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The NSDB natural satellites astrometric database

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ABSTRACT

Context. Any study of the dynamics of the Natural Planetary satellites needs to gather as many astrometric observations as possible of those that have been observed for centuries. This kind of work is partially made by each astronomer starting this kind of study but has never been done for all the satellite systems.
Aims. The goal of our work is to build a database of all the available astrometric observations, together with all the information needed for efficient use of these data, and to avoid astronomers interested in the dynamics of Planetary satellites have to redo this data search.
Methods. To do this we had to find and carefully read all the publications including observational data, international journals, or internal reports to be able to add the observations in the database knowing the reference frame used by the observer, the corrections and reduction made, and the time scale needed to link all the data. We also had to contact observatories and observers to be sure to have the raw data available. We gathered the bibliographic references related to the observations put in the database.
Results. A new database containing about 90 percent of all the observations useful for studying the dynamics of the satellites is now available for the interested community of astronomers. NSDB is accessible on the Internet: `http://www.imcce.fr/nsdc` (IMCCE) and `http://lnfm1.sai.msu.ru/neb/nss/nssnsdcme.htm` (trilingual version of SAI).

Key words. astronomical data bases: miscellaneous – astrometry – planets and satellites: general

1. Introduction

Many institutes in the world are involved in dynamical studies of the natural satellites of planets. Researchers would like to use all the best astrometric data in their work. The fast motion of the satellite systems implies using large samples of astrometric observations, spread over a long period of time and well distributed along the orbits. Old observations have to be used most of the time and researchers would like to find all the data available for that purpose easily. Therefore, there is an urgent need to join all the available knowledge about dynamics and astrometry of the satellites of planets in the form of public databases that include the astrometric observations, physical and orbital parameters, and a full bibliography on the subject. Computer technology and the Internet network allow one to concentrate all these in a unified system of tools that is easily available for any user in the world. In the IMCCE (Paris) the natural satellites database (NSDB) has been developed under the auspices of the Interdivision (I and III) Working Group "Natural Planetary Satellites" of the IAU (International Astronomical Union).

This paper describes the features of this database and proposes projects for its future.

Similar private systems do partially exist in the world; however, some of them were developed in those institutions where new data are obtained but are not accessible. Two independent sources of data on the natural satellites of planets and of methods of studying their dynamics deserve special attention. The first one is the Institut de Mecanique Celeste et de Calcul des Ephemerides (IMCCE). New theories of the motion of planets and satellites have been developed in this French scientific center for more than two centuries; there astrometric observations were performed and also gathered from many collaborating observatories. The second source of data about dynamics of planets and satellites is the Jet Propulsion Laboratory (JPL) in the United States. This research institute is among the first where the data of observations are received from space telescopes and interplanetary missions. In JPL, high-precision numerical models have been developed on the basis of ground-based and space observations. Some other institutes worked on these topics and collaborate with those two institutes, but a public database available to every one would help. We describe in this paper the content of the proposed database and explain how our database was built and how it may help for dynamical studies of the natural planetary satellites.

2. Need for a natural satellite database

The necessity of creating a unified database of observations of natural satellites of planets is justified by many arguments. As is shown by the reality of research in this field, the results of all observations for each group of planetary satellites are used, as a rule, by individual researchers who carefully collect the data from all possible sources and create their own catalog of observations in order to determine satellite orbits (Arlot 1982; Pierce 1974, 1975; Strugnell & Taylor 1990). Creating such a database is a laborious process including the input of numbers from published sources, unification of the form of data presentation, and introduction of various non-standard reductions. In this case, the data collection is oriented toward refining the satellite orbits by the researcher. The introduced reductions often show a subjective character, and parameters are not furnished with descriptions. Such databases turn out to be inaccessible, and other researchers have to repeat the entire work again.

Before the arrival of powerful computers, using all the available data was a challenge. Some astronomers used to convert their observations into normal points by replacing several observations made during one night by only one datum. They also flet more confident when only using their own observations (certain of their quality) and adding a few other good observations to get a sample of data that provides a good fit of the constants of the motion.

After the use of computers, it appeared that it was possible to integrate a maximum of data in the fit of the theoretical models. Then, the databases used by researchers should have similar characteristics and it appeared that it whould be good to gather the observations as they were made, to avoid having to redo the work. During the first session of Commission 20 chaired by Edmondson, President, on August 24, 1973 in Sydney, Australia at the IAU General Assembly, the creation of a Working Group dedicated to the study of the orbits and ephemerides of satellites was proposed and adopted. The problems of the availability of the observations arose and in 1991, during the IAU General Assembly in Buenos Aires, Commission 20 recommended that its Working Group on Natural Satellites study the creation of an international center of astrometric data on the natural planetary satellites. Under the auspices of the IAU, this center would work to make these data widely available to researchers in this area of study. At that time, the electronic facilities were not sufficient to make all the data easily available, and the first connections were made through a Telnet connection. The database grew regularly and benefited from the Internet facilities. Of course, the interest in such a database was to make available most of the observations made, especially those never published and hidden in confidential notes or reports.

Thanks to the work of the Working Group, the database hosted on the servers of IMCCE in Paris became more and more exhaustive. The need for bibliographic connections to make all the information on the observations easily available arose and a new tool was built thanks to the help of the Sternberg Astronomical Institute in Moscow. The values of all useful constants and parameters were added to the database.

3. The different types of astrometric observations

The astrometric data are of several kinds. An astrometric observation is an observation that allows information to be obtained on the position of the observed object. As we will see, it is not only an angular measurement on the celestial sphere.

3.1. Angular measurements

Astrometric positions are defined as observed spherical coordinates of a satellite on the celestial sphere in a given reference frame linked to a reference system. This is not the place to explain the different reference systems and the correspondant reference frames in which the observed coordinates are measured. It is, however, necessary to call the attention of the users of the observed data to be careful with the different reference frames used by the observers. Observations made in different reference frames linked to different reference systems are not coherent and may not be used together to fit any dynamical model without a transformation. In the raw data, we provide observations as published by the authors. We have to deduce the reference frame and the corrections made from the publication. The definition of astrometric coordinates have changed in the past. The published observational coordinates are obtained after some reduction procedures. In the information pages, we try to provide some details on the reduction procedure used. For example, most the of time, regular astrometric positions of solar system bodies are deduced from the positions of reference stars. Uncertainties on the positions of these stars are included in the observed positions deduced from them. For the old star catalogs, some corrections of zonal errors are possible and old observations may be either corrected for these errors or re-reduced using new improved catalogs. The basic reference frame easily accessible to the observers is, most of time, the equator of the date, provided by the rotation of the Earth mainly when reference stars cannot be used.

We would also call the attention of users to the different kinds of coordinates. Unfortunately, errors have been made by some observers themselves when providing the type of their observed coordinates, but, when possible, corrections were made.

3.1.1. Absolute positions (RA and Dec)

a - Coordinates

Absolute positions are provided as right ascensions (RA) and declinations (Dec) in an equatorial frame, the center of which may be the site of observation (topocentric coordinates) or the center of the Earth (geocentric coordinates). Some observers forgotten to note whether the positions are geocentric or topocentric. Fortunately, the difference is greater than the accuracy of the observations and we may decide for the author of the publication about the type of coordinates. Such coordinates depend on the equator and the equinox that will define the reference frame.

b - Epoch: precession and nutation

A so-defined reference frame will be connected to an epoch: the date of the equator and of the equinox that are moving because of the motion of the Earth (precession and nutation). Some observations may have been referred to the equator and equinox of the date of observation or to the date of the beginning of the year. Regularly, the IAU recommends the use of the same reference system for the same date (1900, 1950, 2000). The IAU also recommends that the formulae be used to calculate the precession and nutation to transform observations to the same reference frame. Be careful when using old observations reduced with old precession formulae. The best choice is to go back to the raw observed data and to reduce them with the new formulae.

c - Reference frame

Most of the observations are reduced by the link method using some star catalog (FK4, FK5, HIPPARCOS). The satellite coordinates may then be transformed from the reference frame of the star catalog to the ICRF. It is very important to be aware of how the catalog was built and to what reference system it referred. Some old observations used very poor catalogs and the reduction may be improved with zonal corrections as stated above or through a new reduction using a new catalog. When available, the used catalog is indicated in the comments on the observations.

Some old observations were linked directly to the observed equator of date and are provided as apparent positions. The data are quite different from the link method. We do not know how the refraction was corrected (or not), and the same is true for the aberration. The papers containing the observations must be read carefully in order to get this information.

3.1.2. Relative positions

Relative positions mean that the position of one satellite is provided by referring to another satellite (most of time), to the planet, or to a nearby star. The origin of these coordinates may be defined in different ways. It is very important to know if these positions are differences between angles on the celestial sphere (differential coordinates) or if they are measures of the projection of the celestial sphere on the plane tangent to the celestial sphere (tangential coordinates, for photographic plates or CCD targets). Both measurements are in angles but are not the same. We know the theoretical relationship between them (gnomonic projection), but we do have to know which one was used.

a - Coordinates

The first way to measure relative position between two objects was to provide the separation or angular distance between the two objects (length of the arc joining the two objects) and the position angle (angle between the arc towards the north and the one towards the object, counted positively towards the east both arcs passing through the reference object). The second way to measure relative position is to use the tangential or differential coordinates, ΔX towards east and ΔY towards north. In both cases, the positions are referred to a given point on the celestial sphere.

Differential coordinates:

These observations are given as $\Delta\alpha = \alpha\text{-}\alpha_0$ $\Delta\delta = \delta - \delta_0$ where α, δ are RA and Dec of the satellite and α_0, δ_0 are RA and Dec of the reference absolute position.

Differential ΔX, ΔY: these observations are given as $\Delta X = \Delta\alpha \cos\delta_0$ $\Delta Y = \Delta\delta$. These ΔX and ΔY, measured on the celestial sphere, should not be confused with the tangential coordinates, measured in a plane tangent to the celestial sphere.

Tangential coordinates:

These coordinates are the projections of the positions of the objects on a plane tangent to the celestial sphere at the optical center on the image made by the telescope. If α and δ are the equatorial coordinates of a satellite and α_C, δ_C the equatorial coordinates of the point of tangence C, the tangential coordinates ΔX, ΔY are

$$\Delta X = \frac{\cos\delta \sin(\alpha - \alpha_C)}{\sin\delta \sin\delta_C + \cos\delta \cos\delta_C \cos(\alpha - \alpha_C)} \tag{1}$$

$$\Delta Y = \frac{\sin\delta \cos\delta_C - \cos\delta \sin\delta_C \cos(\alpha - \alpha_C)}{\sin\delta \sin\delta_C + \cos\delta \cos\delta_C \cos(\alpha - \alpha_C)} \tag{2}$$

The X-axis is taken tangent to the small circle $\delta = \delta_C$, positively towards the increasing right ascensions. The Y-axis is taken tangent to the hour circle $\alpha = \alpha_C$ positively towards the increasing declinations.

Since $\alpha - \alpha_C$ and $\delta - \delta_C$ are small, it is possible to develop in $\Delta\alpha = \alpha - \alpha_C$ and $\Delta\delta = \delta - \delta_C$. Then we have:

$\Delta X = \Delta\alpha \cos\delta_C - \Delta\alpha\, \Delta\delta \sin\delta_C + ...$

$\Delta Y = \Delta\delta + 1/2\, (\Delta\alpha)^2 \sin\delta_C \cos\delta_C + ...$

this shows the difference between differential and tangential coordinates.

Both ΔX and ΔY have no dimension and may be converted in image-unit using the focal length of the telescope. The transformation from ($\Delta\alpha$, $\Delta\delta$) to (ΔX, ΔY), named gnomonic projection, is bi-univocal.

The observations feeding the database found in past papers are often presented as differential coordinates and sometimes as tangential coordinates. But really, what are they? Most of time, the observer does not know where the optical center is and makes the measurements Δx and Δy in image units in a pseudo tangential plane, not in an angle on the tangential plane. When the transformation from (Δx, Δy) to (ΔX, ΔY) or to ($\Delta\alpha$, $\Delta\delta$) is made with the link method, the corrections are well made that allow coming back to the tangential reference frame or to differential coordinates through the use of reference stars. Unfortunately, some observers have confused tangential and differential coordinates neglecting the difference, even it may be large with short focus telescopes and large fields. Thanks to good ephemerides, we are able to know whether the published coordinates are differential or tangential. However, when no reference stars were available, the reduction was more difficult and we had to carefully read the publications to understand what type of coordinates published by the observer appears to be pseudo-tangential coordinates.

b - Reduction

The reduction of the observations to relative coordinates may be performed with several methods. In contrast to the reduction of absolute positions in right ascensions and declinations, which needs necessarily reference stars to determine the target's constants, the reduction in relative coordinates may be performed:

- without the target's constants (so without reference stars) if the orientation and the scale are well known (mainly for very small fields -less than a few minutes of degree-);
- with target's constants determined thanks to a nearby field rich in reference stars;
- as for regular absolute coordinates, but transformed into relative coordinates.

3.2. *Observations from space probes*

Many astrometric observations are provided by the space probes. They are provided either as RA and Dec centered on the space probe or as X, Y, Z coordinates, also centered on the space probe. It is very important to know the position of the space probe exactly to use these data of high accuracy.

3.3. *Observations of phenomena*

Some natural satellites of the planets present phenomena such as occultation or eclipse, which may be observed to determine their positions and photometric parameters. For example, the first dynamical models of the Galilean satellites were made exclusively with observations of eclipses by Jupiter. We see below the different types of phenomena for each family of satellites.

Phenomena were observed with an astrometric purpose a long time before the observation of direct astrometric positions. When the instruments did not make precise measurements, the observation of a phenomenon provided astrometric information; for example, when a satellite passes in front of another satellite (an occultation), it is possible to say that the satellites have the same positions within an error not greater than the size of the satellite! In fact, interpreting the observation is more complex when searching for a higher precision, but the observation of phenomena was performed as soon as the satellites of Jupiter were discovered by Galileo and are still being observed.

3.3.1. The satellite-planet phenomena

When the Sun passes through the orbital plane of a satellite, the shadow of the planet may eclipse the satellite and the shadow of the satellite may pass over the disk of the planet. These events, called eclipse of the satellite and transit of the shadow, are observable but do not depend on the observer's position.

When the Earth passes through the orbital plane of the satellites, a terrestrial observer may see the satellite being occulted by the planet or the satellite transiting on the disk of the planet. These events are called occultation of the satellite and transit of the satellite and depend on the observer's position.

These events are well known for the Galilean satellites of Jupiter and have been observed since their discovery. Only the eclipses and the occultations have been used for astrometric purposes. Because these occultations are difficult to observe, the eclipses are the most numerous observations of the Galilean satellites since their discovery. These events also occur for other planets for the satellites close enough to their primary to be hidden by the shadow cone. If they are far from the planet, only the penumbral cone reaches the satellite and makes the event unobservable.

These events occur near the equinox on the planet, since the orbital plane of the satellite and the equatorial plane of the planet are very close to each other for the main satellites of the giant planets. It corresponds to the transit of the Sun in this plane. The Earth also transits in this plane near the transit of the Sun since Earth and Sun are close together in the sky of the giant planets.

For the planet Jupiter, these events are always observable thanks to the large size of Jupiter. Only Callisto does not present events when the Earth and the Sun are too high above its orbital plane (far from the equinox, occurring every 6 years).

For the planet Saturn, these events occur for satellites S-1 to S-7 only one year before and one year after the equinox, which occurs every 15 years, in 1980, 1995, 2009, ... Contrary to Jupiter'events, these events are not easy to observe because they occur close to the planet, where the bright ring makes the observations difficult.

For the planet Uranus, these events occur during several months every 42 years at the equinox, in 1965, 2007, and so on. For the planet Neptune, eclipses of Triton occur during several months every 82 years, in 1964, 2046, and so on. For Pluto, eclipses and occultations of Charon occur during several months every 124 years, in 1980, and so on. For Uranus and Neptune, the observations are difficult because the proximity of the satellite and the bright planet. The similar size of Pluto and its satellite Charon made the observation of these phenomena easy. The only problem is that they are very rare.

The observation

An observation of an eclipse is a photometric observation providing a light curve (magnitude of the satellite depending on time) or an evaluation of the instant of disappearance or reappearance of the satellite (deduced from the light curve or from a visual observation). The time of the event published in the files of data are commonly the time of the mid-extinction or mid-reappearance of the satellite (half flux of the satellite visible) unless there is another specification in the comments.

An observation of an occultation is the evaluation of the time of the contact between the disk of the satellite and the disk of the planet. These observations were only made visually.

3.3.2. The satellite-satellite mutual events

Occultations and eclipses are also possible in the configuration satellite-satellite when two satellites are orbiting on almost the same plane (which is currently the equatorial plane of the planet). One should understand that these events are much rarer than the events implying the planet since the satellites project behind them is a smaller shadow cone. However, such events occur between the satellites orbiting in the same plane (J-1 to J-4, S-1 to S-7, U-1 to U-5) during several months on the same dates as the events implying the planet.

The mutual events are of several types: occultation or eclipse, total, partial, or annular. The light curve, which may differ for these different events, will be inversed in order to deduce the astrometric parameters providing the relative positions of the two involved satellites.

The observation

An observation of a mutual event is a photometric observation of the variation in the light flux received from the satellites. This observation is much more accurate than the observation of an eclipse by the planet because most of the satellites have no atmosphere disturbing the light curve because of the light refraction. The observational data consist in the entire light curve that may be reduced for any photometric or astrometric purpose. For old observations, the basic published data deduced are the time of the minimum of the light curve and the magnitude drop. These data are not sufficient for astrometric purposes, and the observers must be aware that they must publish the entire light curves. If a satellite mutual occultation is observed, the light fluxes of the occulting and occulted satellites must be measured separately before and after the event and provided with the combined light flux of both satellites measured during the mutual occultation. This can be done a few time before and a few time after the event, when the light coming from each satellite may be measured separately. For eclipses, observers must indicate whether the measured flux concerns only the eclipsed satellite or both satellites. As for the occultations, their fluxes must be measured separately before and after the event.

This type of observation is one of the most precise, especially when considering the distribution of albedo and the influence of the phase angle on the apparent brightness of the satellites. New reductions of the data provided by the database may help to reach better accuracy as new data on the albedoes are available.

3.3.3. The occultation of a star by a satellite

It appears from time to time that a satellite will occult a bright star allowing an eventual atmosphere on the satellite to be detected and its diameter to be measured. This type of observation may be of high astrometric interest, providing a point for an absolute observation of the satellites through the RA and Dec position of the star. Since bright stars most of the time have good astrometric positions, it may provide the same data for the satellite.

3.4. The time scale for dating the observations

The time scale associated to the observations is essential for using the data. The same time scale for all the observations of the database is absolutely necessary for dynamical analysis to link all the observations together. One will recall that dynamical studies need to be made in the TT (terrestrial time), which is the extension of the former ET (ephemeris time), supposed to be uniform, which UTC is not. Unfortunately, the astrometric observations are never provided in TT so that one is aware of two items:

- the relationship between the time scale used by the observer and TT;

- the accuracy of the measurement of the timings of the observations by the observer to the time scale used.

The first one should be documented by the observer. Most of the observers, at the present time, use UTC (universal time coordinated) provided through GPS and phone and broadcasted worldwide. However, for some raw data, local national time may have been used. In that case, most of time, the difference to UTC is a round number of hours and the correction is easy to make. For old observations, the time scale provided may be a local mean time or true solar time (and sometimes a sidereal time). Then, it is necessary to know the longitude of the observational site exactly to go back to the universal time. The relationship between UTC and TT is provided by IERS.

The second item concerns the accuracy of the timing. Unfortunately, most of the observers do not provide this information. An error of one second of time corresponds, for a satellite moving at 10 km s^{-1}, to 10 km. From years, the accuracy of the timing to 0.1 s of time is easy to obtain and is sufficient for most uses of the data. The date of an astrometric observation is calculated as the mean time of the exposure: the accuracy of the determination of the beginning and the end of the exposure determines the accuracy of the observation. The quality of the sky is very important and must be communicated by the observers. Be aware that, for long exposures, the changing absorption due to fog or light clouds will move the date of the observation towards the period of clear sky.

4. Precision and accuracy of the astrometric observations – selecting the data

When gathering data to feed the database, we have to eliminate the useless observations and evaluate the precision and the accuracy of the observations.

4.1. The precision

The precision of the observations depends on the care taken by the observer when observing and on the instrument and receptor used. In the database, we provide the nature of the instrument used and the receptor. CCD provides data that is different from visual observations even if it may be right ascension and declination in both cases.

Observations of angular positions have been made.

- Visually using a micrometer or an heliometer, it has been proved that carefully made heliometer observations have a high level of precision.
- Photographic plates offer a very dependable type of receptor. Using a poor star catalog may lead to inaccuracy. For old observations, relative astrometry in the reference frame of the date is much more dependable and useful for satellite systems. The reference frame of the date was easily found by the trail of a star obtained by stopping the telescope. Studies have also shown that long-focus astrometry provides more precise results than short-focus observations.
- CCD frames in CCD observations shorten the exposure time and catch very faint objects. The field covered is smaller than with photographic plates, but this is no longer a problem. Either the observations are made relative, or a new dense star catalog is used.
- Automatic transit circle observations provide absolute RA and Dec equatorial coordinates with a high level of precision since star catalog links the observations of the transit circle night after night.

The precision of the measurement depends on the magnitude of the objects. The images should have a Gaussian profile and a FWHM (full width at half maximum) greater than 2.5 pixels. For very faint objects, this may not be true and the precision may decrease until reaching the pixel size for CCD observations. In contrast, the exposure time for very bright objects may be too short to get a Gaussian profile because of the atmosphere, by needing to integrate the light flux for at least ten seconds of time.

Observation of phenomena were made with very numerous receptors to record the light curve of the flux during events:

- visually by observers who usually observe variable stars. The precision is poor because the events are faster than they can be observed.
- using a photoelectric photometer. These receptors were very numerous and each one has to be described in the database to know how dependable the observation is.
- using photographic films or plates. The photometric precision of such receptors may not be very dependable except when the reciprocity light curve (correspondence between flux and photographic density) has been recorded. The interest of this technique (applied to long phenomena only) is to be two-dimensional allowing a recording of the reference photometric object at the same time as the involved satellite.
- CCD targets. Now used worldwide, these receptors are two-dimensional and the photometric reduction is easy to perform. The precision is very good.

The time scale

We must know how the time of the events has been recorded and must refer to a known time scale such as UTC (cf. 3.4 above). The precision of the timing of the observation is a large part of the precision of the observation itself. The new techniques allow dating of observations within a few milliseconds of time. It was not the case in the past where one tenth of a second of time was the best possible way to use human reflexes.

4.2. The accuracy of the observations

It is much more difficult to evaluate the true accuracy of the observations. Many biases may degrade the precision in spite of the care by the observer. The fautly adjustments of the telescope or of the receptor or an incorrect time scale may provide biases difficult to correct afterwards. Therefore, we calculated O-C's for all the observations in order to find meaningless observations. Looking again at the publication, we were able to solve some problems. The time was moved an entire hour from UTC or the number of the satellite was wrong. Similarly, topocentric and geocentric positions were confused and the O-C's show it clearly. For old observations, the time scale was needed to know the longitude of the observer who forgot to indicate from where he was observing. Most of the time, it was provided in a former publication of observations, even of objects other that natural satellites. However, it was not possible to correct all the biases.

5. The search for observational astrometric data

First of all, the main sources of observations are the publications in international or national journals or in internal notes or reports. Nowadays, some of these are printed publications and some are electronic publications. Most of the data included in the papers are now put at the CDS, but unfortunately, this is not always the case, and some files must be obtained directly from observers. Some data are difficult to access, such as in scientific papers deposited in All-Russian Institute of Scientific and

Technical Information. Data are also taken regularly in electronic form from the Minor Planet Electronic Circulars (MPEC). Some observations are received as mails from the Minor Planet Center (MPC) or from individual observers.

Most old data had been printed in journals and our problem was to find those journals that may only be available in archiving libraries such as the Library of Congress in the USA or the Bibliotheque Nationale in France.

Along with the data, it is necessary to get all the needed information on the reference frames used, the corrections made, and the relationship between the time scale used for the timing of the observations and UTC.

6. Content of the natural satellite database

The formats of data were chosen so that all numerical values would be transferred from the publication or another source into the database without any changes. No reduction was made in published results, so that they would not become dependent on the current status of the models of celestial coordinates and time scales. On the other hand, the user of the database should be clearly informed about the standards used by observers when they published their results. Such an approach has led to each set of observational data for planetary satellites to be placed into the database consisting of a pair of text files, the first of which (Content) includes the description of observations (satellite list, adopted coordinate system and time scale, the title and code of observatory, names of observers, parameters of telescopes, data format, etc.), while the second file (Data) contains immediate numerical values of observational results and is intended to be read by computing programs. Separation of the data in sets is determined merely by the source of data and by the order of their entry into the database.

These raw data are available for the following systems (note that a system is in fact a set of different satellites often observed together, the motions of which are dependent):

- 2 satellites of Mars;
- 4 Galilean satellites of Jupiter;
- 4 inner satellites of Jupiter;
- 54 outer irregular satellites of Jupiter;
- 8 main satellites of Saturn;
- 14 inner satellites of Saturn;
- 38 outer irregular satellites of Saturn;
- 5 main satellites of Uranus;
- 13 inner satellites of Uranus;
- 9 outer irregular satellites of Uranus;
- 2 main satellites of Neptune;
- 6 inner satellites of Neptune;
- 5 outer irregular satellites of Neptune;
- 3 satellites of Pluto.

The observations of phenomena are only available for the Galilean satellites and for the main satellites of Saturn. For the phenomena, we provide, when available, the lightcurve as photometric points (a drawing in jpeg or png format is also proposed), the observational parameters such as the time of the minimum of flux for the mutual events with the magnitude drop, and the time of the half-flux drop for the eclipses by the planet. For some events, astrometric positions are derived from photometric observations and a file of positions is provided. Table 1 provides the number of data for each system present in the database.

To these raw data, it is interesting to add files of the same observations but presented in a standard format that is easier to use.

Table 1. Number of observed positions in the database

Satellites	Period of time	Number of data
M-1 M-2	1877-2005	3438
J-1	1891-2007	3307
J-2	1891-2007	2758
J-3	1891-2007	3086
J-4	1891-2007	3104
all J-1-2-3-4	1891-2007	12 255
J-5	1954-2001	677
J-14	1981-2001	521
J-15	1988	48
J-16	1988-2000	178
all J-5-14-15-16	1954-2001	1424
J-6 J-7 J-8 J-9 J-10 J-11	1894-2008	4598
J-12, J-13	1951-2008	294
J-17 to J-49 and unnumbered	1975-2006	975
all J-6-7-8-9-10-11-12-13-17	1894-2008	3020
S-1	1874-2003	1820
S-2	1874-2007	5786
S-3	1874-2007	9671
S-4	1874-2007	9017
S-5	1874-2007	8072
S-6	1874-2007	7994
S-7	1874-2007	4321
S-8	1874-2007	6833
all S-1-2-3-4-5-6-7-8	1891-2007	57 355
S-10, S-11	1966-2000	188
S-12	1980-1996	286
S-13, S-14	1981-1996	90
S-16, S-17	1994-2002	410
all S-12-13-14-16-17	1966-2002	974
S-9	1904-2008	1520
from S-18 to S-52 and unnumbered	2000-2008	939
all S-9-18-...	1904-2006	2459
U-1	1983-2006	1495
U-2	1983-2006	1529
U-3	1983-2006	1385
U-4	1983-2006	1605
U-5	1983-2006	1430
all U-1-2-3-4-5	1983-2006	7441
U-6 to U-15	1994-2004	65
U-16 to U-20	1984-2006	479
N-1	1877-2006	3095
N-2	1949-2008	667
N-1 N-2	1877-2008	3762
N-3 to N-8	1991-2002	149
N-9 to N-13	1999-2004	170
P-1	1992-2006	78
P-2, P-3	2002-2006	35
all P-1-2-3	1992-2006	113

Table 2. Number of observed phenomena.

Events	Period of time	Number of observations
Galilean satellites		
eclipses	1652–1983	16 802
occultations	1836–1972	4411
mutual events	1985	167
	1991	375
	1997	282
	2003	377
Saturnian satellites		
mutual events	1995	66
grand total	1652-2003	18 480

This work has been done for the Saturnian satellites (Desmars et al. 2008) and is under construction for the other ones.

Such a database has been created by authors in IMCCE in collaboration with SAI with the help of the members of the IAU working group on Natural Planetary Satellites. It is systematically increased by newly published data, as well as by old observations found in rare sources.

At the present time our database includes more than 90% of all observations of natural satellites of planets available in the world.

7. Bibliographic database

The search for publications on a narrow problem under investigation is one of the steps of any research study. Special printed editions and electronic means on bibliography are used for this purpose. With so many publications available, working with bibliographic references is a laborious process. The electronic ADS Abstract Service accessible on the Internet as `http://adsabs.harvard.edu` is an example of quite powerful bibliographic means of. This bibliographic database includes everything that has been published in the field of astronomy all over the world. The completeness of the bibliography and a convenient interface for users made this service very popular in the global community of astronomers. However, it is just this excessive universality that makes it quite difficult to search for required data in this database. This drawback is clearly seen especially when one searches for publications on a preset group of objects and methods of research. Upon specifying key words or context in the paper title, the search engenders a tremendous list through which one has to browse for a very long time. This circumstance has even compelled the developers of the ADS Abstract Service to stop using the system of key words altogether. However, the optimal choice of the area of scientific exploration and creation of a well thought-out system of key words could substantially simplify the search for publications.

In 1996, a decision was made in IMCCE to create a bibliographic database for studies of natural planetary satellites. For this scientific field, a special system of keywords was developed. Since that time, the bibliography has been constantly enriched as a result of cooperation between IMCCE and the Sternberg Astronomical Institute (SAI). By now more than 4000 references on theories of motion, astrometry, and observations and more than 8000 references to the physics of planetary satellites have been collected.

To provide easy access to the bibliographic database through the Internet, a special program has been elaborated in the SAI. Formulation of inquiry is made by using a large number of options. Due to the user-friendly interface of the program, the user gets needed information rapidly. Output of unnecessary references is minimized.

The main source of the bibliographic database is the ADS Abstract Service. References from this database were transformed to change their display. In addition, old keywords assigned by the ADS Abstract Service were completely excluded and, according to the new system, new keywords were assigned. When choosing the keywords, information is used from the titles, abstracts, and contents of publications. We also added considerable bibliography of scientific papers published in less accessible journals such as scientific papers deposited in all-Russian Institute of Scientific and Technical information and others.

The new keywords are not numerous: the goal is to rapidly reach papers dedicated either to a general subject such as observations, theoretical studies, ephemerides, or to a specific object. Each paper is associated to keywords related to the results of the paper. The keywords are not those chosen by the authors but chosen among the keywords available in our database.

A question was raised concerning the papers on physics of the satellites. Do they contain information useful for dynamical studies or astrometric observations? The answer is yes since we need more and more accurate astrometric data, that is to say, more and more accurate physical parameters to perform an accurate astrometric reduction.

Our database of observations also has the following specific feature. The description of observations always includes bibliographic data of a source from which the observational data were taken. In this case, the title of the publication is a "hot" word on the page, and with it one can go to the given reference in our bibliographic database. Further on, one can gain access to this reference in the ADS Abstract Service, and, finally, to the electronic copy of the publication itself.

The system of formulating an inquiry in the bibliographic database is simple and quite flexible. A search is made either by keywords or according to the context in the names of authors, paper title, or its abstract. One can limit the search within a range of publication dates. A provision is made for the possibility of logical combinations of context fragments.

With the output of the results of a bibliographic inquiry, the bibliographic codes of references are served out. The bibliographic code on a page is a "hot" word that sends off to the corresponding reference in the ADS Abstract Service, if there is any. Thus, a reference of interest can be promptly seen in this database.

8. General data and parameters on satellites

For all research on the dynamics of the natural planetary satellites, it is necessary to have a system – complete, well organized, and easily accessible by any user – which includes numerous parameters describing physical properties and the motions of planets and satellites. Of particular importance is to have the newest data close at hand. We provide such data as:

- the masses of the satellites: data issued from the last publications with a link to the publication;
- the sizes of the satellites, radii or tri-axial figures: all the different determinations with link to the papers;
- the photometric parameters allowing the position of the center of mass to be modeled when observing the center of the figure or photocenter. For reducting the observation of phenomena, these parameters are very necessary;
- the rotational parameters and poles: a link to USGS giving the rotational and pole parameters as decided by the IAU/IAG working group on cartographic coordinates and rotational elements;
- the mean orbital and physical parameters such as semi-major axis, eccentricity, inclination, orbital period, magnitude, maximum elongation to the planet;
- the orbital osculating elements: these elements change with time and are available through the ephememerides server MULTI-SAT for each satellite (Emel'yanov & Arlot 2008).

8.1. Other resources useful for natural satellite studies

We created an ephemerides web server of the natural planetary satellites ("MULTI-SAT ephemerides") which may be helpful for analyzing observational data as explained in Emel'yanov & Arlot (2008).

Numerous information in the field of celestial mechanics, astronomy, physics of celestial bodies, and astrometric observations have been created in the world and are accessible through the Internet. Some are similar or complementary to what is developed in this paper and links are proposed to these sites on a specific page of the NSDB website.

9. Future and projects for the NSDB database

Some services of the database are still under construction or in project as listed below:

- All the data are raw data as published by the observers. However, users of these data will have to convert all these observations in the same format, even if not into the same reference frame. We started to put the observations in a single file per object or group of objects observed simultaneouly (four galileans, eight main saturnians, or five main uranians) as done previously by several authors (Strugnell & Taylor 1990; Desmars et al. 2008). Discussions will be continued in the working group on Natural Planetary Satellites for determining a standard format.
- The asteroids now have satellites. In a first step, the observations were rare and had a poor astrometric accuracy. However, the observations become more numerous and more accurate, so we intend to include the data concerning the satellites of asteroids.
- Physical parameters are provided. Do we propose the albedos in the future? To determine the center of mass through the observed photocenter, we need to know more about the albedos. We may need maps of albedoes in several wavelengths. Improvement of the astrometric accuracy should be kept in mind for the future.
- To improve astrometric data, new reductions of old observations may be possible using new star catalogs. For that, the images (CCD or photographic plates) should be available. We propose a tool for identifying the location of these observational archives.
- We also intend to integrate our database in the Virtual Observatory Network (VO), which will help in managing the database: the access to specific observational sites, observation types, observational periods should be easier.

10. Conclusion

Finally, we ask the observers to send their observations to the NSDB database: it will help the community of the astronomers. We may publish some data, comments, and explanations in specific reports. Therefore, as a result of the work described above, a new system of data for natural satellites of planets has been created and is offered to users. The system includes the database of observations, bibliographic database, and the information system on physical, orbital, and rotational parameters of planets and satellites.

One of the interests of the database is also to know what observations are availabe and to encourage new observations when needed.

Access to the elaborated database of natural satellites is organized on the webpages of NSDB that is available on the Internet. The sites URL are `http://www.imcce.fr/nsdc` (IMCCE) and `http://lnfm1.sai.msu.ru/neb/nss/nssnsdcme.htm` (SAI).

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