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Earth rotation derived from occultation records

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Abstract

We determined the values of the Earth's rotation parameter, $\Delta T = \mathrm{TT} - \mathrm{UT}$, around AD 500 after confirming that the value of the tidal acceleration, $\dot{n}$, of the lunar motion remained unchanged during the period between ancient times and the present. For determining of ΔT, we used contemporaneous occultations of planets by the Moon. In general, occultation records are not useful. However, there are some records that give us a stringent condition for the range of ΔT. Records of the lunar occultations in AD 503 and AD 513 are such examples. In order to assure the usefulness of this occultation data, we used contemporaneous annular and total solar eclipses, which have not been used in the preceding work. This is the first work in which the lunar occultation data have been used as primary data to determine the value of ΔT together with auxiliary contemporaneous annular and total solar eclipses. Our ΔT value is less than a smoothed value (Stephenson 1997) by at least 450 s. The result is consistent with our earlier results obtained from solar eclipses.

Key words: Earth — eclipses — history and philosophy of astronomy — occultations

1 Introduction

Ancient observational records of total and annular solar eclipses have been known to provide limits to the value of $\Delta T = \mathrm{TT} - \mathrm{UT}$, where TT is the Terrestrial Time, a uniform measure of time, and UT is the Universal Time determined by the rotation of the Earth (Stephenson 1997; Tanikawa & Sôma 2004). As can be easily seen, the parameter ΔT measures the cumulative effect of changes in the length of a day.

For more than ten years we have been deriving the ΔT values of ancient times (Tanikawa & Sôma 2002, Tanikawa & Sôma 2004; Kawabata et al. 2004; Sôma et al. 2003, 2004; Sôma & Tanikawa 2005, 2006; Tanikawa et al. 2010) from solar eclipse records. The main purpose has been to show the existence of short-term variations of ΔT, 'short-term' being less than a few hundred years. In due course, we realized that in order to attain the purpose, the first thing to be done is to find good epochs for which there is strong evidence that the values of ΔT deviate from the smoothed values (Stephenson 1997).

We expect that the short-term variations of ΔT reflect climate changes due to fluctuations of the solar activity of the time scale of ΔT variations. Our reasoning is as follows. As mentioned above, ΔT represents the accumulated value of any excess or deficit of the rotation speed of Earth with reference to a uniform rotation. The inclination of the ΔT curve with respect to time shows the rotation speed. Therefore, Earth's rotation speed is larger at the steep portions of the ΔT curve, whereas the speed is smaller at the non-steep portions. The speed of Earth's rotation is directly related to the inertial moment, I_{E}, of Earth for a given rotational angular momentum. Then, we can say that I_{E} is smaller when the ΔT curve is steep, whereas I_{E} is larger when the curve is gentle. Here, we say steep or gentle with respect to the average trend of the curve. Now, what is the cause of the variations of I_E during tens to hundreds of years? Our answer at present is the sea level changes of the equatorial regions due to mass changes of the ice caps in the Arctic and Antarctic regions, which are, in turn, due to variations of the insolation. Our supposition is that the surface of Earth was colder when the ΔT curve was steep, whereas it was warmer when the curve was non-steep (Tanikawa & Sôma 2015). The result of the present paper suggests that there was a world-wide cold period before AD 500. This is concordant with the European local cold climate before AD 600 deduced by Büntgen et al. (2011).

Our first results were given in Tanikawa and Sôma (2004). There, we took two epochs at around 188 BC, and at AD 873 for which there were plural observations of deep solar eclipses. A narrow range of ΔT values were obtained at around 188 BC. The range happened to fall almost exactly on the smoothed curve. The range of ΔT for AD 873 is above the smoothed curve with some additional assumption. Otherwise, the range is rather wide. Thus, for the two epochs in which the deviations of ΔT from the smoothed curve may not be large. A part of the results of Tanikawa and Sôma (2004) is reviewed in section 2 of the present work.

The second main results were given in Tanikawa et al. (2010). In this work, several eclipses of the first half (722 BC–481 BC) of the Chunqiu period were analyzed. The ΔT values were on average above the smoothed curve.

The present work is the third trial concerning this direction. Other than the above general purpose, we have two purposes of particular kinds. One is to show the usefulness of ancient records of lunar occultations in China after preliminary efforts in Sôma and Tanikawa (2011, 2015). The other is to obtain ΔT values that deviate from the values on the smoothed curve by large amounts. Some historical astronomers around us seem to look at the smoothed values or the spline curve as giving definite values without errors. One caution to historical astronomers is that do not judge the reliability of the ancient eclipse records on partiality or totality of individual eclipses with reference to the smoothed values because these values may contain errors of a few hundred seconds.

In section 2 we first review a short history of the modern values $\dot{n}$ of the lunar tidal acceleration in the form of a list of selected works. As can be seen in the list, the values became converged after adopting of LLR (Lunar Laser Ranging) data. In the latter half of the section, we show evidence that the modern value of $\dot{n}$ remained unchanged from ancient times. This is shown in figure 1, which depicts the possible ranges of ΔT and $\dot{n}$ for several ancient contemporaneous eclipses. The figure shows that the lunar tidal acceleration between around 200 BC and the present was within $-2''/\mathrm{cy}^2$ and $+1''/\mathrm{cy}^2$ of the modern value determined from LLR data.

In section 3 we show examples of lunar occultation records by a combination of which we could derive the upper and lower bounds of the ΔT value. In the case of the AD 503 occultation, the visibility of the phenomenon is bound from above by the time of the moonrise. In the case of the AD 513 occultation, it is bound from below by the time of the moonset. The annular eclipse of AD 516 at Jiankang and the total eclipse of AD 522, also at Jiankang, were used to determine the range of ΔT. The ΔT values obtained from occultations and eclipses agreed perfectly well. We thus confirmed that occultation data were useful.

In section 4, we conclude our discussions by giving the variations of ΔT in the form of a graph.

2 Tidal acceleration in the Moon's motion

As was discussed by Sôma and Tanikawa (2009), the time dependent quadratic term in the Moon's longitude plays an important role in calculating of the Moon's positions. The gravitational component in the Moon's mean longitude due to the planetary perturbations and the Earth's figure perturbations was given as $6\overset{''}{.}0590\,T^2$ by Chapront, Chapront-Touzé, and Francou (2002) based on the analytical theory ELP2000-96 (Chapront & Chapront-Touzé 1996). Here, T is the time in Julian centuries. Note that the precessional quadratic term $1\overset{''}{.}1054\,T^2$, whose value is due to Capitaine, Wallace, and Chapront (2003), should be added to the sidereal motion term given above if we need the motion referred to the mean equinox of date.

In addition to the gravitational component the tidal component due to the reaction on the lunar motion of the tides raised by the Moon on Earth must be taken into account in the calculation of the Moon's positions and the coefficient of this component has to be determined from observations. We hereinafter denote the tidal acceleration of the Moon by $\dot{n}$. Here, the term "acceleration" is used to mean the doubled coefficient of the quadratic term in the Moon's longitude. Table 1 lists determinations of $\dot{n}$ obtained from past observations. It is noted that some of the large negative values of $\dot{n}$ obtained in the 1970s were largely due to deficiencies in the planetary terms in Brown's theory of the motion of the Moon (Sôma 1985). The values obtained from LLR observations since the 1970s converge well at about $-25\overset{''}{.}8/\mathrm{cy}^2$.

The solar and lunar ephemerides used in our analyses are the JPL's DE406 (Standish 1998). The tidal acceleration intrinsic to DE406 is $-25\overset{''}{.}826/\mathrm{cy}^2$ (Chapront et al. 2001) , which agrees well with the recently derived ones

Table 1. Tidal acceleration of the Moon's mean longitude.*

Authors	$\dot{n}$ in $''/\text{cy}^2$	Method
Spencer Jones (1939)	$-22.44^\dagger$	Lunar occultations and positions of planets
Van Flandern (1970)	-56 ± 16	Lunar occultations with Brown's theory
Morrison (1973)	-42 ± 6	Lunar occultations with Brown's theory
Van Flandern (1975)	-65 ± 18	Lunar occultations with numerical integration
Oesterwinter and Cohen (1975)	-38	Lunar occultations with numerical integration
Morrison and Ward (1975)	-26 ± 2	Lunar occultations and Mercury's transits
Muller (1976)	-30	Eclipses
Calame and Mulholland (1978)	-24.6 ± 5	LLR
Williams et al. (1978)	-23.8 ± 4.0	LLR
Ferrari et al. (1980)	-23.8	LLR and lunar orbiter
Dickey et al. (1982)	-23.8	LLR
Dickey and Williams (1982)	-25.10 ± 1.3	LLR
Newhall et al. (1988)	-24.90	LLR
Dickey et al. (1994)	-25.88 ± 0.50	LLR
Chapront and Chapront Touzé (1996)	-25.62	LLR
Chapront et al. (1999)	-25.78	LLR
Chapront et al. (2001)	-25.836	LLR
Chapront et al. (2002)	-25.858 ± 0.003	LLR

*This table is a reproduction of table 1 in Sôma and Tanikawa (2009) with partial amendments.
†This value was derived by Clemence (1948) based on Spencer Jones' results and it was used in the Ephemerides from 1960 to 1983.

from LLR observations. Morrison and Ward (1975) analyzed the transits of Mercury observed since 1677 and they obtained the tidal acceleration $-26''/\text{cy}^2$ from comparisons with lunar occultations. The fact that this value is consistent with those from LLR observations may indicate that the tidal acceleration was almost constant from the 17th century. It is one of our objectives to show whether the tidal acceleration has been almost constant or not since ancient times.

By using plural contemporaneous solar eclipse records we can determine the ΔT value and the lunar tidal acceleration, $\dot{n}$, simultaneously. The method was briefly described by Sôma et al. (2004) and Kawabata et al. (2004). Here, we give an example of the method using three solar eclipses between 198 BC and 181 BC.

Hanshu (□ □ : Bangu □ □ et al. 1962) is a formal Chinese history book describing the history of China during the former Han Dynasty. In Hanshu the solar eclipses on 198 BC August 7, 188 BC July 17, and 181 BC March 4 were recorded as being annular, almost complete (which means it was not total but very close to total), and total, respectively. Strictly speaking, total eclipses and annular eclipses were not distinguished in the records, but we now know that the eclipse in 198 BC was annular and the eclipse in 181 BC was total. We can assume that the records were based on observations made in Chang-an (□ □), the capital of China at the time. The eclipse in 188 BC was also recorded in Rome as total as given by Stephenson (1997).

Figure 1 gives the area of two parameters, ΔT and $\dot{n}$, where the total or annular solar eclipses were seen in the respective places. The intersection of the three regions of annularity and totality from the three observations represents the allowable region of the two parameters. The region of totality of the eclipse in 188 BC in Chang-an (bounded by the dotted narrow parallels) does not overlap the common region. This is concordant with the non-totality record of

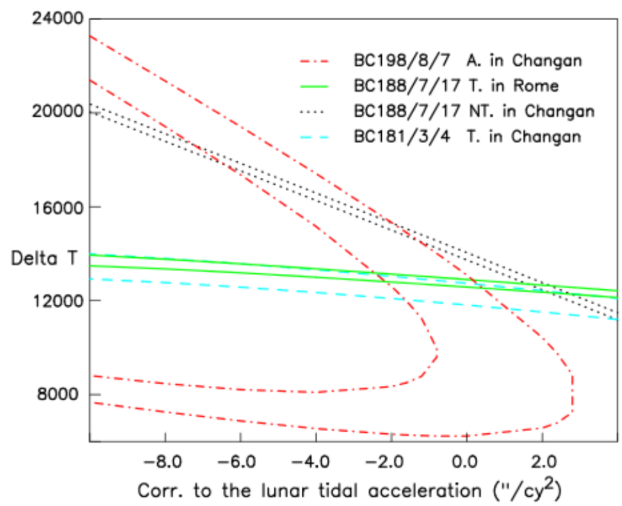

Fig. 1. Total or annular solar eclipse regions on the ($\dot{n}$, ΔT)-plane for four observations of three contemporaneous eclipses between 198 BC and 181 BC from Tanikawa and Sôma (2004). Dates are written in the order of year, month, and day. 'A.', 'T.', and 'NT.' mean annular, total, and non-total, respectively, of the records. The total eclipse took place in the parameter region between the black dotted parallel lines on 188 BC July 17 at Chang-an. That the region is off the common region of the other eclipses means the non-totality of this eclipse at Chang-an, which agrees with the record. (Color online)

the eclipse. The figure indicates that the tidal acceleration, $\dot{n}$, of the Moon is between $-27''.86/\mathrm{cy}^2$ and $-24''.86/\mathrm{cy}^2$, which agrees well with the current tidal acceleration (see Tanikawa & Sôma 2004). If we fix the $\dot{n}$ value as the current one, we could obtain the ΔT value as being between 12581s and 12741s.

In this analysis we assumed that the ΔT value did not change significantly during the 18 years between 198 BC and 181 BC. Also note that the $\dot{n}$ value obtained as described above is not the lunar tidal acceleration value at the times of the eclipses, but is the mean lunar acceleration value during the period between the eclipse epochs and the present. The fact that the lunar tidal acceleration obtained from figure 1 matches with the current one does not necessarily mean that the lunar tidal acceleration has been constant from that period. For this reason we have to investigate lunar tidal accelerations for other periods as well.

3 Lunar occultations and solar eclipses in the beginning of the sixth century AD

The lunar occultation of Venus on AD 503 August 5 was recorded in Weishu (: Weishou 1974) which describes the history of the Northern Wei in the period of South and North Dynasties. The record says:

(AD 503 August 5),
[( )]
Emperor Shizong, Jingming reign period, 4th year, 6th month, *ding-wei* [44], the moon occulted Venus. [Weishu, Annals of Astronomical phenomena, the second of Vol. 1 (the second of Vol. 105), second part, section of unusual lunar events]

The lunar occultation of Saturn on AD 513 August 22 was also recorded in Weishu. The record says:

(AD 513 August 22),
[( )]
Emperor Shizong, Yanchang reign period, 3rd year, 7th month, *wu-wu* [55], the moon occulted Saturn. [Weishu, Annals of Astronomical phenomena, the second of Vol. 1 (the second of Vol. 105), second part, section of unusual lunar events]

These are assumed to have been observed in Luoyang ( ) since it was then the capital of the Dynasty. The longitude and latitude of Luoyang are listed in table 2. Usually the visibility areas of lunar occultations are so wide that they are useless for determining the ΔT value. However, as shown in figures 2 and 3, the lunar occultation of Venus on AD 503 August 5 took place near the moonrise, and as shown in figures 4 and 5, the lunar occultation of Saturn on AD 513 August 22 took place near the moonset. Let us explain the usefulness of these occultation records.

Table 2. Observation sites.

	East longitude	North latitude
Luoyang	112° 28′	34° 45′
Jiankang	118° 47′	32° 2′

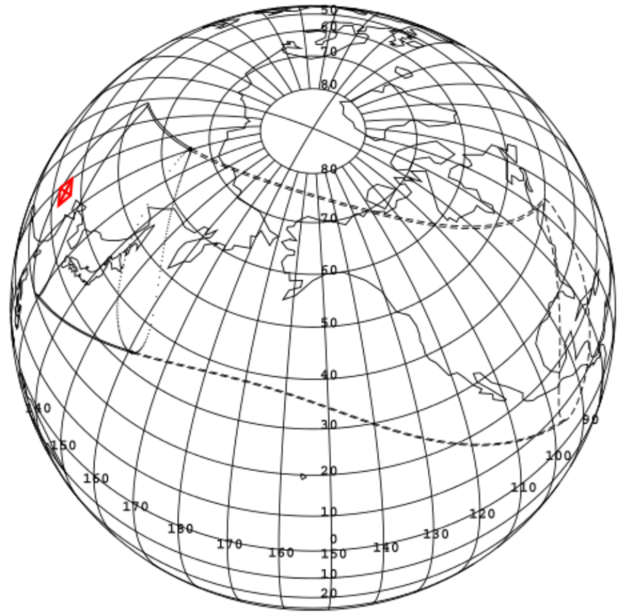

Fig. 2. Lunar occultation of Venus on AD 503 August 5. The shadow band is for $\Delta T = 4500$ s. The cross indicates the place of Luoyang. The area of the solid lines is the visible area at night, while the area of the broken lines is the visible area in the daytime. (Color online)

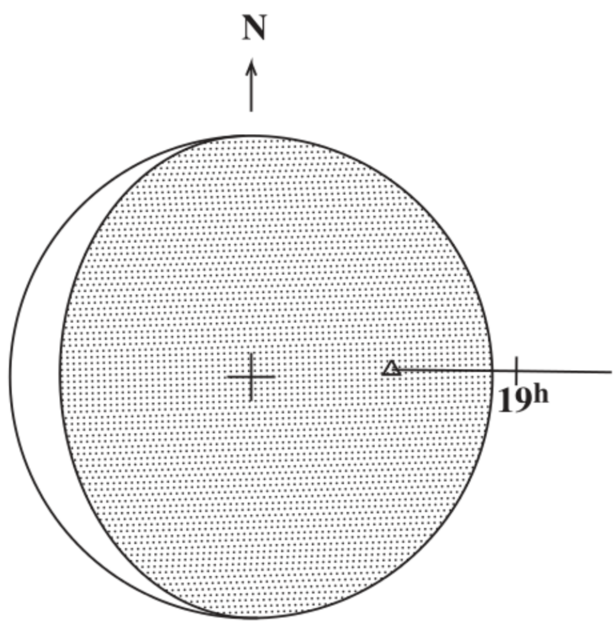

Fig. 3. Egress of Venus from the disc of the Moon at the Lunar occultation of Venus on AD 503 August 5. The open triangle shows the position of Venus at the moonrise looking from Luoyang at $18^{\mathrm{h}}42^{\mathrm{m}}$ UT on AD 503 August 4 with assumption $\Delta T = 4500$ s.

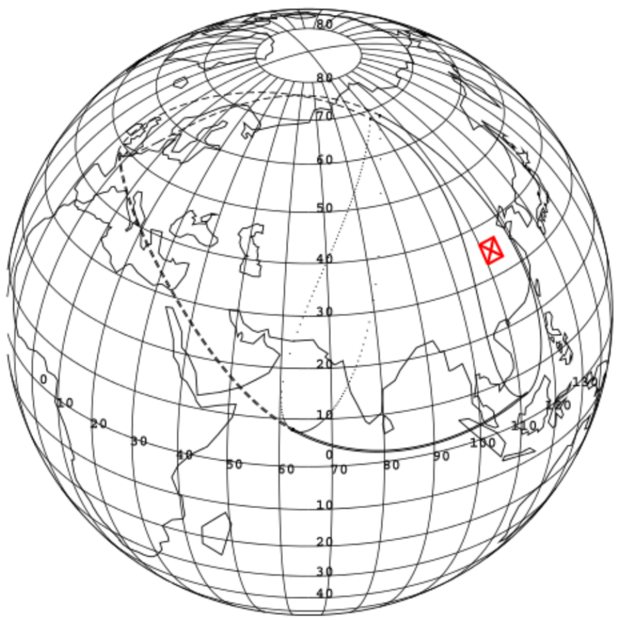

Fig. 4. Lunar occultation of Saturn on AD 513 August 22. The shadow band is for $\Delta T = 4500$ s. The cross indicates the place of Luoyang. The area of the solid lines is the visible area at night while the area of the broken lines is the visible area in the daytime. (Color online)

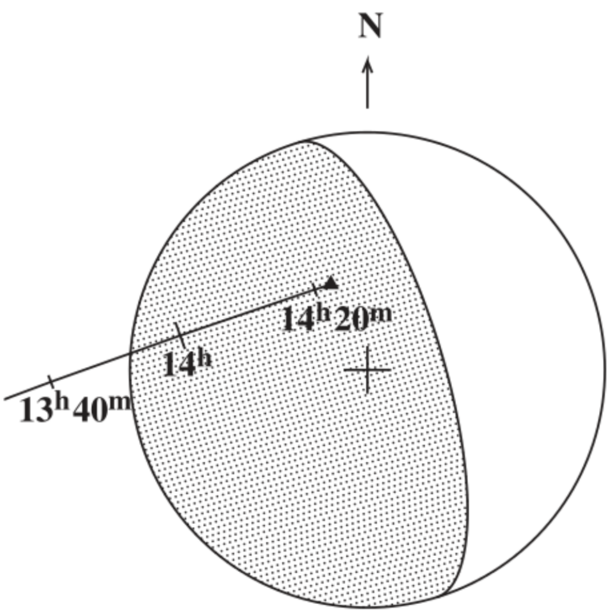

Fig. 5. Ingress of Saturn into the Moon at the Lunar occultation of Saturn on AD 513 August 22. The filled triangle shows the position of Saturn at the moonset looking from Luoyang at $14^{h}22^{m}$ UT on AD 513 August 22 with assumption $\Delta T = 4500$ s.

The occultation on AD 503 August 5 would not have been observable at Luoyang if ΔT was too large because in this case then the occultation band would have shifted to the east, and Luoyang would have been out of the band. This means that there is an upper bound of ΔT in order that the people in Luoyang could have seen the occultation. More precisely, if $\Delta T > 5246$ s, assuming the present value of the lunar tidal acceleration, then Venus was off the lunar disc when the Moon rose. The relative motion of the Moon and Venus is shown in figure 3. Venus egressed from the dark-side of the lunar disc. If $\Delta T < 5246$ s, then the observer in Luoyang actually saw the bright Venus appearing from the dark lunar disc. This is a conspicuous phenomenon. Modern observers may guess that the occultation occurred even when $\Delta T > 5246$ s because they may wind back the time so that Venus goes back to the lunar disc below the horizon. However, the present authors believe that Chinese astronomers reported what they observed.

The occultation on AD 513 August 22 would not have been observable at Luoyang if ΔT was too small, because then the occultation band would have shifted to the west and Luoyang would have been out of the band. This means that there is a lower bound of ΔT in order that the people in Luoyang could have seen the occultation. More precisely, if $\Delta T < 2893$ s, assuming the present value of the lunar tidal acceleration, then Venus was off the lunar disc when the Moon set. The relative motion of the Moon and Venus is shown in figure 5. Saturn ingressed from the dark-side of the lunar disc. If $\Delta T > 2893$ s, then the observer in Luoyang actually saw Saturn disappearing into the dark lunar disc.

Thus, the combination of the two lunar occultations give the lower and upper bounds to the ΔT value, This situation is well illustrated in figure 8 analogous to figure 1. Here, the upper bound and lower bound were shown as being nearly a straight curve with downarrows and uparrows. The sandwiched region is a possible area of ΔT and $\dot{n}$. We obtained the range ΔT as

$$2893\,\mathrm{s} < \Delta T < 5246\,\mathrm{s} \tag{1}$$

from the two occultation records assuming the current value of the lunar tidal acceleration.

In order to confirm the correctness of our method using occultations, we compared the ranges of ΔT obtained as mentioned above and obtained from the two solar eclipses which happened to be contemporaneous.

The first one is the annular solar eclipse on AD 516 Apri1 18 recorded in the Nanshi (□□, □□□: Lidashi □□□ & Liyanshou □□□, 2013) which describes the history of the South Dynasties, and in the Liangshu (□□, □□□: Yaosilian □□□, 2012), which describes the history of the Liang Dynasty of the South Dynasties. The records say:

□□□□□□□□□□ (AD 516 April 18) □□□□□ (□□ □□□□□□□□□□) Tianjian reign period, 15th year, 3rd month, *wu-chen* [5], shuo, solar eclipse. (Liangshu, Emperors' chronicle, second volume, Emperor Wu, Xiaoyan, second,)

□□□□□□□□□□ □□□□, □□ (□□ □□□□ □□□□□□□)

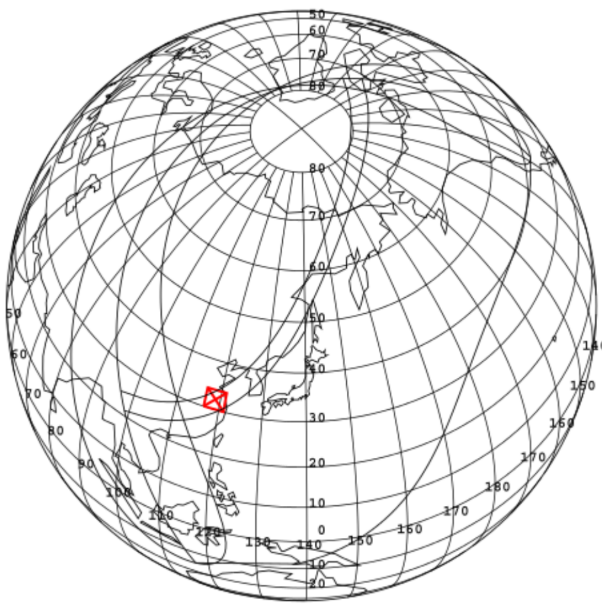

Fig. 6. Solar eclipse on AD 516 April 18. The shadow band is for $\Delta T = 4500$ s. The narrow zone is where the annular eclipse can be seen. The cross indicates the place of Jiankang. (Color online)

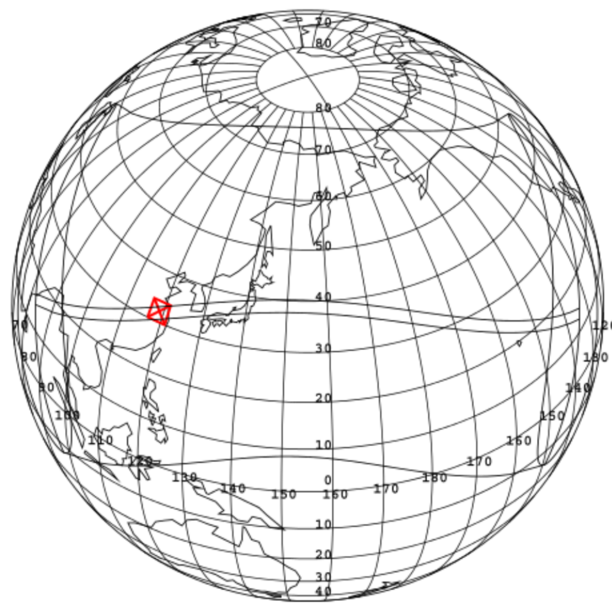

Fig. 7. Solar eclipse on AD 522 June 10. The shadow band is for $\Delta T = 4500$ s. The narrow zone is where the total eclipse can be seen. The cross indicates the place of Jiankang. (Color online)

Tianjian reign period, 15th year, 3rd month, *wu-chen* [5], shuo, solar eclipse, total. (Nanshi, Liang Volume first, sixth volume from the beginning, Emperor Wu, Xiaoyan, first.)

The second one is the total solar eclipse on AD 522 June 10 recorded in the Liangshu. The record says:

□□□□□□□□□ (AD 522 June 10) □□□□，□□ (□□□□□□□□□□□) Putong reign period, 3rd year, 5th month, *ren-shen* [29], shuo, solar eclipse, total. (Liangshu, Emperors' chronicle, third volume, Emperor Wu, Xiaoyan, third)

These eclipses should have been observed in Jiankang (□□) which was the capital of the Liang Dynasty. The longitude and latitude values of Jiankang are given in table 2. The eclipse bands are shown in figures 6 and 7.

The annularity band of the eclipse on AD 516 Apri1 18 is shown by solid parallels running from the upper-left to the lower-right of figure 8, the $\dot{n}$–ΔT diagram. The totality band of the eclipse on AD 522 June 10 is shown by dotted parallels running almost horizontal in figure 8. The common ranges of occultations and solar eclipses fit perfectly well at around 0.0 in the abscissa. In fact, We obtain the range ΔT as

$$3568\,\mathrm{s} < \Delta T < 5090\,\mathrm{s} \quad (2)$$

from the two solar eclipses assuming the current value of the lunar tidal acceleration. The ranges (1) and (2) are consistent each other considering that the occultations and eclipses are separated by ten years. Thus we can conclude that the method using occultation records is as reliable as the method using eclipses.

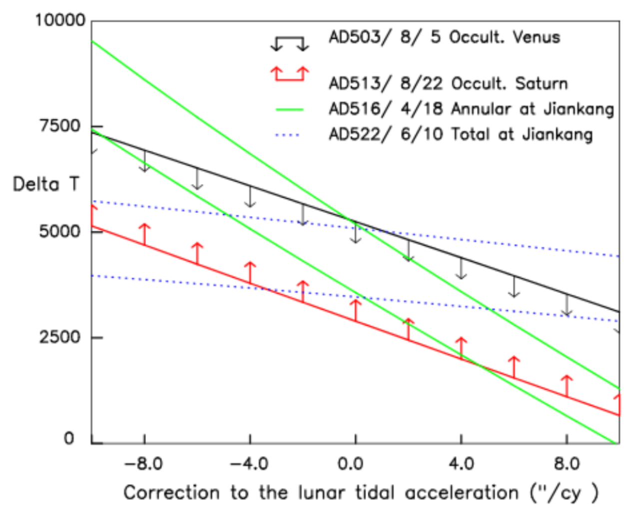

Fig. 8. Regions of the occultations and eclipses on the ($\dot{n}$, ΔT)–plane for four contemporaneous events between the years AD 503 and AD 522. (Color online)

Finally, figure 8 gives us the range of $\dot{n}$ as

$$-4''/\mathrm{cy}^2 < \dot{n} - \dot{n}_{\mathrm{present}} < 4''/\mathrm{cy}^2. \quad (3)$$

This range is not so restrictive as the one obtained from eclipses at around 188 BC, but is consistent with it.

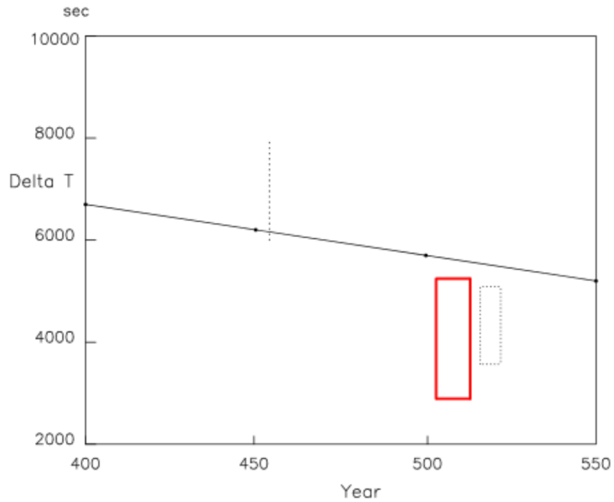

Fig. 9. Ranges of ΔT from occultations in the beginning of the sixth century AD (left box). The ranges obtained from eclipses in AD 516 and 522 are shown by a dotted box. A dotted vertical bar shows the auxiliary range of ΔT from a single eclipse on AD 454 August 10. (Color online)

4 Concluding remarks

We have obtained a rather definite result on the value of ΔT by combining plural contemporaneous occultations with solar eclipses as auxiliary data. The result is shown in figure 9. The box with solid edges in the beginning of the sixth century AD shows the ranges of ΔT from occultations in AD 503 and 513. We separately show the ranges of ΔT from solar eclipses in AD 516 and 522 with a box with dotted-dash edges. In both cases, the true ΔT values are somewhere in the boxes. The straight line traversing the figure from left to right denotes the smoothed ΔT values obtained by Stephenson (1997). It is to be noted that the boxes in figure 9 do not have a probabilistic meaning. The vertical range of a box shows the range of ΔT corresponding to the statement of observers that they saw a particular celestial phenomenon. For the moment, we do not have a method to give a probability of the correctness of the statements of the observers though this is desirable.

As a reference, we show an auxiliary ranges of ΔT with a dotted vertical bar. This is due to a single eclipse on AD 454 August 10 observed total at Jiankang (□□). The records say:

□□□□□□□□□□□□□ (AD 454 August 10)□□□□□ [□□□□□□□□□□ (Chenyue 1974)]
Emperor Xiaowu, Xiaojian reign period, first year, autumn 7th month, *bing-shen* [33], shuo, solar eclipse. (Songshu, Emperors' chronicle, sixth volume, Emperor Xiaowu, Jun)
□□□□□□□□□□□□，□□□□，□，□□□□□
[[□□□□□□□ □□□ (Chenyue 1974)]
Emperor Xiaowu, Xiaojian reign period, first year, autumn 7th month, *bing-shen* [33], shuo, solar eclipse, total. A lot of constellations were bright. (Songshu, annals, 24th volume, Wuxing fifth)
□□□□□□□□□□，□□□□，□□ (□□□□□□□□□□□□)
Emperor Xiaowu, Xiaojian reign period, first year, autumn 7th month, *bing-shen* [33], shuo, solar eclipse, total. (Nanshi, Emperors' chronicle of Song, second volume, Emperor Xiaowu, Jun)

The totality gives $6000\,\mathrm{s} < \Delta T < 8000\,\mathrm{s}$. This gives the value of ΔT consistent with the smoothed curve.

Our important conclusion is that, in the beginning of the sixth century AD, the ΔT values were well below the smoothed trend expressed by an almost straight line that was obtained by Stephenson (1997). An auxiliary data of AD 454 suggests that the ΔT variations for 50 to 60 years between the two epochs are steeper than the smoothed trend.

As a final remark, most records of occultations are useless for our studies since the visible area of an occultation is usually wide. We have shown that there are some occultation records that are useful for deducing of the ΔT and $\dot{n}$ values.

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