including the orbital elements of most of the asteroids (numbered and unnumbered). This part mainly describes Astorb, MPCORB, and AstDyS databases and proposes an analysis of the parameters.

2 Astorb

2.1 Presentation

Astorb database was originally developed at Lowell Observatory by E. Bowell. The database was available on `ftp://ftp.lowell.edu/pub/elgb/astorb.html` and new and regular update can be found on `http://www.naic.edu/~nolan/astorb.html` or `ftp://cdsarc.u-strasbg.fr/pub/cats/B/astorb/astorb.html`. The database consists in an ASCII file of high-precision osculating orbital elements, information about ephemeris uncertainties, and some additional data for all the numbered asteroids and the vast majority of unnumbered asteroids (multi-apparition and single-apparition) for which it is possible to make reasonably determinated computations. It is currently[1] about 50.6 Mb in size in its compressed form (astorb.dat.gz), 186.6 Mb in size when decompressed (astorb.dat), and contains 696 138 orbits. Each orbit, based on astrometric observations downloaded from the Minor Planet Center, occupies one 266-column record. Each line can be read in a FORTRAN format `A6, 1X, A18, 1X, A15, 1X, A5, 1X, F5.2, 1X, A4, 1X, A5, 1X, A4, 1X, 6I4, 1X, 2I5, 1X, I4, 2I2.2, 1X, 3(F10.6,1X), F9.6, 1X, F10.8, 1X, F12.8, 1X, I4, 2I2.2, 1X, F7.2, 1X, F8.2, 1X, I4, 2I2,3(1X,F7.2,1X,I4,2I2)` where parameters are shown in Tables 1& 2 as they are explained on `http://www.naic.edu/~nolan/astorb.html`. Some lines of `astorb.dat` file are presented in Table 3.

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[1] On November 5, 2015.

Table 1: Parameters provided in Astorb database.

Parameter	Format	Description
(1)	a6	Asteroid number (blank if unnumbered).
(2)	a18	Name or preliminary designation.
(3)	a15	Orbit computer.
(4)	a5	Absolute magnitude H, (see Bowell et al., 1989, and more recent Minor Planet Circulars). Note that H may be given to 2 decimal places (e.g., 13.41), 1 decimal place (13.4) or as an integer (13), depending on its estimated accuracy. H is given to two decimal places for all unnumbered asteroids, even though it may be very poorly known.
(5)	f5.2	Slope parameter G (ibid.).
(6)	a4	Color index B-V, mag (blank if unknown; see Tedesco, 1989).
(7)	a5	IRAS[1] diameter, km (blank if unknown; see Tedesco et al., 1989).
(8)	a4	IRAS[1] Taxonomic classification (blank if unknown; ibid.).
(9)	6i4	Six integer codes (see Table 2 for explanation). Note that not all codes have been correctly computed.
(10)	i5	Orbital arc, days, spanned by observations used in orbit computation.
(11)	i5	Number of observations used in orbit computation.
(12)	i4,2i2.2	Epoch of osculation, yyyymmdd (TDT[2]). The epoch is the Julian date ending in 00.5 nearest the date the file was created. Thus, as the file is updated, epochs will succeed each other at 100-day intervals on or after Julian dates ending in 50.5 (19980328, 19980706, 19981014, 19990122,...)
(13)	f10.6	Mean anomaly, deg.
(14)	f10.6	Argument of perihelion, deg (J2000.0).
(15)	f10.6	Longitude of ascending node, deg (J2000.0).
(16)	f9.6	Inclination, deg (J2000.0).
(17)	f10.8	Eccentricity.
(18)	f12.8	Semimajor axis, au.
(19)	i4,2i2.2	Date of orbit computation, yymmdd (MST[3] $=$ UTC-7).
(20)	f7.2	Absolute value of the current 1-σ ephemeris uncertainty (CEU), arcsec.
(21)	f8.2	Rate of change of CEU, arcsec/day.
(22)	i4,2i2	Date of CEU, yyyymmdd (0 hr UT).
(23)	f7.2,i4,2i2	Next peak ephemeris uncertainty (PEU), arcsec, from date of CEU, and date of its occurrence, yyyymmdd.
(24)	f7.2,i4,2i2	Greatest PEU, arcsec, in 10 years from date of CEU, and date of its occurrence, yyyymmdd.
(25)	f7.2,i4,2i2	Greatest PEU, arcsec, in 10 years from date of next PEU, and date of its occurrence, yyyymmdd, if two observations (of accuracy equal to that of the observations currently included in the orbit–typically ± 1 arcsec) were to be made on the date of the next PEU [parameter (23)].

[1] IRAS for Infrared Astronomical Satellite that performed a survey of the sky in infrared wavelenghts in 1983.

[2] Terrestrial Dynamical Time.

[3] Mountain Standard Time, which is the local time in Lowell Observatory.

Table 2: The meanings of the six integer codes [parameter (9)] as described in Astorb documentation. Reference to "type 6:7", for example, means code 6, value 7. Additional information are in italic style.

Code	Value	Explanation
1		Planet-crossing asteroids. *Note: Because some orbits are very poor (or erroneously linked), there may be errors in assignment of these parameter values.*
	1	Aten asteroids ($a < 1.0$ au).
	2	Apollo asteroids ($a > 1.0$ au; $0 < q < 1.0$).
	4	Amor asteroids ($a > 1.0167$ au; $1.0167 < q$).
	8	Mars crossers ($1.3 < q < 1.6660$ au).
	16	Outer-planet crossers (excluding Jupiter and Mars Trojans). Asteroids that cross or pass into the heliocentric distance zones between the perihelion and aphelion distances of Jupiter (4.950 to 5.455 au), Saturn (9.009 to 10.069 au), Uranus (18.274 to 20 089 au), and/or Neptune (29.800 to 30.317 au).
	n	Asteroids (excluding Mars and Jupiter Trojans) that cross both inner- and outer-planet orbits. For example, an asteroid having $n = 24$ crosses the orbits of both Mars ($q < 1.6660$ au) and Jupiter ($Q > 4.950$ au).
2		Orbit computation.
	1	Orbits derived from uncertainty, perhaps erroneously linked observations.
	2	Eccentricity assumed.
	4	Eccentricity and semimajor axis assumed.
	8	Mainly for numbered asteroids, omitted observations have resulted in degradation of a so-called orbit-quality parameter (OQP, see Muinonen and Bowell, 1993), generally by more than 0.1. The corresponding ephemeris uncertainty has increased by about 25% or more.
	16	OQP degrades by more than 0.1 if unsubstantiated observations (e.g., one-night apparitions) are omitted.
	32	Orbit derived from data containing observations not in Minor Planet Center files.
	64	H is unknown. $H = 14$ mag assumed.
	128	Asteroid sought, but not found.
	n	Sum of preceding entries. For example, $n = 3$ pertains to an uncertainly linked orbit for which the eccentricity was assumed.
3		Asteroids observed during the course of major surveys. The definition includes asteroids that were observed but not discovered during the course of a survey.
	1	Palomar-Leiden survey (PLS) asteroids.
	2	Palomar-Leiden T-2 survey asteroids.
	4	Palomar-Leiden T-3 survey asteroids.
	8	U.K. Schmidt Telescope-Caltech asteroid survey (UCAS) asteroids.
	16	Palomar-Leiden T-1 survey asteroids.
	n	Asteroids observed in more than one survey. For example, $n = 3$ denotes an asteroid observed in both the PLS and T-2 surveys.
4		Minor Planet Center (MPC) critical-list numbered asteroids.
	1	Lost asteroid.
	2	Asteroids observed at only two apparitions.
	3	Asteroids observed at only three apparitions.
	4	Asteroids observed at four or more apparitions, last more than ten years ago.

Continued on the next page

Code	Value	Explanation
	5	Asteroids observed at four or more apparitions, only one night in last ten years.
	6	Other poorly observed asteroids observed at four or more apparitions.
	7	Absolute magnitude poorly known (not on MPC critical-list).
5		Lowell Observatory and related discoveries
	1	Asteroids discovered by E. Bowell.
	2	Non-Bowell discoveries from Lowell search programs.
	3	Sum of preceding entries. $n = 3$ pertains to an asteroid discovered jointly by E. Bowell and another person connected with Lowell search programs.
6		Rank, in decreasing importance, for the collaborative program of astrometry using the transit circle of the U.S. Naval Observatory Flagstaff Station.
	10	Exceptionally important, to be observed frequently. Principally space mission targets and occultation candidates.
	9	Asteroids useful for mass determination.
	8	Asteroids for which one or two additional nights' observation are required to satisfy orbit-update requirements. Asteroids of type 6:7 *(i.e. of the following category)* whose ephemeris uncertainties are between 2 and 5 arcsec within the next ten years or so.
	7	Bowell unnumbered discoveries whose ephemeris uncertainties are less than 2 arcsec within the next ten years or so. MPC critical-list asteroids.
	6	Planet-crossers of type 6:5 *(i.e. of the following category)*.
	5	Numbered asteroids whose ephemeris uncertainties are between 2 and 5 arcsec within the next ten years or so. Unnumbered asteroids that should be numberable after one or two more nights' observation.

2.2 Computation in Astorb

This section presents the orbit computation in Astorb as it is presented on http://www.naic.edu/~nolan/astorb.html.

2.2.1 Orbit Computation in Astorb

Orbital elements of asteroids are computed through a variable-timestep differential orbit correction program in an automatic run. Perturbation due to all major planets (Mercury through Pluto, Earth and Moon separately), Ceres (assumed mass $5.0 \times 10^{-10} M_\odot$), Pallas ($1.1 \times 10^{-10} M_\odot$), and Vesta ($1.4 \times 10^{-10} M_\odot$) were included. Since April 2008, perturbations from 10 Hygiea, 15 Eunomia, 52 Europa, 511 Davida, and 704 Interamnia are also included. Planetary positions are derived from JPL's DE405 planetary ephemeris. Positions of the three perturbing asteroids were derived, by iteration, from their orbits in Astorb. Relativistic effects have not been included. The orbit of one numbered asteroid (1566 Icarus) is known to be imperfect as it requires inclusion of relativistic effects. The orbits of other close-Sun-approaching asteroids are doubtless similarly affected, but their observational (O-C) residuals appear to be satisfactory. For numbered asteroids, a uniform policy regarding the inclusion or exclusion of observations in the orbit determination has been adopted: namely, to exclude observations whose great-circle sky-plane residuals exceed 2.3 arcsec[2]. For numbered asteroids of type 2:8 (see Table 2) in the integer-code table above, the Astorb policy has

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[2] They have found from experience that, for well-determined orbits, 2.3 arcsec is an appropriate residual threshold separating "good" and "bad" observations

Table 3: Lines 1, 100 000, 200 000, 300 000, 400 000, 500 000, 600 000 of astorb.dat file

```
    (1)(2)                (3)             (4)    (5)  (6)  (7)  (8)      (9)
     1 Ceres              L.H. Wasserman   3.34  0.12 0.72 848.4 G?       0   0   0   0   0   0
100000 Astronautica       L.H. Wasserman  16.9   0.15                    0   0   0   0   0   0
200000 2007 JT40          L.H. Wasserman  15.9   0.15                    0   0   0   0   0   0
300000 2006 UW30          E. Bowell       17.0   0.15                    0   0   0   0   0   0
400000 2006 DK190         L.H. Wasserman  18.1   0.15                    0   0   0   0   0   0
       2007 AM19          E. Bowell       16.59  0.15                    0   0   0   0   0   3
       2012 RN16          L.H. Wasserman  18.88  0.15                    8   0   0   0   0   6
 (10)  (11) (12)     (13)       (14)       (15)       (16)       (17)         (18)
 78417 6423 20151005 160.030027  72.687087  80.325219 10.591945 0.07575658   2.76808429
 11781  230 20151005 181.863644 199.521661 186.578338 21.190422 0.08739673   1.90474850
  6235  196 20151005 255.676003 203.477358 116.887306  7.702740 0.15133836   2.71103714
  5841   43 20151005 273.234341 305.053022  31.206959  1.402560 0.17573382   3.09339666
  3091   44 20151005 150.829827 178.004406  73.507994  2.307101 0.15737508   2.40232683
    38   38 20151005 354.770951 295.808485 127.179228 27.874626 0.29002115   2.78037945
    88  108 20151005 249.245740 158.516896 226.631531  9.855102 0.49674975   2.63918287
 (19)     (20)    (21)      (22)      (23)                 (24)                 (25)
 20151030 1.3E-02 -6.3E-05 20151106 1.9E-02 20161025 2.5E-02 20180207 2.5E-02 20180207
 20150310 3.8E-02  1.4E-04 20151106 1.5E-01 20160810 2.0E-01 20240909 1.9E-01 20240909
 20150709 5.2E-02  1.6E-04 20151106 1.6E-01 20160610 2.4E-01 20210829 2.7E-01 20250620
 20111014 8.0E-02 -1.1E-04 20151106 1.7E-01 20160707 2.1E-01 20220905 2.1E-01 20250215
 20140913 2.1E-01  6.2E-04 20151106 2.1E-01 20151122 6.9E-01 20210418 6.7E-01 20250612
 20080720 3.6E+03  2.4E+01 20151106 4.3E+03 20151220 4.3E+03 20151220 4.1E+01 20190821
 20131112 4.3E+01  2.1E-01 20151106 2.6E+02 20160703 5.5E+02 20210507 1.1E+01 20251225
```

resulted in degradation of the orbit-quality parameter (OQP), which is a reliable (logarithmic) measure of an asteroid orbit's quality, and which (for non-Earth approachers) correlates well with ephemeris uncertainty. Such asteroids need orbit improvement to the point where the exclusion of "poor" observations no longer degrades the OQP. For unnumbered asteroids, some poor observations have been retained when the OQP and ephemeris uncertainty was improved; these asteroids are identified by integer code 2:16 (see Table 2).

2.2.2 Orbit uncertainty in Astorb

Ephemeris uncertainties are assumed to be along the line of variation[3]. Except for very accurately known orbits (ephemeris uncertainty smaller than 1 arcsec) and very poorly known orbits (arc shorter than 10 days), positional uncertainty perpendicular to the line of variation is usually very small compared to that along the line of variation. The current ephemeris uncertainty [CEU, parameter (20)] and its rate of change [parameter (21)] indicate whether an asteroid ought to be located in an observer's field of view. A CEU greater than all three of the peak ephemeris uncertainties [PEUs, parameters (23) through (25)] implies that the asteroid's ephemeris uncertainty is currently greater than at any time in the next ten years. Such asteroids are prime targets for observation because their orbits are subject to the greatest improvement for years to come. Note that, because ephemeris uncertainties have been computed using 2-body rather than n-body error propagation (see Muinonen and Bowell, 1993), uncertainties for Earth-approaching asteroids may have been misestimated by a factor of several.

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[3] In the linear context, the orbital uncertainty is mainly along one direction which is along the orbit and this direction represents the line of variation. This term was introduced in Milani (1999).

3 MPCORB

Minor Planet Center also provides a database of orbital elements of asteroids. This database (`MPCORB.DAT`), is available at http://www.minorplanetcenter.org/iau/MPCORB.html. The file is 136Mo in decompressed form and contains 697 542 lines (or objects)[4] on a 202-column record. Since April 2016, MPC also provides database in the JSON[5] format.

Table 4: Parameters provided in MPCORB database

	Columns	Format	Use
(1)	1 - 7	a7	Number or provisional designation (in packed form)
(2)	9 - 13	f5.2	Absolute magnitude, H
(3)	15 - 19	f5.2	Slope parameter, G
(4)	21 - 25	a5	Epoch (in packed form, .0 TT)
(5)	27 - 35	f9.5	Mean anomaly at the epoch (degrees)
(6)	38 - 46	f9.5	Argument of perihelion, J2000.0 (degrees)
(7)	49 - 57	f9.5	Longitude of the ascending node, J2000.0 (degrees)
(8)	60 - 68	f9.5	Inclination to the ecliptic, J2000.0 (degrees)
(9)	71 - 79	f9.7	Orbital eccentricity
(10)	81 - 91	f11.8	Mean daily motion (degrees per day)
(11)	93 - 103	f11.7	Semimajor axis (au)
(12)	106	i1	Uncertainty parameter, U
		or a1	If this column contains 'E' it indicates that the orbital eccentricity was assumed. For one-opposition orbits this column can also contain 'D' if a double (or multiple) designation is involved or 'F' if an e-assumed double (or multiple) designation is involved.
(13)	108 - 116	a9	Reference
(14)	118 - 122	i5	Number of observations
(15)	124 - 126	i3	Number of oppositions
			For multiple-opposition orbits:
(16)	128 - 131	i4	Year of first observation
	132	a1	'-'
	133 - 136	i4	Year of last observation
			For single-opposition orbits:
(16)	128 - 131	i4	Arc length (days)
	133 - 136	a4	'days'
(17)	138 - 141	f4.2	r.m.s residual (arcsec)
(18)	143 - 145	a3	Coarse indicator of perturbers (blank if unperturbed one-opposition object)
(19)	147 - 149	a3	Precise indicator of perturbers (blank if unperturbed one-opposition object)
(20)	151 - 160	a10	Computer name
			There may sometimes be additional information beyond column 160 as follows:

Continued on the next page

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[4] On November 10, 2015.

[5] JSON for JavaScript Object Notation, is a lightweight data-interchange format.

	Columns	Format	Use
(21)	162 - 165	z4.4	4-hexdigit flags This information has been updated on 2014 July 16, for files created after 18:40 UTC on that day. The bottom 6 bits (bits 0 to 5) are used to encode a value representing the orbit type (other values are undefined): Value 1 Atira 2 Aten 3 Apollo 4 Amor 5 Object with $q < 1.665$ au 6 Hungaria 7 Phocaea 8 Hilda 9 Jupiter Trojan 10 Distant object Additional information is conveyed by adding in the following bit values: Bit Value 6 64 Unused or internal MPC use only 7 128 Unused or internal MPC use only 8 256 Unused or internal MPC use only 9 512 Unused or internal MPC use only 10 1024 Unused or internal MPC use only 11 2048 Object is NEO 12 4096 Object is 1-km (or larger) NEO 13 8192 1-opposition object seen at earlier opposition 14 16384 Critical list numbered object 15 32768 Object is PHA Note that the orbit classification is based on cuts in osculating element space and is not 100% reliable. Note also that certain of the flags are for internal MPC use and are not documented.
(22)	167 - 194	a	Readable designation
(23)	195 - 202	i8	Date of last observation included in orbit solution (YYYYMMDD format)

3.1 Computation in MPCORB

This section presents the orbit computation in MPCORB as it is presented on http://www.minorplanetcenter.net/iau/info/Perturbers.html.

3.1.1 Orbit Computation in MPCORB

Perturbations included for orbit determination are indicated throught parameters (18) and (19). (18) is the coarse indicator that provides the planets (Mercury to Neptune) and major asteroids included in the

Table 5: Lines 1, 100 000, 200 000, 300 000, 400 000, 500 000, 600 000 of MPCORB.DAT file

```
(1)     (2)    (3)  (4)   (5)         (6)         (7)          (8)       (9)       (10)          (11)
00001    3.34  0.12 K161D 181.38133   72.73324   80.32180   10.59166  0.0757544  0.21400734   2.7681117
A0000   16.9   0.15 K161D 219.36593  199.51563  186.57827   21.19044  0.0874368  0.37494482   1.9046908
K0000   15.9   0.15 K161D 277.72257  203.52088  116.88308    7.70276  0.1514000  0.22083591   2.7107508
U0000   17.0   0.15 K161D 291.36958  305.03719   31.20562    1.40254  0.1757630  0.18113875   3.0935832
e0000   18.1   0.15 K161D 177.32345  177.98615   73.50825    2.30714  0.1574540  0.26473240   2.4021382
K09K28E 18.0   0.15 K161D 298.83613   83.80662  200.23040    7.16554  0.1308354  0.28433631   2.2904167
K06V29O 17.0   0.15 K06B1 151.44397   24.56653  211.25861    3.74989  0.2489280  0.27711673   2.3300266
(12)(13)       (14) (15)(16)      (17) (18)(19)(20)       (21) (22)                    (23)
  0 MP0350795  6580 109 1801-2015 0.60 M-v 30h MPCLINUX   0000      (1) Ceres              20151014
  1 MP0351561   219   8 1982-2014 0.53 M-v 38h MPCLINUX   0006 (100000) Astronautica       20141230
  0 MP0341651   189  11 1998-2015 0.49 M-v 38h MPCLINUX   0000 (200000) 2007 JT40          20150618
  0 MP0207005    43   5 1995-2011 0.29 M-v 38h MPCADO     0000 (300000) 2006 UW30          20110923
  1 MP0306875    41   4 2006-2014 0.26 M-v 38h MPCLINUX   0000 (400000) 2006 DK190         20140728
  0 MP0273943    41   5 1995-2013 0.25 M-v 38h MPCADO     0000          2009 KE28          20131010
    MP0172191    10   1   16 days 0.37         MPCS       2000          2006 VO29          20061114
```

perturbations. The minor planets are indicated by lower-case letters. This allows a distinction to be made between M-P (considering Pluto) and M-p (considering Pallas, and probably Ceres as well). Earth and Moon are considered together as the Earth-Moon Barycenter excepted if precise indicator mentions Earth and Moon separately. (19) is the precise indicator that consists in a two-digit hexadecimal number plus a flag indicating the system used for the perturbing planets (see Table 7). For the first digit, 1 is for Pallas, 2 is for Vesta, 4 is for Eunomia. For example 3 for the first digit means that Pallas and Vesta are included in the perturbations. For the second digit, 1 is for Hygiea, 2 is for Earth, 4 is for the Moon, and 8 is for Ceres. For example, E means Ceres is a perturber and that Earth and Moon are considered separately. The default for Minor Planet Center orbits will henceforth be h (DE403), M-v (coarse) and 38 or 3E (precise, depending on whether the object is an earth-approacher or not).

Table 6: Examples of perturbers taken into account in MPCORB.

Coarse	Precise	Perturbers (Mercury-Neptune+...)
M-c	08	Ceres, EM barycenter
M-c	0E	Ceres, Earth, Moon
M-p	16	Pallas, Earth, Moon (but not recommended)
M-p	18	Ceres, Pallas, EM barycenter
M-p	1E	Ceres, Pallas, Earth, Moon
M-v	38	Ceres, Pallas, Vesta, EM barycenter
M-v	3E	Ceres, Pallas, Vesta, Earth, Moon
M-e	78	Ceres, Pallas, Vesta, Eunomia, EM barycenter
M-e	7E	Ceres, Pallas, Vesta, Eunomia, Earth, Moon
M-h	39	Ceres, Pallas, Vesta, Hygiea, EM barycenter

3.1.2 Orbit uncertainty

In order to quantify the uncertainty in a perturbed orbital solution for a minor planet in a concise fashion, the Minor Planet Center has introduced the U parameter. This is an integer in the range 0 to 9, where 0

Table 7: Signification of flag for perturbing planets

(space)	Undefined/unknown, assume JPL DE200 positions + masses
d	JPL DE200 positions + masses
f	JPL DE245 positions + masses
h	JPL DE403 positions + masses
j	JPL DE405 positions + masses

indicates a very small uncertainty and 9 an extremely large uncertainty. In practice, U is rarely larger than 6. The U value is calculated in the following manner. First, $RUNOFF$ is calculated:

$$RUNOFF = (dT \times e + \frac{10}{P} \times dP) \times \frac{k_0}{P} \times 3600 \times 3 \tag{1}$$

where dT is the uncertainty in the perihelion time (in days), e is the eccentricity, P is the orbital period (in years), dP is the uncertainty in the orbital period (in days), k_0 is the Gaussian constant in degrees ($k_0 = 180/\pi \times 0.01720209895$), 3600 converts to seconds of arc, 3 is a empirical factor to make the formal errors more closely model reality and $RUNOFF$ is the in-orbit longitude runoff in seconds of arc per decade. Then, $RUNOFF$ is then converted to the "uncertainty parameter" (denoted by U) in the range 0 to 9:

$$\mathrm{CONS} = \ln(648000)/9 \sim 1.49 \tag{2}$$

$$U = \mathrm{INT}(\ln(RUNOFF)/\mathrm{CONS}) + 1 \tag{3}$$

where $\ln$ is the natural logarithm, INT is a function that returns the largest integer smaller than the argument (e.g., $\mathrm{INT}(3.5) = 3, \mathrm{INT}(0.99) = 0, \mathrm{INT}(-0.45) = -1$). As a guide, the values of U correspond to the following values of $RUNOFF$ (in seconds of arc per decade): The U value should not be used as a predictor for the uncertainty in the future motion of NEAs.

Table 8: Link between U parameter and $RUNOFF$ value.

U	$RUNOFF$	U	$RUNOFF$
0	< 1.0	5	< 1692
1	< 4.4	6	< 7488
2	< 19.6	7	< 33121
3	< 86.5	8	< 146502
4	< 382	9	> 146502

4 AstDyS/NeoDyS

AstDyS[6] (Asteroids Dynamic Site) and NEODyS[7] also provide data about asteroids. They propose both one-line format, multi-line format databases and individual pages for asteroids. The databases (one-line and multi-line) are divided in three parts: numbered asteroids, multi-opposition asteroids and single opposition asteroids.

The parameters provided in the one-line format are listed in Table 9 and those on the multi-line format are presented in Table 11. These parameters are provided either for the near middle of observational arc or for the near present day.

One of the characteristics of AstDyS database (in multi-line format) is to provide the covariance matrix of the equinoctial elements [8] and the normal matrix of the orbit determination. As these two matrix are symmetric, the database provides only the triangular part of the matrix.

An equivalent extraction as previous databases is provided in Table 10 while an example of multi-line format database is presented for (1) Ceres in Table 12.

The individual pages also present links for previous data and additional information about observations, ephemerides, and orbital elements. Additional parameters about the orbit are given: perihelion, aphelion, ascending node-Earth separation, descending node-Earth separation, Earth MOID[9], and the orbital period. A section is also dedicated to observations with the file of astrometric observations and radar measurements used for orbit determination.

The orbit determination is performed with OrbFit package[10].

Table 9: Parameters of the one-line format database of AstDyS.

Parameter	Description
(1)	Asteroid number or designation.
(2)	Epoch (Modified Julian date).
(3)	Semi-major axis (au).
(4)	Eccentricity.
(5)	Inclination to the ecliptic (degrees).
(6)	Longitude of the ascending node (degrees).
(7)	Argument of perihelion (degrees).
(8)	Mean anomaly at the epoch (degrees).
(9)	Absolute magnitude.
(10)	Slope parameter.
(11)	*Unidentified*

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[6] http://hamilton.dm.unipi.it/astdys/index.php?pc=0

[7] http://newton.dm.unipi.it/neodys/index.php?pc=0

[8] Equinoctial elements are mathematical combinations of orbital elements $(a, h = e\sin(\varpi), k = e\cos(\varpi), p = \tan(i/2)\sin(\Omega), q = \tan(i/2)\cos(\Omega), \lambda_0 = M + \omega + \Omega)$.

[9] Minimum Orbital Intersection Distance: the minimum separation between the instantaneous ellipses of the Earth and the asteroid

[10] http://adams.dm.unipi.it/~orbmaint/orbfit/

Table 10: Lines 1, 100 000, 200 000, 300 000, 400 000, 500 000, 600 000 of AstDyS file in the one-line format

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
'1'	57400.000000	2.7681116169078215E+00	7.5754391585451802E-02	1.0591658344943458E+01	8.0321792879283322E+01	7.2733297078832635E+01	1.8138128643209646E+02	3.41	0.12	0
'100000'	57400.000000	1.9046907321159998E+00	8.7436805587066416E-02	2.1190420563333621E+01	1.8657819436989107E+02	1.9951558975897080E+02	2.1936603101505020E+02	16.75	0.15	0
'200000'	57400.000000	2.7107506569589481E+00	1.5140014812219965E-01	7.7027462544815224E+00	1.1688324426702457E+02	2.0352068751569550E+02	2.7772260420833214E+02	15.79	0.15	0
'300000'	57400.000000	3.0935831835244687E+00	1.7576289248841098E-01	1.4025217508418679E+00	3.1207704679184612E+01	3.0503505241073429E+02	2.9136962289996114E+02	16.94	0.15	0
'400000'	57400.000000	2.4021378843440626E+00	1.5745343459505415E-01	2.3070867140929470E+00	7.3506973435529943E+01	1.7798721976104980E+02	1.7732366722586806E+02	18.10	0.15	0
'2007AM19'	57400.000000	2.7807406327463142E+00	2.9002427366912276E-01	2.7883558636125795E+01	1.2718063163022032E+02	2.9581618948558145E+02	1.5843823313169166E+01	16.59	0.15	0
'2012RN16'	57400.000000	2.6392569004799769E+00	4.9671681905366916E-01	9.8544345511931848E+00	2.2663068380829921E+02	1.5851093379429818E+02	2.7225499816094623E+02	18.87	0.15	0

Table 11: Parameters of the multi-line format database of AstDyS.

Line	Description
1	Asteroid number or designation.
2	*Comments*
3	Equinoctial elements $(a, h, k, p, q, \lambda_0)$
4	Epoch (Modified Julian date)
5	Absolute magnitude and slope parameter
6	*Comments*
7	Model used, actual number in use, and dimension
8	Root mean square of equinoctial elements
9	Eigen values of covariance matrix
10	*Unidentified*
11	Elements of covariance matrix $(c_{1,1}, c_{1,2}, c_{1,3})$
12	Elements of covariance matrix $(c_{1,4}, c_{1,5}, c_{1,6})$
13	Elements of covariance matrix $(c_{2,2}, c_{2,3}, c_{2,4})$
14	Elements of covariance matrix $(c_{2,5}, c_{2,6}, c_{3,3})$
15	Elements of covariance matrix $(c_{3,4}, c_{3,5}, c_{3,6})$
16	Elements of covariance matrix $(c_{4,4}, c_{4,5}, c_{4,6})$
17	Elements of covariance matrix $(c_{5,5}, c_{5,6}, c_{6,6})$
18	Elements of normal matrix $(n_{1,1}, n_{1,2}, n_{1,3})$
19	Elements of normal matrix $(n_{1,4}, n_{1,5}, n_{1,6})$
20	Elements of normal matrix $(n_{2,2}, n_{2,3}, n_{2,4})$
21	Elements of normal matrix $(n_{2,5}, n_{2,6}, n_{3,3})$
22	Elements of normal matrix $(n_{3,4}, n_{3,5}, n_{3,6})$
23	Elements of normal matrix $(n_{4,4}, n_{4,5}, n_{4,6})$
25	Elements of normal matrix $(n_{5,5}, n_{5,6}, n_{6,6})$

Table 12: Extract of AstDyS file in the multi-line format for (1) Ceres

```
1
! Equinoctial elements: a, e*sin(LP), e*cos(LP), tan(i/2)*sin(LN), tan(i/2)*cos(LN), mean long.
 EQU   2.7681116169078215E+00   0.034326859130790  -0.067530693663673    0.091374508943275    0.015583162716141 334.4363763902124
 MJD     57400.000000000 TDT
 MAG   3.414  0.120
! Non-grav parameters: model used, actual number in use, dimension
 LSP   0  0    6
! RMS    2.76796E-09   3.21544E-08   3.03417E-08   3.27605E-08   3.25629E-08   3.80153E-06
! EIG   1.84041E-09   3.03124E-08   3.18154E-08   3.18923E-08   3.35270E-08   6.65009E-08
! WEA   0.02997  -0.03827   0.01744   0.02167   0.05031  -0.99716
 COV   7.661614241771086E-18 -7.553039038420972E-18 -1.340900538839854E-17
 COV   2.522684283786375E-18  9.852438596650412E-19 -7.593646395191519E-15
 COV   1.033903715593665E-15  2.764301414002037E-18  2.390781623466092E-17
 COV   1.432654630213862E-17  7.512167037386238E-15  9.206213122400182E-16
 COV  -4.795863455677349E-18  8.168220857310949E-18 -3.520961611864012E-15
 COV   1.073248366471610E-15  5.285497514689421E-17 -4.069462879575108E-15
 COV   1.060343975217913E-15 -9.674304701947593E-15  1.445161317227356E-11
 NOR   2.948754600670712E+17  9.936013962849662E+14  4.879110439596681E+15
 NOR  -1.553509152128935E+14  1.108912287204146E+15  1.563140923377718E+14
 NOR   9.751361004933434E+14  1.154810557881792E+13 -2.335561489061002E+13
 NOR  -1.299830185382992E+13  2.735921966479937E+09  1.168070624586576E+15
 NOR   3.707973035426126E+12  1.214388018884637E+13  2.851501247440358E+12
 NOR   9.354792138129251E+14 -4.469482242148598E+13  1.649181700235446E+11
 NOR   9.554957059900151E+14  1.219446148559463E+12  1.528882494407523E+11
```

5 Synthesis

5.1 Analysis of parameters

As they provide the orbital elements for all asteroids, Astorb, MPCORB, and one-line format AstDyS databases can be considered as a good starting point for a new asteroid orbital database. They provide the same kind of parameters: number, name (or designation), orbital elements, observation arc, magnitude (H and G slope), date of computation, information about orbital uncertainty. In particular, several parameters are doublons and some parameters provide the same kind of information and have to be unified in a new database (indicated by TBU). Table 13 lists the parameters provided by the databases and presents the utility (in the sense of the parameter can be useful in a database, ✓ means yes, ✗ means no, ? means undefined status) and the possibility to compute these parameters in an independant process. For this point, ✓ means yes, p means probably with a correct definition of the parameter, TBU means that the parameter should be unified (for example, for the orbital arc, first and last year of observations or a period in days), TBI means to be improved (for example for diameter, more recent values can be found), ✗ means no.

Table 13: Utility and independant calculability of parameters in Astorb, MPCORB, and AstDyS/NEODyS.

Number	Description	Utility	Computable
	Parameters from Astorb		
(1)	Asteroid number (blank if unnumbered)	✓	✓
(2)	Name or preliminary designation.	✓	✓
(3)	Orbit computer.	✗	✗
(4)	Absolute magnitude H	✓	✓
(5)	Slope parameter G	✓	✓
(6)	Color index B-V, mag	?	✗
(7)	IRAS diameter, km	TBI	✗
(8)	IRAS Taxonomic classification	TBI	✗
(9)	Six integer codes (see Table 2 for explanation).	✗	✓
(10)	Orbital arc, days, spanned by observations used in orbit computation.	TBU	✓
(11)	Number of observations used in orbit computation.	TBU	✓
(12)	Epoch of osculation, yyyymmdd (TDT)	✓	✓
(13)	Mean anomaly, deg.	✓	✓
(14)	Argument of perihelion, deg (J2000.0).	✓	✓
(15)	Longitude of ascending node, deg (J2000.0).	✓	✓
(16)	Inclination, deg (J2000.0).	✓	✓
(17)	Eccentricity.	✓	✓
(18)	Semimajor axis, au.	✓	✓
(19)	Date of orbit computation, yymmdd (MST, = UTC - 7 hr).	TBU	✓
(20)	Absolute value of the current 1-σ ephemeris uncertainty (CEU), arcsec.	✓	✓
(21)	Rate of change of CEU, arcsec/day.	?	p
(22)	Date of CEU, yyyymmdd (0 hr UT).	TBU	✓
(23)	Next peak ephemeris uncertainty (PEU), arcsec, from date of CEU, and date of its occurrence, yyyymmdd.	?	p

Continued on the next page

Number	Description	Utility	Computable
(24)	Greatest PEU, arcsec, in 10 years from date of CEU, and date of its occurrence, yyyymmdd.	?	p
(25)	Greatest PEU, arcsec, in 10 years from date of next PEU, and date of its occurrence, yyyymmdd.	?	p
	Parameters from MPCORB		
(1)	Number or provisional designation (in packed form)	✓	✓
(2)	Absolute magnitude, H	✓	✓
(3)	Slope parameter, G	✓	?
(4)	Epoch (in packed form, .0 TT)	✓	✓
(5)	Mean anomaly at the epoch, in degrees	✓	✓
(6)	Argument of perihelion, J2000.0 (degrees)	✓	✓
(7)	Longitude of the ascending node, J2000.0 (degrees)	✓	✓
(8)	Inclination to the ecliptic, J2000.0 (degrees)	✓	✓
(9)	Orbital eccentricity	✓	✓
(10)	Mean daily motion (degrees per day)	✓	✓
(11)	Semimajor axis (AU)	✓	✓
(12)	Uncertainty parameter, U	✓	✓
(13)	Reference	✗	✗
(14)	Number of observations	✓	✓
(15)	Number of oppositions	?	✓
(16)	Years of first and last observations	TBU	✓
	Arc length (days)	TBU	✓
(17)	r.m.s residual (arcsec)	✓	✓
(18)	Coarse indicator of perturbers (blank if unperturbed one-opposition object)	TBU	✓
(19)	Precise indicator of perturbers (blank if unperturbed one-opposition object)	TBU	✓
(20)	Computer name	✗	✗
(21)	4-hexdigit flags	?	?
(22)	Readable designation	?	✗
(23)	Date of last observation included in orbit solution (YYYYMMDD format)	TBU	✓
	Parameters from AstDyS (one-line format)		
(1)	Asteroid number or designation	✓	✓
(2)	Epoch (Modified Julian date)	✓	✓
(3)	Semi-major axis (au)	✓	✓
(4)	Eccentricity	✓	✓
(5)	Inclination to the ecliptic (degrees)	✓	✓
(6)	Longitude of the ascending node (degrees)	✓	✓
(7)	Argument of perihelion (degrees)	✓	✓
(8)	Mean anomaly at the epoch (degrees)	✓	✓
(9)	Absolute magnitude	✓	✓
(10)	Slope parameter	✓	✓
	Parameters from AstDyS (multi-line format)		
	Equinoctial elements	TBU	✓

Continued on the next page

Number	Description	Utility	Computable
	Epoch	✓	✓
	Magnitude parameters	✓	✓
	Model information	TBU	✓
	Root mean squares of equinoctial elements	TBU	✓
	Eigenvalues of covariance matrix	TBU	✓
	Perihelion	✗	✓
	Aphelion	✗	✓
	Ascending node-Earth separation	✗	p
	Descending node-Earth separation	✗	p
	Earth MOID	✓	✓
	Orbital period	✗	✓

Note: TBU means 'to be unified' among the two databases.

Each parameter has also to be defined in a consistent unit. For example, MPCORB provides the observational arc in two different format (first and last years of observations or in days if the arc is smaller than one year). In addition, a parameter should remain blank if it is unknown. For example, in Astorb, the absolute magnitude H is assumed to be $H = 14$ when unknown.

5.2 Analysis of orbit computation and orbital uncertainty

Moreover, the indication about orbital uncertainty is very important. A parameter like CEU, which correspond to physical and measurable parameter is preferable to U parameter provided in MPCORB. Actually, the root mean squares (r.m.s) of observations also provide indication of orbit quality whereas CEU provides indication of orbital extrapolation. The CEU can be computed at a specific epoch as in Astorb or could be computed N days after the last computation. This last point may be correlated to rms and should be studied.

Part II

Description of parameters in DynAstVO

1 Introduction

According to Sect. 5, we finally decided to provide parameters that appear to be useful to users and not redundant with other parameters. In this section, we provide the list of parameters given in DynAstVO and we describe each of these parameters.

2 Description of DynAstVO

2.1 Parameters provided by DynAstVO

DynAstVO is the main database that merges all the parameters related to asteroid orbits. The epoch is defined as the mean of all the asteroid observations and so different for all asteroids. Table 14 presents parameters for a DynAstVO database. This database is built in order to be consistent for all asteroids (MBA, NEA, TNO, etc).

The second database DynAstVOs is a light version of DynAstVO where the epoch is the first of July of the current year and so identical for all asteroids. Information about precision of parameters as well as the covariance matrix are not provided in the light version of DynAstVO. Table 15 presents parameters given in the light version of DynAstVO.

Table 14: Parameters of the DynAstVO database

Number	Format	Parameter	Description	Unit
(1)	string	objid	number or designation	
(2)	integer	number	asteroid number	
(3)	string	name	asteroid name	
(4)	string	designation	asteroid designation	
(5)	float	a	semi-major axis	au
(6)	float	e	eccentricity	
(7)	float	i	inclination to the ecliptic (J2000)	degrees
(8)	float	Ω	longitude of the ascending node (J2000.0)	degrees
(9)	float	ω	argument of perihelion (J2000.0)	degrees
(10)	float	M_0	mean anomaly at the epoch	degrees
(11)	float	epoch	epoch (TDB) in Julian date	day
(12)	ISO8601-string	epochc	epoch (TDB) in ISO format	
(13)	string	orbityp	asteroid dynamical type	
(14)	integer	noba	number of optical observations used in the fit	
(15)	integer	nobr	number of optical observations rejected in the fit	
(16)	integer	nobrr	number of radar ranging	

Continued on the next page

Number	Format	Parameter	Description	Unit
(17)	integer	nobvr	number of radar doppler	
(18)	float	jdmin	date of first observation used in Julian date	day
(19)	ISO8601-string	jdminc	date of first observation used in ISO format	
(20)	float	jdmax	date of last observation used in Julian date	day
(21)	ISO8601-string	jdmaxc	date of last observation used in ISO format	
(22)	float	rms	root mean square of observations	arcsec
(23)	float	H	absolute magnitude	
(24)	float	G	slope parameter	
(25)	float	SPU	sky-plane uncertainty at epoch	arcsec
(26)	string	perturb	perturbations included in the model	
(27)	ISO8601-string	datecomp	date of computation in ISO format	
(28)	float	σ_a	standard deviation of semi-major axis	au
(29)	float	σ_e	standard deviation of eccentricity	
(30)	float	σ_i	standard deviation of inclination	degrees
(31)	float	σ_Ω	standard deviation of longitude of ascending node	degrees
(32)	float	σ_ω	standard deviation of argument of perihelion	degrees
(33)	float	σ_{M_0}	standard deviation of mean anomaly	degrees
(34)	float	x	state-vector x position component	au
(35)	float	y	state-vector y position component	au
(36)	float	z	state-vector z position component	au
(37)	float	v_x	state-vector v_x velocity component	au/d
(38)	float	v_y	state-vector v_y velocity component	au/d
(39)	float	v_z	state-vector v_z velocity component	au/d
(40)	float	$c_{1,1}$	Covariance matrix $c_{1,1}$ component	
(41)	float	$c_{1,2}$	Covariance matrix $c_{1,2}$ component	
(42)	float	$c_{1,3}$	Covariance matrix $c_{1,3}$ component	
(43)	float	$c_{1,4}$	Covariance matrix $c_{1,4}$ component	
(44)	float	$c_{1,5}$	Covariance matrix $c_{1,5}$ component	
(45)	float	$c_{1,6}$	Covariance matrix $c_{1,6}$ component	
(46)	float	$c_{2,2}$	Covariance matrix $c_{2,2}$ component	
(47)	float	$c_{2,3}$	Covariance matrix $c_{2,3}$ component	
(48)	float	$c_{2,4}$	Covariance matrix $c_{2,4}$ component	
(49)	float	$c_{2,5}$	Covariance matrix $c_{2,5}$ component	
(50)	float	$c_{2,6}$	Covariance matrix $c_{2,6}$ component	
(51)	float	$c_{3,3}$	Covariance matrix $c_{3,3}$ component	
(52)	float	$c_{3,4}$	Covariance matrix $c_{3,4}$ component	
(53)	float	$c_{3,5}$	Covariance matrix $c_{3,5}$ component	
(54)	float	$c_{3,6}$	Covariance matrix $c_{3,6}$ component	
(55)	float	$c_{4,4}$	Covariance matrix $c_{4,4}$ component	
(56)	float	$c_{4,5}$	Covariance matrix $c_{4,5}$ component	
(57)	float	$c_{4,6}$	Covariance matrix $c_{4,6}$ component	
(58)	float	$c_{5,5}$	Covariance matrix $c_{5,5}$ component	
(59)	float	$c_{5,6}$	Covariance matrix $c_{5,6}$ component	
(60)	float	$c_{6,6}$	Covariance matrix $c_{6,6}$ component	

Continued on the next page

Number	Format	Parameter	Description	Unit
(61)	float	MOID	Minimum Orbital Intersection Distance with Earth orbit	au
(62)	string	SPK-ID	NAIF integer ID code (see Sect.3.7.5)	
(63)	string	DOU-version	Last Daily Orbit Update related to asteroid	

Table 15: Parameters for the light version of DynAstVO database

Number	Format	Parameter	Description	Unit
(1)	string	objid	number or designation	
(2)	integer	number	asteroid number	
(3)	string	name	asteroid name	
(4)	string	designation	asteroid designation	
(5)	float	a	semi-major axis	au
(6)	float	e	eccentricity	
(7)	float	i	inclination to the ecliptic (J2000)	degrees
(8)	float	Ω	longitude of the ascending node (J2000.0)	degrees
(9)	float	ω	argument of perihelion (J2000.0)	degrees
(10)	float	M_0	mean anomaly at the epoch	degrees
(11)	float	epoch	epoch (TDB) in Julian date	day
(12)	ISO8601-string	epochc	epoch (TDB) in ISO format	
(13)	string	orbityp	asteroid dynamical type	
(14)	integer	noba	number of optical observations used in the fit	
(15)	integer	nobr	number of optical observations rejected in the fit	
(16)	integer	nobrr	number of radar ranging	
(17)	integer	nobvr	number of radar doppler	
(18)	float	jdmin	date of first observation used in Julian date	day
(19)	ISO8601-string	jdminc	date of first observation used in ISO format	
(20)	float	jdmax	date of last observation used in Julian date	day
(21)	ISO8601-string	jdmaxc	date of last observation used in ISO format	
(22)	float	rms	root mean square of observations	arcsec
(23)	float	H	absolute magnitude	
(24)	float	G	slope parameter	
(25)	float	SPU	sky-plane uncertainty at epoch	arcsec
(26)	string	perturb	perturbations included in the model	
(27)	ISO8601-string	datecomp	date of orbit computation in ISO format	
(28)	ISO8601-string	dateprop	date of orbit propagation in ISO format	
(29)	float	x	state-vector x position component	au
(30)	float	y	state-vector y position component	au
(31)	float	z	state-vector z position component	au
(32)	float	v_x	state-vector v_x velocity component	au/d
(33)	float	v_y	state-vector v_y velocity component	au/d

Continued on the next page

Number	Format	Parameter	Description	Unit
(34)	float	v_z	state-vector v_z velocity component	au/d
(35)	float	MOID	Minimum Orbital Intersection Distance with Earth orbit	au
(36)	string	SPK-ID	NAIF integer ID code (see Sect.3.7.5)	
(37)	string	DOU-version	Last Daily Orbit Update related to asteroid	

3 Description of parameters

This section describes the parameters provided in DynAstVO database. When the computation of the parameter is long, the full description is provided in the next part

3.1 Object identification

When it is discovered, an asteroid received a provisional designation. After several apparitions, when the orbit is well determined, the object can receive a number and finally sometimes a name.

In that context, the object designation is the number when asteroid has a number or the designation otherwise.

3.2 Asteroid designation

This part comes from MPC website[11] explaining the designation process of newly discovered asteroids.

The Minor Planet Center assigns new provisional designations when it is in possession of at least two nights of observations of an object that cannot be identified immediately with some already designated object.

The standard designation consists of the following parts, all of which are related to the date of discovery of the object: a 4-digit number indicating the year; a space; a letter to show the half-month; another letter to show the order within the half-month; and an optional number to indicate the number of times the second letter has been repeated in that half-month period.

The half-month of discovery is indicated using the following scheme:

---

[11] http://www.minorplanetcenter.net/iau/info/OldDesDoc.html

Letter	Dates	Letter	Dates
A	Jan. 1-15	B	Jan. 16-31
C	Feb. 1-15	D	Feb. 16-29
E	Mar. 1-15	F	Mar. 16-31
G	Apr. 1-15	H	Apr. 16-30
J	May 1-15	K	May 16-31
L	June 1-15	M	June 16-30
N	July 1-15	O	July 16-31
P	Aug. 1-15	Q	Aug. 16-31
R	Sept.1-15	S	Sept.16-30
T	Oct. 1-15	U	Oct. 16-31
V	Nov. 1-15	W	Nov. 16-30
X	Dec. 1-15	Y	Dec. 16-31
I is omitted and Z is unused			

The order within the month is indicated using letters as follows:

A = 1st	B = 2nd	C = 3rd	D = 4th	E = 5th
F = 6th	G = 7th	H = 8th	J = 9th	K = 10th
L = 11th	M = 12th	N = 13th	O = 14th	P = 15th
Q = 16th	R = 17th	S = 18th	T = 19th	U = 20th
V = 21st	W = 22nd	X = 23rd	Y = 24th	Z = 25th
I is omitted				

If there are more than 25 discoveries in any one half-month period, the second letter is recycled and a numeral '1' is added to the end of the designation. If more than 50 discoveries, the second-letter is again recycled, with a numeral '2' appended after the second letter. Discoveries 76-100 have numeral '3' added, numbers 101-125 numeral '4', etc. When possible, these additional numbers should be indicated using subscript characters.

Thus the order of assignment of designations in a particular half-month period is as follows: 1995 SA, 1995 SB, ..., 1995 SY, 1995 SZ, 1995 SA1, ..., 1995 SZ1, 1995 SA2, ..., 1995 SZ9, 1995 SA10, etc.

3.3 Osculating elements

The osculating elements at the epoch represent the orbital elements of a Keplerian orbit around the Sun in the case where no perturbations are present. There are six elements to describe the orbit which are :

- the **semi major axis** a represents the size of the orbit;
- the **eccentricity** e represents the shape of the orbit;
- the **inclination** i is the vertical tilt of the orbit with respect to the reference plane (ecliptic J2000);
- the **longitude of ascending node** Ω horizontally orients the ascending node of the ellipse (the point where orbit passes upward through the reference plane) with respect to the vernal point;
- the **argument of periapse** ω is the orientation of the ellipse in the orbital plane;
- the **mean anomaly at epoch** M_0 is the position of the object along the orbit at the specific time ("epoch").

The two first parameters describe the size and the shape of the orbit whereas the four last angles describe the orientation of the orbit (see Fig. 1).

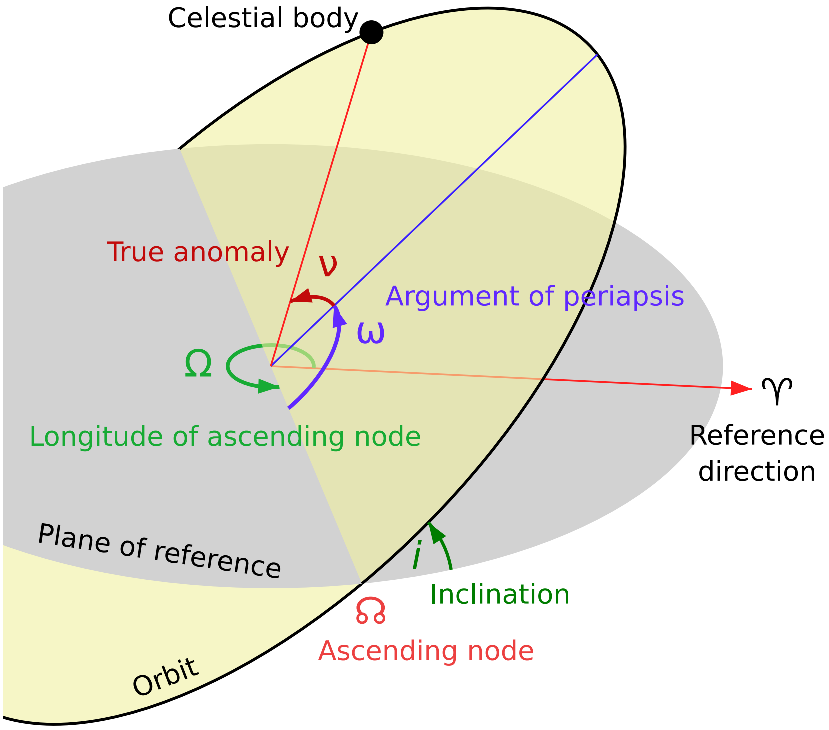

Figure 1: Orbital parameters of an orbit (Source: Wikipedia)

3.4 Type of object

The parameter *type of object* specifies the dynamical class of the object. The osculating elements (a, e, i) are used for the classification, meaning that the dynamical class is defined for the epoch of osculating elements[12].

The dynamical classification of asteroids in DynAstVO is made according to Minor Planet Center[13] and Project Pluto website[14] and presented in Table 16.

In the database, asteroids are divided in four main classes which are **Near-Earth asteroids** with an orbit close to the Earth, **Main-Belt asteroids** belonging to the Main-Belt between Mars and Jupiter, **Centaurs** between Jupiter and Neptune orbits, and **TransNeptunian objects** (TNO) orbiting beyond Neptune.

3.5 Observational parameters

Several parameters are given in DynAstVO about the observation set used to determine the orbit:

- Number of accepted observations by the fitting process;
- number rejected observations by the fitting process;
- number of ranging measurements used for the fitting process;
- number of doppler measurements used for the fitting process;
- date of the first observation used for the fitting process;

---

[12] Due to close approaches with planets, some objects can change their orbit and so on, their dynamical class. For example, Apophis is currently an Aten and will be an Apollo after its 2029-close approach with Earth.

[13] http://minorplanetcenter.net/blog/asteroid-classification-i-dynamics/

[14] http://www.projectpluto.com/mp_group.htm

Table 16: Dynamical classification of asteroids

NEA	$q < 1.3$ au	Near-Earth asteroids
NEA-Atira	$a < 1.0$ au and $Q < 0.983$ au	
NEA-Aten	$a < 1.0$ au and $Q > 0.983$ au	
NEA-Apollo	$a > 1.0$ au and $q < 1.017$ au	
NEA-Amor	$a > 1.0$ au and $q > 1.017$ au	
PHA	MOID< 0.05 au and $H \leq 22$	Potentially Hazardous Asteroid with a minimal distance to the Earth smaller than 0.05 au and and a size bigger than about 150m
MBA	1.78 au $\leq a \leq 5.4$ au	Main Belt asteroids
MBA-I	2.3 au $\leq a \leq 2.5$ au and $i \leq 18°$	Asteroids in inner part of Main Belt
MBA-IIa	2.5 au $\leq a \leq 2.706$ au and $i \leq 33°$	–
MBA-IIb	2.706 au $\leq a \leq 2.82$ au and $i \leq 33°$	–
MBA-IIIa	2.82 au $\leq a \leq 3.03$ au and $i \leq 30°$ and $e \leq 0.35$	–
MBA-IIIb	3.03 au $\leq a \leq 3.27$ au and $i \leq 30°$ and $e \leq 0.35$	–
Hungarias	1.78 au $\leq a \leq 2.00$ au and $16° \leq i \leq 34°$ and $e \leq 0.18$	–
Phocaeas	2.25 au $\leq a \leq 2.50$ au and $18° \leq i \leq 32°$ and $e \geq 0.10$	–
Cybeles	3.27 au $\leq a \leq 3.70$ au and $i \leq 25°$ and $e \leq 0.30$	–
Hildas	3.70 au $\leq a \leq 4.20$ au and $i \leq 20°$ and $e \geq 0.07$	–
Trojans	5.05 au $\leq a \leq 5.40$ au	Asteroids sharing their orbit with Jupiter
Centaurs	5.40 au $\leq a \leq 30.0$	Asteroids between Jupiter and Neptune orbits
TNOs	30.0 au $\leq a$	Asteroids beyond Neptune orbit

- date of the last observation used for the fitting process;
- root mean square of the observations (given in arcsec).

3.6 Magnitude parameters

The absolute magnitude H and the G slope parameter allow to determine the apparent magnitude of an asteroid.

In DynAstVO, the magnitude of asteroids is provided by empirical formula Simon et al. (1997):

$$m = 5\log(r\Delta) + H - 2.5\log\left((1-G)\Phi_1 + G\Phi_2\right)$$

with r the heliocentric distance of the asteroid, Δ is the geocentric distance of the asteroid, H is the absolute magnitude of the asteroid, G is the slope parameter and :

$$\Phi_i = \exp\left(-A_i \tan^{B_i}\left(\frac{\beta}{2}\right)\right) \text{ pour } i = 1, 2$$
$$\text{avec } A_1 = 3.33 \ , \ A_2 = 1.87 \ , \ B_1 = 0.63 \text{ et } B_2 = 1.22$$

H and G are the two parameters related to the magnitude and that can be fitted with comparison to apparent magnitude. H is the apparent magnitude of the asteroid if it is placed at 1 au of the Earth and the Sun and with a phase angle of 0. G represents the variation of the magnitude related to all other parameters.

3.7 Others parameters

3.7.1 Perturbations

The dynamical model (see Sect. 4.1) can takes into account :

- the gravitational perturbations of the Sun, the planets, Moon and Pluto, the four biggest asteroids (Ceres, Vesta, Pallas, Hygiea);
- the relativistic corrections;
- the solar quadrupole moment $J_{2_\odot}$;
- the Earth quadrupole moment $J_{2_\oplus}$.

Consequently, the parameter *perturb* indicates which perturbations are included in the orbit fitting to observations. The parameter consists in a character of 8 letters:

1. the number of planets (8 without Pluto, 9 with Pluto)
2. p (for planets)
3. M (if Moon and Earth are included separately) or B (if Earth-Moon barycenter is considered)
4. the number of massive asteroids
5. a (for asteroids)
6. R (if relativistic effects are included) or '-' (if not)
7. J (if solar quadrupole is included) or '-' (if not)
8. j (if Earth quadrupole is included) or '-' (if not)

For example, most of asteroids have '9pM4aR–' as perturbation parameter, indicating that gravitational perturbations of 9 planets (including Pluto), Earth and Moon considered separately, four massive asteroids and relativistic effects are taken into account.

Note that in some particular cases, we can consider only a Keplerian orbit and in that case, *perturb* is '2body'.

3.7.2 MOID

The MOID (Minimum orbit intersection distance) is defined as the distance between the closest points of the osculating orbits of two bodies. It is used in order of estimating the risk of collision between an asteroid and a planet. In particular, the Earth MOID is used in the close approaches context and to identify Potentially Hazardous asteroids (PHA).

The MOID is only geometrical, meaning that a low MOID does not necessary mean that a collision is inevitable. Moreover, the MOID may change with time when the asteroid orbit is slightly modified during close approaches with planets.

The algorithm of MOID computation is described in Sitarski (1968).

3.7.3 Covariance matrix

The covariance matrix of the system is computed in the fitting process. Numerically, the covariance matrix is:

$$\Gamma \quad = \quad ({}^{t}BWB)^{-1}$$

with the notation used in Sects. 4.4 and 4.4.1.

Finally the elements of the covariance matrix can be written as $(\rho_{ij}\sigma_i\sigma_j)$ where σ_i and σ_j are the standard deviations of parameters i and j and ρ_{ij} is the correlation factor between parameters i and j.

3.7.4 Sky-plane uncertainty

The Sky-Plane Uncertainty (SPU) is computed at the specific date t by propagation of the covariance matrix from epoch t_0 to the date t and by projection on the celestial sphere.

The SPU at date t is then computed by the equation:

$$\mathrm{SPU}(t) = \sqrt{\sigma_\alpha^2 \cos^2\delta + \sigma_\delta^2} \tag{4}$$

3.7.5 NAIF SPK ID Code

The NAIF SPICE provides a library allowing computation of ephemerides (throught specific file with bsp extension). Each object (planet, moons, asteroids, comets, spacecrafts, ...) has an integer code usually called NAIF Integer ID Code[15] used to identify object in the bsp files. In this part we only focus on asteroids.

For numbered asteroids, the NAIF ID code is 2 000 000 + JPL Asteroid Number. For example, 4179 Toutatis has 2004179 for NAIF ID.

For historical reasons, there are three exceptions for asteroids 951 Gaspra (NAIF ID = 9511010), 243 Ida (NAIF ID = 2431010) and its satellite Dactyl (NAIF ID = 2431011).

In DynAstVO database, we assign the same number for numbered asteroid.

For unnumbered asteroids, JPL assigns 3000000-series in their own order. There is no formula to go from SPK-ID to provisional designation (Chamberlain, 2016).

In that context, we develop a formula to assign a NAIF ID for unnumbered asteroids according to their provisional designation.

According to the scheme of provisional designation, the algorithm is divided in two parts : one (called id1) concerning the year and the half-month period, and the other (called id2) concerning the order of the asteroid within the half-month period. For better understanding, we provide example with 2016 RB1.

For the first part (id1), we count the number of half-month period since the 1st of January 1800.

id1 = (year of designation - 1800) × 24 + half-month period

For example, 2016 RB1 has been discovered during the R half-month period (corresponding to 1-15 Sept.) of 2016 which is the 17th half month period of 2016. Consequently id1 = (2016-1800) × 24 + 17 = 5201.

For the second part (id2), we count the order of discovery during ther half-month period (see explanations in Sect.3.2). This number is given by the second letter of the designation and the following number (e.g. B1 for 2016 RB1).

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[15] `http://naif.jpl.nasa.gov/pub/naif/toolkit_docs/FORTRAN/req/naif_ids.html`

$$\text{id2} = \text{following number} \times 25 + \text{second letter of designation}$$

For example for 2016 RB1, id2 = 1 × 25 + 2 (corresponding to B) = 27. It means that 2016 RB1 was the 27$^{\text{th}}$ asteroid receiving a provisional designation during the R half-month period (corresponding to 1-15 Sept.) of 2016.

Finally the NAIF ID code is:

$$\text{NAIF ID} = 1\,000\,000\,000 + \text{id1} \times 100\,000 + \text{id2}.$$

Note if more than 100 000 have a provisional designation during an half period (corresponding to a suffix designation greater than 4000), then the formula has to be changed.

We assign an additional 1 000 000 000 to avoid case of similar NAIF ID with numbered asteroids (for example, without this additional number, objects with year of designation between 1808 and 1812 may have a NAIF ID belonging to 2000000-series, reserved for numbered asteroids).

With our example 2016RB1, NAIF ID is 1520100027.

For each provisional designation, there is one single NAIF ID and the provisional designation can be found by a reverse algorithm.

3.7.6 Last DOU version

The last DOU version provided the code of the last MPECs where the object appears in the MPECs. During first computation of the database, this parameter is assigned as 'INITIA'.

Part III

DynAstVO database processing

This part presents the processing of the DynAstVO database. The global processing is presented in Sect. 1 and the orbit determination is detailed in Sect 4 and astrometric measurements used for orbit determination are presented in Sect 3

1 Global processing of DynAstVO

DynAstVO is updated daily following the block diagram presented on Fig. 2

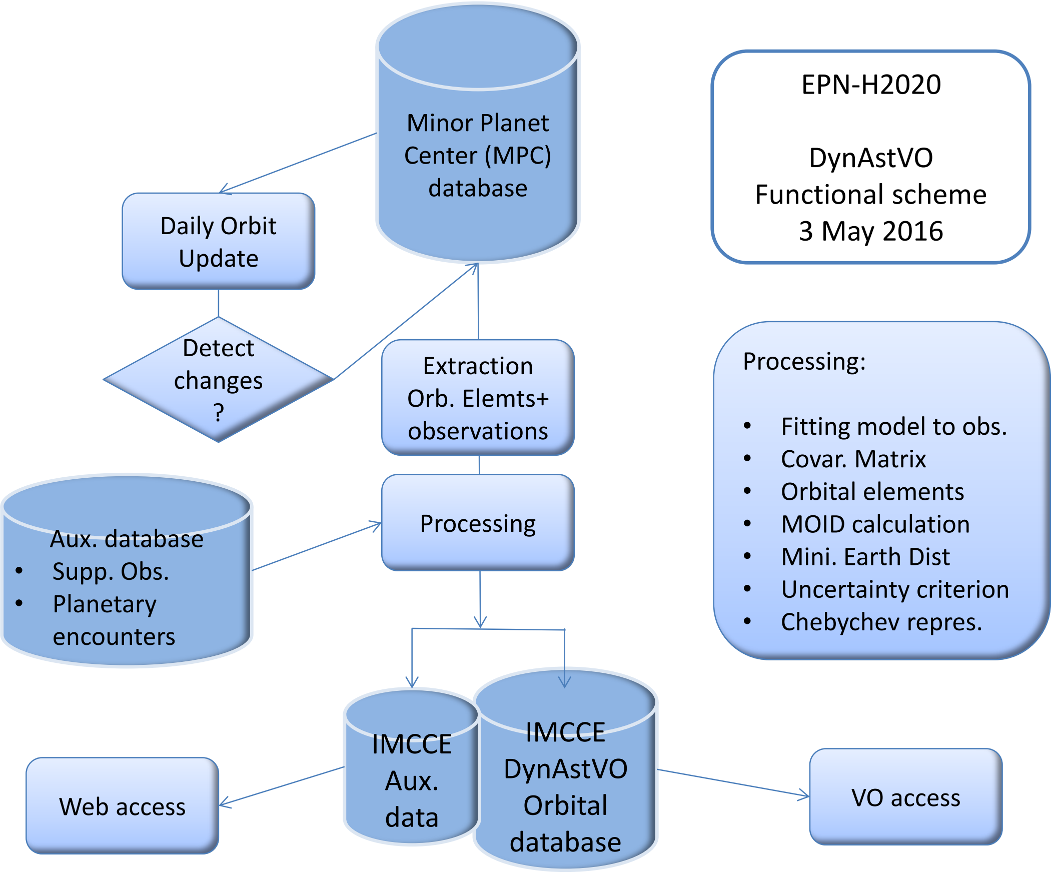

Figure 2: Block diagram of DynAstVO processing

Every day, DynAstVO processing downloads DOU from MPC and identifies objects with new observations. For each of these identified objects, the processing is :

- extraction of the preliminary orbital elements and the whole set of observations (see Sect 3) from

MPC database;
- fitting to observations (see details in Sect 4.4);
- production of individual line of DynAstVO database (with orbital elements, covariance matrix, MOID, uncertainty criterion, ...);

Then the database is updated by adding (for new discovered objects) or replacing the line of object.

2 Minor Planet Electronic Circulars

Among the notes published every day, the MPC also publishes a Daily Orbit Update (DOU) containing new objects or identifications:

- identification of new objects: recently discovered;
- new 1-opposition objects: with only a unperturbed keplerian orbit;
- new 1-opposition objects with a perturbed orbit;
- new muti-opposition objects: objects observed during more than one opposition;
- new double designation objects: objects with an orbit corresping to an other object in the previous database;
- errors of identification;
- errors of double identification;
- errors of double designation;
- astrometric positions of recently observed objects.

The program identifies objects with new observations (new discovered and already known objects) in the DOU and proceeds to update or determination of the orbit.

3 Astrometric measurements

Astrometric measurements for a single asteroid are available on the MPC website. Basically, there are two types of measurements: optical observations that are an angular measurement of the position and radar measurements than can be a measure of the distance or a measure of the velocity of the object.

3.1 Optical observations

For asteroids, optical observation consists in a date of observation (in UTC), the right ascension and the declination of the object. The position of the observer is also required and usually the position is given by the IAU observatory code[16].

The MPC also provide the type of observations that can be photographic, CCD, micrometer, etc (see Table 17).

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[16] The IAU observatories code is available on the MPC website at http://www.minorplanetcenter.org/iau/lists/ObsCodes.html

3.2 Radar measurements

Radar provides two types of measurements: ranging which is a measure of time between the emission and the reception of a signal or a doppler which is a measure of an offset between the emitted frequency and the received frequency.

Ranging can be related to a measure of distance between the observer and the object and the doppler can be transformed in a measure of radial velocity. The methods to compute and derive the radar measurements are fully described in Yeomans et al. (1992), Moyer (1971).

3.3 MPC observation file

The MPC file of observations contains optical and radar measurements in a 80-column record.

The format is presented in Tables 17 and 19.

Column 72 is affected to astrometric reference catalogue and the correspondance between flag and catalogue is presented in Table 18.

The following table presents a sample of the mpc file of observations for (99942) Apophis.

```
99942K04M04N  C2004 03 15.10789 04 06 08.08 +16 55 04.6                om6394691
99942K04M04N  C2004 03 15.11039 04 06 08.58 +16 55 06.1 MPS123345      o53585691
99942K04M04N  C2004 03 15.12365 04 06 11.75 +16 55 15.5 MPS123345      o53585691
99942K04M04N  C2004 03 15.12628 04 06 12.40 +16 55 17.7 MPS123345      o53585691

99942        KC2015 01 03.23411 14 43 01.20 -17 27 36.8          21.6 Rq~1GJQ586
99942        KC2015 01 03.24047 14 43 02.63 -17 27 42.2          21.5 Rq~1GJQ586
99942        KC2015 01 03.24580 14 43 03.82 -17 27 47.1          21.5 Rq~1GJQ586
99942        KC2015 01 03.25200 14 43 05.22 -17 27 52.9          21.7 Rq~1GJQ586
99942        KC2015 01 03.25775 14 43 06.52 -17 27 58.2          21.3 Rq~1GJQ586
99942        KC2015 01 03.26308 14 43 07.72 -17 28 03.2          21.3 Rq~1GJQ586

99942         R2005 01 27.979861               -    10084914   2380 251 JPLRS251
99942         r2005 01 27.979861C                        0250       251 JPLRS251
99942         R2005 01 29.000000  19202850713  -    10251291   2380 251 JPLRS251
99942         r2005 01 29.000000C         4000           025        251 JPLRS251
```

Some particular cases of measurements such as 'roving observer' or satellite observation have their own format that is fully explained on the MPC website[17] but as they are few in number, they are not explained in this document.

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[17] Format for roving observer is explained on `http://www.minorplanetcenter.net/iau/info/RovingObs.html` and for satellite on `http://www.minorplanetcenter.net/iau/info/SatelliteObs.html`.

Table 17: Description of MPC observation file (Source: `http://www.minorplanetcenter.net/iau/info/OpticalObs.html`)

Columns	Format	Use	
1 - 5	A5	Minor planet number	
6 - 12	A7	Provisional or temporary designation	
13	A1	Discovery asterisk	
14	A1	This column contains a alphabetical publishable note or (those sites that use program codes) an alphanumeric or non-alphanumeric character program code. The list of standard codes used for observations of minor planets is given in each batch of MPCs.	
15	A1	Type of observation/measurement	
		A	Converted to the J2000.0 system by rotating B1950.0 coordinates
		P	Photographic (default if column is blank)
		e	Encoder
		C	CCD
		T	Meridian or transit circle
		M	Micrometer
		V/v	"Roving Observer" observation
		R/r	Radar observation
		S/s	Satellite observation
		c	Corrected-without-republication CCD observation
		E	Occultation-derived observations
		O	Offset observations (used only for observations of natural satellites)
		H	Hipparcos geocentric observations
		N	Normal place
		n	Mini-normal place derived from averaging observations from video frames
16 - 32		Date of observation, the format is "YYYY MM DD.dddddd"	
33 - 44		Observed RA (J2000.0), the format is "HH MM SS.ddd"	
45 - 56		Observed Decl. (J2000.0), the format is "sDD MM SS.dd" (with "s" being the sign)	
57 - 65	9X	Must be blank	
66 - 71	F5.2,A1	Observed magnitude and band	
72 - 77	X	Must be blank	
78 - 80	A3	Observatory code	

Table 18: Description of MPC flag of astrometric catalogues (Source: `http://www.minorplanetcenter.org/iau/info/CatalogueCodes.html`)

Char	Catalogue	Char	Catalogue	Char	Catalogue
a	USNO-A1.0	q	UCAC-4	G	Lick Gaspra Cat.
b	USNO-SA1.0	r	UCAC-2	H	Ida93 Cat.
c	USNO-A2.0	s	USNO-B2.0	I	Perth 70
d	USNO-SA2.0	t	PPMXL	J	COSMOS/UKST
e	UCAC-1	u	UCAC-3	K	Yale
f	Tycho-1	v	NOMAD	L	2MASS
g	Tycho-2	w	CMC-14	M	GSC-2.3
h	GSC-1.0	x	Hipparcos 2	N	SDSS-DR7
i	GSC-1.1	y	Hipparcos	O	SST-RC1
j	GSC-1.2	z	GSC (unspec)	P	MPOSC3
k	GSC-2.2	A	AC	Q	CMC-15
l	ACT	B	SAO 1984	R	SST-RC4
m	GSC-ACT	C	SAO	S	URAT-1
n	SDSS-DR8	D	AGK 3	T	URAT-2
o	USNO-B1.0	E	FK4	U	Gaia-DR1
p	PPM	F	ACRS	V	Gaia-DR2

Table 19: Description of MPC observation file (Source: http://www.minorplanetcenter.net/iau/info/RadarObs.html)

Columns	Use
	First line of the record
1 - 12	Identical to columns 1-12 for optical observations
15	"R"
16 - 32	Identical to columns 16-32 for optical observations
33 - 47	Time delay (in μs), implicit decimal point between columns 43 and 44
48 - 62	Doppler shift (in Hz), with the sign always in column 48 and an implicit decimal point between columns 58 and 59
63 - 68	Transmitter frequency (in MHz), implicit decimal point between columns 67 and 68
69 - 71	Observatory code for transmitter site
72 - 77	Blank
78 - 80	Observatory code for reception site (often identical to columns 69-71)
	Second line of the record
1 - 14	Identical to columns 1-12 of first record
15	"r"
16 - 32	Identical to columns 16-32 of first record
33	"S" for surface-returned signals "C" for signals from the (hypothetical) center of mass
34 - 47	Uncertainty on the time delay (in s), implicit decimal point between columns 43 and 44
48 - 62	Uncertainty on Doppler shift (in Hz), implicit decimal point between columns 58 and 59
63 - 68	Continuation of transmitter frequency, if necessary, blank otherwise
69 - 80	Identical to columns 69-80 of first record

4 Orbit determination process

The orbit determination process is based on Desmars (2015). It consists on the numerical integration of the equation of motion that provides the position and velocity vector of the asteroid at any date t related to a state vector (*i.e.* the position and velocity vector at epoch t_0). The equations of motion depend on the dynamical model.

The orbit determination consists in the determination of the state vector that minimises the O-C (difference between observed and computed positions) and is performed throught a Levenberg-Marquardt algorithm (*i.e.* iterative corrections of the state vector by the least-square method).

4.1 Dynamical model and equations of motion

The equations of motion are differential equations related to the heliocentric position vector of the object $\mathbf{r}$. The acceleration of the vector $\ddot{\mathbf{r}}$ is equal to accelerations related to perturbations included in the dynamical model.

$$\ddot{\mathbf{r}} = \sum_k \boldsymbol{\mathfrak{a}_k} \tag{5}$$

4.1.1 Gravitational perturbations

Considering the gravitational perturbations of the Sun, the planets, Pluto,the Moon and biggest asteroids, then the acceleration $\boldsymbol{\mathfrak{a}_G}$ for gravitational perturbations are:

$$\boldsymbol{\mathfrak{a}_G} \quad = \quad -\frac{G(m_\odot + m)}{r^3}\mathbf{r} - G\sum_i m_i \left(\frac{\mathbf{r}-\mathbf{r_i}}{\Delta_i^3} + \frac{\mathbf{r_i}}{r_i^3}\right) \tag{6}$$

where m is the mass of the asteroid, $m_\odot$ is the Sun's mass, m_i is the mass of the body i, $\mathbf{r_i}$ is the heliocentric position of body i, r and r_i are the heliocentric distances of asteroid and body i, and $\Delta_i = |\mathbf{r} - \mathbf{r_i}|$

The heliocentric positions of perturbing bodies are given by planetary ephemerides INPOP13c (Fienga et al., 2014) for planets and by pre-computed Chebyshev polynomia for biggest asteroids.

Regarding to Fig. 3 that provides the distribution of the masses of the biggest Main-Belt asteroids used in INPOP13 ephemeris (Fienga et al., 2014), we have decided to take into account the four biggest asteroids in the perturbations: (1) Ceres, (4) Vesta, (2) Pallas, and (10) Hygiea.

4.1.2 Corrections of relativistic effects

The relativity can be taken into account by correction of relativistic effects. In that case, the acceleration associated to relativistic corrections $\boldsymbol{\mathfrak{a}_R}$ is:

$$\boldsymbol{\mathfrak{a}_R} \quad = \quad \frac{Gm_\odot}{c^2}\left[\left(2(\beta+\gamma)\frac{Gm_\odot}{r^4} - \gamma\frac{\mathbf{v}.\mathbf{v}}{r^3}\right)\mathbf{r} + 2(\gamma+1)\frac{\mathbf{r}.\mathbf{v}}{r^3}\mathbf{v}\right] \tag{7}$$

where $\mathbf{v}$ is the heliocentric velocity, β and γ are relativistic parameters assumed to be equal to 1.

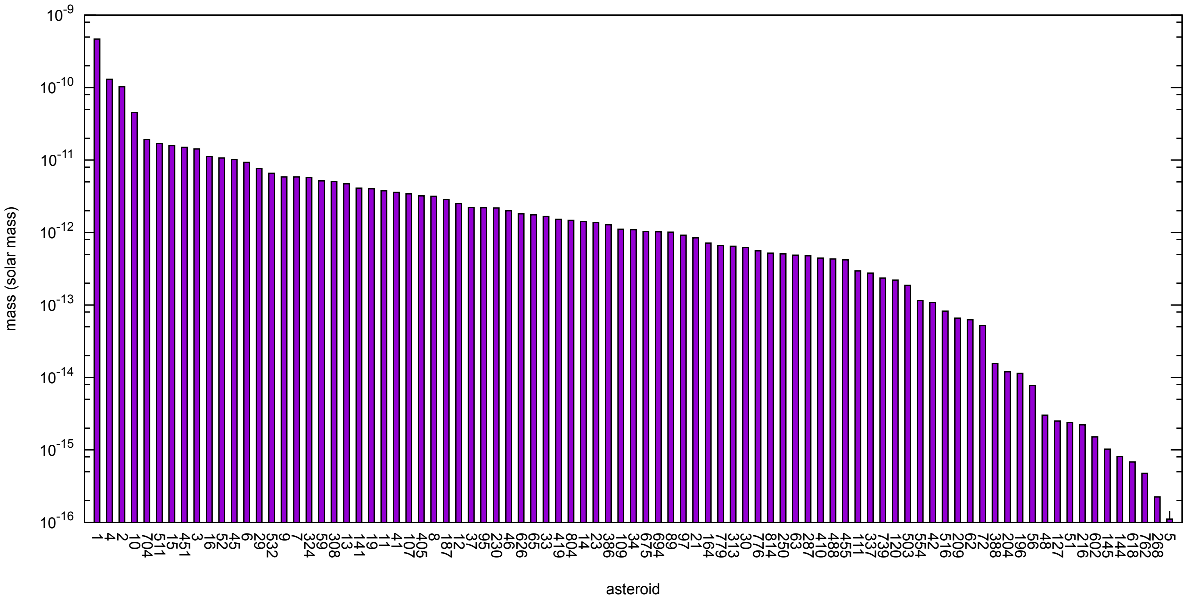

Figure 3: Distribution of the masses of the biggest asteroids

4.1.3 Flatness

The quadrupole moment J_2 can be taken into account according to equation 8:

$$\mathfrak{a}_{J_{2\odot}} = -\frac{3}{2} G m_\odot a_\odot^2 \frac{J_{2\odot}}{r^7} \left((2(\mathbf{K}.\mathbf{r})\, r^2 K_i + \left[r^2 - 5(\mathbf{K}.\mathbf{r})^2 \right] r_i \right) \tag{8}$$

with $a_\odot$ is the Sun radius, $\mathbf{K}$ is the unit vector associated to the direction of the north pole of the Sun. We have an equivalent relation for the flatness of the Earth.

4.2 Comparison of the perturbations

Depending on the type of asteroids (NEA, MBA or TNO), the perturbations that have to be taken into account could be different. Figures 4, 5,& 6 show the comparison in magnitude of the perturbations for specific asteroids over the period 2000-2020. For NEAs, perturbations due to relativity is generally greater than gravitational perturbations of Ceres. Moreover, perturbations of $J_{2_\odot}$ and $J_{2_\oplus}$ can be temporarily greater than perturbations of Ceres.

For TNOs, perturbations due to Earth flatness is negligible and perturbations of Ceres is much important than relativistic acceleration.

4.3 Equation of variation and numerical integration

In order to proceed to the fit of observations, we have also to determine the equations of variation that provide the partial derivative of the position and velocity related to the components (x_i) of the state vector.

As a general rule, if the equation of motion is:

$$\frac{d^2}{dt^2} r_i = a_i, \text{ with } i = 1, ..., 3 \tag{9}$$

then the associated equation of variation is:

$$\frac{d^2}{dt^2}\left(\frac{\partial r_i}{\partial x_j}\right) = \frac{\partial a_i}{\partial x_j} + \sum_{k=1}^{3}\left(\frac{\partial a_i}{\partial r_k}\frac{\partial r_k}{\partial x_j} + \frac{\partial a_i}{\partial \dot{r}_k}\frac{\partial \dot{r}_k}{\partial x_j}\right) \tag{10}$$

$\frac{\partial a_i}{\partial x_j}$, $\frac{\partial a_i}{\partial r_k}$ and $\frac{\partial a_i}{\partial \dot{r}_k}$ are developed analytically and equation 10 is an ordinary differential equation that can be solved by numerical integration.

The equations of motion and the equations of variation of the dynamical model are numerically integrated by a Gauss Radau method developed in Everhart (1985).

4.4 Fitting process

The heliocentric position and velocity $\mathbf{u}(t) = (\mathbf{r}(t), \mathbf{v}(t))$ of the asteroid at time t is a function of time and a state vector (position-velocity at time t_0).

$$\mathbf{u}(t) = \mathcal{F}(\mathbf{u}_0, t)$$

A variation $\Delta\mathbf{u}_0$ of the state vector implies a variation of the position-velocity of the asteroid.

$$\mathbf{u}(t) + \Delta\mathbf{u} = \mathcal{F}(\mathbf{u}_0 + \Delta\mathbf{u}_0, t)$$

We have the relation :

$$\begin{aligned} \Delta\mathbf{u} &= \mathcal{F}(\mathbf{u}_0 + \Delta\mathbf{u}_0, t) - \mathcal{F}(\mathbf{u}_0, t) \\ &\approx \frac{\partial \mathcal{F}(\mathbf{u}_0, t)}{\partial \mathbf{u}_0}\Delta\mathbf{u}_0 \end{aligned} \tag{11}$$

When the variations are small enough, the problem is linear and the last relation can be used.

With matrix notation, the relation (11) becomes:

$$Y = B.X$$

with :

$$\begin{aligned} Y &= \Delta\mathbf{u} = \begin{pmatrix} \Delta r_i \\ \Delta v_i \end{pmatrix} \\ B &= \frac{\partial \mathcal{F}(\mathbf{u}_0, t)}{\partial \mathbf{u}_0} \\ X &= \Delta\mathbf{u}_0 \end{aligned}$$

The fitting process consists in the determination of X while Y the difference between observed and computed poisition and B are known.

The least square method (Eichhorn, 1993) provides the solution that minimise $\|Y - BX\|^2$:

$$X = ({}^tBB)^{-1}{}^tBY \tag{12}$$

In practise, Y is the vector of the difference between observed and computed positions, X is the correction to applied to $\mathbf{u}_0, t)$.

The orbit determination follows the Levenberg-Marquardt algorithm with iterative corrections of the state vector:

- Partial derivatives B and computed positions are determined with preliminary state vector;
- Observed and computed positions are compared and give the Y vector;
- Least square method provides X the correction to applied to the state vector;
- The new state vector is computed : $\mathbf{u}_0 + X$;
- Process is iterated while the corrections to apply are small enough.

The covariance matrix of the system is then given by :

$$\Gamma_0 = ({}^tBB)^{-1}$$

4.4.1 Weighting scheme

The precision of measurements can be taken into account in the least square method by using a weighting matrix. Basically, the weighting matrix is a diagonal matrix where diagonal elements are $w_i = 1/\sigma^2$ with σ is the standard deviation (precision) of measurement i.

The solution of least square method is then given by :

$$X = ({}^tBWB)^{-1t}BWY \tag{13}$$

and the associated covariance matrix is :

$$\Gamma_0 = ({}^tBWB)^{-1}$$

The precision of measurements is hard to estimate. For radar measurements, the precision is given in the MPC database, but for optical measurements, there is no indication. A weighting scheme depending on the date of observation, the catalogue used for the reduction, and the observatory has been developed in previous studies (Carpino et al., 2003, Chesley et al., 2010, Farnocchia et al., 2015).

The weighting scheme adopted in DynAstVO follows Farnocchia et al. (2015). Table 20 presents the estimated precision in arcsec of an observation according to the observatory (IAU observatory code) and the catalogue used for the reduction (MPC flag of the catalogue).

4.4.2 Rejection criteria

To eliminate bad observations that could degrade the orbit determination, we apply a rejection criteria.

The rejection criteria takes into account the expected precision of the observations. For each observation, we compute :

$$\chi^2 = \frac{(\alpha_o - \alpha_c)^2 \cos^2 \delta_o}{\sigma_\alpha^2} + \frac{(\delta_o - \delta_c)^2}{\sigma_\delta^2} \tag{14}$$

and if χ^2 is greater than a fixed value, usually 9 corresponding to the classical 3-σ criteria, then the observation is rejected.

We use an equivalent formulation of χ^2 for ranging and doppler measurements.

When too many observations are rejected, for example more than 50% of the set, then the rejection criteria is increased by 2 (from 9 to 11) and again while less than 50% of observations are rejected.

Table 20: Weight used in DynAstVO (from Farnocchia et al. (2015)). obs is the observatory code, cat is the MPC flag for catalogue, rmsRA and rmsDE are the estimated standard deviation in arcsec associated to observatory and catalogue in right ascension and in declination

obs	cat	rmsRA	rmsDEC	obs	cat	rmsRA	rmsDEC	obs	cat	rmsRA	rmsDEC
ALL	c	0.51	0.40	699	c	0.47	0.39	691	o	0.25	0.28
ALL	d	0.51	0.40	699	d	0.47	0.39	691	s	0.25	0.28
ALL	e	0.33	0.30	691	c	0.32	0.34	689	g	0.26	0.32
ALL	q	0.33	0.30	691	d	0.32	0.34	645	e	0.15	0.15
ALL	r	0.33	0.30	608	c	0.63	0.77	F51	L	0.15	0.15
ALL	u	0.33	0.30	608	d	0.63	0.77	F51	t	0.15	0.15
ALL	t	0.25	0.25	703	C	0.62	0.57	F52	L	0.15	0.15
ALL	L	0.25	0.25	703	d	0.62	0.57	F52	t	0.15	0.15
ALL	o	0.50	0.41	644	c	0.24	0.28	F51	t	0.15	0.15
ALL	s	0.50	0.41	644	d	0.24	0.28	568	L	0.15	0.15
ALL	a	0.59	0.51	703	e	0.49	0.46	568	t	0.13	0.13
ALL	b	0.59	0.51	703	r	0.49	0.46	568	o	0.25	0.25
ALL	h	0.45	0.44	G96	e	0.25	0.21	568	s	0.25	0.25
ALL	i	0.45	0.44	G96	r	0.25	0.21	H01	L	0.15	0.15
ALL	j	0.45	0.44	E12	e	0.41	0.43	H01	t	0.15	0.15
ALL	z	0.45	0.44	E12	r	0.41	0.43	673	*	0.30	0.30
ALL	m	0.56	0.57	683	e	0.61	0.78	G45	*	0.50	0.50
ALL	w	0.44	0.36	683	r	0.61	0.78	250	*	1.30	1.30
ALL	f	0.73	0.64	699	o	0.42	0.41	249	*	60.00	60.00
ALL	g	0.73	0.64	699	s	0.42	0.41	C49	*	60.00	60.00
704	c	0.62	0.60	644	o	0.18	0.17	C50	*	60.00	60.00
								C51	*	1.00	1.00

4.5 Magnitude fitting

The magnitude of asteroids is provided by empirical formula (Simon et al., 1997):

$$m = 5\log(r\Delta) + H - 2.5\log\left((1-G)\Phi_1 + G\Phi_2\right)$$

with r the heliocentric distance of the asteroid, Δ is the geocentric distance of the asteroid, H is the absolute magnitude of the asteroid, G is the slope parameter and :

$$\Phi_i = \exp\left(-A_i \tan^{B_i}\left(\frac{\beta}{2}\right)\right) \text{ for } i = 1, 2$$
$$\text{with } A_1 = 3.33 \text{ , } A_2 = 1.87 \text{ , } B_1 = 0.63 \text{ and } B_2 = 1.22$$

H and G are the two parameters related to the magnitude and that can be fitted with comparison to apparent magnitude. H is the apparent magnitude of the asteroid if it is placed at 1 au of the Earth and the Sun and with a phase angle of 0. G represents the variation of the magnitude related to all other parameters.

The absolute magnitude H is fitted by comparison to apparent magnitude of the object. The G parameter remains unchanged and equal to the MPC value. Observations that have a O-C in magnitude greater than 1.0 are rejected, and no weighting scheme is applied for magnitude (*i.e.* all observations in magnitude have the same weight).

A three-parameter magnitude phase function has been developed by Muinonen et al. (2010) and adopted by IAU in 2012. The new formula should be implemented in the future in the DynAstVO database.

4.6 Sky-plane uncertainty

The Sky-Plane Uncertainty (SPU) is computed at the specific date t by propagation of the covariance matrix from epoch t_0 to the date t and by projection on the celestial sphere.

Numerically, the covariance matrix at date (t) is given by:

$$\Gamma_t = \left(\frac{\partial X}{\partial X_0}\right) \Gamma_0 \left(\frac{\partial X}{\partial X_0}\right)^T \tag{15}$$

where X is a vector of parameters, X_0 is the initial conditions such as $X_0 = X(t_0)$, Γ_0 is the covariance matrix at date t_0 and Γ_t is the covariance matrix at date t. The partial derivatives are computed like in the fitting process.

The covariance matrix at date t projected in the celestial sphere Γ_t^α is given by:

$$\Gamma_t^\alpha = \left(\frac{\partial \alpha}{\partial X}\right) \Gamma_t \left(\frac{\partial \alpha}{\partial X}\right)^T \tag{16}$$

where the partial derivatives are:

$$\frac{\partial \alpha}{\partial X} = \begin{pmatrix} \frac{-y}{\rho^2} & \frac{x}{\rho^2} & 0 \\ -\frac{xz}{\rho r^2} & -\frac{yz}{\rho r^2} & \frac{\rho}{r^2} \\ \frac{x}{r} & \frac{y}{r} & \frac{z}{r} \end{pmatrix} \tag{17}$$

with $\rho = \sqrt{x^2 + y^2}$ and $r = \sqrt{x^2 + y^2 + z^2}$. Finally, the diagonal elements of matrix Γ_t^α provides the variance of the position of the object on the celestial sphere $(\sigma_\alpha^2, \sigma_\delta^2, \sigma_r^2)$.

The SPU at date t is then computed by the equation:

$$\mathrm{SPU}(t) = \sqrt{\sigma_\alpha^2 \cos^2 \delta + \sigma_\delta^2} \tag{18}$$

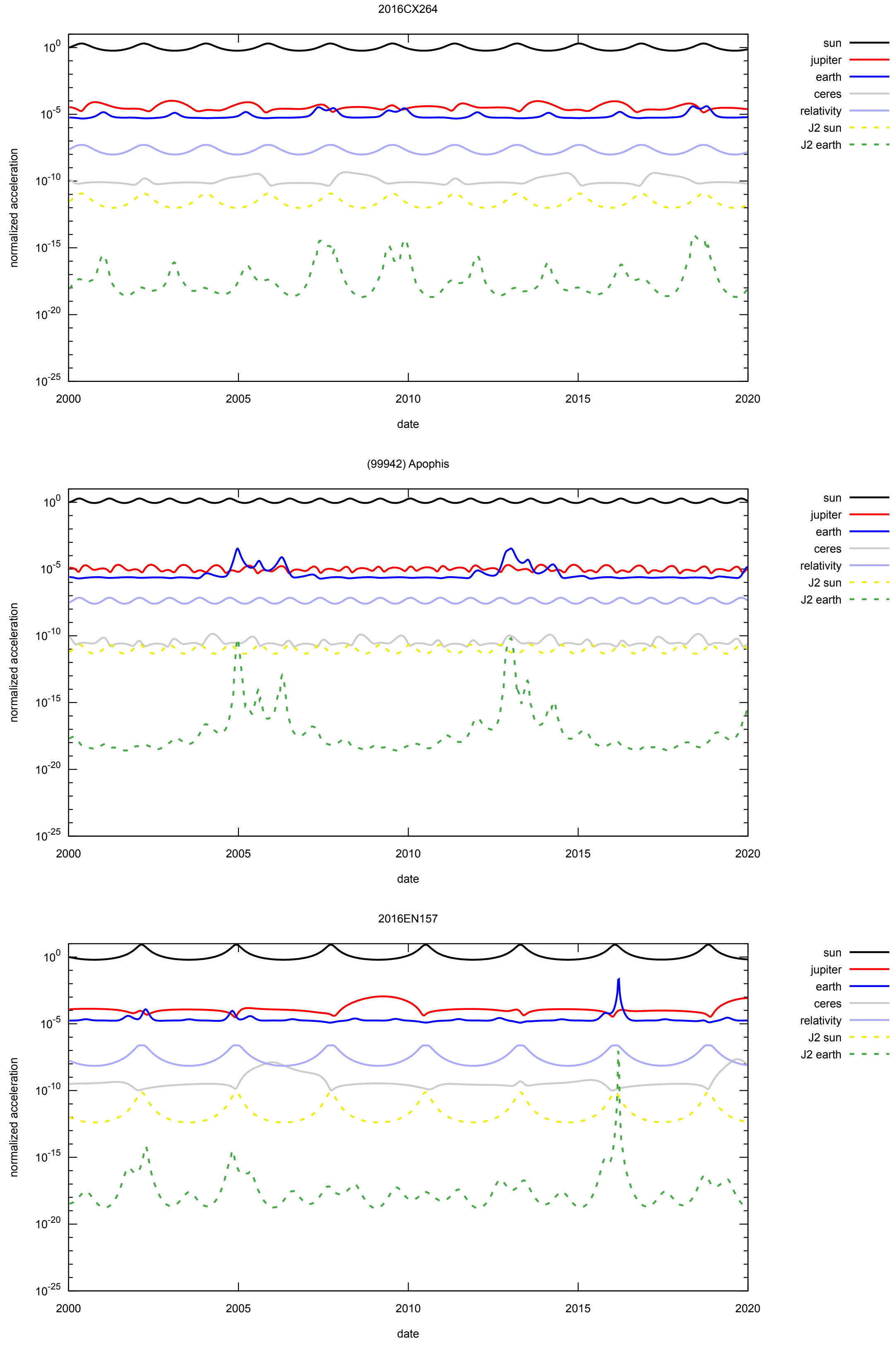

Figure 4: Comparison in magnitude of perturbations on NEAs 2016 CX124, (99942) Apophis, and 2016 EN157

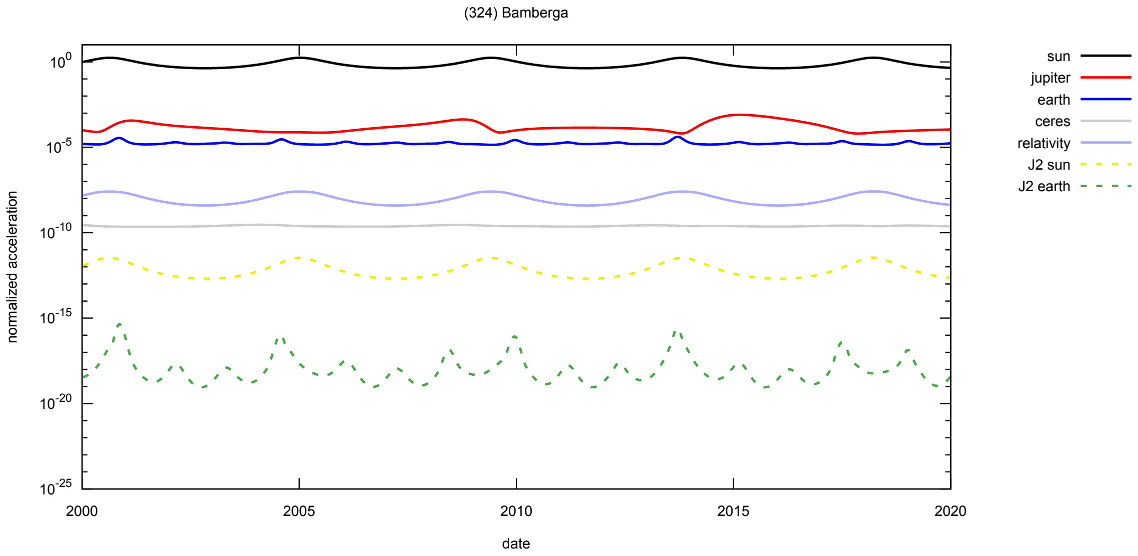

Figure 5: Comparison in magnitude of perturbations on MBA (324) Bamberga

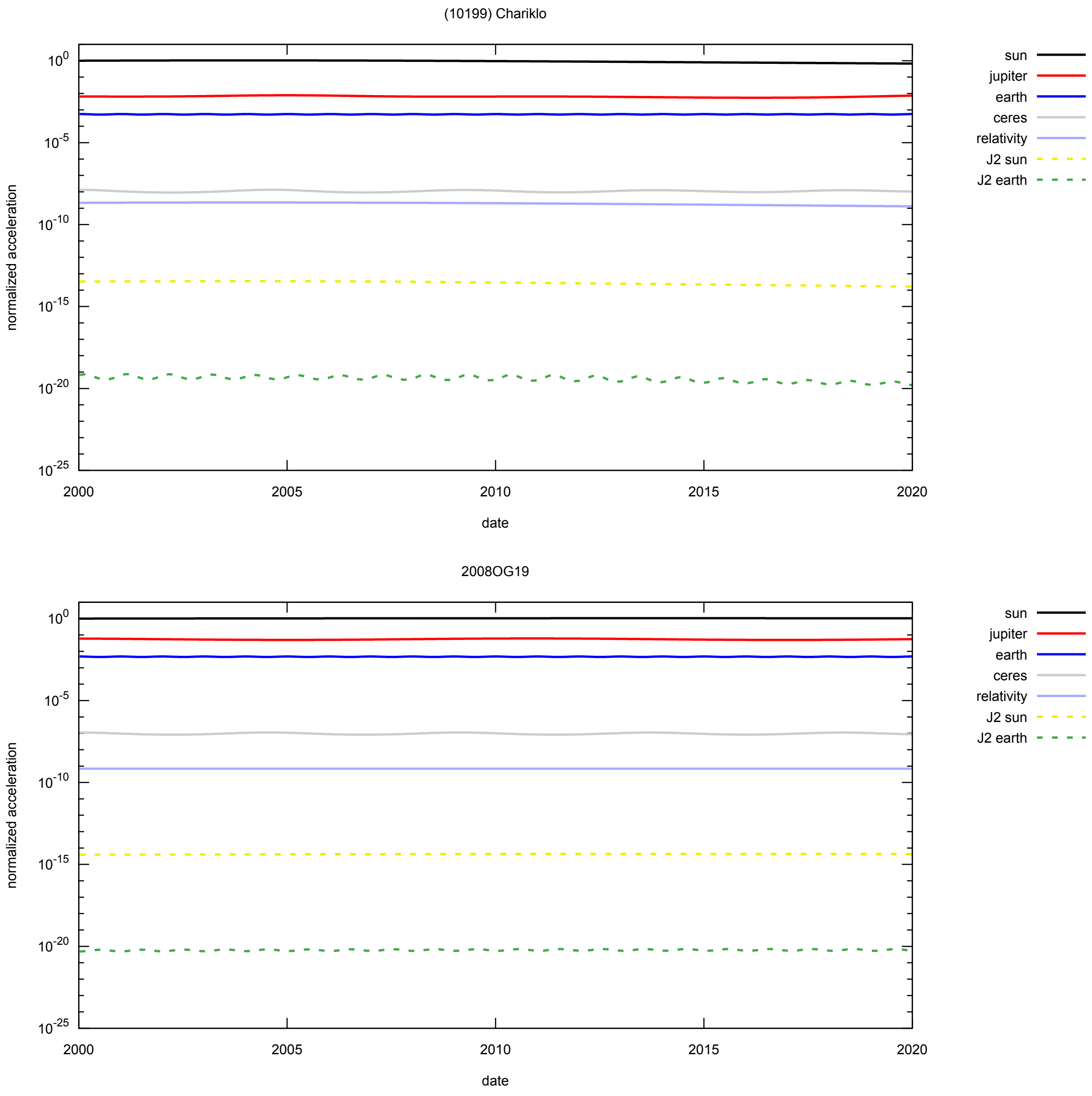

Figure 6: Comparison in magnitude of perturbations on Centaurs and TNOs (10199) Chariklo and 2008 OG19

Part IV

Additional databases

1 CLOSEAPP database

1.1 Parameters of CLOSEAPP

Table 21: Parameters for the Close-approaches with planets database

Number	Format	Parameter	Description	Unit
(1)	ISO8601-string	date	date (TDB) of close approach	
(2)	integer	number	asteroid number	
(3)	string	name	name (or designation) of asteroid	
(4)	string	planet	name of the planet	
(5)	float	$\text{dist}_{\mathrm{au}}$	minimum distance	au
(6)	float	$\text{dist}_{\mathrm{km}}$	minimum distance	km
(7)	float	$\text{dist}_{\mathrm{LD}}$	minimum distance	LD (lunar distance)
(8)	float	dateJD	Julian date (TDB) of close approach	
(9)	float	U_{RA}	uncertainty in right ascension at close approach	arcsec
(10)	float	U_{DEC}	uncertainty in declination at close approach	arcsec
(11)	float	SPU	Sky-Plane Uncertainty at close approach	arcsec
(12)	float	U_{tang}	tangential uncertainty in distance	km
(13)	float	U_{rad}	radial uncertainty in distance	km
(14)	float	v_{rel}	relative velocity	km/s

1.2 Description of parameters in CLOSEAPP databases

1.2.1 Minimum distance parameters

A minimum distance between an asteroid and a planet occures when the relative position vector and the relative velocity vector are orthogonal. The date and the minimum distance of close approaches are determined by bisection method in order to solve the equation:

$$\mathbf{x_P}.\mathbf{v_P} = 0 \tag{19}$$

where $\mathbf{x_P}$ and $\mathbf{v_P}$ are respectively the position and the velocity of the asteroid related to the planet.

If the minimum distance is smaller than a threshold depending on the planet (see Table 22) then the close approach is added to the database.

Finally, the database provide the date in TDB of the close approach, the asteroid and the planet (or moon), the minimum distance in au, km, and lunar distance (LD)[18], the relative velocity between asteroid

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[18] Lunar Distance is 384402 km.

Table 22: Threshold of detection of close approaches depending on the planet (or satellite).

Planet/satellite	**threshold** (au)
Mercury	0.1
Venus	0.2
Earth	0.5
Mars	0.2
Moon	0.1

and planet, and uncertainty parameters of the close approach described in the following section.

1.2.2 Uncertainty parameters

It is possible to determine the uncertainty of the close approaches by determining the Sky-Plane Uncertainty at the date of close approach. The SPU computation, described in Sect. 4.6, consists in the determination of variance in right ascension σ_α^2, in declination σ_δ^2, and in the geocentric distance at a specific date. Consequently, we determine these parameters at the date of minimum distance and define:

- $\mathsf{U}_{\mathrm{RA}} = \sigma_\alpha$
- $\mathsf{U}_{\mathrm{DEC}} = \sigma_\delta$
- $\mathsf{SPU} = \sqrt{\sigma_\alpha^2 \cos^2\delta + \sigma_\delta^2}$
- $\mathsf{U}_{\mathrm{tang}} = \mathsf{SPU} \times \mathsf{distance}$
- $\mathsf{U}_{\mathrm{rad}} = \sigma_r$.

Part V

Analysis and comparision with other databases

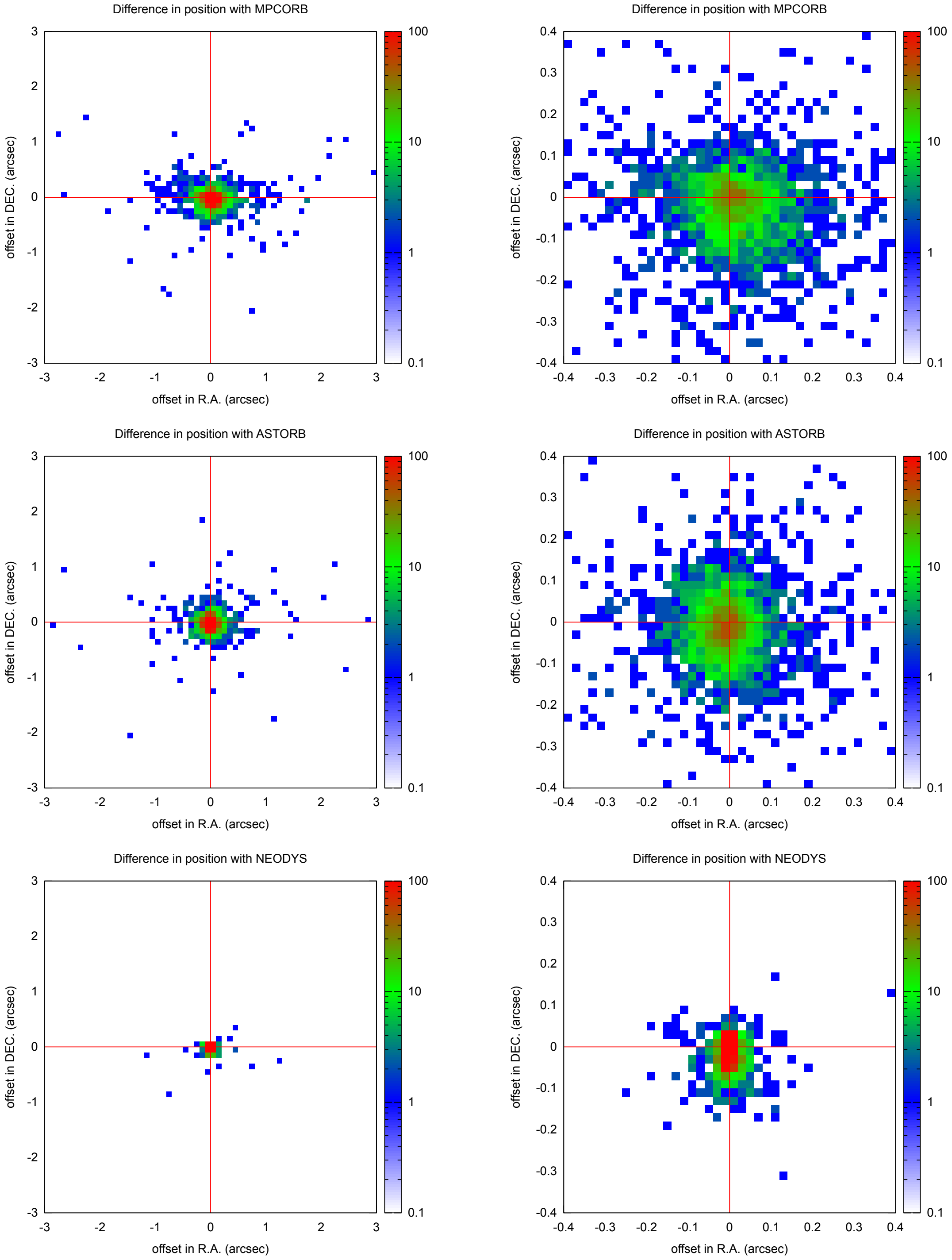

Figure 7: Difference in apparent position for 2238 numbered NEAs in right ascension and declination between several databases and DynAstVO

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