MEETING VENUS
C. Sterken, P. P. Aspaas (Eds.)
The Journal of Astronomical Data 19, 1, 2013

The French Savants, and the Earth–Sun Distance: a Résumé

Suzanne Débarbat

SYRTE, Observatoire de Paris, Bureau des longitudes 61, avenue de l'Observatoire, 75014 Paris, France

Abstract. Transits of Venus have played an important rôle during more than two centuries in determining the Earth–Sun distance. In 2012, three centuries after Cassini's death, the issue has been finally settled by the latest Resolution formulated by the International Astronomical Union.

1. Prologue

From Antiquity up to the sixteenth century, values of the Earth–Sun distance were considered as being 10 to 20 times smaller than nowadays. Then came the Copernican revolution that brought new ideas about the solar system, followed by Johannes Kepler (1571–1630) and Galileo Galilei (1564–1642) and, later in the seventeenth century, Christiaan Huygens (1629–1695), Jean Picard (1620–1682), Gian-Domenico Cassini (1625–1712) and Isaac Newton (1643–1727) with his *Principia*. Powerful instruments were built, new pluridisciplinary groups formed, and novel concepts were presented.

In France, Louis XIV created in 1666 the *Académie Royale des Sciences* and the following year, 1667, the *Observatoire Royal* on the southern outskirts of the capital. Soon after, he demanded, from his academicians, a new geographical map of his kingdom. Picard presented ideas and new instruments to be built, and he performed a careful determination of the dimension of the Earth, along a meridian line represented by the symmetry axis of the observatory under construction. He himself devised three instruments to obtain the needed data: a portable quadrant, a zenith sector, and a level. The campaign occurred in 1669 and 1670.

Meanwhile, in 1666, Louis XIV had invited Huygens, with his famous pendulum clocks, to join the *Académie* and, in 1669, he invited Cassini to join his Parisian colleagues who were monitoring his accurate predictions of the eclipses of the Galilean satellites of Jupiter: at that time, this was the best way for longitude determination inland.

A new era was begun, with all these astronomers meeting within the frame of the *Académie Royale*, fully committed to determining the dimension of the solar system.

2. The first modern determination of the Sun–Earth distance

The result of the 1669–1670 campaign of Picard led him to publish, in 1671, his *Mésure de la Terre* that yielded, for the length of one degree of latitude, the value of 57 060 French *tosses*, the *toile* being equal to 1.95 m. For the radius of the Earth, at that time considered as a sphere, its value in *tosses* was equivalent to 6 375 km. Curiously, the value adopted by the International Astronomical Union in 2009, for the equatorial radius of the Earth is 6 378 km with – of course – four additional decimals, and it is now known that the Earth has not a spherical form: its flatness ratio is $\frac{1}{298}$.

Whatever was the shape of the Earth, Picard's value of the Earth's dimension could be used to obtain the Earth–Sun distance by using Kepler's third law that the planets around the Sun follow an elliptical orbit in such a way that the ratio of the square of their period of revolution to the third power of their average distance to the Sun is a constant.[1]

The method to be employed by the French academicians was the solution of a triangle with baseline that lies between Paris and a place as far away as possible on the Earth. The chosen place was to be Cayenne (Guyana) where the *Académie* sent Richer (1630–1696), one of its members; at that time Mars was at its closest distance from the Earth. The expedition was made in 1672 and 1673. Richer, as well as the astronomers in France, observed the position of Mars relatively to surrounding stars. In a letter, preserved in the Archives of the *Observatoire de Paris*, Richer wrote to Cassini (Ms B5, a, dated *A Caïenne le 20 juillet 1672*)

> ...J'espère que ces observations vous satisferont et M. Picard aussi & que par la vous connoitres si la parallaxe du soleil est sensible ou non...

The result obtained by Cassini, $9\frac{1}{2}''$ is reported, for the year 1673, in *Histoire de l'Académie Royale des Sciences* (Tome I), and the full text in *Mémoires de l'Académie Royale des Sciences* (Tome VIII, p. 53, 117, Paris, 1730), while the *Recueil* had appeared in 1733, the text itself is dated 1684. These various dates led to some confusion.

A detailed study was recently published in the journal *l'Astronomie* by C. Vilain from the *Observatoire de Paris* with a careful examination of the publication *Observations astronomiques et physiques faites en l'Isle de Caïenne* (Vilain 2011). The voyage had several purposes, but in the present paper, the Earth–Sun distance, as determined by Cassini is the only one considered; Vilain's conclusion is that this distance corresponds to about 22 000 Earth radii, compared to 23 445 nowadays adopted, confirming that this distance was known at not more than 10 %. A few years earlier, Toulmonde (2004) published a paper *Parallaxe du Soleil*, in which he gave many technical details.

The parallax of the Sun, – that is, the angle under which the radius of the Earth is seen from the Sun – has now been determined as $8\overset{''}{.}794$ (IERS[2] conventions 2009 and 2010); it is remarkable that some astronomers of the time obtained such value within an error of the order of $0\overset{''}{.}1$ – perhaps less – although Halley (1716) could not decide for any value of the range 1200–7000 Earth radii, see Aspaas (2012), p. 200.

A few years after Richer's return in 1675, the Royal Observatory in Greenwich was created: a new institution to develop astronomy was born.

3. A new method for the Earth–Sun distance: the Venus transits

The story of the first Venus transit ever observed (on December 4, 1639) is very well known. It begins with Kepler's prediction, and is followed by Jeremiah Horrocks

---

[1] i.e., t^2/a^3.

[2] International Earth Rotation and Reference Systems Service, `http://www.iers.org/IERS/EN/DataProducts/Conventions/conventions.html?__nnn=true`

(1619–1641), the only one, with his friend William Crabtree (1610–1644), to be fortunate enough to catch Venus and the Sun between clouds, see also Thorvaldsen's paper in these Proceedings.

Kepler had announced together with the 1631 transit (not 1639), the following one for 1761; astronomers, after 1639, had to wait more than twelve decades... Meanwhile, in 1663, James Gregory (1639–1675) had pointed out that transits over the Sun could lead to determination of the solar parallax. Edmond Halley (1656–1742), who had observed a transit of Mercury on November 7, 1671, showed in his *Catalogus Stellarum Australium* (published 1679) that such transits[3] would thus provide a new method to determine the Earth–Sun distance. But Halley died in 1742, before the 1761 transit. Joseph-Nicolas Delisle (1688–1768) in France took over the task of drawing the astronomical community's attention to the coming transit of Venus, sending out more than one hundred copies of his call together with a corresponding *Mappemonde*; unfortunately, none of these documents is included in the Archives of the *Observatoire de Paris*, see also the paper by Dumont & Gros in these Proceedings. Apparently two of them are known, one in the *Bibliothèque nationale de France* and one at the *Académie des Sciences*.

In the Archives of the *Observatoire de Paris*, there is a manuscript (Ms A 6.9) entitled *Description et usage d'une Mappemonde sur laquelle on a marqué tous les lieux qui doivent voir le passage de Venus sur le Soleil et principalement ceux qui sont les plus avantageusement situez pour trouver la distance du Soleil à la Terre par les observations que l'on enfera présentée au Roy le* (white) *1760 par M. De L'Isle de l'acad. R. des Sciences.* It is to be noted that *au Roy* has replaced *à l'Académie* and, before the date 1760, Delisle had written 1759.

Delisle adds that the *Mappemonde* is the same he employed previously for a transit of Mercury on May 6, 1753. Delisle's work is based on Halley's tables and contains about fifty pages of his handwriting. On the occasion of this Mercury transit Delisle submitted another way for the determination of the Venus and Sun parallaxes. Halley had proposed to provide the determination from the duration of the transit observed from two different places, thus requiring observation of the entire transit. Delisle, however, proposed a slightly different approach: only one of the contacts is necessary, observed from two places. The best contacts are the second or the third contact of Venus with the limb of the Sun with their timings at the two places; but they have to be accurate and another condition is that the local geographical coordinates need to be known with the best possible accuracy. If these conditions are met, the number of potential stations increases by a factor of two.

4. Back to Mars for the Earth–Sun distance

Still waiting for the 1761 Venus transit, the astronomers and, among them Nicolas-Louis Lacaille[4] (1713–1762) returned to the closest approaches of Mars and Venus. While others had observed some Mercury transits, Lacaille launched a call to his European colleagues, indeed with several objectives: observe stars of the southern sky to improve navigation in this hemisphere, test the lunar distance method proposed by the British for this purpose, observe the Moon simultaneously to Joseph-Jérôme Lalande (1732–1807) in Berlin (more or less at the same longitude as the Cape of

---

[3] Halley at first thought that Mercury as well as Venus transits could serve, but he became convinced that Venus was the only possibility.

[4] Also written as La Caille.

Good Hope),[5] observe Mars and Venus for their parallax, measure the length of one degree in latitude, determine longitude and latitude of various places (mostly islands), etc.

Leaving Paris in 1750, Lacaille was well equipped for all these purposes. Before leaving France he had sent his call to astronomers providing them with all the needed data for their observations. Back in 1754, Lacaille determined, among other things, the parallaxes in comparing his observations from South Africa with those made in Europe. Despite the increasing quality of the astronomical instruments since the sixteenth century, Lacaille's solar parallax 9″.5 to 10″.2 was more or less similar to Cassini's results.

5. The 1761 and 1769 transits of Venus

For France, some astronomers were sent to various locations in the world to catch the whole phenomenon. Such were Alexandre-Guy Pingré (1711–1796) at Rodrigues Island, Jean-Baptiste Chappe d'Auteroche (1728–1769) in Siberia (Tobolsk). In France itself the observers could get only the end of the transit but they were very numerous and among them were Giovanni Domenico Maraldi II (1709–1788), Edme-Sébastien Jeaurat (1724–1803), Charles Messier (1730–1817), Jérôme Lalande, Pierre-Charles Le Monnier (1715–1799), Charles-Marie de La Condamine (1701–1774), Nicolas-Louis de La Caille, Jean-Paul Grandjean de Fouchy (1707–1788), Réginald Outhier (1694–1774). In other places in Europe can be mentioned César-François Cassini de Thury (1714–1784) who observed from Vienna with Joseph Liesganig (1719–1799), Pehr Wilhelm Wargentin (1717–1783) in Stockholm and Mikhail Vasil'evich Lomonosov (1711–1765) in Saint Petersburg.

In total sixty-two stations sent their results to the *Académie Royale des Sciences*. They were analysed by several astronomers. Nevil Maskelyne (1732–1811) who went to Saint Helena, provided 8″.6, while the largest parallax value, by Pingré, was 10″.6.[6] The difference was 2″, representing about 20 % of the average of these two values. It was larger than the 10 % obtained almost one century earlier by Cassini I and with whom John Flamsteed (1646–1719) in Greenwich was in good agreement.

The astronomers from these various observatories, and various locations in the world thought that they were not organized well enough. Among them some wanted to go as far as possible from Europe. Some astronomers would be new observers such as Johann Euler (1734–1800) – son of Leonhard (1707–1783) – and Jorge Juan Y Santacilla (1713–1733), a Spanish officer. A special mention has to be made of the famous voyage of Capt. James Cook (1728–1779), who observed from Tahiti, the island that was discovered in 1767 by the British.

Among the French, a special mention must be made of Chappe d'Auteroche, who was in Siberia in 1761 and who went to California in 1769 and died there after the observation; and to Guillaume Le Gentil de la Galaisière (1725–1792) who had arrived in India in due time (in 1761) but could not disembark, decided to wait until 1769, only to suffer bad weather conditions. In Norway, Maximilian Hell (1720–1792) observed the transit from the site of Vardø, providing with California and Tahiti one of the longest distance bases on the Earth. More than a dozen stations

---

[5] The seemingly important role of Sweden in the same project is described in Aspaas 2012, pp. 224–225. See also the paper by Widmalm in these Proceedings.

[6] For original texts and more details, see Aspaas 2012, pp. 200–201.

were placed in order to be able to catch the complete transit. The number of observations sent to the *Académie* was about one hundred and twenty.

The difference between the smallest solar parallax 8″.40 and the largest one 8″.80 was substantially reduced, representing about 5 % of their average, instead of 20 % (Aspaas 2012, p. 324–327); some people decided to make a new analysis of the data such as Pierre-Simon Laplace (1749–1827) with 8″.81 and Johann Franz Encke (1791–1865) with 8″.57. Indeed, the further examinations yielded several values, the extremes being 8″.55 and 9″.12. Two values appeared as the most probable: 8″.8 and 8″.5. Instead of 5 %, the difference appears of the order of 3 %, not so much.

The next transit, however, was not expected until 1874; no observer from the 1760s would be given a chance to witness that. On the other hand, some tried to improve the results obtained in 1761 and 1769, and Carl Friedrich Gauss (1777–1855) provided a new method during the first decade of the nineteenth century: the least-squares determination of error to be associated to their means, weighted or not. Most of them had given ± 0.04", which represents about 3 %.

6. The 1874 and 1882 Venus transits

The astronomers began to search other ways for the determination of the Earth–Sun distance. Some employed the motion of the Moon leading to 8″.6 or 8″.9 such as Peter Hansen (1795–1874) in Denmark. Others made their analysis through the aberration of light, long after its discovery, with the velocity of light by Rømer (1644–1710) and with James Bradley (1693–1762), for the phenomenon of aberration itself. On the Earth the speed of light was obtained around mid-nineteenth century by Hippolyte Fizeau (1819–1896), followed by Léon Foucault (1819–1868) indoors, leading Wilhelm Struve (1793–1864) to 8″.86 and Alfred Cornu (1841–1902) to 8″.80. Urbain Le Verrier (1811–1877) himself made a determination yielding 8″.95, from a study of the motion of the gravity center of the Earth–Moon system around the Sun. All determinations were published just as astronomers were preparing for the 1874 transit of Venus.

Indeed, in France the astronomers began to work on this subject in 1872, the *Académie des Sciences* created a *Commission du passage de Vénus* to make sure that the best places were chosen for the observations. Its president was Hervé Faye (1814–1902), Pierre Puiseux (1820–1883) being its secretary; among the other members were Charles Delaunay (1816–1872) and Le Verrier. This Commission chose five stations: Campbell Island, Saint-Paul Island, Noumea, Peking (not yet Beijing) and Saigon; to observe the complete transit the Indian Ocean was the best place, as well as some eastern parts of Asia. The *Académie* sent a mission to Kompira-Yama mountain (close to Nagasaki) under the direction of Jules Janssen (1824–1907), including Félix Tisserand (1848–1896) and others.

The equipment of astronomers underwent further improvements. The clocks became much better for the timings; there were, besides refractors, also reflectors equipped with silvered mirrors, in addition to small theodolites and transit circles for determination of the local coordinates, latitude and longitude. A new instrument had appeared with Janssen: the *revolver photographique* as he named it; the electric telegraph allowed to synchronize the clocks for both the timings of the contacts and for longitude determinations with a better accuracy. The new technique, issued from photography was well developed from mid-nineteenth century into "astrophotography", under the shorter name astrography, equipping an astrograph with glass plates, also named, if for the Sun, photoheliograph.

Most of the European countries, already engaged in the eighteenth century transits were interested to contribute to the 1874 campaign, and the USA was present with Simon Newcomb (1835–1909) from Washington. The extreme values obtained from the campaign were $8\overset{\prime\prime}{.}76$ and $8\overset{\prime\prime}{.}88$; the difference between theses values, $0\overset{\prime\prime}{.}12$ is not small enough if compared with the $0\overset{\prime\prime}{.}18$ obtained one century before, with the 1769 transit. Harkness (1881, 1888) discussed the relative accuracy of different methods of determining the solar parallax. At the end of his very detailed paper, he assumed that the most probable error would be $\pm 0\overset{\prime\prime}{.}06$ while at the beginning of such measurements it could have been $2'$. It is also a very informative paper regarding the evolution of the measurements of the Sun–Earth distance.

Some astronomers, such as David Gill (1843–1914) at the Cape of Good Hope chose in 1877 to observe Mars again, this time from Ascension Island. From the value $8\overset{\prime\prime}{.}78$ obtained, Gill determined that the mean square error was $\pm\ 0\overset{\prime\prime}{.}01$. For the first time the error attained such a small value, leading to the idea that direct observation of such a planet could be more successful than Venus transits. Nevertheless, astronomers decided to observe the following one in 1882.

As an example of such a campaign, the Belgian astronomers – for the first time engaging in such an operation while observing from San Antonio (Texas) and Santiago (Chile) – obtained $8\overset{\prime\prime}{.}907 \pm 0.084$ which corresponds to $8\overset{\prime\prime}{.}91 \pm 0\overset{\prime\prime}{.}08$, quite disappointing. At the international level, astronomers began to think about a uniformization of constants of general use around 1880; they made the choice of the solar parallax: $8\overset{\prime\prime}{.}80$, assumed to be correct within $\pm 0\overset{\prime\prime}{.}02$. This was made after a careful analysis of a set of constants to be adopted on the occasion of the international project named *Carte du Ciel* launched in 1887. This was formally made on the occasion of the *Conférence internationale des étoiles fondamentales* held in 1896 and involved eighteen observatories. It was confirmed by Jean Bouquet de la Grye (1827–1909) in a memoir on the solar parallax, he presented to the *Académie* in 1904, considering that $8\overset{\prime\prime}{.}80$ was known within $0\overset{\prime\prime}{.}01$.

7. The giant role of the small planets

The first small planet discovered occurred during the night of December 31, 1800, and January 1, 1801, when Giuseppe Piazzi (1746–1826) saw, from Palermo Observatory, a new tiny object later named Ceres. Several others were later discovered and, in 1898, a very favorable one for the parallax determination was discovered by Carl Gustav Witt (1866–1946), Eros, being able to be very close to the Earth: its parallax could attain $60''$, far more than Mars (of the order of half this value).

Some other small planets had been previously attempted for determining the solar parallax, with Victoria, Iris and Sappho around 1890 leading to $8\overset{\prime\prime}{.}801$, $8\overset{\prime\prime}{.}798$, $8\overset{\prime\prime}{.}812$ and to $8\overset{\prime\prime}{.}807 \pm 0\overset{\prime\prime}{.}006$, for a weighted mean, with an error less than half of what was obtained previously. Arthur Robert Hinks (1873–1945) provided, after about ten years of analysis $8\overset{\prime\prime}{.}806 \pm 0\overset{\prime\prime}{.}004$ from visual observations. Such results showed that Eros would be a good candidate ten years later. The 1900–1901 international campaign was very successful: forty-two observatories participated, providing 12 000 observations obtained from photographic plates of Eros with respect to neighboring stars. The technical method employed was the same as for Mars, but the small planets look like stars, without any planetary aspect. The value $8\overset{\prime\prime}{.}80$ was confirmed, and the transits of Venus will not be used anymore. Nevertheless astronomers were waiting for the next best appearance of Eros in 1930–1931.

For the 1930–1931 Eros campaign, and under the influence of the International Astronomical Union (IAU) created in 1919, sixty-four observatories participated, and

Harold Spencer Jones (1880–1960) was in charge of the determination. After a very deep and careful study he provided the result $8''.790 \pm 0''.001$.

From observations of the same minor planet, between 1926 to 1945, Eugene Raba (1913–1974) published in 1950 the value he deduced from its perturbations mostly by the Earth, $8''.79835 \pm 0''.00039$. With such accuracy, smaller than the Spencer Jones result, the values differed far more from the sum of their assumed errors...

8. Some other methods for the Earth–Sun distance

Other possible methods were not forgotten, despite the development in the use of small planets. As an example, one already mentioned issued from the aberration of light, through its speed. In using photometric observations of eclipses for the satellites of Jupiter made at Harvard Observatory, Ralph Allen Sampson (1866–1939) derived a rather accurate value of the solar parallax yielding, in 1909, $8''.80 \pm 0''.02$.

Among such modern determinations can be mentioned the result obtained by Ernest Brown (1866–1938) and Dirk Brouwer (1902–1966), $8''.7925 \pm 0''.0005$ deduced from the parallactic inequality of the Moon; another value was given by Bernard Guinot, in 1958, $8''.787 \pm 0''.003$, issued from a new determination of the aberration constant.

As time went by, new roles were accorded to Venus, the Moon and other celestial objects with the emergence of new techniques during the second half of the 20th century. Such was radar astronomy issued from World War II in using echoes over the Moon and mostly Venus. By the end of the fifties and the beginning of the sixties in Great Britain and in the USA, it was considered that the speed of light was known with a sufficient accuracy. Very often the authors gave more decimals than the error could accept; the rounded values such obtained are from Boston $8''.8022$, from California $8''.794098 \pm 0''.15$... The IAU, in charge of the decision for the astronomical constants, made the choice of $8''.794$ in 1964. This is more or less the end of defining the Earth–Sun distance under the form of the solar parallax, this distance being derived from direct measurements; but the speed of light needs to be better known and an international value adopted. And new improvements will come, both for this numerical value, from new determinations of the length of the meter, new atomic clocks for timing and, on the other side, from the use of space research.

9. The Earth–Sun distance today

For several decades, new definitions of astronomical constants were considered by the IAU, under the responsibility of highly specialized Working Groups. The last but one such meeting occurred in 2009 during the IAU 27th General Assembly in Rio de Janeiro. The set of constants, emanating from discussions at the level of the Working Group *Numerical Standards in Fundamental Astronomy*, has defined the IAU 2009 System of Astronomical Constants.

The first constant in the list is the speed of light $c = 2.99792458 \times 10^8$ m s^{-1}, close to the well-known value 300 000 km s^{-1}. The Earth–Sun distance au comes after seven other constants au $= 1.49597870700 \times 10^{11}$ m, i.e., close to 150×10^6 km.

For comparison with previous values, I mention the distance Earth–Sun obtained forty years ago, viz., $1.49598845 \pm 0.000002 \times 10^{11}$, with $c = 2.997930 \times 10^8$ ms^{-1},

$1.49596600 \pm 0.00000900 \times 10^{11}$ m twenty years ago, with the same value for the speed of light ($c = 2.99792458 \times 10^{8}$ ms^{-1}) $1.49697870691 \times 10^{11}$ m.

The 2009 value of the Earth–Sun distance was given in *Proposals for the masses of the three largest asteroids, the Moon–Earth mass ratio and the astronomical unit*, published by Pitjeva & Standish (2009). These proposals were issued from their detailed study of the available data and discussions among specialists from numerous countries, among whom, for example, figures Nicole Capitaine from the *Observatoire de Paris*. The most accurate values of the Earth–Sun distance was thus obtained from studies in celestial mechanics taking into account small planets, the Earth–Moon system and, as usual for astronomical research, the most fundamental variable: time.

But new discussions took place and, in 2010, a *Proposal for the re-definition of the au* was submitted in Vienna during the *Journées 2010 Systèmes de référence spatio-temporels,* according to previous suggestions (Klioner 2008, Capitaine & Guinot, 2009). The reason is that in the modern context, astronomers wanted to make the system of astronomical constants as compliant as possible with modern dynamical astronomy. The astronomical unit (au) will keep the value of its defining number, as previously given under the form of a conventional number.

At the 28th IAU General Assembly in Beijing in 2012 the discussions on a re-definition of the astronomical unit of length led to the acceptance of IAU RESOLUTION B2 (2012) that recommends the re-definition of the astronomical unit as a conventional unit of length equal to 149 597 870 700 m exactly. The integral text of this resolution is reproduced in the Appendix to this paper.

10. Résumé

J.-D. Cassini admitted $9''\!.5$ for the solar parallax, which is the angular measure for the Sun–Earth distance. Cassini's value was derived from Mars observations, and he published it in 1672. During the 1750s, Lacaille made similar observations and found the same value. Soon after, astronomers employed the two transits of Venus that occurred in 1761 and 1769. The results were more or less disappointing for the astronomers; nevertheless other astronomers, with an improved instrumentation, observed the following ones 1874 and 1882. Meanwhile other methods were attempted up to the discovery of Eros by 1898. After such campaigns and World War II, radar and later more direct measurements occurred leading the IAU to take new decisions for the Earth–Sun distance, au, i.e. astronomical unit, for astronomical unit, in August 2012.

References

Aspaas, P. P. 2012, *Maximilianus Hell (1720–1792) and the eighteenth-century transits of Venus. A study of jesuit science in Nordic and Central European contexts*, A dissertation for the degree of Philosophiae Doctor, University of Tromsø. `http://hdl.handle.net/10037/4178`

Guinot, B. 1958 *Une nouvelle mesure de la constante de l'aberration*, Bull. Astron., 2e série, Tome XXII, p. 150

Harkness, W. 1881, *On the Relative Accuracy of Different Methods of Determining the Solar Parallax*, American Journal of Science, 12, p. 376

Harkness, W. 1888, *Détermination de la parallaxe du Soleil*, translation of Harkness (1881) by A. Bouquet de la Grye (Library of Observatoire de Paris)

IAU 2009 System of Astronomical Constants, Resolution 132 of IAU/GA 2009, in Trans. IAU, Vol. XXVIIB, p. 57, 2010

Pitjeva, E. V. & Standish, E. M. 2009, *Proposals for the masses of the three largest asteroids, the Moon–Earth Mass ratio and the Astronomical Unit*, Cel. Mech. and Dyn. Astron., vol. 103, p. 365

Toulmonde, M. 2004, *Parallaxe du Soleil*, l'Astronomie, vol. 118, pp. 275–289

Vilain, C. 2011, *Cassini, Richer et les distances dans le Système solaire*, *l'Astronomie*, pp. 34–39

Appendix

IAU RESOLUTION B2

on the re-definition of the astronomical unit of length[†]

The XXVIII General Assembly of International Astronomical Union,

noting

1. that the International Astronomical Union (IAU) 1976 System of Astronomical Constants specifies the units for the dynamics of the solar system, including the day ($D = 86400$ s), the mass of the Sun, M_S, and the astronomical unit of length or simply the astronomical unit whose definition[1] is based on the value of the Gaussian gravitational constant,

2. that the intention of the above definition of the astronomical unit was to provide accurate distance ratios in the solar system when distances could not be estimated with high accuracy,

3. that, to calculate the solar mass parameter, GM_S, previously known as the heliocentric gravitation constant, in Système International (SI) units[2], the Gaussian gravitational constant k, is used, along with an astronomical unit determined observationally,

4. that the IAU 2009 System of astronomical constants (IAU 2009 Resolution B2) retains the IAU 1976 definition of the astronomical unit, by specifying k as an "auxiliary defining constant" with the numerical value given in the IAU 1976 System of Astronomical Constants,

5. that the value of the astronomical unit compatible with Barycentric Dynamical Time (TDB) in Table 1 of the IAU 2009 System (149 597 870 700 m±3 m), is an average (Pitjeva and Standish 2009) of recent estimates for the astronomical unit defined by k,

6. that the TDB-compatible value for GM_S listed in Table 1 of the IAU 2009 System, derived by using the astronomical unit fit to the DE421 ephemerides (Folkner et al. 2008), is consistent with the value of the astronomical unit of Table 1 to within the errors of the estimate; and

considering

[†] For the source of this text, and all references, see `http://www.iau.org/static/resolutions/IAU2012_English.pdf`

[1] The IAU 1976 definition is: "The astronomical unit of length is that length (A) for which the Gaussian gravitational constant (k) takes the value of 0.017 202 098 95 when the units of measurements are the astronomical unit of length, mass and time. The dimensions of k^2 are those of the constant of gravitation (G), i.e., $L^3M^{-1}T^{-2}$. The term "unit distance" is also for the length A." Although this was the first descriptive definition of the astronomical unit, the practice of using the value of k as a fixed constant which served to define the astronomical unit was in use unofficially since the nineteenth century and officially since 1938.

[2] Using the equation $A^3k^2/D^2 = GM_S$ where A is the astronomical unit and D the time interval of one day, and k the Gaussian gravitational constant.

1. the need for a self-consistent set of units and numerical standards for use in modern dynamical astronomy in the framework of General Relativity,[3]
2. that the accuracy of modern range measurements makes the use of distance ratios unnecessary,
3. that modern planetary ephemerides can provide GM_S directly in SI units and that this quantity may vary with time,
4. the need for a unit of length approximating the Sun–Earth distance, and
5. that various symbols are presently in use for the astronomical unit,

recommends

1. that the astronomical unit be re-defined to be a conventional unit of length equal to 149 597 870 700 m exactly, in agreement with the value adopted in IAU 2009 Resolution B2,
2. that this definition of the astronomical unit be used with all time scales such as TCB, TDB, TCG, TT, etc.,
3. that the Gaussian gravitational constant k be deleted from the system of astronomical constants,
4. that the value of the solar mass parameter, GM_S, be determined observationally in SI units, and
5. that the unique symbol "au" be used for the astronomical unit.

References

Capitaine, N. & Guinot, B. 2009, *The Astronomical Units*, in Proceedings of the "Journées 2008 Systèmes de reference spatio-temporels", M. Soffel and N. Capitaine (eds.), Lohrmann-Observatorium and Observatoire de Paris, pp. 73–74

Folkner, W.M., Williams, J.G., Boggs, D.H. 2008, Memorandum IOM 343R-08-003, Jet Propulsion Laboratory

Klioner, S. A. 2008, *Relativistic scaling of astronomical quantities and the system of astronomical units*, A&A, 478, pp. 951–958

Pitjeva, E.V. and Standish, E.M. 2009, *Proposals for the masses of the three largest asteroids, the Moon–Earth mass ratio and the astronomical unit*, Celest. Mech. Dyn. Astr., 103, 365, doi: 10.1007/s10569-009-9203-8

---

[3] Relativistically a solar system ephemeris, for which the astronomical unit is a useful unit, is a coordinate picture of solar system dynamics. SI units are induced into such a coordinate picture by using the relativistic equations for photons and massive bodies and by relating the coordinates of certain events with observables expressed in SI units.