Verification of Sunrise and Solar Eclipse Times stated in the Chongxiu-Daming Calendar

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1. Introduction

The Chongxiu-Damingli 重修大明曆 (Greatly Revised Enlightenment Calendar[1], hereafter GRE calendar) was used in the Jin 金 dynasty (AD 1115–1234). This calendar was developed by Zhao, Zhi-Wei 趙知微 in 1171 by greatly revising the Damingli 大明曆 compiled by Yang, Ji 楊級 of the same dynasty in 1127; and it was continued in the subsequent dynasty, the Yuan 元 dynasty (AD 1271–1368), before the enforcement of the Shoushili 授時曆 (Seasons-Granting Calendar) in 1281 (Lee 1996).

It is known that the GRE calendar was a source for the Qitai calendar incorporated in the Zīj-i Īlkhānī, a Persian astronomical handbook compiled by Nasīr al-Dīn Tūsī in 1272 (Isahaya 2013). In Korea, the GRE calendar was used in the Joseon 朝鮮 dynasty (AD 1392–1910) since the reign of King Sejeong 世宗 (AD 1418–1450) to supplement the calculations of solar and lunar eclipse times by the Chiljeongsan-Naepyeon 七政算內篇 (Inner Parts for the Calculations of the Sun, Moon, and Five Planets, hereafter Naepyeon), a Korean calendar, together with the Chiljeongsan-Oepyeon 七政算外篇 (Outer Parts for the Calculations of the Sun, Moon, and Five Planets, hereafter Oepyeon), a Chinese-Islamic calendar.

This study aims to verify the sunrise and solar eclipse times by the GRE calendar, which have received little attention from astronomical societies, based on the Jeongmyoyeon-Gyeosik-Garyeong 丁卯年交食假令 (Example Supplement for the Calculation of the Solar and Lunar Eclipses that Occurred in 1447, hereafter Garyeong). However, in this study, we will not discuss the calculation methods of the GRE calendar and the modern calculation methods in detail, as they will be published elsewhere (Choi et al. 2018). Instead, we introduce the main results with the historical literature associated with the GRE calendar.

2. Historical literature

In China, the main contents of the GRE calendar are recorded in the astronomical chapter of the Jinshi 金史 (History of the Jin Dynasty). The calendar was published as a book, in addition to the Garyong of the GRE calendar in Korea. Both Korean books are currently preserved in the Kyujanggak 奎章閣 Institute for Korean Studies (see Figure 1). The GRE calendar consists of seven chapters: *Qishuo* 氣朔 (Solar Term and New Moon), *Guahou* 卦候 (Hexagram and Seasons), *Richan* 日躔 (Solar Motion), *Guilou* 晷漏 (Sundial and Water Clock),

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[1]In this study, the Chinese term *li* is translated as “calendar” as per astronomy conventions; however, a more appropriate translation for modern concepts would be “system” (Sivin 2009). That is, Greatly Revised Enlightenment System and Seasons-Granting System.

Yuechan 月躔 (Lunar Motion), *Jiaohui* 交會 (Eclipses), and *Wuxing* 五星 (Five Planets). In Appendix A, we list the entire contents of the Garyeong, which we have referred to in this study.

(a) (b) (c)

Figure 1. Historical literature associated with the GRE calendar: (a) Jinshi (source: National Library of Korea), (b) the GRE calendar of Korean edition (source: Kyujanggak Institute for Korean Studies), and (c) the Garyeong (source: Kyujanggak Institute for Korean Studies).

3. Sunrise times

According to the preface of the astronomical chapter of the Jinshi, the GRE calendar was designed based on the Jiyuanli 纪元曆 (Epoch Calendar) of the Northern Song 北宋 dynasty (AD 1127–1279). In order to verify the truth of the records, we reproduced the sunrise and sunset times by the GRE calendar and compared them with results of modern calculations using the astronomical algorithms of Meeus (1998) and the DE405 ephemeris of Standish et al. (1996). For the observation sites, we assumed the historical capitals of the dynasties that used the calendar including Luoyang 洛陽, which was an Old Chinese capital before the Northern Song dynasty. Table 1 lists the historical capitals assumed in this study.

Table 1. Historical capitals assumed in this study for estimating the observation site of sunrise and sunset times in the GRE calendar.

Capital	Longitude	Latitude	Note
Harbin 哈爾濱	126° 57 ′ E	45° 32′ N	Jin dynasty (1115–1127)
Beijing 北京	116° 25 ′ E	40° 15′ N	Jin dynasty (1128–1234)
Kaifeng 開封	114° 18 ′ E	34° 19′ N	Northern Song dynasty (960–1127)
Hanyang 漢陽	126° 59 ′ E	37° 37′ N	Joseon dynasty (1392–1910)
Luoyang 洛陽	112° 27 ′ E	34° 40′ N	Old Chinese dynasties (BC 771 – AD 589)

For the direct comparison of sunrise and sunset times between the GRE calendar and modern calculations, we obtained the daily daytime length (i.e., the period from sunrise to sunset) as it does not require the time conversion between the apparent solar time of the past and the mean solar time of the present (refer to Lee et al. 2011). Figure 2 shows the differences in the daily daytime length between the GRE calendar and modern calculations for each capital. For a quantitative comparison, we determined the mean absolute difference (MAD) of the daily daytime length between the GRE calendar and the modern calculations. We found that the sunrise and sunset times of the GRE calendar are more suitable at Kaifeng rather than those at Harbin or Beijing, i.e., MAD values are 5.58, 15.54

or 37.98 min, respectively, although the MAD value shows the minimum at Luoyang (i.e., 4.44 min). Therefore, we believe that this fact supports the record of the Jinshi that the GRE calendar was compiled based on the Jiyuanli of the Northern Song dynasty.

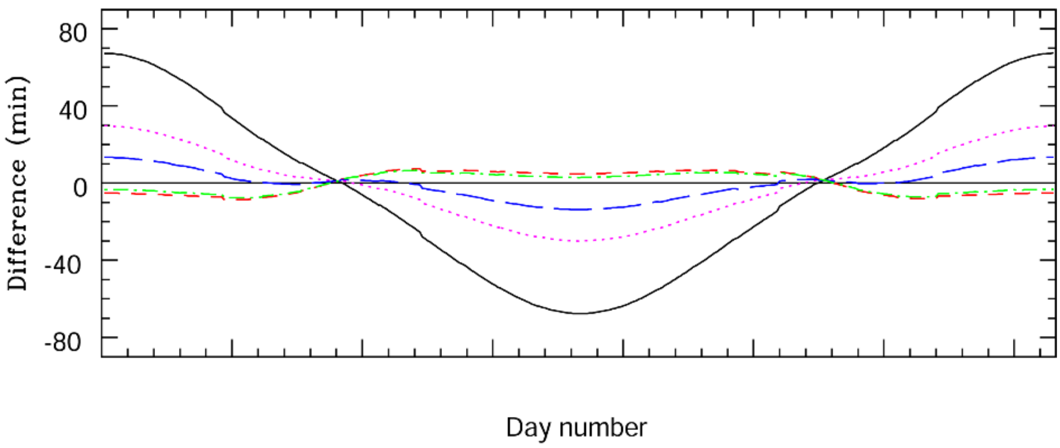

Figure 2. Differences in the daily daytime length between the GRE calendar and modern calculations. The horizontal axis represents the number of days since the winter solstice in 1170 (i.e., December 15). The vertical axis represents the differences for the assumed capitals in units of minutes: Harbin (black solid), Beijing (magenta dotted), Kaifeng (red short-dashed), Hanyang (blue long-dotted), and Luoyang (green dot and short-dashed).

4. Solar eclipse times

In the Garyeong, the calculation of the times of the solar eclipse that occurred on 10 September 1447 is explained as an example (see also Mihn et al. 2014). We verified the calculation procedure of the solar eclipse times and compared them with modern calculations. We used the observation site as Hanyang in the modern calculations to compare the times with other calendars such as the Naepyeon, although the sunrise and sunset times show good agreement at Kaifeng. In Figure 3, we present the diagram of the solar eclipse that occurred on 10 September 1447 using Besselian elements (e.g., Lee 2008). We used a ΔT value (difference between the terrestrial and universal times) of 4.25 min (Morrison and Stephenson 2004). According to our calculations, this partial eclipse began at 17 h 19 min and ended at 19 h 21 min in units of KST (Korean Standard Time, i.e., UT+9 h) at Hanyang. On the other hand, the greatest eclipse (18 h 23 min) occurred just before the sunset time (18 h 35 min).

In Table 2, we summarized the times of the solar eclipse for three stages—*Chukui* 初虧 (first external contact), *Shiji* 食既 (greatest eclipse), and *Fuyuan* 復圓 (last external contact) —for the GRE calendar, Naepyeon, and Oepyeon together with the times from modern calculations. In the table, columns 2, 3, 4, 5, and 6 (i.e., A, B, C, D, and E) are eclipse times from the Gyosilkchubobeob-Garyong 交食推步法假令 (Example Supplement for Calculation Method for Solar and Lunar Eclipses, hereafter Chubobeob), Naepyeon, Oepyeon, the GRE calendar, and modern calculations, respectively. Column 7, 8, 9, and 10 (i.e., A–E, B–E, C–E, and D–E) are the differences of the times with modern calculations. The Chubobeob was compiled by Yi, Sunji 李純之 and Kim, Seok-Je 金石梯 in 1458 and its contents are basically same as the Garyeong of the Naepyeon, but they use slightly different constant values and formulae (Hahn and Lee 2012). As is evident from Table 2, the GRE calendar shows the smallest difference in the greatest eclipse time (i.e., ~1.2 min) but relatively large differences in the first and last external contact times (i.e., ~33 min).

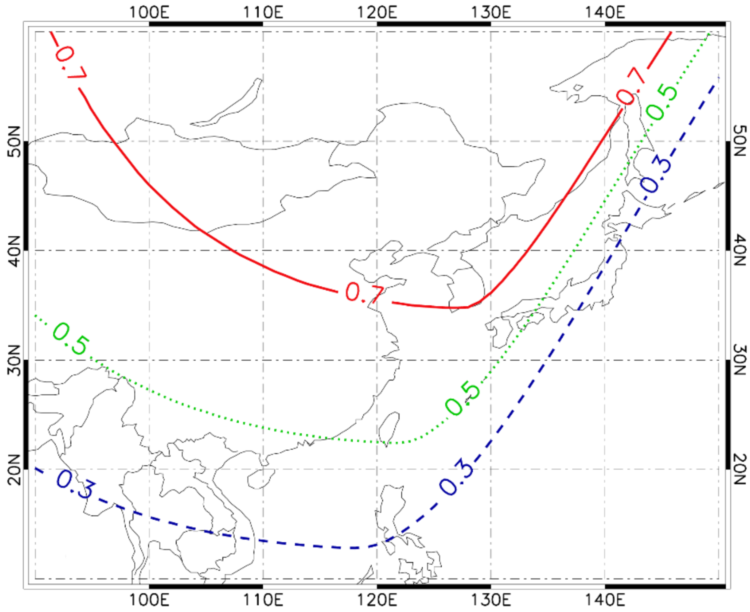

Figure 3. Diagram of the solar eclipse that occurred on 10 September 1447. The blue dashed, green dotted, and red solid lines represent eclipse magnitudes of 0.3, 0.5, and 0.7, respectively.

Table 2. Summary of the times of the solar eclipse that occurred on 10 September 1447.

	A		B		C		D		E		A–E	B–E	C–E	D–E
	h	min	h	min	h	min	h	min	h	min	min	min	min	min
P1	16	33.9	16	06.7	16	50.5	16	50.9	16	53.3	−19.4	−46.6	−2.8	−32.4
GE	17	56.9	17	28.8	17	53.2	17	53.1	17	56.3	+0.6	−27.5	−3.1	−1.2
P4	19	19.9	18	50.9	18	55.9	19	29.3	18	55.3	+24.6	−4.4	+0.6	+34.0

[1]P1, GE, and P4 stand for first external contact, greatest eclipse, and last external contact, respectively.
[2]A, B, C, D, and E are eclipse times from the Chubobeob (Hahn and Lee 2012), Naepyeon (Lee 2007, Hahn et al. 2016), Oepyeon (Ahn 2007), the GRE calendar, and modern calculations (this study), respectively.

It is unknown why the Joseon astronomer selected the solar eclipse of 1447 as an example. As mentioned above, the maximum of this eclipse occurred just before sunset at Hanyang. However, we think that this eclipse was selected as it may a good example to calculate the magnitude at sunset or sunrise time, as its calculation method is explained in the Garyeong. Based on the study for the solar eclipse of 1447, we developed the algorithm for the calculation of solar eclipse times by the GRE calendar. To verify our algorithm, we compared the eclipse times presented in the Yuanshi 元史 (History of the Yuan Dynasty). In the Yuanshi, the eclipse times by the GRE calendar and Shoushili are recorded for 31 solar eclipses, with their observation times. As a first step, we compared the greatest eclipse times for seven solar eclipses for the period from 1183 to 1277, and we found that the three eclipses show differences of 1 *Ke* 刻 (~14.4 min). We believe that a detailed analysis of these differences is required, including the comparison for the first and last external contact times.

Acknowledgements

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Appendix A. Contents of the Garyeong of the GRE calendar.

Contents	Note
求天正冬至 求天正经朔 求弦望及次朔	*Qishuo* 氣朔 (Solar Term and New Moon) chapter
求经朔弦望入氣 求每日損益盈缩朓朒 求经朔弦望入氣朓朒定數	*Richan* 日躔 (Solar Motion) chapter
求每日出入晨昏半晝分	*Guilou* 晷漏 (Sundial and Water Clock) chapter
求經朔弦望入轉 求朔弦望入轉朓朒定數 求朔望定日	*Yuechan* 月躔 (Lunar Motion) chapter
求朔望入交 求朔·望加時入交常日及定日 求朔·望加時入交常日及定日 求人交陰陽曆前後分 求日月蝕甚定餘 求日月食甚日行積度 求氣差 求刻差 求日食去前後定分 求日食分 求日食定用分 求發斂 1) 求日食所起 求日月出入帯食所見分數 求冬至積度日度 求天正冬至加時黄道日度 2) 求日月食甚宿次	*Jiaohui* 交會 (Eclipses) chapter

1)*Guahou* 卦候 (Hexagram and Seasons) chapter, 2)*Richan* 日躔 (Solar Motion) chapter.