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THE ACCURACY OF ECLIPSE TIMES MEASURED BY THE BABYLONIANS

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1. INTRODUCTION

From at least the eighth century B.C., Babylonian astronomers recorded observations of eclipses of the Sun and Moon. Surviving datable observational texts range from around 750 B.C. to 50 B.C.[1] and contain many descriptions of lunar and solar eclipses. Sadly, only a small proportion of the original material is known to be extant. The observations are written on clay tablets, now largely held in the British Museum, using a cuneiform script. Over the past 150 years many scholars have studied the cuneiform script and it is now well understood.

The records of observations of both lunar and solar eclipses made by these Late Babylonian astronomers contain many measurements of the time interval of an eclipse from sunrise or sunset and of the duration of eclipse phases. Comparison of these time intervals with modern computation provides a method of investigating the accuracy of the clocks used at this early period. Possible influences upon the accuracy may include seasonal effects and clock drifts over the length of the measured time interval. In making computations of eclipses in the past it is necessary to take into account changes in the rate of rotation of the Earth. The Earth's rotational clock error, ΔT, resulting from these changes has been deduced from records of both timed and untimed observations of lunar and solar eclipses from various cultures by Stephenson and Morrison.[2]

2. BABYLONIAN OBSERVATIONS OF LUNAR AND SOLAR ECLIPSES

There are three main types of Late Babylonian astronomical text[3] containing eclipse observations: astronomical diaries, 'goal-year texts', and texts devoted wholly to eclipses. The astronomical diaries contain observations of celestial phenomena recorded on a daily basis by the astronomers. All of the datable diaries have been translated and published, together with photographs and transliterations, by Sachs and Hunger.[4]

From the late fourth century B.C. onwards, the Babylonian astronomers used the diaries to produce goal-year texts (texts to assist in the making of predictions for a specific year) and texts devoted to specific phenomena (for example, lists of eclipses stretching back many centuries). These texts provide many additional eclipse observations taken from diaries not now available to us. Translations and transliterations of many eclipse records in these goal-year texts and eclipse lists have been

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provided in an unpublished, but freely circulated, manuscript by Huber.[5]

The Babylonians used a luni-solar calendar. The day began at sunset, and each month began on the night when the lunar cresent was first visible. There were twelve months in most years, each month lasting for 29 or 30 days. To regulate the seasons, an intercalary month was inserted when necessary. Studies of the Babylonian calendar by Parker and Dubberstein[6] allow dates between 626 B.C. and A.D. 75 to be readily converted to the Julian calendar. The equivalent dates of recorded eclipses correspond precisely with the dates given in modern eclipse canons.[7]

Customarily, the Babylonian astronomers recorded the time interval between an eclipse and sunset or sunrise. Babylon lies in a very flat plain and so in clear weather sunset or sunrise would be accurately defined. The duration of the various eclipse phases and an estimate of the degree of obscuration of the Sun or Moon at maximum phase (in fingers or twelths of the lunar or solar diameter) are also often recorded in the eclipse reports. The Babylonian unit of time was the *uš* and was precisely equal to 4 minutes.[8] This is the time taken for the celestial sphere to rotate through one degree, and so it has become customary to translate *uš* as 'degree'. Most times are recorded to the nearest degree. For the early records (before about 560 B.C.), with one exception it seems that the times given are rounded to the nearest 5 (or possibly 10 in the earliest cases) degrees. The exception is a record of a lunar eclipse on 10 April 666 B.C. which states a time of 3 degrees after sunset. Presumably as this time interval was so short, the Babylonian astronomers decided they must quote it to the nearest degree. We shall consider only the period after 562 B.C. where the times are consistently recorded to the nearest degree. It is not known exactly how the Babylonian astronomers made their measurements of time, but it seems that some form of clepsydra (water clock) was used.[9]

A typical example of an eclipse record is that of an observation of a lunar eclipse on 21 March 154 B.C.:

> "[Year 157, king Demetrius Month XII] 15. 5 degrees moonrise to sunset, cloudy, measured. Lunar eclipse, beginning on the south-east side. In 20 degrees of night it made 10 fingers. 6 degrees duration of maximal phase. In 18 degrees from north-east to south-west it became bright. 44 degrees total duration.... During this eclipse, Venus, Mars and Jupiter stood there.... Towards the end, Venus set. The other planets did not stand there.... At 4 degrees after sunset." [LBAT 1440; transl. Huber, pp. 66–67.]

This eclipse report contains many of the features characteristic of the Late Babylonian eclipse records. The account states that the Moon rose 5 degrees (20 minutes) before the Sun set, and became eclipsed. Twenty degrees (80 minutes) after the eclipse started, the Moon was covered to the extent of 10 fingers by the shadow (10/12 of the lunar diameter was obscured), and the observer could detect no change for a further 6 degrees (24 minutes). The eclipse then took 18 degrees (72 minutes) to clear, giving a total duration of 44 degrees (176 minutes). During the eclipse, the planets Venus, Mars and Jupiter were visible, Venus setting before the end. The statement "at 4 degrees after sunset" may be interpreted as being the time when the eclipse began. In this example it is hard to see how it could be anything else; if it were mid-eclipse the interval between first contact and maximal phase would not have been able to be measured at 20 degrees as first contact would be before the Moon rose. Many eclipse records end with a similar statement and so it seems advisable to confirm its meaning in the general case.

The record of an eclipse on 21 November 353 B.C. allows an independent calculation of the time of first contact:

> "Month VIII 14, beginning on the southeast side. After 23 degrees total. 18 degrees duration of maximal phase. After 6 degrees of night, a quarter of the disk had become bright, and it set eclipsed.... At 47 degrees before sunrise." [LBAT 1414; transl. Huber, p. 49.]

In this case, the Moon set eclipsed 23 + 18 + 6 = 47 degrees after first contact. This is in agreement with the time stated at the end of the record, implying that this time must indeed be the time of first contact.

Observations of the total solar eclipse of 15 April 136 B.C. are recorded on two separate Babylonian tablets: a goal-year text (LBAT 1285) and an astronomical diary (BM 45745).

> "Month XII_2 29. Solar eclipse, beginning on the south-west side. In 18 degrees of day ... it became total. At 24 degrees after sunrise." [LBAT 1285; transl. Huber, pp. 93-94.]

> "... day 29. At 24 degrees after sunrise, solar eclipse; when it began on the south and west side ... Venus, Mercury, and the Normal Stars were visible; Jupiter and Mars, which were in their period of invisibility, were visible in its eclipse.... It threw off (the shadow) from west and south to north and east; 35 degrees onset, maximal phase, and clearing." [BM 45745; transl. Sachs and Hunger.]

The time of beginning of the eclipse is implied to be 24 degrees after sunrise in the second tablet, the same time as stated at the end of the first tablet. Thus we may assume that in the general case, the time given in the record of an eclipse is the time of first contact.

3. ACCURACY OF THE ECLIPSE TIMES

To determine the accuracy of the time intervals recorded by the Late Babylonian astronomers, we compared the observed intervals with those deduced using accurate ephemerides of the Sun and Moon and values of the Earth's rotational clock error, ΔT, given by the spline fit of Stephenson and Morrison.[10] For the Sun we have used Newcomb's analytical ephemeris,[11] and for the Moon we have used the analytical ephemeris designated by $j = 2$.[12] A lunar acceleration of $-26''\mathrm{cy}^{-2}$ was adopted

TABLE 1. Error in the first contact time interval.

Julian Date	Type	Observed (deg.)	Calculated (deg.)	Calculated – Observed (deg.)
–561 Mar 2	Lunar	90	82.50	–7.50
–536 Oct 16	Lunar	14	20.00	+6.00
–500 Nov 7	Lunar	77	69.25	–7.75
–482 Nov 18	Lunar	10	6.75	–3.25
–423 Sep 28	Lunar	50	53.50	+3.50
–420 Feb 2	Lunar	19	18.75	–0.25
–407 Oct 31	Lunar	15	14.25	–0.75
–406 Oct 20	Lunar	48	49.75	+1.75
–405 Oct 9	Lunar	14	9.25	-4.75
–396 Apr 5	Lunar	48	48.75	+0.75
–377 Apr 6	Lunar	37	41.25	+4.25
–370 May 17	Lunar	66	57.00	–9.00
–370 Nov 11	Lunar	30	38.50	+8.50
–366 Aug 29	Lunar	56	36.25	–19.75
–352 Nov 21	Lunar	47	41.50	–5.50
–321 Sep 26	Solar	3	3.50	+0.50
–316 Jun 18	Lunar	10	15.75	+5.75
–316 Dec 13	Lunar	44	54.00	+10.00
–307 Jul 8	Lunar	10	9.75	–0.25
–280 Jan 30	Solar	6	2.75	–3.25
–253 Jan 31	Solar	56	64.00	+8.00
–239 Nov 2	Lunar	3	–1.00	–4.00
–225 Aug 1	Lunar	52	70.75	+18.75
–214 Dec 25	Lunar	21	41.50	+20.50
–211 Apr 29	Lunar	20	24.50	+4.50
–211 Oct 24	Lunar	27	62.25	+35.25
–193 Nov 4	Lunar	12	8.00	–4.00
–189 Mar 14	Solar	30	31.25	+1.25
–188 Feb 16	Lunar	34	41.75	+7.75
–169 Jul 28	Solar	20	19.50	–0.50
–162 Mar 30	Lunar	85	96.25	+11.25
–159 Jan 26	Lunar	48	55.25	+7.35
–153 Mar 21	Lunar	4	6.50	+2.50
–142 Feb 17	Lunar	7	8.75	+1.75
–135 Apr 15	Solar	24	26.50	+2.50
–133 Mar 9	Lunar	9	13.50	+4.50
–133 Sep 8	Lunar	32	33.50	+1.50
–132 Feb 13	Solar	50	50.50	+0.50
–128 Nov 4	Lunar	55	55.50	+0.50
–119 Jun 1	Lunar	66	68.75	+2.75
–108 May 1	Lunar	8	9.25	+1.25
–105 Aug 24	Lunar	50	44.50	–5.50
–95 Aug 3	Lunar	57	63.50	+6.50
–79 Apr 10	Lunar	40	39.75	–0.25
–79 Oct 5	Lunar	30	32.50	+2.50

in all computations.[13] The interval between first contact and sunrise or sunset, which is strongly dependent upon the value of ΔT, was determined to the nearest 0.25 degrees by calculating the time of sunrise or sunset at Babylon. Table 1 lists the observed and computed intervals, together with the difference between the computed and observed intervals. The duration of the phases of the lunar eclipses, which

TABLE 2. Error in the duration of the phases of total eclipses.

Julian Date	Type	Observed (deg.)				Calculated (deg.)				Calculated – Observed (deg.)			
		1:2	2:3	3:4	1:4	1:2	2:3	3:4	1:4	1:2	2:3	3:4	1:4
−561 Mar 3	Lunar	-	25	18	-	-	26.00	15.75	-	-	+1.00	−2.25	-
−554 Oct 7	Lunar	17	28	20	-	16.50	24.25	16.50	-	−0.50	−3.75	−3.50	-
−500 Nov 7	Lunar	15	25	25	-	16.75	23.50	16.75	-	+1.75	−1.50	−8.25	-
−406 Oct 20	Lunar	21	12	-	-	16.75	21.50	-	-	−4.25	+9.50	-	-
−405 Apr 15	Lunar	25	19	-	-	16.25	18.50	-	-	−8.75	−0.50	-	-
−377 Apr 6	Lunar	15	21	19	-	15.75	19.00	15.75	-	+0.75	−2.00	−3.25	-
−370 Nov 11	Lunar	22	20	21	-	17.00	21.00	17.00	-	−5.00	+1.00	−4.00	-
−352 Nov 21	Lunar	23	18	-	-	17.00	21.00	-	-	−6.00	+3.00	-	-
−316 Dec 13	Lunar	19	5	16	-	17.00	20.75	17.00	-	−2.00	+15.75	+1.00	-
−272 Feb 16	Lunar	-	19	22	-	-	19.25	15.75	-	-	+0.25	−6.25	-
−225 Aug 1	Lunar	17	10	15	-	16.75	16.00	16.75	-	−0.25	+6.00	+1.75	-
−214 Dec 25	Lunar	21	16	19	-	15.75	20.75	15.75	-	−5.25	+4.75	−3.25	-
−189 Feb 28	Lunar	20	-	-	-	22.00	-	-	-	+2.00	-	-	-
−188 Feb 16	Lunar	16	-	-	-	18.00	-	-	-	+2.00	-	-	-
−149 Jul 2	Lunar	20	12	-	-	20.25	13.00	-	-	+0.25	+1.00	-	-
−135 Apr 15	Solar	-	-	-	35	-	-	-	33.50	-	-	-	−1.50
−123 Aug 13	Lunar	19	24	19	-	16.75	24.50	16.75	-	−2.25	+0.50	+2.25	-
−105 Feb 28	Lunar	-	-	-	60	-	-	-	53.25	-	-	-	−6.75
−105 Aug 24	Lunar	21	21	-	-	16.50	25.50	-	-	−4.50	+4.50	-	-
−87 Mar 11	Lunar	-	-	-	30	-	-	-	53.25	-	-	-	+23.25
−40 Mar 2	Lunar	21	-	-	-	15.00	-	-	-	−6.00	-	-	-

TABLE 3. Error in the duration of the phases of partial eclipses.

Julian Date	Type	Observed (deg.)			Calculated (deg.)			Calculated – Observed (deg.)		
		1:M	M:4	1:4	1:M	M:4	1:4	1:M	M:4	1:4
−423 Sep 28	Lunar	24.5	24.5	-	17.50	17.50	-	−7.00	−7.00	-
−409 Dec 22	Lunar	-	-	60	-	-	47.75	-	-	−12.25
−407 Oct 31	Lunar	-	-	27	-	-	22.75	-	-	−4.25
−396 Apr 5	Lunar	-	-	27	-	-	16.25	-	-	−10.75
−345 Jan 13	Lunar	-	-	23	-	-	23.75	-	-	+0.75
−253 Jan 31	Solar	12	11	-	16.00	15.00	-	+4.00	+4.00	-
−238 Apr 28	Lunar	-	-	40	-	-	35.50	-	-	−4.50
−189 Mar 14	Solar	15	15	-	17.75	19.00	-	+2.75	+4.00	-
−184 Nov 24	Lunar	-	-	44	-	-	11.00	-	-	−33.00
−169 Jul 28	Solar	12	-	-	11.50	-	-	−0.50	-	-
−162 Mar 30	Lunar	-	-	20	-	-	20.75	-	-	+0.75
−153 Mar 21	Lunar	23	21	-	24.75	24.75	-	+1.75	+3.75	-
−142 Feb 17	Lunar	22.5	-	-	24.00	-	-	+1.50	-	-
−132 Feb 13	Solar	20	18	-	21.75	19.25	-	+1.50	+1.25	-
−128 Nov 4	Lunar	21	19	-	21.50	21.50	-	+0.50	+2.50	-
−79 Apr 10	Lunar	23.5	-	-	20.75	-	-	−2.75	-	-
−66 Jan 19	Lunar	-	19	-	-	24.25	-	-	−5.25	-
−65 Dec 28	Lunar	13	-	-	16.75	-	-	+3.75	-	-

are independent of ΔT, and of solar eclipses, which are only weakly dependent upon ΔT, were also calculated to the nearest 0.25 degrees. Tables 2 and 3 list the observed and calculated durations of the eclipse phases and the difference between the computed and observed intervals for total and partial eclipses.

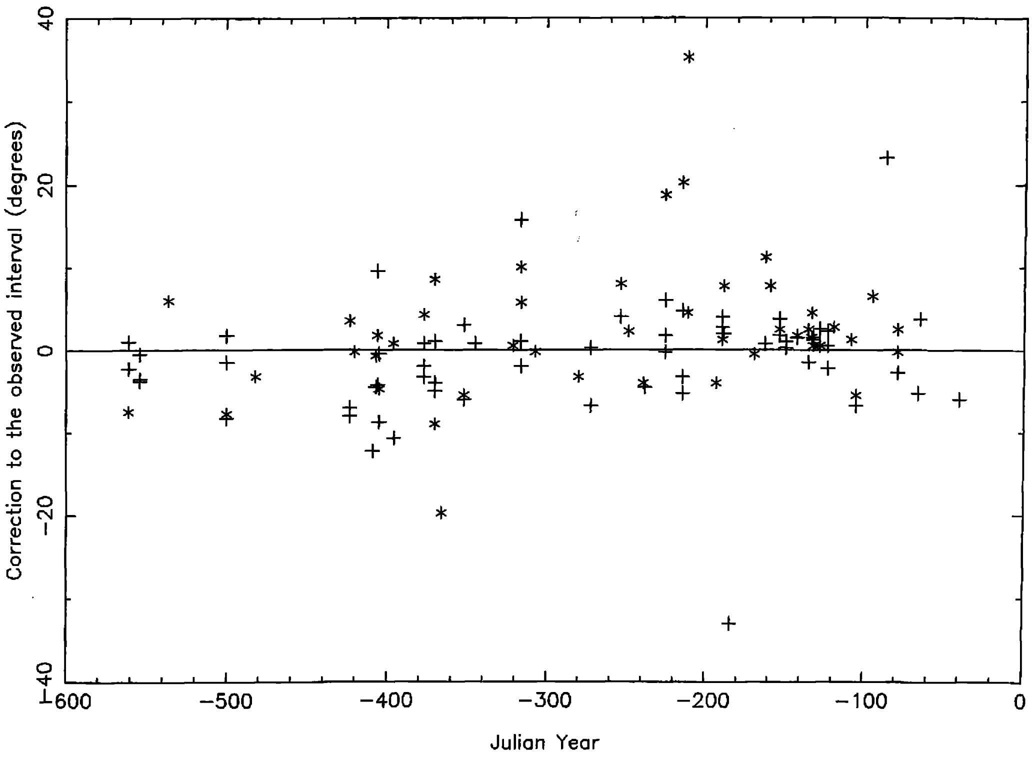

FIG. 1. The correction to the observed first contact interval and phase duration over the Late Babylonian era.

3.1. *Change in Accuracy with Epoch*

The Babylonian observations extend over five hundred years. It is therefore interesting to investigate whether there was any improvement in the accuracy of measurement over such a long period. To do this we considered the accuracy of the available timed measurements as a function of epoch. In Figure 1 we plot the corrections to the observed first contact intervals and to the durations of the eclipse phases against the year. The corrections to the observed first contact intervals are shown as stars and the phase durations as crosses. There appears to be no improvement in accuracy with date, implying that there was no significant improvement in clock design during the five hundred years of the Late Babylonian era.

To test for any dependance of the error in timing on whether the interval was measured from or to the eclipse, the first contact interval data were split into two subsets: (i) lunar eclipses which were timed before sunrise and solar eclipses which were timed before sunset; and (ii) lunar eclipses which were timed after sunset and solar eclipses which were timed after sunrise. There was no significant difference between the trends shown by the two cases. Furthermore, there does not appear to be any significant difference between the corrections to the observed first contact intervals and the durations. Thus we are free to treat all of the data as a single data set. There are two large errors in 212 B.C. and 185 B.C. Presumably these records contain a scribal error as it seems inconceivable, for example, that the Babylonian astronomers should measure the duration of the eclipse in 185 B.C. as 44 degrees (nearly 3 hours), when the computed duration is only 12 degrees (about 45 minutes). It is possible that the symbol for 44 was confused with 14. Another explanation, suggested by Huber,[14] is that the 44 degrees refers to the time interval between the end of the eclipse and sunset instead of the duration of the eclipse. However, this would be unique in all of the preserved Babylonian records of eclipses.

3.2. *Change in Accuracy with Season*

By splitting the data into two subsets of summer (1 April to 30 September) and winter (1 October to 31 March) eclipses and comparing them, we have found that there appears to be no seasonal effect upon the accuracy of the timings. This is surprising as we might expect that the accuracy of a water clock would be affected by the temperature as the viscosity of water, and hence the rate of flow into or out of a container, is strongly dependent upon temperature. It is possible that the Babylonians were aware of the problems caused by temperature change and attempted to minimize them in their clock design.

Furthermore, we would expect there to be a significantly better accuracy during the summer months when there is usually little cloud upon the horizon at Babylon and sunset or sunrise are well defined. Perhaps if cloud cover interfered with observation, for example by covering the horizon when the sun rose or set, then the Babylonian astronomers would not have recorded the time. Good weather is never mentioned in the Late Babylonian astronomical texts,[15] but there are a number of examples, such as the report of the lunar eclipse of 30 April 212 B.C., where cloud partially interfered with the observation:

> "... Lunar eclipse, begining on the south side. Around maximal phase cloudy, not observed. It set eclipsed. At 30 degrees before sunrise." [LBAT 1237; transl. Huber, p. 56.]

In this case, presumably the sky cleared sufficiently near the end of the eclipse for moonset to be observed.

3.3. *Change in Accuracy with Length of Interval Timed*

Assuming that a major source of error in the Babylonian clocks was due to some form of clock drift, we would expect that the longer the time interval measured, the greater the error of measurement. In Figure 2 we plot the correction to the observed intervals against the calculated interval using the same symbols as in Figure 1. The dispersion appears to increase with interval, implying that the error in the measured time is not systematic and that it increases approximately linearly with the length of the interval. This corresponds to a random error in drift. If we disregard the two

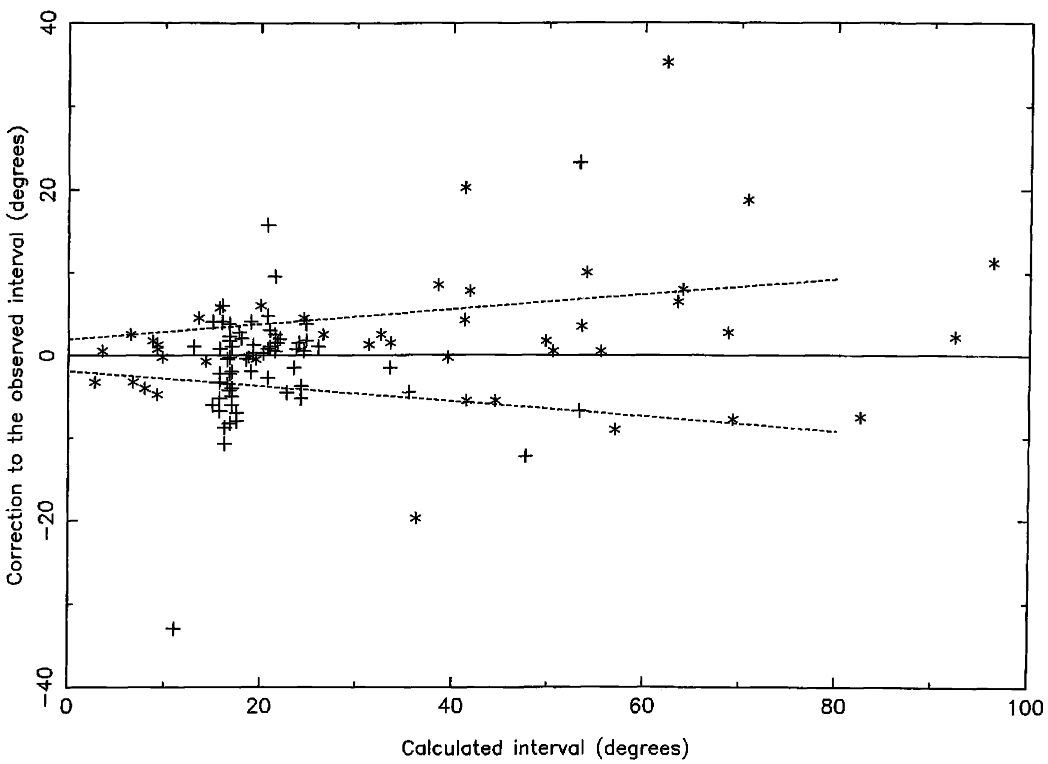

FIG. 2. The correction to the observed first contact interval and phase duration plotted against the calculated interval.

outliers discussed in Section 3.1 above, a straight line fitted to all the remaining data (by reflecting the negative points in the abscissa) has a slope of 0.091 degrees per degree of interval. This means that the Babylonian astronomers were able either to control or correct the rate of their clocks to a mean accuracy of 9%, as illustrated by the two dashed lines in Figure 2.

The intersection of the lines in the figure with the ordinate suggests a zero-point error of nearly 2 degrees (8 minutes). As the Babylonians were timing to the nearest degree, this value is larger than we might expect. There are several factors that could be the cause of this zero-point error. The simplest explanation is that the average accuracy to which the clocks could be read was nearer 2 degrees than 1 degree. The difficulty in determining the exact moment of an eclipse contact, particularily in the case of a lunar eclipse, may also be a factor. However, the lunar eclipse contacts do not appear to be of a poorer accuracy than the solar cases. The zero-point error is probably due to a combination of these factors together with small scribal errors that we are unable to detect.

4. CONCLUSION

Analysis of the Late Babylonian observations of the times and durations of eclipses provides information on the accuracy of clocks used at this period. There is no evidence for any improvement in accuracy over the five-hundred-year period from 562 B.C. to 41 B.C., nor of any change in accuracy with season. This implies that there was no improvement in clock design over the Late Babylonian era and the clocks were designed in such a way as to render changes in temperature unimportant. The Babylonians were able to rate their clocks with a typical error of 9% and read off the time with an accuracy of about 2 degrees (8 minutes).

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