Journal of Astronomical History and Heritage, 28(1), 187–211 (2025).

THE *CONNAISSANCE DES TEMPS*: A FRENCH ASTRONOMICAL EPHEMERIS PUBLISHED SINCE 1679

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Abstract: In this paper we will follow the evolution and progress of French ephemerides from the first publication in 1679 of the yearly handbook, the *Connaissance des temps* (CDT), through to the present day.

The CDT was created to provide ephemerides for users but it also became a scientific journal that explained how the ephemerides could improve their accuracy. To show this, we will track the evolution from kinematics to dynamics for modeling the motion of the main Solar System objects. We also will discuss the long-standing longitude problem, the improvement of the ephemerides, and the impact of the French Revolution on the content of the CDT.

Keywords: France; *Connaissance des temps*; ephemerides; almanacs; longitude.

1 INTRODUCTION

The *Connaissance des temps* (CDT, Figure 1) is known nowadays to be the yearly publication of the French astronomical ephemerides. It is also the oldest publication of ephemerides (positions of Solar System bodies) that exists and has been published without interruption since 1679. Very few studies have been made of the evolution of French ephemerides and their accuracy. Boistel (2022) published a very complete and detailed history of the CDT from its founding up to 1920, focusing on its publication. Seidelmann (2019) discussed the place of the CDT among Western astronomical almanacs. In this paper, we will follow the evolution of the sources and the accuracy of the CDT.

Making a new map of France and improving the ways in which to measure longitude were the first goals assigned to the astronomers when Paris Observatory was founded in 1667. Following these goals, a new publication of ephemerides, the *Connaissance des temps* was created. The CDT published yearly tables, tools and processes to determine the longitudes on Earth and at sea, dates of predicted astronomical phenomena and the positions of the main celestial moving bodies together with scientific papers, observations and topographic surveys. The CDT soon became an essential tool for navigation for centuries.

We may wonder whether the CDT was written for astronomers or sailors. In fact, the Navy found the CDT was too difficult, so in 1889 it succeeded in launching a special almanac, the *Ephémérides Nautiques* (cf. Section 9.4).

The purpose of the present paper is to analyze the evolution and the improvement of the ephemerides of the main objects of the Solar System from 1679 until the present time and to show how the CDT is a reflection of its time, with society and science always linked.

This paper contains eleven Sections. The first Section, numbered 2, is devoted to the creation of the CDT in 1679 and its history, and presents the content of this astronomical handbook. Sections 3 to 6 show the evolution of the ephemerides from the creation of the CDT until 1979 for the main observed celestial bodies. Those celestial bodies are divided into four categories in accordance with the different dynamical problems of their motion, as explained in the corresponding sections: Sun and planets (Section 3), the Moon (Section 4) and the satellites of Jupiter (Section 5), and the minor planets (Section 6). Section 7 describes the ephemerides of the Sun, the Moon, the planets and the Galilean satellites in the CDT after the important transformations made to the CDT starting in 1980 due to the arrival of computers. Section 8 presents the evolution of the time-scale, which was closely linked to the ephemerides in the CDT. Section 9 is related to the longitude problem in navigation and cartography. Section 10 concerns the influence of the French Revolution on the CDT. Finally, Section 11 shows the co-operation with other ephemerides bureaus.

2 HISTORY OF THE CDT: A NOVELTY IN 1679

In France, until 1680 the ephemerides published by Johann Hecker (1625–1675) were the standard reference. They were the heirs of Kepler's ephemerides and were published in Danzig.

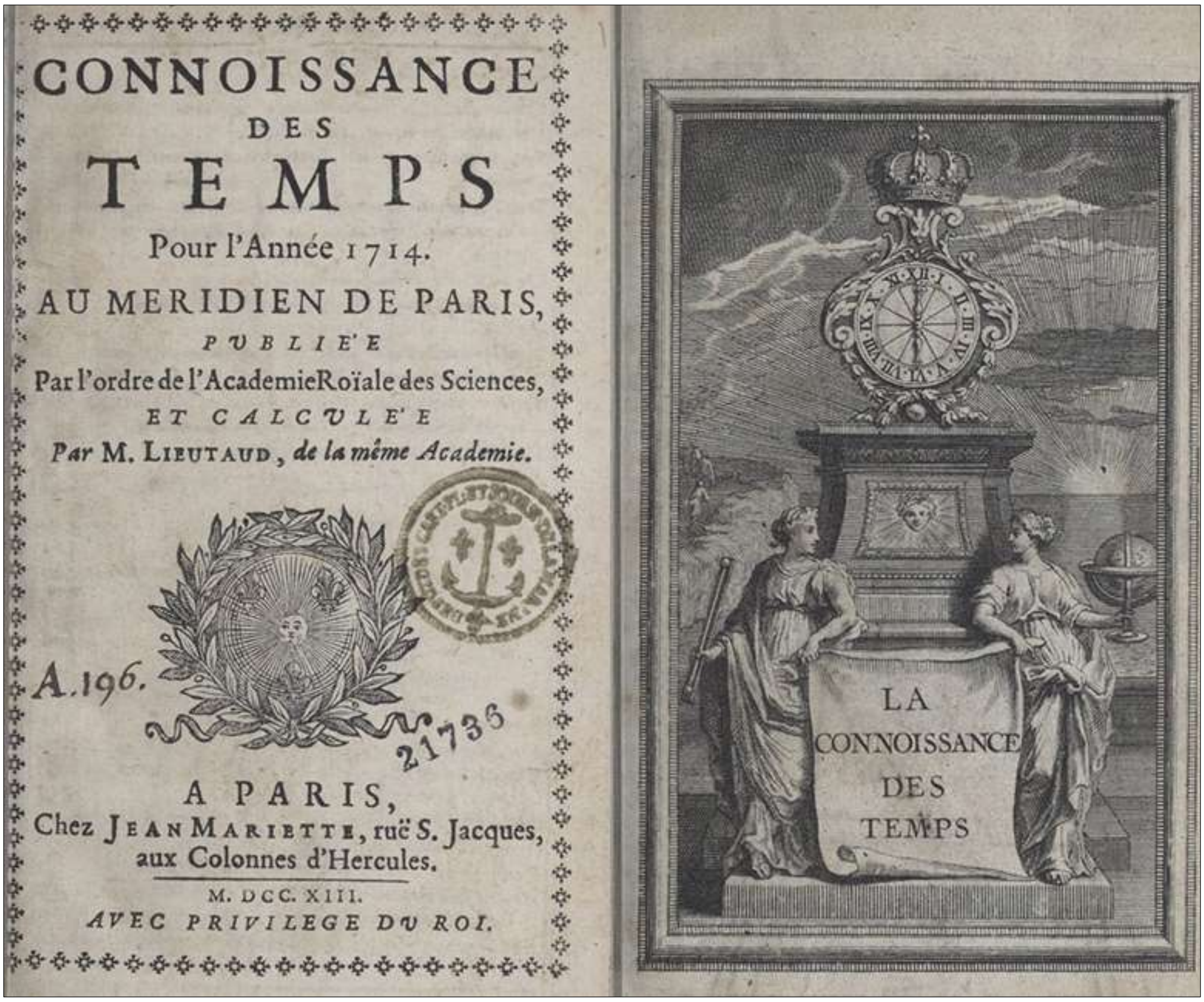


Figure 1: The Title Page and Frontispiece of the CDT for 1714 © IMCCE.

They were established for the meridian of Tycho Brahe's Uraniborg Observatory on the island of Hven in Denmark.

After Hecker's death, Joachim Dalencé (c. 1640–1707), the King's Councillor and Librarian of Louis XIV, aimed to continue the ephemerides. It seems that he was assisted in this by the astronomer Jean Picard (1620–1682), until his death. Dalencé's position made it easy for him to obtain the Royal printing privilege, which was essential at the time.

In the first volume the ephemerides are published monthly. Sunrises and sunsets were provided for everyday in Paris and in some other French cities such as Calais, Lyon and Marseille. This volume gives also right ascension of the Sun and equation of time. Sunrise and sunset times are given to the minute, which is still accurate enough today.

Other tables give concrete data that may be used: the transits of the Moon at the meridian, the apparent distance of the Sun at the equinox 'what astronomers call the right ascension of the Sun', the declination of the Sun, the equation of time (sundials are widely used) and the declination of the magnetized needle (useful for portable sundials that need to be oriented precisely North–South). A description of the position of the Sun and the planets in the sky is also given. Instructions are given for using the tables, in particular for setting clocks (the equation of time) by day and by night.

For the planets, we find the times of entry into the signs of the zodiac, which makes it possible to locate the planets in the sky. Gradually, year after year the information will become more precise, giving the 'true locations' of the planets and the Moon. A table also gives the longitudes and latitudes of the main cities in France.

Non-astronomical physical data are provided, including the length of the pendulum and the unit of time, the density of metals (as well as wine and oil) and a method for detecting counterfeit gold coins. Some volumes, up to 1688, also include the days on which couriers left for the provinces. Finally, there are reports of observations such as that of a comet in the 1681 volume.

Table 1: Displayed accuracy of the ephemerides in the CDT.

Years	Sun		Moon		Planets	
	Right asc.	Declination	Right asc.	Declination	Right asc.	Declination
1679–1700	1 min	1′	1 min	1′	––	––
1700–1785	1 sec	1″	1 min	1′	1 min	1′
1785–1830	0.1 sec	1″	0.1 sec	1′	1 min	1′
1830–1861	0.01 sec	0.1″	0.1 sec	0.1′	1 min	1′
1862–1959	0.01 sec	0.1″	0.01 sec	0.1″	0.01 sec	0.1″
1960–1979	0.01 sec	0.1″	0.001 sec	0.01″	0.01 sec	0.1″
1980–2006	Coefficients: representation accuracy 0.001″					
2007–2020	0.001 sec	0.01″	0.001 sec	0.01″	0.001 sec	0.01″

In the letter to the King preceding the avertissement, we may read that this ephemeris differs from what was done before:

> Lorsque j'eus l'honneur de faire voir à Vostre Majesté le dessein & l'utilité de ce petit livre, elle m'ordonna de le faire achever & me permit en même temps de lui présenter, ce que je fais avec le plus profond respect dont je suis capable, & après l'avoir épuré de toutes les choses ridicules dont ces sortes d'Ouvrages ont été remplis jusqu'à présent.

This is a direct reference to the astrological and other types of forecasts that could be found in other almanacs and in similar works (https://cdt.imcce.fr/exhibits/show/339-ans-de-connaissance-des-te/premi--re-p--riode---1679-1701).

The *Connaissance des temps* was different from other almanacs in that it was not only an almanac publishing ephemerides of the celestial bodies and predicting astronomical phenomena, but also an almanac publishing the results of scientific researches. So, the CDT sought to place itself in the ranks of scientific journals such as the *Journal des Sçavans*, which was published in Paris, or the *Philosophical Transactions of the Royal Society*, which was published in London (both from 1665), and later the *Journal des Observateurs*, which appeared at the beginning of the twentieth century. In Great Britain, the first edition of the *Nautical Almanac*, a publication similar to the CDT, was not published until 1767.

In addition to the tables and raw data, over time the CDT was enriched by additions that relayed scientific articles and the development of contemporary theories and techniques. It thus became a scientific journal, in the modern sense of the term, as a systematic reflection of science in the making of ephemerides.

We will focus here on the evolution of the ephemerides in quality due to the evolution of science and technology between 1679 and the present day, based on the content developed and presented in the CDT.

Over the course of three centuries, the publication evolved, both in terms of content and size. The first volume had 64 pages, but the size subsequent volumes increased rapidly due to the success of the publication and due to the increasing accuracy of the ephemerides which needed to display more digits in the tables (cf. Table 1). Starting from the 1703 edition, the CDT gives, month by month, the sunrises and sunsets of the Sun and the five known planets, Mercury, Venus, Mars, Jupiter and Saturn, their passages at the meridian of Paris, their longitudes, their latitudes and their declinations. It peaked at almost 1000 pages at the beginning of the twentieth century, before dropping to 350 pages today. The increase in the number of pages was due to the desire to satisfy the astronomers and the sailors by including in the CDT data that were useless to one group or the other. The apparition of a specific publication for sailors in 1889 solved the problem. Figure 2 shows how the number of pages varies from year to year. Some significant variations are due to the publication of 'additions', scientific articles and miscellaneous data published at the end of certain volumes. Note that each volume of the CDT contains the year of the published ephemerides in its title, but is published at least one year in advance so the date of the printing is always before the date of the ephemerides.

During the period from 1679 until today, the CDT was prepared by a group of technicians named 'calculateurs' provided by different institutions. In the beginning it was a personal decision to make the CDT, then it came under the authority of the Académie des Sciences until the French Revolution. In 1795, the Académie des Sciences was replaced by the new Bureau des longitudes (BDL) for the making of the CDT. The BDL retained this responsibility, and the CDT was made at Paris Observatory since the Observatory was under the authority of BDL. In 1854, the staff making the CDT (named the 'Service des Calculs') left Paris Observatory when the 'Service' became independent of the BDL. In 1911, the content of the CDT was modified in

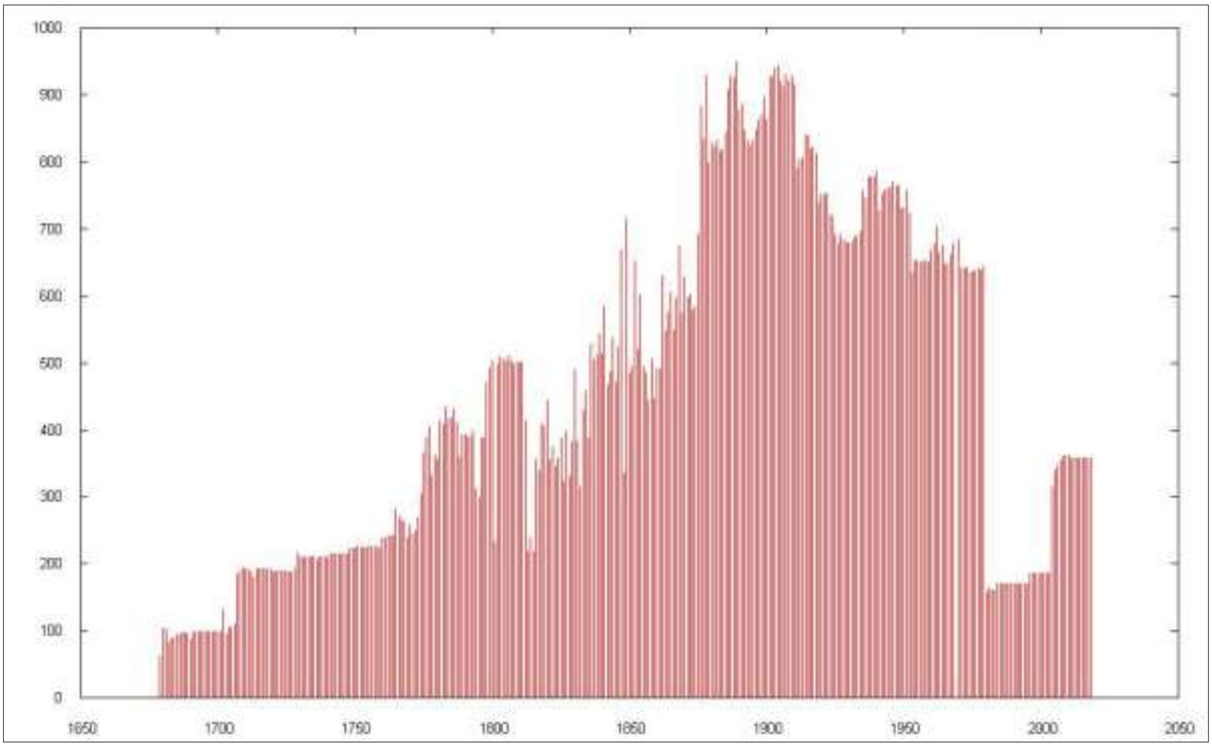


Figure 2: Evolution of the number of pages in the CDT.

following the rules established by the 'Congrès International des Éphémérides'. In 1960, the Service des Calculs became larger and used computers in order to improve the ephemerides, which were still using the theories of Urbain Jean Joseph Le Verrier (1811–1877). In 1980, a major change was introduced in the presentation of the CDT including the fact that calculations were made using computers for the preparation of the CDT and also by the users of the CDT for the determination of positions from the ephemerides (cf. Section 7.1). In 1998, the Service des Calculs du BDL became the IMCCE (Institut de Mécanique Céleste et de Calcul des Ephémérides) returning to Paris Observatory, but still under the scientific responsibility of the BDL. In 2025, the IMCCE became the LTE (Laboratoire Temps Espace), including the creating of time, still within Paris Observatory, the new LTE being in charge of the CDT.

3 THE EVOLUTION OF THE EPHEMERIDES OF THE SUN AND PLANETS FROM THE CREATION OF THE CDT UNTIL 1979

3.1 General Remarks on Planetary Theories

The motion of the planets around the Sun is a particular case of the N-body problem. All the bodies attract each other following the law of gravity but we consider that the masses of the planets are very small compared to the mass of the Sun. The apparent motion of the Sun around the Earth is deduced from the motion of the Earth around the Sun. Such theoretical models are necessary in order to build ephemerides but the models used for that have changed markedly since the beginning of the CDT. The turning point between kinematics and dynamics (celestial mechanics) was 1732, when the gravitational theory of Isaac Newton (1643–1727) was introduced in France.

3.2 The Kinematic and Dynamic Approaches

The quality of the ephemerides completely depends on the quality of the model describing the motions of the celestial bodies. This description was first based on a kinematic approach and further on celestial mechanics theories since the end of the eighteenth century. We see this progress through the 'additions' to the CDT.

The first papers published in the 'additions' tried to define what were called 'inequalities': we have kinematic descriptions of the motions (a representation by a simple mathematical function) which do not aim to model all the forces present in the system but to describe the observed motions. It had been noticed that these motions were not all uniform and circular (as supposed by Aristotle or Ptolemy) nor even elliptical (as proposed by Kepler) but much more complex. Deviations from a simple motion, i.e. 'inequalities', were gradually brought to light thanks to increasingly numerous and accurate observations. Then, the principle of perturbations was better understood and led, using the principle of universal attraction and thanks largely to Pierre-Simon Laplace (1749–1827), to correctly describing the Solar System.

Thus we find, in the CDT for 1764 (pages 210–211), a reflection on Newton's law in a note titled "On the attraction of celestial bodies" where we can read (our English translation):

> Kepler already seemed to perceive this universal tendency, when he said that the tides were the effect of the action of the Moon which attracted the waters; Chancellor Bacon had much the same idea; Doctor Hook, famous Englishman, in a Book on the motion of the Earth printed in 1674, page 27, speaks of it in the most precise manner; Hevelius, in his Treatise on Comets, seems to have the most distinct idea of it; one finds in the Works of Fermat, page 124, a Letter where he speaks of a mutual Attraction between the bodies; finally Newton, more enlightened by Geometry, not only recognized the Attraction, but he perceived its measure by means of the laws of Kepler, he deduced all the phenomena from it; & all the steps that have been taken in astronomy for eighty years provide new proofs of the universality of this law.

Universal attraction was the future foundation of celestial mechanics, and the CDT will reflect the steps of integration and impact on ephemerides.

3.3 Lalande's Influence

During the second half of the eighteenth century we must mention the leadership of Jérôme Lalande (1732–1807) on the *Connaissance des temps*. Several Directors were successively in charge of the CDT (cf. Boistel, 2016) but Lalande was one of very few who had a large influence on the contents and the evolution of the CDT. Officially in charge of the CDT from 1760 to 1775, he continued to work on the ephemerides until his death in 1807. During this period, the CDT was enriched with scientific papers (Lalande was the one who introduced the 'Additions') and the history of research in astronomy. Lalande calculated ephemerides from the best tables of the time: those of Nicolas-Louis de Lacaille (1713–1762) for the Sun (1750) and those of Edmond Halley (1656–1742) for the planets (1759). Those tables were made by fitting a small number of terms given by the theory to the observations. For example, de Lacaille's tables of the Sun contained inequalities of the Earth determined by Alexis Clairaut (1713–1765). Lalande then created his own tables of the Sun and planets that served as a basis for ephemerides published in the CDT until 1808.

Lalande also introduced into the CDT an additional coordinate, the distance from the equinox to the Sun, that is to say, the complement at twenty-four hours of the right ascension of the Sun.

Note that, during this period, the tables of the motion of the Sun and the planets, including Lalande's tables, are built according to a kinematic approach with motions built based on the laws of Johannes Kepler (1571–1630), improved by the introduction of inequalities deduced from observations.

3.4 The Introduction of Uranus in the CDT

Uranus is mentioned for the first time, under the name of the "Comet discovered by M. Herschel", in the 'Avertissement' of the CDT for 1785, written by Edmé-Sébastien Jeaurat (1725–1803), who was then the Director of the publication. He published "… the elements of the orbit of the Comet of 1781, calculated by M. Méchain". The CDT for 1785 was published in 1782, and the identity of Uranus as a planet had yet to be definitively established at this time.

The 'Avertissement' of the CDT for 1786 describes, under the title "*Discovery of the planet Herschel*", how the planetary character of the 'star' discovered by William Herschel (1738–1822) was established following calculations made by Laplace, Pierre Méchain (1744–1804) and Johann Elert Bode (1747–1826). The CDT for 1787 gives, in about thirty pages, the "Tables of the Planet of Herschel" calculated by Jeaurat, Méchain, who takes responsibility for the CDT in 1788, does not provide these tables anymore but adds a "Supplement to the 6th page of each Month for the Planet of Herschel" which gives the first ephemerides of Uranus (rising, setting, passage to the meridian, geocentric longitude and latitude, declination) at intervals of 15 days. These ephemerides were integrated with those of the other planets from the edition of 1789. The CDT then gives the Mercury ephemeris at intervals of 4 days, those of Venus and Mars at intervals of 6 days, those of Jupiter and Saturn at intervals of 8 days and those of '*Herschel*' at intervals of 15 days. As explained in the preceding Section, these ephemerides were computed according to a kinematic approach.

Note also that in addition to the CDT for 1791, there is an article titled "On the planet Herschel" which indicates that Lalande, who has recalculated the elements of the orbit of the planet, identified this as the star observed by John Flamsteed (1646–1719) in 1690, "… which he himself had contested until now."

It is from the 1813 edition of the CDT that

Table 2: Sources and argument of published ephemerides of the Sun and planets in the CDT. PTT refers to Paris True Time, PMT, the Paris Mean Time, GMT, the Greenwich Mean Time, TULV, the uniform time of Le Verrier and TT the Terrestrial Time built from the International Atomic Time TAI called TDT until 1991.

<table>
<tr><th rowspan="2">Dates</th><th rowspan="2">Time argument</th><th colspan="8">Sources of the Ephemerides</th></tr>
<tr><th>Sun</th><th>Mercury</th><th>Venus</th><th>Mars</th><th>Jupiter</th><th>Saturn</th><th>Uranus</th><th>Neptune</th></tr>
<tr><td>Until 1808</td><td>PTT</td><td>Delambre</td><td colspan="3">Lalande</td><td colspan="3">Delambre</td><td>—</td></tr>
<tr><td>1809–1834</td><td>PMT</td><td>Delambre</td><td colspan="3">Lindenau</td><td colspan="3">Bouvard</td><td>—</td></tr>
<tr><td>1863</td><td>PMT</td><td>+Mathieu</td><td colspan="3">Lindenau</td><td colspan="3">Bouvard</td><td>Kowalski</td></tr>
<tr><td>1864</td><td>PMT</td><td colspan="2">Le Verrier</td><td colspan="2">Lindenau</td><td colspan="3">Bouvard</td><td>Kowalski</td></tr>
<tr><td>1865–1870</td><td>PMT</td><td colspan="2">Le Verrier</td><td colspan="2">Le Verrier</td><td colspan="3">Bouvard</td><td>Kowalski</td></tr>
<tr><td>1870–1876</td><td>PMT</td><td colspan="4">Le Verrier</td><td colspan="3">Bouvard</td><td>Newcomb</td></tr>
<tr><td>1877–1878</td><td>PMT</td><td colspan="4">Le Verrier</td><td colspan="2">Bouvard</td><td colspan="2">Newcomb</td></tr>
<tr><td>1879–1883</td><td>PMT</td><td colspan="4">Le Verrier</td><td colspan="2">Le Verrier</td><td colspan="2">Newcomb</td></tr>
<tr><td>1884–1911</td><td>PMT</td><td colspan="6">Le Verrier</td><td colspan="2">Le Verrier</td></tr>
<tr><td>1912–1915</td><td>PMT</td><td colspan="5">Le Verrier</td><td colspan="3">Gaillot</td></tr>
<tr><td>1916–1917</td><td>GMT</td><td colspan="5">Le Verrier</td><td colspan="3">Gaillot</td></tr>
<tr><td>1918–1924</td><td>GMT</td><td colspan="4">Le Verrier</td><td colspan="4">Gaillot</td></tr>
<tr><td>1925–1983</td><td>TULV</td><td colspan="4">Le Verrier</td><td colspan="4">Gaillot</td></tr>
<tr><td>1984–2006</td><td>TT</td><td colspan="4">Bretagnon (VSOP82)</td><td colspan="4">Bretagnon-Simon (VSOP82/TOP82)</td></tr>
<tr><td>2007–2013</td><td>TT</td><td colspan="8">Fienga et al. (INPOP06)</td></tr>
<tr><td>After 2014</td><td>TT</td><td colspan="8">Fienga et al. (INPOP10)
(INPOPXX: new version every two or three years)</td></tr>
</table>

Uranus would appear in the CDT under its current name.

3.5 Laplace's Research

During the years 1770–1825, Laplace studied the consequences of the application of the law of Newton's gravitation on the motion of the bodies of the Solar System and solved several problems concerning planetary theories. First, the theorem of the invariability of the major axes studied the stability of the Solar System, giving the development of the perturbative function at the order 3 and then 5 in eccentricities and inclinations as well as formulae for calculating planetary perturbations. Laplace was also intrigued by irreglarities in Jupiter's and Saturn's motions shown by observations. Building on his own work and on those of Joseph-Louis Lagrange (1736–1813) and Siméon Denis Poisson (1781–1840) on the invariability of the major axes and the mean motions, Laplace made the assumption that these irregularities were due to periodic terms, the period of which was of the order of several hundred years. He deduced from the observations the quasi-commensurability of the mean motions of the two planets in the ratio 2/5 and showed that the variations of these mean motions were due to periodic terms whose argument was $2\lambda J - 5\lambda S$ (where λJ and λS are the mean longitudes of Jupiter and Saturn). Laplace (1785) evaluated at 919 years the period of this great inequality and at 1249 arcsec and 2924 arcsec the corresponding amplitudes in the longitudes of Jupiter and Saturn, respectively. In the 'Additions to the CDT for 1789, an article titled "On the mean motions of Saturn, Jupiter and its satellites" presents a "Communiqué to the Academy on 10 May 1786 by M. De La Place" in which Laplace writes that the period of this inequality is "… about 877 years …" and of amplitude 1200 arcsec for the longitude of Jupiter and 2810 arsec for the longitude of Saturn. These values are remarkably close of the values provided by modern planetary theories which are 935 years for the period of great inequality and 1183 arcsec and 2912 arcsec for the corresponding amplitudes of the perturbations on the mean longitudes of the two planets.

3.6 The Tables of the Sun and the Planets Issued Through Laplace's Work

Most tables of the Sun and planets used in the CDT during the first half of the nineteenth century derived from Laplace's work, as shown in Table 2, which gives the sources and the time argument of the ephemerides of the Sun and planets published in the CDT since 1809.

This is the case for the tables of the Sun by Jean-Baptiste Joseph Delambre (1740–1822) published in 1806 (Delambre and Burg, 1806), the tables of Mercury, Venus and Mars by Bernhard August von Lindenau (1779–1854) and the tables of Jupiter and Saturn by Alexis Bouvard (1767–1843) published in 1808 (Bouvard and Delambre, 1808) then in 1821 (Bouvard, 1821) after Laplace corrected an error of sign in the terms of the fifth order in eccentricity of the great inequality.

Bouvard also published tables of Uranus in 1821. To build his tables he had forty years of regular meridian transit observations, from 1781 (the year of the discovery of Uranus by

Herschel) to 1820, and about twenty old observations dating between 1690 and 1771, made by Flamsteed, James Bradley (1692–1762), Tobias Mayer (1723–1762) and Pierre-Charles Lemonnier (1715–1799), all of whom had mistaken the planet for a fixed star. Bouvard built his tables starting from analytical expressions given by Laplace (1800) for the perturbations of Uranus by Jupiter and Saturn. He could not represent by the same formulae the old observations and the modern ones and decided to reject the old observations building his tables only on meridian transit observations. Despite this, his tables were quickly showing a growing gap with subsequent observations.

The representation of the Sun and the planets in the CDT undergoes, during the first half of the nineteenth century, modifications of another order. From 1835, the mean solar time of Paris replaces the true solar time of Paris as an argument of the ephemerides and from 1838, the ephemerides are published body-by-body.

3.7 The Discovery of Neptune

The investigations that led Le Verrier to discover Neptune are exposed in their entirety in the additions to the CDT for 1849, in an article titled "Research on the motion of the planet Herschel (called Uranus)" (Le Verrier, 1846).

Le Verrier was anxious that the planet he had just discovered should carry his own name, and this explains the rather hypocritical note that he placed at the bottom of the first page of his article (our English translation):

> In my subsequent publications, I will consider it a strict duty to make the name Uranus disappear, and to call the planet only by the name used by Herschel. I deeply regret that the impression already advanced in this writing does not allow me, as of now, to comply with a determination that I will observe religiously in the following. (Le Verrier, 1846).

3.8 The Tables of Le Verrier, Newcomb and Gaillot

After this success, Le Verrier completely takes up the problem of the motion of the Sun and the main planets and builds theories and tables of these bodies (Le Verrier, 1855; 1856; 1857; 1858; 1859; 1860; 1861; 1874). He presents, notably, his theory of Mercury in an 'Additions' article in the CDT for 1848, titled "Theory of the motion of Mercury" (Le Verrier, 1845). In three successive papers Jean Baptiste Aimable Gaillot (1834–1921), a collaborator, and Le Verrier (Gaillot and Le Verrier,1904; 1910; 1913) will then improve the theories of the four big planets Jupiter, Saturn, Uranus and Neptune. At about the same time, theoretical work by Peter Andreas Hansen (1795–1874) gave birth to Neptune's theory of the Russian astronomer Marian Albertovich Kowalski (1821–1884) and, above all, the global theory of the planets by Simon Newcomb (1835–1909).

The tables of Le Verrier and Gaillot were used in the CDT until 1984 but we can see by examining Table 2 that Kowalski's (1855) tables, then those of Newcomb (1898b), were the sources of the ephemerides of Neptune published in the CDT from 1863 to 1883. It is amusing to note that if the tables of the motion of Neptune were only introduced into the CDT in 1863 this was for budgetary reasons (see the response given by Claude-Louis Mathieu (1783–1875) in 1860 to critics of Le Verrier about the CDT, as quoted by Bigourdan, 1932). For Uranus, the tables of Newcomb (1898a) were used from 1877 to 1883.

At the time of Le Verrier and Gaillot, the CDT gradually acquired the form it would retain up to 1979. In 1877 the rectangular coordinates of the Sun were introduced and the ephemerides of Uranus and Neptune became daily. The mean elements of the eight main planets, according to Le Verrier and Gaillot, and those of telluric planets after Newcomb—with corrections by Ross—were introduced in 1914 (Ross and Newcomb, 1917) and for Mars from 1920.

The ephemeris argument of the Sun and planets becomes the mean solar time of Greenwich in 1916 then universal time UT (i.e. the mean solar time of Greenwich + 12 h) in 1925. More precisely, this argument is in fact Le Verrier's uniform time drawn from his theory of Sun. It is, in fact, very close to the ephemerides time (ET).

Detailed information on the theories of Le Verrier, Le Verrier–Gaillot and Newcomb are provided in Simon and Bretagnon (1997).

3.9 The Evolution of the Ephemerides from Kinematics to Dynamics and the Evolution of the Time-Scale

The preceding sections clearly show the evolution of the ephemerides of the Sun and the planets from the kinematic approach to the dynamical one. Until the tables of Lalande, the ephemerides are purely kinematic with tables built according the laws of Kepler improved by inequalities deduced from observations. The transition to the dynamical approach begins with the work of Laplace which correctly describes the Solar System from the consequences of the law of the gravitation. At the end the ephemerides deduced from the works of Le Verrier, Gaillot and Newcomb are purely dynamical.

On another point we may also note the evolution of the time-scale, during this period, from the solar time of Paris until the Le Verrier's universal time. The evolution of the time-scale in the CDT will be studied in detail in Section 7.

4 THE EVOLUTION OF THE EPHEMERIDES OF THE MOON FROM THE CREATION OF THE CDT UNTIL 1979

4.1 General Remarks on Lunar Theory

The building of a solution for the motion of the Moon is a complex problem which is quite different from the planetary problem. The attraction of the Earth is the main perturbation, but the Moon is also disturbed by the Sun and the planets. Moreover, due to the proximity of the Earth and the Moon, the perturbations due to polar flattening of the Earth must be taken in account.

Due to the introduction of a dynamical approach, the ephemeris of the Moon will also exhibit an important evolution (as in the case of the planets and the Sun).

4.2 The First Issues of the CDT

In the CDT for 1679, moonrises and moonsets were listed for every day, in the same French cities as listed sunrises and sunsets (cf. Section 3.3.1). The 1695 edition gives the latitude and longitude for the Moon. As well as the Sun, starting from the 1703 edition, the CDT gives, month by month, the sunrises and sunsets of the Moon, its meridian-passage time in Paris, its latitude and longitude, and its declination.

We may note again the influence of Lalande who calculated ephemerides of the Moon, using the tables of Tobias Mayer (1755). As well as for the Sun, the ephemerides of the Moon were published daily, the ephemeris argument being the true solar time of Paris.

4.3 Laplace's Lunar Research

Laplace's work also concerned the motion of the Moon. He calculated, in particular, the secular accelerations of the mean longitude of the Moon and the longitudes of the node and perihelion of the Moon. In the 'Additions' of the CDT for 1790, in a paper titled "On the secular equation of the Moon" Laplace (1788) estimates the secular acceleration of the mean longitude as 11.135 arcsec, a value that was later reduced to 10.18 arcsec (Laplace, 1799). As Chapront and Chapront-Touzé (1997) explain, the secular accelerations of Laplace consider only the contribution of secular variations of the eccentricity of the Earth's orbit and are very different from actual values (−4.7763 arcsec for the secular acceleration of the mean longitude extracted from the theoretical model ELP, for example).

4.4 Lunar Ephemerides From 1805 to 1861

From the French Republican year XIV (23 September 1805–22 September 1806) to 1816, the ephemerides of the Moon published in the CDT were based on the tables of Delambre and Bürg (1806) and from 1817 to 1861 on Burckhardt's (1812) tables, established at the Bureau des longitudes as shown in Table 3. This table gives the sources and the argument of the ephemerides of the Moon published in the CDT since 1806.

As for the planets, the argument of the ephemeris of the Moon is the apparent solar time in Paris until 1834, then the mean solar time in Paris until 1915.

As indicated by Chapront-Touzé (1997), the tables of Johann Tobias Bürg (1766–1835) and Johann Karl Burckhardt (1773–1825), just like those, earlier, of Mayer, were made by directly associating the observations of the coefficients of a small number of trigonometric terms whose form of arguments was provided by theory. Note that the secular accelerations of the mean longitudes and longitudes of the node and the perigee calculated by Laplace were introduced in the Bürg and Burckhardt tables with slightly modified constants values.

4.5 Hansen's Tables of the Moon

The introduction of Hansen's (1857) tables for the calculation of the ephemerides of the Moon was announced in the 'Avertissement' of the CDT for 1862:

> The positions of the Moon which had first been calculated by the Burckhardt's tables had to be recalculated on Mr. Hansen's new Moon Tables, resulting in a delay in the publication of this volume. (our English translation).

It is with the introduction of these tables that ephemerides of the Moon truly based on a dynamical theory appeared in the CDT. Hansen's tables were used until 1914, but one of them, which provided only a small contribution, was replaced during the period by a table due to Newcomb. From 1882, daily corrections in right ascension and in declination resulting from the longitude correction proposed by Newcomb (1878) were given in a separate table, and were introduced in some calculations (e.g. of eclipses, occultations, and distances from the Moon to the Sun and the stars).

Table 3: Sources and argument of the Moon's ephemerides published in CDT since 1806.

Dates	Time Argument*	Sources of the Ephemerides
Until1805	PAT	Bürg
1806–1816	PAT	Burckhardt
1817–1861	PMT	Burckhardt
1862–1881	PMT	Hansen + Newcomb
1882–1914	PMT	Radau
1915	PMT	Radau
1916–1924	GMT	Radau
1925	UT	Radau
1926–1959	UT	Brown
1960–1965	ET	Brown + Woolard
1966–1967	ET	Brown + Eckert (ILE, j = 0)
1968–1971	ET	Brown + Eckert (ILE, j = 1)
1972–1983	ET	Brown + Eckert (ILE, j = 2)
1984–2006	TT	Chapront-Touzé et Chapront (ELP2000)
From 2007	TT	Fienga et al. (INPOPXX: a new version every two or three years)

Key: PAT refers to Paris Apparent Time, PMT to Paris Mean Time, GMT to Greenwich Mean Time.

To build these tables from his theory, Hansen only adjusted to the observations the integration constants, the mean motions of the node and perigee, the coefficient of parallactic inequality (to fix the ratio of the mean distances between the Earth and the Moon and the Earth and the Sun), the coefficient of the two main perturbations due to the non-sphericity of the Earth, one in longitude, the other in latitude, and finally the value of 21.47 arcsec for the coefficient of the long-period planetary perturbation in sin ($8V_e - 13T_e + 274^\circ 14'$) where V_e and T_e designate the mean longitudes of Venus and the Earth.

4.6 Delaunay's Lunar Research

Charles-Eugène Delaunay (1816–1872) built an analytical theory of the motion of the Moon, studying the particular case of the 3-body problem (Moon, Earth, Sun). Even if Delaunay's analytical developments converged too slowly to be used directly, his work was very useful in improving the theory of the Moon. Delaunay corrected several long-term inequalities introduced in Hansen's tables and his theory was used to build tables published in the CDT, as we shall see in the next Section. His work was the subject of several articles in the 'Additions' to the CDT. We find:

- a presentation of his method of integrating equations of the motion of the Moon in the 'Additions' to the CDT for 1861 (Delaunay, 1858);
- the calculation of the secular acceleration of the Moon and the calculation of the analytic expression of long-term inequality $l + 16T_e - 18V_e$ introduced in Hansen's tables in the 'Additions' to the CDT for 1862 (Delaunay, 1860);
- the calculation of the analytic expression of the long-term inequality $13T_e - 8V_e$ introduced in the tables of Hansen in the 'Additions' to the CDT for 1863 (Delaunay, 1861a; 1861b);
- a "Memoir on the secular equation of the Moon" in the 'Additions' to the CDT for 1864 (Delaunay, 1862); and
- "Analytical Expressions of the Three Coordinates of the Moon" in the 'Additions' to the CDT for 1865 and for 1869 (Delaunay, 1863; 1867).

These analytical expressions were all derived from Delaunay's theory (see Delaunay, 1860; 1861a; 1861b).

4.7 Lunar Ephemerides from 1915 to 1925

From 1915 to 1925 the ephemerides of the Moon published in the CDT were calculated from the tables of Delaunay and Radau (1911). At the same time, they provided the daily differences between the ephemerides from Hansen's tables and corrections from Newcomb (1878) until 1922, then with the ephemerides from the tables of Ernest William Brown (1866–1938). The tables prepared by Jean-Charles Rodolphe Radau (1835–1911) were based on those of Delaunay (1860; 1861a; 1861b; 1863) or the main problem, on Radau's (1895) work for planetary perturbations, and on Hill and Delaunay's (1891) work for perturbations due to the shape of the Earth. According to a decision of the IAU (International Astronomical Union), the ephemeris argument became Greenwich mean solar time from 1916, and universal time UT (mean solar time of Greenwich + 12h) from 1925.

4.8 Lunar Ephemerides from 1926 to 1979

From 1926 to 1979, according the recommendations of the IAU about the preparation of ephemerides between ephemerides offices, the CDT continued to publish ephemerides of the Moon prepared by the Nautical Almanac and Astronomical Ephemeris. Brown's theory was the basis of these ephemerides, even though it would undergo several revisions over time.

From 1926 to 1959, the ephemerides of the Moon were calculated using tables by Brown and Hedrick (1919). These tables were created according to Brown's theory (see Brown, 1899a; 1899b; 1904; 1908; 1910). The secular accelerations of mean longitude and longitudes of the node and perigee came from this theory. Integration constants were determined by Brown (1915) by comparing his theory with observations. The mean motions of the node and perigee of the theory were replaced by values derived from a comparison with the observations. In addition, Brown added to the mean longitude the empirical term: 10.71″ sin [1°.40 (θ–1850)] + 170°.7.

From 1960, the CDT gradually adopted the recommendations made by the IAU in 1952 (UAI, 1954). The argument of the ephemerides was Ephemerides Time (ET). In adopting this resolution, the IAU recommended that the source of the ephemerides should remain Brown's tables with corrections due to Woolard (1952), and suppression of the empirical term from 1960 to 1965, then from 1966, that the ephemerides should be calculated directly from Brown's theory itself and no longer from the tables. The 1966 and 1967 editions took into account corrections by Edgar W. Woolard (1899–1978). The series and methods for the calculations were given in the "Improved Lunar Ephemeris 1952–1959" by Eckert et al. (1954), and the ephemeris thus obtained was called ILE, j = 0.

Introduced in 1968, the new system of constants recommended by the IAU in 1964 (UAI, 1966), resulted in corrections to Brown's theory, calculated by Wallace John Eckert (1902–1971). These corrections appeared in the CDT in the form of a complementary table. Woolard's corrections were replaced by corrections due to Harold Spencer Jones (1890–1960). The ephemeris thus constituted was called ILE, j = 1.

In 1972 the ephemeris ILE, j = 1 was replaced by the ephemeris ILE, j = 2 obtained by replacing the series of solar perturbations in latitude, longitude, and parallax calculated by Brown from a series calculated by Eckert et al. (1966) directly from the series in the rectangular coordinates of Brown. This ephemeris was used in the CDT until 1983, with calculations made at the Bureau des longitudes from the first volume of the new series in 1979.

Detailed information about the theories of Hansen, Delaunay, Radau, Brown and Eckert is available in Chapront-Touzé (1997).

4.9 The Evolution of the Ephemerides from Kinematics to Dynamics, and the Evolution of the Time-Scale

As for the Sun and the planets, the preceding Sections clearly show the evolution of the ephemerides of the Moon from the kinematic approach to the dynamical one. Until 1861 the ephemerides were purely kinematic. As explained in the Section 4.4, the ephemerides of the Moon published in the CDT became based on a dynamical theory with the introduction of Hansen's tables. Afterwards, the ephemerides based on the tables of Radau were from the work of Delaunay. Then, finally, the ephemerides based on the series by Brown and Eckert were purely dynamical.

During this period the time-scale evolved from the Paris True Time to Ephemeris Time.

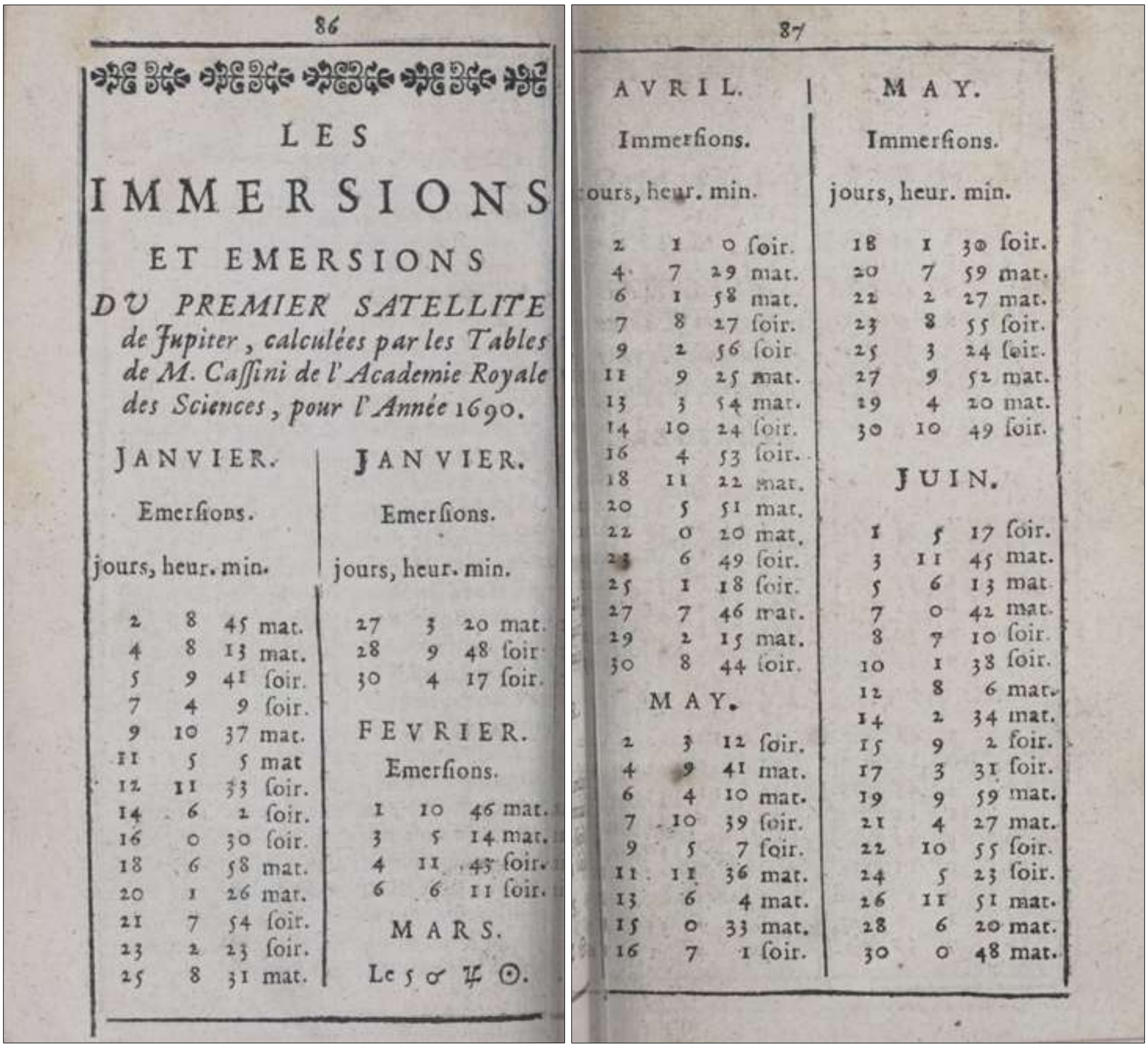
5 THE EVOLUTION OF THE EPHEMERIDES OF THE SATELLITES OF JUPITER FROM THE CREATION OF THE CDT UNTIL 1979

5.1 General Remarks on the Theory of the Galilean Satellites

The four main satellites of Jupiter, named Galilean after their discovery by Galileo Galilei (1564–1642), are among the celestial objects that were the most studied, similarly to the Moon, the Sun and the planets. They were of great importance, and their eclipses (immersions and emersions) were the main way of determining terrestrial longitude, as we will see in Section 9. The dynamics of their motions represented one of the most complex challenges in the Solar System but the most interesting, including all the dynamical problems of a gravitational system. The modeling of their motions is difficult because of their size (Ganymede has a size similar to Mars or Mercury) and mutual gravitational perturbations, because of the polar flattening of Jupiter, the presence of Saturn and the Sun, and the strong tidal effects between them and the planet Jupiter. The modeling of their motions, necessary in building ephemerides, was permanently in progress.

5.2 Ephemerides of the Galilean Satellites from 1690 to 1763

The ephemerides of the Galilean satellites were necessary for the predictions of the eclipses of the satellites as well as for the identification of the satellites. These eclipses were published in the CDT very early, starting with the CDT for 1690 (see Figure 3).



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LES

IMMERSIONS

ET EMERSIONS

DV PREMIER SATELLITE de Jupiter, calculées par les Tables de M. Caſſini de l'Academie Royale des Sciences, pour l'Année 1690.

JANVIER. Emerſions.

jours	heur.	min.
2	8	45 mat.
4	8	13 mat.
5	9	41 ſoir.
7	4	9 ſoir.
9	10	37 mat.
11	5	5 mat
12	11	33 ſoir.
14	6	2 ſoir.
16	0	30 ſoir.
18	6	58 mat.
20	1	26 mat.
21	7	54 ſoir.
23	2	23 ſoir.
25	8	31 mat.

JANVIER. Emerſions.

jours	heur.	min.
27	3	20 mat.
28	9	48 ſoir
30	4	17 ſoir.

FEVRIER. Emerſions.

jours	heur.	min.
1	10	46 mat.
3	5	14 mat.
4	11	45 ſoir.
6	6	11 ſoir.

MARS.

Le 5 ♂ ♃ ☉.

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AVRIL. Immerſions.

jours	heur.	min.
2	1	0 ſoir.
4	7	29 mat.
6	1	58 mat.
7	8	27 ſoir.
9	2	56 ſoir
11	9	25 mat.
13	3	54 mat.
14	10	24 ſoir.
16	4	53 ſoir.
18	11	22 mat.
20	5	51 mat.
22	0	20 mat.
23	6	49 ſoir.
25	1	18 ſoir.
27	7	46 mat.
29	2	15 mat.
30	8	44 ſoir.

MAY.

jours	heur.	min.
2	3	12 ſoir.
4	9	41 mat.
6	4	10 mat.
7	10	39 ſoir.
9	5	7 ſoir.
11	11	36 mat.
13	6	4 mat.
15	0	33 mat.
16	7	1 ſoir.

MAY. Immerſions.

jours	heur.	min.
18	1	30 ſoir.
20	7	59 mat.
22	2	27 mat.
23	8	55 ſoir.
25	3	24 ſoir.
27	9	52 mat.
29	4	20 mat.
30	10	49 ſoir.

JUIN.

jours	heur.	min.
1	5	17 ſoir.
3	11	45 mat.
5	6	13 mat
7	0	42 mat.
8	7	10 ſoir.
10	1	38 ſoir.
12	8	6 mat.
14	2	34 mat.
15	9	2 ſoir.
17	3	31 ſoir.
19	9	59 mat.
21	4	27 mat.
22	10	55 ſoir.
24	5	23 ſoir.
26	11	51 mat.
28	6	20 mat.
30	0	48 mat.

Figure 3: Predictions of the eclipses of Io in the CDT for 1690 © IMCCE.

In the CDT for 1726, one will find a clear explanation of how the eclipses of the Jovian satellites could be used to determine terrestrial longitudes, as we will see in the next Section. From 1730, the CDT included predictions of the eclipses of all four Galilean satellites. The ephemerides would be continuously improved with the tables of Giacomo Filippo Maraldi (1665–1729) replacing those of Giovanni Domenico Cassini (1625–1712) in 1730, even though the motions were still modeled through kinematics. However, improvements came about because there was better knowledge of the inequalities, which were the difference between the true motion and a uniform one. Predictions of the eclipses could then be given to the nearest second of time instead of the nearest minute.

From 1735, a novelty was introduced in the CDT: although eclipse predictions were easily publishable, the ephemerides of the satellite positions (useful for identifying the satellites based on observations) were difficult to publish because of the rapid motion of the satellites—for example, Io made one revolution in about one and a half days! So the CDT began publishing positions in graphical form. Figure 4, for example, shows the configurations of the Galilean satellites in the CDT for 1735). These diagrams would be published continuously until recent times. However, ephemerides in the form of tables that provided even more precise positions than graphics did were published from 1763 on.

5.3 Ephemerides of the Galilean Satellites from 1763 to 1918

From the 1763 issue of the CDT astronomers were aware of the bad quality of ephemerides based upon kinematics, even including some inequalities. Lalande wrote that "… inclinations and nodes of the orbits have badly known var-

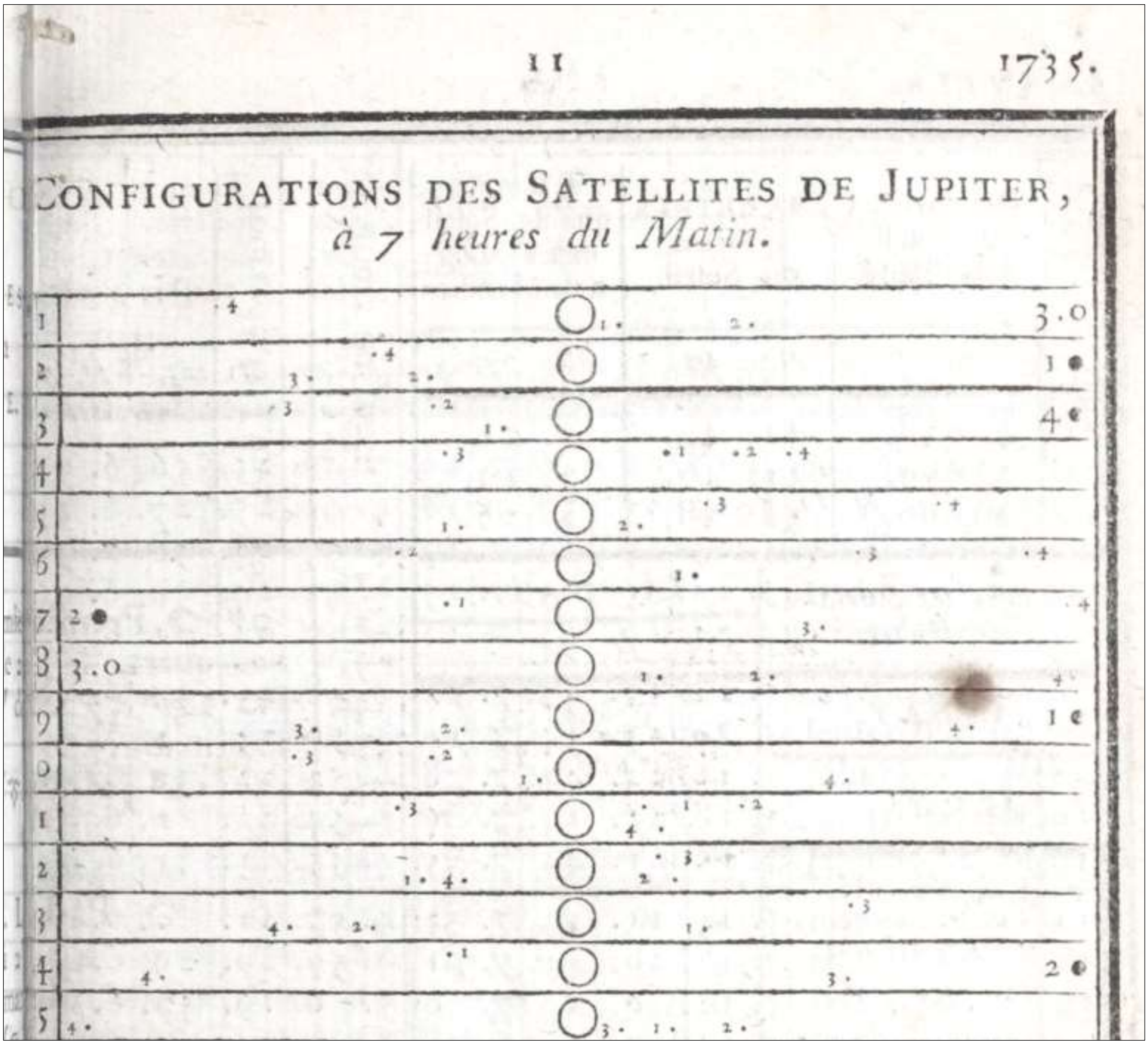


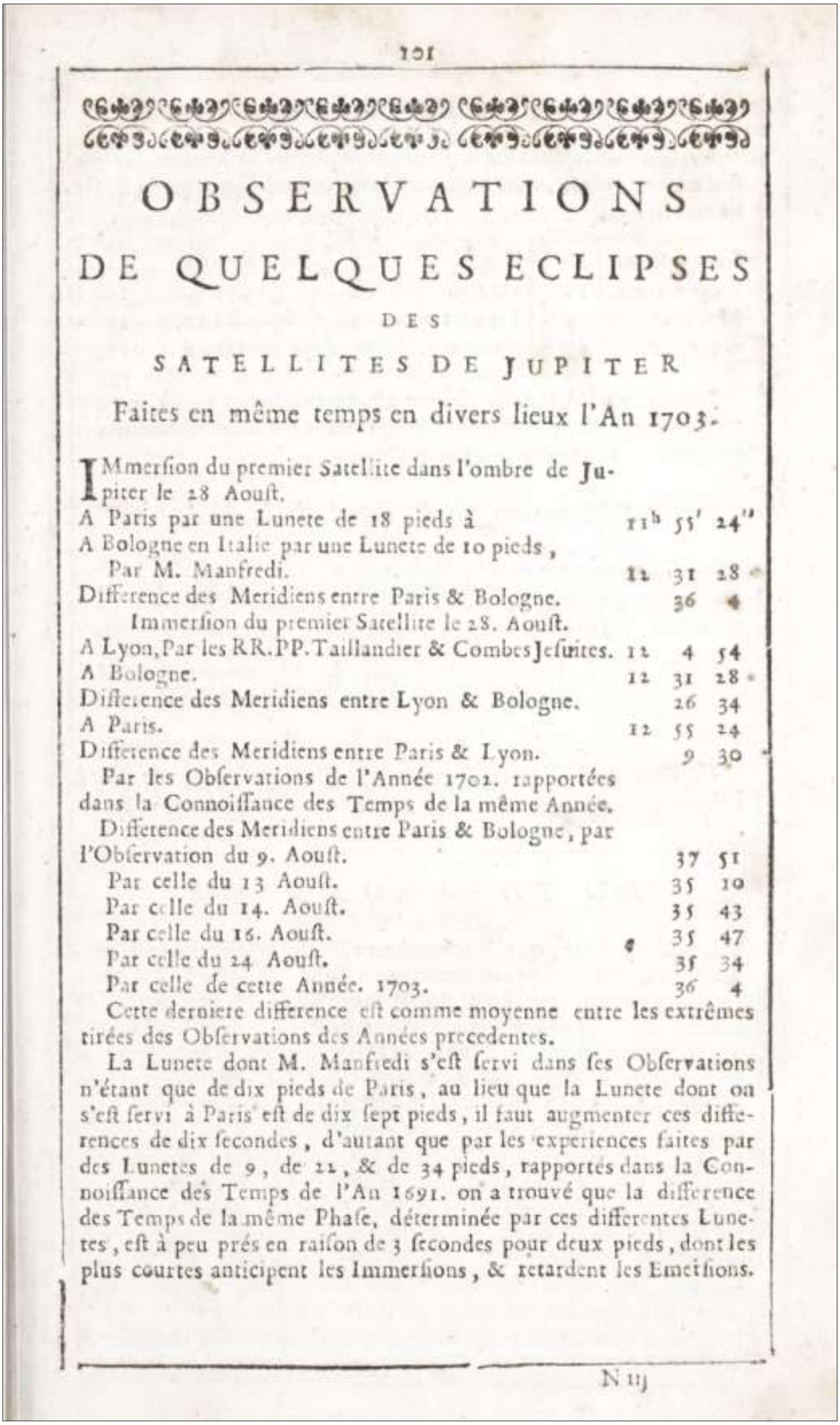
Figure 4: Configurations of the Galilean satellites in the CDT for 1735 © IMCCE. Daily positions of the satellites are shown by points.

iations." Moreover, the bad ephemeris of Jupiter had an influence on one of the satellites. Observations of eclipses were continuously made and published in the CDT (cf. Figure 5) for the determination of the longitudes, and for the evaluation of the quality of the ephemerides. In 1766, the ephemerides were based on the tables by Pehr Wilhelm Wargentin (1717–1783) replacing those of Maraldi. A revolution happened with the 1789 volume, which included a communication from Laplace to the French Academy of Sciences showing an interest in using the laws of gravitation to model the motions of Saturn, Jupiter and their satellites. Laplace referred to Bailly who had abandoned kinematics for dynamics when modeling the motions of the Jovian satellites. In fact, years would pass before astronomers tried to even partially use dynamical equations of motions to try and solve these problems. Tables by Delambre, based on the theoretical work of Laplace replaced those of Wargentin until 1841 when Marie-Charles Damoiseau (1768–1846) improved the ephemerides.

The rapidly changing positions of the satellites made interpolation of positions impossible. In 1763, a method to calculate positions was published in the CDT. This involved making an instrument with moving disks and an alidade, which could show the positions of the satellites. In 1915, Lipót Schulhof (1847–1921) put in the CDT elements, which allowed the calculation of individual positions of the Galilean satellites. This was the only way to provide positions, and it is still used with other more precise formulae nowadays.

5.4 Ephemerides of the Galilean Satellites from 1918 to 1979

Dynamics became very efficient for planets, and as we saw earlier, Le Verrier was able to



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OBSERVATIONS
DE QUELQUES ECLIPSES
DES
SATELLITES DE JUPITER
Faites en même temps en divers lieux l'An 1703.

Immerſion du premier Satellite dans l'ombre de Jupiter le 28 Aouſt.			
A Paris par une Lunete de 18 pieds à	11h	55'	24''
A Bologne en Italie par une Lunete de 10 pieds, Par M. Manfredi.	12	31	28
Difference des Meridiens entre Paris & Bologne.		36	4
Immerſion du premier Satellite le 28. Aouſt.			
A Lyon, Par les RR.PP. Taillandier & Combes Jeſuites.	12	4	54
A Bologne.	12	31	28
Difference des Meridiens entre Lyon & Bologne.		26	34
A Paris.	12	55	24
Difference des Meridiens entre Paris & Lyon.		9	30
Par les Obſervations de l'Année 1701. rapportées dans la Connoiſſance des Temps de la même Année.			
Difference des Meridiens entre Paris & Bologne, par l'Obſervation du 9. Aouſt.		37	51
Par celle du 13 Aouſt.		35	10
Par celle du 14. Aouſt.		35	43
Par celle du 16. Aouſt.		35	47
Par celle du 24 Aouſt.		35	34
Par celle de cette Année. 1703.		36	4

Cette derniere difference eſt comme moyenne entre les extrêmes tirées des Obſervations des Années precedentes.

La Lunete dont M. Manfredi s'eſt ſervi dans ſes Obſervations n'étant que de dix pieds de Paris, au lieu que la Lunete dont on s'eſt ſervi à Paris eſt de dix ſept pieds, il faut augmenter ces differences de dix ſecondes, d'autant que par les experiences faites par des Lunetes de 9, de 22, & de 34 pieds, rapportés dans la Connoiſſance des Temps de l'An 1691. on a trouvé que la difference des Temps de la même Phaſe, déterminée par ces differentes Lunetes, eſt à peu prés en raiſon de 3 ſecondes pour deux pieds, dont les plus courtes anticipent les Immerſions, & retardent les Emerſions.

N iij

Figure 5: Observations of the eclipses of the Galilean satellites providing longitudes of observing sites © IMCCE.

Table 4: Evolution of Galilean satellite ephemerides published in the *Connaissance des temps*.

Dates	Positions	Modeling
1679–1689	–-	–-
1690–1693	–-	Cassini
1694–1697	–-	–-
1698–1729	–-	Cassini
1730–1733	–-	Maraldi
1734	–-	Maraldi
1735–1762	–-	Maraldi
1763–1765	Daily elements	Maraldi
1766–1807	Daily elements	Wargentin–Lalande
1808–1840	Daily elements	Delambre
1841–1880	Daily elements	Damoiseau
1881–1890	Daily elements	Souillard
1891–1914	Daily elements	Souillard
1915–1960	Daily elements	Sampson–Schulhof
1961–1979	Daily elements	Sampson–Schulhof
1980–1984	Chebychev pol.	Sampson–Arlot
1985–1995	Mixed functions	Sampson–Arlot
1996–2005	Mixed functions	Sampson–Arlot
2006–2007	Elongations	Sampson–Arlot
from 2008	Elongations	Lainey

calculate the positions of a supposed yet never observed planet (Neptune) thanks to celestial mechanics. The problem remained difficult for the Galilean satellites and the first actual dynamical theory of the satellites was made by Ralph Allan Sampson (1866–1939). His theory was adapted by Marie Henri Andoyer (1862–1929) in 1918 in order to produce ephemerides, which would remain in the CDT until 1985 (Table 4).

From 1881, better tables of elements due to Cyrille Joseph Souillart (1828–1898) were published in order to make possible the calculation of precise positions of the satellites.

We have to note that, for the other satellites, data such as elongations were provided from 1891 to 1915 when an international agreement occurred (Congrès International des Éphémérides Astronomiques, Paris, 23–26 Octobre 1911). In 1915, the Galilean satellites were entrusted to the CDT and the other natural satellites were entrusted to the British Astronomical Almanac. At the same time, the time argument in the CDT, which was Paris Mean Time, became Greenwich Mean Time. However, the time argument in the ephemerides of the Galilean satellites remained the uniform time used by Sampson in his theory.

In the CDT for 1961, the configurations of the satellites presented as points were made in the form of curves depending on time.

5.5 The Evolution of the Ephemerides from Kinematics to Dynamics and the Evolution of the Time-Scale

As for the Sun, the planets and the Moon, the first ephemerides were based on a kinematic model, a sample uniform mathematical function, with some empirical periodic or secular terms deduced from the observations and allowing a better modeling of the motion of the satellites. However, the motion of the satellites is perturbed by so many bodies (Jupiter, Saturn, the Sun and each satellite on the others) that only a dynamical model based on Newton's law and including the gravitational effect of all these bodies could provide more accurate ephemerides. This revolution was made thanks to Jean-Sylvain Bailly (1736–1793) and Laplace, but the first purely dynamical theory was published by Sampson in 1921 although the ephemerides were made using his work from 1915. However, the dynamics of the Galilean satellites was so complex that Sampson forgot some very small perturbing elements that would only be taken into account after the arrival of electronic computers. Note that better theoretical modeling of the motions of celestial bodies will be efficient in making better ephemerides if the observations used in the fit of the constants of the motion have sufficient accuracy. The evolution of our understanding of the Galilean satellites, and improvements in observing techniques, have been reviewed by Arlot (2019).

As for the ephemerides of the Sun and the planets, the time argument of the ephemeris is a uniform time deduced from the timings of the observations of the satellites made during more than one century.

6 MINOR PLANETS IN THE CDT

Asteroids or minor planets appear in the CDT for 1805, following observations of the first asteroid by Giuseppe Piazzi (1746–1826) in Palermo in 1801. In a “Mémoire sur la découverte de la planète Piazzi” Lalande describes the hesitations over what name to give it: ‘Cérès de Ferdinand’, in honor of the King of Naples, or ‘Juno’ to keep with mythology, or ‘Piazzi’ in honor of the discoverer. The CDT also included observations of this first asteroid (which eventually became Ceres) made in Toulouse in 1802 by Jacques Vidal (1747–1819), and a “Histoire de la planète que M. Olbers a découvert en l’an 10, lue à l’Assemblée publique de l’Institut, le 17 Messidor an 10 (6 juillet 1802)” by Lalande, followed by observations of this planet (which later became Pallas) by Franz Xaver von Zach (1754–1832) and Méchain. The elements of Ceres’ orbit can be found in the CDT for 1806, and observations of Ceres, Pallas, Juno and Vesta are in the CDT for 1809.

Then, as new asteroids were discovered, a list would be provided, increasing from year to year until publication of the CDT for 1896. From the CDT for 1897 onwards, the orbital elements of the year of the principal asteroids and comets were given, along with the constants used to calculate the ephemeris. These elements were no longer published from the 1914 CDT onwards, but the list of constants was expanded to include the orbital elements of Solar System bodies, including some for which no ephemerides were published.

The problems in celestial mechanics had to be solved in order to create asteroid ephemerides of perturbations on asteroids. In the additions to the CDT for 1846, Damoiseau published a study on the “Perturbations de Junon et de Cérès”, in which he proposed to “… déterminer directement les perturbations de la longitude, du rayon vecteur et de la latitude, comme on procède pour les anciennes planètes.” He calculated the perturbations of these variables due to Mars, Jupiter and Saturn.

The determination of asteroid orbits was the subject of several articles in the ‘Additions’ to the CDT. In the 1852 CDT, Antoine-Joseph Yvon Villarceau (1813–1883) applied his method for calculating the elements of the planets to Iris, and reached a result using the interpolation method of Augustin-Louis Cauchy (1789–1857). In the same ‘Additions’, he calculated the elements of the asteroid’s orbit for 17 October 1847, using these elements to find “… the planet towards the end of August 1848 …”, and finding a “… very small …” discrepancy between calculation and observation. In the additions to the CDT for 1876, Gustave Leveau (1841–1911) published a “Determination of the orbit of the planet Hera”, an asteroid discovered “… at the Ann-Arbor Observatory, on the night of September 7, 1868 …”, in which the perturbations of the planets Mars, Jupiter and Saturn were better and better taken into account. The additions to the CDT for 1878 included an article by Schulhof titled “Recherches sur l’orbite de la planète Maïa et éphémérides pour l’opposition de 1876”. This showed that after a new ‘minor planet’ was discovered it had to be tracked in order to calculate its orbit.

The dwarf planet Pluto, discovered in 1930, did not appear in the CDT until 1950, when the CDT began publishing ephemerides calculated using a numerical integration of the motion of the five outer planets by W.J. Eckert, Dirk Brouwer (1902–1966) and Gerald Maurice Clemence (1908–1974) (Astronomical Papers of the American Ephemeris, Volume XII, 1951) until 1980, and then only for the other planets in following years. Similarly, from 1965 to 2006, the CDT published those of the largest asteroids, Ceres, Pallas, Juno and Vesta, using the numerical integration of their motion by Paul Herget (1908–1981) (Astronomical Papers of the American Ephemeris, Volume XVI, Part. III, 1962). From 2007, INPOP was used (Fienga et al., 2008; 2011).

7 THE SUN, MOON, PLANET AND GALILEAN SATELLITE EPHEMERIDES IN THE CDT FROM 1980

7.1 Transformations of the CDT

Important transformations were made to the CDT starting in 1980. The emergence of electronic computers completely change the creation and the use of ephemerides, and therefore the contents of the CDTs. In 1979 a new form of the CDT appeared: the tables of positions disappeared and all of the ephemerides were given in the form of Chebychev polynomials. Positions could be easily calculated with pocket calculators. Since 2005, the CDT has had two parts. The first part contains scientific texts that give the basis of fundamental astronomy and celestial mechanics necessary for an understanding and use of the ephemerides. The second part contains numerical data allowing the calculation of positions of the main objects in the Solar System. The configurations and the phenomena of the satellites are published in a supplement to the CDT.

Another important reform appeared in 1984: the time argument of the ephemerides changed because of the better knowledge of the rotation of the Earth. ‘Temps Uniforme’ was abandoned in favor of Terrestrial Time (TT) using International Atomic Time (TAI).

Surprisingly the Sampson model was still in use for the ephemerides of the Galilean satellites until 2008 due to the complexity of the elaboration of a brand new model taking into account all the perturbations on the satellites. However, the Sampson model was programmed, corrected, and compared with new observations for new constants, and it produced accurate ephemerides in TT. In order to publish less data, but with the same accuracy as the Chebychev polynomials, a new form was included in the supplement to the 1985 CDT and in the CDT itself from 1996, with mixed functions mixing polynomials and periodic functions (Arlot et al., 1986).

7.2 Back to the Tabulated Positions

In fact, the constant progress of computers and means of getting ephemerides through Internet led to more changes to the CDT year after year. In 2006, it appeared that the CDT was no longer used to calculate ephemerides since easily-accessible software and web sites were available for that purpose (it was also possible to upload an electronic CDT from the IMCCE web site). Then, the ephemerides printed in the CDT reverted to tabulated positions, not for interpolation but for checking calculations made by users on their personal computers. The CDT is now published in an electronic form with test data and explanations on sources and the making of ephemerides.

7.3 Sources of the Ephemerides of the Sun, Moon and Planets

7.3.1 Analytical Methods and Numerical Integrations

Nowadays, two methods may be used to integrate the equations of the motion of the Sun, Moon and planets: an analytical method and numerical integrations. In the analytical theories the coordinates have the form of Fourier and Poisson series of arguments, which are functions of time. Numerical integrations give the numerical values of the coordinates for discrete time values.

7.3.2 Sources of the Ephemerides of the Sun, the Moon and the Planets from 1980 until 2006

From 1984 up to 2006, the CDT used the analytical theories of the motions of the Sun, Moon and planets developed at the IMCCE.

For the Sun and the planets, these theories were built by an iterative method that allowed the computation of perturbations up to a high order of masses. They were much more precise than the theories of Le Verrier or Le Verrier–Gaillot. They were adjusted not to the observations but to the numerical integration of JPL DE200 (Standish et al., 1981). These theories were VSOP82 (Bretagnon, 1982) and TOP82 (Simon, 1983).

For the Moon, the main problem (Moon, Earth, Sun) was integrated by an iterative method. Afterwards the complete problem (with perturbations by the planets, perturbations due to the Earth's polar-flattening, etc.) was computed. The theory obtained, ELP 2000-82, was adjusted to the numerical integration DE200 / LE200 of JPL. Resulting from this theory was the ephemeris published in the CDT, ELP 2000 (Chapront-Touze and Chapront, 1983) that was much more precise than the older ephemerides. Since 1989, the mean elements published in the CDT have been from the ELP 2000-85 solution (Chapront-Touze and Cha-pront, 1988).

7.3.3 Sources of the Ephemerides of the Sun, Moon and Planets from 2007

Numerical integration methods are well adapted to computer calculations and give results more precise than analytical methods since the computers have sufficient power. So, since 2007 the sources of planetary and lunar ephemerides, as well as those of the dwarf planet Pluto, have come from the INPOP numerical integrations. These numerical integrations are directly adjusted to the observations. The sources of the ephemerides published in the CDT were successively:

- From 2007 to 2013, INPOP06 (Fienga et al., 2008) made at the IMCCE/ Observatoire de Paris,
- since 2014, INPOP10a (Fienga et al., 2011) and following versions of INPOP, developed every two or three years at the IMCCE/ Observatoire de Paris, Observatoire de la Côte d'Azur.

Note that since 1984, the argument of the ephemeris is Terrestrial Time (TT, which was called Dynamical Terrestrial Time TDT until 1991).

Detailed information on the analytical planetary theories built at the IMCCE are given in Simon and Bretagnon (2021), on ELP theories in Chapront and Chapront-Touzé (1997) and Mignard (2021) and on numerical INPOP integrations in Fienga (2021).

7.4 Sources of the Ephemerides of the Galilean Satellites

7.4.1 Analytical Methods and Numerical Integrations

The difficulty of building a pure analytical theory is to know what will be the most important perturbating terms, since it is quite impossible to calculate all of them by integrating equations.

Sampson (1921) had to choose his perturbating terms and forgot some periodic terms, the long-period ones appearing then as a secular trend by comparing ephemerides to the observations. Even with powerful computers, the analytical approach is still very difficult. Numerical integrations will provide directly numerical coordinates but will not indicate which perturbations are the larger. In order to get this information, a frequency analysis can be made allowing one to eliminate the not-so-useful perturbations.

7.4.2 Sources of the Ephemerides from 1980 to 2007

From 1980 to 2007, the CDT used Sampson's theory that had been recalculated on computers with errors corrected (Lieske, 1977). This was fitted to a large set of observations (contrary to Sampson only using eclipses) and it was possible to derive more precise ephemerides (Arlot, 1982).

7.4.3 Sources of the Ephemerides from 2008

From 2008, a brand-new theory of the Galilean satellites (Lainey et al., 2004a; 2004b) based on numerical integrations replaced the old model. Due to the use of numerical integrations, all of the gravitational perturbations were taken into account. Thanks to spectral analysis, we have knowledge of the different periodic perturbations.

8 TIME IN THE CDT

The name "*Connaissance des temps"* of the book itself ("*Knowledge of the times*") emphasizes the notions of time and knowledge of the time. The making of a confident time-scale useful for all the physical processes was the first goal of the CDT. The definition of a universal time-scale (Paris Mean Time) was necessary for the determination of longitudes. Therefore, when publishing positions of the Sun, the Moon and the planets, the timings have to be defined in a uniform time-scale corresponding to the uniform mathematical parameter of the theoretical models which is the time of Celestial Mechanics.

No astronomical observations useful for ephemerides purpose could be made without a confident time-scale, so the CDT published data allowing one to date an event through a time-scale based on the rotation of the Earth, which is supposed to be uniform (and is the definition of a 'day'), and on the rotation of the Earth around the Sun (which is the definition of a 'year'). Most of the changes in this time-scale have been due to scientific progress or to political events (e.g. French revolution), for some of the units used in the CDT. We will return to this later

This time argument must be formally linked to a concrete time-scale that is easily available to all astronomical observers. As we saw in the preceding Sections this time-scale of the ephemerides has changed greatly during the evolution of the CDT. The rotation of the Earth around its axis and around the Sun and the deduced Paris apparent solar time were first used since they were easily available through sundials. They were replaced in the CDT in 1834 by Paris Mean Time, which was supposed to be uniform since astronomers knew the inequalities of apparent time. In 1916 it was replaced by Greenwich Mean Time (GMT) according to the new definition of the prime meridian of the Earth. The, in 1925 it became Universal Time (UT = GMT + 12h).

However, these time-scales were only a materialization of the theoretical time-scale used to determine the ephemerides and depending on the observations used. Even if the time argument of the planetary ephemerides was called 'Temps Universel' in the CDT, it was actually a uniform time-scale related to the model and to the observations used for the ephemerides from Le Verrier's tables. It was close to the Ephemeris Time used by Newcomb and based on the motion of the Moon. Similarly, for the Galilean satellites the time argument was a uniform time-scale used by Sampson in his theory and directly linked to the observations of the eclipses of the satellites.

The difference between a uniform mathematical time parameter used in the theories and Universal Time in use by observers led to bad ephemerides that were difficult to extrapolate if this Universal Time was not uniform. Improvements were made by abandoning the rotation of the Earth in the definition of the time argument of the ephemerides, replaced first by the motion of the Moon, or by the one of the Earth around the Sun, and finally by Atomic Time which was much more uniform than astronomical time. From 1984, the CDT used TT, Terrestrial Time, based on the International Atomic Time (TAI) in accordance with the theories used in assembling the ephemerides (cf. Tables 2 and 4).

From the beginning, each year the CDT has published the calendar of the year. But even the calendar does not provide a direct time-scale (months and calendar years, are not astronomical units) although it is easier to use for observers than an astronomical time-scale such as the Julian Date. After the Julian Calendar was replaced by the Gregorian Calendar in 1582, there was no need to make astronomical measures in order to be sure that the year provided by the Gregorian Calendar was close to the Tropical Year. So, the CDT merely had to publish a calendar providing the right number of days in the year (and allowing for leap years).

9 THE LONGITUDE PROBLEM

9.1 Introduction

As we said, improving the measurement of longitude on land and at sea, was one of the main goals of the astronomers at the newly-founded Paris Observatory, and this question was then a major one for modern science (cf. Lamy, 2006).

At that time the development of international maritime trade made it essential to know how to accurately determine one's latitude and especially longitude (see de Grijs, 2017).

Navigation and cartography were very difficult because of the impossibility of easily determining the longitude of any point on the Earth.

In fact, if we can calculate the difference between the solar time of a given place and the solar time at a reference site, then we can deduce the longitude angle between the two sites from the time difference. On the other hand, determining latitude was much easier: it was usually just a matter of measuring the elevation of Polaris above the horizon.

The challenge was to know the reference time (solar time) of the reference site anywhere on Earth. The first solution was the use of mechanical clocks to keep the reference time during travels. However, mechanical clocks were not reliable enough and the best ones were too expensive to keep accurate time for more than a few days, and in addition it was necessary to use celestial observations to correct the clocks. The dating and timing of a lunar eclipse on a time-scale of a reference site (like Paris Observatory), could be used to determine the longitude of the 'foreign' observing site, but unfortunately such eclipses were rare and time-keeping at the 'foreign' sites was not always accurate. The challenge, therefore, was to look for other phenomena that were easily observable and occurred more often. For this purpose, the movement of Jupiter's satellites came to play an important role, despite the fact that Jovian satellite phenomena were not easily observable from the deck of a ship.

After the determination of time through a natural easily observable celestial event, it was necessary to know the positions of the planets and bright stars that could be observed with sextants and other small instruments. The CDT published all the ephemerides needed for such observations. Furthermore, the CDT published tables especially designed for sailors, as we will see.

9.2 Determining Longitudes Using the Jovian Satellites

At the time of their discovery, Galileo understood that eclipses of Jupiter's satellites could be used to determine terrestrial longitudes. Unfortunately, predictions were not as easy to make as the observations. Astronomers should be able to determine longitudes by simultaneously observing the same eclipse from two different observing sites (Figure 6a) and the travelers will be able to determine their positions on Earth by observing an eclipse and looking at the CDT to know the Paris time of the eclipse and calculating the longitude difference with Paris (Figure 6b).

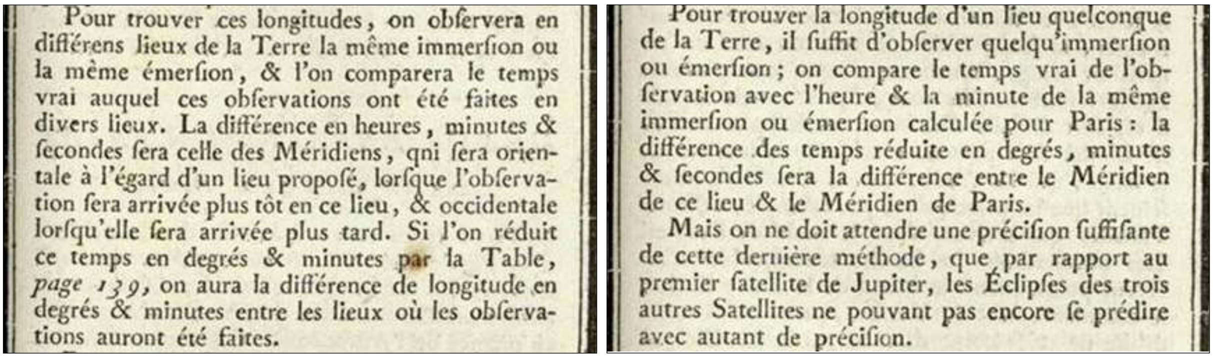
So, predictions of the eclipses of the Galilean satellites were extensively published each year, and with increasing accuracy. Accurate clocks and the adoption of chronometers reduced the need to observe these eclipses during the nineteenth century but the CDT continued to publish the predictions of eclipses in order to help and encourage the observers, knowing that these observations were the only way to improve ephemerides and the dynamical knowledge of such complex systems.

Besides the publication of the prediction of the Jovian eclipses, the CDT published other observations used for longitude determination from 1691 to 1810.

The publication of predictions of eclipses of the Jovian satellites started in 1690 with the eclipses of Io (cf. Figure 3) based upon Cassini's tables that had been published in 1668. The *Connaissance des temps* followed the scientific works, which consolidated the reliability of the published ephemerides. For years, the ephemerides were based on tables made through kinematics, as explained in the previous Section.

9.3 Determination of Longitudes Using 'Lunar Distances'

The eclipses of the Galilean satellites were not observable from the deck of a ship because of the movement of the ship, which was not compatible with the accurate use of a telescope. So another observation was used for the same purpose, namely to measure the distances from the Moon to selected bright stars. This was known as the 'Lunar Distances' method, or simply 'Lunars' (de Grijs, 2020). Such distances were observable as soon as the Moon was moving near bright stars, but measurements of the distances between selected stars and the


Pour trouver ces longitudes, on obſervera en différens lieux de la Terre la même immerſion ou la même émerſion, & l'on comparera le temps vrai auquel ces obſervations ont été faites en divers lieux. La différence en heures, minutes & ſecondes ſera celle des Méridiens, qui ſera orientale à l'égard d'un lieu propoſé, lorſque l'obſervation ſera arrivée plus tôt en ce lieu, & occidentale lorſqu'elle ſera arrivée plus tard. Si l'on réduit ce temps en degrés & minutes par la Table, *page 139*, on aura la différence de longitude en degrés & minutes entre les lieux où les obſervations auront été faites.

Pour trouver la longitude d'un lieu quelconque de la Terre, il ſuffit d'obſerver quelqu'immerſion ou émerſion; on compare le temps vrai de l'obſervation avec l'heure & la minute de la même immerſion ou émerſion calculée pour Paris: la différence des temps réduite en degrés, minutes & ſecondes ſera la différence entre le Méridien de ce lieu & le Méridien de Paris.

Mais on ne doit attendre une préciſion ſuffiſante de cette dernière méthode, que par rapport au premier ſatellite de Jupiter, les Éclipſes des trois autres Satellites ne pouvant pas encore ſe prédire avec autant de préciſion.

Figure 6: The CDT for geographers (left) and for travellers (right) (© IMCCE).

Moon produced less accurate results than the observations of Jovian eclipses.

We find some explanation of this method in the CDT starting in 1759, and from 1774 the CDT published lunar distances provided by the British *Nautical Almanac*. The publication of these distances stopped in 1903 when mechanical clocks were more accurate than the observations of lunar distances.

9.4 The Nautical Ephemerides

The abandonment of the lunar distances method of determining the time did not mark the end of astronomical determinations of longitude. It was still necessary to measure the elevations or culminations of bright stars or planets in order to determine the latitude and longitude of the observer through several methods, including 'les hauteurs égales'. At sea, a sextant could be used to measure the elevation of the Sun, the Moon, planets or bright stars, providing observations that could be used for the calculation of the position of the observer. The *Connaissance des temps* was designed to provide the positions of such objects. Catalogues of stars were published from time to time, and new stars were added regularly. Knowing Universal Time, several ways were available to determine latitude and longitude using the ephemerides published in the CDT.

However, in order to satisfy the Navy, ephemerides extracted from the CDT were published separately from 1889. The booklet was much smaller than the CDT which has >700 pages! This extract became the *Ephémérides Nautiques* a few years latter, and was especially designed for the calculation of positions at sea. It is still published yearly nowadays. Daily ephemerides are provided for the Sun, the Moon, the planets and bright stars.

10 THE FRENCH REVOLUTION AND THE *CONNAISSANCE DES TEMPS*

The French Revolution was a period of rupture and construction. It came at a time of intense scientific progress. The CDT crossed the centuries, following the society it explains and the world it measures. Among the data published by the CDT two fundamental elements led to modifications in the published data: the calendar (a revolutionary calendar) and the units (metric and decimal system).

10.1 A New Calendar

Before the French Revolution, the calendar in use was the Gregorian Calendar and all dates in the CDT came from this calendar. However, this calendar was too closely linked to religion and the old society that was being overthrown. So the French National Assembly decided to use the new calendar of the 'Liberty era' or 'French Republican era' starting on 22 September 1792 old style (SCMC-BDL, 1989). What impact did this have on the CDT and its ephemerides?

The opinion of astronomers regarding this new calendar was quite explicit given their silence! Indeed, while the CDT was the standard reference work in calculations of time, duration and calendar theory, this change was made in its volumes with the greatest silence. In 1795 two volumes suddenly were published. The first was named 1795 but mentioned the beginning of the year on '12 nivôse', while the second, which started on 23 September 1795 was named 'An 5'.

It is quite surprising to note that no mention was made of this primordial change depending on astronomical calculations before it was put into practice, while, as we will see next, the adoption of the metric system was, on the contrary, perfectly documented!

The first mention made, apart from the dates and the calendar itself, was a very complete presentation made by Delambre in the volume of 'An 7' (1798): "Methods to find the Sextiles of the French Calendar" (the CDT for 1798, pp. 318–347). He returns to all the details of this calculation of the true equinox and the intercalations for the next years, which, as we shall see, was one of the main arguments for later abandoning the calendar, and which he attempted to clarify and simplify. Due to the use of the true equinox, it appeared that the first day of the year was not predictable, for on the ‘An 144’ (22 or 23 September 1935) the equinox occurred near midnight, within the uncertainty of the motion of the Sun.

The second mention was a table for the correspondence between the Republican and the Gregorian Calendars published in the CDT for ‘An 9’ (1801).

The third one was similar to the first one by Delambre, but was presented to the Senate by Government representatives. It was a complete paper providing the arguments for abandoning the Republican Calendar and explaining the original reaction of the astronomers against this new calendar (the CDT for 1808, pp. 484–491). However, this text is more political than scientific. Certainly, the Bureau des longitudes (the new institution in charge of the CDT, succeeding the Academy of Sciences) was known not to be fully in favor of such a societal change, but above all it must be remembered that Napoleon Bonaparte was crowned Emperor of France in 1804. These texts dated from 1805 and it was time to disseminate them widely.

10.2 A New System of Units

Already before the French Revolution the standardization of commonly-used units in France had begun. The metric system arose based on the measure of the Earth. Simultaneously, the decimal division of units was adopted for the measure of distances, surfaces, volumes and weights, and for time and angles. In the report condemning the Republican Calendar, all the other decisions concerning the weights and measures were consolidated:

> All the changes, all the reforms that politics approved when genius designed them, that manners sanctioned when the laws enshrined them, that foreign nations will start by envying and will eventually borrow from the French nation, are and will always be carefully maintained by the administration, and strongly protected by the government. Such is, for example, the establishment of new weights and measures, which will always defend against routine, obstinacy or ignorance, the unanimity of the opinion of savans, the invariable basis of their work, nature itself from this base, which is common to all nations, the advantages of division for calculations, finally the need for uniformity for the Empire, and sooner or later the need for uniformity for the world. (Our English translation).

There is therefore no doubt that the reception of the metric system by the academics and members of the Bureau des longitudes was not the same as for the calendar, and that it was indeed entirely favorable to the advent of the metric system. It is now widely used and is the only or the most common system of weights and measures. It is now known as the International System of Units (SI), and is used to measure everyday things such as the mass of a sack of flour, the size of a person, the speed of a car and the volume of fuel in its tank. It is also used in science, industry and commerce.

This application also applies to time, which was intended to be decimal and which we will come back to later, but the 10-day week was abandoned even before the calendar as a whole and went in the same direction.

The calculation of the meter is clearly explained, as well as its use (it replaced the yard, the foot, the inch, etc.) and the means of verifying the calculation of this division of the quarter of the terrestrial meridian using the pendulum.

The units used for lengths, surfaces and weights (through volumes) became linked to the decimal system and to the meter, and finally to the dimensions of the Earth.

Then comes the calculation of the division of time, the duration of the day which has been divided into 10 hours, each hour in 100 minutes, each minute in 100 seconds. One day = 100000 seconds.

We see that the aim was universality in the measurement itself, both via its calculation from data common to all and via its accessibility promised by the decimal system.

The decimalization of time and angles was debated throughout the nineteenth century. It was abandoned for time but was continued for angles on French maps and some French instruments.

At this time, the main contribution of the CDT was the relatively recent scientific method of reproduction and systematic verification to which the Académie des Sciences and the Bureau des Longitudes applied themselves. The revolutionary period was, on many levels, a period of profound upheaval of society and its practices. The CDT, as a work that was both scientific and institutional, revealed these practices and the debates surrounding them, the calculations and theories that were born, evolved and sometimes collapsed. Through the calendar and the metric system we thus have both the detail of their conceptions, of their nature, but also, what they represented for institutions closer to the monarchy and Bonaparte than to Voltaire and Robespierre, but which however could not and did not wish to prevent society from advancing. And while decimal time did not happen, today we all know how universal the metric system has become.

Finally, the CDT continued, even during the new calendar period, to published dates with also the Gregorian Calendar and the hours, minutes and seconds in a non-decimal way for all the angles in right ascension, declination, latitude and longitude, since geometers, surveyors and geographers used the division of angles in grades.

11 INTERNATIONAL AGREEMENTS

The CDT was not the only ephemerides almanac in the world: most of the countries decided to publish their own ephemerides after the CDT was created. Some of them were made with genuine calculations, and the comparison with the CDT was of great interest. Collaborations and exchanges were made with other ephemeris bureaus. For example, in 1774 the Nautical Almanac sent the lunar distances calculated by Nevil Maskelyne (1732–1811) to the CDT, but more cooperation began at the end of the nineteenth century. This was because of the need for standards, which had to be defined through international discussions in order to facilitate comparisons between the different ephemerides, and especially the positions of reference stars. Moreover, it appeared that the making of ephemerides could be shared between the different ephemeris bureaus, thus reducing the amount of work necessary for each country. From 1884, the lunar ephemerides in Hansen's tables, with Newcomb's corrections, were used in the CDTs.

In 1886, the Conférence Internationale des Etoiles Fondamentales was held in Paris in order to unify the star catalogues used as a basis for the ephemerides of Solar System bodies. Resolutions concerning a unique fundamental catalogue were adopted.

In 1911, the Congrès International des Ephémérides Astronomiques was held at Paris Observatory. It decided to start a more active cooperation between the world's ephemerides offices. Calculations and the exchange of data were recommended. In the conclusion of the Congress report we read: "The Congress maintains the use of various sources for the calculation of the fundamental ephemerides of the Sun, the Moon and the planets …", while in the *Connaissance des temps* for 1915 and we read:

> Since 1915, the Connaissance des temps no longer publishes ephemeris relating to the satellites of Mars, Saturn, Uranus and Neptune and to the new satellites of Jupiter: one will find, according to the resolutions of the Congress, the ephemeris of the ring, and of the satellites of Saturn, with the exception of Phoebe, in the Berliner Astronomisches Jahrbuch, and the ephemerides of the satellites of Mars, Uranus and Neptune, as well as those of Phoebe and the new satellites of Jupiter in the American Ephemeris. (Our English translation).

Besides this preparation of ephemerides, the CDT provided Galilean satellite ephemerides to all the other ephemerides offices.

In 1916, a major change occurred concerning the fundamental meridian:

> It is first essential to observe that from this year 1916, the fundamental meridian adopted by the *Connaissance des temps* is the meridian of Greenwich.

In 1919, after the creation of the International Astronomical Union (IAU), a Commission for Ephemerides was formed, and the directors of the various ephemerides offices met during each IAU General Assembly.

In 1925, the ephemerides time argument was defined as follows: "… from the present year 1925, the ephemerides argument is the Civil Time of Greenwich." This was published as a special note, which was added to the CDT for 1925.

However, until the middle of the twentieth century very few improvements were brought to ephemerides—which were considered to be 'perfect'—and it was only the arrival of space projects during the 1960's that encouraged ephemerides bureaus to improve their production. The CDT progressed in the 1980's mainly by adopting new models for ephemerides calculations.

In 1984, we read in the CDT:

> The system of astronomical constants [is the one] adopted by the International Astronomical Union in 1976. The epoch is J2000.0 and the adopted time scale is in accordance with the decisions of the International Astronomical Union. (Our English translation).

The adopted time-scale was the Temps Atomique International + 32.184s.

In 2006, the CDT adopted the following new IAU resolution:

The new IAU resolutions adopted in 2000 and involving, in particular, the use of the non-rotating origin are applied further, since the values of the variables linked to the new concepts are given for the current year.

12 CONCLUDING REMARKS

This institutional handbook of ephemerides is a witness of the evolution of celestial mechanics and then ephemerides. This evolution is shown by the results in the tables of ephemerides and also by a rich set of scientific publications.

In this paper, we have tried to show the evolution and the increasing accuracy of data published in the CDT through the use of the best theoretical models. Year after year, the CDT continued to published ephemerides with more and more accuracy, leading to more and more pages. For that purpose, theories of the motion of the Solar System bodies changed from sample kinematic models to models determined using the laws of celestial mechanics mainly thanks to Laplace who profoundly modified the making of ephemerides.

As we could see, the ephemerides made by Le Verrier were published in the CDT during more than one century from 1864 to 1983 and from that date, ephemerides have been improved regularly using the more and more precise observations, mainly coming from space probes.

Besides the interest in high accurate ephemerides for space probes navigation, another goal remains fundamental. Including all known gravitational or non-gravitational effects in the models used for ephemerides building, will allow, thanks to the comparison of ephemerides to observations, the detection of unknown effects or quantify known effects such as the dissipation of energy inside some of the Solar System bodies. We have here, thanks to ephemerides, a new possibility from Earth-based observations to get constraints on the interiors of the bodies. This is especially true for natural satellites systems.

Today, the availability of ephemerides through the Internet means it is not necessary to have a handbook presenting ephemerides for observers. However, the improvement of ephemerides continues either for our knowledge of the dynamical problems and of the non-gravitational forces in the Solar System, or more simply, for the navigation of space probes towards planets. Several laboratories are working on these improvements and it is necessary to have references.

So, the CDT continues to publish original genuine ephemerides that are essential for the other ephemerides-makers, and allow comparisons between dynamical models. In conclusion, we can understand how the CDT became a reference for accurate ephemerides, their making and how the 346 previously published CDTs are useful in our understanding of the history of ephemerides during the past three hundred years.

All the volumes of the CDT are available at: https://cdt.imcce.fr/collections

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