Mid-continental magnetic declination: A 200-year record starting with Lewis and Clark

Robert E. Criss, *Department of Earth & Planetary Sciences, Washington University, St. Louis, Missouri, USA*

ABSTRACT

Compass and sextant observations by Meriwether Lewis and William Clark are combined to provide the oldest determinations of the magnetic declination in the continental interior of the United States. Over the past 200 years, the magnetic declination near St. Louis has changed from an azimuth of 7.7° east to 0° today. The 1803–1806 declinations are essential to interpreting the travel legs made by Lewis and Clark on their historic journey, and could be used to test and improve existing magnetic models.

INTRODUCTION

Included in Jefferson's ambitious charge to Lewis and Clark for their historic expedition of 1803–1806 was the requirement that they make, with "great pains and accuracy," astronomical measurements to determine the latitude and longitude of all remarkable points along the way (e.g., Preston, 2000). To accomplish this, Lewis received training in the methods of celestial navigation and acquired a sextant, an octant, a "circumferentor" or large-diameter surveyor's compass, and a chronometer that was somewhat troublesome but good for its day (Moulton, 1986–1993). Most of the original instruments have been lost, but all were ably described by Lewis in his 22 July 1804 journal entry (Moulton, 1986–1993, v. 2, p. 410–413). For historical reasons, the data for longitude were not reduced until recently (Preston, 2000), and the calculations for latitude that were made in the field by Lewis and Clark contain variable, small to significant errors that are understandable given the circumstances.

To date, the interest in these observations has been restricted to their primary intended purpose, which was that of determining position. However, Jefferson also required the explorers to note the "variations of the compass" in different locations, and the requisite data were indeed acquired in cases where both compass and sextant were used to make observations. These data seem likewise not to have been reduced before, even though they contain a valuable record of magnetic declination across the United States in the early 1800s. This paper details several different methods whereby this record may be reduced.

Importance of Magnetic Declination

Earth's magnetic field approximates a dipole, though the magnetic north and south poles are neither fixed nor do they coincide with Earth's geographic poles. Nevertheless, the utility of magnetized needles in aiding travelers, mariners, and miners to determine north has probably been known for millennia, although the earliest written reference to the compass may be by Alexander Neckam ca. 1187 A.D. (Hoover and

TABLE 1. MAGNETIC DECLINATION IN 1803–1805 FROM POLARIS AND SOLAR MEASUREMENTS COMPARED TO 2003

| Date	Lat	Long	Polaris[1] Mag. Azimuth	Location	M.D.[2] Polaris	M.D.[3] Eq. 3 best est.	M.D.[4] Eq. 2	BGS[5] Model	2003[6] M.D.	Moulton vol./page[7]
Dec. 2 & 3, 1803	37.99°	89.95°	7.8°	Kaskaskia, Illinois	7.8°	7.4°	7.7°	7.60°	−0.23°	2/119
June 1, 1804	38.56°	92.03°	7°	Osage River, Missouri	7.9°			8.36°	1.37°	2/269
June 2, 1804	"	"	6.2°	"	7.6°	8.2°	7.2°			"
June 20, 1804	39.18°	93.94°	7.9°	Lafayette County, Missouri	9.7°	NA	NA	9.06°	2.82°	2/311
June 27, 1804	39.12°	94.61°	8°	Kansas River, Missouri	9.4°	10.2°	10.3°	9.31°	3.33°	2/326
"	"	"	8°	"	9.4°					"
"	"	"	7.8°	"	9.1°					"
June 9, 1805	47.93°	110.48°	15°	Marias River, Montana	16.7°	17.1°	17.0°	16.39°	14.50°	4/274
July 29, 1805	45.93°	111.50°	13°	Three Forks, Montana	14.7°	16.1°	16.6°	15.91°	14.47°	5/13

1. Magnetic azimuth of Polaris on indicated date, as measured by Lewis and Clark.
2. Magnetic declination in 1803–1805, calculated from Polaris and corrected for the time of measurement.
3. Magnetic declination in 1803–1805, calculated with eq. 3 from the Sun's position and the latitude (Table 2; see footnote 1).
4. Magnetic declination in 1803–1805, calculated with eq. 2 from the Sun's position and the time (Table 2; see footnote 1).
5. Magnetic declination in 1803–1805, calculated from model Bgs1800 (U.S. Geological Survey, 2003).
6. Magnetic declination in 2003, calculated from model IGRF-2000 (U.S. Geological Survey, 2003).
7. Volume and page number of Moulton (1986–1993) providing Lewis and Clark data.

Hoover, 1950). Recognition that magnetic north deviates from true north and that the magnitude of this deviation varies both geographically and temporally led to the establishment of several magnetic observatories to facilitate global exploration. Nearly continuous records of the secular variation of declination have been available since ca. 1570 A.D. for selected sites such as London (Malin and Bullard, 1981). Numerous ship captains augmented this record and hundreds of thousands of observations at sea have been compiled (Jackson et al., 2000), but before ca. 1850, little data existed for the North American interior.

Accurate knowledge of the declination and its variations has numerous applications apart from its importance to navigation at any given place and time, somewhat analogous to the way that today's local weather relates to the extensive records essential to the field of climatology. Historical magnetic measurements can be used to study the variations of Earth's magnetic field and represent one of very few observable manifestations of the complex and evolving processes occurring in Earth's core (e.g., Bloxham, 1995). Of immediate interest here is that knowledge of historical declinations is commonly needed to interpret the observations of early natural scientists. For example, many important early maps of underground mine workings (e.g., Becker,

1882) are oriented relative to magnetic north at the time, as a compass is especially handy when it is impossible to see the Sun or the stars. Similarly, knowledge of the magnetic declination during the Lewis and Clark expedition is needed to understand their sketch maps and the individual travel legs that they report in terms of compass bearings (see below).

Magnetic models for the past 400 years are available but their accuracy depends on both the distribution and quality of available historical data (Jackson et al., 2000; U.S. Geological Survey, 2003). In this regard, Lewis and Clark's observations yield the first determinations of declination in the interior of North America, and the accuracy of those determinations appears to be better than that typical for the period. First, Lewis and Clark's detailed notes define their observational positions much more accurately than those possible out at sea, where determinations of longitude depended on chronometers and were generally good only to the nearest 30'. Moreover, a method is adopted below wherein these accurate positions are used in lieu of the hour angle to *calculate* the declination associated with that position. Lewis and Clark's declinations therefore provide a useful test of the accuracy of available magnetic models for the early 1800s. It will be shown that the declinations determined from
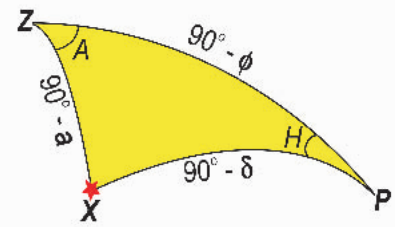

Figure 1. The "astronomical triangle" has legs of great circle arcs on the celestial sphere that connect the observer's zenith (Z), Earth's rotational pole (P), and the Sun or star of interest (X). The angular arc lengths are the respective complements of the observer's latitude (ϕ), the star's altitude (a) relative to the observer's horizon, and the star's declination (δ) relative to the celestial equator as given in the ephemeris tables. Internal angle H is the hour angle, and A is the true azimuth of the object as seen by the observer. Equations 2–4 are derived by applying the spherical laws of sines and cosines to this spherical triangle. Simplified after Smart (1977).

Lewis and Clark's data are systematically greater than those calculated from the latest readily available magnetic models for their place and date by an average of 0.5° and, in some locations, by in excess of a degree.

METHODS AND CALCULATIONS
Correction of Raw Field Data

Lewis and Clark utilized standard methods to measure the magnetic azimuth and altitude of the Sun, or alternatively the magnetic azimuth of Polaris, at times recorded by their chronometer.
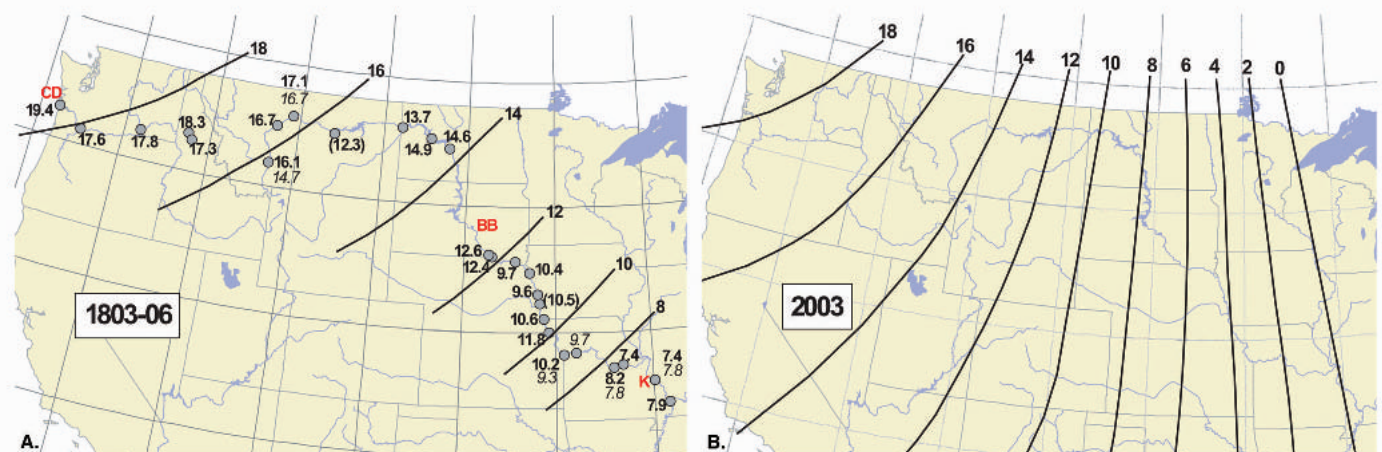
Figure 2. A: Magnetic declination calculated from the solar measurements of Lewis and Clark (bold numbers, Table 2; see footnote 1), based on the latitude and site of observation as determined from their narrative and by comparing modern and historic maps. Numbers represent averages whenever possible, and those given in parentheses indicate irregularities in the reported data; see Table 2 for details. Non-bold numbers represent magnetic declinations utilizing Polaris data (Table 1). Contours are schematic and are based solely on the plotted data. The regular westward increases in magnetic declination strongly support the accuracy of Lewis and Clark's observations. Locations discussed in the text are K—Kaskaskia, Illinois (Fig. 3); BB—Big Bend, South Dakota (Fig. 4); CD—Cape Disappointment, Washington (Fig. 5). B. Magnetic declination calculated for March 2003 utilizing model IGRF-2000 (U.S. Geological Survey, 2003). The agonic line currently passes through St. Louis County, far west of its location in coastal Virginia ca.1803–1806.

The azimuthal measurements by compass, adjusted by a spirit level, are direct readings that appear to be accurate to a quarter of a degree, though they are commonly reported only to the nearest degree. These simple measurements need no additional comment, except that in rare cases, the compass quadrant appears to have been incorrectly read or recorded (e.g., S85°E is actually N85°E).

The sextant measurements also are straightforward but require a few corrections, many of which are mentioned by Lewis in the 22 July 1804 entry or illustrated in Clark's example calculations for latitude (e.g., see the 19 December 1803 entry; Moulton, 1986–1993, v. 2, p. 137). First, angular measure was made between the Sun and its reflected image from an "artificial horizon" (water surface), so the angle recorded is exactly twice the apparent altitude above the real horizon. Half the measured angle (b) must be reduced by the standing error of the sextant, which Lewis reports is 8'45" (see 22 July 1804 entry), and this result corrected for atmospheric refraction and parallax per appropriate tables (e.g., Bowditch, 1939). Alternatively, the total angular correction in degrees is approximately:

$$\text{Correction} = -0.01597/\tan b + 0.00244 \cos b - 0.14583 \qquad (1)$$

where the first term on the right is the correction for refraction, the second term the correction for parallax, and the third term the standing error of the sextant. Thus, half the measured angle plus this adjustment will correct the altitude, if above 15°, to better than ±0.00056° (2 seconds), which is better than the precision of measurement. One final correction is commonly needed, as measure was for convenience most commonly made of the altitude of either the "upper limb" or "lower limb" of the Sun rather than of its center. The solar semi-diameter, which is ~0.267° but for any day is accurately given in the ephemeris tables (Maskelyne, 1803; Garnet, 1804, 1805a, 1805b), needs to be respectively subtracted or added to obtain the true altitude of the Sun's center. This correction was occasionally troublesome for the explorers, possibly because one of the two instrument telescopes inverted the image (see 22 July 1804 entry). For example, Clark's calculations of latitude for "Camp Dubois" on 18–20 December 1803 are too low by about half a degree. It is likely that the semi-diameter was
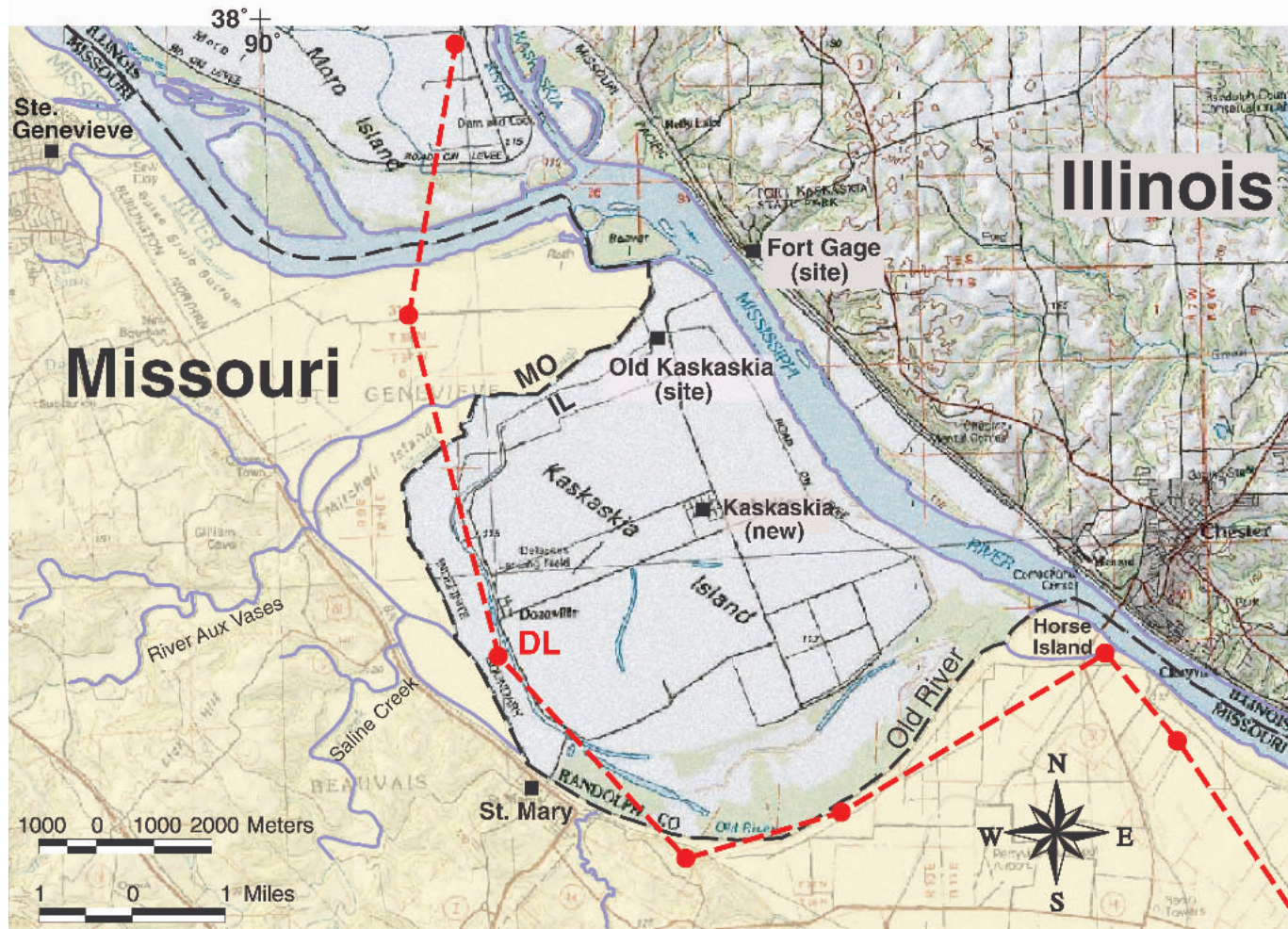

Figure 3. Map of Kaskaskia Island (K, Fig. 2A) and vicinity, Illinois (gray and green background) and Missouri (yellow background). On 27 November 1803, Lewis and Clark camped on the "lower point of the horse Island," situated at that time at the confluence of the Kaskaskia and the Mississippi Rivers. The red dots and dotted line mark the travel legs of the boat as recorded by Clark in the journals but corrected for declination; the point marked DL indicates the projected location of Donohoes Landing. The Mississippi River shifted dramatically in this region during the flood of 1881, abandoning its early channel along the Old River whose course is marked by Clark's traverse and by the modern state boundary, and capturing the former valley of the lower Kaskaskia River. Kaskaskia Island remains part of Illinois even though it is west of the Mississippi River.
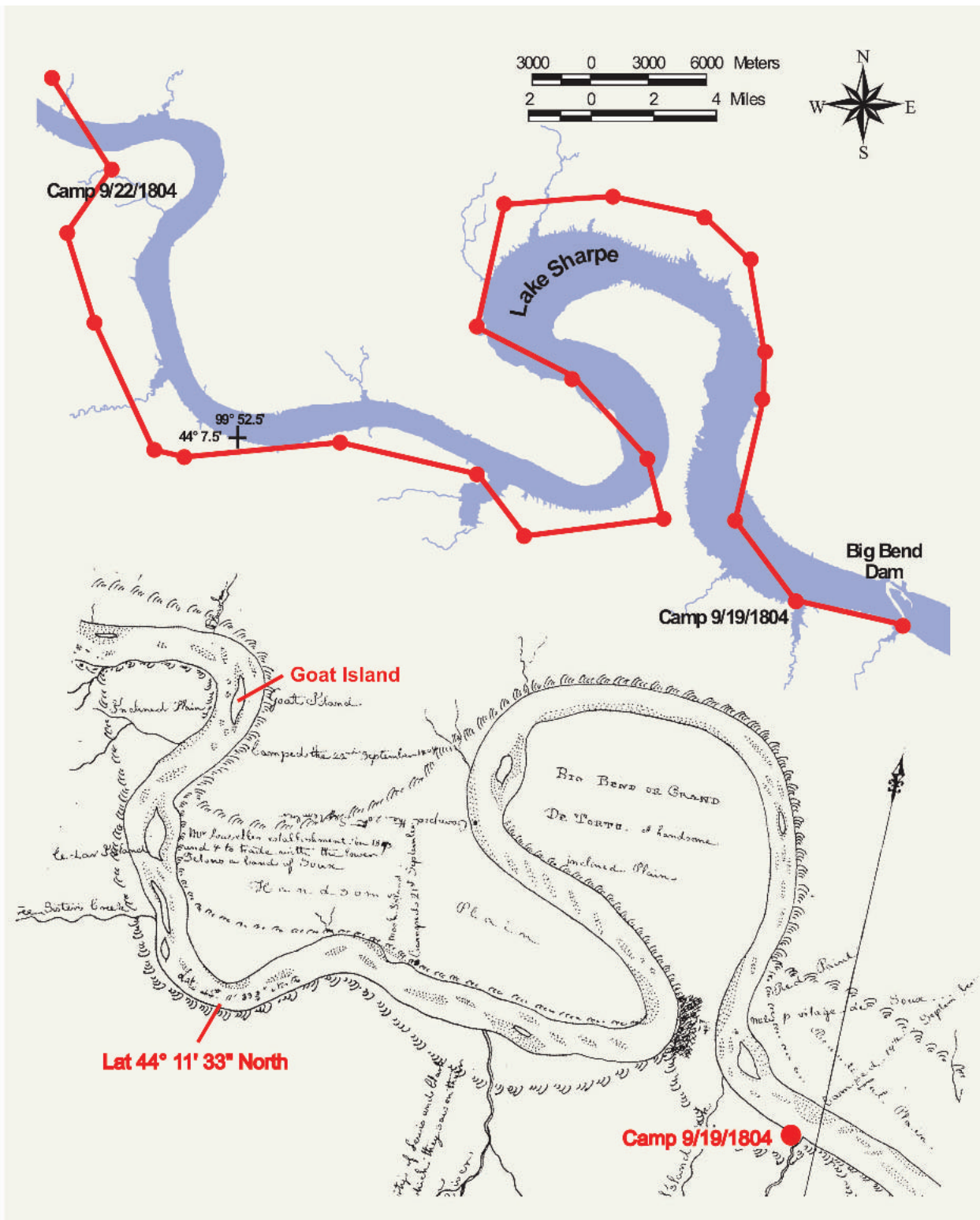
Figure 4. Map of the Big Bend on the Missouri River, central South Dakota (BB in Fig. 2A). The top illustration is a modern map showing Lake Sharpe impounded behind Big Bend Dam. Superimposed are a string of red dots representing the dead-reckoned distances and associated compass bearings for the travel legs reported by Lewis and Clark in the journals for 19–23 September. This string is rotated to account for a compass declination of 12.5° and is indexed to the well-constrained campsite of 19 September 1804. For example, the traverse from what is now Big Bend Dam to the 19 September campsite is reported as "due west 3.5 miles," but plots as 3.5 miles to the N77.5°W. The lower sketch map is part of Clark-Maximilian sheet 11 (a copy of Clark's original 1804 map which is now lost; Moulton, 1983), which has also been rotated by 12.5°. Note the prominent "north" arrow, which clearly represents magnetic north at this location in 1804; this arrow is orthogonal to the aforementioned, "due west 3.5 miles" traverse.
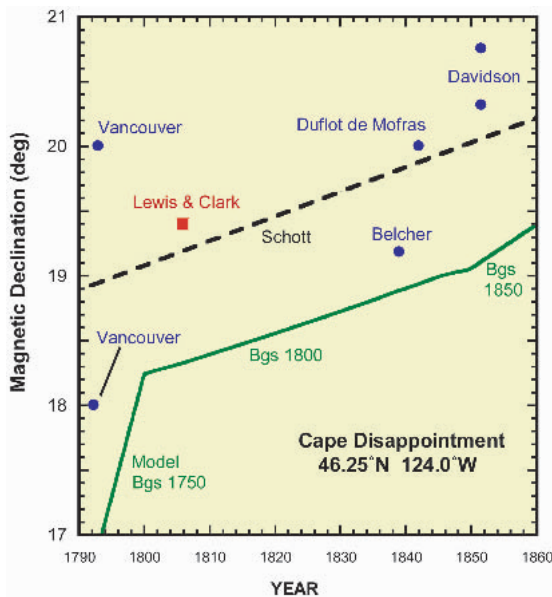
Figure 5. Historical shipboard measurements of the magnetic declination along the Pacific coast near Cape Disappointment, Washington (CD in Fig. 2A), starting with those by Captain George Vancouver in 1792 (Schott, 1856), are compared to Lewis and Clark's determination of 19.4° in 1805 (Table 2; see footnote 1). The dotted line is Schott's (1856) suggested trend for this site; the solid green line calculated from the Bgs models (U.S. Geological Survey, 2003) significantly underestimates the measured declinations.

unintentionally added instead of subtracted, and as a result, Clark's calculated latitude is too low by 0.544°.

Chronometers of the period were unreliable by today's standards, though on numerous days, Lewis and Clark made useful determinations of the apparent time of local noon by the "equal altitudes" method. In short, for a given angular setting of the sextant, sequential ante meridiem apparent times were recorded for the passages of the upper limb, center, and lower limb of the rising Sun. Then, for the same angle, post meridiem times were sequentially recorded for the passages of the setting Sun's lower limb, center, and upper limb. Three good estimates of local noon for that place and day can be made by averaging the three appropriate pairs of numbers, provided that the clock ran steadily during this interval. Suppose at some recorded clock time, the altitude and magnetic azimuth of the Sun were recorded. The "hour angle" for that measurement is accurately estimated by the hourly deviation from the interpolated noon clock time multiplied by 15°/hr (i.e., 360° per 24 hr).

Finally, the position of observation can be calculated from the measurements by several methods. For example, the latitude is easily calculated from the Sun's altitude at apparent noon given the appropriate solar declination from the ephemeris tables (Maskelyne, 1803; Garnet, 1804, 1805a, 1805b). For several reasons these determinations even for latitude are demonstrably not more accurate than ±5 min, and longitude error typically exceeds ±30 min (Preston, 2000). The latitude and longitude of the explorers at any time can be determined far more accurately by comparing their exhaustive notes for each travel leg with historical and modern maps (Moulton, 1983; Harlan, 2003).

Computational Methodology for Polaris

Lewis and Clark made several measurements of the "magnetic azimuth of Polaris" and recorded the time on their chronometer. If Polaris exactly coincided with Earth's rotational axis, then the magnetic azimuth would provide a direct measure of the magnetic declination for that location. Polaris does not precisely coincide with the rotational axis, so a second order correction is necessary.

At the present time (2003), the astronomical declination of Polaris is close to 89.28°, only about 43' from Earth's rotational pole. The latter deviation has decreased for millennia and will attain a minimum of 27' ca. 2100 A.D. In 1805, Polaris' deviation was far larger at 103.95' (Maskelyne, 1806), and subsequently it has decreased by ~0.303 min/yr. In 1805, Polaris could have been as much as 103.95' to either the east or the west of true North, depending on the time, as its apparent daily path described a circle about Earth's rotational pole with a proportionate radius.

Accurate calculation of true North from the position of Polaris can be made by simple trigonometry at any clock time, provided that the time of its "upper culmination" is known for that day. This latter time can be determined from Lewis and Clark's chronometer and the date plus the clock time at local noon. Also required are the right ascension of the Sun on that day, given in the ephemeris tables, and the right ascension of Polaris, which was 0 hr, 53 min, 25 sec in 1805 and has gradually increased to 2 hr, 34 min, 39 sec today. (The right ascension is the equivalent of longitude in the celestial coordinate system, but it is measured from 0 to 24 hr relative to the "first point of Aries," rather than in degrees from the prime meridian. For a more precise definition, see U.S. Naval Observatory, 2003.) Specifically, the local time of the upper culmination of Polaris differs from local noon by the difference between the Sun's right ascension and that of Polaris. Table 1 provides the magnetic declination in 1803–1805 for six locations using this method.

Computational Methodology for the Sun

The magnetic declination can also be determined by the difference between the measured magnetic azimuth and the true azimuth of the Sun at any time. There are two different means to combine the measurements of Lewis and Clark with ephemeris data to calculate this difference. Appropriate data were collected during 1803–1806 for 25 locations between the confluence of the Ohio and Mississippi Rivers and the Pacific Ocean.

Spherical trigonometry can be used to determine the true azimuth of the Sun from measured quantities of interest (Smart, 1977; U.S. Naval Observatory, 2003). Most remarkable are the spherical law of sines and two forms of the spherical law of cosines as applied to the "astronomical triangle," whose three apices are Earth's rotational pole, the observer's zenith, and the Sun, all connected by great circle arcs (Fig. 1). The spherical law of sines allows the true azimuth (A) to be calculated from the Sun's altitude (a) and declination (δ, from ephemeris tables) and the hour angle (H) of observation:

$$\sin A = \cos \delta \sin H / \cos a \qquad (2)$$

This equation has the property of being independent of the latitude. Alternatively, the spherical law of cosines can be used to determine the true azimuth in terms of the Sun's

altitude and declination and the observer's latitude ϕ:

$$\sin \delta = \sin a \sin \phi + \cos a \cos \phi \cos A \quad (3)$$

which is independent of the hour angle (U.S. Naval Observatory, 2003). A complementary relationship relates the hour angle, latitude, altitude, and declination, independent of the azimuth:

$$\sin a = \sin \delta \sin \phi + \cos \delta \cos \phi \cos H \quad (4)$$

Used in conjunction with equation 2 and utilizing H simply as a parameter for computation, equation 4 can be used to readily calculate the apparent path (altitude vs. azimuth) of the Sun across the sky for any latitude for any day for which the solar declination is given. This calculation can be highly refined if further provision is made for the small variation in the solar declination during that day. However, in the following discussion equations 2 and 3 are used to calculate the true solar azimuth from two partially independent sets of input data (Tables 1 and 2[1]).

Due to the periodicity of the trigonometric functions, ambiguity can arise in relating the quantity calculated for A, which normally varies from 0 to 90°, to the true azimuth of the Sun (or star), which conventionally varies from 0 to 360°. This complication relates to the geographic quadrant in which the Sun resides during early mornings and late afternoons in the spring and summer; no ambiguity can occur during fall and winter when the Sun resides from rise to set in the southeast or southwest quadrants. The ambiguity can be eliminated by calculating the complete altitude-azimuth path for the day of interest as discussed above, or more simply by comparing the magnitude of the measured altitude after correction to the quantity B, where:

$$B = \text{invcos} \mid \cos \delta \sin H \mid \quad (5a)$$

or $B = \text{invsin} (\sin \delta / \sin \phi) \quad (5b)$

and where the vertical brackets denote absolute values. Equations 5a and 5b

_____

were respectively derived from equations 2 and 3 for a true azimuth of due east or due west. If the measured altitude (after correction) at a given hour angle is greater than B, then the Sun is somewhere in the south and the conventional azimuth associated with that solar position is the quantity $180 \pm A$. If the measured altitude is less than B, then the Sun lies to the north of an east-west line and the conventional azimuth simply equals $\pm A$ during the ante meridiem, and the quantity $360° \pm A$ during the post meridiem.

RESULTS
1803–1806 Declinations

Lewis and Clark's measurements define the 1803–1806 magnetic declinations for 26 different locations across the continent (Tables 1 and 2; see footnote 1). The calculations of magnetic declination for locations based on the Sun's position, determined with equation 3 or equation 2, are provided in Table 2. The average determination for each location using the preferred equation 3 method is shown in Figure 2A, along with the six determinations based on Polaris. As seen on Figure 2A, the 1803–1806 magnetic declinations systematically increase to the west, from ~7.7° east along the middle Mississippi River to 19.4° at Cape Disappointment. The systematic variations attest to the great care with which Lewis and Clark made and recorded their observations. Shown for comparison (Fig. 2B) is the magnetic declination in 2003 across the western United States. The greatest change in declination has occurred along the middle Mississippi River as the agonic line (0° declination) currently passes through St. Louis County. This westward drift of the agonic line has apparently continued for more than two centuries, but more interesting is the concomitant small decrease in declination on the northwest coast. The contours of declination have become more compressed in the continental interior by westward drift, and their trend has become more northerly.

Most interesting of the early measurements are the six sites where the magnetic declination is based on the compass bearing of Polaris, which in five cases can be compared to the magnetic declination based on the position of the Sun along with either the clock time (eq. 2) or the latitude (eq. 3; Table 1).

Also tabulated are magnetic declinations calculated for each location at the actual date (1803–1806) according to British Geological Survey model Bgs1800, and for 2003 according to model IGRF-2000 (U.S. Geological Survey, 2003).

Good agreement is secured between the three different calculations of magnetic declination for 1803–1805 based on Lewis and Clark's data (Table 1). The agreement is excellent considering that the determinations invariably depend on the compass bearing of either Polaris or the Sun, and these measurements, while occasionally reported by Lewis and Clark to the nearest 1/4 degree, were more commonly reported only to the nearest degree. Nevertheless, the calculations for magnetic declination are reported here to the nearest tenth of a degree in all cases, which is justified because the precision is occasionally this good and because several of the determinations are averages based on multiple observations at a given location. Note that these determinations tend to exceed the declinations calculated from model Bgs1800 (see below).

In comparing the declinations in Table 1, it is useful to note that the various calculations do not have the same probable errors. Magnetic declinations based on Polaris may be easiest to understand, but the required compass measurement may be the most inaccurate of all because of Polaris' high altitude, particularly at high latitude (e.g., Montana). Moreover, the compass was necessarily read at night and probably by candle! Magnetic declinations based on the Sun's position and the clock time may be the next most appealing, as they are based entirely on measurements made by Lewis and Clark, but their chronometer was commonly inaccurate by as much as several minutes each day. A clock error of only four minutes relative to the interpolated time of noon translates into an error of an entire degree in the hour angle! As a result, the most reliable determinations of magnetic declination are based on the probable latitude of Lewis and Clark at the time of their measurement (eq. 3), which can generally be determined on modern maps to ±0.02° or better. Since their sextant was accurate to a few minutes of arc, and the ephemeris tables are extremely accurate, then the

greatest error in the calculated magnetic declination by this method arises from Lewis and Clark's compass reading of the Sun's position.

Kaskaskia Island, Illinois

It is useful to illustrate the combined use of Lewis and Clark's journals and measurements, the calculated declination, and modern maps in a case where a profound change in the course of a major river has occurred. Lewis and Clark kept detailed records of each travel leg on their journey, continuously recording both the compass bearing and the estimated, "dead reckoned" distance to the nearest quarter mile. This record begins at the confluence of the Ohio and the Mississippi Rivers, continues almost without interruption to the Pacific coast, and records in incredible detail their daily travel observations. Comparison of these notes and traverses with modern maps quantifies changes in the landscape and river course.

For example, examination of a modern road map reveals that part of the State of Illinois—notably Kaskaskia Island—lies *west* of the Mississippi River. The detailed notes of Lewis and Clark can be used to illustrate the historical developments that led to this unusual situation. After traveling generally northwest during the afternoon of 27 November 1803, Lewis and Clark came to and camped on the "lower point of the horse Island," situated at that time at the confluence of the Kaskaskia and Mississippi Rivers (Fig. 3). The following morning the explorers parted company, with Lewis continuing northwest by land to the town of (Old) Kaskaskia, and Clark plus the main party continuing upstream and generally southwest with the boats (Moulton, 1986–1993, v. 2, p. 117–118).

The large dots and the dotted line on Figure 3 mark the travel legs of the boat as recorded by Clark, but corrected for the 1803 declination of about 7.5° (Table 1). Clark's course was along a modern-day slough called the Old River that still marks the boundary between the states of Illinois and Missouri. At 1 p.m. they passed Donohoes Landing (Fig. 3), where "boats receive Salt from the Saline Licks" that were located 2.5 miles up Saline Creek (Moulton, 1986–1993, v. 2, p. 118). They then continued

more northerly, but the plotted positions suggest that Clark's estimated distances for these travel legs are a little too large.

Lewis traveled up the historical valley of the Kaskaskia River to the old town of Kaskaskia (founded in 1703), which was already a century old at that time and had been captured by Clark's older brother, General George Rogers Clark, during the American Revolution. Old Kaskaskia was destined to become the first state capital of Illinois. However, the fate of the old town changed during the great flood of 1881, when the Mississippi River underwent a disastrous shift to occupy the course of the lower Kaskaskia River (e.g., Franzwa, 1998). The latter channel was much too small to accommodate the huge Mississippi River, and the consequent erosion and widening ultimately destroyed the old town, requiring its abandonment and relocation to the center of Kaskaskia Island. Kaskaskia Island has since remained part of Illinois despite several court challenges.

Big Bend, South Dakota

A particularly instructive example of Lewis and Clark record keeping and methodology is the Big Bend of Missouri River, which the explorers described and mapped during 19–22 September 1804. Figure 4 (top) shows a modern map of this part of the river, now inundated beneath Lake Sharpe above Big Bend Dam, on which is superimposed a string of connected dots representing the individual travel legs reported in the journals by compass bearing and estimated distance. The plotted points are indexed to the 19 September campsite at the mouth of Night Creek, now Counselor Creek, with the bearing corrected for a declination of 12.5° (cf. Fig. 2A) but with the exact linear scale retained. A detailed sketch map of the same region, representing part of Clark-Maximilian sheet no. 11 (Moulton, 1983), is shown below, also rotated by 12.5°.

The correspondence between the modern map, the rotated travel legs, and the rotated sketch map testifies to the accuracy of Lewis and Clark's work. This comparison is facilitated because it is very unlikely that the former position of the river in this area lies outside what is now Lake Sharpe. Even though

the error of the plotted points would progressively accumulate beyond the 19 September 1804 campsite, note that the plotted point corresponding to the 22 September campsite, described in the journals as being opposite former Goat Island, is projected to lie within 3 miles of its actual position. Note also that were the sketch map and dots not corrected for declination, that Goat Island would lie west and significantly south of the northernmost point on the Big Bend, rather than to the west and significantly north. Thus, the prominent "north" arrow on the sketch map clearly corresponds to magnetic north in 1804. The illustration also provides an example of the accuracy of Lewis and Clark's sextant. Note in the lower left of the sketch map their latitude determination of 44°11'33", which compares favorably with the actual latitude of 44°7'30"; the corresponding positional difference is only about 4 miles. The journals contain several pages of descriptive material for this area, much of which is indexed to the individual travel legs and sketch map. The Big Bend is described in the journals as being more than 30 miles around but only 2000 yards overland across its neck, and as encompassing "a butifull inclined Plain in which there is great numbers of Buffalow, Elk & Goats (pronghorn) in view feeding & Scipping on those Plains…." (Moulton, 1986–1993, v. 3, p. 98).

Cape Disappointment, Washington

A detailed comparison of declinations based on Lewis and Clark's measurements, those made by early observers at sea, and those calculated from magnetic models can be made at Cape Disappointment near the mouth of the Columbia River (Fig. 5). This is the only site where Lewis and Clark were positioned near the coast and so provides the only direct link between their measurements and the large body of oceanic data. Captain George Vancouver made the first declination measurements in this area in 1792, and several measurements were subsequently made when this important area was visited by other ships as compiled by Schott (1856). The declination of 19.4° based on equation 3 and Lewis and Clark's observations of 24 November 1805 (Table 2) agrees very well with the other early measurements,

and also with the equation suggested by Schott (1856; dotted line) to describe the variation of declination in this area (Fig. 5). Note that all of the measured declinations are higher than those calculated from the British Geological Survey models for this 60-year interval; the average discrepancy is nearly 1.5°.

CONCLUSIONS

Observations made by Lewis and Clark can be used to calculate the magnetic declination in the continental interior of the United States in 1803–1806. The reduced data provide the oldest determinations of magnetic declination in the continental interior and are essential to interpreting the travel legs and the thousands of compass bearings reported by Lewis and Clark along their historic journey. The calculations confirm the westward drift of the agonic line and indicate that the temporal changes in declination have been greatest in the mid-continent and smallest along the northwest coast. The declinations based on Lewis and Clark's data are more accurate than those typical of the period and provide a test of the accuracy of magnetic models for this time interval.

ACKNOWLEDGMENTS

REFERENCES CITED

Becker, G.F., 1882, Geology of the Comstock lode and Washoe district: U.S. Geological Survey Monograph, v. 3, 422 p., with Folio Atlas of 21 sheets.

Bloxham, J., 1995, Global magnetic field, *in* Ahrens, T.J., ed., Global earth physics: A handbook of physical constants: Washington, D.C., American Geophysical Union, AGU Reference Shelf 1, p. 47–65.

Bowditch, N., 1939, American Practical Navigator: Washington, D.C., United States Hydrographic Office, U.S. Government Printing Office.

Franzwa, G.M., 1998, The story of Old Ste. Genevieve: Tucson, The Patrice Press, 211 p.

Garnet, J., 1804, The nautical almanac and astronomical ephemeris for the year 1804: New Brunswick, New Jersey, Second American Impression, (microform) Early American imprints, Second series, no. 50378.

Garnet, J., 1805a, The nautical almanac and astronomical ephemeris for the year 1805: New Brunswick, New Jersey, Second American Impression, (microform) Early American imprints, Second series, no. 6854.

Garnet, J., 1805b, The Nautical Almanac and Astronomical Ephemeris for the Year 1806: New Brunswick, New Jersey, Second American Impression, (microform) Early American imprints, Second series, no. 8960.

Harlan, J.D., 2003. http://lewisclark.geog.missouri.edu/campsites/1804/camps.shtml (July 2003).

Hoover, H.C. and Hoover, L.H., 1950, translators, De Re Metallica: New York, Dover, p. 57.

Jackson, A., Jonkers, A.R.T., and Walker, M.R., 2000, Four centuries of geomagnetic secular variation from historical records: Philosophical Transactions of the Royal Society of London, A 358, p. 957–990.

Malin, S.R.C., and Bullard, E., 1981, The direction of Earth's magnetic field at London, 1570–1975: Philosophical Transactions of the Royal Society of London, A 299, p. 357–423.

Maskelyne, N., 1803, The nautical almanac and astronomical ephemeris for the year 1803: London, Commissioners of Longitude.

Maskelyne, N., 1806, Tables requisite to be used with the nautical ephemeris for finding the latitude & longitude at sea: New Brunswick, New Jersey, [microform] Early American imprints, Second series, no. 10465.

Moulton, G.E., 1983, The Journals of the Lewis and Clark Expedition, vol. 1, Atlas of the Lewis and Clark Expedition: Lincoln, Nebraska, and London, University of Nebraska Press.

Moulton, G.E., 1986–1993, The journals of the Lewis and Clark expedition, vols. 2–9: Lincoln, Nebraska, and London, University of Nebraska Press.

Preston, R.S., 2000, The accuracy of the astronomical observations of Lewis and Clark. Proceedings of the American Philosophical Society, v. 144, no. 2, p. 168–191.

Schott, C.A., 1856, An attempt to determine the secular change of the magnetic declination on the western coast of the United States: Report of the Superintendent of the United States Coast Survey, Appendix 31.

Smart, W.M., 1977, Spherical astronomy: New York, Cambridge University Press.

U.S. Naval Observatory, 2003, The astronomical almanac for the year 2003: Washington, D.C.: U.S. Government Printing Office.

U.S. Geological Survey, 2003, Magnetic models: http://geomag.usgs.gov/frames/mag_mod.htm (July 2003).