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The solar eclipse observed by Clavius in A.D. 1567

F.R. Stephenson[1], **J.E. Jones**[2], **and L.V. Morrison**[3]

[1] Department of Physics, University of Durham, DH1 3LE, UK
[2] Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead, Merseyside, L43 7RA, UK
[3] Royal Greenwich Observatory, Madingley Road, Cambridge, CB3 0EZ, UK

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Abstract. The careful description of the solar eclipse of A.D. 1567 by Clavius is used to derive limits to the Earth's rotational clock error (ΔT) of between 145 and 165 sec at this date. This result provides an important link between the ΔT curve as deduced from ancient and medieval eclipse observations and that obtained from telescopic data.

Key words: eclipses – time – Earth

1. Introduction

The German Jesuit mathematician and astronomer Christoph Clavius (1537-1612), who was largely responsible for the reform of the calendar in 1582, was fortunate enough to witness two spectacular eclipses of the Sun in the space of seven years. These events occurred in A.D. 1560 and 1567, roughly half a century before the introduction of the telescope. In his book entitled *In sphaeram Ioannis de Sacro Bosco Commentarius*, published many years later in 1593, Clavius gave brief but graphic accounts of both eclipses.

The first eclipse, which he observed at Coimbra in Portugal whilst a university student, was fully total. He described the effects of the fall of darkness which accompanied the complete disappearance of the Sun. By the time of the second eclipse, he had moved to Rome (arriving there in 1565), and was teaching mathematics at the Collegio Romano (Busard 1971). Here he spent almost the whole of his remaining life. In some ways, his account of this latter eclipse is the more interesting. Although he saw a complete ring of light around the Moon on this occasion, modern computations show that the Moon would barely cover the Sun so that the eclipse was neither annular nor total. Further, quite small variations in the rate of rotation of the Earth would materially alter the appearance of the eclipse at greatest phase. Hence his observation is of geophysical importance.

By analysing historical records of eclipses, it is possible to investigate changes in the Earth's rate of rotation with tolerable precision between about 700 B.C. and A.D. 1450 (Stephenson and Morrison 1995). However, over the next 150 years or so apart from the observations by Clavius in 1560 and 1567, no other records of central eclipses are preserved from Europe. In fact, until the late 17th century when the telescope became widely disseminated in Europe, *reliable* observations of eclipses and occultations of stars by the Moon are rare. These circumstances considerably add to the importance of Clavius' record.

In this paper we shall discuss various aspects of the A.D. 1567 eclipse in detail, with particular reference to its significance in studying past terrestrial rotation. We shall also briefly consider Clavius' observation in 1560.

2. The observational record and its interpretation

Clavius' two eclipse observations are recorded consecutively in his commentary on a textbook by an Englishman named Joannes de Sacrobosco (John of Holywood), who died at Paris in 1256. Sacrobosco was the first European writer in the Middle Ages to give an account of the Ptolemaic system of planetary motions. His textbook, entitled *De Sphaera*, was still widely used in the time of Clavius. The account of the eclipses by Clavius may be translated as follows:

"I shall cite two remarkable eclipses of the Sun, which happened in my own time and thus not long ago. One of these I observed about midday at Coimbra in Lusitania [Portugal] in the year 1559 [*sic*], in which the Moon was placed between my sight and the Sun with the result that it covered the whole Sun for a considerable length of time. There was darkness in some manner greater than night; neither could one see where one stepped. Stars appeared in the sky and (marvellous to behold) the birds fell down from the sky to the ground in terror of such horrid darkness. The other I saw at Rome in the year 1567 also about midday in which although the Moon was placed between my sight and the Sun it did not obscure the whole Sun as previously but (a thing which perhaps never before occurred at any other time) a certain narrow circle was left on the Sun, surrounding the whole of the Moon on all sides" [*In sphaeram Ioannis de Sacro Bosco Commentarius*, p. 508].

These same eclipses seem to have attracted little attention among contemporary astronomers apart from Clavius himself. Although he recorded only the year of each observation, very large solar obscurations are sufficiently rare at any one place to permit the precise dates of both events to be unambiguously derived by modern astronomical computations. As it happens, Clavius has mistaken the year of the first observation. The only large eclipse for many years around A.D. 1559 which was visible in Portugal occurred on 1560 Aug 21. This was total over a fairly wide area, the lunar semi-diameter exceeding that of the Sun by a factor of 1.05 (the maximum ratio for any solar eclipse is 1.08). We compute that near the central line of this eclipse, the total phase would last for 3 1/2 min. At Coimbra (lat = 40.20 deg N, long = 8.42 deg W) totality would occur at about 11.15 a.m. local time.

The year of the second eclipse is correctly given by Clavius; the computed date for this event is 1567 Apr 9. We calculate that greatest phase would occur at Rome at a local time of about 12.10 p.m., in close agreement with the record. (Both eclipses were midweek phenomena, each occurring on a Wednesday). Clavius' experiences in 1560 might well have helped him give a particularly careful description in 1567. Whereas on the former occasion he remarked that the Moon "covered the whole Sun for a considerable length of time", in 1567 he made no allusion to the complete disappearance of the Sun, asserting instead that "a certain narrow circle was left on the Sun, surrounding the whole of the Moon on all sides (*relinquebatur in Sole circulus quidam exilis undique totam Lunam ambiens*)".

Taking Clavius' account of the eclipse of 1567 at face value, it might perhaps seem that he witnessed the ring phase of an annular eclipse. However, computation shows that the eclipse was not annular. As seen from Rome, the topocentric lunar semi-diameter (955".92) was slightly greater than the solar semi-diameter (953".56) by a factor of 1.0025. (It should be noted that there is no evidence that the solar diameter has changed significantly in the last few centuries - Morrison et al. 1988; Toulmonde 1995). Hence if the lunar limb was assumed to be accurately circular, the eclipse of 1567 would be only marginally total, the Moon covering the Sun completely for just 14 sec near the central line. However, when the true profile of the lunar limb is taken into account, several beads of photospheric light would be visible even where the eclipse was central. In consequence, the eclipse was neither fully total nor annular.

Based on P.M. Muller's extensive observations of total solar eclipses, Muller and Stephenson (1975) expressed the opinion that the "certain narrow circle" described by Clavius was the inner corona. This is very intense when an eclipse is only just total. One of us (JEJ) has also observed numerous total solar obscurations and his experiences lead us to endorse the above interpretation, which we shall consider further below.

Clavius was of the opinion that the circle of light which he noticed in 1567 was a unique phenomenon. Based on the evidence available to him, he had good reason for his supposition. Marginal eclipses, such as he witnessed, are very rare at any given place, typically occurring only once in several thousand years. No similar phenomenon is described in any preserved writings prior to Clavius, while even telescopic observations are very rare. For a comparable example, see Mathers (1966). Only a single datable record of the corona is extant from before Clavius' time. In A.D. 968 the corona was described by a Constantinople observer as "like a narrow headband shining around the extreme edge of the (solar) disc" (Stephenson 1997). However, on this occasion the eclipse was fully total, the lunar semi-diameter exceeding that of the Sun by a factor of 1.03. It might be mentioned that accounts of the ring phase (i.e. of a central annular eclipse) are also extremely rare in early literature.

As noted above, Clavius specifically states that he was in Rome when he witnessed the eclipse of 1567. In all probability he would have made his observation at the Collegio Romano itself (lat = 41.90 deg N, long = 12.48 deg east), where he was normally based. This is situated near the centre of Rome, about 2 km east of the Vatican. Although not mentioned by Clavius, it seems quite likely that he might have made some preparations to observe both the eclipses of 1560 and 1567, based on advance predictions. At this period, eclipse predictions were necessarily still fairly crude, but they would be capable of yielding an approximate magnitude and time of occurrence. However, Clavius would be unable to anticipate the precise circumstances of each event and would undoubtedly be taken by surprise at what he saw on both occasions.

3. Basic astronomical computations

The principal aim of this paper is to utilise Clavius' observations of the solar eclipse of 1567 to derive the cumulative effect of changes in the terrestrial rate of rotation at that date. This quantity, known as ΔT, is the difference between Terrestrial Time (TT: a theoretically uniform time-scale defined by the motion of the Moon and planets) and Universal Time (UT: as measured by the rotation of the Earth). Variations in the terrestrial rotation rate on a time-scale of centuries are produced by a variety of factors. These include: (i) lunar and solar tidal friction; (ii) the gradual uplift of terrain which was glaciated during the last ice-age; (iii) global sea-level changes (associated with minor climatic variations); and (iv) coupling between the fluid core and solid mantle of the Earth. Although the amplitude of variations in the length of the mean solar day is small (only a few milliseconds), the cumulative effect over several centuries (each containing 36525 days) is substantial. From the results deduced by Stephenson and Morrison (1995, Table 2), ΔT amounted to approximately 100 sec when Clavius made his observations. It is our aim to refine this value.

It should be mentioned that in order to render the eclipse of A.D. 1560 total at Coimbra (in keeping with the record) we calculate that any value of ΔT between -490 sec and +220 sec would suffice. However, the observation in 1567 yields a much narrower range for this parameter - hence we shall consider it in more detail.

In making the necessary eclipse computations for the eclipse of 1567, we have utilised the following lunar and solar ephemerides. For the Moon we have employed a modification of the ephemeris *j=2* (IAU 1968) in which a value for the lunar tidal acceleration ($\dot{n}$) of -26 arcsec/cy^2 was adopted. This is very close to the current value of $\dot{n}$ derived from lunar laser ranging (Dickey et al. 1994). For the Sun we have used Newcomb's (1895) solar ephemeris. Both of these ephemerides are of high precision, and are more than adequate for our purpose. N.B. in this context, it should be noted that the Jet Propulsion Laboratory lunar ephemeris LE 200 contains a significant error in the

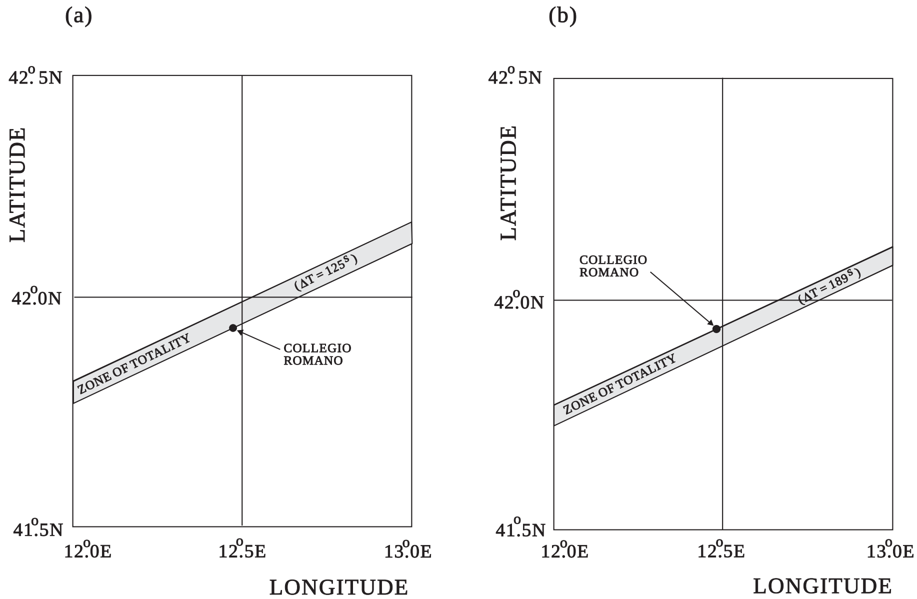

Fig. 1a and b. A section of the track of totality in A.D. 1567 computed for two limiting values of ΔT. A circular lunar outline is assumed here. With ΔT = 125 sec, the southern limit of totality just touches the Collegio Romano, where Clavius probably observed (**a**); for ΔT = 189 sec the northern limit just touches this site (**b**). For ΔT values between these two limits, the eclipse would be central.

lunar longitude prior to A.D. 1750 - reaching nearly 40 arcsec by A.D. 1600 (private communication: Dr E.M. Standish, Jet Propulsion Laboratory, Pasadena, U.S.A.)

In addition to the topocentric lunar and solar diameters (as quoted in Sect. 2), it was necessary to compute several fundamental parameters as outlined by Duncombe (1973). These angles are: (i) the topocentric lunar libration in longitude (L = -5.1 deg); (ii) the solar declination at the time (δ = +11.0 deg); (iii) the Sun's zenith distance at greatest phase (z = 31.0 deg); (iv) the position angle of the axis of the Moon (C_o = 337.6 deg). None of these quantities varies appreciably for any reasonable range of ΔT. On the preliminary assumption of a circular outline for the Moon, we deduced that the eclipse would be total at Rome for only a narrow range of values for ΔT: specifically between 125 and 189 sec (see Fig. 1a and b). Beyond these limits the phase would only be partial.

Fig. 1a depicts the computed track of totality for ΔT = 125 sec; the southern edge just touches the site of the Collegio Romano. Fig. 1b shows the computed track for ΔT = 189 sec; here the northern edge just touches this position.

As noted above, there are sound reasons for believing that Clavius witnessed the eclipse of 1567 from the Collegio Romano, close to the centre of Rome. However, an error in his location by 1 km or so would have an almost negligible effect on the result for ΔT. If he were 1 km from this site towards the north, our revised range of ΔT would be 119 to 183 sec. At a similar distance towards the south of the Collegio Romano, the corresponding range would be 131 to 196 sec. Since the shadow moved in a WSW to ENE direction, the effect of small changes in the east-west location of Clavius would be much less. Hence we shall adopt the preliminary range $125 < \Delta T < 189$ sec. By allowing for the lunar limb profile, this interval can be considerably refined, as discussed below.

In our investigation we have made use of the extremely useful series of lunar limb profile diagrams produced by Duncombe (1973). Based on the limb charts of Watts (1963), these are specifically intended for the investigation of total solar eclipses. The profiles are available for values of L (libration in longitude) from +6 deg to -6 deg at 1 deg intervals. In general, there is little variation in profile for a change in L by 1 deg. We selected Duncombe's diagram for L = - 5 deg for our investigation; this is very close to the computed libration (-5.1 deg). This diagram, which is reproduced (with additions) in Fig. 2, shows both the mean (circular) lunar outline and the true limb. It should be noted that the lunar limb irregularities are exaggerated by a factor of 60 in the radial direction. On Fig. 2 we have marked with the letters A to I several deep depressions at the Moon's limb. In particular, A is Mare Humboldtianum, B Mare Marginis, C Mare Smythii, D Mare Australae, H Mare Orientale, and I the crater Nernst. E, F and G each relate to more than one feature. From the radial scale (in arcsec) it can be seen that these depressions range in depth by up to about 3 arcsec relative to the mean circular outline.

Since the solar semi-diameter in 1567 was only about 2.4 arcsec less than the lunar semi-diameter, it is clear from Fig. 2 that this eclipse cannot have been fully total. The large depressions in the lunar limb, especially at A, C and H, would ensure that whatever value of ΔT is selected, the Sun would never be completely obscured by the Moon. In particular, the appearance of the eclipse would be critically dependent on the value of ΔT.

4. Interpretation

A full description of the method of analysis used will be published elsewhere (Jones 1997). It should be noted that in the present section, the term 'totality' is used in a special sense to mean the interval from smooth-limb second contact to the corresponding third contact. In actual practice, totality did not take place in A.D. 1567.

The following are our estimates of the appearance of the Sun for a series of values of ΔT between the derived limits of 125 and 189 sec. For each individual value, we have carefully considered any portions of the solar limb which would remain

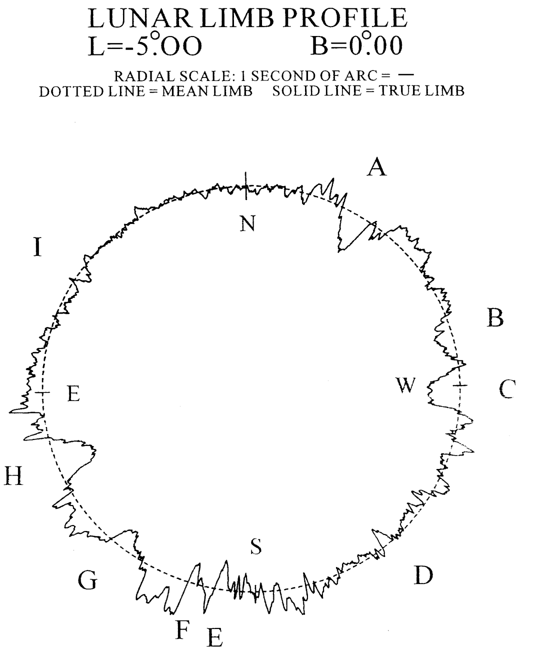

Fig. 2. The lunar limb profile at the eclipse of A.D. 1567 Apr 9, as derived from Duncombe (1973). The letters A to I around the periphery of the figure identify major lunar features. (For details, see text).

uncovered due to depressions along the lunar limb and hence the distribution of Baily's beads at any time during totality. Not only the position, but also the size (i.e. width and depth) of each bead were noted and hence an idea of its apparent brilliance was gained. In each example below we have used the present tense since the individual scenarios are necessarily hypothetical.

(i) ΔT = 125 sec. A string of beads is constantly visible along the jagged south polar region of the Moon. The bead at A does not appear. Hence there is a highly asymmetric appearance throughout a very short totality.

(ii) ΔT = 130 sec. A somewhat similar appearance to (i). Baily's beads, especially E and F, are constantly visible in the south polar regions during totality. Bead D becomes visible just before mid-totality, shortly followed by the appearance of C. Bead H is always visible throughout totality, disappearing just about at third contact. A never appears, hence there is still an asymmetric appearance.

(iii) ΔT = 140 sec. The behaviour is somewhat different from (ii). There is still some bead activity along the south polar region. E is visible all the way to third contact, C and D appear just about mid-totality, with C emerging rapidly about two-thirds of the way through totality. The appearance is a little more symmetrical than in the previous cases. About three-quarters of the way through totality A would appear just before the disappearance of H. This is still not a closely symmetrical case.

(iv) ΔT = 150 sec. At the start of totality, H is very visible as well as G. E is also just visible and in fact persists through most of totality. The only other south polar activity from beads occurs about three-quarters of the way through totality when beads in the region of third contact, including D, appear. A becomes visible just before mid-totality, at about the same time as C appears. H disappears about three-quarters through totality, just as D appears. There is a period just after mid-totality when only four beads are visible, all of them fairly small. Hence a fairly symmetrical eclipse is seen. It is very nearly total, with just about 1/3 arcsec of solar disc protruding at the lowest points of H and C.

(v) ΔT = 160 sec. Baily's beads around second contact are lost rapidly, but A becomes visible almost immediately. After this, for a period nearly one-third of the duration of totality, A and H are small and are the only two beads visible. This is the closest that the eclipse actually reaches to the true total phase. About mid-totality, C appears but the motion of the Moon is such that this bead remains very small indeed until very close to third contact when it enlarges rapidly. H disappears roughly three-quarters of the way through totality.

(vi) ΔT = 170 sec. H and A are seen from second contact. H gets smaller and disappears just after mid-totality. C appears at just about the same time. However, A is constantly more exposed than in previous cases, so that a long-lasting diamond ring effect results in a more asymmetric appearance overall. C enlarges rapidly compared with ΔT = 160 sec and B also appears well before third contact.

(vii) ΔT = 180 sec. A few lingering beads appear after second contact, especially at I. A is very prominent. H is visible until just before mid-totality, but C appears just after mid-totality. Hence for a very brief period, only bead A is visible but it is very prominent. From about three-quarters of the way through totality B and C enlarge rapidly as well.

(viii) ΔT = 185 sec. Persistent bead activity is now evident along the north polar region. At roughly one-third of the way through totality H disappears. C, however, does not appear until after mid-totality. On the other hand, A is always very prominent and is accompanied by constant small bead activity. B appears about 3/4 of the way though totality. Not surprisingly, there is always a rather asymmetric appearance throughout a very short period of totality.

(ix) ΔT = 189 sec. There is now constant bead activity along the north polar region as well as the presence of a very large bead at A. C and B appear just before third contact. The duration of totality is now, of course, extremely short.

5. Discussion

From the above analysis, it is apparent that values of ΔT in the region of 150 to 160 sec produce the nearest conditions to actual totality. Although in this ΔT range there would never be a complete absence of Baily's beads. the two or three that remained would be very small; they would be reminiscent of the beads normally seen within just one or two seconds before or after totality in the more usual kind of total eclipse. In normal total eclipses, the rate of separation of the solar and lunar limbs is in the region of 0.3 to 0.5 arcsec per second of time. The beads seen in the ΔT = 160 sec case would be of the order of 0.3 arcsec above the lunar limb at the lowest part of the respective depressions. This represents a situation very close to true totality. As the inner corona can often be sighted up to

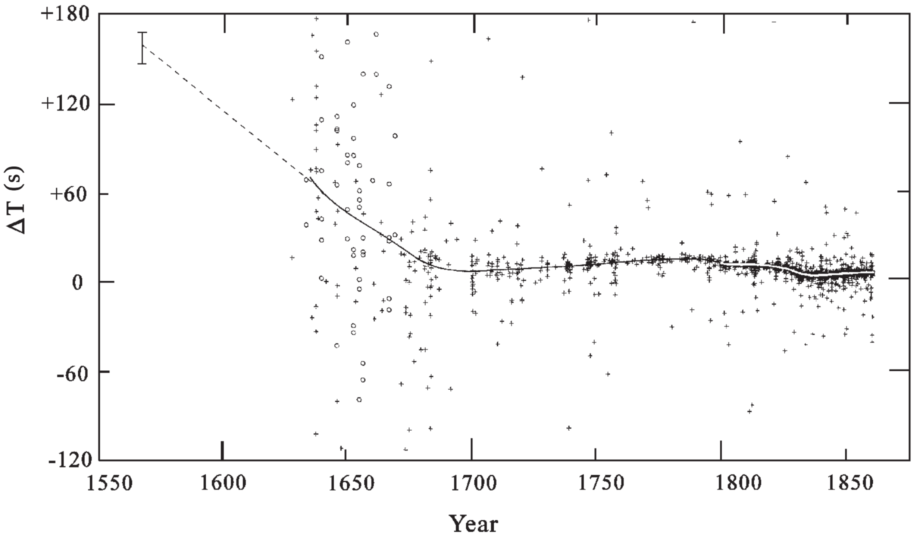

Fig. 3. ΔT curve derived from telescopic observations of occultations (denoted by circles) and solar eclipses (crosses) for the period from A.D. 1620 to 1860 as derived by Stephenson and Morrison (1984). The ΔT limits deduced in the present paper from the 1567 eclipse are shown for comparison.

perhaps a minute before normal totality, there is thus a very good likelihood that it would have been seen in this case fully surrounding the Moon.

One caveat which should be made mentioned is as follows. In the approach to a normal total solar eclipse the last beads are concentrated near the point of second contact. The inner corona is seen around the rest of the Moon away from this point which is, of course, flooded with light. In the present eclipse the beads would be distributed around the Moon at several points so that their brilliance could drown the inner corona over a wider area. However, as the beads would be so small this effect may not have been appreciable; the fact remains that Clavius witnessed a complete ring of light around the edge of the Moon.

A further point may be that the constant presence of beads of light would mean that Clavius would not have been dazzled as beads appeared in different locations. The dazzling diamond ring effect seen at a normal total solar eclipse is due to the eye becoming dark-adapted during totality. Finally, note that with ΔT in the region of 160 sec there would be a relatively lengthy period of near-totality, giving an observer more opportunity to notice the corona.

One additional qualification to this analysis is that small corrections to the lunar limb profile should be applied according to Morrison and Appleby (1981). These suggest slight alterations to the datum of the mean lunar limb, a displacement of its centre and a certain amount of ellipticity. The corrections vary with libration and the angle J, and hence vary from feature to feature. Applying these corrections to the most prominent features on the limb, only A (0.22 arcsec deeper) would be significantly affected. This slight adjustment would tend to favour $\Delta T = 160$ sec as being closer to totality than $\Delta T = 150$ sec.

Allowing some latitude, we infer that in A.D. 1567 a value of the Earth's rotational clock error ΔT in the range 145 to 165 sec would be needed to provide the appearance of the eclipse in that year described by Clavius. Certainly $\Delta T = 140$ sec seems unlikely, as does $\Delta T = 170$ sec.

6. Conclusion

Our result of $145 < \Delta T < 165$ sec, provides a valuable link between the pre-telescopic ΔT curve and the corresponding curve derived from telescopic data. The form of this latter curve is poorly established before about A.D. 1675 (Stephenson and Morrison 1984). Our derived limits in A.D. 1567 are marked in Fig. 3, which also shows the scatter of data points determined from telescopic observations between 1620 and 1860. Our result confirms the fit by Stephenson and Morrison (1984) to the early telescopic data (before A.D. 1675).

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