A HISTORY OF WESTERN ASTRONOMICAL ALMANACS

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Abstract: Astronomical data were the basis for calendars, time, phenomena predictions, and theories about the universe from the earliest days. Knowledge developed independently in different countries and then was exchanged when international trading developed. There was an apparent lack of development of knowledge during the middle ages. Then at the reformation period a new increase in theories, observations, and knowledge developed. The advent of the printing press brought the availability of almanacs in large numbers for everyday use. The requirements of calendars, navigation, and astronomical information led to national almanacs and improved accuracies. The need for standards for reference systems, including ephemerides, time scales, astronomical constants, and star catalogs led to international cooperation. New technologies, computers, and the space age led to improved accuracies and new reference systems. Calculators and computers led to new methods of access to almanac data, including data online.

Keywords: almanacs, ephemerides, calendars, cultures BC, astronomical phenomena, celestial navigation, national almanac offices, astronomical history.

1 INTRODUCTION

From earliest times astronomical information was used for determining calendars, time, climate, farming, seasons, and phenomena predictions, including eclipses. Some evidence includes astronomical alignments, stone circles, clay tablets, and oral histories. Many cultures developed calendars based on solar and lunar cycles, with varying accuracies and methods of adjusting for the differences in the even cycles. Religious holidays were based on equinoxes as the epoch of calendars. Star catalogs and planetary motions were recorded. Determinations of geographic locations and distances were attempted. Times of day were based on sunrises and sunsets, with varying lengths of hours. The difference between apparent and mean solar times was recognized and uniform lengths of hours were introduced based on methods of timekeeping. Developments in different cultures took place independently and knowledge was shared due to international trade and communication (see Nha et al., 2017; Stern, 2012).

The first observer, probably in the third millennium BC, noted the motions of the Sun, Moon, planets, and stars. This led to the first ability to predict positions of planets and eclipses. The earliest records of astronomical data are found in India, Babylonia, Greece, Egypt, and the Far East (China and Korea). The astronomies of India and Greece are very different. It appears developments took place independently in the different countries, and then there was communication due to trade between the countries.

This paper takes a narrower geographical perspective and only examines 'Western almanacs' and their origins. For our purposes, the following definitions are used. *Treatises* are 'how to texts', such as Ptolemy's *Almagest* of AD 150 and Copernicus's *De Revolutionibus* of AD 1543. *Tables* are orbital elements and tables of terms, usually Fourier terms, which are calculated for a specific date. These were used to determine the positions of planets for astronomical and astrological purposes. In most cases multiple dates were not desired. Examples are Ptolemy's *Handy Tables* of AD 150, the Ptolemaic-based *Alfonsine Tables* of AD 1320, which were not significantly improved over the *Handy Tables*, and Copernican based *Prutenic Tables* of AD 1551 (Gingerich, 2017). The word *ephemeris* is derived from ancient Greek *epi*, which means about and *hemera*, which means day. Ephemeron means short lived and temporarily valid, i.e. something that is valid for a day. In Greek an ephemeris can be a newspaper. Thus, in astronomy an *ephemeris* (plural *ephemerides*) is a tabulation of the positions of a planet or satellite for a series of equally spaced dates, such as daily for a year. These were computed from tables until the availability of punched card equipment and computers. *Almanacs* provide ephemerides and astronomical data usually for a year, with daily information as useful for the purpose of the almanac. Thus, astronomical, nautical, and air almanacs are designed for astronomical observations and astronomy, navigation of ships, and airplanes, respectively. *Calendars* are designed to follow the solar and/or the lunar periods, with some relations to the vernal equinox for religious purposes (McCarthy and Seidelmann, 2018).

2 THE ORIGIN OF THE WESTERN ALMANAC

2.1 Babylonia

Writing on clay tablets was invented near the end of the fourth millennium BC in the city of Uruk in southern Mesopotamia. During the third millennium BC stars and constellations were included on the tablets. In the second millennium

BC texts of astronomical phenomena appeared. A large number of clay-baked cuneiform tablets recorded the passage of daily life on the plains between the Tigris and Euphrates Rivers, and some gave the positions of the Sun, Moon, planets, and stars. Sumerian astronomy and record keeping was adopted by their neighbors to the north, the Babylonians, after conquest and absorption. Initially, the Babylonians' motivation seemed primarily calendrical, but became a religious conduit between Earth and Heavens. From these beginnings around 2500 BC, there is a continuous path to present-day astronomy (Steele, 2000).

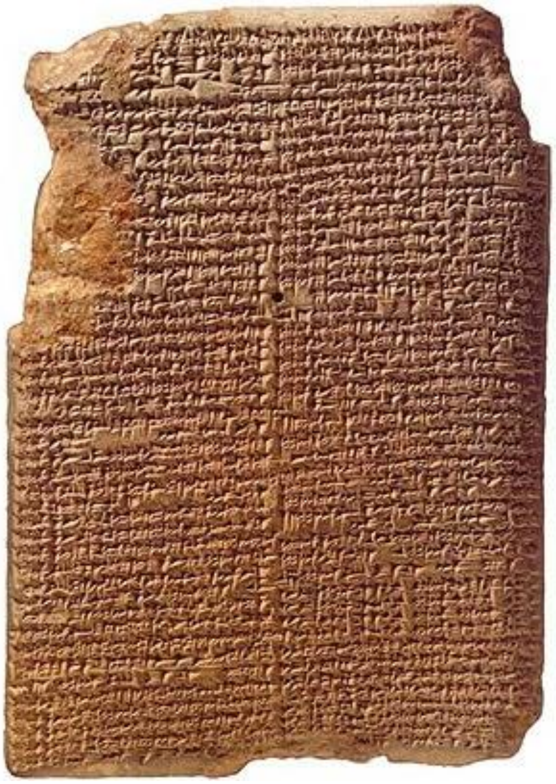


Figure 1: One of two clay tablets containing the astronomical text, *Mul-Apin* (https://es.wikipedia.org/wiki/MUL.APIN).

The Babylonian tablets dating from the first half of the second millennium BC gave celestial omens. For Mesopotamia, the events in the sky were considered messages from the gods to warn people of potential events. By prayers, rites, and sacrifices, the predictions could be prevented. Astrology, from Hellenistic times, implied belief in powers emanating from the stars and planets, which caused things to happen on Earth, and they could not be escaped (Hunger, 2009).

After the Hittite Conquest in 1530 BC astronomical traditions were improved and catalogs of helical risings of the Moon and stars appeared. The organization of the sky was sought, such as the *Three-stars-each* texts, probably dating to between 1500 and 1000 BC. For each month of the Babylonian calendar three constellations, which would be visible, were listed, one to the North, one near the equator, and one to the South. Tablets from 1500 and 1250 BC gave methods of calculating the position of Venus; a simple pattern repeated at intervals of about eight years. These tablets were part of the set of omens known as *Enuma Anu Enlil*, astronomical compilations and omens that may have been from as much as a thousand years earlier. By the seventh century BC timings of lunar eclipses appear. By the fifth century BC a celestial coordinate system, in the form of the zodiac with 12 constellations of 30 degrees each, was developed. By the time of Cambyses in 521 BC the phases and positions of the Moon were recorded within a fraction of an *usb,* a time unit of about 4 minutes (Steele, 2000).

In the second half of the first millennium BC new techniques for insight into the future were developed and one was called *horoscopes*. It is really not correct to call these Babylonian texts *horoscopes*, because they lack consideration of the point of ecliptic rising at the time of birth, which was called *horoskopes* in Greek. So the detail, from which the name *horoscope* is derived, is not present in the Babylonian *horoscopes.* Babylonian horoscopes were computed for private persons, as well as for the king, and rarely contained predictions. There were almanacs containing predicted data as needed for composing horoscopes, such as in which zodiacal sign the different planets were in a given month. The almanacs were likely prepared based on the periods when astronomical phenomena reoccur (Hunger, 2009).

An astronomical text, *Mul-Apin* (Figure 1), which means Plough star after its first word, probably goes back to the thirteenth century BC. It contained six lists of stars and constellations, periods of visibility of planets, two schemes of intercalation of calendars, and a table of the length of the shadow of a stick at different times of the day and seasons. In the seventh century BC Babylonian scholars tried to forecast when and where certain phenomena would happen. Eclipses of Sun and Moon were described in detail. The Babylonian calendar used lunar months beginning with the first visibility of the lunar crescent after New Moon. The months were 29 or 30 days long, 12 months being approximately 354 days. A month was added when the seasons no longer fitted the calendar. In early times the king decided intercalation. Regular intercalation, according to the *Mul-Apin,* was applied from the seventh century BC. By around 500 BC a cycle of 19 years with 7 fixed intercalations was introduced. The *Mul-Apin* lists the amount of water to flow in or out of a water clock to measure daylight at different times of the year. At night, time was measured by the culmination of stars. Appropriate stars were listed in the *Mul-Apin* (Hunger, 2009).

The Babylonians used a ‘Metonic’ year of 12 ordinary and 7 intercalary (13 month) lunar years, i.e. a cycle of 235 lunations. The Metonic year is 14 minutes short of the sidereal year and 6 minutes longer than the tropical year. The years are usually counted in the “Seleucid Era” (S.E.) beginning with the new crescent of 3 April –310 (Neugebauer, 1967). The synodic month was their fundamental time measurement. Ptolemy retained the Metonic year, but took it as his tropical year. This difference is small, but accumulates to a day in 240 years and a whole week by Copernicus’ time, so the *Almagest Tables* of solar motion had fallen behind by 7 degrees (Moesgaard, 1983).

After the fall of the Assyrian empire (612 BC) and the rise of Persia (539 BC), systematic observations of planetary events began, astronomy that was missing from earlier years in Babylonia. The oppositions of Jupiter repeating in 80 year intervals, Saturn at 59 years, Mars at 47 years, and Venus at 8 years, were known. Predictions joined observations on tablets (Steele, 2000). Astronomical diaries from Babylonia contain records of continuous and systematic observations, so they are sources of natural and astronomical phenomena in the BC era (Hayakawa et al., 2016). A diary tablet usually covers half a year, but some cover single months. There are only a half dozen from before 400 BC, but there is coverage for almost every year for the second century BC (Sachs and Hunger, 1988; 1989).

Once Babylonian influence was not so dominant, the Greek astronomers decided on cinematic models, and the Babylonian methodology became inapplicable. The historical significance of Babylonian astronomy is that here, for the first time in human history, purely mathematical methods were shown to provide a most successful description, and hence prediction, of natural phenomena, free of philosophical principles —which have been the obstacle to scientific development (Neugebauer, 1967; 1983).

2.2 Greece

The first Greek philosophy took place in Miletus, a trading center on the Asiatic coast. Indian and Babylonian science was antecedents of Greek science. Greek Culture was due to Mesopotamians and Egyptians, which together formed the basis of western science (Kak, 2007).

Greek astronomy was shaped by Babylonian observations and mathematical astronomy as transmitted in the second and first millennia BC (Jones, 2015a). The Greeks inherited records of thousands of heavenly occurrences from the Babylonians. The Greeks obtained entire complex computational schemes from Babylonia (Neugebauer, 1988). The Babylonians kept records of eclipses and calculated their recurrences by series known as Saros, intervals of 18 years and 11 days. Thales of Miletus (624–546 BC), the ‘Father of Philosophy’, learned geometry in Egypt about 600 BC and brought it back to Greece. He forecast the total eclipse of the Sun of 28 May 585 BC. However, the Chinese kept eclipse records from 2137 BC (Ionides and Ionides, 1941). The Greeks sought accurate planetary tables after accepting astrology from the Babylonians. Greek mathematical astronomy was fundamentally geometrical in conception, but became more quantitative and numerical due to Babylonian astronomy (Jones, 2015b). The Greeks also adopted the sexagesimal number system from the Babylonians. About 300 BC Euclid’s *Elements* synthesized the achievements of his predecessors.

Around 200 BC Apollonius of Perga (fl. late third to early second centuries BC) proposed the use of eccentric circles, where the planets move at a uniform angular velocity, but with the center of the circle not at the Earth. This let the planet to vary in distance from the Earth. He also proposed for the planet to move uniformly on a little circle, or epicycle, whose center moved uniformly on a large circle centered on the Earth. According to Archimedes and Plutarch, in 270 BC Aristarchus of Samos (310–230 BC) proposed that the Earth spun on its axis and moved in a circular orbit around the Sun with the Moon orbiting the Earth. While astronomy was becoming more sober, serious, and technical at that time, this proposal was not generally accepted. Aristotle (384–322 BC), his greatest pupil, disagreed due to the lack of feeling of motion on Earth.

The spherical shape of the Earth was known to Pythagoreans, long before Plato (ca. 428–348 BC). The Greek sense of symmetry required a spherical Earth at the center of spherical heavens. The stars rotated daily about the Earth, except for the ‘wandering stars’, in Greek the planets. Multiple spinning spheres explained the motion of these planets. Aristotle studied scientific geography and gave reasons for the Earth being a sphere (Ionides and Ionides, 1941).

In the second century BC Hipparchus of Rhodes (ca 120–190 BC; Figure 2) was the first careful observer and competent mathematical Greek astronomer. He compiled a catalog of over 800 stars and discovered precession of the equinox. He prepared a table of eclipses for the next 600 years. He used Apollonius’ tools to construct geometrical models of the motions of the Sun and Moon. A number of Greek papyri from Oxyrhyncus in Egypt, dating from the first century BC to the sixth century AD, are closely related to Babylonian arithmetic schemes and depend on Greek kinematic models (Jones, 1999).

Figure 2: Hipparchus of Rhodes (https://en.wikipedia.org/wiki/Hipparchus#/media/File:Hipparchos_1.jpeg).

In AD 150 Ptolemy (ca AD 100–170; Figure 3) created accurate geometrical models for compiling positions of the planets for centuries in the *Almagest,* largely based on the work of Hipparchus. This was unrivaled for 1400 years until the fifteenth century (Hoskin, 1983). Due to the availability of Euclid's and Ptolemy's works, writings of their predecessors largely vanished.

By the second century AD the Greeks could predict eclipses, chart the planets, catalog stars, discover precession, know the Earth was spherical, and guess that the Earth moved around the Sun.

Figure 3: Ptolemy as depicted by a sixteenth-century engraving (https://en.wikipedia.org/wiki/Ptolemy#/media/File:Ptolemy_16century.jpg).

3 PRE-SEVENTEENTH CENTURY ALMANACS

3.1 The Early Period

After the end of the Roman Empire the science of astronomy declined in Western Europe. Barbarians and empire building took attention away from sciences, which were pursued in monasteries, by noblemen, and the Islamic Golden Age. Nicolaus Copernicus (1473–1543; Figure 4) formulated a heliocentric model of the Universe with the Sun at the center. He published this in *De Revolutionibus Orbium Coelestium* (*On the Revolutions of the Celestial Spheres*) just before his death in 1543. This started the Copernican Revolution and new determinations of positions of the Sun, Moon, and planets. Erasmus Reinhold (1511–1553), Professor of Higher Mathematics, Dean, and Rector at the University of Wittenberg, published *Prutenicae Tabulae* (*Prussian Tables*) in 1551. The tables spread the calculation methods of Copernicus, however according to Gingerich (1973) they were framed to be independent of the movement of the Earth. These tables and Copernicus' writings were the foundation of Calendar Reform by Pope Gregory XIII in 1582.

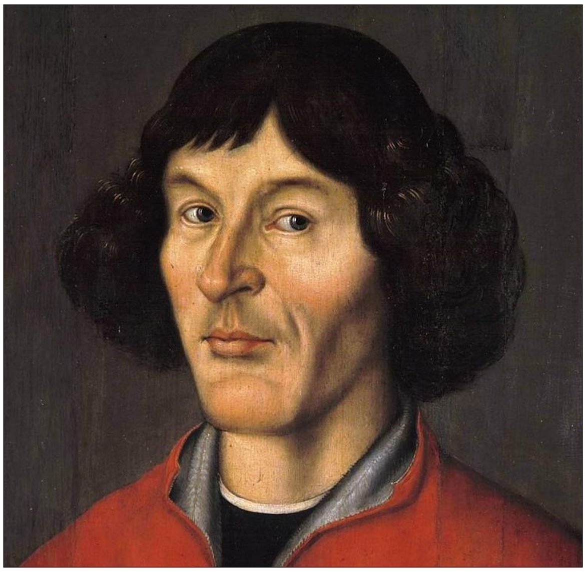


Figure 4: A portrait dated about 1580 of Nicolaus Copernicus at the Town Hall in Toruń (https://en.wikipedia.org/wiki/Nicolaus_Copernicus#/media/File:Nikolaus_Kopernikus.jpg).

Nostradamus (1503–1566), an astrologer for wealthy patrons, wrote an almanac for 1550 and years after. In 1555 he published *Les Prophecies*, a collection of 942 poetic quatrains supposedly predicting future events. Nostradamus has attracted supporters, who with the popular press have claimed he has accurately predicted major world events. Most academic sources consider his predictions vague and useless for accurate predictions. The translations of the original sixteenth century French are of poor quality and maybe deliberately mistranslated.

The Romans, Hebrews, and Greeks used a cumbersome numerical system using letters of the alphabet. This made it difficult to deal with large numbers and to do mathematics. The Babylonians counted in base 60, so they could multiply and divide large numbers. This gave them an advantage in dealing with long time periods and calendars.

Prior to the seventeenth century there was neither the need for nor the ability to provide ephemerides or almanacs. The needs for astronomical positions were for observing and astrology, so positions of astronomical bodies were only needed for individual dates. Computations for unneeded dates were wasted. There were no movable-type printers for printing tabular material. Only three manuscripts are currently known of calculated daily planetary positions, that date between 24 BC to AD 1450.

3.2 Islamic Astronomy

In AD 762 the Abbasid Caliphate became prominent in the growing Islamic Empire and moved to Baghdad. The House of Wisdom was an academy established in Baghdad for astronomical research. The trade routes allowed the mixing of knowledge from India, China, Persians, Greeks, Egyptians, and Jews. Islamic scholars preserved knowledge while translating it into Arabic and increasing it. Arabs knew astronomy and used it to navigate in the deserts. They also needed to know the direction of Mecca and time of day for prayers. During the Islamic period AD 900–1400 astronomical *zijes*, which are texts with astronomical tables, were numerous, but few have survived (see King and Samso, 2001). One Arabic ephemeris for AD 1326–1327 is preserved in the Egyptian National Library (2011).

Zij al-Sindh by al-Khwarizmi (ca 780–850) in AD 830 contains tables for the motions of the Sun, Moon, and five planets (Toomer, 1973). Al-Battani (858–929) wrote *Klitabal-Zij*, improving on Ptolemy's *Almagest,* and including a star catalog, solar, lunar, planetary, and trigonometric tables. This and other books reached Europe and would influence Kepler, Galileo, and Tycho (Hartner, 1970). Rahman Al Sufi (903–986) wrote his *Book of the Fixed Stars* (Figure 5) correcting mistakes by Ptolemy and documenting the order of magnitudes of stars and giving Arabic names to stars that remain in use (Hafez et al., 2011). Al Biruni (973–1048) invented the first planisphere to track the movements of the stars and constellations over the year. This device is considered one of the first analog computers (Boilot, 1955). Abu Ishaq Ibrahim al-Zarqali (1029–1088), also known as Arzachel, invented the equitorium to chart the movement of the Sun, Moon, and planets, and he devised a lunisolar computer to calculate the time of year and phases of the Moon (Puig, 2014). In 1267 Jamal ad-Din, a Persian astronomer, presented Kublai Khan with an astronomical almanac, which was later known in China as the *Ten Thousand Year Calendar,* or *Eternal Calendar*. In China he was known as Zhamaluding and in 1271 he was the first Director of the Islamic Observatory in Beijing. Omar Khayyam and collaborators constructed a *zij* and the Persian Solar Calendar, the *jalali calendar,* a modern version of which is still in official use in Iran (Dalen, 2014). This was the Islamic Golden Age leading up to the Renaissance (see Kennedy, 1998; King, 1999; King and Samso, 2001; Saliba, 1994).

Figure 5: The constellation "Lepus" (The Hare) in al-Sufi's *Book of the Fixed Stars*. At the top of the figure is an image of the constellation (in duplicate). In the lower part is the table of stars in this constellation, including their ecliptical coordinates and estimated magnitudes (after Hafez et al., 2011: 124).

3.3 Early Ephemerides

Prior to the printed ephemerides, two manuscript ephemerides were prepared by European astronomers or astrologers. One for AD 1426 is preserved in the Bibliotheque Nationale in Paris, and another for AD 1442–1458, by London astrologer Richard Trewythian, is in the British Library (re the latter, see Page, 2001). The format of these manuscripts is similar to earlier fragments and future printed ephemerides. They have martius aprilis

Tabula ascēdētis et duodecim domorum

dies mensium	hore	minuta	1 / 7 cācer g	2 / 8 leo g	3 / 9 leo g	4 / 10 virg g	5 / 11 scor g	6 / 12 sagi g	dies mensium	hore	minuta	1 / 7 leo g	2 / 8 leo g	3 / 6 virg g	4 / 10 libr g	5 / 11 scor g	6 / 12 capc g
1	0	0	12	3	26	20	0	7	1	1	53	5	29	25	21	28	1
2	0	4	13	4	27	21	1	8	2	1	56	5	30	26	22	29	2
3	0	8	13	5	28	22	2	9	3	2	0	6	♍1	27	23	30	3
4	0	11	14	6	29	23	3	10	4	2	4	7	2	28	24	30	4
5	0	15	15	7	30	24	4	11	5	2	7	8	3	29	25	♐1	5
6	0	19	16	8	♍1	25	5	12	6	2	11	9	3	30	26	2	5
7	0	22	17	8	2	26	6	12	7	2	15	9	4	♎1	27	3	6
8	0	26	17	9	3	27	7	13	8	2	18	10	5	2	28	4	6
9	0	30	18	10	4	28	8	14	9	2	22	11	6	3	29	4	7
10	0	33	19	11	4	29	9	14	10	2	25	12	7	4	30	5	8
11	0	37	19	12	5	30	9	15	11	2	29	12	8	5	♏1	6	9
12	0	41	20	12	6	♎1	10	16	12	2	33	13	9	5	2	7	9
13	0	44	21	13	7	2	11	17	13	2	37	14	9	6	3	8	10
14	0	48	22	14	8	3	12	18	14	2	41	14	10	7	4	9	11
15	0	52	22	15	9	4	13	18	15	2	44	15	10	7	4	9	11
16	0	55	23	16	10	5	14	19	16	2	48	15	11	8	5	10	12
17	0	59	24	17	11	6	15	20	17	2	52	16	12	9	6	10	12
18	1	2	25	18	12	7	16	21	18	2	56	17	13	10	7	11	13
19	1	6	25	18	13	8	17	21	19	3	0	17	14	11	8	12	14
20	1	01	26	19	13	9	17	22	20	3	3	18	15	12	9	13	15
21	1	13	27	20	14	10	18	23	21	3	7	19	16	13	10	14	15
22	1	17	28	21	15	11	19	24	22	3	11	20	16	14	11	15	16
23	1	20	28	22	16	12	20	24	23	3	15	20	17	15	12	15	17
24	1	24	29	22	17	13	21	25	24	3	19	21	18	16	13	16	18
25	1	28	30	23	18	14	22	26	25	3	23	22	19	17	14	17	18
26	1	31	30	24	19	15	23	27	26	3	26	23	20	18	15	18	19
27	1	35	♌1	25	20	16	23	27	27	3	30	23	21	19	16	18	20
28	1	38	2	25	21	17	24	28	28	3	34	24	22	20	17	19	21
29	1	42	3	26	22	18	25	29	29	3	38	25	23	21	18	20	22
30	1	46	3	27	23	19	26	29	30	3	41	26	24	22	19	21	23
31	1	49	4	28	24	20	27	30	0	0	0	0	0	0	0	0	0

Figure 6: A page from Zacuto's *Book of Tables on the Celestial Motions or the Perpetual Almanac* (https://upload.wikimedia.org/wikipedia/commons/c/cd/AlmanachPerpetuum.jpg).

vertical columns for the different celestial bodies and horizontal rows for specific dates.

Johannes Muller (1436–1474) from Konigsberg in Bavaria took the name Regiomontanus and made observations and wrote a book on trigonometry. In the 1470s he used the *Alfonsine Tables* to calculate 32 years of daily planetary positions, which were used to print ephemerides in 1474 for 1475–1506 (Zinner, 1990). Abraham Ben Samuel Zacuto (1452–1515; Chabás and Goldstein, 2000) was a Professor at the University of Salamanca in Spain and took refuge in Lisbon, Portugal, where he was Royal Astronomer and Historian to King John II. While in Salamanca from 1470–1478 he wrote *The Great Book*, which contained 65 detailed astronomical tables (ephemerides) in almanac format of the positions of the Sun, Moon, and planets on the meridian of Salamanca. The calculations were based on the *Alfonsine Tables*. His book was translated into Castillan and Latin, and had the title, *Book of Tables on the Celestial Motions or the Perpetual Almanac* (Figure 6). The almanac gave solar declinations, so navigators could use the Sun for determining latitude. Supposedly Columbus used Zacuto's tables.

Figure 7: A drawing of Johannes Stoffler made by Jean-Jacques Boissard in 1630 (https://upload.wikimedia.org/wikipedia/commons/e/ef/Stoeffler1.jpg).

Johannes Angelus (1453–1512) (also called Engel), a medical doctor and mathematician in Vienna, published almanacs and astrological calendars in German and Latin from 1484. *Astrolabium Planum*, with tables of astrological calculation and horoscopes, was published in Augsburg in 1488. Further editions were published in 1494 and 1502. He published ephemerides in 1510 and 1512 with daily planetary positions and planetary aspects. These were in the format of the ephemerides of Regiomontanus. Angelus titled the ephemerides *Almanach Aovum atque Correctum* and said in the prefaces the planetary longitudes were more accurate than in common almanacs. Studies show that his ephemerides are different from those from the *Alfonsine Tables*, but not more accurate (Dobrzycki and Kremer, 1996).

Johannes Stoffler (1452–1531; Figure 7), Chair of Mathematics at the University of Tubingen, published his *Almanach Nova* in 1499, in collaboration with Jacob Pflaum. This continuation of the ephemeris of Regiomontanus had a large circulation with 13 editions until 1551. In 1518 Stoffer published *Calendarium Romanum Magnum,* whose tables were restricted to the positions and syzygies of the Sun and Moon. The introductory chapters described how the tables could be used for keeping time, administering medical remedies, predicting eclipses, and calculating mobile feast days (Vescovini, 2014).

Johannes Stadius (1527–1579), sixteenth century Professor of Mathematics at the University of Leuven, went to Turin in 1554 and also worked in Paris, Cologne, and Brussels. His 1554 *Ephemerides Novae at Auctae* corrected and improved the ephemerides of the *Alfonsine*

Tables predicting the positions of the Sun, Moon, and planets at a given moment of time. This was both an astronomical and astrological work and the joining of medicine and mathematics.

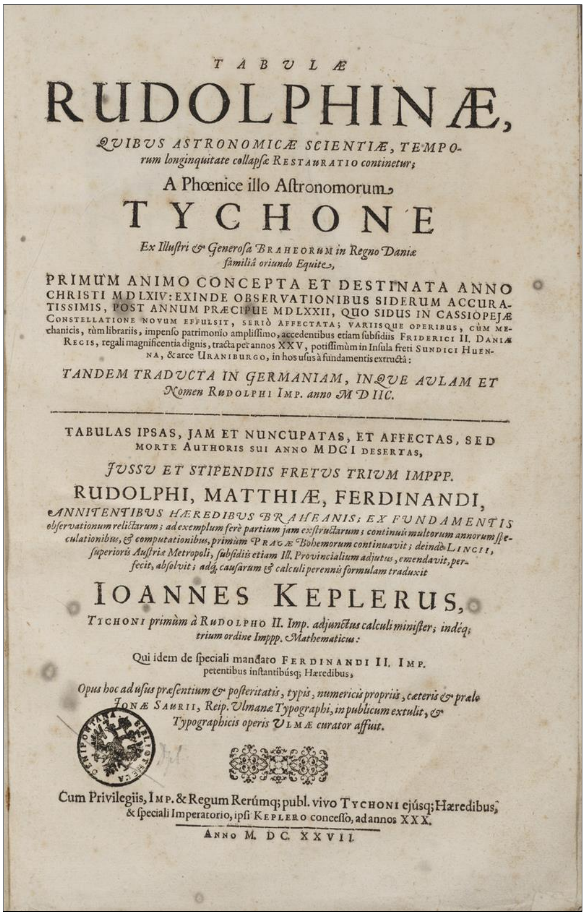
Contrary to popular stories there were no real improvements in the calculation tables from Ptolemy until Johannes Kepler (1571–1630; Figure 8) published his *Rudolphine Tables* (Figure 9) in 1627 (Gingerich, 2017). Using observations made by Tycho Brahe, Kepler improved the predictions by two orders of magnitude. Kepler's first volume for 1617–1620 was not based on the complete *Rudolphine Tables*, but volumes for 1621–1636 followed the new tables precisely. A competing, simpler, old-fashioned, complete set of tables was published a little later by Dutch astronomer Philip Lansbergen (1561–1632). In the 1630s astronomers had little means to judge the results from Kepler's complex methods of computing planetary positions versus Lansbergen's simpler tables, which were similar in style to the *Alfonsine Tables*. Later, Noel Duret proved that Kepler's results were superior (Gingerich, 2017).

Subsequently the distribution of astronomical data and ephemerides began in different countries at different times and for different reasons. For an overview of British almanacs at this time see Capp (1979). There is a series of publications, in *Nature* in 1873 and 1874 under the title "Astronomical Almanacs", without a designated author, on the detailed history of the *Connaissance des temps, The Nautical Almanac*, and the J*ahrbuch* of Berlin. The changes in personnel, sources of data, changes in accuracies, and sources of errors are detailed (Astronomical Almanacs, 1873, 1874).

3.4 Calendars

Printed calendars and almanacs became popular in the fifteenth century and provided ordinary people with basic knowledge for their daily routines (Nha et al., 2017). Gutenberg published a calendar. Earlier calendars were superseded by Regiomontanus' calendar, which was much more accurate. Johannes Muller von Konigsburg (1436–1476; Figure 10) was better known as Regiomontanus (Zinner, 1990). He was Professor of Astronomy and Mathematics at the University of Vienna and then Astronomer to King Matthias Corvinus of Hungary. He built an observatory in Nurenberg in 1471 and his own private press to publish his discoveries. He printed the first edition of his calendar in 1472. In 1475 he was summoned to Rome by Pope Sixtus IV to assist in the reform of the calendar. On the way to Rome he commissioned the publication of his *Calendarium* by Erhard Ratdolt of Venice in 1476. Although Regiomontanus' calendar was only valid for the location of his ob-

Figure 8: A portrait of Johannes Kepler by an unknown artist, painted in 1610 (https://en.wikipedia.org/wiki/Johannes_Kepler#/media/File:Johannes_Kepler_1610.jpg).



TABULÆ
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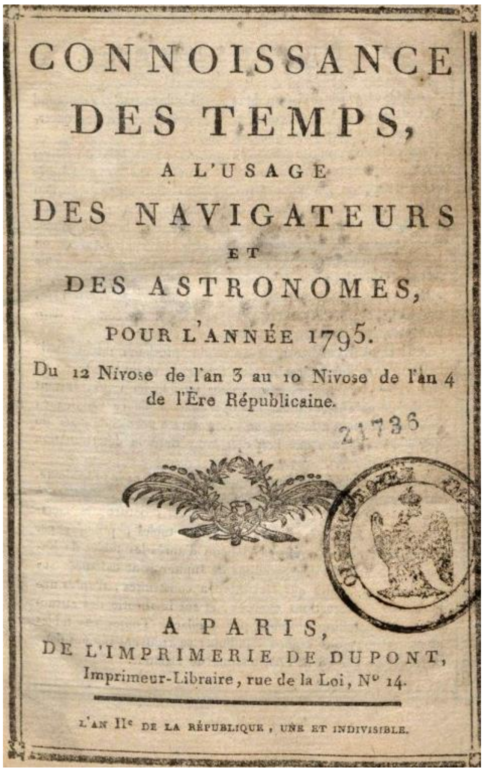
QUIBUS ASTRONOMICÆ SCIENTIÆ, TEMPOrum longinquitate collapsæ RESTAURATIO continetur;
A Phœnice illo Aſtronomorum
TYCHONE
Ex Illuſtri & Generoſa BRAHEORUM in Regno Daniæ familiâ oriundo Equite,
PRIMUM ANIMO CONCEPTA ET DESTINATA ANNO CHRISTI MDLXIV: EXINDE OBSERVATIONIBUS SIDERUM ACCURATISSIMIS, POST ANNUM PRÆCIPUE MDLXXII, QUO SIDUS IN CASSIOPEJÆ CONSTELLATIONE NOVUM EFFULSIT, SERIÒ AFFECTATA; VARIISQUE OPERIBUS, CÙM MEchanicis, tùm librariis, impenſo patrimonio ampliſſimo, accedentibus etiam ſubſidiis FRIDERICI II. DANIÆ REGIS, regali magnificentia dignis, tracta per annos XXV, potiſſimùm in Inſula freti SUNDICI HUENNA, & arce URANIBURGO, in hos uſus à fundamentis extructâ:
TANDEM TRADUCTA IN GERMANIAM, INQUE AULAM ET Nomen RUDOLPHI IMP. anno MDIIC.

TABULAS IPSAS, JAM ET NUNCUPATAS, ET AFFECTAS, SED MORTE AUTHORIS SUI ANNO MDCI DESERTAS,
JUSSU ET STIPENDIIS FRETUS TRIUM IMPPP.
RUDOLPHI, MATTHIÆ, FERDINANDI,
ANNITENTIBUS HÆREDIBUS BRAHEANIS; EX FUNDAMENTIS obſervationum relictarum; ad exemplum ferè partium jam exſtructarum; continuis multorum annorum ſpeculationibus, & computationibus, primùm PRAGÆ Bohemorum continuavit; deindè LINCII, ſuperioris Auſtriæ Metropoli, ſubſidiis etiam Ill. Provincialium adjutus, emendavit, perfecit, abſolvit; adq; cauſarum & calculi perennis formulam traduxit
IOANNES KEPLERUS,
TYCHONI primùm à RUDOLPHO II. Imp. adjunctus calculi miniſter; indéq; trium ordine Imppp. Mathematicus:
Qui idem de ſpeciali mandato FERDINANDI II. IMP. petentibus inſtantibúsq; Hæredibus,
Opus hoc ad uſus præſentium & poſteritatis, typis, numericis propriis, cæteris & prælo JONÆ SAURII, Reip. Ulmanæ Typographi, in publicum extulit, & Typographicis operis ULMÆ curator affuit.
Cum Privilegiis, IMP. & Regum Rerúmq; publ. vivo TYCHONI ejúsq; Hæredibus, & ſpeciali Imperatorio, ipſi KEPLERO conceſſo, ad annos XXX.
ANNO M. DC. XXVII.

Figure 9: The title page of Kepler's *Rudolphine Tables* (https://en.wikipedia.org/wiki/Johannes_Kepler#/media/File:8107-2Keplertp.png).

Figure 10: An eighteenth-century drawing of Regiomontanus (https://en.wikipedia.org/wiki/Regiomontanus#/media/File:Johannes_Regiomontanus.jpg).

servations, a table of selected latitudes and time differences enabled the data to be corrected for different locations. The calendar could aid navigators in gauging their positions from calculating the altitudes of stars and planets. Columbus used a similar book for his first journey to the Americas in 1492 (Coleman, 1999).



CONNOISSANCE
DES TEMPS,
A L'USAGE
DES NAVIGATEURS
ET
DES ASTRONOMES,
POUR L'ANNÉE 1795.
Du 12 Nivose de l'an 3 au 10 Nivose de l'an 4 de l'Ère Républicaine.

A PARIS,
DE L'IMPRIMERIE DE DUPONT,
Imprimeur-Libraire, rue de la Loi, N° 14.

L'AN IIe DE LA RÉPUBLIQUE, UNE ET INDIVISIBLE.

Figure 11: The title page of the 1795 issue of *Connaissance des Temps*, which announced the formation of the Bureau des Longitudes (https://www.france-pittoresque.com/spip.php?article5864).

4 THE EMERGENCE OF 'MODERN' ALMANACS

4.1 France

In 1666 Jean de la Caille (1645–1723), a bookseller in Paris published, at his expense, the *Astronomical Ephemerides* of Johannes Hecker (1611–1687; also known as Hevelius), a Danzig astronomer. These ephemerides were based on the rules of the *Rudophine Tables* and the observations of Tycho Brahe and Kepler (Astronomical Almanacs I, 1873).

Jean Picard (1620–1682; Picolet, 1987), a French astronomer, created the *Connaissance des Temps* in 1678 and the first issue for 1679 for astronomers was by a private publisher. While this was a private undertaking, it was with the aegis of King Louis XIV, and astronomers were quoted as responsible for the contents. In 1702 the Académie Royale des Sciences took scientific responsibility, and after that a member of the Académie, such as le Fevre, Lalande, or Mechain, was responsible for the contents. The computations were made by the publisher's staff or outside scientists.

The Bureau des Longitudes (BdL) was established in 1795 by the Convention (during the Revolution) as an Academy that specialized in astronomy, time, geodesy, and navigation (see Figure 11). Initially it had ten members, but now there are thirteen. With only a consultative voice there are corresponding members and representatives of major establishments, such as CNES, Institut Geographique National, Paris Observatory, and the Hydrographic Institute of the Navy. Until 1854 the BdL was the governing body of Paris Observatory and all national astronomical instruments. It replaced the Academy with responsibility for the *Connaissance des Temps*, but it was only in 1802 that computations were performed by a staff of seven, supervised by a member of the BdL. In the second part of the nineteenth century the BdL was responsible for all French discovery and astronomy missions, such as for the two transits of Venus. New publications were added, like the *Annuaire du BdL*, a popular, reduced precision ephemerides, *Éphémérides Nautiques* in 1889, and *Éphémérides Aéronautiques* in 1938, for navigation. In 1916 the edition of the *Connaissance des Temps* introduced GMT. The tables for the Moon were improved by Rodolphe Radau (1835–1911), and the satellites of Jupiter by Marie Henri Andoyer (1862–1929), while tables prepared by Urbain Jean Joseph Le Verrier (1811–1877) were used for the planets until 1965. After Andoyer's death in 1929, BdL members ceased significant interventions, one principal calculator remained in the BdL offices, and com-putations and proof reading were done by ten home calculators.

In 1959 André-Louis Danjon (1890–1967), Director of Paris Observatory and member of the BdL, asked Jean Kovalevsky (1929–2018) to take over the office and create a modern scientific group. Most of the calculators accepted full time positions and learned programming on the Paris Observatory computer, which was acquired in 1960 at the Meudon Annex. Young scientists began research in celestial mechanics and by 1963 all of the *Connaissance des Temps* was computerized and sent to the printer in machine-readable form (Kovalevsky, pers. comm., 2017). Since 2015, the BdL is no longer responsible for the *Éphémérides Aéronautiques*.

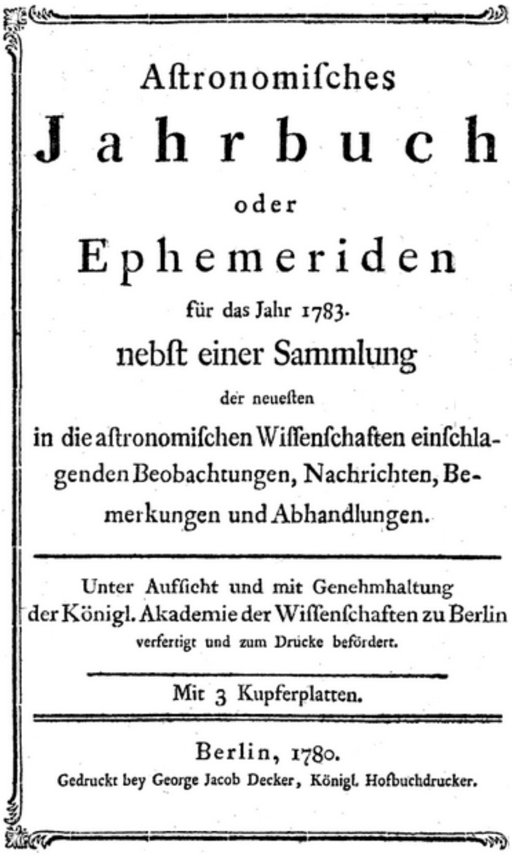
The great increase of the staff (between 30 and 40 persons) involved the transformation of the "Service des Calculs" into the "Service des Calculs et de Mécanique Céleste du Bureau des Longitudes". Since the space for the personnel became too small, it progressively moved to a new building at Paris Observatory. The full Service settled at Paris Observatory and became an Institute attached to the Observatory under the name of "Institut de Mécanique Céleste et de Calcul des Éphémérides" (IMCCE) by the decision of the Ministry on 2 June 1998. Within Paris Observatory, responsible for its administration, it has a certain independence compared with other bodies of the Observatory. The responsibility of the BdL for the Éphémérides is ensured by the presence of four members of the BdL on the Directing Board of the IMCCE and within a "Commission des Éphémérides" composed of four members of IMCCE, four members of the BdL, and two exterior members (Kovalevsky and Barlier, pers. comm., 2018).

The IMCCE has developed a planetary and lunar ephemerides development program both by numerical integration and general theories (Fienga et al., 2015). Since about 1968, all the contents of the *Connaissance des Temps* were progressively computed from theories elaborated by the staff. The variations in the theories used for the *Connaissance des Temps* (successive versions of INPOP) are a continuous history found in the prefaces.

4.2 Germany

On 10 May 1700 Kurfurst Friedrich III von Brandenburg, an elector of the German kings and emperors, whose castle at Colin an der Spree later became the center of Berlin, issued the Calendar Edict ('Kalender-Patent' in German). This edict introduced the Catholic Gregorian Calendar into the Protestant country. To introduce the calendar correctly positions for astronomers and an observatory were created in Berlin (see Wielen, 2001). To finance the astronomers a calendar tax was established. Each calendar required a tax stamp for permission to sell it or to own it. This tax paid the salaries of the astronomers. The tax was waived in the nineteenth century.

While the main task of the astronomers was to prepare the calendar, they became active in both observational and theoretical research. *Astronomical Ephemerides* started in 1749 by Grischow in Berlin and continued until 1754. In 1774 Lambert revived the ephemerides as the (Berliner) *Astronomisches Jahrbuch* (BAJ) for 1776 with ephemerides and news concerning astronomical sciences (cf. Figure 12). The first issue of the German Nautical Almanac, *Nautisches Jahrbuch,* was published in 1776 and it was separate from the BAJ, unlike the British,


Aſtronomiſches
Jahrbuch
oder
Ephemeriden
für das Jahr 1783.
nebſt einer Sammlung
der neueſten
in die aſtronomiſchen Wiſſenſchaften einſchlagenden Beobachtungen, Nachrichten, Bemerkungen und Abhandlungen.

Unter Aufſicht und mit Genehmhaltung
der Königl. Akademie der Wiſſenſchaften zu Berlin
verfertigt und zum Drucke befördert.

Mit 3 Kupferplatten.

Berlin, 1780.
Gedruckt bey George Jacob Decker, Königl. Hofbuchdrucker.

Figure 12: The title page of the *Astronomisches Jahrbuch* for 1783 (https://de.wikipedia.org/wiki/Berliner_Astronomisches_Jahrbuch#/media/File:Berliner_Ephemeriden_178).

American, and Spanish nautical almanacs. In 1776 the Prussian Academy published a collection of astronomical tables, *Sammlung Astronomischer Tafeln,* in three volumes. They were the bases for the BAJ ephemerides from 1779 for many years. In the period, of about 1790–1820, Lalande said in his *Bibliographie Astronomique* about the J*ahrbuch,* that "… all astronomers are obligated to know German, for this work cannot be dispensed with." (Astronomical Almanacs VII, 1873). The 1830 edition contained many reforms by Johann Franz Encke (1791–1865; Figure 13) of the astronomical data to improve accuracies and correct errors. The BAJ was published from 1776 to 1959. From

1844 to 1851 the BAJ included lunar distances for navigational purposes. From 1852 the *Nautisches Jahrbuch* (NJ) was published by the Prussian Ministry of Trade based on the ephemerides of the BAJ (Wielen, pers. comm., 2017). The Theoretical Department of Berlin Observatory was separated into the Rechen-Institut zur Herausgabe des Berliner Astronomischen Jahrbuchs in 1874. In 1896/1897 the Institute became independent of the Berlin Observatory and was named the Konigliches Astronomisches Rechen-Instutut, a Royal Prussian Institute linked to the University of Berlin. The BAJ used the Berlin meridian from 1776 to 1915. In 1916 the Greenwich meridian was introduced in accordance with the Paris Conference of 1911. In May 1944 the Astronomisches Rechen-Institut was attached to the German Navy.

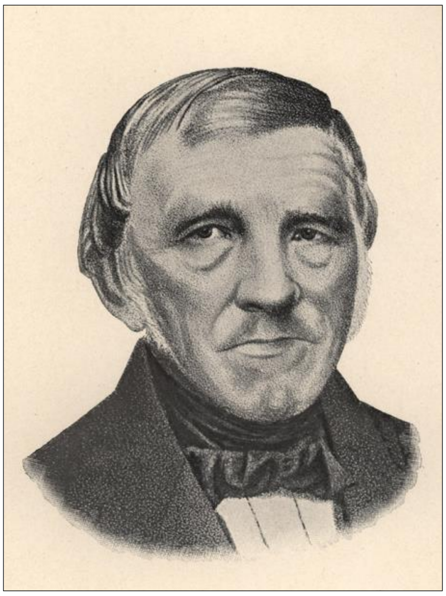


Figure 13: Johann Franz Encke (https://en.wikipedia.org/wiki/Johann_Franz_Encke#/media/File:Johann_Franz_Encke.jpg).

During World War II the exchange of astronomical ephemerides and almanac data between the U.S. Naval Observatory and H.M. Nautical Almanac Office and the Astronomisches Rechen-Institut continued as before. This was accomplished through Bertil Lindblad of Stockholm Observatory in neutral Sweden (Wielen and Wielen, 2016). This was done with approvals from the highest levels, as I understand it, on the basis that safe navigation at sea by all was in the best interests of everyone. Germany did not join the IAU until 1952, as the IAU was originally for allied countries (Kochhar et al., 2015).

In July 1944 the Astronomisches Rechen-Institut was moved from Berlin to Sermuth to avoid bombing in Berlin. In April 1945 the US Army occupied Sermuth. In June 1945 the US Army moved the institute to Heidelberg, before the area around Sermuth was turned over to the Soviet Army in exchange for the Western Sectors of Berlin. A few members of the institute, who lived on the eastern side of the river Mulde at Sermuth, had to stay under Soviet control. They moved to the Observatory at Potsdam-Babelsberg near Berlin and remained an eastern part of the Astronomisches Rechen-Institut until 1956, when they became part of the Babelsberg Observatory (Wielen, 2001). By international agreement the BAJ was discontinued in 1960 and the *Apparent Places of Fundamental Stars* (APFS) was taken over by the Astronomisches Rechen-Institut in 1960. The Astronomishes Rechen-Institut considers the Calendar Edict its foundation.

4.3 Great Britain

Around AD 1500 almanacs with calendars and astronomical data were printed in England. After 1540 astrological prognostications were added to the almanacs, which increased the popularity of the almanacs. In the sixteenth century about 600 almanacs were printed. In the seventeenth century essays on subjects like astronomy, astrology, and medicine were added and about 200 almanacs were published (Chapman, 2007; Nicolson, 1939). In 1664 40,000 copies of Vincent King's Almanak were sold, and more than 360,000 copies of other almanacs were sold (Kelly, 1991).

The motions of the Sun and planets are sufficiently slow that the differences in appearance in different parts of Europe could be ignored, however, the Moon's motion is more rapid so constant correction factors were applied for the different locations. The data were determined from some of the ephemerides available at that time, but the sources were not usually identified. The sources could be identified by the values listed (ibid.). At first the accuracies were not very good. There were no English tables for the Sun, Moon, or planets. The ephemerides were all for Europe. Computational astronomy was not well known in England. In the 1650s Wing and Leybourne compiled the first English planetary tables.

The Royal Observatory was founded in 1675 by decree of King Charles II with John Flamsteed (1646–1719) as the first Royal Astronomer (Forbes et al., 1975). On 22 October 1707 four Royal warships struck the reefs of the Isles of Sicily and 2,000 men were drowned. In 1714 the Longitude Act was passed by Parliament and the Board of Longitude was established to examine the problem and set up a prize of 20,000 pounds for a person who solved the problem of accurate navigation. The practical use of chronometers for navigation at sea dates to John Harrison's first time piece, H1, in 1735. In February 1765 Nevil Maskelyne (1732–1811; Figure 14) proposed to the Board of Longitudes the publication of a Nautical Ephemeris designed to determine longitude at sea by the method of lunar distances. In 1765 Parliament approved authorizing compilation and printing of *The Nautical Almanac and Astronomical Ephemeris*. The first issue was for 1767 (see Figure 15). A handbook for using the method of lunar distances, *Tables Requisite to be Used with the Astronomical and Nautical Ephemeris*, was published by Maskelyne. While the use of Harrison's chronometer was more accurate, the use of lunar distances was cheaper.

The Nautical Almanac fell into disrepute due to many errors in the early 1800s, when John Pond (1767–1836) and Thomas Young (1773–1829) were responsible. In 1831 William S. Stratford (1789–1853) was appointed superintendent with the task of setting up an Office and improving the Almanac. The Nautical Almanac Office (HMNAO) was established as a separate institution under the Admiralty in 1832. The Almanac for 1834 contained more data for astronomers and improvements in content and presentation. John R. Hind (1823–1895) was the longest serving superintendent, holding the office for 38 years, from 1853 to 1891. He introduced many changes and ensured an accurate and on schedule almanac. In 1896 the first part of the *Nautical Almanac & Astronomical Ephemeris*, the *Nautical Almanac*, was published separately for mariners. In 1914 it was renamed the *Nautical Almanac Abridged for the Use of Seamen*, but generally known as the *Abridged Nautical Almanac,* which was the title on the book's spine (Reed, 2015). After the Conference de 1896 at the Bureau des Longitudes, Newcomb's tables and constants were adopted for 1901 and onwards.

Leslie J. Comrie (1893–1950) was Superintendent from 1930 to 1936. He introduced the use of punch card equipment for the calculation using Fourier synthesis of the principal terms in the motion of the Moon for 1936–2000. He used the equipment for computations for the publications and for other projects. After an investigation and formal enquiry concerning the operations of the office, Comrie's appointment was terminated and Donald H. Sadler (1908–1987) was appointed the new Superintendent, from 1936 to 1970. He continued the use of punched card equipment and, in addition to the almanac publications, took on outside computations for the Admiralty. HMNAO was one of the first Departments of the renamed Royal Greenwich Observatory to move to Herstmonceux Castle in Sussex in 1949. It then acquired its own punch-card machines and in 1959 its own electronic computer.

Joint publications by HMNAO and the US Nautical Almanac Office (USNAO) of *The Nautical Almanac*, *The Air Almanac*, and the publication with different titles in the two countries, *The American Ephemeris and Nautical Almanac* and *The Astronomical Ephemeris*, began in 1960. The title of the nautical almanacs were both changed to *The Nautical Almanac* in 1960, the content was changed in the two publications to

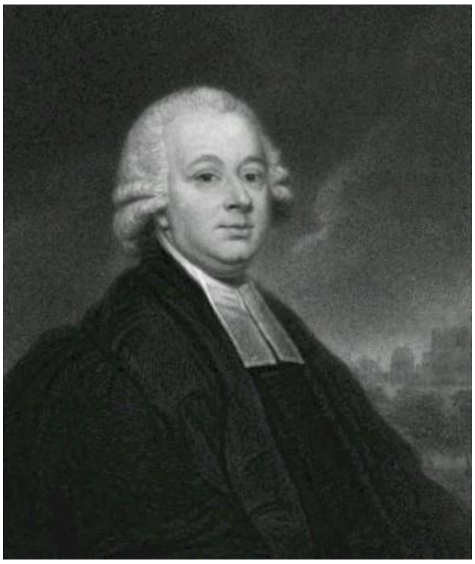
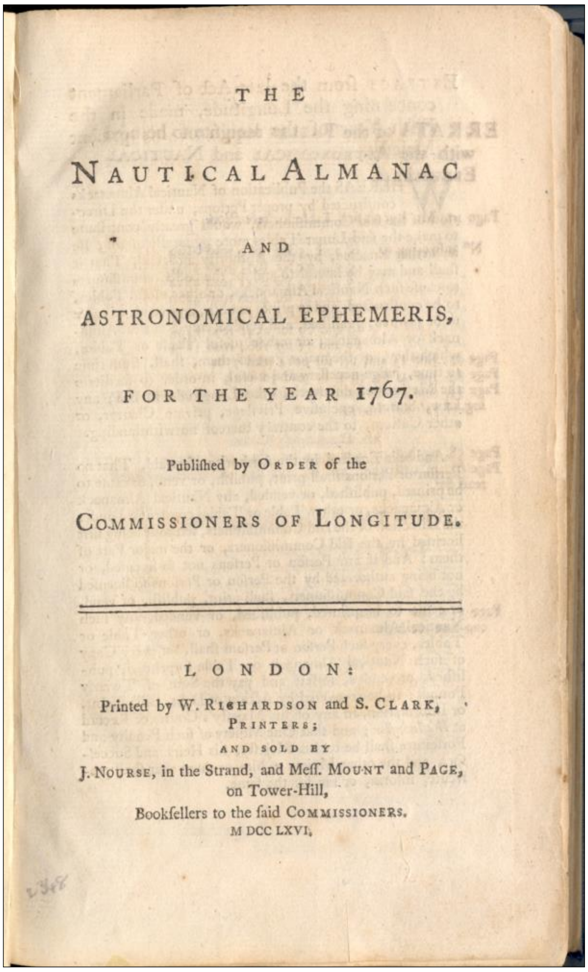


Figure 14: The Reverend Dr Nevil Maskelyne (https://en.wikipedia.org/wiki/Nevil_Maskelyne#/media/File:Maskelyne_Nevil.jpg).



THE

NAUTICAL ALMANAC

AND

ASTRONOMICAL EPHEMERIS,

FOR THE YEAR 1767.

Published by ORDER of the

COMMISSIONERS OF LONGITUDE.

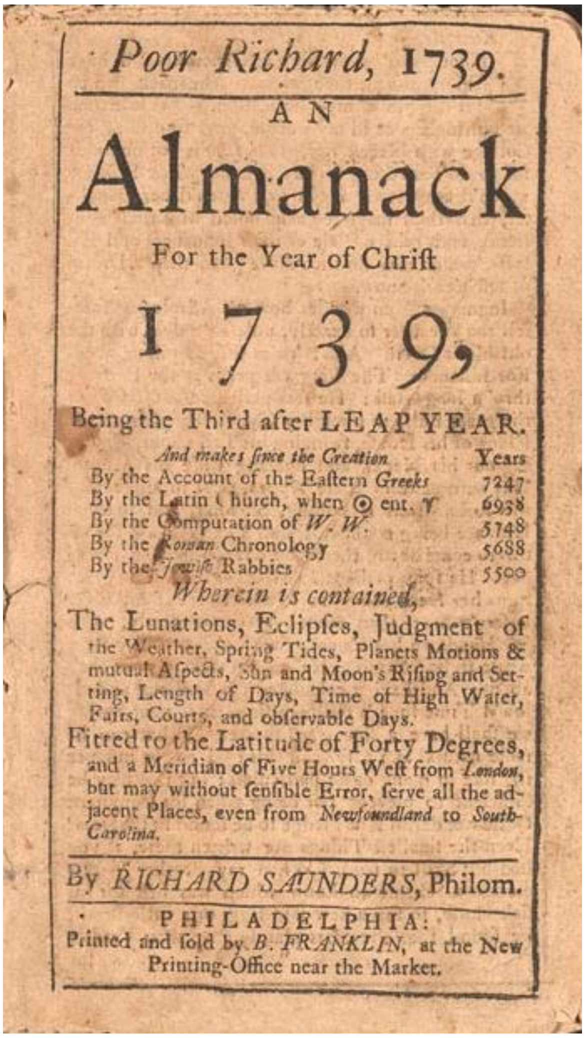
LONDON:

Printed by W. RICHARDSON and S. CLARK,
PRINTERS;
AND SOLD BY
J. NOURSE, in the Strand, and Mess. MOUNT and PAGE,
on Tower-Hill,
Booksellers to the said COMMISSIONERS.
M DCC LXVI.

Figure 15: The title page of the first *Nautical Almanac* (http://astro.ukho.gov.uk/nao/history/nao_1767.html).

be identical in 1958. All publications were calculated jointly, shared with the other, and published in both countries. In 1981 the astronomical ephemeris was completely redesigned by George Wilkins, the HMNAO Superintendent (1970–1989), and P. Kenneth Seidelmann, the USNAO Director. The computations were shared, and a single printing of *The Astronomical Almanac* in the USA was begun (see Wilkins, 1999).

The Royal Greenwich Observatory was relocated to Cambridge in 1990, with Bernard D. Yallop as Superintendent of HMNAO from 1989 to 1996. Andrew T. Sinclair was named Head of HMNAO for 1996–1998. When the RGO was closed in 1998, HMNAO was moved to Rutherford Appleton Laboratory, and in 2006 to the UK Hydrographic Office in Taunton in Somerset, back under the Admiralty (Hohenkerk, 2016).



Poor Richard, 1739.

AN

Almanack

For the Year of Chriſt

1739,

Being the Third after LEAP YEAR.

And makes ſince the Creation	Years
By the Account of the Eaſtern *Greeks*	7247
By the Latin Church, when ☉ ent. ♈	6938
By the Computation of *W. W.*	5748
By the *Roman* Chronology	5688
By the *Jewiſh* Rabbies	5500

Wherein is contained,

The Lunations, Eclipſes, Judgment of the Weather, Spring Tides, Planets Motions & mutual Aſpects, Sun and Moon's Riſing and Setting, Length of Days, Time of High Water, Fairs, Courts, and obſervable Days.

Fitted to the Latitude of Forty Degrees, and a Meridian of Five Hours Weſt from *London*, but may without ſenſible Error, ſerve all the adjacent Places, even from *Newfoundland* to *South-Carolina*.

By *RICHARD SAUNDERS*, Philom.

PHILADELPHIA:
Printed and ſold by *B. FRANKLIN*, at the New Printing-Office near the Market.

Figure 16: The title page of *Poor Richard's Almanac* for 1739 (https://en.wikipedia.org/wiki/Poor_Richard%27s_Almanack#/media/File:Poor_Richard_Almanack_1739.jpg).

4.4 The United States

Almanack Calculated for New England by Mr. Pierce was published in 1639 on the first printing press brought from England. From 1643 to 1649 almanacs were published yearly in Cambridge, Massachusetts. Annual almanac prints were of 3,000–5,000 copies. More than 14,000 different almanacs were printed in America from the colonial period through the nineteenth century. Almanacs developed from ephemerides into information on the basic needs and interests of a family. The times of sunrise/sunset, phases of the Moon, and positions of specific stars were of greatest interest. Weather prognostication became a popular feature of almanacs. Astrology was of interest for agricultural chores, medical treatments, and undertaking long voyages. Almanacs added literary material such as proverbs, verses, essays, and short stories. *Poor Richard's Almanac* (Figure 16) by Benjamin Franklin (1706–1790), published from 1736 to 1758, contained humor and satirical material converted from sayings of great writers of the past. With the approach of the American Revolution almanacs included maps of the progress of the war (Kelly, 1991). From 1802 to 1850s Blunt, Garnett, Megarey, Patten republished the British *Nautical Almanac and Astronomical Ephemeris* in America (Reed, 2015).

The naval appropriations act of 3 March 1849 authorized the publication of data necessary for navigation. The US Nautical Almanac Office (USNAO) was established in Cambridge, Massachusetts, that year with Lt. Charles Henry Davis (1807–1877) as the first Superintendent. *The American Ephemeris and Nautical Almanac* was published in 1852 with data for 1855, and included an Appendix with Chauvent's tables for correcting lunar distances. The purpose was to provide data for the USA and to avoid buying British publications. There were separate tables based on the Greenwich Meridian as preferred by navigators and on a prime meridian through the U.S. Naval Observatory, for promoting astronomy in the USA (Waff, 1997). In 1858 the *Almanac for the Use of Navigators*, a concise book for navigators with reprinted portions of *The American Ephemeris and Nautical Almanac,* was published, and in 1882 the title was officially changed to *The American Nautical Almanac*.

In 1866 the almanac office moved to Washington DC and in 1893 it was physically located at the present site of the U.S. Naval Observatory (USNO—see Figure 17), of which it became a part over the next few years. Simon Newcomb (1835–1909; Figure 18) was Superintendent from 1877 to his retirement in 1897. Newcomb supervised the development of theories of the motions of the Sun, Moon, and planets, and the establishment of a reference system, including astronomical constants, mean solar time, and ephemerides. In 1916 the *American Nautical Almanac* was no longer an extract from the

Figure 17: In 1893 the US Nautical Almanac Office moved to the newly-built main building of the U.S. Naval Observatory, shown here (courtesy: Geoff Chester).

American Ephemeris and Nautical Almanac, but a separately prepared volume. A list of 55 numbered navigation stars appeared for the first time. In 1934 the *American Nautical Almanac* was significantly revised with Greenwich Hour Angles in parallel with Right Ascensions. This followed the experimental publication of the *Air Almanac* with extensive GHA tables in 1933 (Reed, 2015).

In 1940 Wallace Eckert (1902–1971) left Columbia University to serve as Head Astronomer and Director of the Nautical Almanac Office at the U.S. Naval Observatory. With the war approaching and the need for publishing *The Air Almanac*, Eckert adopted machine methods he had perfected at Columbia. *The Air Almanac* went through three stages: the 1941 issue (the first regular issue) was printed with hand-set movable type; the 1942–1945 issues were printed directly on a modified IBM 305 accounting machine; and the 1946 and subsequent issues were printed on a card-operated table printer, designed by Eckert in 1941, but not delivered by IBM until 1945. Not a single error was ever reported in those Air Almanacs. Paul Herget (1908–1981) adopted the machine methods to *The American Ephemeris and Nautical Almanac* beginning in 1940. On the night shift Herget built tables for locating German U-boats by triangulation of radio signals. When published in 1943, allied shipping loses in the Atlantic were reduced from 30% to 6%.

In 1958 the unified *Nautical Almanac* was introduced for the US and British navies, but the title *American Nautical Almanac* was retained until 1960. UT replaced GMT in the nautical and air almanacs in the 1980s. In 1981 *The Astronomical Almanac*, printed in the US, replaced *The Astronomical Ephemeris* printed in the UK and *The American Ephemeris and Nautical Almanac* printed in the US. The bases for the publication were changed by international agreement in 1984. *The Air Almanac* was reduced from three to two volumes per year in 1977 and to one volume in 1987. The *Almanac for Computers* was introduced in 1977, *The Floppy Almanac* in 1986, and *MICA* in 1993.

In 1983 *The Nautical Almanac: Yachtsman's Edition* was licensed for sale by independent publishers: Paradise Cay Yacht Sales. The content was identical to the Nautical Almanac, with occasional brief articles, additional tables, sight reduction forms, and advertisements (Reed, 2015). In 1989 concise sight reduction tables and instructions for sight reductions by computer

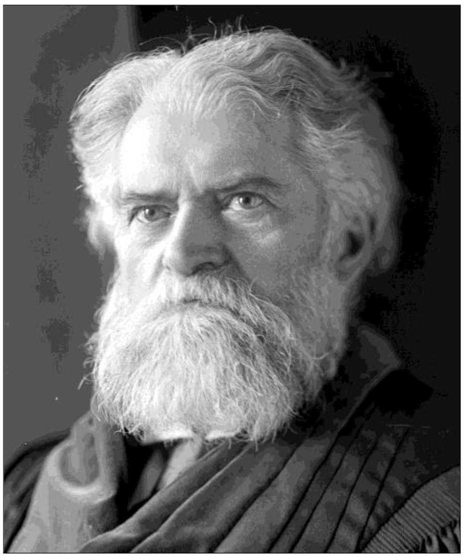


Figure 18: Canadian-born Simon Newcomb (https://en.wikipedia.org/wiki/Simon_Newcomb#/media/File:Simon_Newcomb_01.jpg).

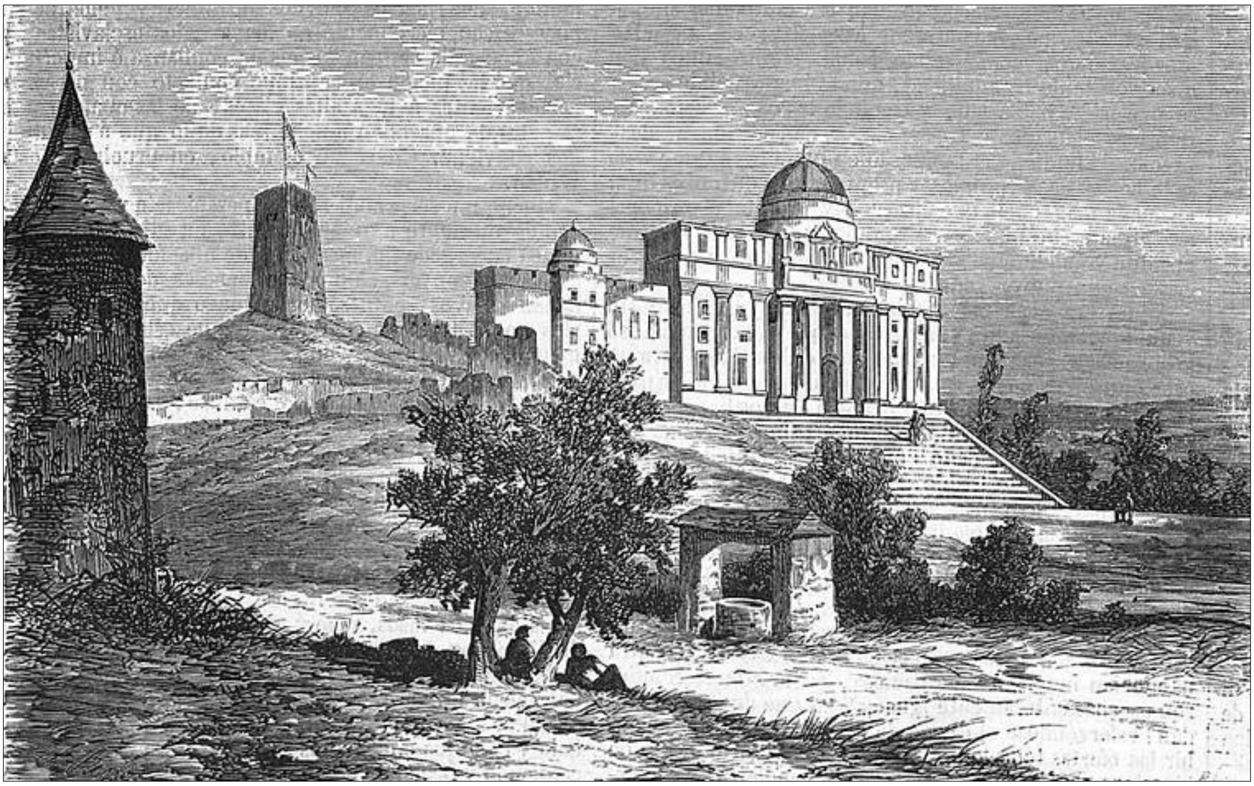


Figure 19: An 1861 drawing of the Real Instituto y Observatorio de la Armada in San Fernando https://es.wikipedia.org/wiki/Real_Instituto_y_Observatorio_de_la_Armada#/media/File:1861-03-17,El_Museo_Universal,_Vista_del_Observatorio_de_San_Fernando,_Ruiz.jpg 17,_

were introduced, so *The Nautical Almanac* was a self-contained edition for navigators.

The Explanatory Supplement to The Astronomical Ephemeris and The American Ephemeris and Nautical Almanac was published in 1961, giving an explanation of the methods used to determine the material published in the almanacs and the documentation of reference material. Editions of *The Explanatory Supplement to the Astronomical Almanac* were published in 1992 and 2012, updating the explanations and documenting the new developments and reference systems (*Explanatory Supplement*, 1961; Seidelmann, 1992; Urban and Seidelmann, 2012). Detailed histories of the US Nautical Almanac Office are given by Steven Dick (1999; 2003).

4.5 Spain

Jorge Juan (1713–1773), Director of the Naval Academy, had the idea of an astronomical observatory in the tower at the *Castillo de la Villa* in Cadiz, where the Naval Academy was located. In 1753 the first instrument was placed at the Real Observatorio de Cadiz (Royal Cadiz Observatory) as it was originally called. The Real Instituto y Observatorio de la Armada (Royal Institute and Observatory of the Spanish Navy) was founded in 1753 in San Fernando for navigation purposes (Figure 19). The Royal Observatory in Madrid was built for purely astronomical work in 1790. The *Almanaque Nautico y Ephemerides Astronomicas* was first published in 1792. In 1855 the Spanish Nautical Almanac name was simplified to *Almanaque Nautico*. In 1961 the Spanish *Almanaque Nautico*, which had evolved into a publication primarily for astronomers, was renamed *Efemerides Astronomicas*. A year later *Alamanaque Nautico para uso de los navegantes* recovered the name *Almanaque Nautico* (Reed, 2015).

Now the San Fernando Observatory includes, as one of four scientific departments, the Ephemeris Department, whose main duty is determination of ephemerides and dissemination to sailors, astronomers, and geodesists. The Time Department of the Observatory is responsible for determining the Official Time in Spain.

4.6 Russia

Pulkova Observatory was opened in 1839 with Fredrick Georg Wilhelm von Struve (1793–1864) as the first Director. The principal work was star positions and astronomical constants, including precession, nutations, aberrations, and refractions. The Pulkova meridian passes through the observatory main building and is the reference meridian of geographical Russian maps.

The astronomical institutions in Russia went though management changes, ideological offenses, and purges and disappearances after the October Revolution of 1917. Pulkova Observatory and the astronomical institutes in Petrograd were seriously affected. Many prominent astronomers resisted the changes and paid dearly for their efforts. In 1919 two scientific institutes were founded connected to Petersburg University; the Calculating Institute and the Astronomical-Geodetic Institute. The Calculating Institute was led by B.V. Numerov (1891–1941; Figure 20) and undertook publication of an astronomical annual. In 1923 the two institutes were united as the Astronomical Institute led by B.V. Numerov, until his arrest in 1936. The Institute published astronomical annuals and studied motions and computation of positions of minor planets (Aitken, 1924). Many astronomers were arrested or dismissed in 1936–1937 (Nicolaidis, 1990). In 1939 The Astronomical Institute was renamed the Institute of Theoretical Astronomy (ITA) of the USSR Academy of Sciences. The Pulkova Observatory buildings were destroyed during the siege of Leningrad (1941–1944), but the main instruments and much of the library were saved. The Observatory was reopened in May 1954. In 1989 the Institute of Applied Astronomy (IAA) of the Russian Academy of Sciences was founded and replaced the ITA. The IAA has developed a planetary and lunar ephemerides development program since 2012 (Pitjeva and Pitjeva, 2013).

The Russian publications are *The Astronomical Yearbook of the USSR* since 1922, *Bulletin of the Astronomical Institute* since 1924, *Ephemerides of Zinger's Pairs* since 1930, *Naval Astronomical Yearbook* since 1930, and *Air Astronomical Yearbook* since 1936.

4.7 Vienna, Austria

Astronomy played an important role in the University of Vienna since its beginning in 1365. Vienna's first observatory was built in 1730 by Giovanni Giacomo Marinoni (1676–1755). The Jesuits built their observatory in 1733 (Udias, 2003). Upon Marinoni's death in 1755, his instruments went to the University for the first university observatory. Maximillian Hell (1720–1792), Director of Vienna Observatory from 1755, published ephemerides on the meridian of Vienna. The ephemerides of Vienna started for the year 1757 upon the model of the Abbé de la Caille of France. *Canon of Eclipses* (Figure 21) by Theodor Ritter von Oppolzer (1841–1886) was one of the famous books written at Vienna Observatory (Universitat Wien, 2018).

4.8 Milan, Italy

In 1774 the *Ephemerides of Milan* for 1775 appeared and the series continued into the late nineteenth century.

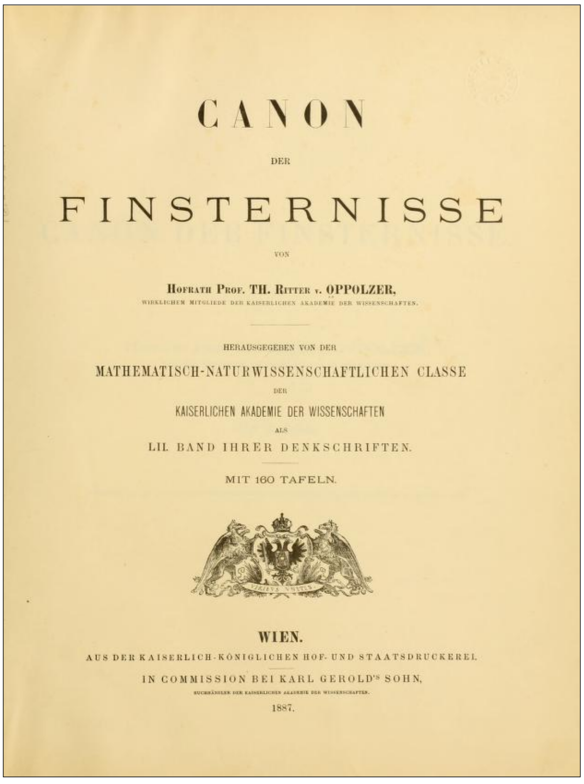
4.9 Portugal

The Portuguese ephemerides began in 1799 (Astronomical Almanacs III, 1873).

Figure 20: Boris Numerov (https://en.wikipedia.org/wiki/Boris_Numerov#/media/File:%D0%9D%D1%83%D0%BC%D0%B5%D1%80%D0%BE%D0%B2_%D0%91%D0%92.jpg).

4.10 The Jet Propulsion Laboratory (JPL)

In the 1960s JPL began a program of Development Ephemerides by numerical integration of the Solar System planets and a lunar ephemeris. The main purpose was for radar observations and to determine improved ephemerides for planetary missions. They collected available optical observations to be fitted with the ephemerides. When retroreflectors were placed on the Moon (see Figure 22), significant improvements of the lunar ephemeris were possible (e.g. see Bender et al., 1973). They produced a series of improving Development Ephemerides over the years. In 1976 a new reference system, including astronomical constants, time scales, star catalog, and ephemerides was adopted. Development Ephemerides/Lunar Ephemeris (DE200/LE200) was adopted as the international ephemerides and introduced in 1984. Since then, improved ephemerides have been adopted as international standards (Standish et al., 1992; Standish and Williams, 2012) and JPL continues



CANON
DER
FINSTERNISSE
VON
HOFRATH PROF. TH. RITTER v. OPPOLZER,
WIRKLICHEM MITGLIEDE DER KAISERLICHEN AKADEMIE DER WISSENSCHAFTEN.
HERAUSGEGEBEN VON DER
MATHEMATISCH-NATURWISSENSCHAFTLICHEN CLASSE
DER
KAISERLICHEN AKADEMIE DER WISSENSCHAFTEN
ALS
LII. BAND IHRER DENKSCHRIFTEN.
MIT 160 TAFELN.
WIEN.
AUS DER KAISERLICH-KÖNIGLICHEN HOF- UND STAATSDRUCKEREI.
IN COMMISSION BEI KARL GEROLD'S SOHN,
BUCHHÄNDLER DER KAISERLICHEN AKADEMIE DER WISSENSCHAFTEN.
1887.

Figure 21: Title page of the Canon of Eclipses, 1887 (https://archive.org/details/canonderfinstern00oppo/page/n5).

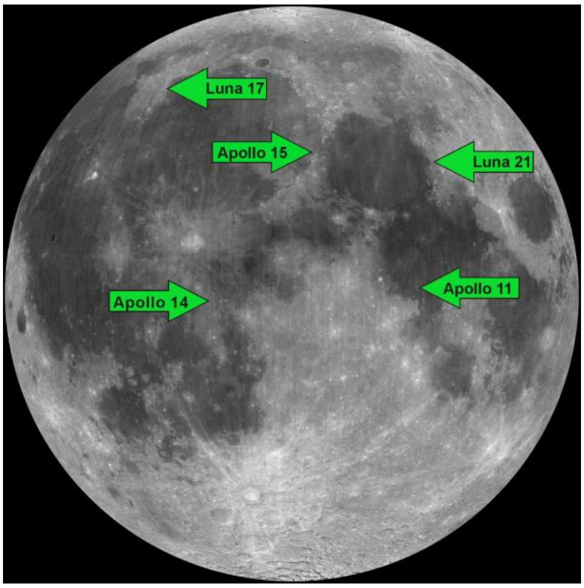


Figure 22: Locations of the retroreflectors left on the Moon during various Apollo and Luna missions (https://ilrs.cddis.eosdis.nasa.gov/images/figure1_reflectors.jpg).

to develop improved ephemerides (Folkner et al., 2014).

4.11 Massachusetts Institute of Technology (MIT)

In the 1960s MIT began a program of determining Solar System ephemerides in parallel with JPL for radar observations. The two programs competed for a number of years and did some comparisons to establish the accuracies of the ephemerides (Ash et al., 1996; 19967).

5 MERIDIANS

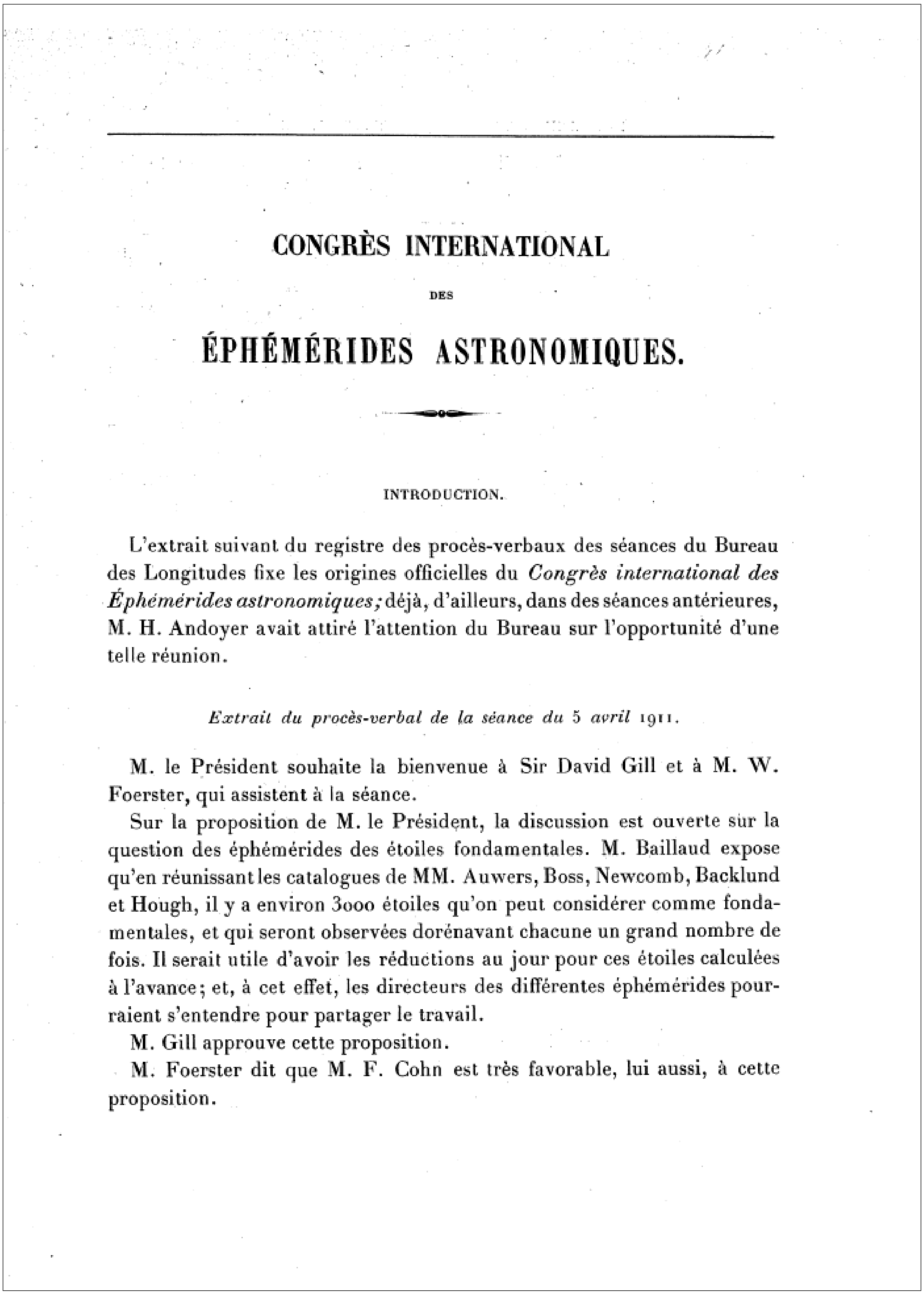
Each country used their own prime meridian for geographic locations until the International Meridian Conference in Washington in October 1884 (Bartky, 2007; Howse, 1980). The meridian passing through the center of the transit instrument at the Observatory in Greenwich was adopted as the initial meridian for longitude (Figure 23). Longitude was to be counted in two directions up to 180 degrees, east longitude being positive and west longitude being negative. The mean solar day was to begin at midnight on the initial meridian (*Explanatory Supplement*, 1961). Until computers required the use of plus and minus values, W and E were generally used to designate West and East longitudes. Since the relationship between local meridians in distant countries and Greenwich could not be accurately determined, many countries continued to use their own prime meridian for geographical positions and the Greenwich meridian for navigation. Over the years with better determinations of the distances and adoption of international cooperation, the Greenwich meridian was adopted as the international standard for longitudes and time scales.

With the availability of GPS receivers in the 1990s people could hold a receiver on the Greenwich prime meridian and discover the receiver did not read zero (see Figure 23). The zero meridian was in fact 102 meters to the east. In 1984 the BIH changed from astronomical coordinates to geodetic coordinates for geographical locations. The Earth Orientation observations had changed from optical astronomical observations to Very Long Baseline Interferometry (VLBI) radio observations and lunar and satellite laser measurements. The difference between the two coordinate systems is the Deflection of the Vertical at each location, and at Greenwich that difference is 102 meters (Malys et al., 2015).

Figure 23: The Airy meridian (dashed line) adopted by the 1884 Meridian Conference and the actual ITRF zero meridian (solid line) (imagery copyright 2014 Google Maps. Infoterra Ltd & Bluesky).

6 INTERNATIONAL COOPERATION

In May 1896 the Conference Internationale des Étoiles Fondamentales was held in Paris. Resolutions concerning the fundamental catalogue, calculation of apparent places of stars, and nutation, aberration and solar parallax fundamental constants were adopted. Also Newcomb's definitive values of luni-solar and planetary precession were agreed upon. The Congrès International des Éphémérides Astronomiques at Paris Observatory in 1911 (Figure 24) was the beginning of active cooperation between the national ephemerides offices. Distribution of calculations between the ephemerides offices of France, Germany, Great Britain, Spain, and the United States, and exchanges of data were recommended. Official approval of the recommendations was required in some cases.



CONGRÈS INTERNATIONAL

DES

ÉPHÉMÉRIDES ASTRONOMIQUES.

INTRODUCTION.

L'extrait suivant du registre des procès-verbaux des séances du Bureau des Longitudes fixe les origines officielles du *Congrès international des Éphémérides astronomiques;* déjà, d'ailleurs, dans des séances antérieures, M. H. Andoyer avait attiré l'attention du Bureau sur l'opportunité d'une telle réunion.

Extrait du procès-verbal de la séance du 5 avril 1911.

M. le Président souhaite la bienvenue à Sir David Gill et à M. W. Foerster, qui assistent à la séance.

Sur la proposition de M. le Président, la discussion est ouverte sur la question des éphémérides des étoiles fondamentales. M. Baillaud expose qu'en réunissant les catalogues de MM. Auwers, Boss, Newcomb, Backlund et Hough, il y a environ 3000 étoiles qu'on peut considérer comme fondamentales, et qui seront observées dorénavant chacune un grand nombre de fois. Il serait utile d'avoir les réductions au jour pour ces étoiles calculées à l'avance; et, à cet effet, les directeurs des différentes éphémérides pourraient s'entendre pour partager le travail.

M. Gill approuve cette proposition.

M. Foerster dit que M. F. Cohn est très favorable, lui aussi, à cette proposition.

Figure 24: First page of the Discussion in the report of the Congrès International des Éphémérides Astronomiques, published in the *Annales du Bureau des Longitudes*, Volume 9, page A3 (1913).

The International Astronomical Union was founded in 1919 and Commission 4 (Ephemerides) provided formal contacts among the directors of the national ephemerides offices. In 1938 Commission 4 recommended the single publication of the Apparent Places of Fundamental Stars, which avoided duplicate calculations and publications. Further cooperation has continued as specified for the different countries (*Explanatory Supplement*, 1961).

7 WORLD WAR II

As discussed under Germany above, Nautical Almanac data were provided by the US and British to Germany through Sweden for the purposes of safe navigation. During the war some of the sharing of computations by the countries was suspended and countries had to do their own computations of additional data. After the war a number of astronomers migrated to Western countries to continue their careers and provide scientific expertise. Radar capabilities developed for the war found scientific applications in astronomy and led to the field of radio astronomy (see Sullivan, 2009).

8 THE COLD WAR

During the 'Cold War' international exchanges of almanacs, ephemerides, and observations continued. The US Nautical Almanac Office provided copies of the almanac data and ephemerides to the Institute of Theoretical Astronomy in Leningrad. It was recognized that a number of observatories in Eastern Europe gave incorrect longitudes and latitudes for their locations. In some cases occultation observations were reported, in which cases it was possible to determine the accurate locations of the observatories from the observations.

9 ACKNOWLEDGEMENTS

I wish to thank F. Barlier, Y. Fu, T. Fukushima, Y. Ji, M. Katayama, J. Kovalevsky and R. Wielen for providing data used in this paper, and Professor Wayne Orchiston for helping prepare this paper for publication.

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