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Addendum 2020 to 'Measurement of the Earth's Rotation: 720 BC to AD 2015' The Supplement

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Historical reports of solar eclipses are added to our previous data-set (published in *Proc. R. Soc. A* 2016, **472**, https://doi.org/10.1098/rspa.2016.0404) in order to refine our determination of centennial and longer-term changes since 720 BC in the rate of rotation of the Earth. The revised observed deceleration is $-4.59 \pm 0.08 \times 10^{-22}$ rad s^{-2}. By comparison the predicted tidal deceleration based on the conservation of angular momentum in the Sun-Earth-Moon system is $-6.39 \pm 0.03 \times 10^{-22}$ rad s^{-2}. These signify a mean accelerative component of $+1.8 \pm 0.1 \times 10^{-22}$ rad s^{-2}. There is also evidence of an oscillatory variation in the rate with a period of about 14 centuries.

S1. Introduction

This Supplement to the Addendum contains the new eclipses that we have included in our analysis discussed in the main part of the paper. This has resulted in updated observational data which are listed in the various tables below.

All the tables from our original 2016 paper [1] and this Addendum are available in ASCII text files named `Table-Sxy.txt` or `Table-Sxy.2020.txt` where `xy` is the table number. For updated tables `2020` is the year of the version and are available from http://doi.org/10.1098/rspa.2020.0776

The electronic supplementary material is also available online at rs.figshare.com.

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This supplement consists of six sections of auxiliary material comprising:

S2. Compilation of the archive

Marek Zawilski [2] has compiled an extensive archive of reports of solar eclipses from ancient times to +1905 witnessed in Europe and the Near East. The reports discussed here are a subset taken from that archive, consisting of total, central annular and large eclipses in the pre-telescopic period +840 to +1598.

Many of the quoted texts in the archive have already been published, principally by Ginzel [3], Newton [4], [5] and Stephenson [6]. However, none of these compilations contains a complete collection of the reports of the eclipses. The collection by Ginzel terminates in the year +1415. Although it contains valuable quotations, there are many omissions. The extensive compilations by Newton cover the period till the end of the 13th century, but do not contain data from many regions of Europe and the Near East. The work of Stephenson contains most of the information from Europe and the Near and Far East appertaining to the determination of changes in the Earth's rotation.

Almost all of the eclipse descriptions from Europe in Zawilski's archive have been checked against publications containing the original historical texts. As far as we are aware, some of the reports have not been published before. This mainly relates to the data in the period of 14th to 16th centuries. In many cases of newly found texts, it was necessary to verify their provenance and the most probable place of observation of the solar eclipse. Often, similar fragments of texts turn out to be copies of earlier ones, which had been assigned to other later compilations. In such cases, identical or similar earlier available sources, and the circumstances of their inception were examined.

The English translations cited by Zawilski are mainly based on the compilations by A. N. Vyssotsky [7], Newton (*loc. cit.*) and Stephenson (*loc. cit.*), or from other historical publications. Several translations differ in detail from those given by Stephenson and Newton. Especially in the case of the latter author, who often does not give the complete texts as found in the original sources. Also, his translations are not always accurate. The texts derived from the Russian annals (letopises) have been revised and supplemented by Dr. M.L. Gorodetsky of Moscow State University.

In the English translations, the original dates, which are in various calendars, have been changed to the corresponding dates in the Julian/Gregorian calendar. As well as the descriptions of eclipses, the texts sometimes contain subsidiary information, which is helpful in evaluating whether or not the eclipse was total or central annular, and in confirming the place of observation.

The compiler of the archive has not personally inspected all the original reports, because many of the sources are not available in Poland, especially those contained in manuscripts. However, numerous publications available on the Internet, and consultation with several experts, furthered the assessment of the new material.

S3. Calculation of eclipse tracks

We have developed our own programs for the calculation and plotting of the eclipse tracks. The basic coordinates of the Sun and Moon are extracted from the Jet Propulsion Laboratory's long-term ephemerides DE 431 [8] and the algorithms for finding their positions for the particular date and time and the position of the track of the eclipse on the Earth are taken from *The Explanatory Supplement* [9], [10], together with routines from the International Astronomical Union's Standards of Fundamental Astronomy [11]. The map outlines were from Natural Earth [12]. The preliminary values of ΔT used in the calculations were taken from Morrison *et al.* [13].

NASA solar eclipse data were initially used while searching for historical descriptions of solar eclipses. These tracks are slightly different from those presented in the graphics in this supplement, which is mainly due to differences in the ΔT value for individual historical eclipses.

S4. Selection of critical reports for the determination of ΔT

We have inspected the archive for reports of eclipses that could potentially contribute to the measurement of variations in the Earth's rotation in the 9th to 16th centuries AD. Here we display and analyse the critical observations using maps of the eclipse tracks calculated with a preliminary value of ΔT. The possible range of solutions for ΔT is determined from the displacement of the track east or west, such that the critical places of observation are brought on to one of the edges of the track. A displacement of the track 1° east increases the preliminary value of ΔT by 240 seconds. Thus, for example, in the plot of the eclipse of +1239 June 3 below, a calculated displacement eastwards of the track by $1\overset{\circ}{.}17$ brings Cerrato on to the northern edge of the track. This is equivalent to increasing the preliminary value of $\Delta T[+825]$ by 280 seconds. Therefore, for totality at Cerrato $\Delta T < +1105$ seconds.

A lower constraint on ΔT is derived from Toledo, which is located near the southern edge of the track. In this case, a small shift west by $0\overset{\circ}{.}03$ brings Toledo on to the southern edge of the track, which is equivalent to increasing the preliminary value of ΔT by 6.6 seconds. Therefore, for totality at Toledo (rounding to the nearest 5 seconds) $\Delta T > +830$ seconds.

Combining these limits from Cerrato and Toledo gives the range of solution $+1105^s > \Delta T > +830^s$.

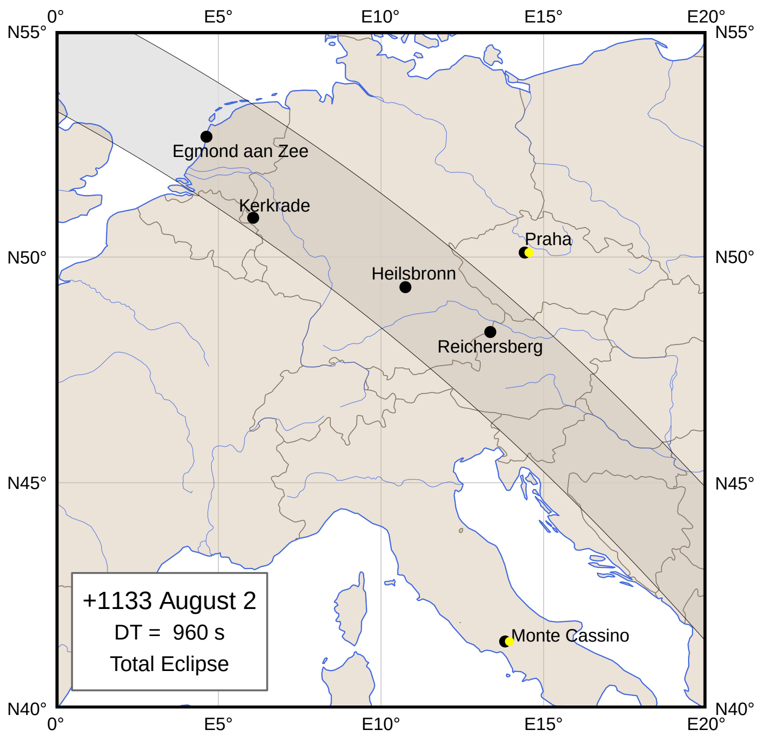
Where the difference in longitude between a pair of places recording the same eclipse, such as those of Cerrato and Toledo in +1239, is close to the path width projected parallel to the equator, the constraint on ΔT is tighter than it would be otherwise. This is tempered by the angle of the track to the equator at that place. For example, in +1239 the track runs almost parallel to the equator for places in the north of Italy, and hence the range of solutions for ΔT is extended compared to those in Spain for which the track is significantly inclined to the equator.

We discuss critically the original reports and their English translations in chronological order. It is vital that the description of totality or central annularity, and the identification of the place of observation are both secure. Also, there should be no ambiguity as to whether the report describes a total or a partial eclipse. The main problem with many historical accounts is that they are not specific in this respect. From experience, we have found that a report of the appearance of stars is not in itself a sufficient condition of totality. We have found quite a number of reports from places some distance outside the computed belt of totality where the sighting of 'stars' is reported, even though the sky would have been too bright to see 'stars', other than Venus and possibly Jupiter. A statement that the whole Sun was eclipsed, or the Sun completely lost its brightness, are desirable indications of totality. Also, supplementary information about the degree of darkness and the behaviour of animals, such as birds, are useful indicators of a spectacular eclipse. Accounts of partial eclipses should clearly mention that some part of the Sun remained visible throughout. Usually reports in chronicles, which were contemporaneous with the eclipse are generally more reliable than those compiled many years later. Given these provisos, we did not find any suitable reports in the archive before the 12th century.

The purported places of unambiguous accounts of the eclipses are plotted in the maps of the tracks. Most accounts are too imprecise for our present purpose. For each eclipse we analyse in detail the most reliable accounts from pairs of places which constrain the track, as these provide the tightest bounds on ΔT. For some eclipses only a useful record is available from a single place, and this leads to a range in ΔT equivalent to the width of the track parallel to the equator at that place. Places with reports of total or central annular eclipses are shown as black dots: partial eclipses are shown as crescents. Places with putative reports of totality may not necessarily lie within the belt of totality or central annularity shown in the maps, as these are dependent on preliminary estimates of ΔT. Likewise, partial eclipses may lie inside the belt of totality. Some of the conflicting solutions for ΔT have to be resolved later in the discussion of the all the collected results, when geophysical considerations of the temporal behaviour of the Earth's rotation are invoked (see section ?? of the main paper).

S5. Analysis of reports of 16 solar eclipses used in the main paper

+1133 August 2, Total Eclipse



Kerkrade, The Netherlands

Annales Rodenses

> *Anno Dominicae incarnationis mill. cent. XXXIII factae sunt tenebrae obscurato iam sole in toto orbe circa meridiem, quasi integra, diei hora, luna existente XVII. IIII Nonas Augusti. Nam tunc velut in nocte apparuerunt stellae, et volucres coeli avolavere, et terra maduit rore, concussique homines ingenti pavore, opinati sunt ultimum diem accidisse . . .*

Roden Annals

> *In the year 1133 from incarnation of the Lord, there was a darkness over the whole Earth because the Sun was darkened around midday, for almost a whole hour of the day, the Moon being on its 17th of, on August 2. For then, just as at night, stars appeared, and the birds in the sky flew away, and the ground became wet with dew, and men were struck with very great terror; they thought that the last day had come . . .*

Presumably "17$^{\text{th}}$ day" is a scribal error for "27$^{\text{th}}$ day".

For totality at Kerkrade, $\Delta\mathrm{T} < +1115^{\mathrm{s}}$.

Reichersberg, Austria

Magni Presbyteri, ***Annales Reicherspergenses***

> ***Hoc anno [1133] fuit illa magna eclipsis solis in 4. Non. Aug. circa medium diem, luna 27. existente, 13. anno decennovalis cycli.***
> ***Post meridiem inter horam septimam et octavam visa est eclipsis solis in leone, si tamen non fuit prodigium et signum in sole.***
> . . . . . . ***plurimae iuxta solem stellae visae sunt, plurimorum corda luce desperata conpuncta sunt, sol quasi non esset omnio latuit per horam fere dimidiam instar noctis fuit, facies mundi miserabilis, horribilis, nigra, mirabilis.***

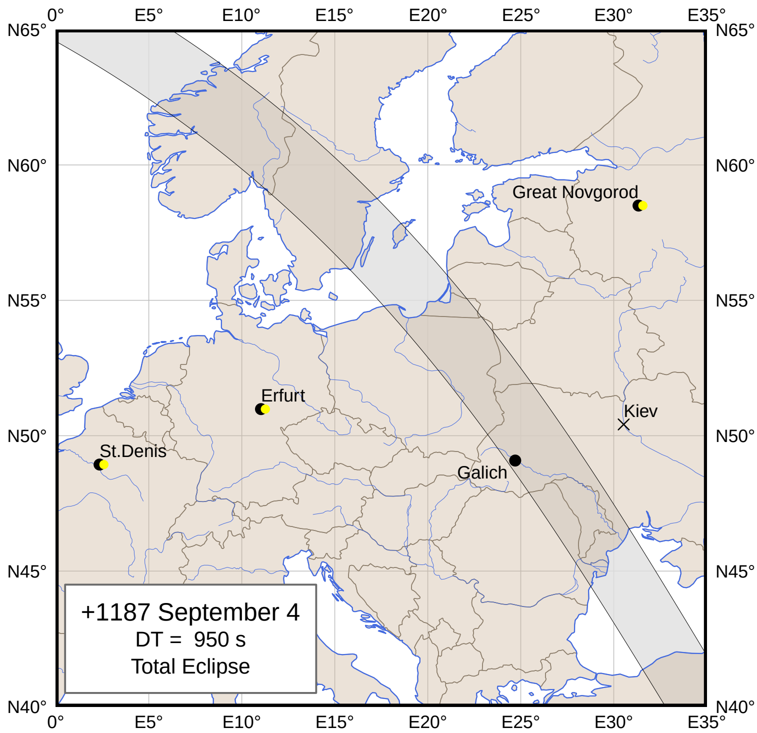
Annals of Reichersberg by Presbyter Magnus

> *In this year [1133] was a great eclipse of the sun on the 4th day before the Nones of August (August 2) about midday, on the 27th of the moon, in the 13th year of the 19-year cycle. After midday, between the seventh and eighth hours, an eclipse of the sun was seen in Leo, so there was no prodigy and sign in the sun. . . . . . . Very many stars were seen near the sun, the hearts of many were transfixed, despairing of light. The sun, as if it did not exist, was entirely concealed; for almost half an hour it was like night, the face of the world was miserable, horrible, black, wonderful.*

For totality at Reichersberg, $\Delta\mathrm{T} > +530^{\mathrm{s}}$.

Combining observations made at Kerkrade and Reichersberg gives the constraint $+1115^{\mathrm{s}} > \Delta\mathrm{T} > +530^{\mathrm{s}}$.

+1187 September 4, Total Eclipse



Galich, West Russia/Ukraine

Ипатьевская Летопись

Ipat'yevskaya Letopis'

Въ лѣто 6695 ... Того же лѣта бысть знамение месяца сентября 15 день: тма бысть по всей землѣ, якоже дивитися всимь человеком, солнце бо погибе, анебо погоре облакы огнезарными. Таковая бо знамения не на добро бывають; в тои бо день того месяца взять бысть Ерусалим безбожными Срацины, знамения же та не по всеи землѣ бывають, но на нюже страноу Владыка что хощеть навести. Тогда бо глахоуть тмоу бывшюю вь Галичи,яко и звезды видити, середъ дни солнцю померькшю, вь Киевской стороне никто же не види вь ть час

V leto 6695 ... Togo že leta byst' znameniye mesyaca sentyabrya 15 den': tma byst' po vsey zemle, yakože divitisya vsim čelovekom, solnce bo pogibe, a nebo pogore oblaky ognezarnymi. Takovaya bo znameniya ne na dobro byvayut'; v toy bo den' togo mesyaca vzyat byst' Ierusalim bezbožnymi Sraciny, znameniya že ta ne po vsey zemle byvayut', no na nyuže stranu Vladyka čto choščet' navesti. Togda bo glachut' tmu byvsyuyu v Galiči, yako i zvezdy viditi, serede dni solncu pomer'kšyu, v Kievskoy storone nikto že ne vidi v' te čas.

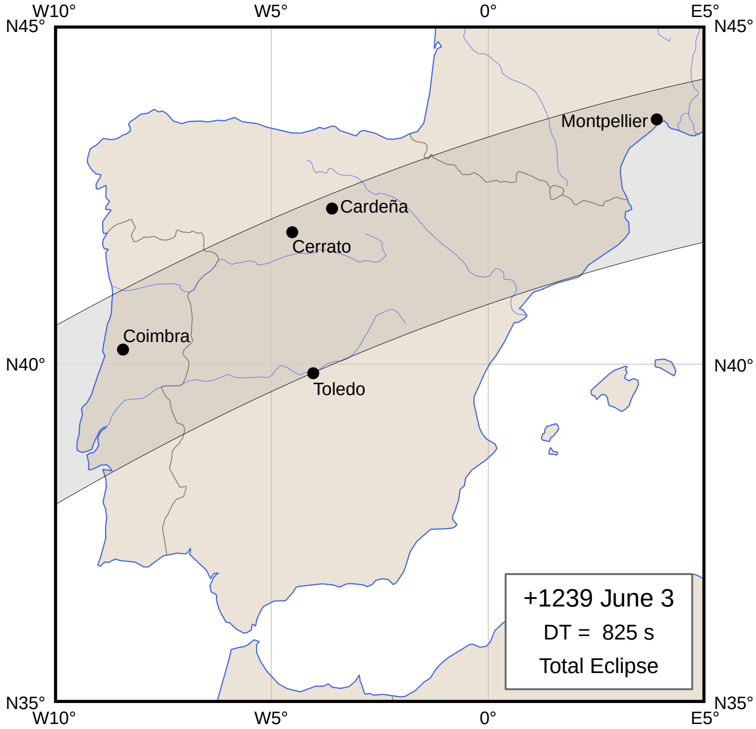
Hypatian Annals

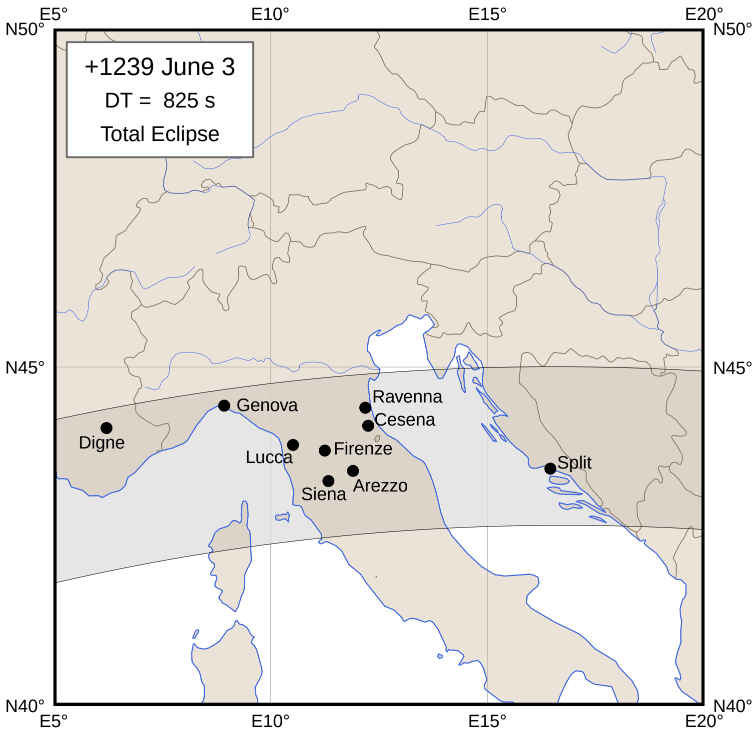
> *In the year 6695 [1187] . . . During the same year there was a sign in the sky, on the 15 [correct : fourth] day of September. There was darkness all over the earth and the people were much astonished. The sun perished and all the sky was aglow with flame like clouds. Such apparitions do not forbode anything good because that very day of that very month Jerusalem was captured by the godless. However, these signs are not visible all over the earth but only in such places where the Almighty wishes to bring some misfortune. Also it was said [proclaimed] that there was a great darkness in Galich where even the stars were visible as the sun went out in the middle of the day. But in the vicinity of Kiev nobody saw anything at this time [hour].*

These annals come from the compilation of Galich-Russia annals and other Russian chronicles, which were found in the monastery near Kostroma. The place of observation is clearly stated. The eclipse may have been seen through thin clouds, the "flamelike" appearance caused by the light of the solar chromosphere. At Kiev no-one reported the eclipse, even though it was large there. On the other hand, places further from the track (shown in the plot) reported seeing a partial eclipse. Presumably it was overcast at Kiev. The information about the besiege of Jerusalem is faulty. That event took place on +1187 October 2. The city of Ascalon was besieged by Saladin on +1187 September 20.

For totality at Galich $+1065^{\mathrm{s}} > \Delta\mathrm{T} > +45^{\mathrm{s}}$.

+1239 June 3, Total Eclipse





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Cerrato, Spain

Chronicon del Cerratense

> ***Anno gratiae M.CCXXXIX .iii. Nonas Junij, Feria VI. obscuratus est sol totus in meridie.***

Chronicle by Manuel of Cerrato

> *In the Year 1239, on June 3, on Friday, the whole sun was eclipsed at midday.*

Although the report from Cerrato is brief, it actually states that the eclipse was total, and it was nearly contemporaneous with the event. In our paper Morrison *et al.* [13], we used a report from Cardeña, which is less explicit about totality than the report from Cerrato.

For totality at Cerrato $\Delta\mathrm{T} < +1105^{\mathrm{s}}$.

Toledo, Spain

Anales Toledanos II. (segundos)

> ***Escurecio el Sol Viernes hora de VI. e duro una pieza entre VI. e IX. e perdio toda su fuerza, e fizose como noche, e parecieron Estrellas y a quantas e di si clarecio el Sol luego, mas a grand pieza no torno en su fuerza. Despues cobro su fuerza como solie aver, Era MCLXXVII.***

The second *Toledo Annals*

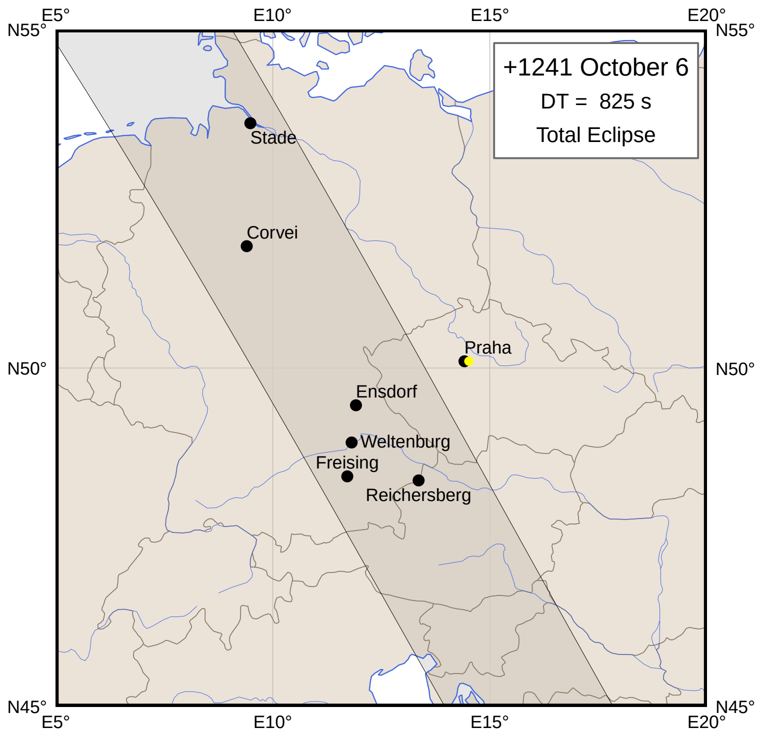
> *The Sun was obscured on Friday at the sixth hour [of the day] and it lasted for a while between the sixth and the ninth [hour] and it lost all its strength and it was as though night and many stars appeared, and then the Sun grew bright again of its own accord, but for a long time it did not regain the strength that it usually has. Afterwards [the Sun] recovered its strength as previously, Era 1177.*

Spanish historians occasionally counted years from the inception of the Julian calendar in 38 BC, rather than the Christian era. Hence, 1177, corrected for a scribal error to 1277, is equivalent to AD 1239. It is likely that the author was an eyewitness to the event.

For totality at Toledo $\Delta\mathrm{T} > +830^{\mathrm{s}}$.

Combining the results from Cerrato and Toledo produces the constraint, $+1105^{\mathrm{s}} > \Delta\mathrm{T} > +830^{\mathrm{s}}$.

+1241 October 6, Total Eclipse



Stade, Germany

Annales Stadenses

> ***A.D. 1241. [. . .] Eclipsis solis octava Michaelis, scilicet 2. Nonas Octobris, die dominica post meridiem modicum stellis apparentibus et sole penitus a nostris visibus occultato. Et tanta erat coeli serenitas ut nulla in aere nubus appareret***

Stade Annals

> *A.D. 1241. [. . .] An eclipse of the sun on the octave of St.Michael, namely on the second day before the Nones of October (October 6), on Sunday, some time after midday, with stars appearing and with the sun completely hidden from our sight. And so clear was the sky that no clouds appeared in the air.*

The author of the account, Albertus, who was Abbot of Stade from +1232 onwards, probably witnessed the eclipse. For totality at Stade $\Delta T > +625^s$.

Freising, Germany

Annales S.Stephani Frisingensis

> ***1241.2.Nonas Octob. eclipsis solis facta est, ita ut stelle pleniter apparerent in celo in medio die.***

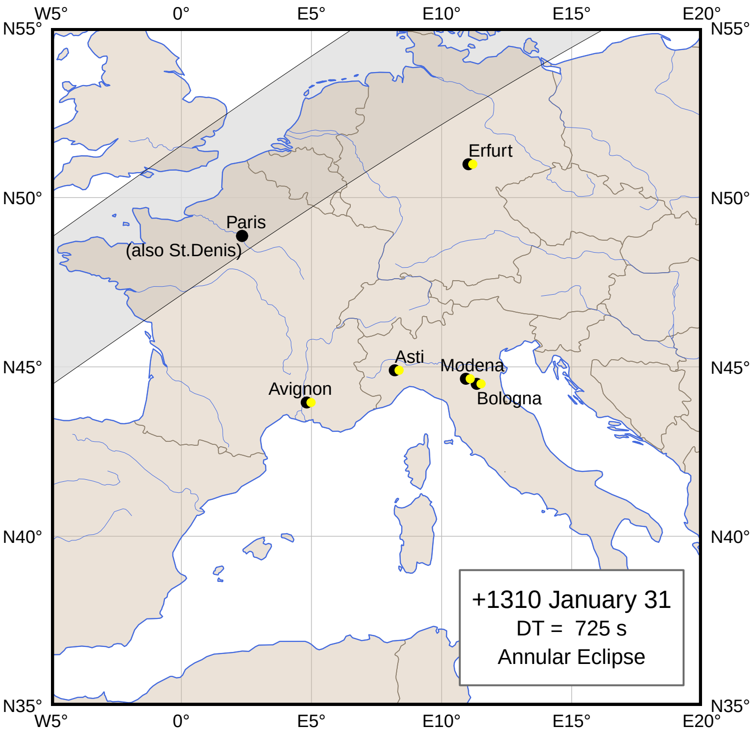
Annals of St.Stephen of Freising

> *A.D. 1241, on the second day before the Nones of October (October 6), there was an eclipse of the sun, such that stars appeared plentifully in the sky in the middle of the day.*

'Plentiful' appearance of stars strongly suggests totality. For totality at Freising, $\Delta T < +1005^s$.

Combining Freising with Stade produces the constraint $+1005^s > \Delta T > +625^s$.

+1310 January 31, Annular Eclipse



Paris, France

Tractatus a fratre G. Marchionis OFM

> ***Sexta via est quia stante eadem linea AB originate a B transeunte per centrum D ipsius lune et per centrum solis E, aliquando totus sol nobis occultabitur, aliquando non eclipsabitur totaliter, ymmo remanebit notabilis circumferentia solaris circumdans lune emisperium, sicut fuit visum Parisius anno domini 1309 [recte: 1310] ultima die Januarii hora quasi septima cuius rei non potest alia reddi ratio quam <vel: added interl.> solis et <vel: added interl.> lune in suis ecentricis maior et minor elongatio sicut evidenter ostendit decima figura et 11^a.***

A treatise by brother Guy de la Marche OFM

> *The sixth way is that the rest of the line AB originate from B and which passes through the centre D of the moon itself and through the centre of the sun, E, and sometimes the whole sun is occulted to us, and sometimes not eclipsed totally, and more correctly, it remains a significant solar circumference, which encompasses the hemisphere of the moon, as it has been seen at Paris in the year of the Lord 1309 [correctly: 1310] on the last day of January, about the seventh hour [after sunrise] of which a cause could not be given anything as sun and the moon in their eccentricity (?) to a greater and lesser elongation as clearly shown in the tenth and 11th figure.*

The report clearly refers to a central annular eclipse seen in Paris. This is supported by a similar report from St. Denis nearby. For a central annular eclipse in Paris $\Delta T > +460^s$.

Erfurt, Germany

Chronica S. Petri Efrordensis Moderna

> ***1310. Eodem anno facta est ecl. solis particularis in vigilia S. Brigittae.***

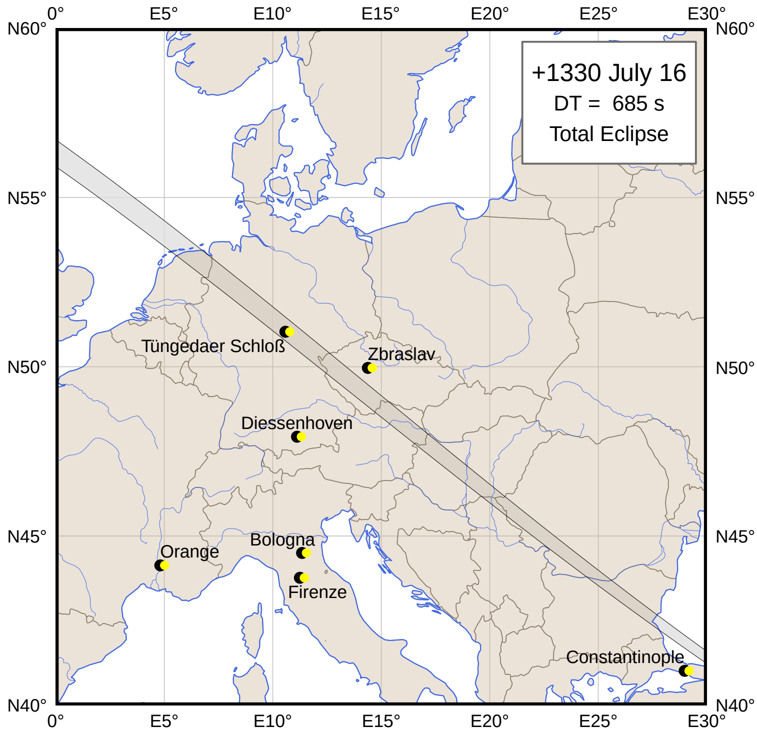
The modern chronicle of S. Peter of Erfurt

> *1310. In that year there was a partial eclipse of the sun in the eve of the St. Brigida's day.*

For a partial eclipse at Erfurt $\Delta T < +1555^s$.

Combining Erfurt with Paris produces $+1555^s > \Delta T > +460^s$.

+1330 July 16, Total Eclipse



Zbraslav, Bohemia

Chronicon Aulae Regiae **Lib.II**

> ***1330. [...] Eodem anno Idus Julii octava hora diei sol in tantum eclipsatur, ita quod de corpore eius tantum una parva extremitas ad modum lune trium noctium videbatur ...***

Chronicle of the Royal Hall, Book II; quoted by Ginzel [3]

> *1330. [...] In the same year on Ides of July (July 15) at the eight hour of the day the sun was so greatly eclipsed that only a small extremity of its body, like a three-night-old moon, was seen ...*

The monastery Aulae Regiae is situated in the town of Zbraslav in the Czech Republic. The given date of the 'Ides of July' is one day wrong for this eclipse. This is clearly an account of a partial eclipse.

Tüngedaer Schloß, Germany

Johann Binhard; *Thüringer Chronik*

> ***Anno 1330. [...] Den 16. Julij im Mittag umb 12. Uhr als die Sonn im 24 theil deß Krebs gewesen, ist sie auff eylff Punct finstert worden.***

Johann Binhard; *Thuringia Chronicle*

> *In the year 1330. [...] On 16 July at midday at 12 hour when the sun was in 24th part [degree?] of Cancer, it was eclipsed for eleven digits.*

Constantinople, Asia Minor (eclipse of 1330)

Nicephori Gregorae, *Historiae Byzantinae*

> ***Tunc autem circa horam duodecimam, die Iulii decima sexta, solis obscuratio facta est et non minor undecim digitis, observata nempe ab eo, qui in parallelo***

> ***per Byzantium ducto habitaret : quo tempore sol partem Cancri vigesimam quartam pertransibat. Eius porro eclipseos observandae initium a medio Iapyge et Thrascia, finis ab initio fere Subsolani fuit.***

Histories of Byzantium, by Necephoras Gregoras

> *In the year of Christ 1330 [. . .] Then, however, about the twelfth hour, the sixteenth day of July, a darkening of the sun, and not less than for eleven inches, was observed, namely by one who lived in the parallel running through Byzantium; at the time the sun passed the twenty-fourth part [degree?] of Cancer. Moreover, its eclipse was observed from the beginning in the middle of Iapygia [nowadays: Apulia] and Thracia, the end from the beginning almost in the south-east.*

Eleven 'inches' is equivalent to eleven 'digits', and both are a measure of the degree of totality, where twelve units is a total eclipse. Thus, the reports from Tüngedaer Schloß and Constantinople are both putative descriptions of a very large eclipse, which was almost total at those places. However, Stephenson [6] points out that the report from Constantinople was seen in the parallel of Constantinople rather than the city itself, and specifies regions such as Thrace where the observations were made. Thus, the report from Constantinople is insecure in this respect.

There are also doubts about the origin of this report from Tüngedaer Schloß. The text itself may be original—even if we are not sure about the place—but the chronicle was simply a compilation of events from the beginning of 17th century by Binhard. Moreover, the description looks like a copy of a calendar, and not an observational account. Therefore, we judge that this account should also be regarded as unreliable, especially concerning the reported greatest phase of '11 digits", which could have been a prediction rather than an observation. We are left with the reliable report that the eclipse was partial at Zbraslav, which gives one bound of $\Delta T < +910^s$.

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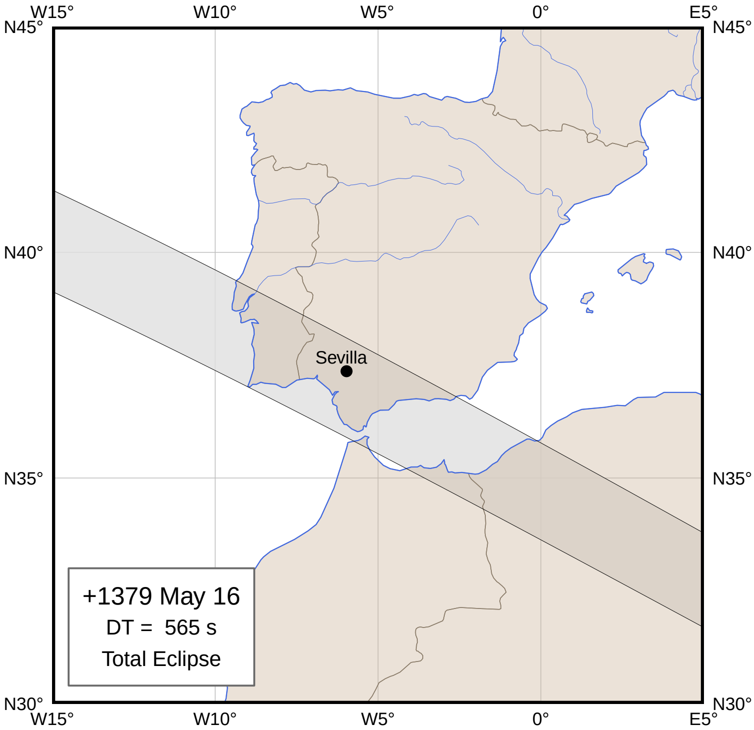
+1379 May 16, Total Eclipse



Sevilla, Spain

Pedro López de Ayala
Cronicas de los Reyes de Castilla
Crónica del Rey don Enrique Segundo de Castilla
Año décimocuarto—1379
Compendio

> ***A diez e seis del mismo mes de Mayo un lunes de visperas, fizo el sol eclipse, e se oscurecio todo el, que non se veian los omes unos a otros, e apparecion las estrellas en el cielo, asi como si fuera media noche. E duro aquella escuridad una hora. Y fallecio el Rey el lunes, a 30 del mismo mes.***

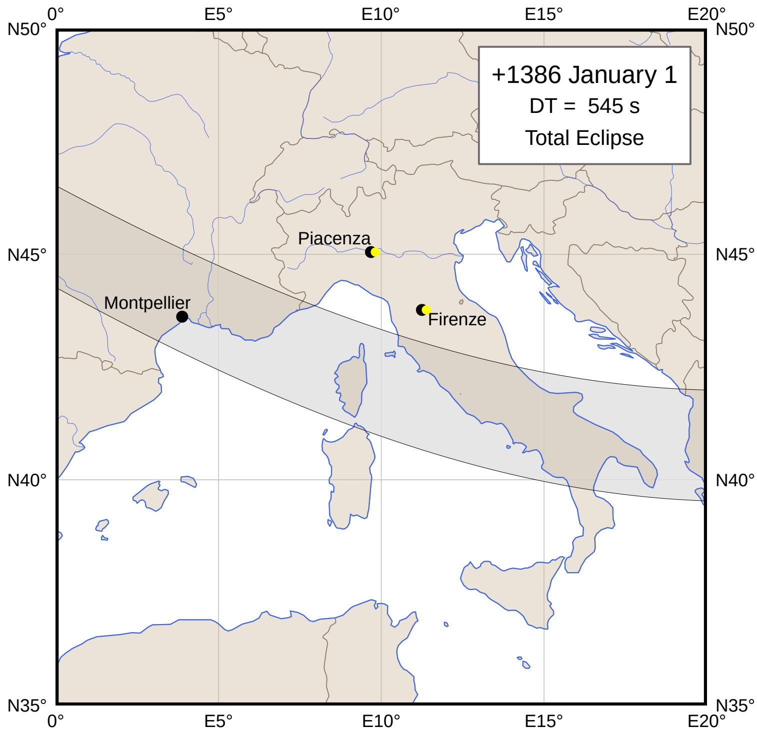
Pedro López de Ayala
Chronicles of the Kings of Castile
The chronicle of King Henry the Second of Castile
Fourteenth year—1379
Compendium

> *On the sixteenth day of that month of May, on Monday vespers, there was a solar eclipse, and it obscured totally, in such a way that men could not see each other, and stars appeared in the sky as at midnight. And this obscuration lasted for one hour. And the King died on Monday, on the 30th day of that month.*

King Henry II. of Castile died at Sancto Domingo de la Calzada in northern Spain on +1379 May 29, having arrived there on April 26. Pedro López de Ayala (+1332 to +1407) might have been an eyewitness of the eclipse. He described numerous natural phenomena which took place in Sevilla. The first part of his chronicle, which covers only the reign of Pedro I, was printed at Sevilla in +1495. The first complete edition was printed in +1779 to +1780 in the collection of *Crónicas Españolas*, under the auspices of the Spanish Royal Academy of History.

For totality at Sevilla, $+1525^{\mathrm{s}} > \Delta\mathrm{T} > +105^{\mathrm{s}}$.

+1386 January 1, Total Eclipse



Montpellier, France

Petit Thalamus, ***Les chroniques célestes, La chronique romane***

> ***En l'an MCCCLXXXV [recte : MCCCLXXXVI], item, lo dilus premier iorn de genoier, que era luna nova, entre la segunda e la tersa hora del jorn fo eclipsi de Solhel tan gran e tan escur que aparian la estelas claras e lusens en lo cel.***

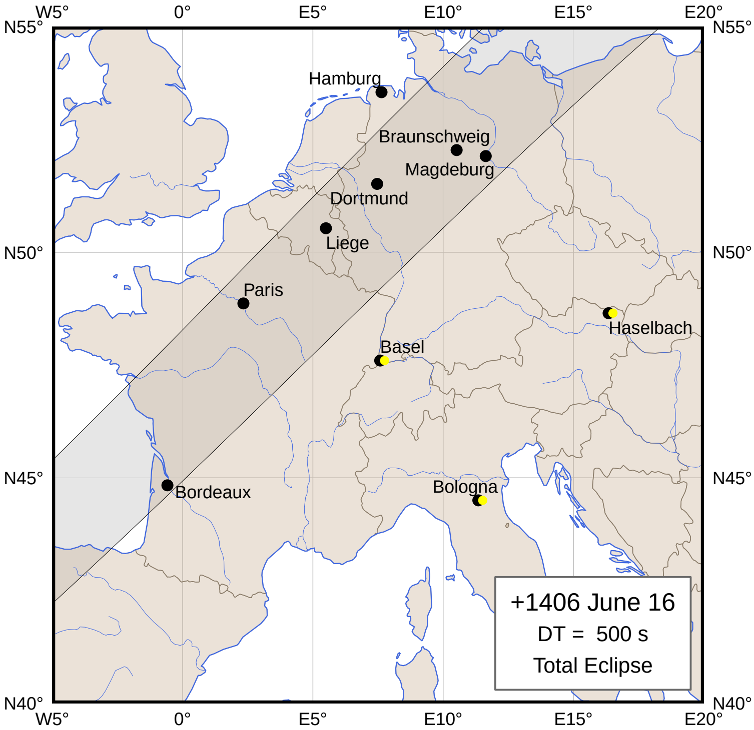
Petit Thalamus, *The heavenly chronicles, The Roman chronicle*

> *Also, in the year 1385 [correct: 1386], on Monday, on the eerie 1st day of January, at new moon, between the second and the third hour of the day, there was an eclipse of the sun so big and so dark that stars appeared bright and shiny in the sky.*

The chronicle was compiled from local sources.

For totality at Montpellier $+1075^s > \Delta T > -650^s$.

+1406 June 16, Total Eclipse



Bordeaux, France

Archives municipales de Bordeaux. ***Livre des Bouillons.***

> ***E en apres, l'an mil quatre centz e seys, en lo mes de junh, a XVI. jorns deudeit mes, murit lo sorelh, en tant que fet una granda escuritat, que hom no conoyosse de un deney, si era deney o mealha, tant pauc cum si era nuyt.***

The municipal archives of Bordeaux. *The Book of Bouillons.*

> *And afterwards, in the year 1406, in June, on the 16th day of the said month, the sun died, so much so there was great darkness, so that one could not recognise a coin—whether it was one coin or more—and there was night for a short time.*

Totality at Bordeaux is supported by another definite report from Magdeburg, Germany, which is similarly placed relative to the southern edge of the track. For totality at Bordeaux $\Delta T > +400^s$.

Liege, Belgium

Chronique latine **de Jean de Stavelot**

> ***Anno 1406 [. . .] Eodem anno sexta decima junii, inter sextam et septimam horam ante meridiem, erat ecclipsis solis totalis, ita ut aurora, que fuerat lucida et serena, facta est tam obscura quam nocte media.***

Latin Chronicle by Jean de Stavelot

> *In the year 1406 [. . .] In that year on the 16th of June, between the sixth and the seventh hours before midday, there was a total eclipse of the sun, with the result that the morning-dawn which was bright and clear, became as dark as at midnight.*

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Hamburg, Germany

Adami Tratzigeri ***Chronica Hamburgensis***

> ***A.1406 am Tage Annunciat. Mariae, des Morgens umb 6. Uhren, wurd die Sonne gantz bedeckt, und so eine grosse Finsternisse, dass die Leuthe vermeineten, ess solte die Welt vergangen sein*** *...*

Hamburg Chronicle by Adam Tratziger

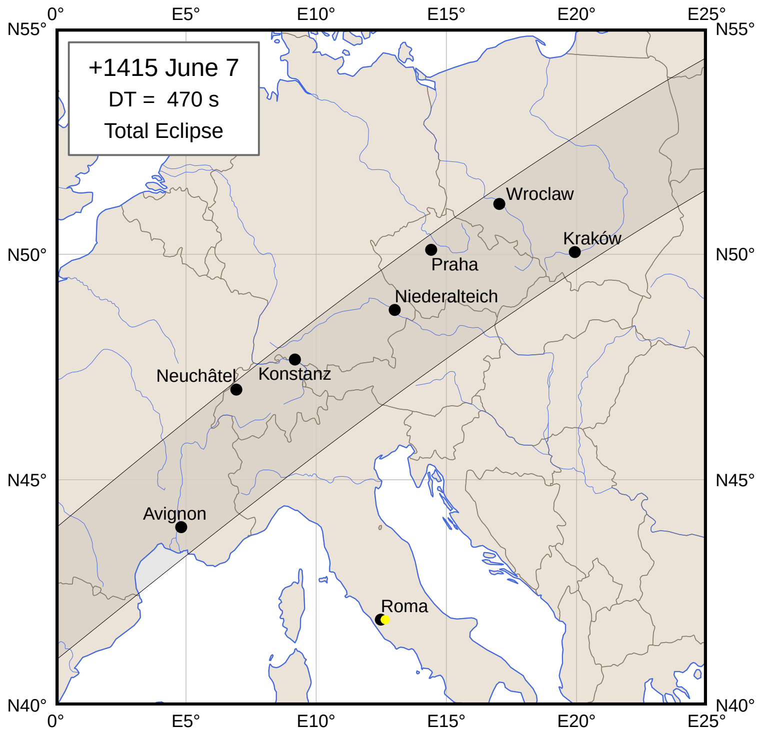
> *In the year 1406, on the day of the Annunciation of the Virgin Mary, in the morning at 6thhour, the sun was entirely covered, and [there was] such a great eclipse that people believed it should be the end of the world.*

The report of totality at Hamburg is incompatible with totality at Bordeaux and Magdeburg. The author of the report lived in Hamburg and was connected to the City Council. He collected many older accounts of events in the Hamburg area. However, the exact place of observation cannot be identified with certainty. We have decided to trust the reports from Bordeaux and Magdeburg in preference to Hamburg. For totality at Hamburg, $\Delta T < +170^s$.

The report from Liege is the most trustworthy account of totality for a place near the northern edge. For totality at Liege, $\Delta T < +900^s$.

Combining Liege with Bordeaux gives the constraint, $+900^s > \Delta T > +400^s$.

+1415 June 7, Total Eclipse



Kraków, Poland

Kalendarz i nekrolog domu altarystów kościoła Wniebowzięcia Panny Marii (Mariackiego) w Krakowie

> ***Junius***
> ***[...]***
> ***7 XIII D VII Id. Celestini et Luciani martyrum***
> ***1 4 X 5 [probably 1415] erat totalis eclipsis in Sole 7 Iunii hora XI***

The calendar and the necrology of the house of altarists of the Church of the Assumption of Virgin Mary in Cracow

> *June*
> *[...]*
> *7 XIII D VII Id. [the day] of Celestinus and Lucianus the martyrs*
> *1 4 X 5 [probably 1415] there was the total eclipse of the Sun*
> *on June 7th at the 11th hour [after sunset]*

The report of totality at Kraków is supported by the report from Avignon, which is similarly placed relative to the southern edge. For totality at Kraków $\Delta T > +200^s$.

Wrocław, Poland

Chronica Sigismundi **Rosiczi**

> ***Eclipsis solis feria sexta. Eodem anno 1415 post octavam corporis Christi hora duodecima circa incensionem lune fuit eclipsis totalis solis, que stetit citra medias horam fuitque terror et metus multibus hominibus.***

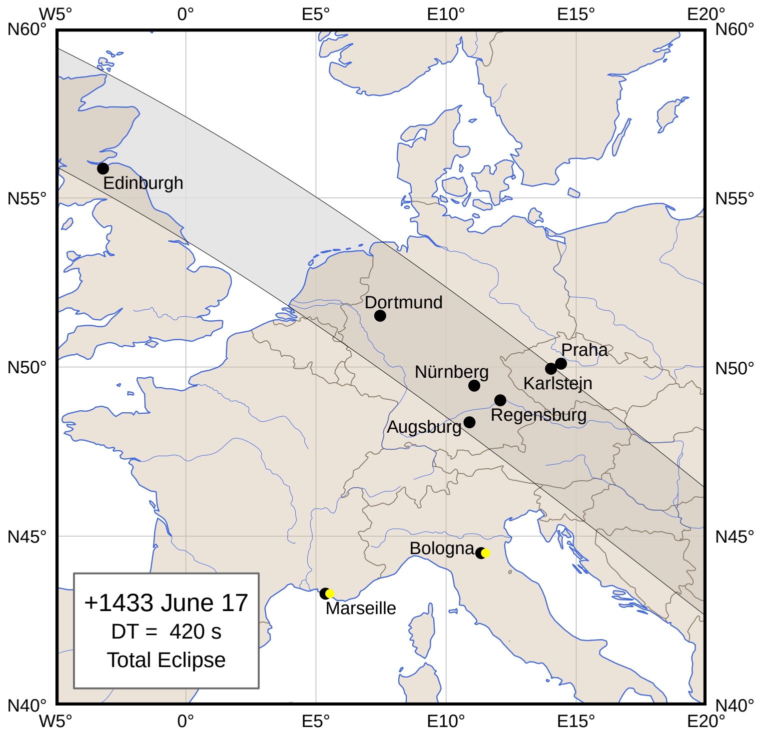
Chronicle by Sigmund Rositz

> *An eclipse of the sun on Friday. In the same year 1415, after the octave of Corpus-Christi [June 6], at the 12th hour [after sunset], at about the re-lighting of the moon, there was a total eclipse of the sun, which stood still for close to half-an-hour and there was terror and alarm among many people.*

Rositz used notes preserved in Wrocław and his report is independent from other known sources. The adjacent notes in the chronicle for March and August relate to events in the city. The report from Wrocław is supported by a clear statement of totality at Paha, Bohemia. For totality at Wrocław $\Delta\mathrm{T} < +705^{\mathrm{s}}$.

Combining Wrocław with Kraków gives the constraint $+705^{\mathrm{s}} > \Delta\mathrm{T} > +200^{\mathrm{s}}$.

+1433 June 17, Total Eclipse



Karlštejn, Bohemia

Kronika **Bartoška z Drahonic**

> ***Item eodem anno ac videlicet XXXIII** [. . .]*
>
> ***Eodem anno feria IV post s.Viti hora quasi vigesima prima sol ecclipsabatur per totale suum corpus. Et eadem septimana et post duas ebdomadas erant magne inundaciones aquarum, sic quod ipso tempore a festo Marie Magdalene** . . .*

Chronicle by Bartošek of Drahonice

> *Also in the same year, namely [14]33 [. . .]*
>
> *In the same year on Wednesday after St.Vitus' day [i.e. June 15] at about the twenty first hour [after sunset] the Sun eclipsed totally in its body. And the same week and for two weeks afterwards there were great inundations of water like in that time on the Mary Magdalene's feast . . .*

Although Karlštejn is not specifically mentioned in the first account, this was where the scribe Bartošek (c.+1380 to +1443) was writing his chronicle of contemporaneous events. We are reasonably confident that the eclipse was indeed total at Karlštejn, and therefore $\Delta T > +385^s$.

Totality at Praha was recorded by Jan Šindel (Hradec Králové, 1370-c.1443), who was a professor of mathematics and astronomy at Charles University and became the rector of the University in 1410. In 1423-1436 he worked in Nuremberg as a physician. We conclude that his account originates from Nurnberg and not Praha, and we therefore discount totality at Praha.

Augsburg, Germany

***Chronik* des Hector Mülich**

> ***1433. Am 17. tag junii zwischen vier und fünf stund gen nacht ward ain vinsternus, das man liechter müßt anzünden, also gar ward die sunn verdeckt.***

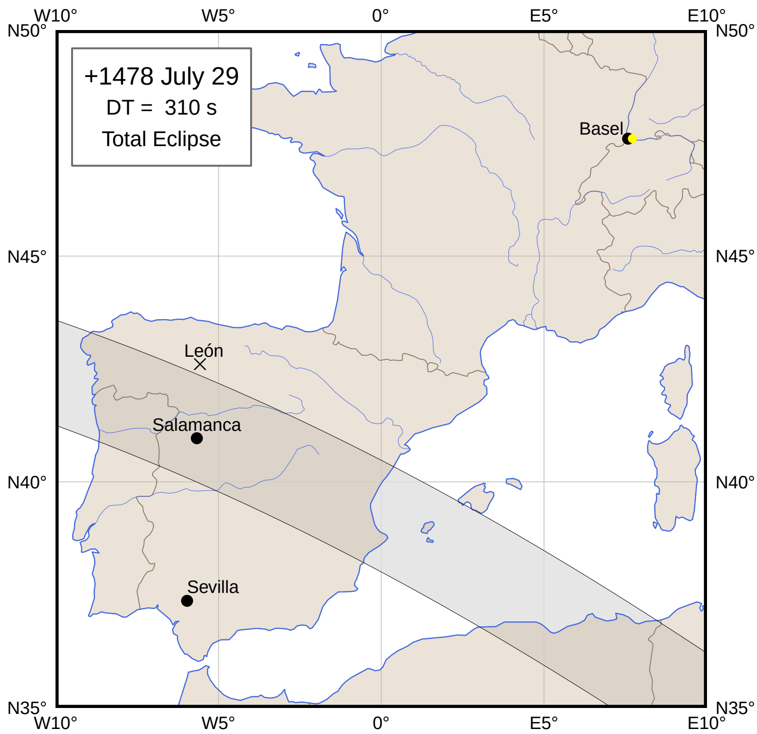
Chronicle by Hector Mülich

> *1433. On the 17th day of June between the fourth and the fifth hour before night, there was an eclipse, [so dark] that one had to light lamps, as the sun was completely covered.*

For totality at Augsburg $\Delta\mathrm{T} < +570^{\mathrm{s}}$.

Combining Augsburg with Karlštejn gives the constraint, $+570^{\mathrm{s}} > \Delta\mathrm{T} > +385^{\mathrm{s}}$.

+1478 July 29, Total Eclipse



Salamanca, Spain

Abraham Zacut, *Sefer Yuhasin, Libro de las Genealogias*

> ***En el año 5238, el miércoles 29 Av [=29 Julio de 1478] a mediodía en España, hubo un eclipse solar distinto a todo lo que se habia visto, pues [el cielo se oscureció] como si fuese medianoche.*** [The original report was written in Hebrew.]

Abraham Zacut, *The Book of Genealogies*

> *In the year 5238, on Wednesday 29 Av [= 29 July 1478] on midday in Spain, there was a solar eclipse distinctly total as it had been seen, and then [the sky darkened] as if it was midnight.*

León, Spain

Archive of the León cathedral

> ***[1478] Ovo eclinsi en el sol entre las doze oras e la una despues de medio día, e oscureciose el sol e parecion las estrellas en el cielo, e duro por poco espacio.***

Archive of the León cathedral

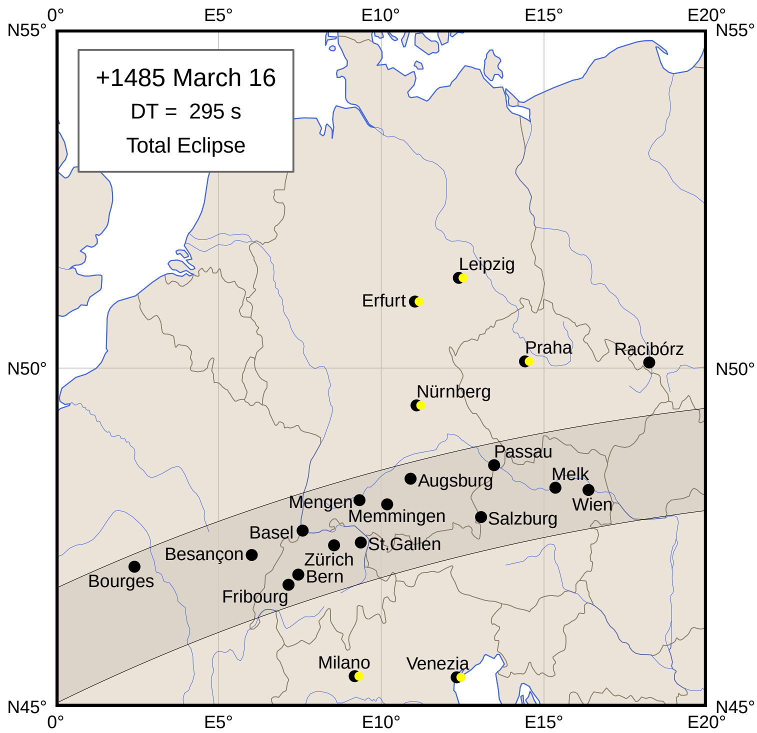
> *[1478] A solar eclipse took place between twelve hours and one hour after midday, and the sun darkened, the stars appeared in the sky, and it lasted very few moments.*

Zacut did not say explicitly that he observed the eclipse at Salamanca. However, he lived there till +1492 and was an active scientist in the field of astronomy at the local University. An assumption that the eclipse was total at Salamanca, whilst not definite, is highly probable. Two reports purporting to be from Sevilla assert that the eclipse was total there. However, the exact place of one of the reports is not known. In order for totality at Sevilla, ΔT would have to be less that about -1500^{s}, which contradicts the evidence from other eclipses around that period.

León is well placed close to the northern edge, which would give a lower bound to $\Delta\mathrm{T}$. Unfortunately, it does not record whether the eclipse was total. However, it does hint that it was total just for 'a few moments', which would suggest it was close to the northern edge of the track.

For totality at Salamanca $+1095^{\mathrm{s}} > \Delta\mathrm{T} > -725^{\mathrm{s}}$.

+1485 March 16, Total Eclipse



Fribourg, Switzerland

***Die Grosse Freiburger Chronik* des Franz Rudella**

> ***[1485] Uffm 12. merzens verfinsterte die sonn allerdingen, ward also finster, als ob es nacht wær. Die hüner unnd das gf<l>•gel [geflügel] flog alles uff zø der ruw, wäret by eim vierteil einer stund, daruff volgtend vil th•rer [theurer] unnd unglückhaffte iaren.***

The Great Fribourg Chronicle by Franz Rudella

> *[1485] On March 12 [recte: 16] the sun darkened all things, there was so dark as if were night. Hens and poultry all of them went to rest, it lasted one quarter of an hour, then followed on very disastrous and unlucky years.*

A report from Bern nearby probably describes totality. However, the report from Fribourg is more graphic, and we adopt that as the defining position. For totality at Fribourg $\Delta T > -215^s$.

Bourges, France

***Chronique de Bourges*, 1467-1506, par Jean Batereau**

> ***Anno D. M CCCC^{0} octuagesimo quarto, die XVI^{a} mensis Marcii, hora tercia, supervenit eclipsis solis perfectus ac si esset nox, et venit quasi subito et duravit tantum quantum staretur ad dicendum Domine ne et Beati quorum, vel circa, et erat tempus oppacum.***

Chronicle of Bourges, 1467-1506, by Jean Batereau

> *In the year of Our Lord 1484 [correctly : 1485 in the new style], on the 16th day of the month of March, at the third hour, a complete eclipse of the sun arrived, as if it was night,*

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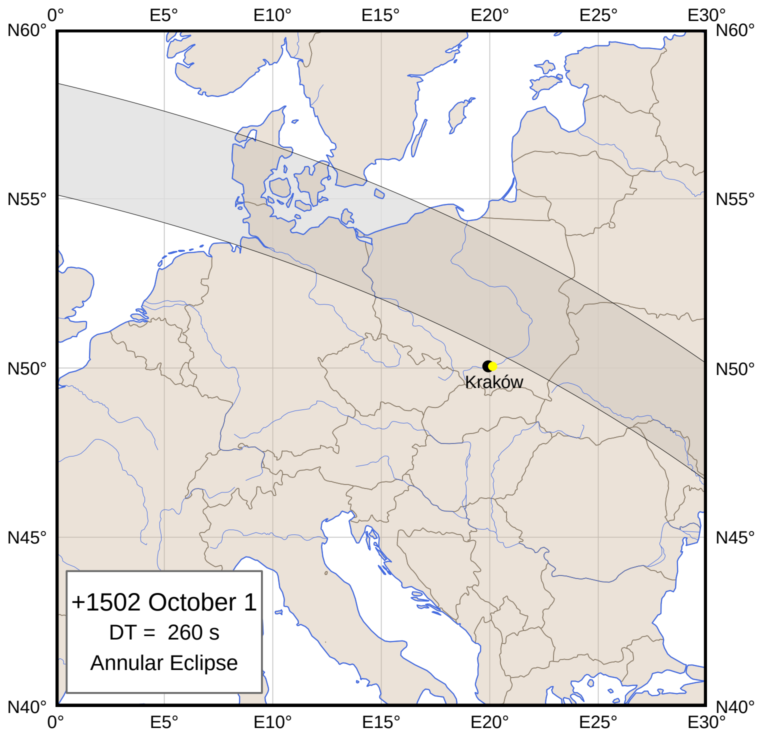
> *and it arrived quite suddenly and lasted for such a time that it was sufficient to say [the psalms] O Lord, rebuke me not and Blessed are those or about, and the time was obscured.*

Jean Batereau was the rector of the University of Bourges. Totality at Bourges is supported by the definite reports from Augsburg and Mengen. For totality at Bourges $\Delta T < +520^s$.

The eclipse was not total at Racibórz, so the account possibly relates to other regions of central Europe or repeats a prediction.

Combining Bourges with Fribourg gives $+520^s > \Delta T > -215^s$.

+1502 October 1, Annular Eclipse



Kraków, Poland

Marcin Biem, (Kraków professor of astronomy and astrology)

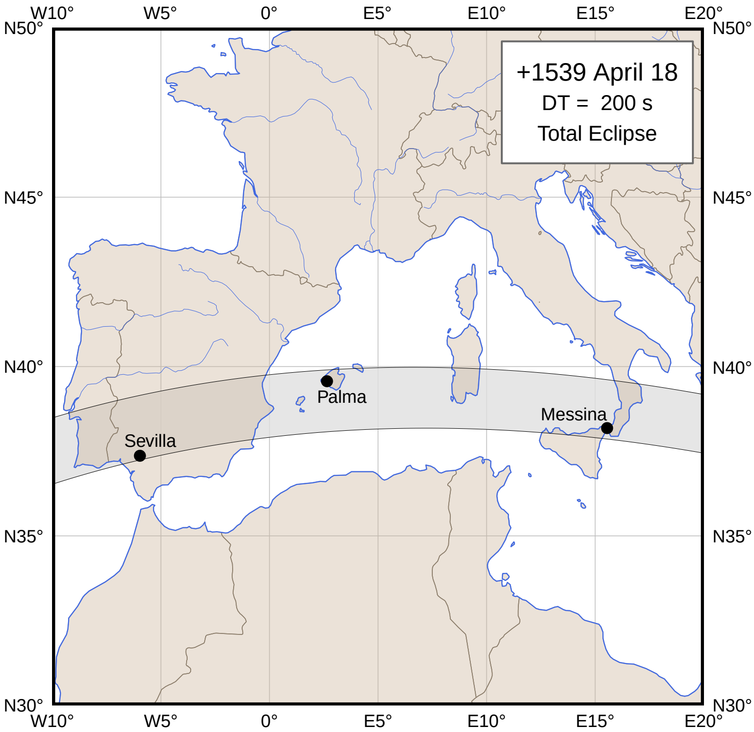
Observation of the partial eclipse of 1502

Beginning of the eclipse:	*13^h 15^m past sunset*	[= 5:21 UT]
Maximum of the eclipse (<11 digits):	*14^h 24^m past sunset*	[= 6:30 UT]
End of the eclipse:	*15^h 29^m past sunset*	[= 7:35 UT]

[Sunset September 30 = 16:06 UT]

Although the timings are systematically early, there is no question that the eclipse was partial at Kraków, and in that case $\Delta T > -125^s$.

+1539 April 18, Total Eclipse



Sevilla, Spain

Diego Ortiz de Zúñiga ***„Anales Eclesiasticos y Seculares de la Ciudad de Sevilla"***

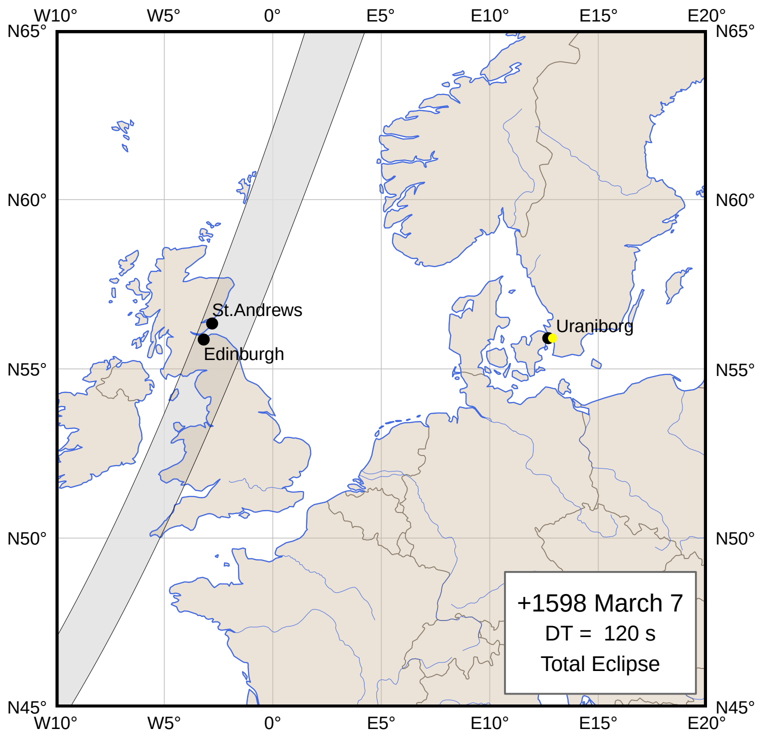
> ***En el año de 1539. fatal à España por la muerte de la Emperatriz Doña Isabel, que succedio Iueves primero de Mayo, à que el Miercoles diez y ocho de Abril, aula precedido, no sin temores de ser amago de infelicidad grande, eclipse cosi total de Sol; pero eclipsose en la Emperatriz el Sol de España, que despedia hermosos rayos de benignidad, y clemencia.***

Ecclesiastical and Secular Annals of the City of Sevilla by Diego Ortiz de Zúñiga

> *On the year 1539, fatal for Spain because of the death of the Empress Madame Isabel, which happened on Thursday (?) May 1st, and what was predicted by Wednesday, 18th of April, not without fear to see such threat of a big misfortune, such total eclipse of the Sun; but in the Empress eclipsed the Sun of Spain, what extinguished the beautiful rays of kindness and mercy.*

The tightest constraint on $\Delta\mathrm{T}$ is set by totality at Sevilla, for which $+2345^{\mathrm{s}} > \Delta\mathrm{T} > -10^{\mathrm{s}}$. The upper bound is redundant for the present purpose.

+1598 March 7, Total Eclipse



St. Andrews, Scotland

Diary of Mr. James Melville, 1556-1610

In the month of February 1598 upon the 25th day being the Saturday betwixt nine and ten hours before noon a most fearful and conspicuous eclipse of the sun began which continued about two hours space The whole face of the sun seemed to be darkness and covered about half a quarter of an hour so that none could see to read upon a book the stars appeared in the firmament and the sea land and air were so stilled and stricken dead as it were that through astonishment herds families men and women were prostrate to the ground. Myself knew out of the Ephemerides and Almanack the day and hour thereof and also by natural philosophy the cause and set myself to note the proceedings in a basin of water mixed with ink thinking the water but common. But when it came to the extremity of darkness and my sight lost all the sun I was stricken with such heaviness and fear that I had no refuge but prostrate on my knees commended myself to God and cried mercy This was thought by all the wise and godly very prodigious so that from pulpits and by writings both in prose and verse admonitions were given to the ministers to beware that the changeable glistering shew of the world should not get in betwixt them and Christ.

On that I gave this warning:

In Februar the twentie fyue exack,
We saw the Sunne the tent hour of the day,
Begin to loss his light and turn to blak,
Whilk piece and piece his whait did weare away,
The cause is this as lerned men do say,
The darksum bodie of the changing moone,
Cam in betwix our sight and Phœbus gay,

And hid from ws his halsome light sa soone.
Amid the meittings of our Kirk this done,
Portends the dark and variable warld,
Sall com betwix the Kirk and Chryst abone,
And mak bir pastors crewked blind and thral'd,
Then statlie starrs stik fast and tak gud tent,
The dragons taill will reng the firmament.

Edinburgh, Scotland

David Calderwood 1575-1650, ***The history of the Kirk of Scotland***

A FEAREFUL ECLIPSE

Upon Saturday, the 25th of Februar, betuixt nyne and tenne houres before noone, beganne a fearefull eclipse, which continued about two houres. The whole face of the sunne seemed to be covered and darkened about half a quarter of an houre in suche measure that none could see to reade on a booke. The stares appeared in the firmament. Sea, land, and aire, was still, and stricken dead as it were. The ravens and fowles flocking together mourned exceedinglie in their kinde. Great multitudes of paddocks ranne together, making an uncouth and hideous noise; men and weomen were astonished, as if the day of judgement had beene coming. Some woeomen swooned. The streets of Edinburgh were full of cryes. Some ranne off the streets to the kirk to pray. The like fearfull darknesse was never seene in this land, so farre as we can reade in our histories, or understand by tradition.

David Calderwood 1575-1650, *The history of the Church of Scotland*

A FEAREFUL ECLIPSE

On Saturday, the 25th of February [of the Julian cal.], between nine and ten in the forenoon, began a fearful eclipse, which continued about two hours. The whole face of the sun seemed to be covered and darkened for about half a quarter of an hour, in such measure that none could see to read a book. The stars appeared in the firmament. Sea, land and air were still, and stricken dead as it were. The ravens and fowls flocking together mourned exceedingly in their way. Great multitudes of puddocks [frogs, toads] ran together, making an uncouth and hideous noise; men and women were astonished, as if the day of judgment had come. Some women swooned. The streets of Edinburgh were full of cries. Some men ran off the streets to the kirk to pray. Such a fearful eclipse was never seen in this land, so far as we can read in our histories, or understand by tradition.

There are some striking similarities in the reports from St. Andrews and Edinburgh, and this suggests that they are not entirely independent. However, as they are similarly placed relative to the track of totality, the limits on ΔT do not change much between them. To error on the safe side, we take the lower limit from Edinburgh ($\Delta T > -360^s$) and the upper limit from St. Andrews ($\Delta T < +245^s$).

Thus for this eclipse, we have the constraint $+245^s > \Delta T > -360^s$.

A summary of all the bounds on ΔT drived from all the results of this section are given in table **S1**.

Data Accessibility. Web pages are available from HM Nautical Almanac Office's website at http://astro.ukho.gov.uk/nao/lvm, which contain tables of lod and ΔT at various intervals, together with estimates of their errors and related material.

Authors' Contributions. L.V.M. carried out the analysis of the values of ΔT; M.Z. collected the eclipse records; F.R.S. provided the estimation of the eclipse records, and C.Y.H. wrote and ran the computer programs to calculate and analyse the results as well as plot the tracks of each eclipse. All authors contributed to writing/revising the paper, approve the final version and agree to be accountable for all aspects the work.

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The tables continue on the next page.

S6. Tables

Limits:	Summary of the bounds (see table **S1**) on ΔT from the observations analysed in section S5
Locations:	Table **S4** lists the latitudes & longitudes of the places plotted on the maps
Values:	Table **S6** for values of ΔT and lod
Revised:	Stephenson *et al.* 2016 [1]
Table S10	Untimed total and annular solar eclipses (see table **S2**)
Table S11	Untimed partial solar eclipses (see table **S3**)
Table S15	Updated polynomial coefficients that represent the spline (see table **S5**)

Table S1. Summary of the bounds on ΔT from the observations analysed in section S5.

Year	Type	Upper >	ΔT > Lower	Places
+1133	total	+1115	+530	Kerkrade; Reichersberg
+1187	total	+1065	+45	Galich
+1239	total	+1105	+830	Cerrato; Toledo
+1241	total	+1005	+625	Freising; Stade
+1310	annular	+1555	+460	Erfurt; Paris
+1330	partial	+910	—	Zbraslav
+1379	total	+1525	+105	Sevilla
+1386	total	+1075	−650	Montpellier
+1406	total	+900	+400	Liege; Bordeaux
+1415	total	+705	+200	Wrocław; Kraków
+1433	total	+570	+385	Augsburg; Karlštejn
+1478	total	+1095	−725	Salamanca
+1485	total	+520	−215	Bourges; Fribourg
+1502	partial	—	−125	Kraków
+1539	total	+2345	−10	Sevilla
+1598	total	+245	−360	St. Andrews; Edinburgh

Table S2. Untimed total and annular solar eclipses

Year	ΔT(s) Limits		Region	Source
	Upper bound	Lower bound		
−708	+21100	+20160	China	S10
−600	+21900	+21120	China	S10
−548	+21640	+16160	China	S10
−309	+17160	+13300	Greek	S10
−197	+13020	+ 6360	China	T1
−187	+12900	+12590	Europe	T1
−180	+12700	+11780	China	S10
−135	+12140	+11220	Babylon	S10
−9	+10720	+8640	Babylon	S10
+65	+8900	+8450	China, Luoyang	T1
+65	+9630	+9150	China, Guangling	T1
+71	+9830	+9440	Greek	S10
+306	+7890	+6550	China	T1
+454	+7800	+6030	China	T1
+616	+2990	+2270	China	T1
+761	+3260	+1700	China	S10
+840	+6800	+1940	Europe	S10
+873	+3740	+1820	Arab	S10
+912	+2580	+840	Arab	S10
+968	+2620	+1560	Europe	S10
+975	+4480	+1160	Japan	S10
+1061	+2140	+800	Arab	S10
+1124	+2700	+980	Europe	S10
+1133	+1115	+530	Europe	T2,P4
+1147	+1160	+280	Europe	S10
+1176	+1600	+600	Arab	S10
+1185	+10500	−2100	Europe	S10
+1187	+1065	+ 45	Europe	T2,P6
+1221	+960	−9600	China	S10
+1239	+1105	+830	Europe	T2,P8
+1241	+1005	+625	Europe	T2,P10
+1267	+800	−900	Europe	S10
+1275	+1280	−740	China	S10
+1292	+1820	− 60	China	S10
+1310	+1555	+460	Europe	T2,P11
+1361	+1760	+500	China	T1
+1379	+1525	+105	Europe	T2,P15
+1386	+1075	−650	Europe	T2,P16
+1406	+900	+400	Europe	T2,P17
+1415	+705	+200	Europe	T2,P19
+1431	+680	−200	Europe	S10
+1433	+570	+385	Europe	T2,P21
+1478	+1095	−725	Europe	T2,P23
+1485	+520	−215	Europe	T2,P25
+1539	+2345	− 10	Europe	T2,P28
+1560	+210	−480	Europe	S10
+1567	+165	+145	Europe	S10
+1598	+245	−360	Europe	T2,P29

continued above . . .

ΔT(s) : Correction to the Earth's clock in seconds
Upper/lower bound : Limits on ΔT, dependent on the eclipse phenomena
Region : Where the eclipse was observed
Source : Origin of the values of ΔT
S10 : Table S10 in Stephenson *et al.* [1]
T1 : Table 1 in the main paper
T2 : Table 2 in the main paper
Pn : Page number in this Supplement where the eclipse is analysed

Table S3. Untimed partial solar eclipses

Year	ΔT(s) Limits		Region	Source
	Lower bound	Upper bound		
−430	+12620	[+11760]	Greek	S11
−393	+14280	[+12640]	Greek	S11
−241	+12260	[+11680]	Babylon	S11
−187	[+14100]	+13780	China	S11
−79	+8460	[+8160]	China	S11
−27	+9480	[+8050]	China	S11
+120	+8980	+8140	China	S11
+360	[+9420]	+7100	China	S11
+494	[+6600]	+5980	China	S11
+702	+2720	[+1440]	China	S11
+729	+1180	[+400]	China	S11
+822	- - -	+4000	China	S11
+1004	+ 1980	+1760	Arab	S11
+1133	· · ·	+1440	Europe	S11
+1135	[+3800]	+1840	China	S11
+1147	· · ·	+1660	Europe	S11
+1178	· · ·	+1140	Europe	S11
+1330	[+1220]	+910	Europe	T2,P13
+1502	− 125	- - -	Europe	T2,P27
+1605	- - -	+1060	Europe	S11

continued above . . .

ΔT(s) : Correction to the Earth's clock in seconds
Upper/lower bound : Limits on ΔT, dependent on the eclipse phenomena
[ ] : Uncritical limit
· · · : Redundant limit
- - - : Only one viable limit
Region : Where the eclipse was observed
S10 : Table S10 in Stephenson *et al.* [1]
T2 : Table 2 in the main paper
Pn : Page number in this Supplement where the eclipse is analysed

Table S4. List of locations plotted on the maps.

Place/Region	Latitude	Longitude
	° ′	° ′
Arezzo, Italy	N 43 28	E 011 54
Asti, Italy	N 44 54	E 008 12
Augsburg, Germany	N 48 22	E 010 54
Avignon, France	N 43 57	E 004 49
Basel, Switzerland	N 47 36	E 007 35
Bern, Switzerland	N 46 57	E 007 27
Besançon, France	N 47 14	E 006 01
Bologna , Italy	N 44 30	E 011 21
Bordeaux, France	N 44 50	W 000 35
Bourges, France	N 47 04	E 002 25
Braunschweig, Germany	N 52 16	E 010 31
Cardeña, Spain	N 42 18	W 003 36
Cerrato, Spain	N 41 57	W 004 31
Cesena, Italy	N 44 08	E 012 15
Coimbra, Portugal	N 40 13	W 008 25
Constantinople, Asia Minor	N 41 01	E 028 59
Corvei, Germany	N 51 48	E 009 24
Diessenhoven, Germany	N 47 56	E 011 07
Digne, France	N 44 06	E 006 13
Dortmund, Germany	N 51 31	E 007 28
Edinburgh, Scotland	N 55 52	W 003 11
Egmond aan Zee, The Netherlands	N 52 40	E 004 38
Ensdorf, Germany	N 49 27	E 011 55
Erfurt, Germany	N 50 59	E 011 02
Firenze (Florence), Italy	N 43 46	E 011 15
Freising, Germany	N 48 24	E 011 43
Fribourg, Switzerland	N 46 48	E 007 09
Galich, West Russia/Ukraine	N 49 05	E 024 42
Genova (Genoa), Italy	N 44 26	E 008 56
Great Novgorod, Russia	N 58 30	E 031 20
Hamburg, Germany	N 53 33	E 007 38
Haselbach, Austria	N 48 39	E 016 21
Heilsbronn, Germany	N 49 20	E 010 45
Karlštejn, Bohemia	N 49 57	E 014 02
Kerkrade, The Netherlands	N 50 52	E 006 04
Kiev, Ukraine	N 50 25	E 030 32
Konstanz, Germany	N 47 40	E 009 11
Kraków (Cracow), Poland	N 50 03	E 019 56
Leipzig, Germany	N 51 20	E 012 23
León, Spain	N 42 36	W 005 34
Liege, Belgium	N 50 32	E 005 30
Lucca, Italy	N 43 51	E 010 31

continued above . . .

Place/Region	Latitude	Longitude
	° ′	° ′
Magdeburg, Germany	N 52 08	E 011 38
Marseille, France	N 43 18	E 005 22
Melk, Austria	N 48 14	E 015 21
Memmingen, Germany	N 47 59	E 010 11
Mengen, Germany	N 48 02	E 009 20
Messina, Italy	N 38 11	E 015 33
Milano (Milan), Italy	N 45 27	E 009 11
Modena, Italy	N 44 39	E 010 56
Monte Cassino, Italy	N 41 29	E 013 49
Montpellier, France	N 43 37	E 003 53
Neuchâtel, Switzerland	N 47 00	E 006 56
Niederalteich, Germany	N 48 46	E 013 01
Nürnberg (Nuremberg), Germany	N 49 27	E 011 05
Orange, France	N 44 08	E 004 49
Palma (de Mallorca), Spain	N 39 34	E 002 39
Paris, France	N 48 52	E 002 20
Passau, Germany	N 48 34	E 013 28
Piacenza, Italy	N 45 03	E 009 41
Praha (Prague), Bohemia	N 50 06	E 014 25
Racibórz, Poland	N 50 05	E 018 14
Ravenna, Italy	N 44 24	E 012 11
Regensburg, Germany	N 49 01	E 012 05
Reichersberg, Austria	N 48 20	E 013 22
Roma (Rome), Italy	N 41 54	E 012 29
Salamanca, Spain	N 40 58	W 005 40
Salzburg, Austria	N 47 48	E 013 04
Sevilla (Seville), Spain	N 37 22	W 005 58
Siena, Italy	N 43 19	E 011 20
Split, Dalmatia/Croatia	N 43 30	E 016 27
St. Andrews, Scotland	N 56 20	W 002 48
St. Denis, France	N 48 56	E 002 21
St. Gallen, Switzerland	N 47 25	E 009 22
Stade, Germany	N 53 37	E 009 29
Toledo, Spain	N 39 52	W 004 02
Tüngedaer Schloß, Germany	N 51 02	E 010 35
Uraniborg, Denmark	N 55 54	E 012 42
Venezia (Venice), Italy	N 45 26	E 012 19
Weltenburg, Germany	N 48 54	E 011 49
Wien (Vienna), Austria	N 48 12	E 016 22
Wrocław, Poland	N 51 07	E 017 02
Zbraslav, Bohemia	N 49 58	E 014 23
Zürich, Switzerland	N 47 23	E 008 33

Table S5. Polynomial coefficients for $\Delta\mathrm{T}$ from −720.0 to 2019.0 (2020 August)

Row i	Years K_i	K_{i+1}	Polynomial coefficients a_0	a_1	a_2	a_3
1	−720.0	−100.0	20371.848	−9999.586	776.247	409.160
2	−100.0	400.0	11557.668	−5822.270	1303.151	−503.433
3	400.0	1000.0	6535.116	−5671.519	−298.291	1085.087
4	1000.0	1150.0	1650.393	−753.210	184.811	−25.346
5	1150.0	1300.0	1056.647	−459.628	108.771	−24.641
6	1300.0	1500.0	681.149	−421.345	61.953	−29.414
7	1500.0	1600.0	292.343	−192.841	−6.572	16.197
8	1600.0	1650.0	109.127	−78.697	10.505	3.018
9	1650.0	1720.0	43.952	−68.089	38.333	−2.127
10	1720.0	1800.0	12.068	2.507	41.731	−37.939
11	1800.0	1810.0	18.367	−3.481	−1.126	1.918
12	1810.0	1820.0	15.678	0.021	4.629	−3.812
13	1820.0	1830.0	16.516	−2.157	−6.806	3.250
14	1830.0	1840.0	10.804	−6.018	2.944	−0.096
15	1840.0	1850.0	7.634	−0.416	2.658	−0.539
16	1850.0	1855.0	9.338	1.642	0.261	−0.883
17	1855.0	1860.0	10.357	−0.486	−2.389	1.558
18	1860.0	1865.0	9.040	−0.591	2.284	−2.477
19	1865.0	1870.0	8.255	−3.456	−5.148	2.720
20	1870.0	1875.0	2.371	−5.593	3.011	−0.914
21	1875.0	1880.0	−1.126	−2.314	0.269	−0.039
22	1880.0	1885.0	−3.210	−1.893	0.152	0.563
23	1885.0	1890.0	−4.388	0.101	1.842	−1.438
24	1890.0	1895.0	−3.884	−0.531	−2.474	1.871
25	1895.0	1900.0	−5.017	0.134	3.138	−0.232
26	1900.0	1905.0	−1.977	5.715	2.443	−1.257
27	1905.0	1910.0	4.923	6.828	−1.329	0.720
28	1910.0	1915.0	11.142	6.330	0.831	−0.825
29	1915.0	1920.0	17.479	5.518	−1.643	0.262
30	1920.0	1925.0	21.617	3.020	−0.856	0.008
31	1925.0	1930.0	23.789	1.333	−0.831	0.127
32	1930.0	1935.0	24.418	0.052	−0.449	0.142
33	1935.0	1940.0	24.164	−0.419	−0.022	0.702
34	1940.0	1945.0	24.426	1.645	2.086	−1.106
35	1945.0	1950.0	27.050	2.499	−1.232	0.614
36	1950.0	1953.0	28.932	1.127	0.220	−0.277
37	1953.0	1956.0	30.002	0.737	−0.610	0.631
38	1956.0	1959.0	30.760	1.409	1.282	−0.799
39	1959.0	1962.0	32.652	1.577	−1.115	0.507
40	1962.0	1965.0	33.621	0.868	0.406	0.199
41	1965.0	1968.0	35.093	2.275	1.002	−0.414
42	1968.0	1971.0	37.956	3.035	−0.242	0.202
43	1971.0	1974.0	40.951	3.157	0.364	−0.229
44	1974.0	1977.0	44.244	3.199	−0.323	0.172
45	1977.0	1980.0	47.291	3.069	0.193	−0.192
46	1980.0	1983.0	50.361	2.878	−0.384	0.081
47	1983.0	1986.0	52.936	2.354	−0.140	−0.165
48	1986.0	1989.0	54.984	1.577	−0.637	0.448
49	1989.0	1992.0	56.373	1.648	0.708	−0.276
50	1992.0	1995.0	58.453	2.235	−0.121	0.110
51	1995.0	1998.0	60.678	2.324	0.210	−0.313
52	1998.0	2001.0	62.898	1.804	−0.729	0.109
53	2001.0	2004.0	64.083	0.674	−0.402	0.199
54	2004.0	2007.0	64.553	0.466	0.194	−0.017
55	2007.0	2010.0	65.197	0.804	0.144	−0.084
56	2010.0	2013.0	66.061	0.839	−0.109	0.128
57	2013.0	2016.0	66.920	1.007	0.277	−0.095
58	2016.0	2019.0	68.109	1.277	−0.007	−0.139

For the year and fraction (Y) extract the coefficients a_0, a_1, a_2, a_3 from row i, where $K_i \le Y \le K_{i+1}$. Then form $t = (Y - K_i)/(K_{i+1} - K_i)$ and thus calculate $\Delta\mathrm{T} = a_0 + a_1\, t + a_2\, t^2 + a_3\, t^3$ seconds.

Table S6. Values, from −720 to +2019, of $\Delta\mathrm{T}$ and lod evaluated using the spline (2020)

Year	ΔT	lod	Year	ΔT	lod	Year	ΔT	lod
	s	ms		s	ms		s	ms
−720.0	+20370	−44.2	+100.0	+9410	−27.5	+1000.0	+1650	−13.7
−700.0	+20050	−43.9	+200.0	+8420	−26.3	+1100.0	+1220	− 9.9
−600.0	+18470	−42.6	+300.0	+7480	−25.8	+1200.0	+ 910	−7.2
−500.0	+16940	−41.0	+400.0	+6540	−25.9	+1300.0	+ 680	−5.8
−400.0	+15470	−39.2	+500.0	+5590	−25.9	+1400.0	+ 480	−5.2
−300.0	+14080	−37.0	+600.0	+4650	−25.1	+1500.0	+ 290	−5.3
−200.0	+12770	−34.6	+700.0	+3760	−23.5	+1600.0	+ 110	−4.3
−100.0	+11560	−31.9	+800.0	+2940	−21.1	+1700.0	+ 14	−0.6
0.0	+10440	−29.4	+900.0	+2230	−17.8	+1800.0	+ 18	−1.0
+100.0	+9410	−27.5	+1000.0	+1650	−13.7	+1900.0	+ 2	+3.1
+1800.0	+18.37	−1.0	+1900.0	− 1.98	+3.1	+2000.0	+63.81	+0.9
+1810.0	+15.68	0.0	+1910.0	+11.14	+3.5	+2010.0	+66.06	+0.8
+1820.0	+16.52	−0.6	+1920.0	+21.62	+1.7	+2019.0	+69.24	+0.8
+1830.0	+10.80	−1.6	+1930.0	+24.42	0.0			
+1840.0	+ 7.63	−0.1	+1940.0	+24.43	+0.9			
+1850.0	+ 9.34	+0.9	+1950.0	+28.93	+1.0			
+1860.0	+ 9.04	−0.3	+1960.0	+33.07	+0.9			
+1870.0	+ 2.37	−3.1	+1970.0	+39.93	+2.7			
+1880.0	− 3.21	−1.0	+1980.0	+50.36	+2.6			
+1890.0	− 3.88	−0.3	+1990.0	+56.99	+1.9			
+1900.0	− 1.98	+3.1	+2000.0	+63.81	+0.9			

See HM Nautical Almanac Office's website at http://astro.ukho.gov.uk/nao/lvm for a more detailed list with error estimates.