PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# The Direction of the Earth's Magnetic Field at London, 1570-1975

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# THE DIRECTION OF THE EARTH'S MAGNETIC FIELD AT LONDON, 1570–1975

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[Pullouts 1 and 2]

CONTENTS



The observations of magnetic declination and dip made in London over the past 400 years comprise one of the longest and most complete series of such data for anywhere in the world. They give an indication of secular change on a time scale intermediate between that of recent observatory measurements and of archaeomagnetic measurements. We have attempted to catalogue all direct measurements of declination and dip, paying particular attention to completeness in the earlier years, and tracing the data to their original source wherever possible. Sufficient details of the observations are given for an assessment of their reliability and accuracy. The data are then corrected to a single site, fitted with a continuous smooth curve, and discussed.

## 1. Introduction

Observations of the departure of the compass from the true north, that is of the magnetic declination or variation, go back, in Europe, to the early 16th century. Observations of dip start in 1576. In the great age of exploration there was a feeling that a device that could show the way across an ocean in storm and darkness was something extraordinary, almost miraculous. Poets good and not so good sang the virtues of the lodestone, for example:

The Loadstone is the stone,
the onely stone alone,
Deserving praise above the rest,
whose vertues are unknowne.

*The Mariner's Judgement* (R. Norman 1581)

The considerable public interest and the practical concerns of mariners led to numerous observations and to commentaries on them.

Today we have a detailed knowledge of the current state of the field and rather elaborate theories of its origin. These developments have given a new interest to the early observations and have led the International Association of Geomagnetism and Aeronomy to request their collection and critical study (resolution 21 of the Kyoto conference of IAGA held in 1973). A few years ago the authors of this paper discovered that they had been independently collecting such data for London; they decided to pool their results and publish them in a joint paper. Such work involves extensive search and reading in libraries, and the collection of notes and copies of the relevant parts of books; it is probably best pursued as a hobby, making use of opportunities as they occur. One of us (E.C.B.) started his collection in the 1950s, the other more recently. The chance that has given us two independently collected sets of data has widened the field of search and should have reduced the likelihood of error or misinterpretation.

## 2. Purpose of the collection

The Earth's magnetic field shows variations on all time scales, from fractions of a second to hundreds of millions of years. Modern observations at permanent magnetic observatories give fair resolution of the spectrum at periods of up to 11 years (Banks 1969; Black 1970; Harwood & Malin 1977), and some information, though little resolution, to periods of 50 years. The older observations go back 400 years though only at a few places and with greatly increased uncertainty. The purpose of this paper is to provide the data for the magnetic declination and dip at London for the whole period from the first measurements, which were made about 1570, to 1975. Many previous lists have been published, but it seems that most of these are direct or indirect copies of well known 19th century lists (Hansteen 1819, Barlow 1829). The resulting lists have serious deficiencies which we have endeavoured to rectify by an examination of the original sources and by an extensive search of the literature. As an example of the deficiencies of the existing lists, a published observation made by King Charles II in 1665 is omitted from all the lists. We hope we have removed all the accumulated errors produced by repeated copying and also identified all the bogus observations. It is too much to hope that we have found all the recorded observations and we hope that anyone who finds any that are not in our list will let us know.

It happens that the changes in declination at London have been exceptionally large and are of considerable interest for the dynamo theory of the origin of the field and of its changes. How could the declination have been 11° E in the late 16th century, at a time when the north magnetic dip-pole and the dipole axis were not far from their present positions to the north of Hudson's Bay? The subsequent swing of the field to 24° W in 1820, still without any substantial shift of the pole, is equally remarkable. Presumably an exceptionally large eddy or magneto-dynamic wave passed under Europe from east to west, near the surface of the Earth's core.

We have gone some way in collecting the rather meagre pre-1800 observations from elsewhere in the British Isles and also the observations in and around Paris, which are more systematic and more numerous than those for London. We hope to publish these in later papers. It is desirable that someone should critically examine the data for the few places in central and eastern Europe that have long series of observations. It should be possible to trace the disturbance across Europe and perhaps, by examining observations made at sea, to follow its fading beneath the Atlantic. The splendid collection of Bemmelen (1899), based largely on the logs of Dutch ships, gives a good indication of what is possible, but does not extend to dates after 1750.

The data collected in this paper fill a gap between the modern observatory measurements and the much less detailed archeomagnetic and paleomagnetic measurements. The scatter in the long series, such as those at London and Paris, also gives an idea of the errors to be expected in such measurements and may be taken as some indication of the reliability of shorter series at other places.

## 3. Sources of the data

Whatever the shortcomings of the existing lists they do constitute a natural starting point for a search of the 16th, 17th and 18th century literature. Many of the observations in the lists have names and dates, and sometimes references; these can be tracked to their original sources which often yield additional observations. Further search depends on a knowledge of who was

Table 1. Number of years with observations in lists of declination and dip at London

| | declination | | | | | dip | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| author | 16 c | 17 c | 18 c | 1800–49 | total | 16 c | 17 c | 18 c | 1800–49 | total |
| Halley (1683) | 1 | 3 | — | — | 4 | — | — | — | — | — |
| Churchman (1794) | — | 5 | 6 | — | 11 | — | — | — | — | — |
| Hansteen (1819) | 1 | 6 | 22 | 8 | 37 | 1 | 1 | 14 | 3 | 19 |
| Barlow (1829) | 1 | 6 | 24 | 8 | 39 | 1 | — | 15 | 4 | 20 |
| Walker (1866) | 1 | 6 | 5 | 6 | 18 | 1 | — | 3 | 4 | 8 |
| Lloyd (1874) | 1 | 5 | 3 | 12 | 21 | — | — | — | — | — |
| Abbadie (1890) | 1 | 3 | 4 | 2 | 10 | 1 | 3 | 9 | 2 | 15 |
| Guillemin (1891) | 1 | 5 | 6 | 5 | 17 | 1 | 2 | 3 | 5 | 11 |
| Felgentraeger (1892) | 1 | 13 | 19 | 15 | 48 | — | — | — | — | — |
| Weyer (1895) | 2 | 8 | 24 | 7 | 41 | — | — | — | — | — |
| Bemmelen (1899) | 2 | 13 | 1 | — | 16 | — | — | — | — | — |
| Gaibar-Puertas (1953) | 2 | 6 | 8 | 6 | 22 | 1 | 1 | 14 | 5 | 21 |
| Malin & Bullard | 6 | 37 | 50 | 56 | 149 | 1 | 5 | 32 | 50 | 88 |

interested in the Earth's field, supplemented by a search of likely titles from bibliographies and discussions such as those of Mottelay (1922), Balmer (1956), Taylor (1954) and Gartrell (1975), and by much random reading of the 16th and 17th century literature of science and navigation.

A representative selection of the lists with a summary of their contents is given in table 1. In criticizing the lists it should be made clear that the authors of many of them were covering the whole world and could not be expected to conduct the kind of search of the original sources that we have been able to make for London.





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The publications, *Journal Books* and *Register Books* of the Royal Society are particularly valuable sources of information on early London observations. However, not all of the clues have led us to the observations. One case is particularly tantalizing: we learn from the Royal Society *Journal Book* that, on 26 May, 1670, 'Dr. Croon aquainted the company, that one Sir Nicholas Millet had mentioned to him and Mr Hook, that he had a manuscript of his own writing which contained the observations of the variations of the needle, made for seventeen or eighteen years in one and the same place. They were desired to procure a sight and the perusal of that manuscript for the Society', and on 28 July, 1670, '...Dr. Croon aquainted the Society, that one Sr. Nicholas Millet of Battersy, had a manuscript, containing the observation of the magnetik needle for many years; and that he thought him not unwilling to give perusal of it to the Society, if spoken to; the Doctor was desired to peruse the book, together with Mr. Hook, and to make a report of it to the Society'. If authentic, these data would be of immense value, but we have been unable to find the manuscript, or any further reference to it, in the Royal Society, British Library or from the Local Historian of the Battersea District Library. The only Millet observations we have been able to find are those reported by Sellar (1694) for May 1670. The letters of Millet in the British Library are mainly concerned with cargos and financial matters. They show that he was captain of the *Loyal Merchant* and spent most of his time at sea between 1663 and 1667, so the series of observations is either incomplete, or not made exclusively by Millet.

It is curious that Hooke apparently made no magnetic observations of his own, though he was requested to do so by the Royal Society several times and wrote knowledgeably on the subject. He was one of those present during the Royal Society observations of 1664 and 1665.

It is also surprising that published ships' logs of the 16th and 17th centuries do not show observations in London at the start or end of voyages; even Halley did not make such measurements, or at any rate did not include them in the log of the *Paramour*. The collection of logs in the care of Trinity House was unfortunately destroyed in an air raid during the last war. We have not examined the Admiralty archives.

After about 1720 the number of observations increases and it becomes less important to find isolated measurements. The long series by Graham (1724, 1749) and Gilpin (1806) are sufficient to connect with the systematic programmes of observation at Greenwich.

## 4. Methods of observation

### 4.1. *Declination*

The measurement of declination ($D$) requires a determination of true north and of magnetic north. Until very recently true north was invariably determined via an astronomical observation, usually of the Sun or the pole star. When at sea, with a clear horizon, the magnetic azimuth of the rising or setting sun could be compared with the true azimuth given in an ephemeris such as the Caroline tables, for the appropriate latitude and date. This was the method used by Halley, who also took account of atmospheric refraction.

When there were no satisfactory tables an admirable method of determining the north from the Sun was that used by Borough (1581). He noted the azimuth of the Sun as it ascended and descended through a chosen almacantur, using a quadrant to define the altitude. The mean of these two azimuths gives true north, and is independent of refraction. A simpler version of this method, using the shadow of a vertical wire, is described by Bourne (1574). If only a single observation is made of the altitude and azimuth of the Sun, true north can still be determined with the aid of an ephemeris. This method was commonly used in the 17th and 18th centuries.

In the 19th and 20th centuries true north was still commonly determined from a solar observation, particularly when doing field work. However, the altitude measurement has been replaced with a time measurement. A theodolite is clamped at a fixed azimuth and the time of transit of the Sun across this azimuth is noted. The readily attained accuracy of 0.4 s is sufficient to define the north to 0.1′.

At observatories, true north is usually obtained by observing polaris with a theodolite, both directly and reflected in mercury. These observations are reduced with the aid of pole star tables and a knowledge of the time of observation which is much less critical than for a solar observation.

Since the direction of true north does not change with time, at least to the accuracy required for declination measurements, it need be determined only very infrequently for each site. It can be recorded either by inscribing a meridian line on a fixed object (as was done by Gunter (1624) on the dial in the King's gardens at Whitehall), or by noting the true azimuth of a distant reference mark, as is the practice at observatories and survey stations.

For the early determinations of declination, the magnetic azimuth was determined by means of magnetized needles fixed to a pivoted card, as described and illustrated by Moore (1681). In better instruments the card was dispensed with and the compass needle was fitted with an agate cup which rested directly on the pin. Various refinements were added, such as a reversible agate cup to allow the needle to be mounted either side up (and hence remove errors due to a difference between the magnetic and geometrical axes of the needle), mirrors to avoid parallax when reading the needle, verniers and a microscope to improve the reading of the circle, etc. Cavendish (1776) gives a good illustrated description of the Royal Society instrument, which was a fine example of such a compass. Some observers used needles several feet long; a few inches to a foot was more usual.

The main problems with pivoted compass needles are the friction in the bearings and the difficulty in persuading them to stay horizontal. Indeed, it was this latter problem that led Norman to his discovery of dip. These difficulties are overcome with a suspended magnet, as in the Kew-pattern magnetometer, which can also be used for measuring horizontal intensity. A detailed description of this instrument and its use is given by Stewart & Gee (1903). It is essentially the same instrument that is used for absolute measurements of declination in present day observatories.

Perhaps the main advantage of the modern observatory data over earlier data is that they refer to the mean value over a whole year rather than being the mean of a series of spot values. This is achieved by interpolating between the absolute observations by means of a continuous magnetogram record of the variations. In this way, any periodic or irregular variation present at the time of the observation can be removed. Modern survey observations are similarly corrected by assuming that the departure of an instantaneous observation from the mean of the year is the same as that for a nearby observatory.

### 4.2. *Dip*

For dip, the reference datum is the horizontal, which is readily defined by a spirit level, mercury dish, or via a plumb line.

Until the beginning of this century dip was invariably measured with a dip circle, consisting of a magnetic needle free to turn about a horizontal axis at the centre of a vertical graduated circle. It was usual to observe with the plane of rotation of the needle in the magnetic meridian (defined to sufficient accuracy by a simple compass), though dip can readily be deduced from observations made in two perpendicular azimuths. Eccentricity of the axis is overcome by reading both ends of the needle and taking the mean, and misalignment of the magnetic and geometrical axes of the needle is allowed for by observing with one face of the needle first east, then west. A more serious problem is that the axis of rotation does not, in general, pass through the centre of gravity of the needle. It can be made to do so by means of counterweights, adjusted with the plane of rotation of the needle perpendicular to the magnetic meridian, but it is easier to allow for it by making two sets of measurements with the sense of magnetization of the needle changed in between, by stroking the needle with a magnet. This method is strictly valid only if the magnetic moment is the same for each direction, when the tangent of the true dip is the mean of the tangents of the two measures. For many years the mean angle was taken at Greenwich, instead of the mean tangent; thus a small but systematic error was introduced which was corrected retrospectively in 1910.

Another serious problem with the dip circle is mechanical resistance to rotation. Various means were tried to overcome this, such as a roller bearing as described by Nairne (1772), or a cylindrical axle rolling on agate flats or knife edges, but the problem was never completely solved. Despite numerous detailed refinements, the dip circle changed remarkably little in its essentials from that which Norman built in 1586 to the Airy apparatus of 1861.

The dip circle remained in use as a field instrument until quite recently, but at Greenwich it was replaced by the dip inductor in 1914. The dip inductor consists of a coil of wire connected via a commutator to a galvanometer, and mounted within a vertical circle on a firm horizontal base. When the coil is rotated (by means of a band or cable drive) it generates a current except when its axis of rotation is aligned with the magnetic vector. The null point is found by adjusting the orientation of the axis, and the dip is read off. This instrument is still in use at some observatories, though its use has generally lapsed. Its main drawbacks are the vibrations caused by the rotation, and the difficulty of adjusting the lignum vitae bearings to allow free rotation without slackness. New instruments are being developed, based on the same principle but overcoming the drawbacks, but these are not relevant to the London observations.

Nowadays it is usual to deduce dip from measurements of the horizontal and either the vertical or total magnetic intensity (see notes 76 and 111 of Appendix A). These may be reduced to the mean of the year via magnetograph records as described in §4.1.

## 5. Presentation of the data

The observations of declination and dip are listed in chronological order in tables A1 and A2, respectively, of Appendix A. The tables also give the date of each observation to the nearest tenth of a year (if it is known to that accuracy), the observer, the site of the observation, and the number of a note in Appendix A where further details of the observation can be found. We have also included (in parentheses) 'observations' which appear in the literature, but which we believe to be spurious. These are included only for completeness and should not be used in any scientific study of the data.

The numerical form in which the angular measures are given corresponds as closely as possible to that used in its source; sometimes degrees and decimals or fractions, sometimes degrees, minutes and seconds, etc. However, we have converted the rhumb, or point (equivalent



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to $11\frac{1}{4}°$) and centesimal grade (equivalent to 0.9°) into degrees and minutes. The centesimal grade had a short vogue, particularly in France, towards the end of the 19th century and has recently reappeared on electronic calculators. In earlier years, the grade was an alternative name for a degree; see, for example, Digges (1571): '...a circle divided in 360 grades or degrees'.

Where several observations were made at the same site, all those made in the same year have been combined into a single mean, even if they were made by different observers. For this purpose the circumcision style year was used (i.e. starting at January 1.0).

The notes of Appendix A are intended to amplify the information given in the tables, referencing the source and giving further details of the observation, where these are known. For the less accessible sources, the relevant passage is usually quoted verbatim. In all cases, we have sought the earliest reference to each observation, frequently going back as far as the observer's manuscript notes. We do not reference subsequent quotations of the data unless these differ in some way from an earlier source. Thus a misquotation that is perpetuated in many later compilations will be referred to only once, and an entirely accurate compilation would not be referred to at all. Minor changes, such as rounding, or conversion to grades or decimals of a degree, are disregarded.

Dates in the notes are in the form in which they were originally given. Thus, in general, dates before 1752 refer to the Julian calendar and later dates refer to the Gregorian calendar. Where a span of dates is indicated, it is implicit that they are inclusive.

Where we have tabulated means of observations that other compilers have given separately, the separate observations are given in the notes. We have also noted the original versions of any observations that we have recomputed. In this way, any observation, whether published by the observer or a compiler, whether real or spurious, should appear in Appendix A. If it does not do so we have missed it, and would be most grateful to be informed of its existence.

The notes also give information that may help an assessment of the quality of the observation, such as the instrument used, the number of observations contributing to the mean and the method of observation. Another important factor which is less easy to assess is the skill of the observer, but some clue to this may be obtained from the biographical notes of Appendix B; for example, an experienced instrument-maker such as Norman would probably make a better observer than King Charles. The main purpose of the biographical notes is to add some human flesh to the bare bones of the observations and to set them in context. While we have tried to make sure that the information in them is correct, it is very far from complete. Our sources of biographical data (which we do not quote) are many and various, but we rely heavily on the *Dictionary of National Biography* (Smith, Stephen & Lee 1967), Taylor (1954) and the Royal Society obituaries. No separate entries are made for the more recent observers, but a few personal details of some of these are given in the 'personnel' sections of the notes on observatory data.

## 6. Site differences

The data tabulated in Appendix A have been observed at some 50 different sites. Their distribution is shown in figure 1. All the sites can be enclosed in a circle of radius 36 km, and a good representation of the temporal changes in declination and dip is given by a plot of the listed observations against time. However, it is clear that, at least for some of the stations (e.g. Greenwich and Kew) there are site differences that greatly exceed the errors of observation, and it would do less than justice to the observations to plot them without some attempt to

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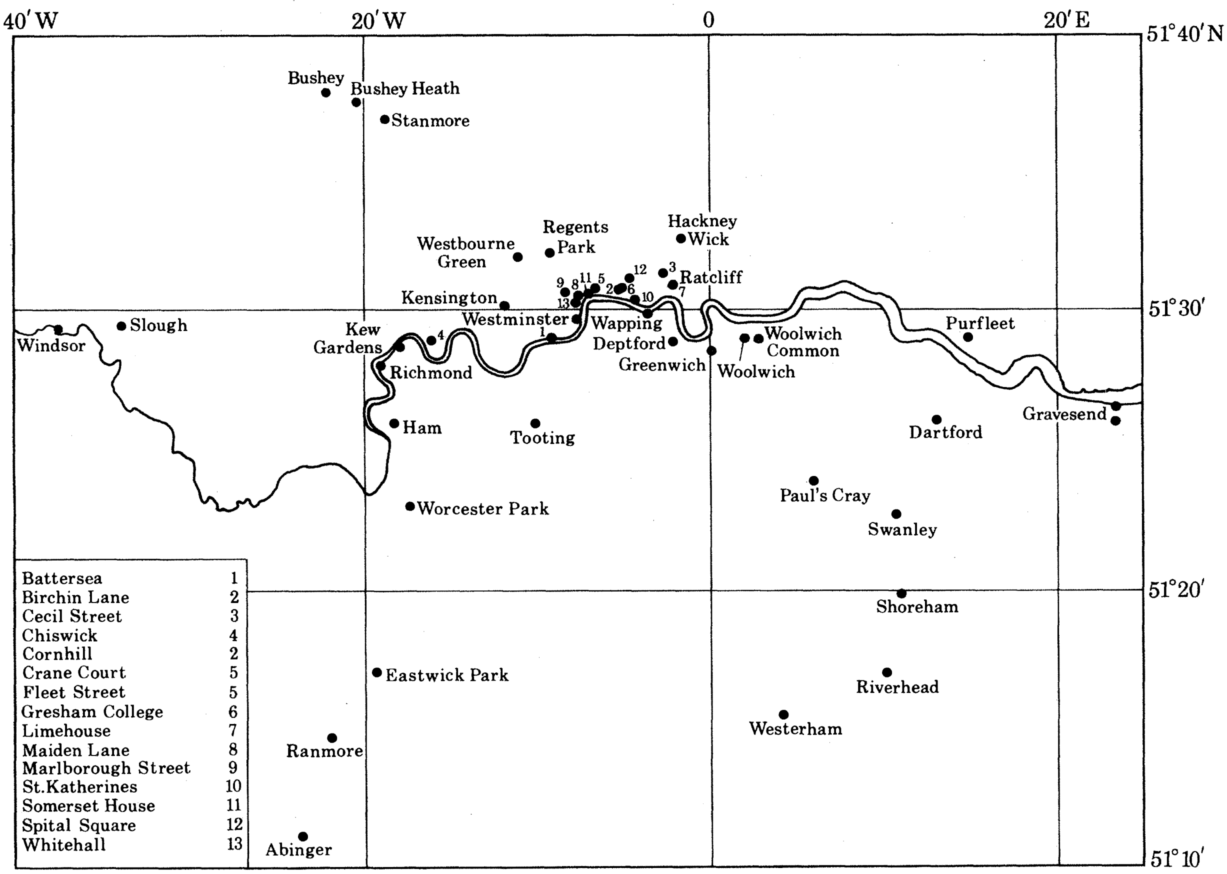


FIGURE 1. The sites of the observations.

adjust them to a common site. The site chosen is Greenwich, since the temporal distribution and quantity of observations made there are better than for any of the other sites.

The site differences are partly due to the gradient of the regional field and partly due to local anomalies, either natural or artificial. The effect of natural anomalies is unlikely to change greatly with time, but both the regional gradient and the artificial anomalies are liable to change. For example, the rapid decrease in dip as measured at Somerset House between 1790 and 1791 is largely due to the introduction of iron into the building.

Some estimate of the regional gradient can be obtained for those dates when observations were made at several sites at about the same time, e.g. 1835, 1890 and 1914, by fitting a simple model. However, the temporal changes in the parameters of such models are erratic, and removal of site differences based on the models does little to reduce the overall scatter amongst data from sites that did not contribute to the model. This suggests that the contribution of the regional gradient to site differences is small compared with that from local anomalies.

Since there is little we can do about temporal changes in artificial anomalies (except where they have been carefully monitored, as at Greenwich; see note 69), we have assumed that the site differences were constant over the period of observations at each site. The corrections that have to be applied to adjust the observations to Greenwich have been determined by inter-comparison of observations made at similar times at different sites. In most cases, the comparison is made directly with Greenwich data, but for several stations the route is indirect. Where there are contemporary estimates of site differences (e.g. by Canton (1759) and Cavendish (1776), see notes 53 and 56), these are accepted. For sites where a number of observations were made contemporaneously with observations at Greenwich, several estimates of the site difference are available, and the mean is adopted. In some cases there is only one observation from which a site correction can be obtained. When the correction is applied to that observation the value becomes identical with that observed at Greenwich and has no independence. However, this is of little importance since there are only a few such cases and they all occur at times when the Greenwich value is well defined by observatory data.

With one exception, the unknown corrections occur before 1780, when the absence of such corrections is of less importance because of the uncertainties in the observations. The exception is dip at Somerset House. This is a particularly difficult site since, as detailed in note 94, iron was introduced within 6 metres of the instrument in 1790 and the final few observations strongly suggest that the site was becoming yet more disturbed.

The corrections to Greenwich are given in table 2, together with the geographical coordinates and the interval over which observations were made for each site. An unknown correction is indicated by a question mark; a dash indicates that no observations were made of that element.

## 7. The corrected data

The data of tables A1 and A2 have been adjusted to Greenwich by using the corrections given in table 2, and plotted against time. Unknown site corrections are assumed to be zero, and the values tabulated in parentheses are omitted.

Declination is shown in figure 2 (pullout 1). The annual rate of change between 1620 and 1780 is remarkably steady at about 11′ west. There are no departures from this simple linear drift that cannot be ascribed to uncertainties in the data. Before 1600 the data suggest that the rate of change was smaller, and this may well be true. After 1780 the rate of change decreased rapidly to near zero, at which value it remained until about 1830. Since that date the secular change has been eastward at about 8′ $a^{-1}$, though with significant long-term departures from this value which are undoubtedly real. The short-term oscillations near 1840 are probably spurious, and the scatter near 1890 is the result of including survey observations, but the kink at 1970 is real and is clearly visible in data from all observatories in northern Europe.

The dip data are shown in figure 3 (pullout 2). They are much more scattered and less complete than those for declination, particularly before 1850, reflecting the difficulty in obtaining an accurate measure from a dip circle, and the lack of interest in dip compared with that in declination. Nevertheless, several trends can be seen. The dip increased to a maximum near 1720 and then decreased at a rather uniform rate of about 3′ $a^{-1}$ until 1860, after which the rate of decrease diminished. From 1910 to 1947 the dip showed a small, steady increase which changed rather suddenly after that date to a small decrease, which is still continuing.

The evidence for the initial increase in dip is strongly dependent on Norman's observation in 1576. He gives details of this which leave no doubt of his skill as an instrument maker and observer (Norman 1581), but it is still possible that his site was anomalous. However, it seems unlikely that the local anomaly could amount to the 2° required to reduce the rate of increase to zero, let alone to 9° which would be required to make the observation compatible with the post-1720 trend. The observations of Bond – another competent observer – tend to confirm the increase.

The section of the curve between 1786 and 1812 is based solely on Somerset House data. For the reasons given in §6, these data are believed to be unreliable, so the apparent jumps in dip during this interval are probably spurious.

Table 2. Site positions and site differences from Greenwich

| site | N. lat. 51°+ (′) | long. (′) | dates of observations | correction to Greenwich: declination (′) | correction to Greenwich: dip (′) |
|---|---|---|---|---|---|
| Abinger | 11.1 | 23.2 W | 1925–1957 | 12.8 E | +16.3 |
| | | | 1975 | — | +11.5 |
| Battersea | 29.0 | 9.0 W | 1670 | ? | — |
| Birchin Lane | 30.8 | 5.1 W | 1772 | — | ? |
| Bushey | 38.0 | 22.0 W | 1837–1838 | 5.7 E | — |
| Bushey Heath | 37.7 | 20.2 W | 1817–1822 | 15.6 E | — |
| Cecil Street | 31.4 | 2.5 W | 1773 | ? | ? |
| Chiswick | 29.0 | 16.0 W | 1828 | — | +4.0 |
| Cornhill | 30.8 | 5.1 W | 1772 | — | ? |
| Crane Court | 30.9 | 6.5 W | 1716–1780 | 7.0 W | ? |
| Dartford | 26.2 | 13.1 E | 1891 | 12.1 W | +1.3 |
| Deptford | 29.0 | 2.0 W | 1622–1634 | ? | — |
| Eastwick Park | 17.0 | 19.0 W | 1838 | — | +8.1 |
| Fleet Street | 30.9 | 6.5 W | 1723–1748 | 32.0 E | +21.0 |
| Gravesend | 26.6 | 23.4 E | 1576 | ? | — |
| Gravesend | 26.0 | 23.4 E | 1891 | 13.7 W | +5.6 |
| Greenwich | 28.6 | 0.0 | 1680–1900 | 0.0 | 0.0 |
| Greenwich | 28.6 | 0.3 E | 1901–1926, 1975 | 0.0 | 0.0 |
| Gresham College | 30.9 | 4.9 W | 1686–1702 | 9.0 W | ? |
| Ham | 26.0 | 18.0 W | 1833–1838 | — | −25.3 |
| Hackney Wick | 32.7 | 1.7 W | 1813–1815 | 7.4 W | — |
| Kensington | 30.2 | 11.7 W | 1834, 1835 | — | +8.2 |
| Kew | 29.0 | 18.0 W | 1720 | — | +5.0 |
| Kew Gardens | 29.0 | 18.0 W | 1838 | — | +2.0 |
| Limehouse | 31.0 | 2.0 W | 1580, 1600, 1622 | ? | — |
| Maiden Lane | 30.6 | 7.5 W | 1838 | — | −2.5 |
| Marlborough St. | 30.7 | 8.2 W | 1775 | 22.5 W | ? |
| Paul's Cray | 24.0 | 6.0 E | 1634 | ? | — |
| Purfleet | 29.1 | 15.0 E | 1888–1926 | 3.1 W | −0.8 |
| Ranmore | 14.6 | 21.6 W | 1888–1926 | 14.8 E | +12.9 |
| Ratcliff | 31.0 | 2.0 W | 1576 | — | ? |
| Regent's Park | 32.1 | 9.1 W | 1818–1854 | — | −0.9 |
| Richmond | 28.1 | 18.8 W | 1854–1924, 1975 | 23.1 E | −6.5 |
| Riverhead | 17.0 | 10.1 E | 1890 | 12.2 W | +12.2 |
| St. Katherine's | 30.4 | 4.2 W | 1586 | ? | — |
| Shoreham | 20.1 | 10.9 E | 1890 | 12.4 W | +9.2 |
| Slough | 29.5 | 33.7 W | 1936–1975 | 30.4 E | −5.0 |
| Somerset House | 30.7 | 6.9 W | 1786–1824 | 9.8 W | ? |
| Spital Square | 31.2 | 4.5 W | 1759 | 0.0 | — |
| Stanmore | 36.9 | 18.6 W | 1890 | 11.4 E | −7.5 |
| Swanley | 22.7 | 10.7 E | 1890 | 11.9 W | +5.8 |
| Tooting | 26.0 | 10.0 W | 1838 | — | +1.7 |
| Wanstead | 34.0 | 2.0 W | 1720 | — | −4.5 |
| Wapping | 30.0 | 3.5 W | 1666 | ? | — |
| Westbourne Green | 32.0 | 11.0 W | 1835–1838 | — | +2.6 |
| Westerham | 15.5 | 4.2 E | 1890 | 8.6 W | +12.5 |
| Westminster | 30.0 | 7.6 W | 1837 | — | 0.0 |
| Whitehall | 30.3 | 7.6 W | 1664–1669 | ? | — |
| Windsor | 29.4 | 37.4 W | 1888–1926 | 34.2 E | −7.4 |
| Woolwich | 29.0 | 2.0 E | 1830–1857 | 1.5 E | 0.0 |
| Woolwich Common | 29.0 | 3.0 E | 1822–1825 | — | 0.0 |
| Worcester Park | 23.0 | 17.0 W | 1838 | — | +8.5 |

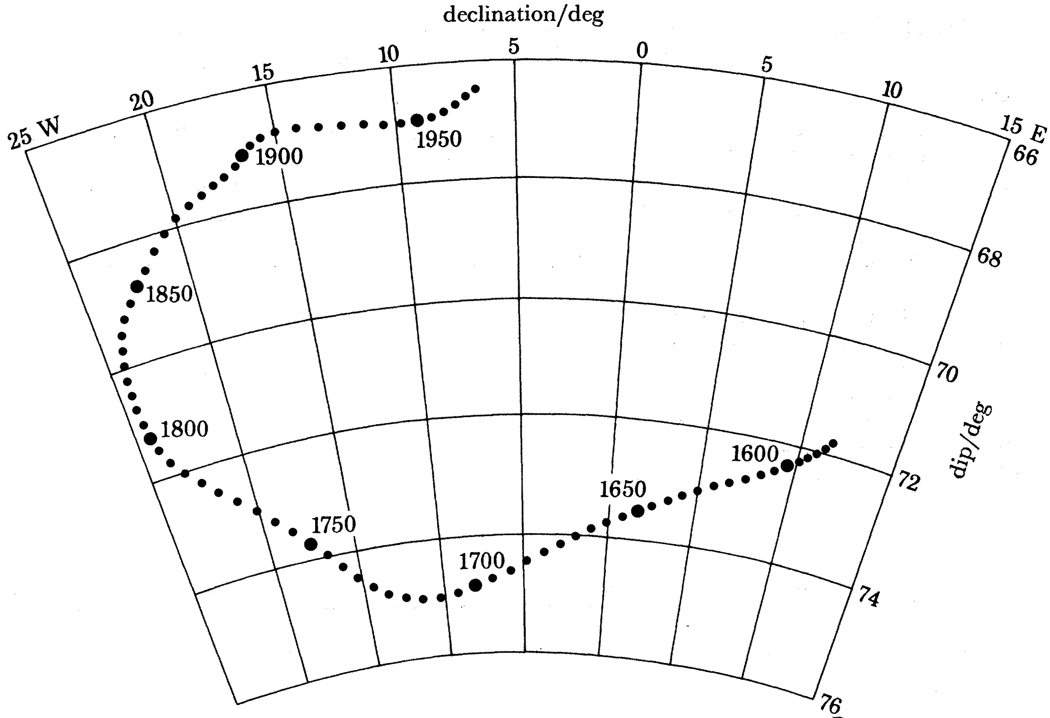


FIGURE 4. The direction of the Earth's magnetic field at Greenwich, zenithal equidistant projection. The points, plotted for every fifth year, are from spline fitting of the data shown in figures 1 and 2.

After Bauer (1895), we have plotted both declination and dip on a polar diagram to show the motion of the north-seeking end of a freely suspended magnetic needle (figure 4). The points are plotted at five-year intervals, with every tenth point drawn larger, to give some indication of the rate at which the curve is described. The way in which the five-yearly values were interpolated from the data is explained in the next section. The curve is more erratic than that of Bauer and much less suggestive of a periodic variation. However, it is a more realistic representation, since it is based on many more data and does not involve extrapolation.

## 8. Discussion

The information available on declination and dip in London is summarized in figures 2 and 3, but for many purposes it is more convenient to have a continuous curve rather than the isolated points defined by the observations. Such a curve should be produced objectively as far as possible and should take account of the relative uncertainties of the observations. Since we have no *a priori* knowledge of the mathematical form of the curve, we have chosen to use least-squares spline functions, following Reinsch (1967). The data have been weighted from 0 to 10 as indicated in table 3. The weights are assigned subjectively, taking account of the method of observation and reduction, quality of instrumentation, number of individual observations, experience of the observer, and uncertainty of the site correction. It is solely because of this last factor that the dip observations at Somerset House are given zero weight. Having assigned the weights, we still have the degree of smoothing as a free parameter. Spline fitting finds the smoothest curve in a well defined sense subject to the misfit parameter $S$ being equal to a

Table 3. The weights assigned to the observations

(The observations are referred to by the note numbers that appear in the final columns of tables A 1 and A 2, with further qualification in parenthesis.)

| weight | note number |
|---|---|
| 0 | 1, 2, 3, 11, 14, 20, 21 (dip only), 23, 25, 26, 28, 38–41, 48–50, 57–59, 60 (dip only), 62, 69 (1864), 71, 73, 79–81, 85, 86, 87 (first 2), 91, 93, 94, 100, 102 |
| 1 | 4–10, 12, 13, 15–19, 21 (declination only), 24, 27, 29–37, 42–44, 52, 54, 55 (1774, 1775), 56, 65–67, 82–84, 87 (last 3), 90, 92, 95–99, 103–106, 107 (single observers), 108, 109 (Regent's Park) |
| 2 | 22, 46, 47, 51, 55 (1776–1780), 72, 78, 88, 89, 101, 107 (more than one observer), 110, 111 |
| 3 | 74, 75 |
| 4 | 53, 59, 60 (declination only), 61, 63, 64, 68, 69 (1840–1845), 70 (1842) |
| 5 | 69 (1846, 1847), 76 (1957), 77, 109 (Richmond) |
| 6 | 69 (1848, 1849) |
| 7 | 69 (1850, 1851) |
| 8 | 69 (1852, 1853), 70 (1856) |
| 9 | 69 (1854, 1855), 70 (1857, 1858) |
| 10 | 69 (1856–1926), 70 (1859–1924), 76 (1925–1956) |

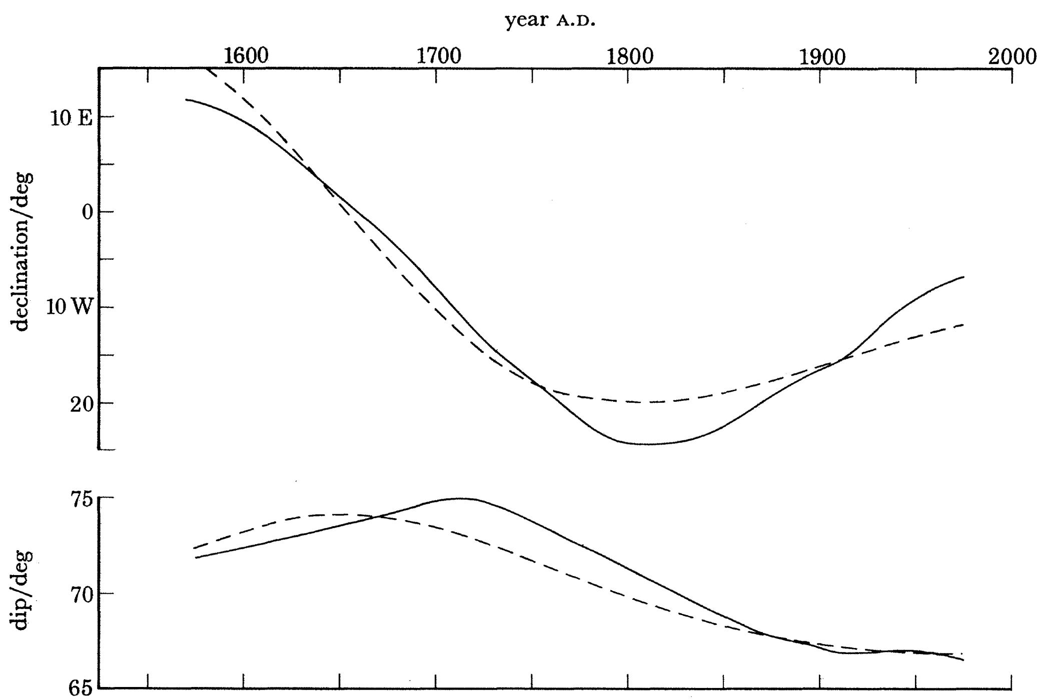


Figure 5. Spline fitting of the data corrected to Greenwich (continuous curves). Westward-drifting dipole model (dashed curves).

specified value; $S$ is the weighted sum of squared residuals and is analogous to $\chi^2$; smoothness is quantified by the integral of the square of the second derivative. The degree of smoothing has been chosen empirically to give a curve that closely reproduces the observatory data without introducing improbable features in the earlier years. The chosen values of $S$ are 0.05 for declination, and 0.025 for dip, corresponding to a standard deviation of $S^{\frac{1}{2}\circ}$ for an observation of unit weight. The resulting curves are shown by the solid lines of figure 5. Figure 4 is based on these curves, with the use of the value calculated for every fifth year.

Having thus obtained an equal-interval representation of the data, it is of interest to examine its harmonic content, but first we need to remove some of the long-term trends. Again, this is conveniently done via the spline functions by choosing a large value of $S$ to give a very smooth curve. Figure 6 shows the power spectrum of the difference between the smooth and the less smooth spline functions, based on five-year values and tapered with a triangular filter. We have used only the last 250 years because of the sparseness and uncertainty of the earlier observations. The main feature of these spectra is the absence of any obvious lines. In particular, there is no evidence of the 60-year line commonly suggested in analyses of much shorter series of data (e.g. Currie 1973). The absence of an 11-year line, corresponding to the sunspot cycle, is entirely due to the smoothing process. That such a variation is present in the original data is clearly shown by the residuals of the observatory data from the smooth curve.

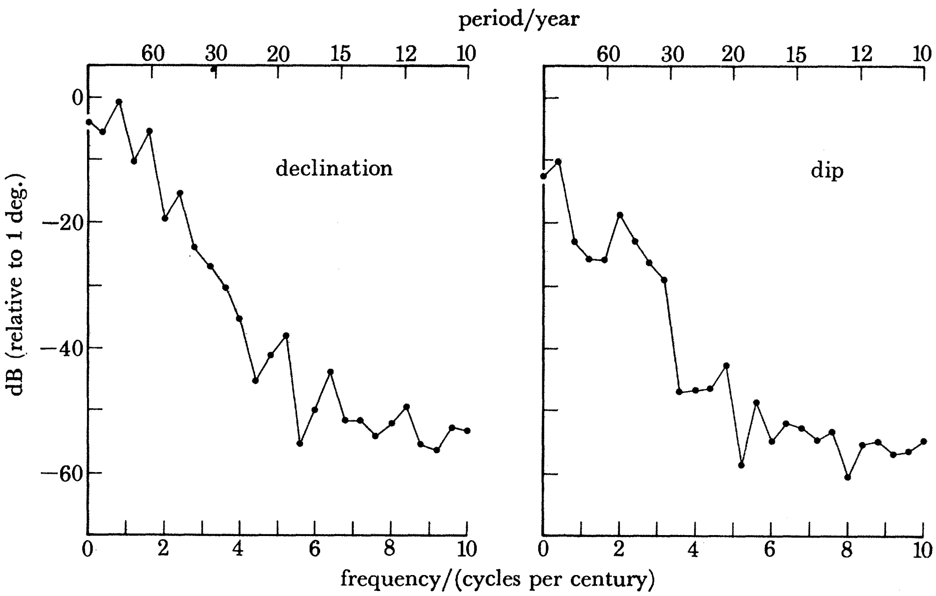


FIGURE 6. Power spectra of five-year values from spline fitting of the data corrected to Greenwich for the last 250 years.

The overall pattern, with dip showing a maximum at about the time when declination is decreasing most rapidly, is highly suggestive of an electrical eddy current drifting westwards near the core surface. As a crude model, we may approximate the Earth's main magnetic field by a centred axial dipole of unit moment, and the field due to the eddy by a radial dipole at the surface of the core drifting westwards at a uniform rate at the latitude of London. The north, east and vertical components of the magnetic field (and hence declination and dip) at London due to these two dipoles can be obtained by differentiating the expressions for the potential of an eccentric dipole given by Hurwitz (1960). The best fit (shown by the broken lines of figure 5) is given by a dipole of moment $-0.03$ with a westward drift of 0.17° per year that is immediately below London in 1634. For such a crude model the fit to the data is remarkably good. It could be greatly improved by representing the main field with an eccentric dipole, changing the depth of the 'eddy' dipole, and allowing the drift rate and intensity to vary with time. However, there seems little point in introducing such refinements into a discussion of data from a single site.

The only other site for which there is a comparable series of declination and dip data is Paris, and we plan to publish a similar study of these data in the near future. A comparison of the London and Paris curves should give a much clearer picture of the eddy current and its movements. It should also help to establish the reality of earlier features of the curve, and the geographical extent of the later ones.

We are particularly grateful to Professor R. L. Parker for advice and practical assistance in the analysis of the data. We are also greatly indebted to the librarians of the British Library, Huntington Library, Royal Astronomical Society, Royal Greenwich Observatory, Royal Observatory Edinburgh and the Royal Society for their help. The work was completed while one of us (S.R.C.M.) was a Green Scholar at the Scripps Institution of Oceanography.

## Appendix A. Tables of declination and dip observations, and associated notes

Table A1. Declination ($D$) (east until 1661, then west)

| date | $D$ | observer | site | note |
|---|---|---|---|---|
| 1540 | (7.2° E) | — | — | 2 |
| 1550 | (11° 13′ E) | — | — | 3 |
| 1560 | (9.6° E) | — | — | 2 |
| *ca.* 1570 | ($\approx 4\frac{1}{2}$° E) | — | — | 1 |
| *ca.* 1570 | $\approx 11\frac{1}{4}$° E | Digges? | — | 4 |
| | ° ′ ″ | | | |
| 1576.5 | 11 30 E | Frobisher | Gravesend | 5 |
| *ca.* 1580 | 11 15 E | Norman | — | 6 |
| 1580.8 | 11 19 E | Borough | Limehouse | 7 |
| 1581.6 | 10 49 E | ,, | ,, | 8 |
| 1586 | 10 38 45 E | Polter | St Katherine's? | 9 |
| 1600 | (9 16 E) | — | — | 3 |
| *ca.* 1600 | 11 00 E | — | Limehouse | 10 |
| 1612 | (6 10 E) | — | — | 11 |
| *ca.* 1622 | 6 15 E | Gunter | Deptford | 12 |
| 1622.5 | 5 $56\frac{1}{2}$ E | ,, | Limehouse | 13 |
| *ca.* 1632 | < 6 15 E | Marr | Whitehall | 14 |
| 1633.5 | < 5 E | Gellibrand | Deptford | 14 |
| 1634.4 | 4 5 E | ,, | ,, | 15 |
| 1634.5 | 3 57 E | ,, | Paul's Cray | 16 |
| 1640 | 3 6 40 E | Bond *et al.* | — | 17 |
| 1648 | 2 0 E | Bond | — | 18 |
| 1657.5 | 0 0 | ,, | — | 19 |
| 1661 | (11) | — | — | 20 |
| | After this, all declinations are to the west | | | |
| | ° ′ ″ | | | |
| 1661.5 | 0 45 30 | — | — | 21 |
| 1664.5 | 0 | Moray *et al.* | Whitehall | 22 |
| 1665.4 | 0 | King Charles II | ,, | 23 |
| 1665.4 | 1 22 30 | Bond *et al.* | ,, | 24 |
| 1666.4 | 0 36 | Sellar | Wapping | 25 |
| 1666.5 | (1 35 36) | Bond | — | 26 |
| 1668 | 1 56 | ,, | — | 27 |
| 1669 | < $\frac{1}{2}$ | Boyle | Whitehall? | 28 |
| 1670.4 | 2 6 | Millet | Battersea | 29 |


PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Table A1 (*continued*)

| date | D ° | D ′ | observer | site | note |
|---|---|---|---|---|---|
| 1672 | 2 | 30 | Halley | — | 30 |
| 1680.1 | 4 | 8 | Flamsteed | Greenwich | 31 |
| 1683 | 4 | 30 | Halley | — | 32 |
| 1686.5 | 4 | 45 | ,, | Gresham College | 33 |
| 1687.5 | 5 | | Royal Society | ,, ,, | 34 |
| 1688.5 | 4 | | ,, ,, | ,, ,, | 34 |
| 1690.3 | 5½ | | ,, ,, | ,, ,, | 34 |
| 1691.6 | 5 | 50 | ,, ,, | ,, ,, | 34 |
| 1692.3 | 6 | | ,, ,, | ,, ,, | 34 |
| 1692.4 | 6 | 0 | Halley | ,, ,, | 35 |
| 1693.1 | 6 | 30 | Flamsteed | Greenwich | 36 |
| 1693.4 | 6 | 20 | Royal Society | Gresham College | 34 |
| 1694.5 | 6 | 30 | ,, ,, | ,, ,, | 34 |
| 1695.4 | 6 | 50 | ,, ,, | ,, ,, | 34 |
| 1696.6 | 6 | 55 | ,, ,, | ,, ,, | 34 |
| 1698 | 7 | 0 | Cassini & Flamsteed | Greenwich | 37 |
| 1698.5 | 7 | 25 | Flamsteed | ,, | 36 |
| 1698.8 | 7 | | Halley | River Thames | 38 |
| 1699.6 | 7 | 30 | Flamsteed | Greenwich | 36 |
| 1700 | (7 | 12) | — | — | 39 |
| 1700 | (7 | 45) | — | — | 40 |
| 1700 | (8 | 0) | — | — | 11 |
| 1700 | (9 | 40) | — | — | 41 |
| 1701.3 | 7 | 50 | Halley | Gresham College | 42 |
| 1702.5 | 8 | 30 | ,, | ,, ,, | 43 |
| 1707.5 | 9 | 38 | Royal Society | ,, ,, | 34 |
| 1708.5 | 10 | 10 | ,, ,, | ,, ,, | 34 |
| 1709.5 | 10¾ | | ,, ,, | ,, ,, | 34 |
| 1709.5 | 10 | 30 | ,, ,, | ,, ,, | 34 |
| 1710.5 | 10 | 40 | ,, ,, | ,, ,, | 34 |
| 1710.5 | 10 | 12 | Flamsteed | Greenwich | 36 |
| 1711.1 | 10 | 22 | ,, | ,, | 36 |
| 1716.4 | 12 | 0 | Halley | Crane Court | 44 |
| 1716.5 | 11 | 15 | Flamsteed | Greenwich | 36 |
| 1717 | (10 | 42) | — | — | 11 |
| 1719.3 | 11½ | | Royal Society | Crane Court | 34 |
| 1720 | (13 | 0) | — | — | 45 |
| 1720 | (13 | 10) | — | — | 41 |
| 1722.7 | ≈ 13 | 48 | Graham | Crane Court | 46 |
| 1723.0 | 14 | 9 | ,, | Fleet Street | 46 |
| 1723.2 | 14 | 17 | ,, | ,, ,, | 47 |
| 1724 | (11 | 45) | — | — | 11 |
| 1725 | (11 | 56) | — | — | 11 |
| 1730 | (13 | 0) | — | — | 11 |
| 1735 | (14 | 16) | — | — | 11 |
| 1740 | (15 | 40) | — | — | 48 |
| 1740 | (16 | 0) | — | — | 49 |
| 1740 | (16 | 10) | — | — | 11 |
| (1744) | (16 | 30) | — | — | 50 |
| 1745.2 | 17 | 0 | Graham | Fleet Street | 51 |
| 1745 | (16 | 53) | — | — | 11 |
| 1746.5 | 17 | 16 | Graham | Fleet Street | 51 |
| 1747.6 | 17 | 35 | ,, | ,, ,, | 51 |
| 1748.0 | 17 | 40 | ,, | ,, ,, | 51 |
| 1749.0 | 17 | 22½ | Bradley | Greenwich | 52 |
| 1750 | (17 | 54) | — | — | 11 |
| 1750 | (17 | 22) | — | — | 40 |
| 1750.5 | 17 | 25 | Bradley | Greenwich | 52 |
| 1752.7 | 17 | 55 | ,, | ,, | 52 |



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

TABLE A1 (*continued*)

| date | D ° | ′ | ″ | observer | site | note |
|---|---|---|---|---|---|---|
| 1754.5 | 18 | 3 | | Bradley | Greenwich | 52 |
| 1756.9 | 18 | 33 | | ,, | ,, | 52 |
| 1757.6 | 18 | 32½ | | ,, | ,, | 52 |
| 1759.5 | 19 | 3 | | Canton | Spital Square | 53 |
| 1760 | (19 | 12) | | — | — | 11 |
| 1760 | (19 | 30) | | — | — | 41 |
| 1765 | (20 | 0) | | — | — | 11 |
| 1770 | (20 | 35) | | — | — | 11 |
| 1770 | (19 | 57) | | — | — | 40 |
| 1773 | 21 | 9 | | Heberden | Cecil Street? | 54 |
| 1774 | (21 | 3) | | — | — | 11 |
| 1774 | (22 | 20) | | — | — | 41 |
| 1774.7 | 21 | 16 | | Royal Society | Crane Court | 55 |
| 1775 | (21 | 30) | | — | — | 11 |
| 1775.5 | 21 | 43 | | Royal Society | Crane Court | 55 |
| 1775.6 | 21 | 30½ | | Cavendish | Marlborough Street | 56 |
| 1775.6 | 21 | 46½ | | ,, | Crane Court | 56 |
| 1776.5 | 21 | 47 | | Royal Society | ,, ,, | 55 |
| 1777.5 | 22 | 12 | | ,, ,, | ,, ,, | 55 |
| 1778.5 | 22 | 11 | | ,, ,, | ,, ,, | 55 |
| 1778 | 19 | 20 | | Middleton | — | 57 |
| 1779.5 | 22 | 20 | | Royal Society | Crane Court | 55 |
| 1780.5 | 22 | 31½ | | ,, ,, | ,, ,, | 55 |
| 1785 | (22 | 50) | | — | — | 58 |
| 1786.8 | 23 | 17.6 | | Gilpin | Somerset House | 59 |
| 1787.5 | 23 | 21.1 | | ,, | ,, ,, | 59 |
| 1788.4 | 23 | 29.1 | | ,, | ,, ,, | 59 |
| 1789.7 | 23 | 37.7 | | ,, | ,, ,, | 59 |
| 1790.3 | 23 | 39.0 | | ,, | ,, ,, | 59 |
| 1791.3 | 23 | 36.1 | | ,, | ,, ,, | 59 |
| 1792.6 | 23 | 43.9 | | ,, | ,, ,, | 59 |
| 1793.5 | 23 | 49.5 | | ,, | ,, ,, | 59 |
| 1794.5 | 23 | 56.0 | | ,, | ,, ,, | 59 |
| 1795.6 | 23 | 58.3 | | ,, | ,, ,, | 59 |
| 1796.6 | 24 | 0.1 | | ,, | ,, ,, | 59 |
| 1797.6 | 24 | 0.9 | | ,, | ,, ,, | 59 |
| 1798.6 | 24 | 0.6 | | ,, | ,, ,, | 59 |
| 1799.6 | 24 | 1.7 | | ,, | ,, ,, | 59 |
| 1800 | (24 | 36) | | — | — | 59 |
| 1800.6 | 24 | 3.1 | | Gilpin | Somerset House | 59 |
| 1801.6 | 24 | 4.3 | | ,, | ,, ,, | 59 |
| 1802.6 | 24 | 6.7 | | ,, | ,, ,, | 59 |
| 1803.6 | 24 | 8.8 | | ,, | ,, ,, | 59 |
| 1804.6 | 24 | 8.3 | | ,, | ,, ,, | 59 |
| 1805.6 | 24 | 8.7 | | ,, | ,, ,, | 59 |
| 1806.5 | 24 | 8.6 | | Royal Society | ,, ,, | 60 |
| 1807.7 | 24 | 10.2 | | ,, ,, | ,, ,, | 60 |
| 1808.5 | 24 | 10 | | ,, ,, | ,, ,, | 60 |
| 1809.5 | 24 | 11 | | ,, ,, | ,, ,, | 60 |
| 1811.7 | 24 | 14 | 2 | ,, ,, | ,, ,, | 60 |
| 1812.8 | 24 | 16 | 30 | ,, ,, | ,, ,, | 60 |
| 1813.6 | 24 | 17 | 23 | Beaufoy | Hackney Wick | 61 |
| 1813.7 | 24 | 16 | 40 | Royal Society | Somerset House | 60 |
| 1814.5 | 24 | 19 | 5 | ,, ,, | ,, ,, | 60 |
| 1814.5 | 24 | 17 | 40 | Beaufoy | Hackney Wick | 61 |
| 1815 | (27 | 18) | | — | — | 41 |
| 1815 | (24 | 27) | | — | — | 62 |
| 1815.4 | 24 | 19 | 37 | Beaufoy | Hackney Wick | 61 |
| 1815.5 | 24 | 17 | 50 | Royal Society | Somerset House | 60 |



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

TABLE A1 (*continued*)

| date | *D* ° | ′ | ″ | observer | site | note |
|---|---|---|---|---|---|---|
| 1816.5 | 24 | 17 | 54 | Royal Society | Somerset House | 60 |
| 1817.5 | 24 | 17 | | ,, ,, | ,, ,, | 60 |
| 1817.6 | 24 | 36 | 4 | Beaufoy | Bushey Heath | 61 |
| 1817.9 | 24 | 12 | | Pond | Greenwich | 63 |
| 1818.5 | 24 | 15 | 43 | Royal Society | Somerset House | 60 |
| 1818.5 | 24 | 38 | 24 | Beaufoy | Bushey Heath | 61 |
| 1818.7 | 24 | 19 | | Pond | Greenwich | 64 |
| 1819.5 | 24 | 36 | 14 | Beaufoy | Bushey Heath | 61 |
| 1819.5 | 24 | 21 | | Pond | Greenwich | 64 |
| 1819.5 | 24 | 14 | 47 | Royal Society | Somerset House | 60 |
| 1820 | (24 | 11) | | — | — | 62 |
| 1820.5 | 24 | 21 | | Pond | Greenwich | 64 |
| 1820.5 | 24 | 34 | 30 | Beaufoy | Bushey Heath | 61 |
| 1820.5 | 24 | 11 | 44 | Royal Society | Somerset House | 60 |
| 1821.5 | 24 | 11 | 18 | ,, ,, | ,, ,, | 60 |
| 1821.5 | 24 | 22 | | Pond | Greenwich | 64 |
| 1822.2 | 24 | 31 | 00 | Beaufoy | Bushey Heath | 61 |
| 1822.5 | 24 | 23 | | Pond | Greenwich | 64 |
| 1822.5 | 24 | 9 | 55 | Royal Society | Somerset House | 60 |
| 1823.5 | 24 | 9 | 48 | ,, ,, | ,, ,, | 60 |
| 1823.5 | 24 | 23 | | Pond | Greenwich | 64 |
| 1824.2 | 24 | 24 | | ,, | ,, | 64 |
| 1824.5 | 24 | 9 | 33 | Royal Society | Somerset House | 60 |
| 1831 | (24 | 0) | | — | — | 41 |
| 1831.5 | 24 | 12 | | Foster | Woolwich | 65 |
| 1837.5 | 23 | 59 | | Ross | Bushey | 66 |
| 1838.3 | 23 | 59.4 | | ,, | ,, | 67 |
| 1839.5 | 23 | 44.6 | | Royal Observatory | Greenwich | 68 |
| 1840.5 | 23 | 33.8 | | ,, ,, | ,, | 68 |
| 1840.9 | 23 | 22.0 | | ,, ,, | ,, | 69 |
| 1841.5 | 23 | 16.2 | | ,, ,, | ,, | 69 |
| 1842.5 | 23 | 14.6 | | ,, ,, | ,, | 69 |
| 1842.5 | 23 | 13 | | Kew ,, | Richmond | 70 |
| 1843.5 | 23 | 11.7 | | Royal ,, | Greenwich | 69 |
| 1844.5 | 23 | 15.3 | | ,, ,, | ,, | 69 |
| 1845.5 | 22 | 56.7 | | ,, ,, | ,, | 69 |
| 1846.5 | 22 | 49.6 | | ,, ,, | ,, | 69 |
| 1847.5 | 22 | 51.3 | | ,, ,, | ,, | 69 |
| 1848.5 | 22 | 51.8 | | ,, ,, | ,, | 69 |
| 1849.5 | 22 | 37.8 | | ,, ,, | ,, | 69 |
| 1850 | (22 | 29) | | — | ,, | 71 |
| 1850.5 | 22 | 23.5 | | Royal Observatory | ,, | 69 |
| 1851.5 | 22 | 18.3 | | ,, ,, | ,, | 69 |
| 1852.5 | 22 | 17.9 | | ,, ,, | ,, | 69 |
| 1853.5 | 22 | 10.1 | | ,, ,, | ,, | 69 |
| 1854.5 | 22 | 0.8 | | ,, ,, | ,, | 69 |
| 1855.5 | 21 | 48.4 | | ,, ,, | ,, | 69 |
| 1856.5 | 21 | 43.5 | | ,, ,, | ,, | 69 |
| 1857.0 | 21 | 46 | | Evans | Woolwich | 72 |
| 1857.5 | 21 | 35.4 | | Royal Observatory | Greenwich | 69 |
| 1858.5 | 21 | 30.3 | | ,, ,, | ,, | 69 |
| 1858.5 | 21 | 54 | 8.0 | Kew ,, | Richmond | 70 |
| 1859.5 | 21 | 47 | 22.1 | ,, ,, | ,, | 70 |
| 1859.5 | 21 | 23.5 | | Royal ,, | Greenwich | 69 |
| 1860.5 | 21 | 14.3 | | ,, ,, | ,, | 69 |
| 1860.5 | 21 | 39 | 51.1 | Kew ,, | Richmond | 70 |
| 1861.5 | 21 | 31 | 36.4 | ,, ,, | ,, | 70 |
| 1861.5 | 21 | 5.5 | | Royal ,, | Greenwich | 69 |
| 1862.5 | 20 | 52.6 | | ,, ,, | ,, | 69 |

TABLE A1 (*continued*)

| date | D ° | ′ | ″ | observer | | site | note |
|---|---|---|---|---|---|---|---|
| 1862.5 | 21 | 23 | 32.8 | Kew Observatory | | Richmond | 70 |
| 1863.5 | 21 | 13 | 16 | ,, | ,, | ,, | 70 |
| 1863.5 | 20 | 45.9 | | Royal | ,, | Greenwich | 69 |
| 1864.5 | (20 | 40) | | ,, | ,, | ,, | 69 |
| 1864.5 | 21 | 3 | 35 | Kew | ,, | Richmond | 70 |
| 1865.5 | 20 | 59 | 3 | ,, | ,, | ,, | 70 |
| 1865.5 | 20 | 33.9 | | Royal | ,, | Greenwich | 69 |
| 1866.5 | 20 | 28.0 | | ,, | ,, | ,, | 69 |
| 1866.5 | 20 | 51 | 10 | Kew | ,, | Richmond | 70 |
| 1867.5 | 20 | 40 | 26 | ,, | ,, | ,, | 70 |
| 1867.5 | 20 | 20.5 | | Royal | ,, | Greenwich | 69 |
| 1868.5 | 20 | 13.1 | | ,, | ,, | ,, | 69 |
| 1868.5 | 20 | 33 | 9 | Kew | ,, | Richmond | 70 |
| 1869.5 | 20 | 26 | 24 | Whipple | | ,, | 70 |
| 1869.5 | 20 | 4.1 | | Royal Observatory | | Greenwich | 69 |
| 1870.5 | 19 | 53.0 | | ,, | ,, | ,, | 69 |
| 1870.5 | 20 | 18 | 52 | Whipple | | Richmond | 70 |
| 1871.5 | 20 | 10 | 31 | ,, | | ,, | 70 |
| 1871.5 | 19 | 41.9 | | Royal Observatory | | Greenwich | 69 |
| 1872.5 | 19 | 36.8 | | ,, | ,, | ,, | 69 |
| 1872.5 | 20 | 7.2 | | Whipple | | Richmond | 70 |
| 1873.5 | 19 | 58.1 | | ,, | | ,, | 70 |
| 1873.5 | 19 | 33.4 | | Royal Observatory | | Greenwich | 69 |
| 1874.5 | 19 | 28.8 | | ,, | ,, | ,, | 69 |
| 1874.5 | 19 | 50.4 | | Whipple | | Richmond | 70 |
| 1875.5 | 19 | 41.4 | | ,, | | ,, | 70 |
| 1875.5 | 19 | 6 | | — | | — | 73 |
| 1875.5 | 19 | 21.2 | | Royal Observatory | | Greenwich | 69 |
| 1876.5 | 19 | 8.3 | | ,, | ,, | ,, | 69 |
| 1876.5 | 19 | 4 | | — | | — | 73 |
| 1876.5 | 19 | 31.9 | | Figg & Whipple | | Richmond | 70 |
| 1877.5 | 19 | 22.4 | | Figg | | ,, | 70 |
| 1877.5 | 18 | 57.2 | | Royal Observatory | | Greenwich | 69 |
| 1878.5 | 18 | 49.3 | | ,, | ,, | ,, | 69 |
| 1878.5 | 19 | 13.8 | | Figg | | Richmond | 70 |
| 1879.0 | 18 | 41 | | — | | — | 73 |
| 1879.5 | 19 | 6.2 | | Figg | | Richmond | 70 |
| 1879.5 | 18 | 40.5 | | Royal Observatory | | Greenwich | 69 |
| 1880.5 | 18 | 32.5 | | ,, | ,, | ,, | 69 |
| 1880.5 | 18 | 58.0 | | Figg | | Richmond | 70 |
| 1881.5 | 18 | 50.5 | | ,, | | ,, | 70 |
| 1881.5 | 18 | 27.1 | | Royal Observatory | | Greenwich | 69 |
| 1882.5 | 18 | 22.3 | | ,, | ,, | ,, | 69 |
| 1882.5 | 18 | 44.8 | | Figg | | Richmond | 70 |
| 1883.5 | 18 | 40.0 | | Figg & Baker | | ,, | 70 |
| 1883.5 | 18 | 15.0 | | Royal Observatory | | Greenwich | 69 |
| 1884.5 | 18 | 7.6 | | ,, | ,, | ,, | 69 |
| 1884.5 | 18 | 32.1 | | Baker | | Richmond | 70 |
| 1885.5 | 18 | 24.7 | | ,, | | ,, | 70 |
| 1885.5 | 18 | 1.7 | | Royal Observatory | | Greenwich | 69 |
| 1886.5 | 17 | 54.7 | | ,, | ,, | ,, | 69 |
| 1886.5 | 18 | 16.9 | | Baker | | Richmond | 70 |
| 1887.5 | 18 | 12.5 | | ,, | | ,, | 70 |
| 1887.5 | 17 | 49.1 | | Royal Observatory | | Greenwich | 69 |
| 1888.3 | 17 | 38.2 | | Rücker | | Purfleet | 74 |
| 1888.4 | 17 | 51.5 | | Thorpe | | Ranmore | 74 |
| 1888.4 | 18 | 12.2 | | ,, | | Windsor | 74 |
| 1888.5 | 17 | 40.4 | | Royal Observatory | | Greenwich | 69 |
| 1888.5 | 18 | 6.7 | | Baker | | Richmond | 70 |

TABLE A1 (*continued*)

| date | D ° | D ′ | observer | site | note |
|---|---|---|---|---|---|
| 1889.4 | 17 | 58.8 | Baker | Richmond | 70 |
| 1889.5 | 17 | 34.9 | Royal Observatory | Greenwich | 69 |
| 1890.5 | 17 | 28.6 | ,, ,, | ,, | 69 |
| 1890.5 | 17 | 50.6 | Baker | Richmond | 70 |
| 1890.5 | 17 | 20.0 | Briscoe | Westerham | 75 |
| 1890.5 | 17 | 16.7 | Gray | Swanley | 75 |
| 1890.5 | 17 | 16.4 | Thorpe & Gray | Riverhead | 75 |
| 1890.5 | 17 | 16.2 | Briscoe | Shoreham | 75 |
| 1890.6 | 17 | 39.5 | Rucker & Thorpe | Stanmore | 75 |
| 1891.3 | 17 | 10.8 | Watson | Gravesend | 75 |
| 1891.3 | 17 | 12.3 | ,, | Dartford | 75 |
| 1891.5 | 17 | 41.9 | Baker & R. S. Whipple | Richmond | 70 |
| 1891.5 | 17 | 23.4 | Royal Observatory | Greenwich | 69 |
| 1892.5 | 17 | 17.4 | ,, ,, | ,, | 69 |
| 1892.5 | 17 | 36.7 | Baker & R. S. Whipple | Richmond | 70 |
| 1893.5 | 17 | 28.8 | ,, ,, | ,, | 70 |
| 1893.5 | 17 | 11.4 | Royal Observatory | Greenwich | 69 |
| 1894.5 | 17 | 4.6 | ,, ,, | ,, | 69 |
| 1894.5 | 17 | 23.0 | Baker & Boxall | Richmond | 70 |
| 1895.5 | 17 | 16.8 | ,, ,, | ,, | 70 |
| 1895.5 | 16 | 57.4 | Royal Observatory | Greenwich | 69 |
| 1896.5 | 16 | 51.7 | ,, ,, | ,, | 69 |
| 1896.5 | 17 | 10.8 | Baker & Boxall | Richmond | 70 |
| 1897.5 | 17 | 6.4 | ,, ,, | ,, | 70 |
| 1897.5 | 16 | 45.8 | Royal Observatory | Greenwich | 69 |
| 1898.5 | 16 | 39.2 | ,, ,, | ,, | 69 |
| 1898.5 | 17 | 1.4 | Baker & Boxall | Richmond | 70 |
| 1899.5 | 16 | 57.1 | ,, ,, | ,, | 70 |
| 1899.5 | 16 | 34.2 | Royal Observatory | Greenwich | 69 |
| 1900.5 | 16 | 29.0 | ,, ,, | ,, | 69 |
| 1900.5 | 16 | 52.7 | Baker & Boxall | Richmond | 70 |
| 1901.5 | 16 | 48.9 | Kew Observatory | ,, | 70 |
| 1901.5 | 16 | 26.0 | Royal Observatory | Greenwich | 69 |
| 1902.5 | 16 | 22.8 | ,, ,, | ,, | 69 |
| 1902.5 | 16 | 44.8 | Kew ,, | Richmond | 70 |
| 1903.5 | 16 | 40.5 | ,, ,, | ,, | 70 |
| 1903.5 | 16 | 19.1 | Royal ,, | Greenwich | 69 |
| 1904.5 | 16 | 15.0 | ,, ,, | ,, | 69 |
| 1904.5 | 16 | 37.9 | Kew ,, | Richmond | 70 |
| 1905.5 | 16 | 32.9 | ,, ,, | ,, | 70 |
| 1905.5 | 16 | 9.9 | Royal ,, | Greenwich | 69 |
| 1906.5 | 16 | 3.6 | ,, ,, | ,, | 69 |
| 1906.5 | 16 | 28.5 | Kew ,, | Richmond | 70 |
| 1907.5 | 16 | 23.1 | ,, ,, | ,, | 70 |
| 1907.5 | 15 | 59.8 | Royal ,, | Greenwich | 69 |
| 1908.5 | 15 | 53.5 | ,, ,, | ,, | 69 |
| 1908.5 | 16 | 16.9 | Kew ,, | Richmond | 70 |
| 1909.5 | 16 | 10.8 | ,, ,, | ,, | 70 |
| 1909.5 | 15 | 47.6 | Royal ,, | Greenwich | 69 |
| 1910.5 | 15 | 41.2 | ,, ,, | ,, | 69 |
| 1910.5 | 16 | 3.2 | Kew ,, | Richmond | 70 |
| 1911.5 | 15 | 55.3 | ,, ,, | ,, | 70 |
| 1911.5 | 15 | 33.0 | Royal ,, | Greenwich | 69 |
| 1912.5 | 15 | 24.3 | ,, ,, | ,, | 69 |
| 1912.5 | 15 | 46.5 | Kew ,, | Richmond | 70 |
| 1913.5 | 15 | 37.0 | ,, ,, | ,, | 70 |
| 1913.5 | 15 | 15.2 | Royal ,, | Greenwich | 69 |
| 1914.4 | 15 | 26.7 | Walker | Ranmore | 74 |
| 1914.4 | 15 | 41.8 | ,, | Windsor | 74 |

32-2


PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

TABLE A1 (*continued*)

| date | D ° | ′ | observer | site | note |
|---|---|---|---|---|---|
| 1914.4 | 15 | 4.8 | Walker | Purfleet | 74 |
| 1914.5 | 15 | 6.3 | Royal Observatory | Greenwich | 69 |
| 1914.5 | 15 | 27.8 | Kew ,, | Richmond | 70 |
| 1915.5 | 15 | 18.4 | ,, ,, | ,, | 70 |
| 1915.5 | 14 | 56.5 | Royal ,, | Greenwich | 69 |
| 1916.5 | 14 | 46.9 | ,, ,, | ,, | 69 |
| 1916.5 | 15 | 8.8 | Kew ,, | Richmond | 70 |
| 1917.5 | 14 | 59.6 | ,, | ,, | 70 |
| 1917.5 | 14 | 37.1 | Royal ,, | Greenwich | 69 |
| 1918.5 | 14 | 27.8 | ,, ,, | ,, | 69 |
| 1918.5 | 14 | 50.4 | Kew ,, | Richmond | 70 |
| 1919.5 | 14 | 40.9 | ,, ,, | ,, | 70 |
| 1919.5 | 14 | 18.2 | Royal ,, | Greenwich | 69 |
| 1920.5 | 14 | 8.6 | ,, ,, | ,, | 69 |
| 1920.5 | 14 | 31.0 | Kew ,, | Richmond | 70 |
| 1921.5 | 14 | 19.9 | ,, ,, | ,, | 70 |
| 1921.5 | 13 | 57.6 | Royal ,, | Greenwich | 69 |
| 1922.5 | 13 | 46.7 | ,, ,, | ,, | 69 |
| 1922.5 | 14 | 8.8 | Kew ,, | Richmond | 70 |
| 1923.5 | 13 | 57.3 | ,, ,, | ,, | 70 |
| 1923.5 | 13 | 35.1 | Royal ,, | Greenwich | 69 |
| 1924.5 | 13 | 22.8 | ,, ,, | ,, | 69 |
| 1924.5 | 13 | 45.1 | Kew ,, | Richmond | 70 |
| 1925.5 | 13 | 22.7 | Stevens & Finch | Abinger | 76 |
| 1925.5 | 13 | 9.9 | Royal Observatory | Greenwich | 69 |
| 1926.2 | 13 | 1.2 | ,, ,, | ,, | 69 |
| 1926.5 | 13 | 9.2 | Ordnance Survey | Ranmore | 74 |
| 1926.5 | 13 | 31.5 | ,, ,, | Windsor | 74 |
| 1926.5 | 12 | 50.7 | ,, ,, | Purfleet | 74 |
| 1926.5 | 13 | 10.4 | Stevens & Finch | Abinger | 76 |
| 1927.5 | 12 | 58.4 | ,, ,, | ,, | 76 |
| 1928.5 | 12 | 47.0 | Stevens, Finch, Rickerby | ,, | 76 |
| 1929.5 | 12 | 35.8 | Stevens & Rickerby | ,, | 76 |
| 1930.5 | 12 | 24.6 | ,, ,, | ,, | 76 |
| 1931.5 | 12 | 13.7 | ,, ,, | ,, | 76 |
| 1932.5 | 12 | 2.6 | ,, ,, | ,, | 76 |
| 1933.5 | 11 | 51.7 | ,, ,, | ,, | 76 |
| 1934.5 | 11 | 41.1 | ,, ,, | ,, | 76 |
| 1935.5 | 11 | 30.3 | ,, ,, | ,, | 76 |
| 1936.5 | 11 | 20.0 | ,, ,, | ,, | 76 |
| 1936.8 | 11 | 37.6 | Compass Observatory | Slough | 77 |
| 1937.5 | 11 | 34.1 | ,, ,, | ,, | 77 |
| 1937.5 | 11 | 10.4 | Stevens & Rickerby | Abinger | 76 |
| 1938.5 | 11 | 1.4 | ,, ,, | ,, | 76 |
| 1938.5 | 11 | 22.2 | Compass Observatory | Slough | 77 |
| 1939.5 | 11 | 8.7 | ,, ,, | ,, | 77 |
| 1939.5 | 10 | 51.9 | Stevens, Chamberlain, Rickerby | Abinger | 76 |
| 1940.5 | 10 | 43.0 | Chamberlain & Rickerby | ,, | 76 |
| 1940.5 | 11 | 0.5 | Compass Observatory | Slough | 77 |
| 1941.5 | 10 | 33.8 | Chamberlain & Rickerby | Abinger | 76 |
| 1941.6 | 10 | 49.6 | Compass Observatory | Slough | 77 |
| 1942.5 | 10 | 42.5 | ,, ,, | ,, | 77 |
| 1942.5 | 10 | 24.8 | Chamberlain & Rickerby | Abinger | 76 |
| 1943.5 | 10 | 16.2 | ,, ,, | ,, | 76 |
| 1943.7 | 10 | 36.5 | Compass Observatory | Slough | 77 |
| 1944.5 | 10 | 27.6 | ,, ,, | ,, | 77 |
| 1944.5 | 10 | 7.8 | Chamberlain & Rickerby | Abinger | 76 |
| 1945.5 | 9 | 59.5 | ,, ,, | ,, | 76 |
| 1945.5 | 10 | 16.8 | Compass Observatory | Slough | 77 |

TABLE A1 (*continued*)

| date | *D* ° | ′ | observer | site | note |
|---|---|---|---|---|---|
| 1946.5 | 10 | 7.0 | Compass Observatory | Slough | 77 |
| 1946.5 | 9 | 51.1 | Chamberlain & Rickerby | Abinger | 76 |
| 1947.5 | 9 | 43.1 | ,, ,, | ,, | 76 |
| 1947.5 | 9 | 58.6 | Compass Observatory | Slough | 77 |
| 1948.5 | 9 | 51.5 | ,, ,, | ,, | 77 |
| 1948.5 | 9 | 35.4 | Chamberlain & Rickerby | Abinger | 76 |
| 1948.7 | 9 | 37 | O'Beirne | Ranmore | 74 |
| 1949.5 | 9 | 27.5 | Chamberlain & Rickerby | Abinger | 76 |
| 1949.5 | 9 | 42.7 | Compass Observatory | Slough | 77 |
| 1950.5 | 9 | 36.9 | ,, ,, | ,, | 77 |
| 1950.5 | 9 | 19.7 | Chamberlain *et al.* | Abinger | 76 |
| 1951.5 | 9 | 12.2 | ,, ,, | ,, | 76 |
| 1951.5 | 9 | 29.4 | Compass Observatory | Slough | 77 |
| 1952.5 | 9 | 22.2 | ,, ,, | ,, | 77 |
| 1952.5 | 9 | 4.7 | Chamberlain *et al.* | Abinger | 76 |
| 1953.5 | 8 | 57.5 | ,, ,, | ,, | 76 |
| 1953.5 | 9 | 15.1 | Compass Observatory | Slough | 77 |
| 1954.5 | 9 | 8.0 | ,, ,, | ,, | 77 |
| 1954.5 | 8 | 50.9 | Chamberlain *et al.* | Abinger | 76 |
| 1955.5 | 8 | 43.6 | ,, ,, | ,, | 76 |
| 1955.5 | 9 | 0.5 | Compass Observatory | Slough | 77 |
| 1956.0 | 8 | 40.8 | Geological Survey | Ranmore | 74 |
| 1956.5 | 8 | 54.5 | Compass Observatory | Slough | 77 |
| 1956.5 | 8 | 36.8 | Chamberlain *et al.* | Abinger | 76 |
| 1957.1 | 8 | 32.7 | Rowe | ,, | 76 |
| 1957.5 | 8 | 48.8 | Compass Observatory | Slough | 77 |
| 1958.5 | 8 | 42.9 | ,, ,, | ,, | 77 |
| 1959.5 | 8 | 37.6 | ,, ,, | ,, | 77 |
| 1960.5 | 8 | 31.1 | ,, ,, | ,, | 77 |
| 1961.5 | 8 | 25.0 | ,, ,, | ,, | 77 |
| 1962.5 | 8 | 18.9 | ,, ,, | ,, | 77 |
| 1963.5 | 8 | 11.7 | ,, ,, | ,, | 77 |
| 1964.5 | 8 | 7.0 | ,, ,, | ,, | 77 |
| 1965.5 | 8 | 1.3 | ,, ,, | ,, | 77 |
| 1966.5 | 7 | 56.9 | ,, ,, | ,, | 77 |
| 1967.5 | 7 | 51.2 | ,, ,, | ,, | 77 |
| 1968.5 | 7 | 47.0 | ,, ,, | ,, | 77 |
| 1969.5 | 7 | 44.1 | ,, ,, | ,, | 77 |
| 1970.5 | 7 | 40.4 | ,, ,, | ,, | 77 |
| 1971.5 | 7 | 33.3 | ,, ,, | ,, | 77 |
| 1972.5 | 7 | 29.1 | ,, ,, | ,, | 77 |
| 1973.5 | 7 | 21.8 | ,, ,, | ,, | 77 |
| 1974.5 | 7 | 14.7 | ,, ,, | ,, | 77 |
| 1975.5 | 7 | 9.3 | ,, ,, | ,, | 77 |

TABLE A2. DIP

| date | dip ° | ′ | observer | site | note |
|---|---|---|---|---|---|
| 1540 | (69.4) | | — | — | 2 |
| 1560 | (70.4) | | — | — | 2 |
| *ca.* 1576 | 71 | 50 | Norman | Ratclif | 78 |
| 1600 | (72) | | Wright | — | 79 |
| 1600 | (73 | 00) | — | — | 71 |
| 1610 | (73) | | Wright | — | 80 |
| 1613 | (72 | 30) | Ridley | — | 81 |
| 1657 | 73 | 55 | Bond | — | 82 |
| 1661 | (70) | | — | — | 21 |
| 1673 | 73 | 47 | Bond | — | 82 |

TABLE A2 (*continued*)

| date | dip ° | ′ | ″ | observer | site | note |
|---|---|---|---|---|---|---|
| 1676 | (73 | 30) | | — | — | 71, 82 |
| 1677.2 | 73 | 24 | | Wynne | Gresham College | 83 |
| 1677.5 | 74 | 30 | | Grew | ,, ,, | 84 |
| 1684.1 | 71 | 47 | | Pagit | ,, ,, ? | 85 |
| 1700 | (74 | 30) | | — | — | 86 |
| 1719 | $73\frac{3}{4}$ | | | Whiston | London | 87 |
| 1720 | 75 | 12 | | ,, | ,, | 87 |
| 1720 | 75 | $9\frac{1}{2}$ | | ,, | Kew | 87 |
| 1720 | 75 | $14\frac{1}{2}$ | | ,, | Greenwich | 87 |
| 1720 | 75 | 19 | | ,, | Wanstead | 87 |
| 1720 | (74 | 27) | | — | — | 71 |
| 1723.3 | 74 | 41 | | Graham | Fleet Street | 88 |
| 1746.5 | $73\frac{1}{2}$ | | | ,, | ,, ,, | 89 |
| 1749.0 | 73 | 30 | | Bradley | Greenwich | 52 |
| 1750.5 | 73 | 30 | | ,, | ,, | 52 |
| 1752.7 | 73 | 25 | | ,, | ,, | 52 |
| 1754.5 | 73 | 25 | | ,, | ,, | 52 |
| 1756.9 | 73 | 25 | | ,, | ,, | 52 |
| 1757.5 | 73 | 20 | | ,, | ,, | 52 |
| 1772.3 | 72 | 16 | | Nairne | Cornhill | 90 |
| 1772.3 | 72 | 18 | | ,, | Birchin Lane | 90 |
| 1773 | (72 | 19) | | Heberden | Cecil Street? | 91 |
| 1775.5 | 72 | 30 | | Cavendish | Crane Court | 92 |
| 1775.7 | 72 | 31 | | ,, | Marlborough Street | 92 |
| 1776.5 | 72 | 30 | | Royal Society | Crane Court | 55 |
| 1777.5 | 72 | 25 | | ,, ,, | ,, ,, | 55 |
| 1778.5 | 72 | 26 | | ,, ,, | ,, ,, | 55 |
| 1779.5 | 72 | 21 | | ,, ,, | ,, ,, | 55 |
| (1780 | 72 | 8 | | Gilpin?) | — | 93 |
| 1780.5 | 72 | 17 | | Royal Society | Crane Court | 55 |
| 1786.8 | 72 | 5.7 | | Gilpin | Somerset House | 94 |
| 1787.5 | 72 | 5.7 | | ,, | ,, ,, | 94 |
| 1788.0 | 72 | 4.0 | | ,, | ,, ,, | 94 |
| 1789.5 | 71 | 54.7 | | ,, | ,, ,, | 94 |
| 1790.0 | 71 | 53.7 | | ,, | ,, ,, | 94 |
| 1791.0 | 71 | 23.7 | | ,, | ,, ,, | 94 |
| 1795.8 | 71 | 11.4 | | ,, | ,, ,, | 94 |
| 1797.8 | 70 | 59.2 | | ,, | ,, ,, | 94 |
| 1798.5 | 70 | 55.2 | | ,, | ,, ,, | 94 |
| 1799.8 | 70 | 52.2 | | ,, | ,, ,, | 94 |
| (1800 | 70 | 35 | | ,, ?) | — | 93 |
| 1801.3 | 70 | 35.6 | | ,, | ,, ,, | 94 |
| 1803.8 | 70 | 32.0 | | ,, | ,, ,, | 94 |
| 1805.6 | 70 | 21.0 | | ,, | ,, ,, | 94 |
| 1808.5 | 70 | 1 | | Royal Society | ,, ,, | 60 |
| 1811.7 | 70 | 32 | 30 | ,, ,, | ,, ,, | 60 |
| 1818.3 | 70 | 34 | 39 | Kater | Regent's Park | 95 |
| 1818.5 | 70 | 51 | | Royal Society | Somerset House | 60 |
| 1819.2 | 70 | 33 | 16 | Sabine | Regent's Park | 96 |
| 1820 | 70 | 7.64 | | — | — | 97 |
| 1820.5 | 71.6 | | | Royal Society | Somerset House | 60 |
| 1821.7 | 70 | 3 | | Sabine | Regent's Park | 98 |
| 1822.0 | 70 | 15.25 | | Christie | Woolwich Common | 99 |
| 1824.3 | 70 | 9.2 | | Foster | ,, ,, | 99 |
| 1825.9 | 70 | 0.4 | | ,, | ,, ,, | 99 |
| 1826 | (69 | 57) | | — | — | 100 |
| 1828.6 | 69 | 47 | | Sabine, Dougles | Chiswick | 101 |
| 1830 | 69 | 38 | | Kater | — | 102 |
| 1830 | (69 | 37) | | — | — | 71 |

Table A2 (*continued*)

| date | dip ° | ′ | ″ | observer | site | note |
|---|---|---|---|---|---|---|
| 1830.9 | 69 | 37.5 | | Segelcke | Woolwich | 103 |
| 1831 | 69 | 40 | | Home, Fisher | — | 104 |
| 1831.4 | 69 | 25 | | Foster | Woolwich | 65 |
| 1833.3 | 69 | 43 | | — | ,, | 65 |
| 1833.6 | 69 | 52 | 38 | Home | Ham | 105 |
| 1834.0 | 70 | 17 | 42 | ,, | ,, | 105 |
| 1834.7 | 69 | 18.9 | | Lloyd | Kensington | 106 |
| 1835 | 69 | 17.3 | | Ross | Westbourne Green | 106 |
| 1835.8 | 69 | 17.3 | | Lloyd | Kensington | 106 |
| 1836.5 | 69 | 22.7 | | ,, | Westbourne Green | 107 |
| 1837.5 | 69 | 17.5 | | Bache, Phillips, Ross | ,, ,, | 107 |
| 1837.6 | 69 | 18.55 | | Sabine | Westminster | 107 |
| 1837.8 | 69 | 25 | 12 | Home | Ham | 105 |
| 1837.9 | 69 | 23.9 | | Johnson, Sabine | Regent's Park | 107 |
| 1838.4 | 69 | 19.0 | | Fox | Maiden Lane | 107 |
| 1838.5 | 69 | 8 | | ,, | Eastwick Park | 107 |
| 1838.5 | 69 | 14.5 | | ,, | Tooting | 107 |
| 1838.5 | 69 | 14.9 | | Ross, Phillips, Bache, Fox | Westbourne Green | 107 |
| 1838.8 | 69 | 16.45 | | Sabine | Kew Gardens | 107 |
| 1838.8 | 69 | 6.75 | | ,, | Worcester Park | 107 |
| 1839.7 | 69 | 20 | | Lefroy | Woolwich | 65 |
| 1842.4 | 69 | 2.0 | | ,, | ,, | 108 |
| 1842.8 | 69 | 00 | | Blackwood | ,, | 65 |
| 1843.5 | 69 | 0.6 | | Royal Observatory | Greenwich | 69 |
| 1844.5 | 69 | 0.3 | | ,, ,, | ,, | 69 |
| 1845.5 | 68 | 57.5 | | ,, ,, | ,, | 69 |
| 1846.5 | 68 | 58.2 | | Lefroy | Woolwich | 108 |
| 1846.5 | 68 | 58.1 | | Lovelace, Breen, Downs | Greenwich | 69 |
| 1847.5 | 68 | 59.0 | | Downs, Lovelace, Humphries | ,, | 69 |
| 1848.3 | 68 | 51 | | — | Woolwich | 65 |
| 1848.5 | 68 | 54.7 | | Royal Observatory | Greenwich | 69 |
| 1849.5 | 68 | 51.3 | | ,, ,, | ,, | 69 |
| 1850 | (68 | 48) | | — | ,, | 71 |
| 1850.5 | 68 | 46.9 | | Royal Observatory | ,, | 69 |
| 1851.5 | 68 | 40.4 | | ,, ,, | ,, | 69 |
| 1852.5 | 68 | 42.7 | | ,, ,, | ,, | 69 |
| 1853.4 | 68 | 31 | | Bellot & Stanton | Woolwich | 65 |
| 1853.5 | 68 | 44.6 | | Royal Observatory | Greenwich | 69 |
| 1854.5 | 68 | 47.7 | | ,, ,, | ,, | 69 |
| 1854.65 | 68 | 30.55 | | Welsh, Sabine | Regent's Park | 109 |
| 1854.65 | 68 | 31.6 | | ,, ,, | Richmond | 109 |
| 1855.5 | 68 | 44.6 | | Royal Observatory | Greenwich | 69 |
| 1856.5 | 68 | 43.5 | | ,, ,, | ,, | 69 |
| 1856.5 | 68 | 27.67 | | Kew Observatory | Richmond | 70 |
| 1857 | (68 | 24.87) | | — | — | 2 |
| 1857.5 | 68 | 31.2 | | Criswick, Downs | Greenwich | 69 |
| 1857.6 | 68 | 25.1 | | Welsh, Chambers | Richmond | 70 |
| 1858.5 | 68 | 23.0 | | ,, ,, | ,, | 70 |
| 1858.5 | 68 | 28.3 | | Downs, Criswick | Greenwich | 69 |
| 1859.5 | 68 | 26.9 | | ,, ,, | ,, | 69 |
| 1859.5 | 68 | 21.6 | | Chambers | Richmond | 70 |
| 1860.5 | 68 | 19.7 | | ,, | ,, | 70 |
| 1860.5 | 68 | 30.1 | | Downs | Greenwich | 69 |
| 1861.5 | 68 | 21.0 | | Downs, Criswick, Nash | ,, | 69 |
| 1861.5 | 68 | 18.1 | | Chambers | Richmond | 70 |
| 1862.5 | 68 | 15.6 | | ,, | ,, | 70 |
| 1862.5 | 68 | 9 | 37 | Nash, Criswick | Greenwich | 69 |
| 1863.5 | 68 | 7.5 | | Nash | ,, | 69 |
| 1863.5 | 68 | 12.6 | | Chambers, Whipple | Richmond | 70 |

TABLE A2 (*continued*)

| date | dip ° | ′ | ″ | observer | site | note |
|---|---|---|---|---|---|---|
| 1864.5 | 68 | 9.9 | | Whipple | Richmond | 70 |
| 1864.5 | 68 | 4 | 3 | Nash | Greenwich | 69 |
| 1865.5 | 68 | 2 | 40 | ,, | ,, | 69 |
| 1865.5 | 68 | 8.7 | | Whipple | Richmond | 70 |
| 1866.5 | 68 | 6.1 | | ,, | ,, | 70 |
| 1866.5 | 68 | 1 | 16 | Nash | Greenwich | 69 |
| 1867.5 | 67 | 57 | 12 | ,, | ,, | 69 |
| 1867.5 | 68 | 3.3 | | Whipple | Richmond | 70 |
| 1868.5 | 68 | 2.1 | | ,, | ,, | 70 |
| 1868.5 | 67 | 56.5 | | Nash | Greenwich | 69 |
| 1868.6 | 68 | 1.84 | | Elagin | Richmond | 110 |
| 1869.5 | 68 | 1.0 | | Whipple | ,, | 70 |
| 1869.5 | 67 | 54.8 | | Nash | Greenwich | 69 |
| 1870.5 | 67 | 52.5 | | ,, | ,, | 69 |
| 1870.5 | 67 | 58.6 | | Whipple | Richmond | 70 |
| 1871.5 | 67 | 56.6 | | ,, | ,, | 70 |
| 1871.5 | 67 | 50.3 | | Nash | Greenwich | 69 |
| 1872.5 | 67 | 47.8 | | ,, | ,, | 69 |
| 1872.5 | 67 | 54.1 | | Whipple | Richmond | 70 |
| 1873.5 | 67 | 51.9 | | ,, | ,, | 70 |
| 1873.5 | 67 | 45.8 | | Nash | Greenwich | 69 |
| 1874.5 | 67 | 43.6 | | ,, | ,, | 69 |
| 1874.5 | 67 | 50.0 | | Whipple | Richmond | 70 |
| 1875.5 | 67 | 48.5 | | Figg, Whipple | ,, | 70 |
| 1875.5 | 67 | 42.4 | | Nash | Greenwich | 69 |
| 1876.5 | 67 | 41.0 | | ,, | ,, | 69 |
| 1876.5 | 67 | 46.7 | | Figg | Richmond | 70 |
| 1877.5 | 67 | 45.3 | | ,, | ,, | 70 |
| 1877.5 | 67 | 39.7 | | Nash | Greenwich | 69 |
| 1878.5 | 67 | 38.2 | | ,, | ,, | 69 |
| 1878.5 | 67 | 43.5 | | Figg | Richmond | 70 |
| 1879.5 | 67 | 42.4 | | ,, | ,, | 70 |
| 1879.5 | 67 | 37.0 | | Nash | Greenwich | 69 |
| 1880.5 | 67 | 35.7 | | ,, | ,, | 69 |
| 1880.5 | 67 | 42.2 | | Figg | Richmond | 70 |
| 1881.5 | 67 | 41.3 | | ,, | ,, | 70 |
| 1881.5 | 67 | 34.7 | | Nash | Greenwich | 69 |
| 1882.5 | 67 | 34.2 | | ,, | ,, | 69 |
| 1882.5 | 67 | 40.9 | | Figg | Richmond | 70 |
| 1883.5 | 67 | 40.5 | | Figg, Baker | ,, | 70 |
| 1883.5 | 67 | 31.7 | | Nash | Greenwich | 69 |
| 1884.5 | 67 | 29.7 | | ,, | ,, | 69 |
| 1884.5 | 67 | 39.1 | | Baker | Richmond | 70 |
| 1885.5 | 67 | 37.9 | | ,, | ,, | 70 |
| 1885.5 | 67 | 28.0 | | Nash | Greenwich | 69 |
| 1886.5 | 67 | 27.1 | | ,, | ,, | 69 |
| 1886.5 | 67 | 37.3 | | Baker | Richmond | 70 |
| 1887.5 | 67 | 37.0 | | ,, | ,, | 70 |
| 1887.5 | 67 | 26.6 | | Nash | Greenwich | 69 |
| 1888.3 | 67 | 27.5 | | Rücker | Purfleet | 74 |
| 1888.4 | 67 | 16.4 | | Thorpe | Ranmore | 74 |
| 1888.4 | 67 | 34.9 | | ,, | Windsor | 74 |
| 1888.5 | 67 | 25.6 | | Nash | Greenwich | 69 |
| 1888.5 | 67 | 35.5 | | Baker | Richmond | 70 |
| 1889.3 | 67 | 34.1 | | ,, | ,, | 70 |
| 1889.5 | 67 | 24.3 | | Nash | Greenwich | 69 |
| 1890.5 | 67 | 23.0 | | ,, | ,, | 69 |
| 1890.5 | 67 | 32.5 | | Baker | Richmond | 70 |
| 1890.5 | 67 | 10.5 | | Briscoe | Westerham | 75 |

TABLE A2 (*continued*)

| date | dip ° | ′ | ″ | observer | site | note |
|---|---|---|---|---|---|---|
| 1890.5 | 67 | 17.2 | | Gray | Swanley | 75 |
| 1890.5 | 67 | 10.8 | | Thorpe, Gray | Riverhead | 75 |
| 1890.5 | 67 | 13.8 | | Briscoe | Shoreham | 75 |
| 1890.6 | 67 | 30.3 | | Rücker, Thorpe | Stanmore | 75 |
| 1891.3 | 67 | 16.2 | | Watson | Gravesend | 75 |
| 1891.3 | 67 | 20.5 | | ,, | Dartford | 75 |
| 1891.5 | 67 | 21.5 | | Nash, McClellan | Greenwich | 69 |
| 1891.5 | 67 | 33.2 | | Baker, R. S. Whipple | Richmond | 70 |
| 1892.5 | 67 | 32.0 | | ,, ,, | ,, | 70 |
| 1892.5 | 67 | 20.0 | | Nash | Greenwich | 69 |
| 1893.5 | 67 | 17.9 | | Nash, Claxton | ,, | 69 |
| 1893.5 | 67 | 29.0 | | Baker, R. S. Whipple | Richmond | 70 |
| 1894.5 | 67 | 27.6 | | Baker, Boxall | ,, | 70 |
| 1894.5 | 67 | 17.4 | | Claxton, Nash | Greenwich | 69 |
| 1895.5 | 67 | 16.1 | | Nash, Claxton | ,, | 69 |
| 1895.5 | 67 | 25.4 | | Baker, Boxall | Richmond | 70 |
| 1896.5 | 67 | 22.7 | | ,, ,, | ,, | 70 |
| 1896.5 | 67 | 15.1 | | Nash, Edney | Greenwich | 69 |
| 1897.5 | 67 | 13.5 | | ,, ,, | ,, | 69 |
| 1897.5 | 67 | 19.6 | | Baker, Boxall | Richmond | 70 |
| 1898.5 | 67 | 17.6 | | ,, ,, | ,, | 70 |
| 1898.5 | 67 | 12.1 | | Nash, Edney | Greenwich | 69 |
| 1899.5 | 67 | 10.5 | | ,, ,, | ,, | 69 |
| 1899.5 | 67 | 14.7 | | Baker, Boxall | Richmond | 70 |
| 1900.5 | 67 | 11.8 | | ,, ,, | ,, | 70 |
| 1900.5 | 67 | 8.8 | | Nash, Edney | Greenwich | 69 |
| 1901.5 | 67 | 6.4 | | ,, ,, | ,, | 69 |
| 1901.5 | 67 | 9.5 | | Kew Observatory | Richmond | 70 |
| 1902.5 | 67 | 8.0 | | ,, ,, | ,, | 70 |
| 1902.5 | 67 | 3.8 | | Nash, Edney | Greenwich | 69 |
| 1903.5 | 67 | 1.2 | | ,, ,, | ,, | 69 |
| 1903.5 | 67 | 6.5 | | Kew Observatory | Richmond | 70 |
| 1904.5 | 67 | 5.1 | | ,, ,, | ,, | 70 |
| 1904.5 | 66 | 57.6 | | Bryant, Edney | Greenwich | 69 |
| 1905.5 | 66 | 56.3 | | ,, ,, | ,, | 69 |
| 1905.5 | 67 | 3.8 | | Kew Observatory | Richmond | 70 |
| 1906.5 | 67 | 2.2 | | ,, ,, | ,, | 70 |
| 1906.5 | 66 | 55.6 | | Bryant, Edney | Greenwich | 69 |
| 1907.5 | 66 | 56.2 | | ,, ,, | ,, | 69 |
| 1907.5 | 67 | 1.6 | | Kew Observatory | Richmond | 70 |
| 1908.5 | 67 | 0.9 | | ,, ,, | ,, | 70 |
| 1908.5 | 66 | 56.3 | | Bryant, Edney | Greenwich | 69 |
| 1909.5 | 66 | 54.1 | | ,, ,, | ,, | 69 |
| 1909.5 | 66 | 59.7 | | Kew Observatory | Richmond | 70 |
| 1910.5 | 66 | 58.7 | | ,, ,, | ,, | 70 |
| 1910.5 | 66 | 52.8 | | Bryant, Edney | Greenwich | 69 |
| 1911.5 | 66 | 52 | 6 | ,, ,, | ,, | 69 |
| 1911.5 | 66 | 57.2 | | Kew Observatory | Richmond | 70 |
| 1912.5 | 66 | 56.5 | | ,, ,, | ,, | 70 |
| 1912.5 | 66 | 51 | 46 | Bryant, Edney | Greenwich | 69 |
| 1913.5 | 66 | 50 | 27 | ,, ,, | ,, | 69 |
| 1913.5 | 66 | 55.8 | | Kew Observatory | Richmond | 70 |
| 1914.4 | 66 | 36.1 | | Walker | Ranmore | 74 |
| 1914.4 | 66 | 57.3 | | ,, | Windsor | 74 |
| 1914.4 | 66 | 52.9 | | ,, | Purfleet | 74 |
| 1914.5 | 66 | 50.8 | | Royal Observatory | Greenwich | 69 |
| 1914.5 | 66 | 55.8 | | Kew ,, | Richmond | 70 |
| 1915.5 | 66 | 56.6 | | ,, ,, | ,, | 70 |
| 1915.5 | 66 | 51.6 | | Royal ,, | Greenwich | 69 |

TABLE A2 (*continued*)

| date | dip ° | ′ | observer | site | note |
|---|---|---|---|---|---|
| 1916.5 | 66 | 52.2 | Royal Observatory | Greenwich | 69 |
| 1916.5 | 66 | 57.5 | Kew ,, | Richmond | 70 |
| 1917.5 | 66 | 58.0 | ,, ,, | ,, | 70 |
| 1917.6 | 66 | 53.0 | Royal ,, | Greenwich | 69 |
| 1918.5 | 66 | 52.8 | ,, ,, | ,, | 69 |
| 1918.5 | 66 | 58.4 | Kew ,, | Richmond | 70 |
| 1919.5 | 66 | 57.7 | ,, ,, | ,, | 70 |
| 1919.5 | 66 | 53.3 | Royal ,, | Greenwich | 69 |
| 1920.5 | 66 | 53.6 | ,, ,, | ,, | 69 |
| 1920.5 | 66 | 57.9 | Kew ,, | Richmond | 70 |
| 1921.5 | 66 | 57.7 | ,, ,, | ,, | 70 |
| 1921.5 | 66 | 53.0 | Royal ,, | Greenwich | 69 |
| 1922.5 | 66 | 52.3 | ,, ,, | ,, | 69 |
| 1922.5 | 66 | 57.6 | Kew ,, | Richmond | 70 |
| 1923.5 | 66 | 57.0 | ,, ,, | ,, | 70 |
| 1923.5 | 66 | 51.9 | Royal ,, | Greenwich | 69 |
| 1924.5 | 66 | 51.6 | ,, ,, | ,, | 69 |
| 1924.5 | 66 | 56.5 | Kew ,, | Richmond | 70 |
| 1925.5 | 66 | 51.4 | Royal ,, | Greenwich | 69 |
| 1925.5 | 66 | 35.1 | Stevens, Finch | Abinger | 76 |
| 1926.1 | 66 | 53.2 | Royal Observatory | Greenwich | 69 |
| 1926.5 | 66 | 37.8 | Ordnance Survey | Ranmore | 74 |
| 1926.5 | 66 | 58.9 | ,, ,, | Windsor | 74 |
| 1926.5 | 66 | 51.3 | ,, ,, | Purfleet | 74 |
| 1926.5 | 66 | 36.3 | Stevens, Finch | Abinger | 76 |
| 1927.5 | 66 | 36.2 | ,, ,, | ,, | 76 |
| 1928.5 | 66 | 37.3 | Stevens, Finch, Rickerby | ,, | 76 |
| 1929.5 | 66 | 37.2 | Stevens, Rickerby | ,, | 76 |
| 1930.5 | 66 | 38.2 | ,, ,, | ,, | 76 |
| 1931.5 | 66 | 38.1 | ,, ,, | ,, | 76 |
| 1932.5 | 66 | 39.1 | ,, ,, | ,, | 76 |
| 1933.5 | 66 | 39.4 | ,, ,, | ,, | 76 |
| 1934.5 | 66 | 39.7 | ,, ,, | ,, | 76 |
| 1935.5 | 66 | 40.9 | ,, ,, | ,, | 76 |
| 1936.5 | 66 | 41.8 | ,, ,, | ,, | 76 |
| 1937.5 | 66 | 42.7 | ,, ,, | ,, | 76 |
| 1938.5 | 66 | 43.2 | ,, ,, | ,, | 76 |
| 1939.5 | 66 | 43.5 | Stevens, Chamberlain, Rickerby | ,, | 76 |
| 1940.5 | 66 | 43.9 | Chamberlain, Rickerby | ,, | 76 |
| 1941.5 | 66 | 44.3 | ,, ,, | ,, | 76 |
| 1942.5 | 66 | 43.9 | ,, ,, | ,, | 76 |
| 1943.5 | 66 | 44.5 | ,, ,, | ,, | 76 |
| 1944.5 | 66 | 44.3 | ,, ,, | ,, | 76 |
| 1945.5 | 66 | 44.3 | ,, ,, | ,, | 76 |
| 1946.5 | 66 | 45.4 | ,, ,, | ,, | 76 |
| 1947.5 | 66 | 45.2 | ,, ,, | ,, | 76 |
| 1948.5 | 66 | 44.4 | ,, ,, | ,, | 76 |
| 1949.5 | 66 | 44.0 | ,, ,, | ,, | 76 |
| 1950.6 | 66 | 43.0 | ,, *et al.* | ,, | 76 |
| 1951.5 | 66 | 42.1 | ,, ,, | ,, | 76 |
| 1952.5 | 66 | 41.0 | ,, ,, | ,, | 76 |
| 1953.5 | 66 | 39.5 | ,, ,, | ,, | 76 |
| 1954.5 | 66 | 38.1 | ,, ,, | ,, | 76 |
| 1955.5 | 66 | 37.3 | ,, ,, | ,, | 76 |
| 1956.0 | 66 | 40.7 | Geological Survey | Ranmore | 74 |
| 1956.5 | 66 | 37.4 | Chamberlain *et al.* | Abinger | 76 |
| 1957.1 | 66 | 37.5 | Rowe | ,, | 76 |
| 1975.5 | 66 | 26.9 | Malin, Barraclough | Greenwich | 111 |
| 1975.5 | 66 | 15.4 | ,, ,, | Abinger | 111 |
| 1975.5 | 66 | 31.9 | ,, ,, | Slough | 111 |
| 1975.5 | 66 | 31.7 | ,, ,, | Richmond | 111 |

*Notes*

(1) Bourne (1574, ch. 23):

> ...those compasses that are made here with vs in Englande whereof the needle dothe stande .4. or .5. degrees vnto the Eastwards of y^e North (as doth appeare by all the needles made for dials & also in the compasses) if they would haue the North point to stande due North, then the ende of the wyers vnder the carde of the compasse should stande foure or fiue degrees vnto the Eastwards of the Flouredeluce.

While this is hardly a genuine observation, its early date justifies its inclusion. Bourne lived in Gravesend, so it is likely that the compasses to which he refers were made in London. Since secular variation was not then known, the four or five degree offset could be a tradition that had persisted for many years, though presumably it originally had an observational basis. In chapter 6, Bourne explains how to measure $D$ by two methods, both of which are illustrated with numerical examples which give a value of one point (equivalent to $11\frac{1}{4}°$) E.

(2) In his inaugural dissertation, Bauer (1895) gives a table of $D$ and dip for London in steps of 20 years, starting with 1540: $-7.2°$ (?), $+69.4°$ (?); 1560: $-9.6°$ (?), $+70.4°$ (?) (the negative sign implies east). The values in this table were obtained by smoothing and extrapolating observations listed in another table whose earliest entry is '$-8°$ (?), 1540, van Bemmelen Karte'; Bemmelen (1893) lists the observations used in the production of his chart, including nothing earlier than 1576 for England (see note 5). Thus it is clear that Bauer's early values do not represent experimental determinations. However, they have been widely quoted in lists of observations, sometimes with question marks (as above), sometimes with written disclaimers (see, for example, Hazard 1925), and elsewhere without reservation (see, for example, Swann 1929).

(3) Doubtful; quoted by Black (1905) in an appendix 'Collected from different authorities'.

(4) Digges (1571, first book, ch. 29): '...the variation of the compasse...which in England is $11\frac{1}{4}$ grades or neere therabout...' The book is 'framed by Leonard Digges, gentleman, lately finished by Thomas Digges his sonne', so it is not certain which (if either) was responsible for the observation. It may simply be that it was common knowledge among sailors that the compass had to be offset by one point in England to give true north. If the note appeared in the original 'framing' by Leonard Digges, its date would be about 20 years earlier. The Digges' lived in Barham, Kent, about 50 miles ESE of London.

(5) Hakluyt (1589) (new edition, 1965) reproduces an account written by Christopher Hall (master of the bark *Gabriel*) of Martin Frobisher's voyage in search of the North-West Passage made in 1576. 'The 12. day' (of June) 'being over against Gravesend, by the castle or blokehouse we observed the latitude, which was 51. degrees 33. min. And in that place the variation of the Compasse is 11. degrees and a halfe'. This declination is undoubtedly east, but it is not clear whether Hall is reporting an observation or merely stating an accepted value.

Stevin (1599) gives a table of $D$ values collected by Petrus Plancius, including 'Londen in Engelant 11. 30.' (east). According to Crone (1961) Stevin's source appears to be a Plancius manuscript in the Public Record Office at The Hague (Loketkas Admiraliteit no. 10), which also gives the sources of the data, quoted by Crone as follows:

> The foregoing foundations and grounds are found certain by true and frequent experiences and observations, made with great diligence and skill by many learned men, intelligent masters, and good navigators of Spain, Portugal, France, England, The Netherlands

and many other nations in many countries and places of Europe, Asia, Africa, Peruana and Mexicana both south and north of the equator.

It seems likely that the London value is that of Frobisher.

(6) Norman (1581, ch. 9): 'I will declaire what the variation is heere in London, by mine own observation...', and later on the same page: '...this place or Cittie of London whose latitude I finde to bee 51 degrees 32 min. and the Variation of the Needle from this meridian of the Pole to be 11 degrees 15 minutes'. This is distinct from Borough's observation given in the Appendix of the same book, though Bauer (1895) combines the two. There is no clue to the date of the observation other than the year of publication. Cavallo (1787) and Mascart (1900) give 1576, with no source or observer, and Raulin (1867) gives 1576, Burrow, 11° 15′. If it is Norman's observation to which they refer, the date is probably by analogy with that usually quoted for Norman's dip observation (note 78). Gaibar-Puertas (1953) gives 1576, Borough, 11° 15′, making reference to Mascart (1900) and Abbadie (1890), though Abbadie's sole sixteenth century entry is '1580 12.50 g. E' (equivalent to 11° 15′ E) 'Burrows', and clearly refers to a different observation (see note 7).

Table A 3 (Borough 1581, ch. 3)

Limehouse, 16 Oct. 1580

Forenoone

| Elevation of the sunne | Variation of the shadowe from the north of the needle Westwards | Elevation of the sunne | Variation of the shadowe from the north of the needle Eastwards | Variation of the needle fro the pole or axis |
|---|---|---|---|---|
| 17° | 52° 35′ | 17° | 30° 0′ | 11° 17½′ |
| 18 | 50 8 | 18 | 27 45 | 11 11½ |
| 19 | 47 30 | 19 | 24 30 | 11 30 |
| 20 | 45 0 | 20 | 22 15 | 11 22½ |
| 21 | 42 15 | 21 | 19 30 | 11 22½ |
| 22 | 38 0 | 22 | 15 30 | 11 15 |
| 23 | 34 40 | 23 | 12 0 | 11 20 |
| 24 | 29 35 | 24 | 7 0 | 11 17 |
| 25 | 22 20 | 25 | fro N to W 0.8 | 11 14 |

(7) Borough (1581, ch. 3) gives a table of observations made in Limehouse, and concludes 11¼° E for $D$. Table A3 is the table from chapter 3 of the third edition (Borough 1596) 'Newly corrected and amended by M.W.B.' (Borough). The mean of these values (after correction of Borough's slight arithmetical error in the penultimate line) is 11° 19′ E. Near the end of chapter 3 Borough states: 'I doo finde the true variation of the needle or compass at Limehouse to be about 11. d. ¼ or 11. d. ⅓', and at the end of chapter 4: 'So I conclude the variation at Limehouse to be about 11¼ from North to East, or South to West'.

Borough's observation has been widely quoted, but with considerable variety both in the value of $D$ and in the spelling of the observer's name (Burrow, Burrowes, Boroughs, Burroughs, etc.); Petit (1667) gives 11° 11′; Gellibrand (1635) quotes 11° 15′ on page 7, but subsequently reworks Borough's data to get 11° 16′. Sellar (1694) reproduces Borough's table, giving 00° 28′ in place of 'fro N to W 0.8', and 11° 04′ in place of 11° 14′ in the next column. He also omits all fractions from the final column, and deduces a mean value of 11° 17′ for $D$. Black (1905) quotes 11° 15′, 11° 17′ and 11½° in various parts of his book. Mountaine & Dodson (1758) quote 'one point easterly'. Churchman (1794) gives 11° 0′ E (corrected by Gellibrand for refraction);

this result is from the morning observations only, which contain systematic errors (including refraction) that are removed by considering the full set of observations. Although Gilbert (1600) gives no source for his value of $11\frac{1}{3}°$, it is almost certainly from Borough. However, Stoderto (1615) gives 'Londini $11\frac{1}{3}$ gr. Or. observuvit Gilbertus' with the fraction printed very small and without a horizontal bar, so that it looks remarkably like a colon. This may be the source of Kircher (1643, p. 402): 'Guglielmus Gilbertus, Londini, 11° 0''; see also note 10. Gaibar-Puertas (1953) gives '1580, +12° 35', Borough y Burrows', quoting his sources as Abbadie (1890) (see note 6); Arago (1854) who gives 1580, 11° 15′ Est, Burrows; Bauer (1897) who gives Boroughs, London in 1580, 11° 15′ east; and Mascart (1900) who gives 1580, 11° 18′ E Limehouse, Borough. Even if he had mistaken Abbadie's centesimal grades for degrees, Gaibar-Puertas's mean still lies outside the range of the data.

(8) Curiously, this observation seems to have been neglected, though it appears in the same book (Borough 1581) as the more famous observation of the previous year. Chapter 7 gives two observations made in Limehouse, 29 July 1581 in the forenoon: (i) elevation of sun 21° 0′, variation 100° 30′ W; (ii) elevation of sun 50° 0′, variation 48° 0′ W. Borough adopts 16° 14′ N for the declination of the sun and calculates $D$ as $11\frac{1}{4}°$. However, unlike the 1580 experiment, this method of measuring $D$ does not eliminate the effect of atmospheric refraction. Reworking the data by using Tuckerman's tables and allowing for refraction gives for (i) 10° 29.2′ E and for (ii) 11° 8.0′ E, with a mean of 10° 49′ E. (N.B. the latitude of Limehouse is 51° 31′, not 51° 32′ as used by Borough.)

(9) Polter (1605): 'the Compasse heere with us at London, is set at halfe a poynte variation eastward, where it should be 10. degrees 38. minutes 45. second by my owne observations'. In the 1644 edition this sentence is followed by '(which was made in the yeere 1586)'. The observation was probably made in Polter's house, near St Katherine's Docks.

(10) To the second edition (and subsequent editions) of his 'Certain errors in Navigation detected and corrected', Wright (1610) appends 'An addition touching on the variation of the compasse' which includes a list of $D$-values obtained 'partly for myself, but for the most part by others', including two values for Limehouse: 11° 0′ E and 11° 15′ E. No dates are given. The latter observation is clearly that of Borough (note 7), but the former is a mystery; it may be one of Wright's own observations.

Kircher (1643) ascribes a London value of 11° 0′ E to William Gilbert, but this may be due to a transcription error (see note 7).

(11) Quoted by Cavallo (1787), but no source or observer is given. The values for 1724, 1725, 1730 and 1735 are similarly quoted by Churchman (1794), but for 1770 he gives 19° 57′ W. (See also note 13.)

(12) Gunter (1624) suspected that $D$ varied with time from the difference between Borough's 1580 value and '...only 6 gr 15 m as I have sometimes found if of late'. Gellibrand (1635, p. 7) gives 1622, 6° 13′ E, by Gunter. As his successor to the chair of astronomy at Gresham College, it is not unlikely that Gellibrand had access to Gunter's papers, so his value may be a new reduction of Gunter's original data. The site could be Whitehall (see note 14) but is more probably Deptford (see note 15).

(13) The extract from Gunter (1624) quoted in note 12 continues:

> Hereupon I enquired after the place where Mr Borough observed, and went to Limehouse with some of my friends, and took with us a quadrant of three foot Semidiameter, and two Needles, the one above 6 inches, and the other 10 inches long, where I made the semi-

diameter of my Horizontal Plane AZ 12 inches: and towards night the 13 of June 1622, I made observation in several parts of the ground, and found as followeth.

He then gives a table (table A 4) which is reproduced by Gellibrand (1635) and Sellar (1694), who gives 5° 55′ E as the mean. The solar azimuth was calculated from the solar altitude. The mean value of 5° 56½′ given here is obtained from the data in table 4 by correcting the Sun's altitude for refraction before using Tuckerman's tables to deduce the corresponding azimuth.

Table A 4 (Gunter 1624)

| sun's altitude | magnetic azimuth | sun's azimuth | variation |
|---|---|---|---|
| 19° 00′ | 82° 02′ | 75° 52′ | 06° 10′ |
| 18 05 | 80 50 | 74 44 | 06 06 |
| 17 34 | 80 00 | 74 06 | 05 54 |
| 17 00 | 79 15 | 73 20 | 05 55 |
| 16 18 | 78 12 | 72 32 | 05 40 |
| 16 00 | 77 50 | 72 10 | 05 40 |
| 10 10 | 71 02 | 64 49 | 06 13 |
| 09 52 | 70 12 | 64 25 | 05 47 |

Other references to this observation are by Petit (1667) and Raulin (1867), who give 6° E, 1612; Boyle (1671) gives '1612 above 6 degrees'; however, most other authors agree on 1622. Raulin (1867) gives, besides his '1612' value, 6° 30′ for Gunter in 1622. Halley (1683, 1692) opts for 6° E; Bemmelen (1899) gives 5° 57′ E, while Becquerel (1840) gives 6° 12′ E and Mascart (1900) gives 6° 15′. Gaibar-Puertas (1953) gives 6° 17′ as the mean of the values quoted by Mascart (1900), Arago (1854) and Abbadie (1890), presumably assuming Abbadie's value of 6.6 g. to be in degrees rather than centesimal grades. Two authors quote the result to a second of arc: Hevelius (1670), 5° 36′ 30″ and Bond (1676), 05° 55′ 37″. Churchman (1794) 'calculates' 6° 12′ E in a numerical example, giving the date as 1722, but also gives a table including 6° 0′ 0″ E for 1622.

(14) There is no doubt that the observations were made, but the values obtained are less certain. Gellibrand (1635, p. 16): '...an aquaintance of ours' (indicated in the margin to be 'Mr John Marr') 'lately applying *Mr Gunters* owne Needle to the side of the Cubicall Stone of his *M*ajesties Diall in White Hall garden, could not finde the variation so great as 6 gr. 15 min: formerly found; whereupon resolving with some friends to make an experiment hereof, we went to Diepford the last year 1633 the day the suns entrance into the summer solstice', and, having measured D at the same place as Gunter, 'found it to be much less than 5°'. Petit (1667) gives 4° E, 1633, Gellibrand, but this may refer to the 1634 observation. Cavallo (1787) gives 4° 5′ E for both 1633 and 1634, and Churchman (1794) also gives 4° 5′ E for 1633, but neither of these authors quotes his source.

(15) Gellibrand (1635, p. 7): 'And myself in this present year 1634 with some friends had recourse to Dedpford (where Mr. Gunter had heretofore made the same observations with those in Limehouse) and found it not much to exceed 4 degrees'. This is accompanied by table A 5. The mean value of $D$ is thus 4° 5′ E. When refraction is taken into account, the morning values are increased by one or two minutes of arc, and the afternoon values decreased, leaving the mean unchanged. The instruments used were two 12 in† needles, a 6 ft‡ quadrant for measuring the Sun's altitude and a 2 ft horizontal quadrant for the magnetic azimuths. In addition, Gunter's original 10 in needle was found to agree with the 12 in needles.

† in = inch = $2.54 \times 10^{-2}$ m. ‡ ft = foot ≈ 0.3 m.

Walker (1794) ascribes the observation to Gilbert. Sellar (1694) reproduces table A 5, but omits the last morning observation, and obtains a mean value of 4° 6′ E; Bond (1676) gives 4° 03′ 00″ and Hevelius (1670) gives 4° 3′ 30″ E at Limehouse. Churchman (1794) gives 4° 1′ 53″ E 'by the mean of nine azimuths', but this value is lower than the mean of the nine smallest values. Gaibar-Puertas (1953) gives 4° 30′ as the mean of values quoted by Arago (1854) (4° 6′) and Mascart (1900) (4° 5′)!

Table A 5 (Gellibrand 1635)

June 12, 1634, garden of Mr John Welles:

| | Sun's altitude | Sun's azimuth (calculated) | magnetic azimuth | variation |
|---|---|---|---|---|
| morning | 44° 45′ | 110° 06′ | 106° 00′ | 4° 06′ E |
| | 46 30 | 113 10 | 109 00 | 4 10 |
| | 48 31 | 117 01 | 113 00 | 4 01 |
| | 50 54 | 122 03 | 118 00 | 4 03 |
| | 54 24 | 130 55 | 127 00 | 3 55 |
| afternoon | 44 37 | 109 53 | 114 00 | 4 07 |
| | 40 48 | 103 50 | 108 00 | 4 10 |
| | 38 46 | 100 48 | 105 00 | 4 12 |
| | 36 43 | 97 56 | 102 00 | 4 04 |
| | 34 32 | 95 00 | 99 00 | 4 00 |
| | 32 10 | 91 55 | 96 00 | 4 05 |

Table A 6 (Gellibrand 1635)

Paul's Cray, July 4 1634, afternoon

| Sun's altitude | magnetic azimuth | Sun's azimuth | variation |
|---|---|---|---|
| 40° 55′ | 111° 30′ | 107° 30′ | 4° 0′ |
| 40 1 | 110 0 | 106 5 | 3 55 |
| 39 41 | 109 30 | 105 34 | 3 56 |
| 38 42 | 108 0 | 104 5 | 3 55 |
| 35 32 | 103 30 | 99 32 | 3 58 |
| 34 49 | 102 30 | 98 32 | 3 58 |
| 33 41 | 101 0 | 97 0 | 4 0 |
| 32 57 | 100 0 | 96 2 | 3 58 |
| 32 9 | 99 0 | 94 58 | 4 2 |
| 31 25 | 98 0 | 94 0 | 4 0 |
| 30 39 | 97 0 | 93 1 | 3 59 |
| 29 29 | 95 30 | 91 31 | 3 59 |
| 27 51 | 93 30 | 89 28 | 4 2 |

(16) Gellibrand (1635, p. 18): '...I caused the same instruments' (as were used in Deptford, see note 15) 'to be transported to *Paules Cray* in *Kent* distant from *London* SE and by S about 12 miles, where the fourth of July following (Fide Astronomica) I made the subsequent animadversions, hardly amounting to 4 degrees. The latitude of the Place I finde by the same large Quadrant to be 51 gr. 24 min.' Then follows table A 6. '...the observations made in this place do all make the variation fall neere upon 4 degrees.' On re-working the results with the use of Tuckerman's tables and by correcting for refraction, the mean is found to be 3° 57′ E. Sellar (1694) gives 4° 01′ E.

(17) Bond (1676, p. 13) gives a table of *D*-values for London including '1640 Bond & others 3° 6′ 40″'. This value is correctly quoted (with a little judicious rounding) by Felgentraeger

(1892) who gives the site of the observation as Whitehall Gardens, but the only evidence for this appears to be by analogy with subsequent observations by Bond. (see note 24).

(18) Bond (1648, p. 103): 'in the paralell of London, there is two deg. 00 Easterly variation to the Eastward of London, and 2 deg 00 Easterly variation to the Westwards of London...'. Since the Kalendar was published annually and Bond was well aware of the rapid change of $D$ in London, this is likely to be a 1648 value. (On the same page, he forecasts that $D$ will be zero in 1657.)

(19) Bond (1676, p. 3) states 'I did foretell...that in the year 1657, there would be no variation at all in London; which is found to be so...'. No further information is given, so 'finding it to be so' might be by direct observation (by Bond or another), interpolation or extrapolation from other observations, or just hearsay. However, Philippes (1696), who succeded Bond as editor of Tap's *Sea-man's kalendar*, gives more credence to and a better date for the observation, saying of Bond's prediction '...it came to pass exactly; so that in July 1657, it was observed there was no Variation in London'. Sellers (1667) (elsewhere spelt Seller or Sellar), in a letter from Wapping dated 12 April 1667, describes 'some experiments I have tryed' with compass needles 'here at London when there was noe variation known'. However, he does not appear to have compared the magnetic meridian with a geographical meridian, so this cannot be considered as an observation of $D$. The result has been widely and variously quoted: 'no variation at London' (Halley 1692); 'no variation' (Graham 1749); 0° 0′ (Cavallo 1787); 'de 1657 à 1662, à Londres, la déclinaison était nulle' (Becquerel 1840); 0°.00 (Bauer 1895); 'the needle pointed to the true North' (Black 1905). Felgentraeger (1892) gives the site as Whitehall Gardens, but there appears to be no evidence for this. Raulin (1867) gives 0° 0′ for 1654, 1657 and 1662, ascribing the extreme dates to Gellibrand (who had died in 1636!).

(20) Philipott (1661, p. 15) writes of the compass 'at London it varies eleven Degrees, that is, almost one Rhomb'. However, the book is a child's text written by an academic rather than a practical man, and it is unlikely that this improbable value has any observational basis.

(21) In reply to a letter from Henry Power of Halifax dated 16 October 1661, Dr Croone wrote from Gresham College on 9 January 1662 as follows (British Library MS additional 6193, p. 107): 'The declination of the needle I could not learn soe accurately as you wish and I too. In June last according to the best observ. it was 45′ 30″ W. Its inclination is now 70 gr...' Power (1664, p. 166) quotes the $D$ value and gives the site as London. Croone was probably answering Power's query in his capacity as registrar of the Royal Society, so the observer and site are obscure; however, Bond was in communication with the Royal Society at that time, and both the precision and numerical value of the $D$ observation are in good accord with others by Bond. Bond's observations of dip bear no relation to the value given by Croone, which is probably spurious.

(22) The Royal Society *Journal Book* records that, on 15 June 1664 'It was ordered that, Sir Robert Moray, Mr. Balle, and Mr. Hooke do meet at a time convenient for them, to make an Observation concerning the Variation of the Needle, which was affirmed by one Bond to be now 1ᵈ 30′ westward' (presumably from his magnetical hypothesis rather than observation). At the meeting of 22 June 'Dr. Pell was joined to the Curators formerly appointed for making the Observation of the Variation of the Magnetic Needle in Whitehall garden.' And on July 6: 'The observation of the variation of yᵉ Needle was ordered to be made the first fair day after Thursday in White-hall-Garden, about 2 in the afternoon, meeting at Sʳ Robert Moray's Lodgings.' 13 July 1664: 'Sʳ Robert Moray made some Report of the Observation of Needle's

variation; viz. that much uncertainty was found in it; The Needle standing one time between 1. d. and 1. d. 30′ westward, another time about 1$^{d}$ 30′ Eastward, but at last directly North and South.'

(23) Entry in the Royal Society *Journal Book* for 24 May 1665: 'The President acquainted the society, that something had been tryed to observe the Variation of the Needles Variation; and that the King had been pleased himself to make the observation on Friday last' (19 May 1665) 'in Whitehall garden, and had found no variation at all, the Needle standing in the Meridian.'

(24) Entry in the Royal Society *Journal Book* for 7 June 1665: 'Ordered also, that to morrow June 8th about 5 of the clock in the Evening, the Variation of the Variation of the Needle be

Table A 7

Mr Philips, White-hall. Junÿ 8...A°: 1665

| Sun's altitude | magnetic azimuth | Sun's azimuth | variation |
|---|---|---|---|
| 27° 24′ | 95° 30′ | 94° 00′ | 1° 30′ |
| 25 57 | 97 10 | 95 44 | 1 26 |
| 24 12 | 99 00 | 97 54 | 1 06 |
| Mr Marre | | | |
| 27° 26′ | 5° 30′ | | 1° 26′ |
| 25 54 | 7 10 | | 1 50 |
| 24 9 | 9 0 | | 1 6 |

observed in Whitehall garden, by the same Committee formerly appointed for it, viz. Lord Brounkner, Sr Robert Moray, Sr Paule Neile, Dr Wren, Mr Oldenburg, Mr Hook; and that Mr Marre and Mr Bond have notices given them, by the Operator, to bring their Needles and Instruments to the said place.' The observations of two of the party are preserved in the Royal Society Classified Papers, 1660–1740, vol. 9 (ii), p. 1. (table A 7). Clearly, Philips' azimuths are measured from south, and Marre's from west, so the two sets of magnetic azimuths are identical, and probably not independent. The solar altitude observations are, however, independent, and were probably made simultaneously with two instruments (if the measures are assumed to be accurate, there would be less than 20 s between the measures by the two observers; too short a time to set and read a circle to the accuracy given). The solar azimuths deduced and quoted by Philips are incompatible with those implicit in Marre's data. A new reduction of the data gives $D = 1° \, 21' \, \mathrm{W} \pm 11'$ (r.m.s.).

Apparently, these were not the only observations made on that occasion, since, according to Bond (1676, p. 13): 'in 1665, Mr. Robert Hooke...Mr. William Mar, Mr. Richard Shortgrave ...and Henry Bond, sen., on 8 June, in the King's Majesties Private Garden at Whitehall, observed the variation and found it to be 1 d. 22 m. 30 sec. West'. Some authors combine this with Bond's 1666 observation (note 26), for example Bauer (1895, 1898) and Petit (1667) who states 'an artist in London affirms, that whereas heretofore the Declination was Eastwards, 'tis now about one degree and a half to the West.' Gilpin (1806) erroneously ascribes the observation to Gellibrand. Wolf (1872) quotes 1° 22′ for 1665 without giving an observer.

(25) Sellar (1694, p. 150) gives details of several $D$ observations, including: 'John Sellar at Hermitage' (Wapping) 'near London, with 6′ quadrant for altitude, 1666, 51° 32′ latitude', giving a mean value of 34′ W. This becomes 36′ W when the Sun's azimuth is recalculated with refraction taken into account. His observations are reproduced in table A 8. Becquerel (1840) gives 34′ W and Felgentraeger (1892) gives its decimal equivalent but Bauer (1895,




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1898) finding such an anomalous value hard to believe, adds 1°, quoting 1.57° W; Bond (1676) gets most indignant about this observation, which he quotes as 41′ (see note 26).

Table A 8 (Sellar 1694)

| | Sun's altitude | magnetic azimuth | Sun's azimuth | declination |
|---|---|---|---|---|
| June 4, morning | 26° 00′ | 85° 00′ | 84° 36′ | 0° 24′ W |
| | 27 30 | 87 00 | 86 26 | 0 34 W |
| June 13, afternoon | 8 24 | 62 00 | 62 21 | 0 31 W |
| | 8 09 | 61 30 | 61 51 | 0 21 W |
| | 7 38 | 60 45 | 61 29 | 0 44 W |
| | 7 07 | 60 00 | 60 47 | 0 47 W |
| June 14, morning | 29 30 | 89 30 | 88 40 | 0 50 W |
| | 31 20 | 91 30 | 91 03 | 0 27 W |

(26) Bond (1676, p. 14): 'There is one that puts out in print that in 1666, he did observe at the Hermitage in Wapping, with a large quadrant, and found the variation to be 41 minutes. How large soever his Quadrant was, his understanding in this business was very little, and, I fear, something else less.

'The variation here at London in June 1666 was 1° 35′ 36″. I know not what title to give to that 41′ observer, except it be, Mr. Impudent Ignoramus.' The real reason for Bond's outburst would seem to be that Sellar's observation (which is admittedly anomalous) does not fit in with Bond's predictions (Bond 1668). It seems likely that the value given by Bond is from his hypothesis rather than the result of direct observation. Whiston (1721) brackets this with the 1665 observation by the Royal Society party (note 24) as being made 'in the Privy-Garden at Whitehall', though he quotes no other source than that given above. Cavallo (1787) gives 1666, 1° 35½′ and Walker (1794) gives 1° 35′, with no further details.

(27) Bond (1668) gives a table predicting the value of $D$ in London for each year from 1668 to 1706. The value for 1668 may well be an observation, since he is unlikely to have risked having his 'scheme' proved wrong immediately. Further, according to the Royal Society *Journal Book*, the 1668 value is 'affirmed', whereas the later years are 'predicted'.

(28) Boyle (1671): 'And at a place within halfe a League of London, trying with a long and curious Needle purposely made and poised, I could scarce discern any declination at all, and if the needle declined sensibly any way from the Pole, it seemed to do so a little towards the other side of Heaven than that towards which it did decline before. And having* afterwards by the help of a meridian Line, much prized for haveing been accurately drawn by eminent Artificers, made an Observation in London itself, though I made it with two Instruments, whereof one was a choice one, differing from the former and from one another; I could not satisfy my self that I could discerne the Declination of the needle to exceed half a degree, if it amounted to so much.' '*A.D. 1669.' (Boyle's marginal note.) The 'prized meridian line' may have been that in the Privy Garden at Whitehall.

(29) Sellar (1694, p. 150) gives details of various $D$ observations, including: 'May 28, 1670, afternoon, taken by the Worshipfull Sir Nicholas Millet, at his house at Battersea', the individual results are 1° 54′, 2° 09′, 2° 14′, 2° 14′, 2° 08′, 1° 59′ and 2° 13′, giving a mean value of 2° 06′ W. Becquerel (1840) misprints the observation as 2° 66′ and Bauer (1895) misprints the year as 1870.40.

(30) Halley (1683, 1692). Halley was sixteen years old when he made this observation.



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(31) At the Royal Society meeting of 1680, January 29 'Mr COLWALL moved, that a magnetical needle might be made for the Society, and that it might be Lent to Mr. FLAMSTED to make Observations at Greenwich of the Variation of the needle, and it was Ordered that such a needle Should be made, and That Mr. FLAMSTED might care to have it very well made.' (Royal Society *Journal Book* No. 6). On 25 February Flamsteed wrote to the Royal Society giving details of the determination of the true azimuth of Bromley Windmill observed from the Royal Observatory, Greenwich, noting 'the bearing of Bromley Windmill from the Meridian of the Needle taken yesterday was 1 degree or at most $1\frac{1}{4}$ to the Westwards' and hence concluding '4° 00′ or at most $4\frac{1}{4}$ deg. Westerly' for declination (Royal Observatory MS 15, f170). The letter was read to the society and copied into the *Register Book* (vol. 5, p. 223) on 4 March. In the published version (Flamsteed 1725), the observation is given as '4gr vel $4\frac{1}{2}$'. Birch (1756) also gives '4 or $4\frac{1}{2}$ degrees at most to the west', misquoting the Royal Society minutes for February 26.

Hooke, in a letter to Sturm dated 5 April 1680 (British Library MS 1039, f173 Sloane) writes 'Your advertisment concerning the variation of the magnetical needle' (Sturm's letter to Hooke dated February 10, received March 13) 'came very opportunely even when we were upon that very enquiry, and we had newly made the observation of the variation at Greenwich about 4 miles east of London and found it about $\sim 4\frac{1}{4}$ degrees to the westward of north....' Elsewhere in the letter, Hooke refers to himself as 'I', so 'we' probably refers to the Royal Society, of which Hooke was then secretary, and the observation is almost certainly that of Flamsteed. There is no indication in his diary (Robinson & Adams 1935) that Hooke went to Greenwich about this time, or observed there. Felgentraeger (1892), quoting from a subsequent letter from Sturm, gives: Year, 1680.5; Date?; D. 4°.5 W; Observer, Hooke; and notes that the observation was made at Greenwich.

(32) Halley (1683) gives 4° 30′ W; at 0° 0′ E, 51° 32′ N.

(33) From the Royal Society *Journal Book*: 'June 16 1686. E. Halley made y^e^ observation of y^e^ Variation of y^e^ Needle upon y^e^ Stone in y^e^ Area of Gresham Colledge & having found y^e^ true meridian y^e^ Box being apply'd thereto y^e^ Needle declin'd 4°:45′ from y^e^ North to y^e^ West & y^e^ Needle being diverted by y^e^ Aplication of Iron did 4 severall times restore it Self to y^e^ same point exactly.'

(34) The Royal Society *Journal Book* records a number of observations made by the Society (without specifying an observer) as follows:

22 June 1687: 'There was an Experiment made of the Variation of the Magneticall Compass, but by reason of the Wind it could not be determined as it ought, however, it was several times found about 5gr Westerly.'

11 July 1688: 'The Variation of the magnetical needle was this day tried and by severall Observations was found to be about 4 degrees Westwards, but the wind insinuating it self under the Glass, so as to keep the needle always in motion, it was ordered to repeat it again, when there should be no wind stirring.'

23 April 1690: 'the weather being very still, and the box well filled, the triall of the Variation of the magnetical Needle was made, and it was found, that the Needle does now varie somewhat better than $5\frac{1}{2}$ degree to the westwards'.

1 August 1691: 'The Variation of the Compass was this day Observed, & it was found to be 5° 50′ to the Westward.'

13 April 1692: 'The Variation of the Magneticall Needle was observed very near 6 West.'





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25 May 1692: 'The Variation of the Magneticall Compass was this Day observed the needle playing upon the Glass globule point and it was found to be nearly 6. gd Westward or rather Something more.' The glass globule is explained in the entry for 11 May 1692: 'Halley produced a Contrivance for a point for a Magneticall Needle to turn upon which was by a Small Glass Cane Stuck on the Brass pin on which it formerly turned, which Cane was Curiously pointed by Drawing the End at a lamp and then melting the Small End down to a Globule of Glass which was Smaller than the brass point on which it was used to play, the Roundness Smallness and Smoothness of this blebb of glass Caused the Needle to Vibrate much longer and faster than formerly and seemed to be much better fixt for finding the Variation than before.'

25 May 1693: 'The Variation of the Magneticall Needle was this Day Observed in Gresham College, and it was found Accurately 6°. 20′ to the West.'

18 July 1694: 'The Variation of the Magneticall Needle was this Day Observed, and it was found to Decline to the Westward 6°. 30′ Exactly.'

5 June 1695: 'The Variation of the Magneticall Needle was this Day tryed in Gresham College and it was found to Decline 6°. 50′ to the Westward.'

5 August 1696: 'The Variation of the Compass was this Day Observed in Gresham College and was found to be very near 7 Degrees perhaps 6°. 55′, a very good Observation tryed on both Sides of the Box, and may stand as a Rule to Verify those that follow.'

2 July 1707: 'The Variation of the Magneticall Needle was Observed To be near 10d. Westward of the North part of the Meridian.

'The Variation of the Magneticall Needle was Tryed after rectifying what was Amiss there being no Wind and by Severall Shakeings of the Needle it was found to Settle about Nine Degrees & 37′.. or 38′. after Each Shakeing.'

30 June 1708: 'The Variation of the Needle was observed at Gresham College June 23d, was 10d. 10′ West from the North.'

22 June 1709: 'The Variation of the Needle was Observed to be 10¾ gr: West of the North.'

13 July 1709: 'July 13th The Variation of the Needle was found about 10°.-30′ from North Westward or Something Less.'

21 June 1710: 'The Variation of the Needle was Observed to be 10 Degrees 40 Min: West of the North, it was a Windy day.'

9 April 1719: 'The Society went down into the Court Yard to Observe the Variation of the Compass as Usual and it was 11½ to West.' This observation was made after the Royal Society had moved from Gresham College to Crane Court.

Halley was present for most of the observations, and that of 25 May 1692 is almost certainly that referred to by Halley (1692); see note 35.

(35) Halley (1692) gives: 6° 0′ W, London (myself), probably referring to the observation recorded in the Royal Society *Journal Book*, 25 May 1692 (see note 34). This value is quoted by Felgentraeger (1892), giving the reference 'Phil. Trans. 1691 Heft 193'; although there two papers by Halley in that number of *Philosophical Transactions*, neither mentions magnetic observations. Abbadie (1890) gives 1692 1.53 g. W (≡1° 22.6′ W) Halley, presumably confusing the observation with that of Bond (note 24).

(36) Flamsteed (1725) lists several observations made at the Royal Observatory, Greenwich (including that of 1680 February 24, see Note 31). The earliest record of these (Royal Observatory MS **15**, f170v) is a series of latin notes in Flamsteed's hand, obviously entered on a number of different occasions, on the reverse of his copy of his letter to the Royal Society of 25 February

1680 (see note 31). A fair copy of these notes (Royal Observatory MS 15, f171), presumably made by Crossthwaite, Flamsteed's assistant, differs from the original only in details of spelling and in the omission of the names of some of the witnesses. This copy has been translated by Laurie (1953). In essence, the observations are as follows:

1693 February 2, 6° 30′ W by the Royal Society's one-foot needle, 7° W by Lord Greenville Collins' 8-inch needle.

February 3, at 3 p.m., $5\frac{1}{2}$° W, after polishing the pivot, but immediately afterwards 'he' (presumably Collins) noticed that there were iron keys in the vicinity. (Laurie (1953) translates 'clavos' as nails, but keys seems more likely.)

February 4, $6\frac{1}{2}$° W after further adjustments 'cum D[l] Collinsii acu invenimus variationem fuisse 6° 30′ utrisque quam proxime consentionibus' (using Lord Collins' needle we found the variation to be 6° 30′ within very close limits). 'We' presumably means Flamsteed and Collins.

1698 July 22, with the same needle the variation was similarly found to be 7° 30′, or certainly not less than 7° 20′ W.

1699 August 25, near noon: $7\frac{1}{2}$° W.

1710 July 22, morning, 10° 12′ W (after re-magnetizing, repairing and re-centering the needle).

1711 February 3, morning, 10° 22′ W.

1716 June 23, 11° 15′ W (by using both the long and the short needle).

(37) Cassini, le fils (1699): 'J'ai pris à l'Observatoire d'Angelterre avec Monsieur Flamsteed la déclination de l'Aigulle aimantée, que nous trouvâmes de 7 degrez du Septentrion vers l'Occident' (Cassini's visit to England was from 26 December 1697 to about 1 April 1698).

(38) The first observation of declination from Halley's journal of his first voyage in the *Paramour* was 7° W on the Thames at approximately 51° 30′ N, 0° 40′ E, 27 October 1698 (Ault & Wallis 1913). Bauer (1913) considers the observations made on these voyages to be reliable to 'within one degree and even one-half degree, or as closely as he generally observed the Sun's amplitude'.

(39) Weyer (1895) gives 7° 12′ W read from Halley's chart. This is a reasonable interpolation between the 7° and 8° isogonics on either the World chart or the Atlantic chart.

(40) Given by Churchman (1794) without reference or observer.

(41) Listed by Becquerel (1840), who gives no references. Raulin (1867) ascribes the 1700 value to Halley.

(42) From the Royal Society *Journal Book*: '1701, May 7. M[r] Halley tried the Experiment of the Variation of the Needle this day, with the two Needles which he had with him in his late Voyage: and by the One the Variation was 7°. 40′. by the other 8°. 00″. W.'

(43) From the Royal Society *Journal Book*, 1702, July 8: 'M[r] Halley Observed the Variation of the Needle, which was found to be 8° $\frac{1}{2}$ Westward, or very near it.'

(44) From the Royal Society *Journal Book*, 1711, October 18: 'The Minutes of y[e] last Meeting being read, and mention made of y[e] Variation, of y[e] needle, D[r] Halley was desired to take y[e] Variation this Year at Gresham College, and assist in fixing a new Meridian in some convenient place in the House or Repository of y[e] Society in Crane Court, against y[e] Year ensuing.' '1716, May 24. Dr. Halley Reported that he had Drawn a Meridian Line on the Stone Erected

in the Society's Yard before the Repository, and that the Variation was found at present to be full Twelve Degrees.' This observation is also published by Halley (1716).

(45) Given by Lloyd (1874) without reference or observer.

(46) In his manuscript Journal of Observations made on the Variation of the Magnetic Needle, in 1722 & 1723 (Royal Society Library reference Cl. P. ix(2)33), Graham lists more observations than he published (Graham 1724, see note 47), including over 50 made between 27 August 1722 and 5 February 1723. These are obviously less reliable than his subsequent series, varying from 13° 28′ to 14° 30′ W (mainly due to a change of site within his house) with a mean value of 14° 9′ W. He notes that the value of 'greater than 13°:45′ and less than 13°:50′' obtained on 27 August 1722 was consistent with a similar measure he made on the marble stone in the Royal Society's garden at Crane Court.

(47) Graham (1724, p. 107; see also p. 408): 'From *February 6* 1722 to the 10th of *May* following, I made over a thousand Observations in the same Place; and the greatest Variation Westward, was 14° = 45′, and the least – 13° = 50′. It was seldom less than 14°, or greater than 14° = 35′.' Note that Graham gave his dates in the Annunciation style, with the year beginning on March 25. Thus there is no conflict with his subsequent quotation of these results (Graham 1749) as 14° 17′ W 'towards the beginning of the year 1723.' Most authors give the year as 1723, but Walker (1794) gives 'Graham, 1722, 14°. 22′ W', Thomson (1813) gives '1722 14° 20′ W Graham' and Bauer (1895) gives '1722 Graham 14°. 2?'.

(48) Quoted by Churchman (1794) and Walker (1794), but with no reference or observer.

(49) Given by Guillemin (1891) without reference or observer.

(50) Atkinson (1744, p. 255) gives a worked example of the determination of declination, giving 16° 30′ W at latitude 51° 32′ N, but with no date or longitude.

(51) Graham (1749). Means of twelve observations made at his house in Fleet Street. He is a little sparing with his dates, so his table is reproduced below, with inferred dates given in parentheses and yearly means added:

'Some observations, made during the last 3 years...

| | | | | | | |
|---|---|---|---|---|---|---|
| 1745 | March | 26... | 17° | 0′ W | 1745.2 | 17° 0′ W |
| (1745 | March) | 29 | 17 | 0 | | |
| (1746) | March | 18 | 17 | 10 | 1746.5 | 17° 16′ W |
| (1746 | March) | 21 | 17 | 10 | | |
| (1746) | April | 22 | 17 | 15 | | |
| (1746) | May | 4 | 17 | 18 | | |
| (1746 | May) | 14 | 17 | 20 | | |
| (1746 | May) | 16 | 17 | 15 | | |
| (1746) | Dec | 18 | 17 | 25+ | | |
| (1747) | Febr | 24 | 17 | 30 | 1747.6 | 17° 35′ W |
| 1747 | Dec | 19 | 17 | 40 | | |
| (1748) | Jan | 4 | 17 | 40–' | 1748.0 | 17° 40′ W. |

(The paper was read on April 21, 1748.) The same dates were inferred by Hansteen (1819). Felgentraeger (1892) quotes 17.32° for 1746 (which is the mean of all twelve observations),


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noting that these are the first useful observations in which the diurnal variation is taken into account. Weyer (1895) deduces similar means including: 1746.3, 17° 15′ W (mean of seven observations) and 1747.5, 17° 35′ W (mean of two observations). Becquerel (1840, p. 252) gives 17° 48′ for 1748. Gaibar-Puertas (1953) gives 1745, −17° 05′, misquoting Abbadie (1890).

(52) Mountaine & Dodson (1758, p. 18):

'The following are *Dr. Bradley's* Observations made at the Royal Observatory at *Greenwich*

| | Variation West | Dip |
|---|---|---|
| 1749 *Jan.* 7 | 17 d. 22½ m. | 73 d 30 m |
| 1750 *June* 24 | 17 25 − | 73 30 |
| 1752 *Aug.* 28 | 17 55 + | 73 25 − |
| 1754 *June* 25 | 18 03 | 73 25 − |
| 1756 *Nov.* 16 | 18 33 | 73 25 − |
| 1757 *Aug.* 5 | 18 30 to 35 | 73 15 to 25' |

(53) Canton (1759) gives 2708 observations made throughout 1759 at Spital Square (including some made after the paper was read). He remarks that 'the absolute variation of the needle westward, or the angle it made with the true meridian line at the respective times...differs less than two minutes of a degree from that at Greenwich, where the reverend Dr. Bradley was so kind as to give me several opportunities of taking it, in his presence, by the curious apparatus for that purpose, belonging to the royal observatory'. The mean of twelve monthly means is 19° 03′ W. Felgentraeger (1892) gives 1759.29 Canton 18.97°, which he obtained by graphical interpolation from the night-time values observed in January and July (the two least disturbed months).

(54) Gilpin (1806) quotes this value 'Obligingly communicated by his son, the present Dr. Heberden.' Dr Heberden senior had his practise in Cecil Street, which was probably the site of the observation. Becquerel (1840) ascribes the observation to Gilpin.

(55) Observations made in the Royal Society rooms at Crane Court are listed (anonymously) for each year from 1774 to 1780 (see also note 56). Their means are as given in table A 9. The

TABLE A 9

| year | no. of obs. | between | mean $D$ | mean dip | reference (*Phil. Trans. R. Soc. Lond.*) |
|---|---|---|---|---|---|
| 1774 | 60 | Aug. 21, Sept. 5 | 21° 16′ W | — | 1775 **65**, 165 |
| 1775 | 60 | June 18, July 4 | 21 43 W | 72° 30′ | 1776 **66**, 351–352 |
| 1776 | 66 | June 21, July 7 | 21 47 W | 72 30 | 1777 **67**, 383–384 |
| 1777 | 56 | July 11, July 24 | 22 12 W | 72 25 | 1778 **68**, 599–600 |
| 1778 | 57 | June 29, July 13 | 22 11 W | 72 26 | 1779 **69**, 321–323 |
| 1779 | 56 | July 2, July 15 | 22 20 W | 72 21 | 1780 **70**, 305–306 |
| 1780 | 56 | June 5, June 18 | 22 31½ W | 72 17 | 1781 **71**, 225–226 |

$D$ values have been corrected for 'instrumental error'. This correction is the angle between the magnetic and geometrical axes of the compass needle, determined by inverting the needle (Cavendish 1776). In 1774, the correction was found to be 10′ E; from 1775 to 1777 it was 'insensible'; in 1778 (following an alteration to the needle) it was 9¼′ E; in 1779, 9½′ E, and for 1780 we have assumed it to be 9½′ E.

The published mean for 1779 is 22° 28′, but internal evidence suggests it should be 22° 20′. Hansteen (1819) ascribes the $D$ observations of 1774 and 1775 to Cavendish (see note 56). The 1775 $D$ value is given for 1777 by Raulin (1867); Gaibar-Puertas (1953) gives it as 21° 44′ owing to a slight error in converting Abbadie's (1890) value from centesimal grades to degrees.

Felgentraeger (1892) gives 1778.51, 22.238° and 1779.52, 22.492° for *D*, the latter being the published value before correction for instrumental error. The unreferenced value of 1779.02, R. Soc., 22.36° given by Bauer (1895) is the mean of the values given by Felgentraeger for 1778 and 1779. Rees (1820) gives 22° 10′ for 1780, which is the mean of the Royal Society observations for 1779 and 1780, corrected (by $15\frac{1}{2}'$) to the Marlborough Street site (see note 56).

(56) Cavendish (1776) describes the Royal Society's magnetic instruments, and finds a site difference of $15\frac{1}{2}'$ between Crane Court and the garden of a house in Marlborough Street, about $1\frac{1}{4}$ miles west of Crane Court. The observations made at Crane Court were believed to be affected by iron in the building, and the intention was to correct them to an iron-free site.

Mean of 29 observations made with the Royal Society instrument in garden, Marlborough Street between 21 July and 1 August 1775: 21° 29.4′ W.

Mean of 29 simultaneous observations made in the house, Marlborough Street: 21° 30.7′ W.

Mean of 13 observations made with the Royal Society instrument at Crane Court, 2 and 4 August: 21° 46.5′ W.

Mean of 13 simultaneous observations made in the house, Marlborough Street: 21° 32.3′ W.

The weighted mean of the Marlborough Street observations is 21° $30\frac{1}{2}'$ W for 1775.6. This may be the source of the unreferenced value of 21° 30′ for 1775 given by Walker (1794). It seems likely that Cavendish was responsible for all the Crane Court observations (see note 55), but there is no direct evidence for this.

(57) In a letter from William Cragg of 25 Princes Square, Ratcliffe Highway to Thomas Young (Secretary to the Board of Longitude) dated 9 February (18)'25: 'I have recollected, and found, a Copy remarks, by Middleton in 1778. Of the following experimentals... Middleton at London in 1778 19° 20′ West.' (Board of Longitude papers **32** (R.G.O. **571**), §39, p. 477.)

(58) Rees (1820); no source or observer.

(59) Gilpin (1806). Observations made in the Royal Society rooms in Somerset Place (corrected to Somerset House woodyard by subtracting 5.4′) with the instrument described by Cavendish (1776). Each monthly value given in Gilpin's Table III 'may generally be considered as a mean of 600 observations.' The results quoted here are means of all the monthly values available for each year, as follows:

1786, September–December, inclusive;
1787 and 1793, January–December, inclusive;
1788, January, June, July and October;
1789, June and December;
1790, January and July;
1791, January, April and July;
1792, January, May, and August–December, inclusive;
1794, January, July, August and September;
1795–1805 inclusive, March, June, July, September and December.

Other sources quote these results in slightly different ways. Gilpin (1806), in a separate table, gives 23° 19′ for 1787, 23° 57′ for 1795, 24° 6′ for 1802 and 24° 8′ for 1805, which are means of June and July only. Rees (1820) gives values which appear to be means of June and July for 1787, 1797—1802, and July only for 1803–1805. The list of Hansteen (1819) contains numerous minor errors. Becquerel (1840, p. 252) gives 23° 89′ for 1790, which is clearly a misprint of 23° 39′, given correctly on p. 251. Becquerel (1840, p. 251, but not pp. 214 or 252) also gives

24° 36′ for 1800; this may be a misprint of 24° 3.6′, which is Gilpin's figure for March 1800. Felgentraeger (1892) makes small adjustments to correct for an empirically deduced annual cyclic variation. Gaibar-Puertas (1953) gives −23° 22′ for 1786 and −24° 07′ for 1800, misquoting Abbadie (1890) and erroneously referencing Bauer (1897). Churchman (1794) uses the 1794 value in several numerical examples, but ascribes it to the Royal Observatory, Greenwich. He also publishes a letter he received from Sir Joseph Banks, President of the Royal Society, dated 1 September 1787 and containing the following: 'The Royal Society having lately removed to a new house, the first series of observations relative to the variation is only now in its course. I cannot therefore tell you with the utmost precision what the variation is there, our instrument at present gives 23° 8′ West...'. This value is also quoted by Weyer (1895) with Banks as the observer.

The Meteorological Journal of the Royal Society (*Phil. Trans. R. Soc. Lond.* 1805 Appendix to part I, p. 27) gives monthly means for 1804 which are all 2.4′ greater than those in Gilpin's paper, but the Meteorological Journal for the following year contains the following: '*Note.* Subtract 2′ from the variation of last year, for the error of the instrument.' The Meteorological Journal for 1805 (*Phil. Trans. R. Soc. Lond.* 1806 Appendix to part I, pp. 26, 27) gives the declination for June only, and agrees with the June value of 24° 7.8′ given by Gilpin (1806).

(60) Until 1823, the Royal Society frequently included values of *D* and dip in its Meteorological Journal which was appended to part I of *Philosophical Transactions* (except for 1810, when the magnetic data appeared on page v of part II, and 1823, when the magnetic data for 1821, 1822 and 1823 were on page 152 of part II). The 1824 value is the final entry in a table 'furnished by the Royal Society' to Boner (1825); all his other entries agree with those given in *Philosophical Transactions*.

*Declination.* The data are for the following months:

1806, 1808, 1809 and 1815–1823 inclusive, June;
1807, 1811 and 1813, September;
1812, October;
1814, June, July, August and September.

Thomson (1813) quotes the 1811 value and ascribes it to Lee. Hansteen (1819) quotes the 1809 and 1814 values, ascribing them to Gilpin. Becquerel (1840) quotes values which agree with those given here within 1′ for all years (except 1813 where he has 24° 20′ and 1814 for which he gives no value), and ascribes those from 1806 to 1812 to Waddell, and those for 1813 and 1815–1823 to Beaufoy. Raulin (1867) quotes these results, with numerous minor errors, and ascribes them all to Gilpin: Raulin's 1814 figure is further corrupted by Gaibar-Puertas (1953), via Abbadie (1890).

*Dip.* Only five values of dip are given, the first being that of Gilpin for 1805 (see note 94); the others are as follows:

June 1808, dip 70° 1′ (*Phil. Trans. R. Soc. Lond.* 1809, Appendix to part I)
September 1811, dip 70° 32′ 30″ (*Phil. Trans. R. Soc. Lond.* 1812, Appendix to part I)
June 1818, dip about 70° 51′ (*Phil. Trans. R. Soc. Lond.* 1819, Appendix to part I)
'Mean variation of the magnetic needle
June 1818...24° 14′ 47″ west
June 1820...24° 11′ 44″ west
Dip. about 71.6' (*Phil. Trans. R. Soc. Lond.* 1821, Appendix to part I).

The final entry has been quoted in full to show the ambiguity in both the value and the date of the dip observation. The final two values of dip are distinctly anomalous, and Sabine (1822) suggests that this is because they were made in a built-up area. He quotes the final value as '71° 6′ or 71° 42′', the confusion arising because a decimal point was (and occasionally still is; see, for example, *Times Atlas*, 1967) commonly used to separate degrees and minutes.

(61) Observations made by Beaufoy using a compass theodolite by Dolland. He observed $D$ with two magnets at morning, noon and evening of most days, though the evening observations were omitted during the winter months. From 30 March 1813 to the end of September 1815, the site was Beaufoy's private observatory at Hackney Wick (Beaufoy 1813, 1814, 1815). Observations were resumed at his new observatory at Bushey Heath, near Stanmore, in April 1817 and continued until December 1820 (Beaufoy 1817, 1819, 1820, 1821), with an additional month (March 1822) to confirm that $D$ had indeed passed its most westerly value (Beaufoy 1822). The results are published in monthly tables with occasional summaries. The values given here are derived from Beaufoy's monthly means, giving equal weight to morning, noon and evening data, even though there are fewer of the latter. Becquerel (1840) gives 1813, Colonel Beaufoy, 24° 20.17′. For 1818, Wolf (1872) gives 24° 38′, Fleming (1897) gives 24° 34′ and Mascart (1900) gives 24° 30′ 'max oest', but none give any further details.

(62) Given by Lloyd (1874) without reference or observer.

(63) Before starting his regular observations (see note 64), Pond made several 'trial runs', experimenting with different needles, observing at different times of day, and recording the results in a notebook. Such observations were made on 82 different days between 6 July 1817 and 11 March 1818. Their mean is 24° 12′.

(64) Pond (1820, 1824) gives observations made at Greenwich with Dolland's needle at 8 a.m., noon, 4 p.m. and 8 p.m., from 9 June 1818 to the end of 1820. The tables have many gaps, but most days are represented, if not all hours. The following notes are included: 1818 September 13: 'Some Iron was found on the outside of the building which damaged† the Needle', 1818 October 25: 'The Ivory Circle taken away and replaced by a Brass one.'

The Abinger yearbook for 1933 (see note 76) gives annual means based on Pond's data as 1818: 24° 19.4′ (mean of 7 months, June–December) and 1819: 24° 21.6′. 'Corrections for a presumed diurnal inequality have been applied to the monthly means according to the hour of observation, the quantities being derived from a year – 1910 – in a corresponding relation to the cycle of solar activity.' The 1934 yearbook includes also the 1820 data of Pond, and revises the 1818 and 1819 values, with corrections applied for diurnal variation based on 1909, 1910 and 1911, to 1818, 1819 and 1820, respectively. These are the values tabulated here. It is not clear why the 1819 value should have changed, unless the 1933 calculations were later found to be in error. Although the last published values were for 1820, Pond's observations were continued until 3 May 1824 (with the omission of September and October 1822), and are recorded in manuscript. These values have been adjusted for diurnal variation by using corrections based on 1911–1914 for 1821–1824, respectively. The following notes appear: 'February 10' (1823) 'examined the Circle by the Magnetic Transit and Meridian Mark and found The Variation marked 3′ too great' and on the last page of the observations 'By examining the Instrument it appears to have given the Variation $3\frac{1}{2}$ minutes too Great.' Accordingly, 3′ has been subtracted from the 1822 and 1823 values, and $3\frac{1}{2}$′ from the 1824 value.

† In Pond's original manuscript, this reads 'deranged'.

(65) Observations made at Woolwich by Royal Navy personnel before leaving on overseas surveys. From manuscripts in the archives of the Geomagnetism Unit of the Institute of Geological Sciences.

(66) Sabine (1870). Bauer (1895) gives: 1837.50 J. C. Ross 23.60°.

(67) Sabine (1839) gives an observation by Ross at Bushey as: April 3 1838; 23° 59′ 24″ W 'being the *mean* variation at the epoch named, obtained by observations repeated every fifteen minutes from 7 a.m. to 7 p.m. for several successive days'.

(68) Observations made at the Royal Greenwich Observatory at intervals of 5 min throughout the four international 'term-days' of 1839 (Airy 1840) using a magnet 2 ft long, made by Meyerstein of Göttingen, on an 8 ft 9 in suspension, observed through a theodolite. 'The observations were distributed among the six assistants and myself.' The daily means are as follows:

| 22/23 Feb. | 24/25 May | 30/31 Aug. | 29/30 Nov. |
|---|---|---|---|
| 23° 21.27′ W | 23° 0.64′ W | 23° 5.27′ W | 23° 4.73′ W |

These give a grand mean of 23° 8.0′ W.

Similar observations for the term-days of 1840 are given by Airy (1842). The daily means are:

| 28/29 Feb. | 10/11 May | 28/29 Aug. | 28/29 Nov. |
|---|---|---|---|
| 22° 56.76′ W | 23° 3.65′ W | 23° 38.09′ W | 23° 23.62′ W. |

The observations before August 1840 were made in the presence of a copper damping-bar 'which appeared to exercise a magnetic action' (Airy 1842). The effect of the bar appears to have been to decrease the declination by 36.6′; hence the corrected mean values of 23° 44.6′ W for 1839 and 23° 33.8′ W for 1840.

(69) The magnetic station of the Royal Greenwich Observatory commenced regular observations on 8 November 1840 and remained in operation, more or less continuously, until the end of May 1926. Details of the observations, instruments and personal establishment are given in annual volumes published by the observatory, usually as part of *Greenwich Observations*, but for some years separately as *Magnetical and Meteorological Observations made at the Royal Observatory, Greenwich*.

*Declination observations*. In 1838 the Meyerstein magnet (see note 68) was installed in the south arm of a new, iron-free, cruciform building in the observatory grounds. Declination was measured at intervals of 2 hours throughout the day and night (excluding Sundays), from November 1840 until the beginning of 1848, when photographic registration permitted reliable interpolation over longer intervals, and the observations were reduced to four each day. The Meyerstein magnet continued to be the absolute declination instrument until 1901.0. Photographic recording of the variations in declination, horizontal and vertical intensity was introduced in 1847. During the first half of 1864 a basement was excavated under the magnetic observatory to provide a thermally stable environment for new photographic recording instruments, which were installed in the same year. In the 1864 yearbook of the Royal Greenwich Observatory Airy writes: 'As none of the observations made in the room were entirely satisfactory, I have thought it best to suppress their printing, preserving them in manuscript for reference....' However, Raulin (1867), apparently quoting a letter from Airy, gives 20° 40′ W for 1864. The new declination variometer magnet by Troughton and Simms was similar to the Meyerstein and mounted vertically below it, to avoid mutual interference. Because of secular change, it was necessary to move the Meyerstein magnet more and more to the west so that it could be observed from the fixed pier of the theodolite, but tests in 1887 and 1889 suggested that the resulting mutual interference was neglible. More serious was the introduction of iron into new buildings, in the vicinity of the magnetic observatory, from July 1895, the effect of which was to increase $D$ by about 4′, until 1899 when the increase was 10.8′. From August 1896 supplementary observations of $D$ were made with a new declinometer based on a hollow cylindrical magnet (Elliot No. 75) at a 'clean' site in Greenwich Park, 350 yards east of the observatory, and the mean declination was corrected to this site. A new magnetic pavilion on the Greenwich Park site was completed at the end of September 1898. At 1901.0 the Meyerstein magnet was finally dismounted and the Elliot No. 75 declinometer in the new pavilion became the absolute declination instrument. Photographic registration continued in the magnetic observatory basement until 1915, when it was transferred to a new magnetograph house 50 ft northwest of the magnetic pavilion.

*Dip observations*. From 1843, dip was measured with a 9-inch dip circle by Robinson ('one of the last instruments completed by that artist before his death') in a small wooden hut 64 ft SSE of the magnetic observatory. Observations were made approximately weekly at 9 p.m. and 3 a.m., and, from 1852 to 1855, also at 9 a.m. In the 1856 yearbook Airy writes: 'In the Spring of the year 1857, upon a careful examination of the needles and their mounting, defects were discovered which tended to throw great doubt on the accuracy of the results for Dip through several years. In the first place, it was found that, upon raising the pivots from their agate bearings, the upper end of the needle came in contact with the interior of the graduated circle, and there seemed to be evidence that it had sometimes struck with considerable force. The effect of this would be to create and to increase unsteadiness in the connexion of the axis with the needle, and in all cases so to disturb the relative position that the apparent Dip would be increased. In the second place, the different parts of the apparatus interfered with each other in such a way that it was difficult to clean the agates properly; and this would introduce irregularities.

'Under all circumstances, it appeared best to supress the observations of Dip for the year 1856.

'It is to be feared that the results given by the observations of some years past are too great by several minutes.' Nevertheless, yearbooks from 1910 quote an annual mean dip for 1856 of 68° 43.5′. Airy then set about designing a new and improved form of dip circle, and in October 1861 the 'Airy apparatus', constructed by Troughton and Simms, replaced the old circle, introducing a discontinuity of about 7′. In addition to 3-, 6- and 9-inch needles (which produced systematically different results), some flat, loaded needles were tried; but these were abandoned after a few years and their results omitted from the means. The frequency of observation built up steadily from one per week to about twelve per month by 1870, and then remained at that level.

In the summer of 1863 the dip hut was removed, and dip was subsequently measured in the most westerly of seven 'magnetic offices' near the south boundary of the observatory. The erection of telescope domes necessitated a further change of site in the spring of 1883, this time to the New Library, and again, at the end of September 1898, to the magnetic pavilion in Greenwich Park.

Schuster (1891) suggested that the discrepancies between the results from needles of different length were the result of flexure, the shorter needles giving more reliable results; so from 1893



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the annual means were based on results from the 3-inch needles only. It was not until 1910 that the real explanation of the discrepancies was given: that the true dip is obtained from the mean of the tangents (not the angles) of the results obtained with the needle magnetized first in one direction, then the other. Corrections for this effect, back to 1868, and for level error, back to 1875, are given in the 1910 yearbook, together with a list of corrected annual means.

A dip inductor was purchased from the Cambridge Instrument Company in 1912, used experimentally in 1913, and in 1914 adopted as the standard dip instrument in place of Airy's apparatus, although weekly observations were still made with the latter for another year. The practice of correcting the dip observations for diurnal variation, before calculating the annual mean, was also introduced in 1914. In the 1914, 1915 and 1916 yearbooks the annual mean dip was given as 66° 51.3′, 66° 52.0′ and 66° 52.8′ (though the 1914 value was wrongly entered as 66° 51.2′ in the summary of annual means until 1920). In 1926, the values were revised to those given here, derived from the annual means of horizontal and vertical intensity, thus correcting for the non-uniform distribution of absolute dip observations throughout the year.

*Personnel.* In 1840 the Astronomer Royal (George Bidell Airy) formed a Magnetical and Meteorological Department with James Glaisher as Superintendent, and two junior staff. The number of juniors was increased to three from 1843 to 1848, then reduced to two again as photographic registration eased the observing burden. From 1852 Glaisher had one assistant (Thomas Downs, who had joined the Department in October 1845) and two, three, or four supernumary computers. In 1864, William Carpenter Nash succeeded Downs as assistant, first to Glaisher and then (from 1875) to William Ellis, who was Superintendent until 1893; he finally became Superintendent himself from 1894 to 1903. Nash had a staff of five computers one of whom, David J. R. Edney, was promoted to established computer in 1896 and to junior assistant in 1912. Edney retired on 20 June 1915. Walter William Bryant became superintendent in 1904 in succession to Nash, and was himself succeeded (following his death on 31 January 1923) by William Moody Witchell. The department reached its maximum size in 1915 when, besides Bryant and Edney, it employed four computers and three Belgian refugees. Edney was not replaced (until G. F. Wells became junior assistant on 17 May 1923), and from 1918 to 1922 Bryant had only three computers to assist him. One of these was Miss E. D. Lang, the first woman to work in the department.

The observers of dip are usually specified in the yearbook. Those named in table A2 are the observers responsible for all but a few of the year's observations. The remaining few were made by various people such as the Astronomer Royal, Lieutenents Rikatcheff and Ielagin of the Imperial Russian Navy, Balfour Stewart of the Kew Observatory, and a few by Sydney Chapman in 1911 while he was Chief Assistant at the Royal Observatory. These appear to be the first, and almost certainly the least, of his many contributions to geomagnetism!

It is less easy to ascribe the $D$ observations to individuals as the tabulated means result from direct measurement of declination, scaling and calibrating photographic records, and much calculation, probably involving all members of the department. For this reason the $D$ observations are credited to the observatory (as is also the case for dip when the list of observers becomes obscure or lengthy). Mention should, however, be made of Nash's contribution. As assistant to two meteorologically inclined Superintendents and later as Superintendent himself, he appears to have been responsible for almost all of the direct magnetic measurements and instrumental adjustment for nearly forty years.

(70) The Kew Observatory is situated in the Old Deer Park, Richmond, and, since 1842, has

primarily been concerned with meteorology. According to Scott (1886), the first magnetic observations were made there in 1850, though Sabine (1870) gives a value of declination for Kew Observatory dated 1842.5. However, it was not until 1856 that regular monthly observations of dip and horizontal intensity were commenced, followed in 1858 by $D$ observations and regular photographic recording of the variations. Magnetic observations continued to be made at Kew until Chree's retirement at the end of 1924, in spite of the fact that, for at least the last ten years, the site had been severely affected by interference from electric trams. The observations were made in a wooden hut, copper fastened, 300 ft from the observatory building.

The results for years before 1870 appear in various places: Sabine (1861, 1863); Stewart (1866, 1870); Black (1905); and an unpublished manuscript dated June 1872. From March 1869 until 1901.0 the results are published in the *Proceedings of the Royal Society of London* as part of the annual *Report of the Kew Committee*, except for the final year when, as the result of an administrative change, they were part of the *Report on the Observatory Department of the National Physical Laboratory*. Reports for subsequent years up to 1909 are published by the National Physical Laboratory. From 1910.5 the Kew Observatory became the responsibility of the Meteorological Office, who published the results in the *British Meteorological and Magnetic Year Book* until 1922, and then in *The Observatories' Year Book*.

*Declination observations*. The absolute declination instrument (which was also used for horizontal intensity measurements) was a unifilar magnetometer, made by William Jones. Absolute observations were made monthly at first, then twice each month, and eventually weekly. Annual mean values for 1858–1862, based on hourly mean values, but excluding disturbed data, are given by Sabine (1863) to a tenth of a second of arc, misquoted by Gaibar-Puertas (1953) and correctly quoted (with some rounding) by Walker (1866), Bock & Schumann (1948), Black (1905), and in an unsigned manuscript note dated June 1872. The latter two references appear to be the only sources (apart from Gaibar-Puertas 1953) of annual mean data for the years 1863–1868 (though Evans (1872) gives the somewhat unlikely value of 20° 50.0′ for 1865 'obtained through the kindness of the observatory superintendent, Samuel Jeffery, Esq.' and Guillemin (1891) gives a value for 1863 rounded to the nearest minute). The exact agreement between these two sources and with other sources for earlier years gives some degree of confidence in them. The manuscript note states that the means for 1862–1866, 1868 and 1869 were 'derived from Hourly Observations' and those for 1867, 1870 and 1871 were 'from Periodical Observations corrected to Mean'. These means are tabulated for 1869–1871 in preference to the following values, which are means of the monthly absolute observations given by the Kew Committee: 1869 (April–December only) 20° 30.0′ W; 1870 20° 24.0′ W; 1871 (except June) 20° 16.2′ W. For 1872–1875 we have a straight choice between Black (1905) (whose unreferenced data for Kew are for this interval unsupported by an alternative source) and the monthly absolute observations of $D$ made at noon and listed each year (October–September) by the Kew Committee. We have opted for the latter in table A1, but, for completeness, Black's values are: 1872 20° 0′ 31″ W; 1873 19° 57′ 44″ W; 1874 19° 51′ 58″ W; 1875 19° 41′ 14″ W. The remainder of Black's values (for 1876–1882) agree with those deduced from the data of the Kew Committee. Guillemin (1891) gives 19° 7′ for 1879. The Kew Committee monthly mean absolute data observed at noon continue to be the source of listed annual means until 1889. For the twelve months from October 1889 to September 1890, the report of the Kew Committee gives mean monthly values 'corrected for the diurnal range' as well as means of the absolute values. The correction is appreciable: 5.6 ± 0.2′ E based on the twelve differences, and the value given in table A1 is the mean of the corrected values from January to September.

From 1891, the form of the annual report changes, giving 24 hourly mean values for each month based on five selected quiet days. The interval covered by each report changes from October–September to January–December, thus omitting October–December of 1889. From 1892, annual mean values based on the hourly mean tabulations are given in the text of the report (the 1892 report including values for both 1890 and 1891). Chree (1904) critically examines the annual mean values of all elements at Kew for the interval 1890–1900, but makes no adjustment to the $D$ values.

More detailed yearbooks were published from 1911, but the annual mean continued to be based on the five selected quiet days of each month, until observations ceased at the end of 1924.

*Dip observations.* From 1856 until October 1860, between 0 and 38 observations were made each month with any of twelve dip-circles constructed by Henry Barrow. Thereafter, Barrow No. 33 was adopted as the observatory absolute instrument, and two observations were made on successive days near the middle of each month; this was later increased to one observation each week, at which level it remained until the end of 1924.

Details of all the observations from November 1857 to December 1860 are given by Sabine (1861) who also quotes the means as follows: 'July 1, 1858, mean of 115 observations...68° 23′.2'; 'July 1, 1859, mean of 96 observations...68° 21′.5'; 'July 1, 1860, mean of 71 observations... 68° 19′.8' (from 3½-inch needles); 'July 1, 1860, mean of 20 observations...68° 20′.04' (from 6- and 9-inch needles). However, the date means only that the observations were taken throughout the year; the 1858 mean includes all observations taken between November 1857 and the end of 1858. In a later publication, Sabine (1863) gives monthly means of the absolute observations of dip from April 1857 to March 1863 (with interpolated values for December 1857, and February and June 1859) and from these deduces annual means for years ending on 31 March. Similar 'skew' annual means are given, for the interval from April 1864 to March 1869, by Stewart (1870), and from April 1869 to March 1875 by the Kew Committee. It is these skew means that are quoted by Guillemin (1891) and by Black (1905).

Another set of annual means is given by Stewart (1866): 'During the years from 1856 to 1859 inclusive, monthly observations were made with a circle known as the Kew circle, two needles being always used, and the mean of the two results taken as the true dip.

'From this circle we have the following results:

| Year | Mean dip |
|---|---|
| 1856 | 68° 27′.67 |
| 1857 | 24.36 |
| 1858 | 22.80 |
| 1859 | 20.73 ' |

'In 1859 it was resolved to substitute another circle for the Kew circle as the action of the latter was not considered to be quite satisfactory; and accordingly since this date Barrow's circle No. 33 has been employed.

'From this circle we have the following results:

| Year | Mean dip |
|---|---|
| 1860 | 68° 20′.21 |
| 1861 | 18.21 |
| 1862 | 15.58 |
| 1863 | 12.66 |
| 1864 | 9.88 ' |

Except for 1856 (when we have no other data) there seems no reason to prefer these values to those derived from all the circles before 1860; accordingly, the values given in table 2 are means (from January to December for each year) of the monthly values published by Sabine (1863), Stewart (1870) and the Kew Committee, up to August 1889. The values of Stewart for 1860–1864 given above should agree with the values given in table A2, and the slight differences can only be ascribed to arithmetic errors.

The mean for 1890 is that given by the Kew Committee in their report for 1891, and is based on quiet days only. In a critical discussion of the annual mean data from 1890 to 1900, Chree (1904) revises the values of dip given by the Kew Committee by up to 2.7′ between 1891 and 1896, leaves the 1897–1900 values unchanged, and quotes no value for 1890. Chree's revised values are given in table A2.

Until the closure of the magnetic observatory in 1924, the annual values for dip continued to be means of absolute observations from Barrow No. 33.

*Personnel*. Although never formally a member of the Kew staff (since he was a regular army officer and also had commitments throughout the British Empire), the man most directly responsible for the foundation and organisation of the magnetic observatory at Kew up to 1877 was Edward Sabine. He provided instruments, was responsible for the reductions (at Woolwich), and provided clerical staff in the form of two Royal Artillery sergeants. The Kew staff consisted of a Superintendent, an Assistant (who normally made the magnetic observations) and a number of junior staff.

John Welsh was Superintendent from 1852 until the rigours of magnetic surveying in Scotland led to his early death in 1859, when he was succeeded by Balfour Stewart, who had been Assistant since 1855. Stewart's assistant was Charles Chambers from 1857 until he left for India in 1863, eventually to become director of the Colaba observatory, Bombay. George Whipple, who joined the staff as a 'boy' in 1858, succeeded Chambers as Assistant, first to Stewart and then to Samuel Jeffery (Superintendent from 1871–1876), before himself becoming director from 1876 until his early death, after an illness lasting seven months, on 8 February 1893. Whipple's Assistant was T. W. Baker, who was commended by the Kew Committee for the excellent way he ran the observatory during Whipple's illness and for some months after his death. Whipple was replaced by Charles Chree (6th Wrangler 1883), who was Superintendent from 15 May 1893 until magnetic observations ceased at the end of 1924; Baker remained as Assistant until his retirement in 1912 after 52 years at Kew.

The observers named in tables A1 and A2 are those who were (according to the reports of the Kew Committee) responsible for the absolute observations. In doubtful cases the observations are ascribed to the 'Kew Observatory'.

(71) Given by Wolf (1872) for Greenwich, but without reference.

(72) Evans (1862) gives a table including: 'Woolwich, Compass Observatory, 50° 29′ N, 0° 2′ E, 1857 Jan 1, 21° 46′, Mr. Evans, R.N.' Also quoted by Sabine (1870) who gives the date as 1875.5.

(73) In several of the *Annuaire* of the Bureau of Longitudes, Paris, M. Marié-Davy gives $D$ values for various ports, including London, as follows:

19° 6′ for 15 June 1875 (*Annuaire pour l'An 1876*, p. 534),

19° 4′ for 15 June 1876 (*Annuaire pour l'An 1879*, p. 461),

18° 41′ for 1 January 1879 (*Annuaire pour l'An 1880*, p. 469).



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(74) The sites occupied in 1888 by Rücker & Thorpe (1890) during their first survey of the British Isles included Purfleet (51° 29′ 7″ N, 0° 14′ 58″ E) on 4 April; west of Windsor near the point where the river makes a bend towards the railway bridge (51° 29′ 22″ N, 0° 37′ 25″ W) on 31 May; on Ranmore Common, half way between the post office and church (51° 14′ 38″ N, 0° 21′ 36″ W) on 21 May. These sites were re-occupied in May 1914 by Walker (1919) and in 1926 by the Ordnance Survey (1927). The Ranmore site was re-occupied by O'Beirne (1949) on 8 September 1948 and by observers from the Geological Survey in 1956 (Avann & Barraclough 1975).

(75) Rücker & Thorpe (1896) made a second, more extensive survey of the British Isles for epoch 1890, including many more sites than were used in their previous survey (note 74) and collaborating with several other observers. The sites near London were:

Westerham, in Squeereys Park, (51° 15′ 30″ N, 0° 4′ 12″ E) where Mr Briscoe observed on 24 June 1890;
about 1 mile SE of Swanley Junction (51° 22′ 44″ N, 0° 10′ 43″ E) where Mr Gray observed on 25 June 1890;
near the middle of Riverhead Green (51° 16′ 57″ N, 0° 10′ 5″ E) where Dr Thorpe and Mr Gray observed on 1 July 1890;
Shoreham, in Kent, (51° 20′ 8″ N, 0° 10′ 54″ E) where Mr Briscoe observed on 19 July 1890;
Stanmore (51° 36′ 54″ N, 0° 18′ 35″ W) where Professor Rücker and Dr Thorpe observed on 28 July 1890;
Gravesend (51° 26′ 0″ N, 0° 23′ 25″ E) where Mr Watson observed on 1 May 1891;
Dartford (51° 26′ 15″ N, 0° 13′ 5″ E) where Mr Watson observed on 2 May 1891.

(76) In anticipation of the electrification of railways near Greenwich, a new site for the magnetic station of the Royal Greenwich Observatory was selected at Abinger, about 26 miles SW of the centre of London. The Abinger observatory was in operation from February 1925 until further electrification of railways disturbed the site, and the observatory closed down on 18 April 1957. All the results appear in observatory yearbooks published by the Stationery Office with the following titles: *Results of the magnetic(al) and meteorological observations*... (1925–52); *Results of the magnetic observations made at... Abinger* (1953–5); *Magnetic results 1956* (*Abinger*), and *Magnetic results 1957* (*Abinger and Hartland*).

*Observations*. The absolute declination observations for the whole period were made with a declinometer based on a hollow, cylindrical magnet (by Elliott Bros) observed with a Watts Theodolite, situated in a non-magnetic wooden building. The annual means are based on hourly mean values read from magnetograms, with baseline values determined from the absolute observations. All available days are included. The magnetograms were obtained with Greenwich-style variometers until these were replaced with La Cour variometers in 1938.

Annual mean values of dip are calculated from the corresponding values of horizontal intensity ($H$) and vertical intensity ($Z$), which were based on hourly mean values for all days. Until 1927 the baseline values for $H$ were determined from absolute observations with a Kew-pattern unifilar magnetometer. Thereafter, $H$ was measured with a Schuster–Smith coil magnetometer (Smith 1923). A similar device (Dye 1928) was introduced in August 1928 for absolute determinations of $Z$. Until then the $Z$ baseline had been derived from the $H$ data and measurements of dip (at least twelve each week) made with a dip inductor similar to that used at Greenwich. From observations made near the end of 1928, 'a systematic difference was found to exist between the results from the Coil and the Inductor, the Inductor giving values larger by 21$\gamma$ in the mean'. This was found to be due to wear in the bearings of the inductor. Thus, the adoption of the coil as standard absolute instrument from 1929.0 introduced a discontinuity of about $-0.9'$ in dip. About six observations per week continued to be made with the dip inductor until 1952, and occasional observations thereafter, but these were used only as a check on the Coil magnetometer.

Small discontinuities in $H$ and $Z$ introduced in 1938, 1953 and 1955 did not affect dip.

*Personnel.* Observations at Abinger were made by a resident observer (W. Stevens until 17 July 1939, then E. A. Chamberlain until 31 July 1956), usually with one assistant (H. F. Finch until 18 June 1928, then P. Rickerby until 1 July 1956). From 1954, the staff at Abinger increased to four in anticipation of the new station at Hartland, which was expected to run in parallel with Abinger during the International Geophysical Year (1957.5–1959.0). However, after Rickerby and Wilmoth had gone to Hartland in July 1956, and Chamberlain retired in the same month, only one junior observer, P. Rowe, was left at Abinger, and it proved impractical to continue observations after April 1957, despite weekly visits by Finch and Leaton from Herstmonceux, and casual assistance at weekends.

Supervision of the station, including reduction and publication of data, was by the Magnetic and Meteorological Department of the Royal Greenwich Observatory. W. Witchell was Superintendent of the 'Mag. & Met.' department until his retirement on 26 April 1948 after 25 years in that capacity. He was succeeded by H. F. Finch, who had earlier been junior observer at Abinger.

(77) Regular observations of $D$ have been made at the Admiralty Compass Observatory in Ditton Park, Slough (some 16 miles W of central London) since September 1936. Until June 1970, between 89 (in 1940) and 505 (in 1956) measurements of $D$ were made each year with a Kew-pattern unifilar magnetometer in a non-magnetic hut to the west of 'Turner 1'. The mean number of observations each year was 239. From July 1970 to August 1974 an average of about seven observations each month was made in the 'test hut' to the north of 'Turner 1' with a somewhat less accurate Watts Absolute Compass. Observations with a Kew magnetometer (now adapted for digital read-out) recommenced in September 1974 in a new hut between 'Turner 1' and the moat.

The values given in table A1 are based on monthly means of the original observations (kindly loaned by Mr E. C. Chaston) after they had been corrected for a diurnal variation assumed to be the same as at Abinger for years of corresponding sunspot number. Unless it was stated otherwise, the times of the observations were taken to be civil time. For all except seven of the years (1936, 1941, 1942, 1943, 1963, 1964 and 1975) all twelve monthly means were available. There is an unexplained (and uncorrected) discontinuity of about 3′ after an instrumental adjustment in September 1938. All observations from April 1942 to 26 June 1957 have been increased by 2.5′, after a re-calibration of the azimuth which confirmed the value used, up to 1941. In February 1943 the magnetometer box was found to be warped, causing a displacement of the suspension head. This was probably the reason for the anomalous and erratic observations from December 1942 to February 1943, so data for these months have been omitted. A jump discontinuity of about 13′ resulted from disturbance of the magnetometer on [illegible] June 1955. This corrected a drift that had been accumulating since August 1954. The drift was removed, assuming that it had increased linearly with time. During 1959 and 1960, readings were commonly taken with a new magnetometer in the south park.

These have been decreased by 0.6′ to bring them into accord with the 'old magnetometer' standard.

(78) Norman (1581, ch. 4): '...the declination of the north pole of the touched needle, which for this cyty of London I finde by exact observations to be about 71 degrees 50 mynutes'. He repeats this value in chapter 9. Norman consistently uses the word 'declination' for dip (and 'variation' for $D$) as, for example, in the full title of his book *The new Attractive Containing ae short discourse of the Magnes or Loadstone: and amongst other his vertues of a new discovered secret and subtill propertie, concerning the declination of the needle, touched therewith under the plaine of the horizon Now first found out by Robert Norman. Hydrographer.* The method of observing (with a horizontally pivoted needle) is described in detail, but no indication is given of the date or site of the observation. It is reasonable to assume that the observation was made at '...his house in Ratclif' though Whiston (1721) erroneously refers to Norman as 'a compass maker at Wapping'. The date of the observation is discussed by Mitchell (1939) and the universally quoted 1576 appears to have been originated by Bond (1676); there seems no reason to prefer any other date. Gaibar-Puertas (1953) gives the 'observadores' as 'Borough y Norman'.

(79) The origin of this 'observation' is a note by Edward Wright in his encomiastic preface to *De Magnete* (Gilbert 1600), where he refers to the angle of dip '...*ut in latitudine nostra Londinensi ad gradum ferè septuagesimum secundum*...'; (...in our latitude of London, for example, to about the seventy-second degree...). There is no way of telling if this is an observation or merely a quotation of Norman's result (note 78). Whiston (1721) quotes Norman's value, then cites *De Magnete*: '...it was about 24 years afterward almost 72° as Mr. Wright assures us'. Hansteen (1819) ascribes the observation to Gilbert.

(80) In the second and third editions of *Certain errors*..., Wright (1610, 1657) includes a table of dip for each degree of latitude from the equator to the pole based on the relation

$$\text{dip} = 90-\lambda+(45-\tfrac{1}{2}\theta-\lambda)\ \theta/90\ \text{deg},$$

where $\theta$ denotes latitude and $\cos\lambda = \sin\theta/(2+2\sin\theta)^{\frac{1}{2}}$. This comes from a geometrical construction, apparently devised to give zero at the equator, 90° at the pole and an acceptable value of dip for London. The table and construction do not appear in the first edition (Wright 1599). Mountaine & Dodson (1758) quote a value of 'about 73 d. by Calculation', giving Wright (1657) as their source.

(81) Several indications of dip in London are given by Ridley (1613) as follows: two figures, in chapters 35 and 40, show dip-circles with the needle indicating 72°. The dip-circle shown in chapter 40 surmounts a compass whose needle indicates 10° E, but the plane of the dip-circle is in the true, not the magnetic meridian. If the figure accurately illustrates the experiment and there was no mutual interference between the two needles, the true dip would be 71° 44′. In chapter 39 Ridley gives values of dip for each degree of latitude from 0° to 90°, computed to 1 s of arc using Wright's construction (note 80), though without acknowledgement. Whiston (1721) summarizes Ridley's dip information, writing of dip in London 'where, A.D. 1613, it was between 70° and 73°; but nearest 72°, as Dr. Ridley's Two Schemes of the Dipping Needle, with one of his Tables of its Inclination, imply'. Barlow (1829) gives Ridley, 1613, 72° 30′, which is presumably the mean of the computed and depicted values. Gaibar-Puertas (1953) gives 73° 14′ for 1613, misquoting Abbadie (1890).

(82) Bond (1676 p. 32): '73° 55′, the greatest Inclination here at London, which was in the year 1657.' On page 65 he gives a table including London, 51° 32′ N, 0° 00′, dip 73° 47′. Although published in 1676, it is indicated on page 19 that the book was written in 1673. There is some mutual inconsistency, however, since we have 73° 47′ for 1673, 73° 55′ for 1657, and a note on page 19 stating that dip altered by less than 6′ from 1657 to 1673. No experimental details are given, and it may be that these values are further examples of Bond's calculations (see notes 26 and 27). Cavendish (1776) quotes Bond, 73° 47′ for 1676, but most other authors follow Whiston (1721) who writes of London dip: 'Where it was, A.D. 1676 about 73° 30′. as Mr. Bond's scheme of the Dipping Needle informs us.' Gaibar-Puertas (1953) gives 1676 73° 50′ Bond, misquoting Abbadie (1890).

(83) From the Royal Society *Journal Book*: 'March 15th 1676/7. Mr Wynne produced two other Inclinatory needles; both which stood true, before they were touched, at any Degree where they were put. And the one of them being touched on both ends stood at 73 d. one way, and 74½ the other way; tryed several times: the other being touched first one end only, stood at 72¼ deg. one way, and 73 d. the other way: but when afterwards it was touched at both ends, it stood at 73¾ deg. one way, and 73¼ deg the other way.' The mean of these observations, giving equal weight to each needle, is 73° 24′. The meeting place of the Royal Society in 1677 was Gresham College.

(84) From Hooke's diary (Robinson & Adams 1935), reporting a meeting of the Royal Society on Thursday, 21 June 1677: '...Grew read on the use of the gutts and shewd the blind gutt of a horse, and the needles which dippd to between 74 and 75'.

(85) Pagit's experiments on the effect of applying heat to a dipping needle are recorded in the Royal Society *Register Book*, volume 6, page 40. Four experiments were conducted with the needle in the meridian, and for these the dip (before application of heat) was as follows: February 4, 72° 5′; February 5, 72° 2′; February 6, 72°; February 12, 71°. The year was 1684 and the site was probably Gresham College. It is not specified if the 'meridian' was magnetic or geographical; if the latter, all the dip observations should be reduced by about 3′.

(86) Swann (1929): 'A value of 71° 50′ was recorded for the Dip in London in 1576, a value of 74° 30′ in 1700, and the present value is about 67°'. He gives no source for the 1700 value, and its validity is doubtful.

(87) Whiston (1721) includes two dip charts, the first of which gives London, 73¾°, of which he writes on page 91 'myself observed the dipping needle of one foot, unpois'd, the last year 1719'. It seems that the unpoised needle was not reliable since the observations made in 1720 with a poised needle 4 ft long gave over 75°, as did his smallest needles (Whiston 1721, p. 49). The values of dip for 1720 given in table A2 are from a table inset into Whiston's second chart. The value of 75° 10′ frequently quoted in the text is presumably based on these. Hansteen (1819) gives 74° 27½′ for Whiston, which is the mean of the 1719 and 1720 observations: 73° 45′ and 75° 10′. Gaibar-Puertas (1953) gives 1720 75° 13′, misquoting Abbadie (1890) who gives 1720, Whiston, 81.94 g. (≡ 73° 45′) and 83.52 g. (≡ 75° 10′).

(88) Graham (1725) describes eight experiments made on 22 March 1723 with a 12.1-inch dipping needle, mainly concerned with the period of oscillation, but also giving values of dip which vary between 73° 15′ and 74° 30′. He notes, however, that the 90° division was not vertically below the axis of the needle, and that the measures of dip were therefore too small. He then lists 61 values of dip observed (after correcting the error) between 29 March and 2 May 1723. They range from 74° 20′ to 75° 00′ and have a mean value of 74° 41′. The site is probably

the house in Fleet Street where he observed $D$ from 1745 to 1748, and where he died in 1751. These observations have been summarized in various ways; Cavendish (1776) writes 'Mr. Graham in 1723 made it between 73½ or 75°, his different trials varying so much'; Hansteen (1819, p. 44) gives Graham 1723 $\left.\begin{matrix}74° & 0'\\ 75° & 10'\end{matrix}\right\}$ 74° 35′, but later (p. 36 of Appendix) gives Graham $\left\{\begin{matrix}\text{29 März}\\ \text{2 Mai}\end{matrix}\right\}$ 1723 74° 42′. Thompson (1887) gives 1720, 74° 42′ (max), which probably derives from Hansteen (1819), as do the two values given by Raulin (1867) of 1723 Graham 74° 35′ and, separately, 1732 74° 42′ with no observer. Gaibar-Puertas (1953) gives 1723 74° 30′ Graham, misquoting Abbadie (1890) and Mascart (1900).

(89) Graham (1749) gives $D$ data from March 1745 to January 1748, observed in Fleet Street, then writes 'The Inclination of the dipping Needle has been during the same time about 73½ degrees.'

(90) Nairne (1772) describes and illustrates two dipping needles which he made for the Board of Longitude, and gives the results of observations made with them at his house, at 20, Cornhill. With the first needle, on 21 April 1772, he made six observations with one face of the needle east, then west, and repeated the series with the needle magnetized in the opposite sense. Omitting two observations when the end of the axis touched an agate plane, we may obtain four means, one for each orientation, and the mean of these is 72° 17′ (individual values range between 72° 0′ and 72° 30′). A similar, though less extensive, set of observations with the other needle at Nairne's house on 22 April gives 72° 15′. 'Lest any thing magnetical should have affected the needle in Mr. Nairne's house' a further set of observations was made in a room in Birchin Lane, giving 72° 18′. Sabine (1822) combines Nairne's observations with those of Cavendish for 1776 to obtain a mean value of 72° 25′ for 1774, presumably rounded to the nearest 5′. Barlow (1829) gives Nairne, 1772, 72° 19′. Gaibar-Puertas (1953) gives 1772 72° 33′ Cavendish, misquoting Abbadie (1890) who follows Barlow.

(91) Becquerel (1840) gives '1773, 72° 19′, Heberden' for dip in London, with no further details. This may be a misquotation of Barlow (1829) (see note 90). If Heberden was the observer, then the most likely site for the observation would be Cecil Street (see note 54).

(92) The value tabulated for 1775.5 is the 'mean of the four means' based on 68 observations made in the Royal Society rooms at Crane Court between 19 June and 4 July (*Phil. Trans. R. Soc. Lond.* 1776 **66**, 352). Cavendish (1776) describes the instrument (by Nairne) and discusses the observations. He also adds a table giving values of dip observed in the garden of a house in Marlborough Street with various dip circles and needles on 15 April, and 10, 11, 13 and 14 October giving a mean value of 72° 31′ for 1775.7. The Royal Society instrument gave a reading 7′ lower at Marlborough Street than at Crane Court. Hansteen (1855, 1857) gives 'Cavendish 1775,78 72° 31′,0' apparently based on the Marlborough Street data, but ignoring the fact that one of the dates was 15 April, and rounding to 1′, despite the quotation of an extra decimal place. Gaibar-Puertas (1953) gives 72° 34′, misquoting Abbadie (1890).

(93) Becquerel (1840). In his discussion of London dip between 1576 and 1805, Gilpin (1806) makes no mention of such an observation.

(94) Gilpin (1806). Observations made in the Royal Society rooms in Somerset Place (corrected to Somerset House woodyard by adding 20′) using the instrument described by Cavendish (1776). Gilpin's table 5 contains monthly means and the number of 'sets' of observations of dip that contribute to each mean, a 'set' consisting of four measurements (needle

first east, then west; repeated with the poles reversed). The values given here are means of all the monthly values available for each year, as follows:

| | | |
|---|---|---|
| 1786 | Sep.–Dec. inclusive | 28 sets |
| 1787 | Jan.–Dec. inclusive | 171 sets |
| 1788 | Jan. | 15 sets |
| 1789 | Jan. and Dec. | 8 sets |
| 1790 | Jan. | 7 sets |
| 1971 | Jan. | 4 sets |
| 1795 | Oct. | 14 sets |
| 1797 | Oct. | 30 sets |
| 1798 | Apr. and Oct. | 32 sets |
| 1799, 1803 | October | 16 sets |
| 1801 | Apr. | 16 sets |
| 1805 | Aug. | 16 sets |

The excessive change in dip between 1790 and 1791 is probably the result of the introduction of four iron braces into the floor of the room above, about 18 ft from the dip instrument. The correction to the woodyard was determined after the iron was introduced, but Gilpin has applied the same correction to all his observations. The 1805 value is also given in the Meteorological Journal for that year (*Phil. Trans. R. Soc. Lond.* 1806 **96**, end of part I). Barlow (1829) quotes a series of Gilpin values which are those for the first available month of each year, except for 1797, where his value of 70° 59.4′ appears to be a simple misprint. Becquerel (1840) gives '1790, 71° 33′, Gilpin'; unless this is a misprint, it seems likely that Becquerel has attempted to remove the 1790/1791 discontinuity by assuming that the correction to the woodyard was entirely due to the introduction of iron in December 1790, and that no correction should be applied before that date. Walker (1866) gives values of 72° 8.60′ for 1786 and 70° 36.00′ for 1801, both values differing slightly from those given by Gilpin, to whom Walker ascribes (at least) the first value. Raulin (1867) quotes annual means based on Gilpin's data, mostly correctly, but with the following slight aberrations: 1786 September 72° 5′ (cf. Gilpin's 72° 8.1′) and 1797 October 70° 59.4′ (cf. Gilpin's 70° 59.2′). The single value of 71.3° for Gilpin, 1795.0, quoted by Bauer (1895) may be reproduced by taking the mean of all the yearly means, each yearly value being given equal weight.

(95) Quoted by Sabine (1819): sixteen observations by Captain Kater on 13 April 1818 in Regent's Park (51° 31′ N, 0° 08′ W). Christie (1825) ascribes the observation to Kater and Sabine, and rounds down to 70° 34′.

(96) Sabine (1819): sixteen observations by Captain Sabine, March 1819, in Regent's Park.

(97) Hansteen (1855, p. 45), no further details are given.

(98) Sabine (1822) describes several observations made at an iron-free site: 'Whence 70° 03′ may be considered as the mean dip of the needle towards the north in the Regent's Park, in August and September 1821'. He later reports the same results (Sabine 1829) as 70° 04.5′ for August 1821, then (Sabine 1839) as 70° 02.9′ for the middle of August, and again (Sabine 1861) 'The mean of the ten experiments was 70° 2′.9 N corresponding to the epoch 1821.65: the extremes being 70° 00′.1 and 70° 05′.9. The whole of the experiments were made by myself.' Observed between 3 and 10 August 1821 in the nursery garden of Mr Jenkins in Regent's Park using an 11½-inch circle by Nairne. Gaibar-Puertas (1953) gives 70° 08′, misquoting Abbadie (1890).

(99) Christie (1825): '...I have had the opportunities of observing the dip at this place. With a very good instrument, by T. JONES of Charing Cross, having a 7-inch needle, consisting of two circular arcs, on Captain KATER'S construction, the mean of 40 observations, 10 with the face of the instrument east, 10 with the face west, and the same with the pole reversed, gave the dip 70° 15.25 on the 23 d December, 1821, between the hours of 1 and 4 P.M. the observations being made in my garden. With another instrument, also by T. JONES, having an 8-inch rectangular needle, the mean of 40 observations made in my garden, (about a mile from the former place of observation) near noon on the 5th and 6th May, 1824, gave 70° 06.5 for the dip. With the same instrument, but using a needle on MEYER'S construction, the mean of 40 observations near noon on the 8th May, 1824, gave the dip on the same spot 70° 10'.5.' Parry & Foster (1826) refer to 'Mr. Christie's garden on Woolwich Common', and detail observations made there by Foster:

| | | |
|---|---|---|
| 1824 May 5, 5 a.m., needle 2, | 70° 55.94′ | 70° 9.2′ N |
| 1824 May 6, Noon, needle 4, | 70 6.46 | |
| 1824 May 8, $5^h$ $37^m$ p.m., needle 1, | 69 25.2 | |

| | | |
|---|---|---|
| 1825 Dec 4, $11^h$ $10^m$ a.m. to $2^h$ p.m., needle 4, | 70° 10.1′ | 70° 00.4′ |
| 1825 Dec 4, $2^h$ $50^m$ to $4^h$ $37^m$ p.m., needle 2, | 69 54.7 | |
| 1825 Dec 5, $1^h$ $30^m$ to $4^h$ $10^m$ p.m., needle 1, | 69 56.5 | |

The needles were as follows: 'No. 1. A rectangular needle, 7¾ inches in length, constructed by JONES on MEYER's principle, having a light cylindrical arm at right angles to its axis, for screwing on a small brass sphere. 2. The same needle, with a sphere somewhat larger. 4. A plain rectangular needle of the same length as the above.' 'Each of the registered observations on the dip, were deduced from five readings of the needle, in each of its different positions.' Although there are differences in detail, it is fairly clear that Foster's 1824 observations are the same as those described by Christie, Christie's 70° 10.5′ value being the mean of Foster's observations of 5 and 8 May.

(100) Hansteen (1826) gives a table of magnetic intensity and dip, including 69° 57′ for London, but with no date, observer or source (though he mentions Professor Oersted as responsible for some intensity observations made in England in 1823, and presented elsewhere in the paper). Since this value does not appear in his subsequent compilations (for example, Hansteen 1855, 1857), it may well be estimated from earlier data, rather than an actual observation. This value may also be the source of '1826 69° 55′ Hansteen' given by Gaibar-Puertas (1953), since his list of references includes one that is similar to Hansteen (1826) given here, though not cited in connection with this observation. The references he does cite are Arago (1854) and Hazard (1932), neither of which includes the relevant value.

(101) Sabine (1829) details four series of his own observations made with various needles on a 12-in instrument, and one series of observations by Mr David Douglas on a 6-in instrument, all made between 11 and 20 August in the Horticultural Garden at Chiswick, from which he deduces a mean value of 69° 47′. The site was chosen to coincide as nearly as possible with the line of equal dip passing through Regent's Park, which was about 6 miles distant and had become excessively built-up since 1821. Guillemin (1891) gives 69° 49′.

(102) Becquerel (1840) gives '1830 69° 38′ Kater' for London, with no further details.

(103) Hansteen (1855) quotes the mean of eight observations made by L. Segelcke (a

Norwegian sub-lieutenant) in Mr Barlow's garden at Woolwich using an eccentric needle 6 in long, made by Ertel. The first four observations gave a mean of 69° 36.6′; the needle was reversed and the second four observations gave 69° 38.4′. The date is quoted as 1830.91, but is later (Hansteen 1857) given as 1830.31. Raulin (1867) rounds up to 69° 38′ and Thompson (1887) misses badly with 69° 3′.

(104) Fisher (1833) '...experiments made during last summer' (1832, since the paper was received in November 1832 and read in January 1833) 'by Captain Sir Everard Home, Bart. F.R.S. near London...another series had been previously made by myself at London in 1830. The mean between both results is probably nearest the truth...The dip...being 69° 40''. Home's site was probably Ham, see note 105.

(105) Fisher (1838) gives a list of dip observations made by Sir Everard Home, including the following values for Ham, near London:

| | |
|---|---|
| 1833 July 20 and 29, | 69° 52′ 38″ |
| 1834 January 4, | 70° 17′ 42″ |
| 1837 October 6, | 69° 25′ 12″ |

Sabine (1839) writes in a footnote: 'The needle employed by Sir Everard Home...appears... to have given dips exceeding the truth by about half a degree.'

(106) Lloyd, Sabine & Ross (1836) give in their table V: London, August 1834, 69° 18.9′; London, September, October 1835, 69° 17.3′. Their table IV shows that these observations were made by Lloyd at Sir James South's private observatory in Kensington, the former being the mean of three determinations on 28 and 29 August, and the latter the mean of seven determinations on 19 and 22 September, and 23 and 24 August. They also give 69° 17.3′ as the mean dip from '...the recent observations of Captain James Ross in London...eight different needles were employed, and from eight to ten observations were made with each, the result of each separate observation being the mean of eighty readings'. Sabine (1839) implies that these observations were made in 1835 at Westbourne Green.

(107) Sabine (1839) reports on the magnetic survey of Great Britain including numerous dip observations made in or near London. He lists individual observations in a separate table for each observer and summarizes them in other tables, though with some inconsistencies. Further summaries appear later (Sabine 1840, 1870). A few additional observations, unconnected with the survey of Great Britain, were made by Bache (1841). The values given here in table A2 are means of all observations for a single site made during the same year, regardless of observer.

The value for 1836 by Lloyd is based on four observations made on 19 and 21 April and another four made on 4 October; these are almost certainly the data which Hansteen (1855, 1857) quotes as 'Lloyd 1836.53 69° 22′.5', rounding to 0.5′. Raulin (1867), presumably quoting Hansteen, has type-setting trouble and ends up with 1836 Lloyd 22° 5′! (He has similar trouble with '1837 Ch. R. J. S. 20° 0″ and '1838 Phil. Fox 18° 9'' which are presumably misquotations of Hansteen (1855), who gives 'Philips, Ross, Johnson, Sabine, 1837.63, 69° 19′.9' and 'Philips Fox, 1838.30, 69° 18′.9' as well as other values based on Sabine's 1839 report.)

Sabine's 1837 observations were made in the cloister gardens, Westminster, on 27 July (mean of two), but are incomplete, as the polarity of the needle was not reversed; his tabulated value includes a 'correction' for this, and a small arithmetical error. Similar observations in Regent's Park on 14 and 15 November 1837 have been omitted from the mean, since Sabine and Captain Johnson each made an additional seven complete sets of observations there on 15 and 16

November. The site was that used in 1821, but the more recent value is considered to be anomalously high due to local disturbance.

The Westbourne Green value for 1837 is the mean of two observations by Professor Phillips on 30 May, two observations by Bache on 16 June, and four observations by Ross on 9 and 10 August. Ross's data appear to have been wrongly transcribed from 69° 16.05′ in the table of his observations to 69° 20.2′ in the summary tables. Here, we adopt the lower value.

Ross's three sets of observations in the garden of Bushey Lodge were made on 30 and 31 July, and 27 and 28 August 1837. Mr Fox's observations were made near Maiden Lane on 22 May, in Eastwick Park on 16 June, and at The Grove, Tooting, on 14 June 1838. Sabine made a single set of observations in Worcester Park on 8 October, and another set in the garden of the Palace at Kew on 13 October, 1838.

The Westbourne Green value for 1838 is the mean of data from Bache (15 August), Fox (8 June), Phillips (28 March) and Ross (6 and 8 March, 10 and 25 April, 16 June, 6, 7 and 10 July, 4 and 10 December) comprising twenty-one sets of observatations, one each by Bache and Fox, two by Phillips, and the rest by Ross.

Guillemin (1891) gives 1838 69° 17′, Black (1905) gives 1838 69° 17.60′, and Chree (1926) gives 1838 69° 17.3′ which is the value given by Sabine (1839) as the mean of all the data in his summary table X, 'corresponding to the beginning of May, 1838'.

(108) Lefroy (1883) gives observations of dip that he made at the Royal Military Repository, Woolwich, with a circle of 9 in diameter, made by Gambey, both before and after his exemplary survey work in Canada. The mean of eight observations made between 27 May and 1 June 1842 was 69° 2.0′, and a further eight between 8 and 12 June 1846, gave a mean of 68° 58.2′. The probable errors of these means are quoted as 0.59′ and 0.74′ for 1842 and 1846, respectively. Some additional observations made in 1842 with Fox's circle are not included, since this instrument was used purely for intensity measurements, with approximate measures of dip as a by-product.

(109) Sabine (1861) reports dip measurements made by himself and Welsh in August and September 1854 at the Kew Observatory, Richmond (mean of ten observations) and at the Regent's Park site of 1821 and 1837 (mean of eight observations), giving a site difference of 1.05′ which Sabine does not consider to be significantly different from zero.

Quoted by Hansteen (1855, 1857) as 68° 31′ 14″, Bauer (1895) as 68.51°, and presumably the source of the unassigned values of 68° 31′ by Guillemin (1891), 68° 31.21′ by Black (1905) and 68° 31.1′ by Chree (1926).

(110) Elagin (1869) measured dip at several European observatories with a circle by Barrow (borrowed from Kew) using two $3\frac{1}{2}$-inch needles. The mean of six observations made in the magnet house of Kew Observatory between 4 and 7 August 1868 was 68° 3.87′ (though in his tables II and III this becomes 68° 3.80′). Comparison with instruments at other observatories indicated a correction of 2.03′ to be applied to the Barrow circle, giving 68° 1.84′.

Elagin's observations at Greenwich are tabulated also in that observatory's yearbook (with minor discrepancies) and have been included in the annual mean for Greenwich.

(111) In 1975 D. R. Barraclough and S. R. C. Malin measured horizontal intensity with a Q.H.M. and total intensity with a proton magnetometer at the four London observatories, as closely as possible reoccupying the most recent sites of the absolute observations. The values were adjusted to the mean of the year using Hartland observatory as control, and then used to calculate dip. The details are as follows: 16 April, Greenwich, 9 m NW of estimated centre

of the 'new magnetic pavilion' in Greenwich Park (to avoid the effect of a cast iron drain cover which is unacceptably close to the centre). The 'magnetic enclosure' site is now open parkland, with no trace of the original buildings. 21 April, Abinger, site of absolute building (now overgrown with trees and bushes; no trace of original building). 30 April, Slough, test hut. 8 May, Richmond, site of magnetic hut, now between two wooden buildings with iron gutters, but adequately remote from them.

## Appendix B. Biographical Notes

### *George Biddell Airy* (1801–1892)

Senior Wrangler in 1823, he remained at Cambridge where he became Lucasian and then Plumian professor. In 1835 he succeeded Pond as Astronomer Royal at Greenwich, and set about reorganizing the observatory. Under his direction the observatory (if not the staff) flourished; he formed a Magnetical and Meteorological Department, designed and acquired a new transit telescope, the 'Great Equatorial' telescope and 'Airy's apparatus' for measuring dip. He also provided new standard measures, telegraphic distribution of the time signal, and gave advice to all comers. His personal researches were mainly concerned with astigmatism of the eye and its correction, determination of the mass of Jupiter from observations of its fourth satellite and that of Venus from its perturbing effect of the Earth's orbit, studies of tides, the 1874 and 1882 transits of Venus, and a determination of the density of the Earth from pendulum measurements at the top and bottom of a mineshaft. He retired in 1881.

### *Mark Beaufoy* (1764–1827)

The son of a Quaker brewer, he became an authority on naval architecture, Colonel of the Tower Hamlets Militia, and the first Englishman to ascend Mont Blanc. His definitive series of observations of the eclipses of Jupiter's satellites, made at his private observatory in Hackney Wick, earned him the silver medal of the Royal Astronomical Society. In 1815 he moved to Bushey Heath, near Stanmore, where he observed the change of sign of secular variation in declination.

### *Henry Bond* (1600?–1678)

Mathematician. Describes himself as a 'Teacher of Navigation and other parts of the Maths in Storehouse Yard in Ratcliff' (the Royal Dockyard). For about twenty years he edited *Tapp's seaman's kalendar*, and also published various works concerning the possibility of finding the longitude from magnetic observations. It seems likely that Bond's prediction of secular variation, based on two moving poles, was the clue that led Halley to his westward-drift hypothesis, though Halley himself was disparaging about Bond's work. Sir Charles Cavendish described Bond as 'an humble man, who speaks very meanly of himself'.

### *William Borough* (1536–1599)

Started as a merchant seaman and rose to 'captaine general' on the Russian trade route. He was an enthusiastic and successful exterminator of pirates, both in the merchant service and, later, when he became comptroller of the Queen's Navy. As commander of the Lion, he assisted Drake in 'singeing the King of Spain's beard' at Cadiz. On a subsequent mission he was arrested by Drake for questioning (justifiably, as it turned out) the wisdom of a land attack on Lagos. Borough's crew then mutinied. Although the charges against Borough were dropped, his career prospects were not enhanced and he commanded only a small vessel, the Bonavena, in the Armada.

*Robert Boyle* (1627–1691)

Fourteenth child of the first ('Great') Earl of Cork, and step-brother of the first Earl of Orrery. He travelled extensively in Europe as a youth before settling in London to pursue his two main interests – chemistry and theology. He also studied anatomy and was an accomplished linguist. Though an enthusiastic founder member of the Royal Society, he declined its presidency. He also declined to take holy orders, the provostship of Eton, and a peerage, thus remaining the only untitled member of his family. 'Boyle's Law', concerning the compressibility of gas, resulted from experiments with an air pump which he built with the assistance of Robert Hooke. Although he attempted the transmutation of base metals, his scientific approach to chemical experimentation was far removed from, and helped to dispel, the occult practices of the alchemists. He distinguished between mixtures and compounds, attempted to weigh light, developed the corpuscular theory, and financed the printing of the Indian, Irish and Welsh Bibles, as well as the Turkish New Testament.

*James Bradley* (1693–1762)

His early interest in astronomy was fostered by his uncle, the Reverend James Pound, with whom he deduced the solar parallax from observations of Mars. His study of the motions of the Jovian satellites earned him the Savilian chair at Oxford, where he discovered and explained the phenomenon of aberration, an achievement for which he was justly acclaimed. In 1742 he succeeded Halley as Astronomer Royal, and re-equipped the observatory with various instruments, including apparatus for measuring declination and dip. Further meticulous observing was rewarded with a second discovery of fundamental importance, the phenomenon of nutation.

*John Canton* (1718–1772)

Described by Dr Thomson as 'one of the most successful experimenters in the golden age of electricity'. In addition to researches of his own, he successfully repeated Franklin's lightning experiments. In his own opinion, his most important discovery was an artificial means of making magnets, but 'Canton's phosphorous' was probably remembered longer. Also to his credit is the discovery that the geomagnetic diurnal variation is greater in summer than in winter. He was a friend of Joseph Priestley and lived in Spital Square.

*Jaques Cassini* (1677–1756)

Second of four generations of Cassinis who directed the Paris Observatory. He is more famed as a geodesist than an astronomer (though he supplied the first tables of the satellites of Saturn), his main work being the measurement of the meridian from Dunkirk to Perpignan and, based on this, his discussion of the figure of the Earth and demonstration of its polar flattening. He observed the declination at Greenwich with the Astronomer Royal, John Flamsteed, while on a 'grand tour' during which he visited Italy, Holland and England.

*Henry Cavendish* (1731–1810)

A great experimentalist who investigated a wide range of phenomena, including the nature of heat, composition of water, electricity and photosynthesis. His most famous geophysical experiment was that in which he compared the gravitational attraction of a known mass with that due to the Earth, and hence deduced the mean density of the Earth. A very retiring man, he lived the life of a recluse, his only human contact being with his scientific colleagues whom he met at the Royal Society, and even there he hardly spoke a word. He instructed his servants by means of written notes. Cavendish left a fortune of £1 175 000.

*John Flamsteed* (1646–1719)

A sickly Derbyshire youth, at the age of 19 his father sent him to Ireland for a 'miracle cure' at the hands of Valentine Greatrackes, but to no effect. Greatrackes waived his fee, but Flamsteed remained in poor health all his life. He graduated at Cambridge in 1674 and a year later was appointed as the first Astronomer Royal, with a fine new house in Greenwich Park (built by Wren), a salary of £100 per annum, but no instruments except for two clocks and a sextant given him by Sir Jonas Moore. His task was to improve the catalogues of star positions so that they could be used, in conjunction with an accurate lunar ephemeris, to determine the longitude at sea by the method of 'lunar distances'. A cautious and thorough observer, he wished to publish the results with equal care. However, Newton was impatient for the data and was loaned the preliminary results for his own use. He then made a lifelong enemy of Flamsteed by publishing the results without the owner's permission and with numerous errors. Flamsteed collected and destroyed as many copies as he was able; his own version eventually appeared in his monumental *Historia Cœlestis Britannica*.

*Martin Frobisher* (1535?–1594)

A Yorkshire-born navigator, who made three voyages in search of the North-West Passage. From one of these he returned with the horn of a sea unicorn, which he presented to the Queen, together with many tons of equally spurious gold ore. When the deficiencies of the ore were pointed out to him, he merely collected another boatload, which (he claimed) was better. In 1585 he was made vice-admiral to Drake, and sailed with him on the West-Indies expedition. Frobisher aquitted himself particularly well in the Armada, and received a knighthood and the command of his own squadron. He is buried in Plymouth and London.

*Henry Gellibrand* (1597–1636)

Professor of astronomy at Gresham College (from 1627) in succession to Gunter (q.v.). He is generally credited with the discovery of geomagnetic secular variation, though his observations merely confirmed Gunter's earlier discovery (which admittedly Gunter himself doubted). Gellibrand is described by Gordon Goodwin as 'a plodding industrious mathematician, without a spark of genius'.

*George Gilpin* (flourished 1766–1810)

Gilpin spent most of his time assisting others. He was assistant to William Wales on Cook's second voyage, then assisted Neville Maskelyne at the Royal Greenwich Observatory before becoming clerk to the Royal Society, where he assisted the fellows with their experiments. From 1796 he was also secretary to the Board of Longitude. His duties at the Royal Society included making regular meteorological and magnetic observations, though his assiduity in the latter went far beyond the call of duty. With Sir Charles Blagden, he determined the temperature at which water has its greatest density.

*James Glaisher* (1809–1903)

First superintendent of the Magnetical and Meteorological Department of the Royal Greenwich Observatory, which post he held from 1838 to 1874. He was one of the founders of scientific meteorology, improving the instrumentation, devising a nationwide observing network and establishing (in 1848) a regular daily weather report. More spectacular were his ballooning feats. Of the many ascents he made (ostensibly to gather meteorological data) the highest was on 5 September 1862 when he ascended with Coxwell to 37000 feet. At 29000 feet Glaisher lost consciousness and Coxwell temporarily lost the use of his limbs. However, he managed to operate the release valve by pulling its cord with his teeth, and they descended safely.

*George Graham* (1675–1751)

After an apprenticeship to Tompion (whose grave he shares), Graham succeeded his teacher as the greatest clockmaker of his day. He combined outstanding mechanical skill with considerable ingenuity, inventing the dead-beat escapement and the mercury pendulum. Besides timepieces, he constructed many other beautiful mechanical devices, including the original orrery, a mural quadrant for Halley, and a zenith sector and transit instrument for Bradley. Graham was a Quaker, and kept his money in a tin box rather than accept interest from a bank. He also refused interest on loans made to his friends. His greatest achievement in geomagnetism was the discovery of the diurnal variation.

*Edmund Gunter* (1581–1626)

Professor of astronomy at Gresham College from 1619. An exceptional practical mathematician, he invented numerous useful devices including some that are still in use, such as the slide rule (originally known as Gunter's rule) and the surveyor's chain, as well as others that served for many years, such as Gunter's scale or 'the Gunter', which was a device for solving navigational problems. He also published a table of sines and tangents and coined the words 'cosine', 'cotangent' etc. He inscribed the dials in the King's garden at Whitehall, making due allowance for declination, and noted the secular change in declination, of 5° in 42 years, at Limehouse. However, he suspected an error and did not follow this work up, so the discovery of secular variation is usually attributed to his successor, Gellibrand. John Aubrey relates the following anecdote: 'When he was a Student at Christchurch, it fell to his lott to preach the Passion Sermon, which some old divines that I knew did heare, but 'twas sayd of him then in the University that our Saviour never suffered so much since his Passion as in that sermon, it was such a lamentable one – *Non omnia possumus omnes* [All things are not possible to all men.]. The world is much beholding to him for what he hath donne well.'

*Edmond Halley* (1656–1742)

The son of a rich London soap-boiler, Halley attended Oxford University, but left before he graduated to observe the southern stars from St. Helena. He was subsequently given an honorary M.A. by order of the King. Although justly remembered for accurately predicting the return in 1758 of the comet that now bears his name, Halley has other claims to fame, too numerous to list, in the fields of mathematics, astronomy, geodesy, geomagnetism and cartography. Not least of his contributions was the part he played in the production of Newton's *Principia*, first by encouraging its writing and then by financing its publication. He became the second Astronomer Royal in 1720. Curiously, in view of his long interest in geomagnetism, he does not appear to have made any magnetic observations while in office at Greenwich.

*William Heberden* (1710–1801)

Skilled and erudite physician, first at Cambridge University then in private practice in Cecil Street, London. He held various high offices in the Royal College of Physicians and published important papers on, for example, angina pectoris and chicken pox. He retired at the age of 76 to Windsor.

*Henry Kater* (1777–1835)

First introduced to surveying as a lieutenant in Madras. He is best known for his reversible pendulum which won him the Copley medal of the Royal Society and with which he made seven precise observations of gravity on a north–south line from the Isle of Wight to the Orkneys. He was also involved with the definition of standard weights and measures, and was the inventor of 'Kater's floating collimator'.

*Robert Moray* (*ca* 1600–1673)

Spent much of his life as a regular soldier in France, where he eventually became colonel of the Scotch regiment. Devoted to the Royalist cause, he was knighted by Charles I, and acted as a secret envoy between Scotland and France on the King's behalf. After narrowly failing to arrange the King's escape, he returned to his regiment in France, and became a confidant and friend of Charles II. He returned to Britain shortly after the Restoration, where he continued to enjoy the King's friendship and played a leading role in the government of Scotland. He was a founder member of the Royal Society and had a wide circle of friends in London society. He died suddenly in the Whitehall Gardens and was buried at the King's expense in Westminster Abbey.

*Edward Nairne* (1726–1806)

Optical, mathematical and philosophical instrument maker. Still remembered for 'Nairne's electrical machine', an electrostatic generator intended for medical use, and based on a design by his friend, Joseph Priestley. The compass and dip circle of the Royal Society were made by Nairne. (Not to be confused with the 'Sandwich Bard'.)

*Robert Norman* (flourished 1590)

An instrument maker who lived in Radcliffe and described himself as 'an unlearned mechanician'. However, not only did he make a fundamental geophysical discovery, but the manner in which he made it and the clarity with which he described the experiments would serve as an example even to the most learned of scientists. The refusal of a balanced compass needle to remain horizontal when magnetized had been previously noted independently by Hartmann, but the invention of the dip circle to investigate the phenomenon and the first realistic measurement of dip must be credited to Norman.

*John Pond* (1767–1836)

Pond's observations of stellar declinations, published 1806, proved that the quadrant by Bird that was still in use at Greenwich had become distorted and was obsolete. Despite (or perhaps because of) this, Pond was made Astronomer Royal in 1811. He modernized the instrumentation, increased the staff and was a meticulous observer. However, because of his poor health and lack of administrative ability he allowed the observatory to deteriorate. He retired in 1835 on full pay, and was succeeded by Airy (q.v.).

*Mark Ridley* (1560–1624)

Chief physician to the Czar (Boris Gudanoff), but returned to England after the Tsar's death to practice in London. On the title-page of his book on magnetical bodies and motions, he describes himself as 'one of the 14 elect of the London College of Physicians'. Ridley was an acquaintance of William Gilbert.

*James Clark Ross* (1800–1862)

Sailed on seven expeditions to the Arctic, two under his uncle, four under Parry, and a final one in 1848 under his own leadership in search of the ill-fated Sir John Franklin. On his sixth expedition he led a sledging party in search of the North Magnetic Pole, which he located on 1 June, 1813. He was involved in the 1838 survey of the British Isles (with Sabine and Lloyd), then turned his attention southward, leading an expedition with the *Erebus* and *Terror* to the Antarctic. Though he failed to achieve his ambition of setting foot on both the North and South magnetic poles, he discovered many new geographical features which he named after his ships, colleagues and patrons, including Victoria Land and Albert Mountains. He received a knighthood on his return.

*Edward Sabine* (1788–1883)

An incredibly industrious man whose many achievements (the rank of general, a knighthood, the Copley medal and subsequently presidency of the Royal Society) were all the result of application rather than any special brilliance. Like Ross (q.v.) he accompanied Parry to the Arctic and collaborated in the magnetic survey of the British Isles. His main interests were geomagnetism and (with Kater) pendulum measurements of gravity. He was responsible for the establishment of many magnetic observatories throughout the British Empire (including the Kew Observatory) and, with his staff at Woolwich, undertook a large proportion of the task of reducing and publishing the observations.

*John Seller* (flourished 1700)

Hydrographer to the King. However, his main hydrographic work, the *English Pilot*, is based more on plagiarism than surveying! Despite dire warnings to his readers to observe the sanctity of his copyright, Seller's work is largely based on Dutch maps, with the original headings imperfectly deleted and English headings added, over Seller's name. He lived at the Hermitage in Wapping, and owned a shop near the Royal Exchange.

*William Whiston* (1667–1752)

Followed his father into the church, but his unorthodox views made him something of a misfit, and, a few years after the publication of his first book *A new theory of the Earth*, he embarked on an academic career, succeeding Newton as Lucasian professor. His religious views got him into trouble, and in 1710 he was dismissed from the university for Arianism. Unrepentant, Whiston went to London where he practised and preached 'primitive Christianity', and gave lectures on scientific and other matters. He became interested in the problem of finding the longitude and, believing that this could be done by means of magnetic dip, made a survey of England and produced the first dip chart. When he was approaching 80 he forecast that the millennium would start in 1766, and from that date there would be no more gaming-tables in Tunbridge Wells.

*Edward Wright* (1558?–1615)

The first man to put navigation on a sound mathematical footing. He is perhaps more deserving than Mercator of the credit for the map projection that bears the latter's name. Mercator had produced only a crude and empirical solution to the problem of drawing a chart in which rhumbs are straight lines, and his charts were not favoured by navigators; Wright produced a correct arithmetical solution to the problem, which involved a numerical integration of arcsin $x$. The projection then rapidly gained general acceptance.

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THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

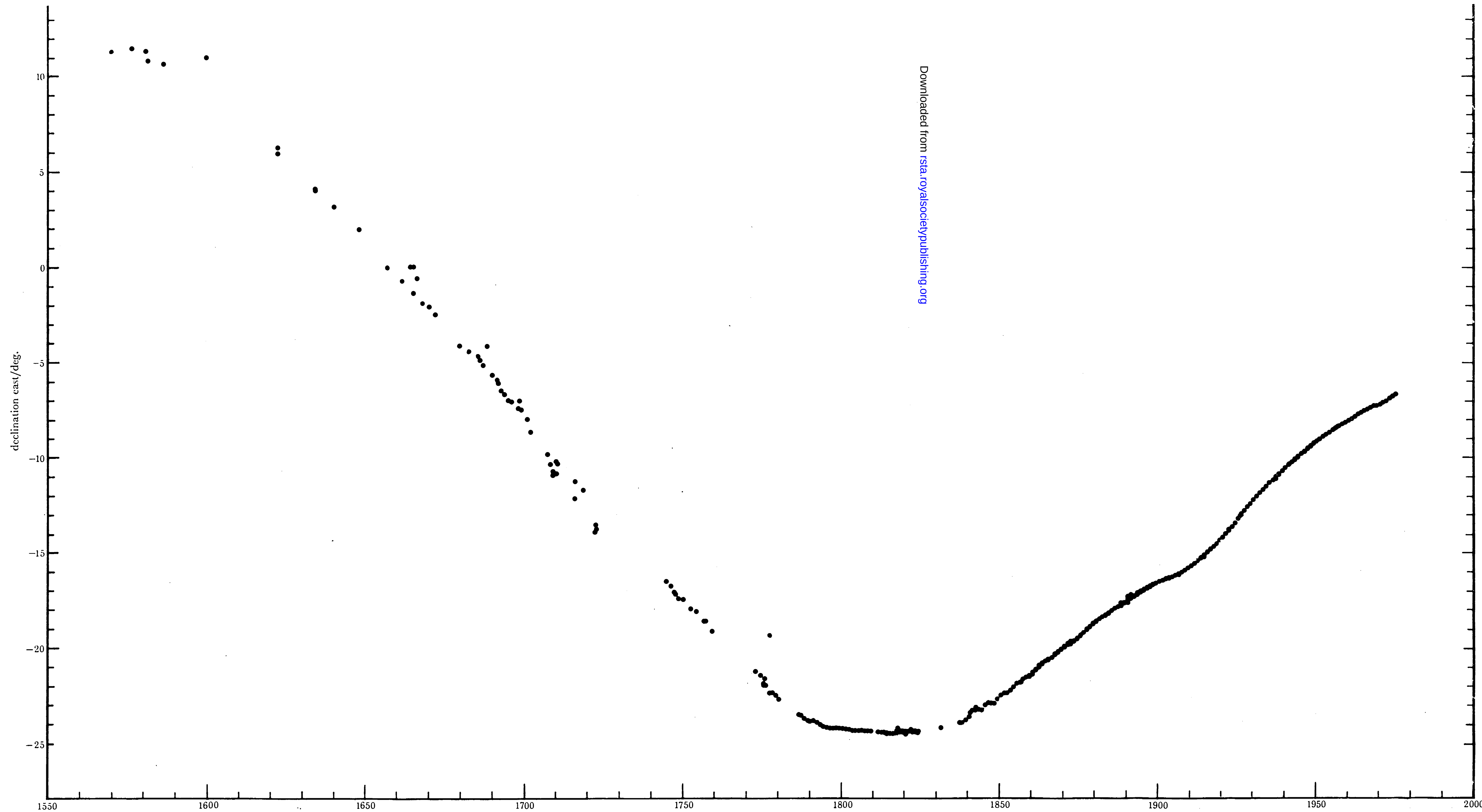
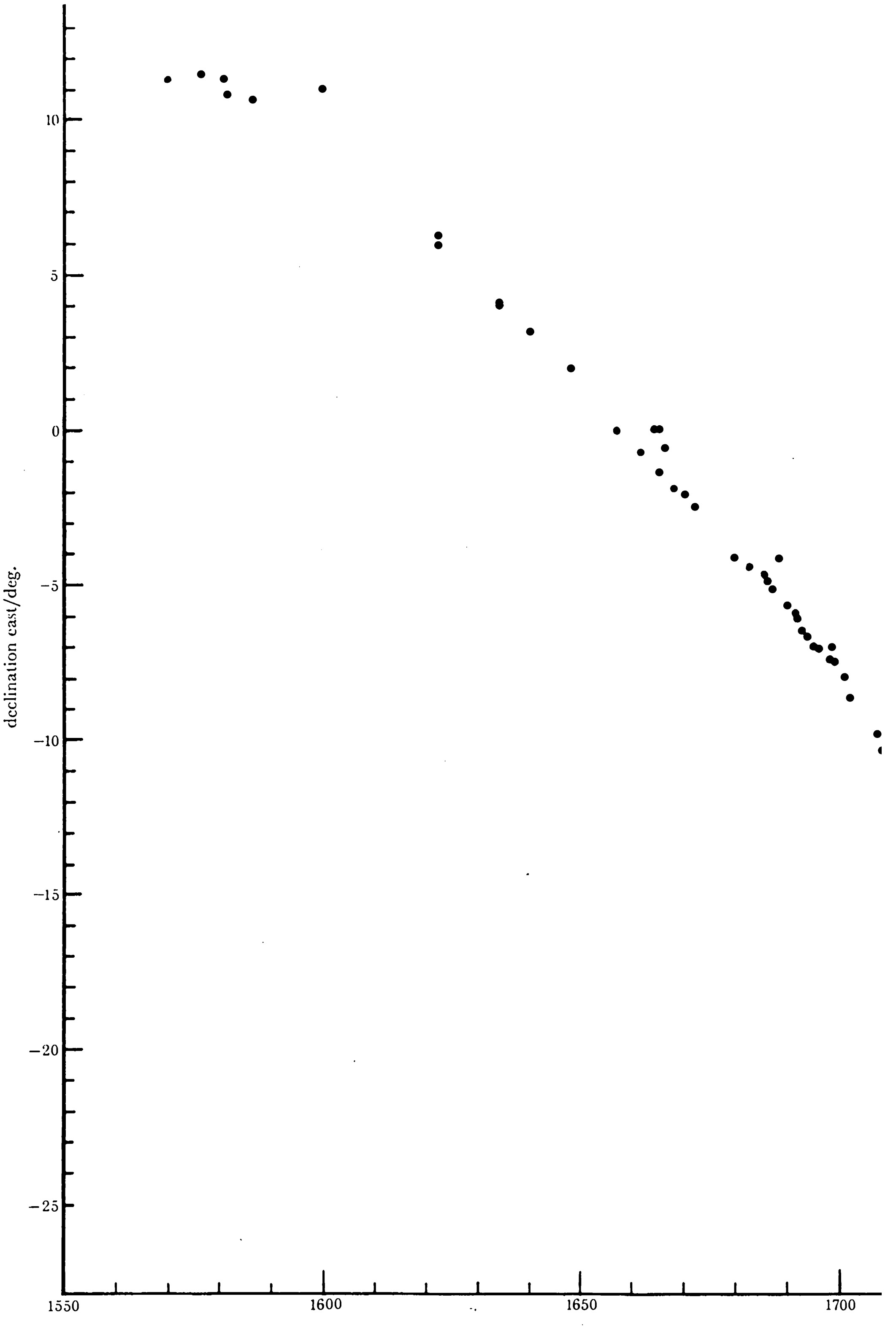



FIGURE 2. The observations of declination, corrected to Greenwich.

(*Facing p.* 424)


declination east/deg.
10
5
0
−5
−10
−15
−20
−25
1550
1600
1650
1700

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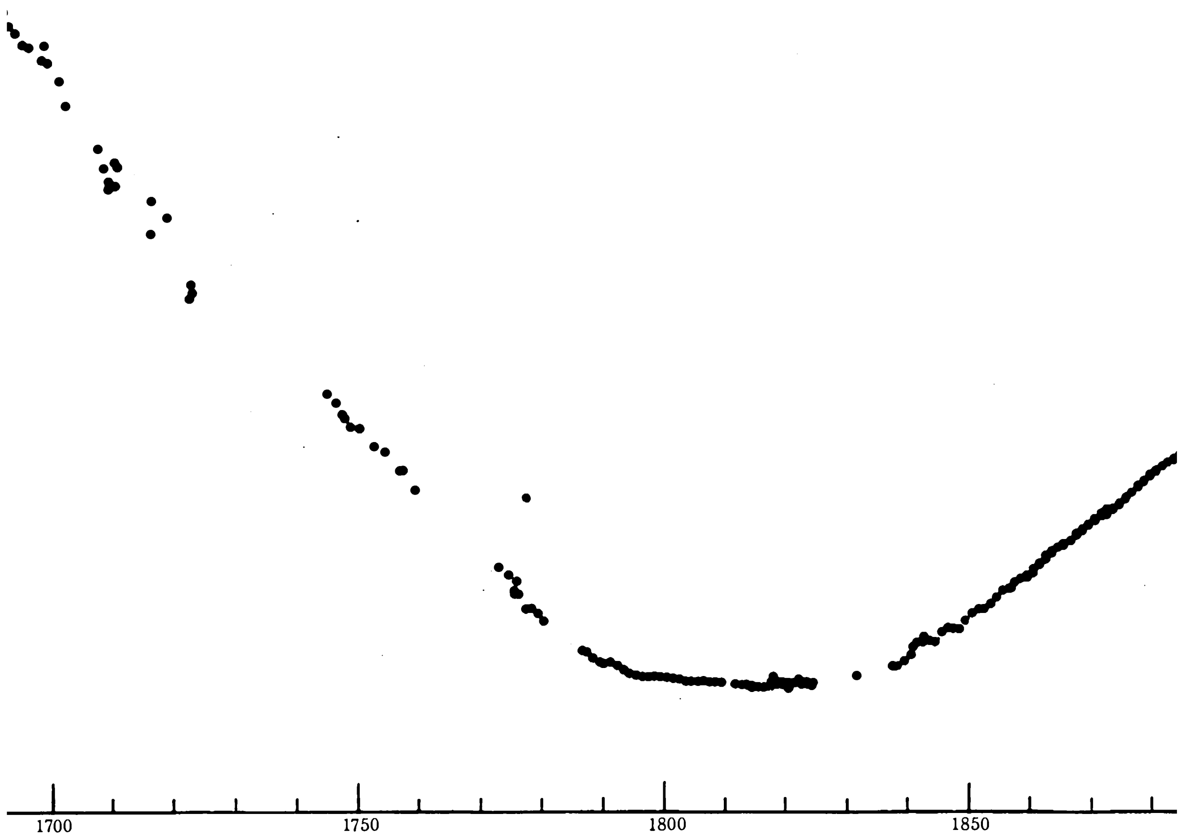
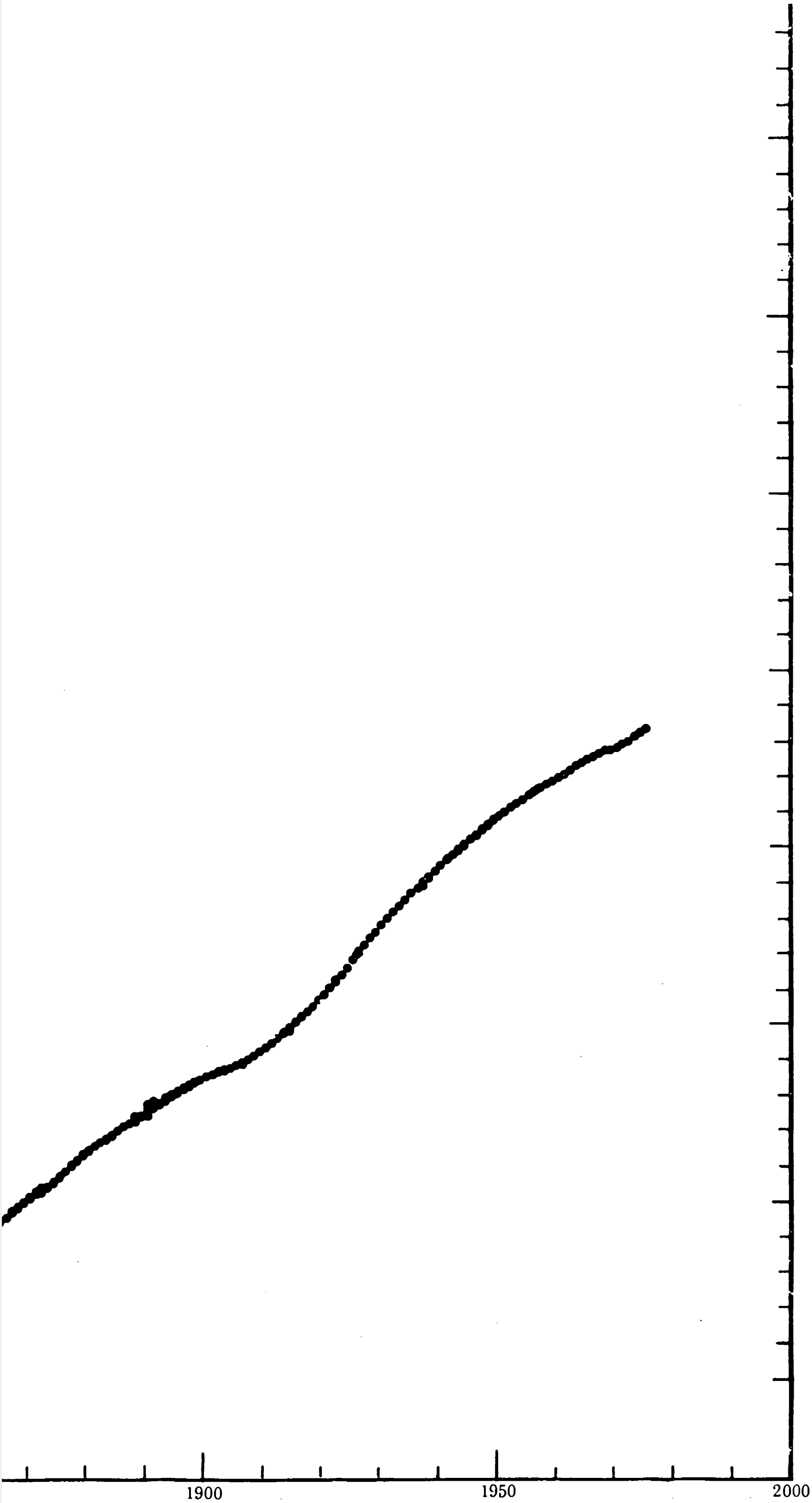



Figure 2. The observations of declination, corrected to Greenwich.





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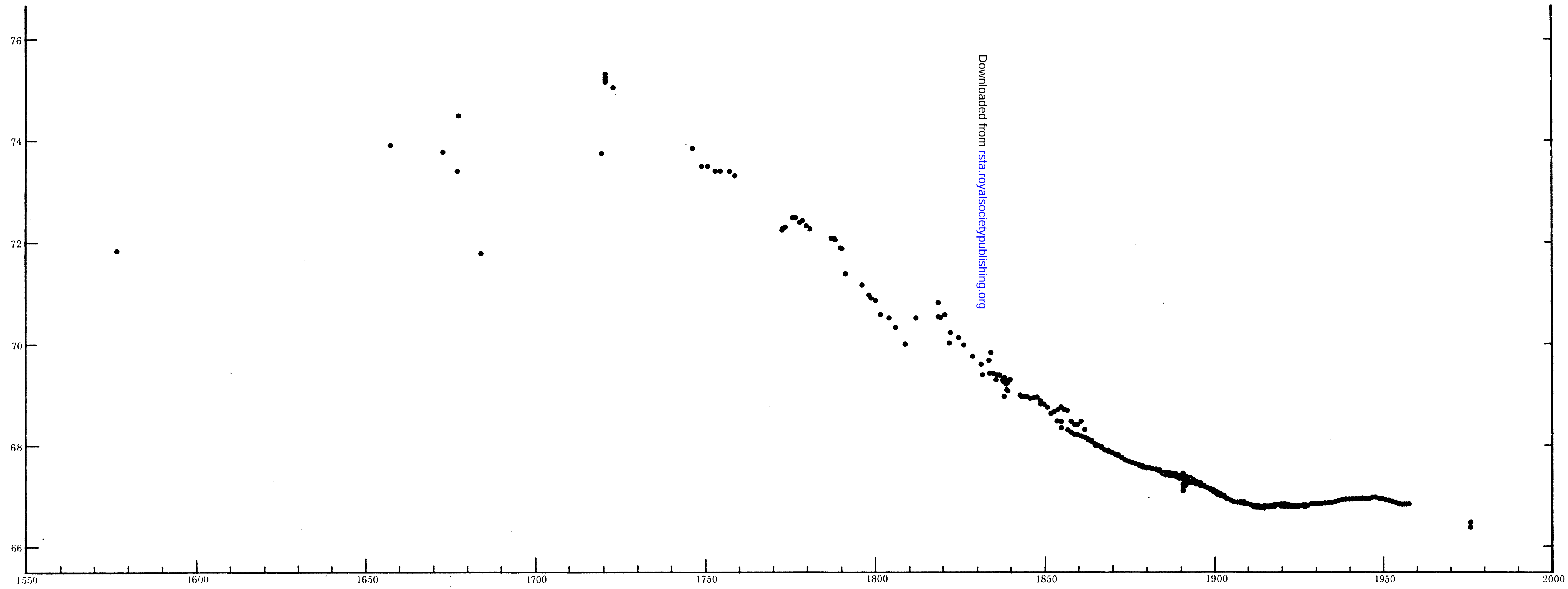
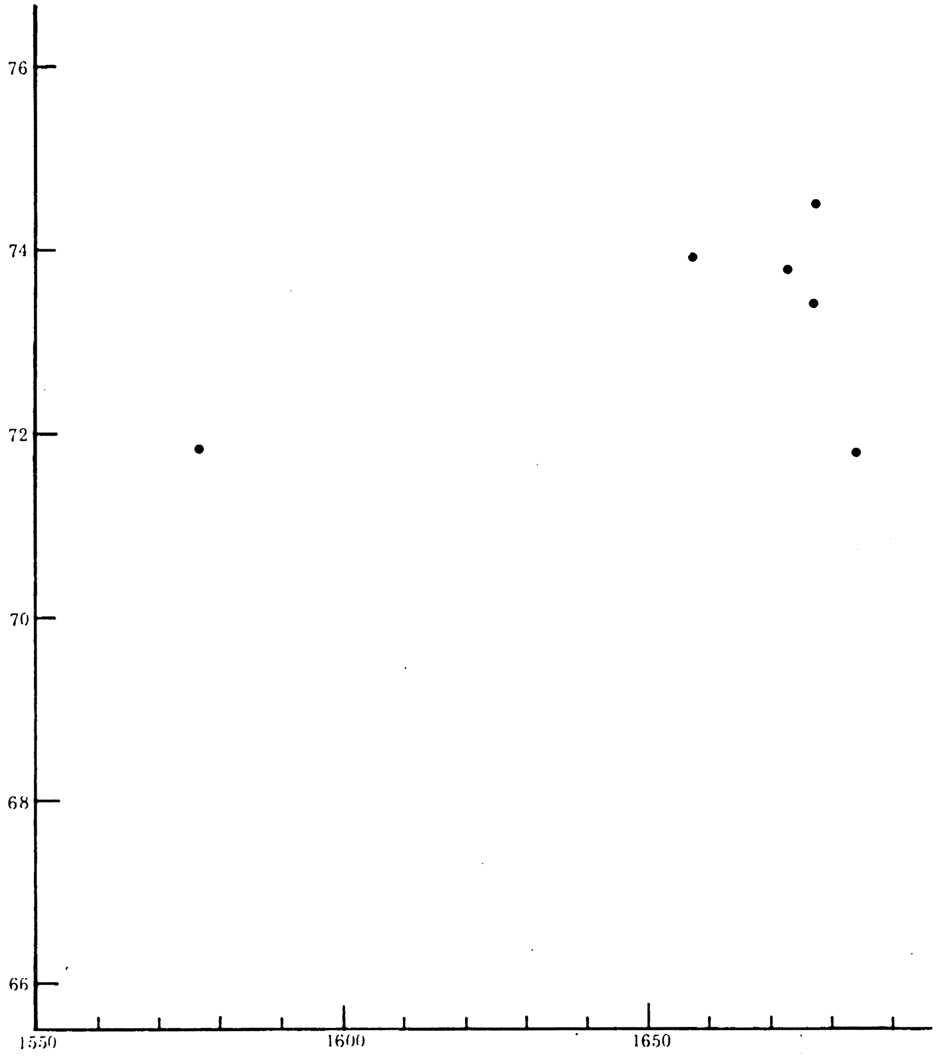





FIGURE 3. The observations of dip, corrected to Greenwich.



76
74
72
70
68
66
1550
1600
1650

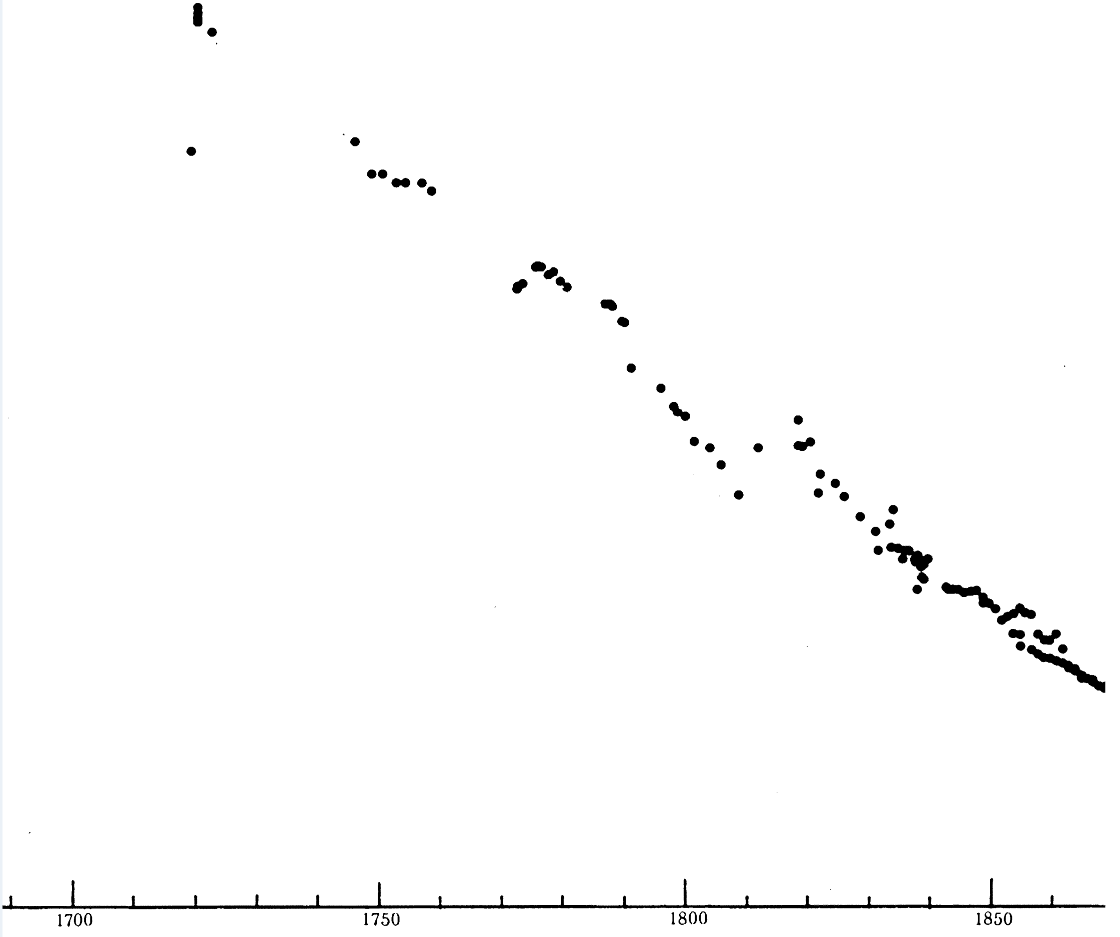
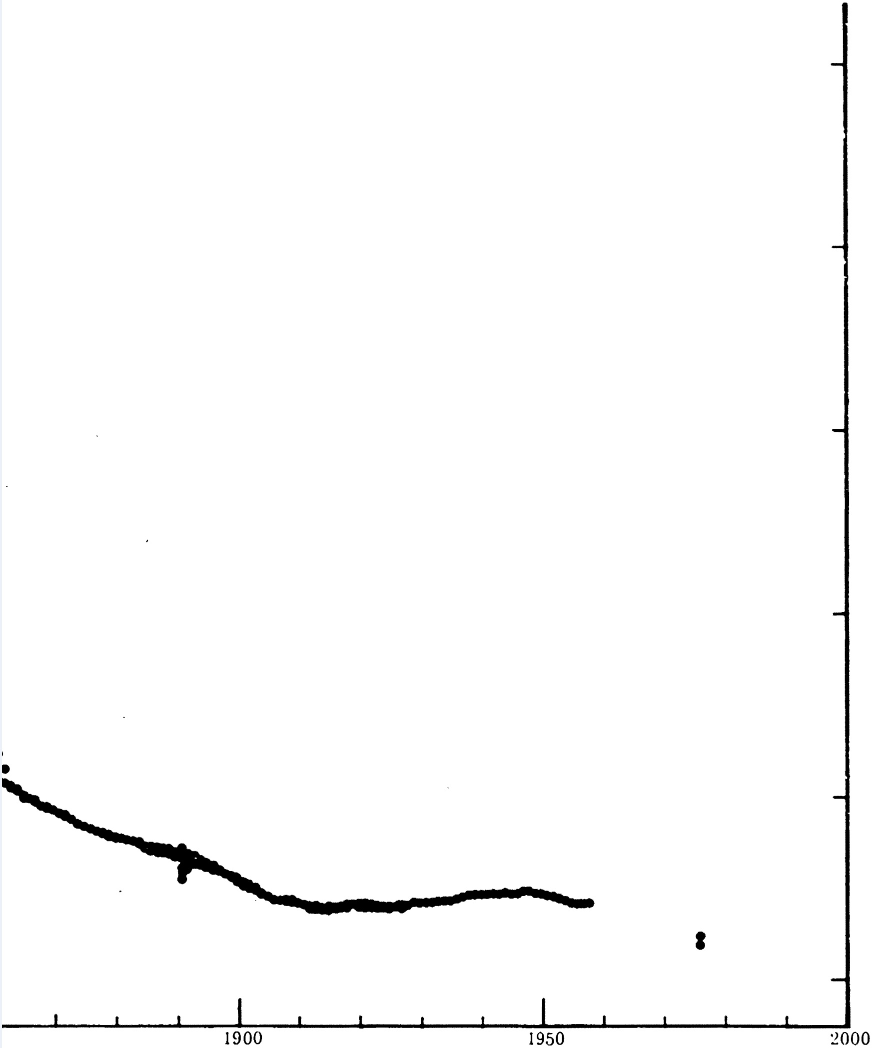



FIGURE 3. The observations of dip, corrected to Greenwich.


1900
1950
2000

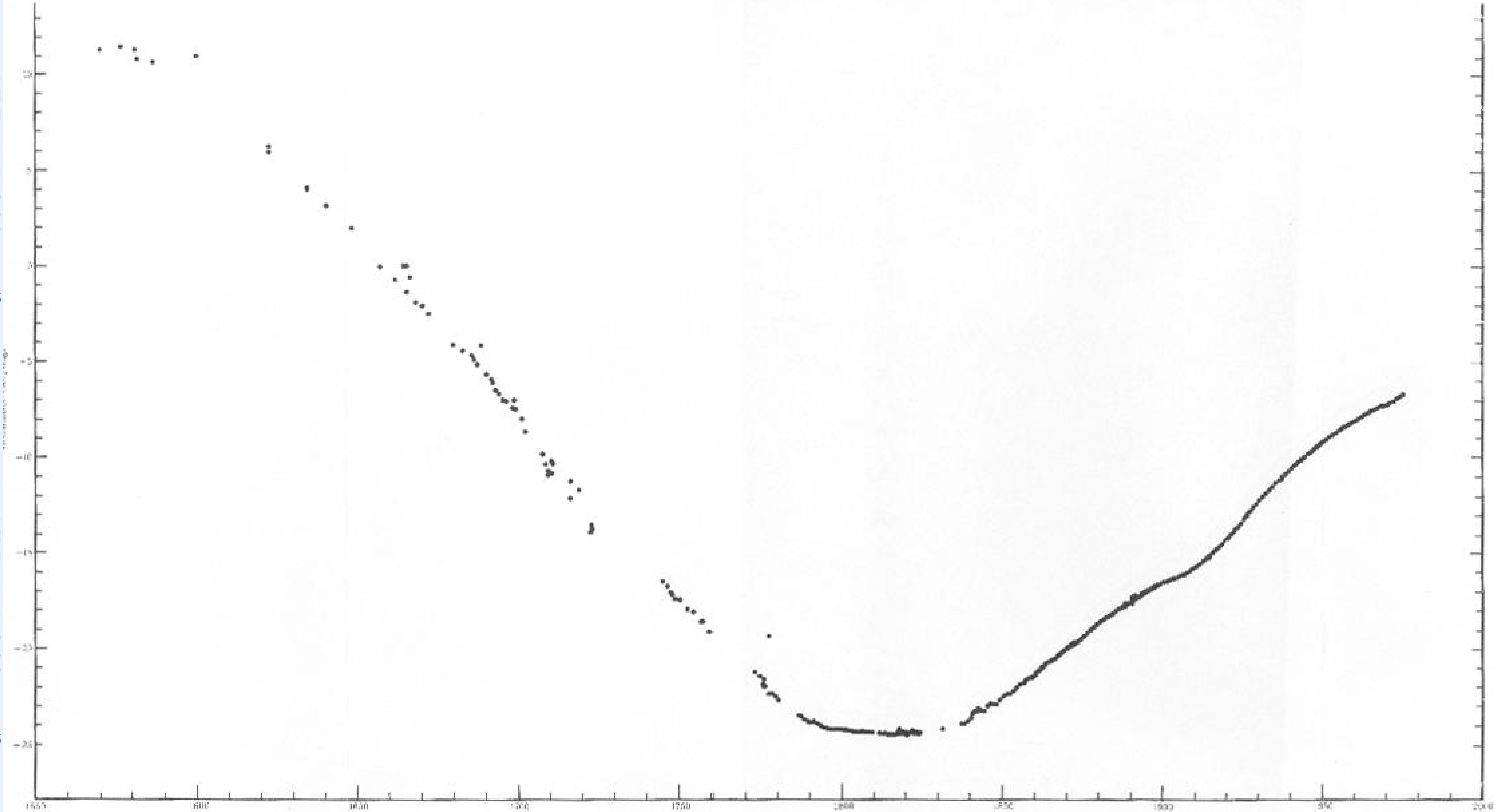



Figure 2. The observations of declination, corrected to Greenwich.



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