EVOLUTION OF EPHEMERIDES REPRESENTATION AND DIFFUSION

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Abstract. There has been, and continues to be, a close interaction between celestial mechanics used for the generation of ephemerides, mathematical techniques, and computer technology. As the computer capabilities of the ephemerides offices and the users of ephemerides have improved, the methods of determining and the accuracies of ephemerides have changed and the medium and representation of the ephemerides provided to the user have evolved.

Ephemerides have been provided in the form of theories, tables, tabulations, polynomials, graphics, and subroutines by means of the printed page, punched cards, magnetic tape, floppy disks, CD/ROMs, and electronic mail. As mathematical techniques and computer technology continue to develop and the requirements for ephemerides evolve, the methods of representing and diffusing ephemerides will continue to improve.

1. Introduction

The evolution of ephemerides representation and diffusion can be tied to the technological and cultural developments over the years. In the latter years, technological development has been mostly the development of computer technology, including the speed, size, and memory capabilities of the computer and the media used for storage of computer data. In many cases, the changes that have taken place in ephemerides can be tied to people and dates, when significant changes in procedure were introduced. In parallel, the changes of ephemerides can be tied to scientific developments that required changes, or observations that differed from the ephemerides and thus required scientific developments.

The paper will cover the early years of ephemerides, the development period as ephemerides representation and diffusion flourished, and then

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TABLE 1. Early Ephemerides

DATES	PREPRINTING
3000 - 2000 BC	Stonehenge (equinoxes, solstices)
700 - 100 BC	Linear zigzag functions (eclipses, lunar crescent visibility)
200 BC	Apollonius–Planetary motion (eccentric and epicyclic motion)
200 BC	Hipparchus–star catalog–precession
	Numerical values in geometric models
200 AD	Ptolemy–"Almagest"–"Handy Tables"
800 AD	Venerable Bede–computers–Easter from lunar solar cycles
900 AD	al-Khworizmi "Zij"–lunar crescent–astrology
900 AD	al-Battani "Zij"–sines replace chords
1000 AD	Toledan Tables
1200 AD	Roger Bacon–Easter and astronomy differences
1252 (1320)	"Alfonsine Tables" (Paris or Castile?)
1474	Johann Muller "Regiomontanus"
1496	Abraham Zactus "Almanach Prepetuum"
1500	Almanacs – configurations, Tables (Phases of Moon, Transits of planets rising & settings, wit and wisdom)
1545	Copernicus "De Revolutionibus" tables
1550	Erasmus Reinhold's "Prutenic Tables"
1600	John Tapp "Seaman's Kalendar" (Sun, Moon, bright stars for seamen)
1627	Kepler "Rudolphine Tables" (elliptic orbits, parameters from Tycho)
1676	Mariners New Calendar

the computer period when diffusion techniques were driven by computer technology. Finally, conclusions and expectations for future development of ephemerides are considered.

In this paper, I will define an ephemeris as a communication of a predicted astronomical event. This definition allows the consideration of oral tradition which does not survive forever, but is sophisticated and enduring. There is also the question of the purpose of ephemerides, and we will touch on some of these different purposes as we trace their history. Cultural requirements, calendars, religion, navigation, and scientific interests have been involved, and also astrology has been a consideration throughout the whole period.

2. Early Years

The earliest representations of ephemerides (Table 1) that survive to this day are the standing stones as exemplified by Stonehenge, which provides information on the equinoxes and solstices, and dates back to 2000 to 3000

TABLE 2. Ephemerides and Scientific Developments

Date	Person	Scientific Development
350 BC	Aristotle	Geocentric universe
200 BC	Apollonius	Epicycle, eccentric motion
200 BC	Hipparchus	Precession
200 AD	Ptolemy	Mathematical astronomy
1545	Copernicus	Sun-centered solar system
1609-19	Kepler	Laws of motion
1687	Newton	Universal law of gravity
1750	Mayer	Lunar Tables
1772	Euler	Lunar Tables
1772	Lagrange	Libration points
1784	Laplace	Solar system stability
1801	Gauss	Orbit determination
1835	Hamilton	Generating functions, quaternions
1846	LeVerrier,Adams	Discovery of Neptune
1860	LeVerrier	Planetary theories
1878	Hill	Lunar equations of motion
1900	Newcomb	Astronomical standards, planetary theories
1919	Einstein	Theory of relativity
1927	DeSitter	Variation in Earth rotation
1930	Brown	Lunar theory
1958	Brouwer,Vinti	
	Kozai, Garfinkel	Artificial satellite theory
1960	Danjon, Clemence	Ephemeris Time

BC. Usually Aristotle is credited with the concept of the geocentric universe, and Apollonius with the introduction of eccentric and epicycle circular motions to provide planetary motions. Based on the construction of a star catalog in the second century BC, Hipparchus was able to detect precession and he was also able to apply numerical values to the parameters in the geometric planetary models. In 200 AD, Ptolemy developed mathematical astronomy in his "Almagest." Then, his "Handy Tables" enabled one to calculate celestial longitude and latitude of the Sun, Moon, and planets and the phenomena for different terrestrial latitude regions. In the eighth century, the Venerable Bede was concerned with the calculation of the date of Easter based on solar/lunar cycles of various degrees of accuracy. In the Middle Ages, Ptolemy was followed by the Islamic astronomers who were interested in the visibility of the lunar crescent for Islamic calendar purposes. They also were, of course, interested in astrology. al-Khwarizmu produced the first major Islamic tables, "Zij," in the ninth century. The Alfonsine Tables were introduced in the thirteenth century. Their origin is uncertain, either being the court of Alphonso X in Castile or in Paris. The Copernicus tables in "De Revolutionibus" of 1543 were difficult to use. But Erasmus Reinhold's "Prutenic Tables" made the methods of Copernicus more accessible to almanac makers until the Rodolphine tables of Kepler, which were based on elliptic orbits and parameters from Tycho.

In about 1500 the printing press became available and almanacs became popular. These almanacs included configurations of the planets, phases of the Moon, transits of the planets, times of risings and settings and, in addition, some wit and wisdom.

The reasons for ephemerides and their diffusion developed over the years: scientific curiosity, the cultural reasons of calendar and religious dating, seasons, agricultural purposes, and, of course, astrological thoughts. Ephemerides became paramount for purposes of navigation and the determination of time.

In the 1600s, the Seaman's Calendar became available containing the positions of the Sun, Moon, and bright stars for sailors. During this period of introduction of the methods of printing and presenting ephemerides, there was a corresponding process of scientific development (Table 2) which included the Sun-centered solar system of Copernicus, the laws of motion of Kepler, the Universal law of gravity of Newton, and lunar tables of Euler.

The situation with regard to ephemerides, computing, and scientific development was addressed in the seventeenth century by Leibniz who wrote "Also the astronomers surely will not have to continue to exercise the patience which is required for computation. It is this that deters them from computing or correcting tables, from the construction of Ephemerides, from working on hypotheses, and from discussions of observations with each other. For it is unworthy of excellent men to lose hours like slaves in the labor of calculation which could safely be relegated to anyone else if machines were used."

The foundations of celestial mechanics include the concepts of libration points by Lagrange, the question of solar system stability by Laplace, the orbit determination method necessitated by discoveries of the minor planets as developed by Gauss, and the generating function and quaternions developed by Hamilton. A primary scientific discovery based on ephemerides was the accurate prediction of Neptune by LeVerrier and Adams. Planetary and lunar theories were developed by LeVerrier and Newcomb which, based on their accuracy levels and those of the observations, led to the requirement for the theory of relativity by Einstein, and the recognition that the rotation of the Earth was variable by de Sitter.

TABLE 3. Examples of National Almanacs (Navigation & Astronomy)

1679	Connaissance des Temps (France)
	(French Academy; Bureau des Longitudes)
1767	Nautical Almanac and Astronomical Ephemeris (UK)
1776	Berliner Astronomisches Jahrbuch (Germany)
	Nautisches Jahrbuch
1791	Efemerides Astronomicas (Spain). Almanaque Nautico
1855	The American Ephemeris and Nautical Almanac (USA)
1923	Annuaire Astronomique (USSR)
1933, 1941	American Air Almanac (USA)
1937	British Air Almanac (UK)
1943	Japanese Ephemeris (Japan)
1958	Indian Ephemeris and Nautical Almanac (India)
1975	Almanac for Computers (USA)
1982	Floppy Almanac
1993	Multiyear Interactive Computer Almanac (MICA)
1994	Redshift

TABLE 4. Ephemerides Accuracy Values

Date	Purpose	Accuracy	
BC	Eclipse prediction	30"	
1750	Navigation	1"	
1900	Scientific investigation (masses)	1"	
1960	Dynamical reference frame	0."1	
1965	Space mission	0."01	Moon 10 km
1990	Dynamical reference frame	0."001	Moon 1 cm

3. Development Period.

In the development of ephemerides, there arose the need for almanacs for navigation and astronomy. Thus, the Connaissance des Temps from France in 1679 became the first of the national almanacs. It predates the Bureau des Longitudes, whose bicentennial we celebrate at this meeting. Other countries followed with astronomical and navigational publications (Table 3). There arose from the national ephemerides and almanacs, the need for international standardization which led to the establishment of a standard meridian, standard time, standard astronomical constants, a single reference frame, and the beginnings of a general method of international cooperation. During the course of this time, there was also a continuing progress in the accuracy of ephemerides (Table 4). This progress is tied to the scientific developments which were either driven by the accuracy requirements or made possible the improvements in accuracies.

TABLE 5. Ephemerides Dissemination Techniques

Date	Method	New Technology	Technique
2000 BC	standing stones	alignments	observations
700 BC	tablets	clay	tables
200 BC	scribes	paper	tables
1500	book	printing press	tables, graphs
1900	books	photographs	theories
1940	punched cards	punched cards	tables
1960	magnetic tapes	computers	tabular
1965	magnetic tapes	computers	theories
1975	printed	hand calculators	Chebychev series
1982	floppy disks	personal computers	programs
1990	CD/ROM	compact disks	graphics, images
1994	electronic	networks	tables, graphics, images, programs

TABLE 6. Computers for Ephemerides

Date	Place	Person	Equipment	Purpose
1623	Tubingen	Schickard	desk calculator	
1642	France	Pascal	adding machine	
1693	Mainz	Leibniz	desk calculator	
1822	Cambridge	Babbage	difference integrate	
1854	Sweden	Seheitz	Babbage design	planetary distances
1863	Sweden	Wiberg	difference	logarithms
	America	Grant	difference	logorithms
1909	Berlin	Hamann	difference	Peters logarithms
1929	UK NAO	Comrie	printing calculator	Almanacs
1933	Columbia U	Eckert	punched cards	orbit computation
1940	USNO	Eckert	punched cards	Air Almanac
		Clemence		Theory of Mars
1947	Cincinnati	Herget	punched cards	minor planets
1948	IBM HQ	Eckert	IBM SSEC	outer planets
1948	Yale U	Brouwer	punched cards	star measuring
1954		Herget	UNIVAC I	Jupiter VIII
1954	Dahlgren VA	Herget	NORC	minor planets

4. Computer Development and Dissemination Techniques.

There has been a close relationship between the advancement of computers and computer technology and the methods in computing and disseminating ephemerides. In the early days, before electronic computers, tabular representations of theories were the most efficient methods for people to calculate ephemerides and to determine daily positions of the bodies (Table 5). With the arrival of punched cards, the application of those tables could be automated and the ephemerides more rapidly and correctly computed (Table 6). The electronic computer made the computation of special perturbations, or numerical integration, a much more attractive means of computing ephemerides, so that the IBM Selective Sequence Electronic Calculator (SSEC) was used to compute by numerical integration the ephemerides of the five outer planets. The general method of computing ephemerides became by means of numerical integration. At the present time, the only means of achieving the accuracy required for lunar laser ranging or radar ranging is by means of numerical integration.

The method of disseminating ephemerides has followed somewhat different routes. Tabular methods of providing data have existed since the technology of clay tablets. With the advent of paper and the printing process, the printing of the theories of the motions of the bodies and tables for computing ephemerides was introduced, both as a means of communicating a scientific accomplishment, and as a means for others to compute the ephemerides themselves. With the introduction of punched cards, both the ephemerides in tabular type form and the theories could be recorded in machine-readable format (1940 - 1965). This was followed by magnetic tapes, which provided a more compact, or more rapidly readable, format for providing the information (1962-1985). On magnetic tapes, data at uniformly spaced time intervals covering long periods of time could be provided so that people could interpolate for whatever time they wanted from the ephemerides.

With the introduction of the hand-held calculator (1974), there was a desire for a method whereby one could make a limited number of entries into the hand-held calculator and interpolate the data to determine celestial positions for specific times. This led to the publication of Chebychev polynomials for specific time limits, to be used with the hand-held calculator. With the advent of the personal computer (1980) came the floppy disk. Now the previously printed data could be stored on a floppy disk and accessed by a program also stored thereon. This technology let to the supplement of the printed book with a floppy disk to provide ephemeris data. The arrival of the CD ROM (1990) permitted much more data storage and led to the ability to include graphics. The availability of networks whereby people can access data from all over the world (1994), has provided a new means of disseminating the data in the forms of tables, graphs, programs, and pictures.

In the early days the data were provided in a tabular form and in graphs, or plots, of the planetary positions with respect to the stars, although I have yet to see an example of such an early plot that still exists. Then the capability for computing and the availability of the theories for people to calculate their own positions became desirable in the early 20th century. With the advent of computers and magnetic tapes, the tabular material was widely used on sequential storage. Now with the advent of the faster computers and more storage capability, programs based on theories, or based on compact Chebychev representation of sequential data, are more desirable than reading long sequential series of data. With the development of computer graphics and imaging capability, we now see graphics coming back as a popular augmentation to the accurate ephemerides.

5. Conclusion

Over the years there has been a close tie between ephemerides and cultural, scientific, and technological developments, computer technology, and individuals. There has also been, and unfortunately continues to be, a close tie between the ephemerides and astrology. It appears that a change in this progression should not be anticipated. It is my expectation that the future should see the distribution of data and information via networks, so the users (astronomers, space scientists, navigators, or the general public) can call up a graphic presentation of selectable scales showing the configurations of the planets, satellites, and stars for any time. In addition, they can call up numerical values to whatever accuracy is desired. In addition, standardized software packages will be available so that computations can be embedded in their own programs, without each individual writing all the software oneself.

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