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Results of geomagnetic observations in Central Africa by Portuguese explorers during 1877–1885

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Abstract

In this short contribution, geomagnetic measurements in Central Africa made by Capelo and Ivens – two Portuguese explorers – during the years 1877 and 1885 are provided. We show the scarce number of geomagnetic observation in Africa compiled until now. These Portuguese explorers performed a considerable amount of measurements of geomagnetic declination (44 measurements), inclination (50) and horizontal component (50) of the geomagnetic field. We compared the results attained by these keen observers with those derived from the global geomagnetic model by Jackson et al. [Jackson, A., Jonkers, A.,Walker, M., 2000. Four centuries of geomagnetic secular variation from historical records. Philos. Trans. R. Soc. Lond. 358, 957–990].

Keywords: Geomagnetic field; Africa; Historical observations; 19th Century

1. Introduction

Geomagnetism can be regarded has a relatively ancient science, with measurements of the declination field being performed in Europe since the early 16th century, with some observations possibly earlier than 1450s (Gouk, 1988). Soon it become apparent that the declination values for specific places (e.g. London and Paris) were slowly changing (Malin and Bullard, 1981; Alexandrescu et al., 1996, 1997; Barraclough et al., 2000). We know now that this change reflects the slow variation of the main magnetic field (secular variation). From a reconstruction perspective the greatest difficulty in studying long-term changes in the magnetic field of our planet arises from the lack of reliable long time series (Jackson et al., 2000).

In recent decades, there has been a growing effort by several research groups to produce large historical geomagnetic collections (e.g. Whaler and Gubbins, 1981; Shure et al., 1982; Barraclough, 1982; Gubbins, 1983; Gubbins and Bloxham, 1985; Bloxham et al., 1989; Bloxham and Jackson, 1992). These partially overlapping efforts have been merged in recent years, and added with even more original data, in what constitutes the most comprehensive compilation of historical geomagnetic data ever assembled, covering the period 1510–1930 (Jackson et al., 2000). The availability of these long and global datasets, together with modern observatory and satellite data have allowed to develop several time-dependent models, with the latest version being the geomagnetic field *gufm1* covering several

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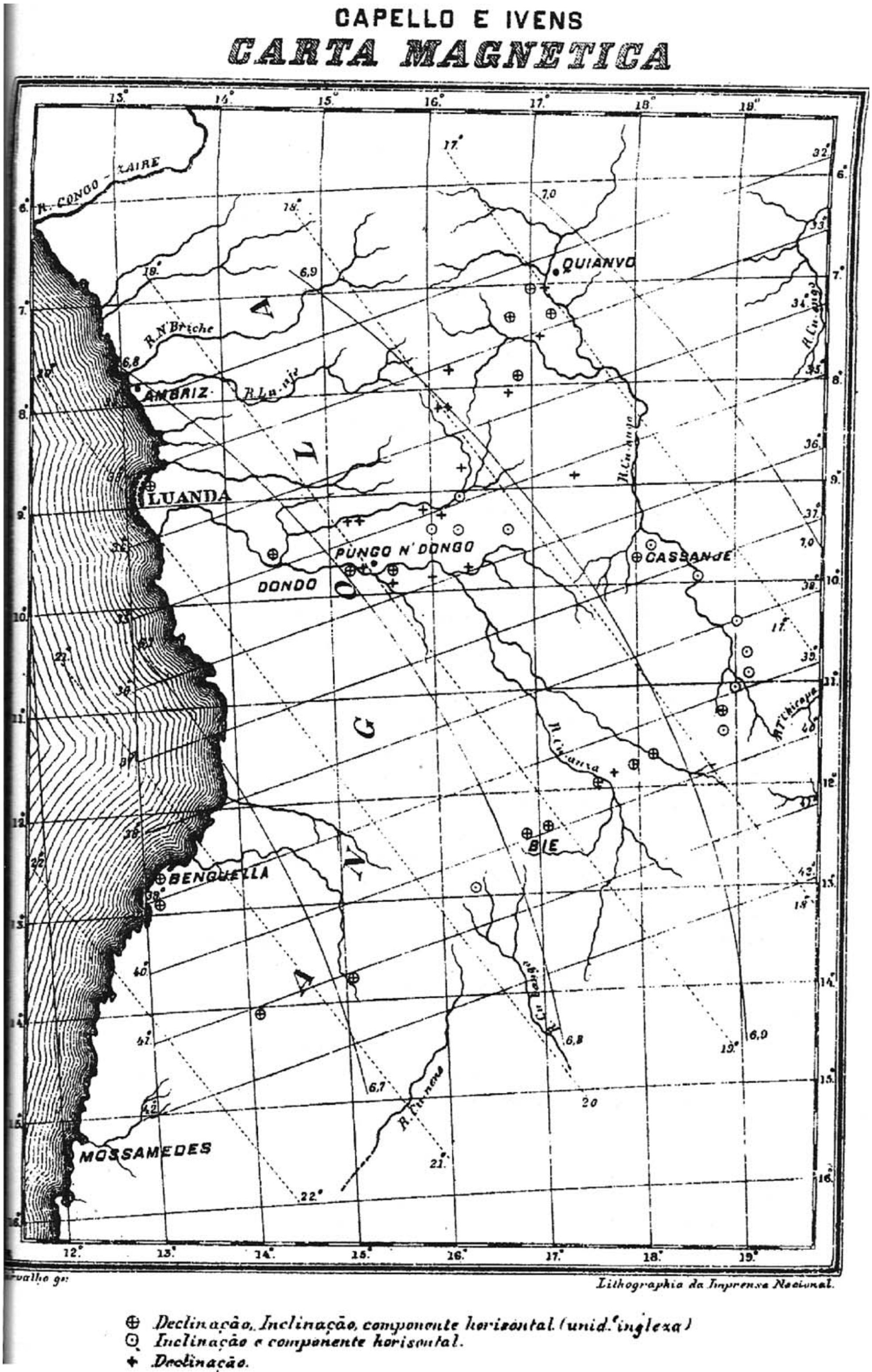

Fig. 1. Magnetic Chart published by Capelo and Ivens corresponding to geomagnetic values recorded in the first expedition during 1877–1879 (values given in Table 2). These locations correspond to diamonds depicted in Fig. 2.

centuries (Jackson et al., 2000; Jonkers et al., 2003, hereafter J03).

Whatever the period analysed in J03 it is immediately striking the predominance of oceanic over land observations. This imbalance towards maritime observations reflects the crucial necessity of navigators to make correct measurements of declination and inclination values when traveling in open ocean, an essential task to maintain a correct and safe trajectory for both mercantile and navy vessels. Throughout the second half of the 19th century several countries started to promote large-scale expeditions to cross entire continents and complement our knowledge on the surface geomagnetic field. This was particularly evident in North America, Russia and India and to a lesser extent in Australia (Stern, 2002). At the end of the century Africa and South America represented the two continents with the lowest density of geomagnetic observations. It is within this context that the recovery of this data set (covering large sections of the southern African region) by these two Portuguese explorers can be considered of relevance.

The main objective of this paper is to describe the new data set of geomagnetic observations obtained in the two scientific expeditions in Africa led by the two Portuguese explorers; Hermenegildo Capelo (1841–1917) and Roberto Ivens (1850–1898). They performed a considerable amount of measurements of geomagnetic declination (44 measurements), inclination (50) and horizontal component (50) of the geomagnetic field. The relevance of these two new datasets will be highlighted when put in African context. Finally, we will present an objective comparison of these values with those obtained for the same spots and years using a recent geomagnetic model.

2. Capelo and Ivens and the relevance of their observations

Capelo and Ivens were both officers of the Portuguese army with a strong scientific background. They were designated to perform two large-scale expeditions to the interior of Africa, between the two Portuguese colonies Angola and Mozambique, located at opposite shores of the continent and with significant extensions of unexplored land in between (including large sections of what is now Angola, Zaire, Zambia, Zimbabwe, and Mozambique). Both expeditions are described in great detail in two books (1) *De Benguela às Terras de Iaca* (From Benguela to the lands of Iaca), (2) *De Angola á Contracosta* (From Angola to the eastern coast of Africa). Both books became classics of exploration literature (in Portuguese) with several editions (latest in 1998), provoking a comparable impact in Portugal to what the adventures of Livingstone and Stanley represented for Great Britain at the time (Livingstone, 1858; Ingersoll, 1872; Stanley, 1872; Stanley, 1885). Interestingly, a considerable amount of meteorological and geophysical data can be found reproduced fully in these two volumes, as well as several graphics and maps covering the explored regions (see example in Fig. 1). Incredibly, to the best of our knowledge, none of these geomagnetic values were ever included in any published compilation of historical geomagnetic measurements (Jackson et al., 2000; J03 and references within these two).

The contribution of Capelo and Ivens to improve the amount of data covering the southern African continent since the 16th century can be seen in Fig. 2, where open diamonds (closed circles) correspond to geomagnetic observations performed by the two Portuguese on their first (second) expedition. For the sake of clarity we have only plotted data from JO3 that falls within the southern African box (10°E-35°W, 30°S-10°N), therefore avoiding the majority of geomagnetic observations obtained over the southern Atlantic and Indian oceans (not relevant in this context). It should be stressed that Fig. 2

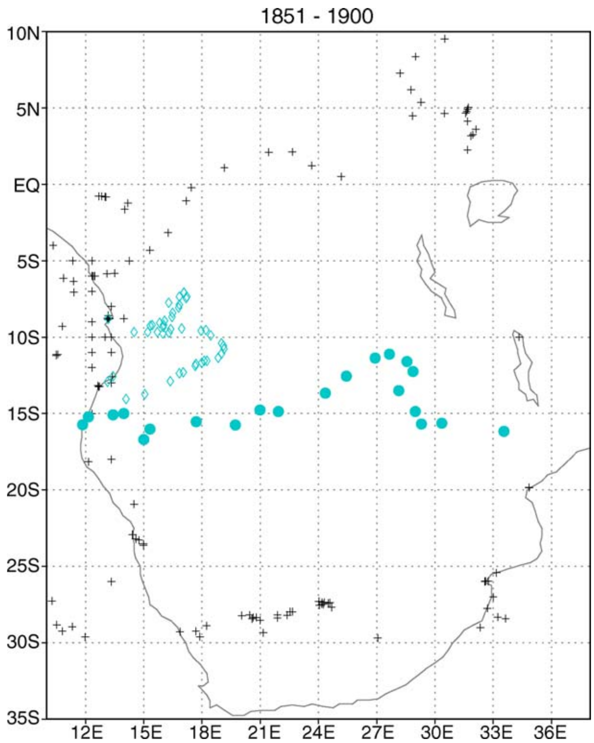

Fig. 2. Crosses represent the location of all geomagnetic measurements for an African box (10°E-35°W, 30°S-10°N) between 1851 and 1900 (data from Jackson et al., 2000 and JO3). Open diamonds (closed circles) correspond to geomagnetic observations made by Capelo and Ivens on their first (second) expedition.

merges observations undertaken at very different years throughout the 50 years period considered.

3. Measurements metadata

We had access to plenty of information on instruments and observational procedures used by Capelo and Ivens (1881a, 1886). It should be stressed that the expeditions led by these explorers did not went unnoticed in France and England. In France they have published an article in *Bulletin de la Société de Géographie* with results from the first voyage (Capelo and Ivens, 1881b), including most of the meteorological data and a magnetic field map (similar to the one depicted in Fig. 1). In England they have published the work "From Benguella to the Territory of Yacca" (Capelo and Ivens, 1882). Unfortunately, this version does not include any appendices with the geomagnetic observations, although it does provide information on the computation of geographical location and altitude.

Based on the information provided in the two books published in Portugal (Capelo and Ivens, 1881a, 1886) we know where and when were their observations performed, and also which instruments and methodology they have used. All the instruments employed by the explorers are listed in Table 1 and were calibrated against similar standard instruments well preserved at the Instituto Geofísico Infante D. Luis in Lisbon. By calibrating the instruments prior and after their long expeditions they were able to compute time-variable corrections. In pages 395–396 of Capelo and Ivens (1886) the authors provide detailed information on the corrections applied to all meteorological readings performed during their second journey. Some of the instruments could not be calibrated afterwards as a consequence of misfortunes, such as the breaking of the Mackneill barometer at the end of March 1878 or several others that were destroyed by a campfire in the 20th of June 1878.

Meteorological observations were performed at 6 a.m. and 20 p.m. (local time) and also at 7 a.m. (Washington meridian time). However, whenever the expedition stopped to raise a campsite at least four meteorological measurements were made. The hypsometer was used to compute the standard atmospheric pressure while the barometer was employed to assess changes of pressure within a given day.

The values of latitude and longitude were determined based on precise astronomical measurements of the azimuth and altitude of both Sun and Moon. We would like to underline their widespread scientific curiosity also to astronomical events, namely to track the occultation of Jupiter's satellites or the transit of Mercury on the 6th of May of 1878. Finally, to compute the altitude they employed a Baudin hypsometer and made observations of the boiling temperature point.

Concerning the characterization of the geomagnetic field Capelo and Ivens performed three types of geomagnetic measurements, namely the horizontal component (H) the inclination (I) and declination (D). In general, the observations of H and I were realized between 2 p.m. and 4 p.m. when they was camping for more than 1 day. The hour of measurement of D was the hour of the measurement of the local hour angle.

Values of H were determined with an unifilar magnetometer. This instrument consists of a suspended magnet of inertial moment J and magnetic moment m. If we displace the magnet from its equilibrium position under the influence of a magnetic field H field than it will acquire

Table 1
Quantity and names of instruments used by Capelo and Ivens during their expeditions into Central Africa

First voyage	Second voyage
6 Hypsometers Baudin (nos. 107–112)	2 Barometers type George
1 Barometer Mackneill	2 Barometers aneroid by Casella
2 Barometers aneroid by Casella (nos. 2182 and 2183)	4 Hypsometers
3 Thermometers Geisseler (nos. 55–57)	3 Thermometers
1 Psychometer Geisseler	3 Thermometers (maximum temperature)
1 Thermometer no. 2	3 Thermometers (maximum temperature)
3 Thermometers with cover	1 Psychometer
2 Thermometers (minimum temperature)	3 Thermometers unifilares
2 Thermometers (maximum temperature)	1 Barograph Richard
1 Thermometer Secretan (minimum temperature)	2 Chronometers Dent
1 Magnetometer unifilar	1 Magnetometer unifilar
1 Dover inclinometer	1 Small inclinometer by Dover (no. 66)
1 Declinometer	Two declination compasses by Casella
	Sextants, artificial horizontal, etc.

Table 2
Statistical characteristics of differences between model (gufm1) and observed geomagnetic values made by Capelo and Ivens during his first (1877–1879) and second (1884–1885) expeditions

	First expedition	Second expedition	All measurements
$D_{mod} - D_{obs}$ (°)			
Mean	−0.07	−0.77	−0.31
S.D.	0.64	0.87	0.79
N	29	15	44
$I_{mod} - I_{obs}$ (°)			
Mean	0.85	−0.03	0.52
S.D.	0.58	0.27	0.65
N	31	19	50
$H_{mod} - H_{obs}$ (nT)			
Mean	727	103	489
S.D.	652	262	618
N	31	19	50

an oscillation period T given by

$$T = 2\pi\sqrt{\frac{J}{mH}}. \tag{1}$$

Therefore, by knowing m and J and measuring the period T it was possible to compute the values of H (Udías and Mezcua, 1997). Capelo and Ivens have used the following expression in order to perform corrections to all their measurements taking into account the observed temperature:

$$T_{cor}^2 = T^2[1 - q(t - 25)], \tag{2}$$

where T_{cor} is the corrected value of the observed oscillation period T, that was obtained at temperature t (°C) and q is a correcting factor determined experimentally. Therefore Eq. (1) can be re-written as:

$$H = \frac{4\pi^2 J}{mT^2[1 - q(t - 25)]}. \tag{3}$$

For their first (second) expedition they have calibrated their instruments in Lisbon before leaving in June 1877 (December 1883) and after returning in March 1880 (November 1885). In June 1877, before leaving for their first expedition, they have obtained a value of $q = -0.001\,°C^{-1}$ valid between 0 and 30 °C. During their second expedition they have used two magnetic bars in their magnetometer. Prior to 1885 they employed the H_2 bar with $q = -0.00019\,°C^{-1}$, while afterwards they have changed to the H_{35} bar with $q = -0.00024\,°C^{-1}$.

Capelo and Ivens have used different units to record their magnetic measurements, namely the English units and Gauss (G) units. Here, we have converted all their measurements to nanoteslas (nT) using the following conversion factors: 1 English unit = 21.69 G, 1 G = 10^5 nT.

To measure the inclination I it was applied the standard procedure in late 19th century based on the use an inclinometer or dip circle. For their first expedition the explorers used an inclinometer from Dover instruments, and after several test measurements performed in Lisbon, concluded that the instrument error was on the order of ±12′. Interestingly, in their account of these observations they have clearly stated their dissatisfaction with the lack of stability of this inclinometer (Capelo and Ivens, 1881a). Therefore, for their second expedition, the two explorers have acquired a new instrument from Dover (labelled #66) that according to their preliminary tests possessed an average error of only ±6′.

Finally concerning the declination D values Capelo and Ivens employed several different compasses. For their first expedition they have used a declinometer based

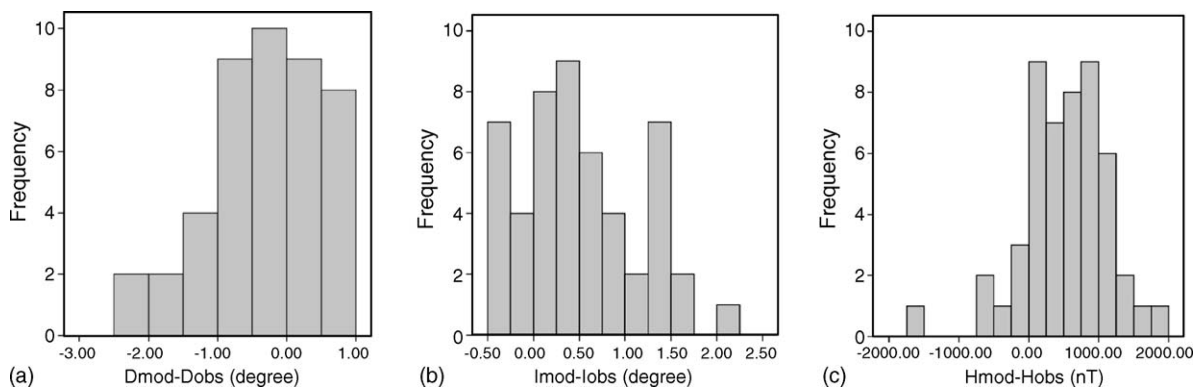

Fig. 3. Histograms of de differences between model (gufm1) and observed values for (a) geomagnetic declination, (b) geomagnetic inclination and (c) horizontal component.

on Solar azimuth. For their second exploration journey they decided to rely on a set of compass from Casella that are based on the Kater system. These apparatus have average errors of less than 10′.

4. Comparison with a geomagnetic model

We have information on the instruments used and the methodology employed to perform measurements, therefore we have a reasonable idea on the range of instrumental errors associated with these observations. However, without the "true geomagnetic field" for the 1870s and 1880s in this region of Africa it is impossible to compute these errors. Thus, we have compared the observational data recorded by Capelo and Ivens with the geomagnetic field generated by the model gufm1 (Jackson et al., 2000). Accordingly, we have calculated the value of the three standard components; D, I and H using this model for those dates and geographical coordinates provided by Capelo and Ivens. In this way, we

Table 3
Geomagnetic observations recorded during the first expedition of Capelo and Ivens (1877–1879)

Date	Lat.	Long.	Alt. (m)	Horizontal (nT)	Inclination (°)	Declination (°)
1 November 1877	−12.57	13.42	6	23575	−39.433	−21.80
18 November 1877	−12.92	13.13	98	23626	−39.733	−21.73
22 December 1877	−14.05	14.08	869	25189	−40.617	−21.35
26 January 1878	−13.73	15.05	1642	26208	−40.183	−20.97
28 February 1878	−12.88	16.37	1697	24046	−39.917	–
8 April 1878	−12.37	16.83	1572	23926	−40.000	−19.97
23 May 1878	−12.30	17.03	1464	24433	−39.867	−18.53
1 June 1878	−11.88	17.65	1149	24391	−39.000	−18.38
7 June 1878	−11.75	17.68	1188	–	–	−18.98
13 June 1878	−11.68	17.98	1078	24497	−39.883	−18.37
18 June 1878	−11.55	18.12	1112	24880	−39.900	−18.50
1 July 1878	−11.55	18.25	1189	–	–	−18.10
9 July 1878	−11.35	18.83	1300	24576	−39.650	−17.22
18 July 1878	−11.08	19.00	1340	24599	−39.083	–
20 August 1878	−10.77	19.13	1226	25046	−39.233	–
17 September 1878	−10.57	19.10	1180	24825	−38.967	–
3 October 1878	−10.40	19.00	1194	25332	−37.767	–
14 October 1878	−9.88	18.45	961	25397	−38.367	–
4 November 1878	−9.58	17.95	945	25733	−35.300	–
25 December 1878	−9.53	18.20	882	25669	−35.550	–
19 February 1879	−9.43	16.95	1126	25576	−35.550	–
12 March 1879	−9.47	16.38	1100	25124	−35.100	−19.07
25 March 1879	−9.33	16.00	1100	25890	−35.233	–
26 March 1879	−9.20	16.02	1029	–	–	−18.92
18 April 1879	−8.93	16.07	1060	25798	−35.000	−17.55
2 May 1879	−8.68	16.45	1219	–	–	−18.62
7 May 1879	−8.42	16.48	817	–	–	−17.93
12 May 1879	−8.07	16.80	659	–	–	−18.10
17 May 1879	−7.88	16.83	657	26554	−33.300	–
26 May 1879	−7.45	17.18	495	–	–	−17.45
29 May 1879	−7.35	17.22	390	26706	−33.333	–
4 June 1879	−7.08	17.07	395	–	–	−17.73
6 June 1879	−7.10	17.07	381	27840	−33.050	–
11 June 1879	−7.35	16.83	463	27287	−32.267	–
18 June 1879	−7.75	16.28	898	–	–	−17.47
3 August 1879	−9.07	15.82	1037	25599	−35.400	−17.68
5 August 1879	−9.22	15.43	731	–	–	−18.70
7 August 1879	−9.25	15.33	–	–	–	−18.32
18 August 1879	−9.67	15.70	1020	25475	−35.500	−18.83
14 September 1879	−9.77	15.98	–	–	–	−18.07
15 September 1879	−9.72	16.30	–	–	–	−18.50
17 September 1879	−9.67	15.20	692	24419	−35.250	–
30 September 1879	−9.67	14.50	93	25475	−36.000	−19.20
8 November 1879	−8.80	13.17	50	26300	−33.400	−19.30

are able to compare the values of any geomagnetic measurements derived from the model (D_{mod}, I_{mod} and H_{mod}) and the corresponding values measured by Capelo and Ivens (D_{obs}, I_{obs} and H_{obs}).

If both the observations and the model are not affected by any systematic *bias* than the differences between them should be centered in zero. This comparison is presented in this section.

The main statistical characteristics of the difference between the value given by the model and the observed value are show in Table 2, while the corresponding distribution of these differences can be seen in Fig. 3. For the geomagnetic measurement of *D*, *I* and *H*, the values observed and computed agree relatively well, with the average difference being less than 20′, 32′ and 500 nT, respectively. These differences seem to be partially related to the presence of the high-amplitude crustal anomaly of Bangui located in central Africa (Herrero-Bervera et al., 2004; Ravat et al., 2002). In particular, the first expedition of Capelo and Ivens, that reveals much larger errors of *H* than the second expedition (Table 2), crossed the southern branch of this Bangui anomaly. Readers looking for more information on this strong anomaly should go to NASAs website: http://denali.gsfc.nasa.gov/research/crustal_mag/prep/ where maps of the magnetization of the earth's crust are shown, based on measurements of the magnetic field made by NASA satellites Magsat, OGO-2, OGO-4, and OGO-6.

Furthermore, It seems reasonable to attribute (at least partially) the apparent improvement of *I* errors (Table 2) to changes on inclinometer from the first to the second expedition. The distribution of the differences for the *D* measurement is practically symmetrical in respect to zero. However, the distributions of the differences for *I* and *H* are slightly asymmetrical presenting a positive bias which is most probably associated with the non-Gaussian nature of errors close to the crustal field anomaly of Bangui.

5. Results and conclusions

The measurements of geomagnetic field (*D*, *I* and *H*) made by Capelo and Ivens in 1877–79 and 1884–1885 during two expeditions into Central Africa are shown in Tables 3 and 4. Taking into account the very low density of geomagnetic observations obtained for the interior of Africa at any time, this re-compilation of data obtained by the two Portuguese explorers represents a clear improvement on the overall knowledge of

Table 4
Geomagnetic observations recorded during the second expedition of Capelo and Ivens (1884–1885)

Date	Lat.	Long.	Alt. (m)	Horizontal (nT)	Inclination (°)	Declination (°)
13 March 1884	−15.73	11.85	4	23440	−41.870	−22.10
11 April 1884	−15.22	12.15	6	–	–	−21.97
7 May 1884	−15.00	13.97	1728	–	–	−21.28
22 May 1884	−15.08	13.42	1728	23870	−41.413	–
13 June 1884	−16.70	15.00	1067	24050	−43.500	−21.42
24 June 1884	−16.02	15.32	1110	23690	−43.468	−22.30
16 July 1884	−15.53	17.70	1188	23700	−43.625	−20.43
9 August 1884	−15.75	19.72	1198	23710	−44.765	−18.52
22 August 1884	−14.77	20.98	1081	23810	−43.922	−18.47
2 September 1884	−14.87	21.93	1032	24110	−44.010	−19.60
28 September 1884	−13.67	24.35	1071	24470	−43.610	–
13 October 1884	−12.55	25.43	1217	–	–	−15.70
3 November 1884	−11.37	26.92	1260	25590	−41.620	–
17 December 1884	−11.37	26.92	1260	–	–	−14.68
13 January 1885	−11.12	27.65	1260	–	–	−13.52
2 February 1885	−11.60	28.55	1070	25780	−41.765	–
20 February 1885	−11.60	28.55	1070	25380	−42.208	–
23 February 1885	−11.60	28.55	1070	25650	−42.338	−15.40
22 March 1885	−12.25	28.87	1167	25810	−42.645	–
6 April 1885	−13.50	28.13	1197	24710	−44.110	–
19 April 1885	−14.87	28.98	493	24320	−46.528	–
27 April 1885	−15.68	29.30	344	24040	−47.395	−17.63
7 May 1885	−15.63	30.35	365	24050	−47.658	–
13 May 1885	−15.63	30.35	365	–	–	−18.33
9 June 1885	−16.17	33.55	163	24110	−48.658	–

the geomagnetic field in that area. In particular it may help the geomagnetic scientific community to improve the accuracy of time-dependent model of the geomagnetic field over that region of the Globe.

A large amount of information on measurement methods and instruments used in these two explorations is provided in literature and partially reproduced here. We are confident that the observations were undertaken with considerable care, in order to partially offset the constant changes of the surrounding environment, particularly those related with temperature. This constant monitoring allowed to re-calibrate the instruments, and therefore to assure the reliability of the registered values. These data have been analysed by means of a comparison with the global geomagnetic model gufm1 (Jackson et al., 2000). The values of the data are in good agreement with those obtained with the gufm1 model, when we run this for the same pairs of lat.–long. and for the considered years. The values of observed inclination and horizontal component present a small positive drift respect to the model values. These small drifts can be explained by two main error sources, namely: (1) the presence of a conspicuous large crustal geomagnetic anomaly relatively close to the location of many readings (Bangui anomaly), particularly those obtained in the first expedition, (2) the lack of precision of the geomagnetic model due the scarcity of observation for this epoch in the interior of Africa.

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