AEROMAGNETIC SURVEY OF PORTUGAL
Northern Panel

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(Received April 1988)

ABSTRACT — In an earlier paper (Miranda et al., 1987) we presented the southern panel of the Aeromagnetic Survey of Portugal. With the conclusion of the northern one, here discussed, the survey is accomplished and an accurate mapping of the total magnetic field, for the 1980.0 epoch, is achieved.

The fitting of the two panels of the survey, for the chosen reference epoch, is made using the IGRF80 model, whose quality is judged from the array of magnetic repeat stations established by the Instituto Nacional de Meteorologia e Geofísica.

The analytical representation of the normal field is poorly constrained by the survey data suggesting the use of the IGRF80 model.

Finally, we present the total field anomaly map for the Portuguese mainland territory.

1 – GENERAL PROCESSING SCHEME FOR THE NORTHERN PANEL

1.1 – *Flight operations*

The flight operations of the northern panel were conducted by the geophysical team of the Portuguese Air Force and took place between the 11 June and the 30 July 1981. The total flight time for this panel was 26 hours, corresponding to approximately 6900 km of geomagnetic profiles.

The methodology followed was similar to that described for the southern panel (op. cit.). *Synthetically,* the magnetic field was measured every second with a Geometrics G803 magnetometer. The mean flight height of 10000 feet was barometrically controlled and the horizontal position was monitored by 10 sec interval photographs taken by a synchonized camera.

The Hayford-Gauss coordinates of each photo center were geometrically identified on 1:25000 topographic maps. The true flight lines are displayed in Fig. 1 for all the survey (northern and southern panels).

1.2 — *Daily variation of the field*

Magnetic reference stations were installed in Vila Real and Tomar (see Fig. 1). The Vila Real station provided the primary reference for the entire survey area, the Tomar station being kept only as a safeguard.

The Vila Real reference station operated successfully 24 hours a day during all survey operations, assuring a «continuous» monitoring of the magnetic field's daily variation, with a repetition rate of 10 sec.

The annual mean value for the reference station at the 1981.5 epoch was deduced by comparison between its mean hourly value and the corresponding ones at Coimbra Observatory, for the interval 00.00 a.m. to 01.00 a.m. and for all the period covered by the survey operations.

The mean difference between the two stations is:

$$\overline{T}_{C,\,s} - \overline{T}_{VR,\,s} = 412 \pm 11 \ \text{nT}$$

where $\overline{T}_{C,\,s}$ is the mean value for the Coimbra Observatory and $\overline{T}_{VR,\,s}$ that for the Vila Real reference station.

The value of the standard deviation is mainly due to the variability in Coimbra total field values, calculated from H and Z measurements.

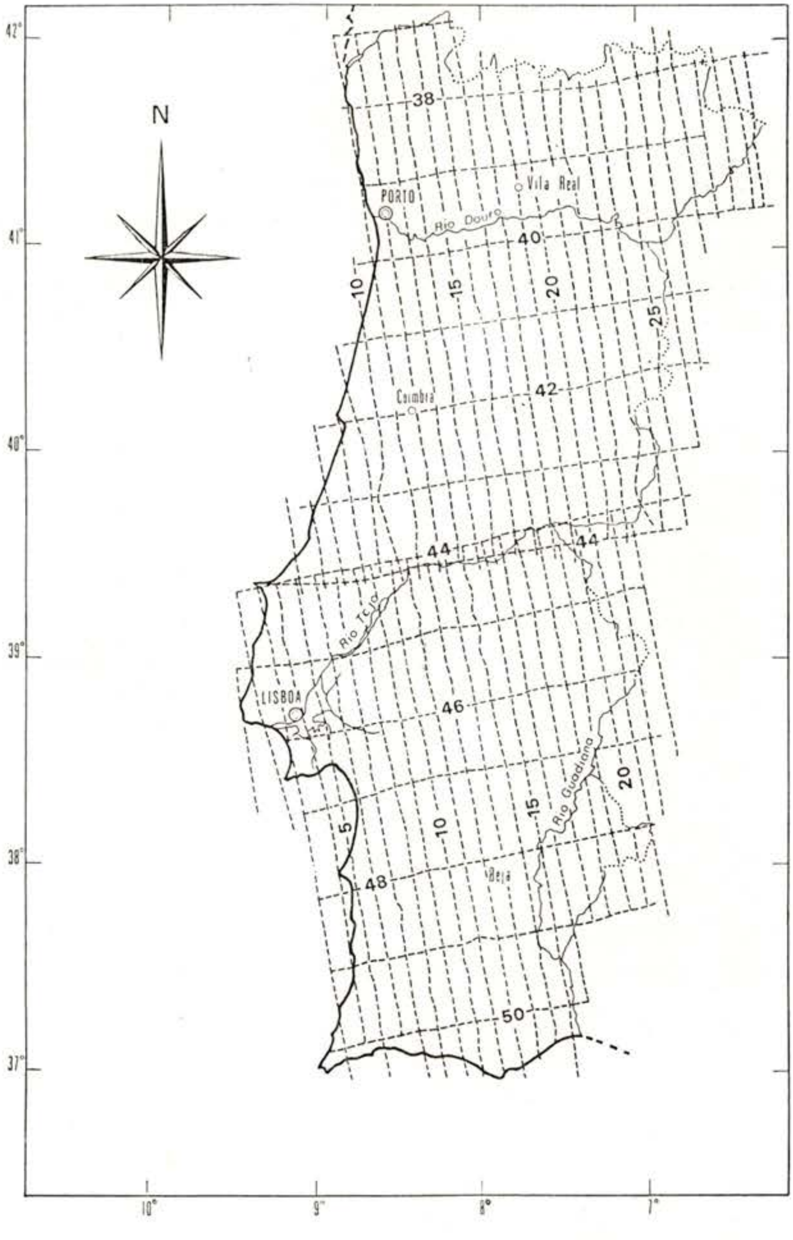

Fig. 1 — Actual flight lines of the Aeromagnetic Survey of Portugal as deduced from photo identifications.

The annual mean value for Vila Real reference station is then:

$$\bar{T}_{VR,\,1981.5} = 44499 \text{ nT} \pm 11 \text{ nT}$$

A comparison between the Vila Real and Chambon-la-Forêt Magnetic Observatory daily values for the same period, carried out as a subsidiary check, lead to a similar value (44500 ± 12 nT). The similarity of both central values seems to indicate that the mean difference Coimbra-Vila Real is well established.

Daily variation was then determined from the differences (T_{VR} (t) − 44499 nT) and applied to all field records.

1.3 — *Flight lines levelling*

The cross errors between flight and tie-lines were calculated and corrected as discussed for the southern panel. We must emphasize that flight lines 5 and 31, as they were only crossed by one tie-line, are poorly constrained, increasing the uncertainly in the corresponding field values.

The flight lines 25 and 27 and some of the tie-lines were disturbed and their mean values were significantly changed during the levelling processes as we imposed the condition that the mean cross over error for each flight line should be zero.

The residual cross errors are shown in Fig. 2. Their values are of the same order of magnitude as those presented for the southern panel, with a standard deviation of near 4.6 nT.

All the flight lines were then corrected with spline interpolation of the cross differences.

1.4 — *Data gridding*

The corrected values of the field records were filtered by «smoothing splines» (Reinsch, 1967) as described for the southern panel. The smoothing effect is, as before, very small, and mainly

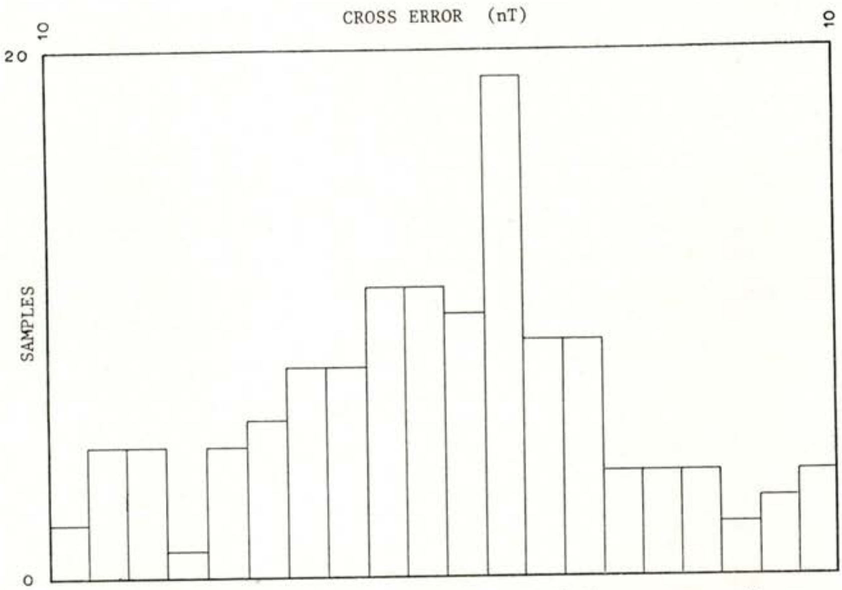

Fig. 2 — Residual errors for the northern panel of the aeromagnetic survey of Portugal.

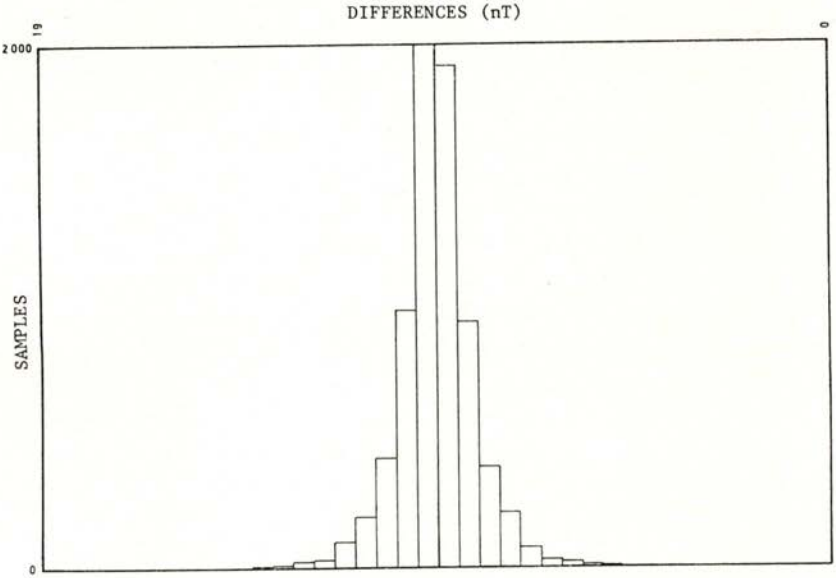

Fig. 3 — Differences between field values before and after smoothing.
(a) Coimbra Magnetic Observatory.
(b) SMN (Simona — Miranda do Douro) station.

contributes to spike elimination. In Fig. 3 we present the histogram of the differences before and after smoothing.

The projection of the flight lines over the regular grid produced a matrix with dimension (316,28) corresponding to a 10.230 km spacing between profiles (with east azimuth −7,5 degrees) and a 1 km spacing along each one.

These least squares values are significantly different from those that were found for the southern panel (10.014 km and −9.8 degrees) and, also, from the chosen value of equispacement for the representation of data.

2 – FITTING OF THE NORTHERN AND SOUTHERN PANELS

2.1 – *Secular variation model*

The southern panel was reduced to the 1979.0 epoch and the northern one to 1981.5. It was natural to choose the almost central 1980.0 epoch as the final reference of the survey.

The secular variation of the main field between 1980.0 and both individual reference epochs can be estimated from the repeat magnetic network established by the I. N. M. G. since 1952 in the portuguese territory.

From 1952 to 1962 and after 1973 the repeat stations were regularly occupied and it is possible to calculate the secular variation of the different elements (H, Z, D) in the array. Since 1978 the total field has been independently measured with a proton precession magnetometer and its secular variation can be better estimated.

As there is a relatively large number of observations (in the two periods mentioned above we almost have measurements every year) it is better to integrate all the known data in a single mathematical model for each station and then to use the explicit mathematical expression to directly compute the corresponding differences for the intervals 1979.0-1980.0 and 1980.0-1981.5.

The known existence of two «jerks» of the main field near the 1969.0 and the 1979.0 epochs imposes a necessary discontinuity

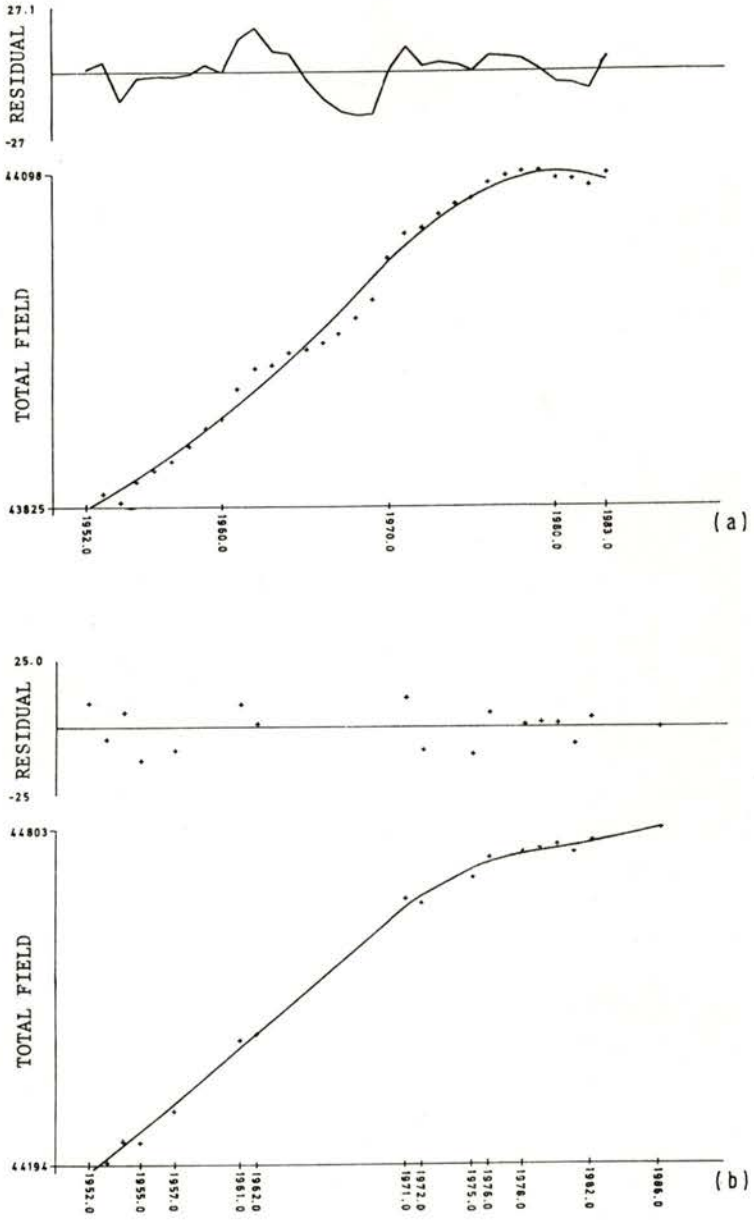

Fig. 4 — Comparison between the measured values of the total magnetic field and the interpolation by the use of a second degree polynomial for each of the intervals 1952-69; 1969-79 and 1979-86. The polynomials and their first time derivative are continuous in all the domains.

in the second time derivative of the secular variation. Consequently it was assumed that the total field could be expressed as a piecewise continuous second degree time polynominal whose coefficients differ for the three intervals (1952.0-1969.0; 1969.0-1979.0; 1979.0-1986.0) but in such a way that both the polynomials and their first time derivative are continuous throughout.

This assessment is in good agreement with the secular variation of the total field measured in Coimbra Observatory (see Fig. 4a).

The coefficients for all the repeat stations according to their effective period of occupation are presented in the table of Fig. 5. The results seem reasonable for the array, with the exception of the Algarve stations where large discrepancies are observed or the time series is very short (e. g. ARP).

STATION	A_1	B_1	A_2	B_2	A_3	B_3
COI	0.1903	7.65	−0.5902	14.29	−0.9931	2.48
CUM	0.1083	8.27	−0.7521	12.31	0.1568	−2.73
BCF	0.2216	9.94	−0.8103	17.43	−0.2347	1.27
SMN	0.0235	16.73	−0.7524	17.53	0.2069	2.48
ARP	—	—	−0.8715	13.70	−0.5956	1.50
CLV	0.0476	13.13	−0.5886	14.75	−0.9162	2.97
OLH	—	—	−1.0870	16.82	−0.0850	1.61
MRC	0.2520	7.01	−0.9502	15.57	0.3284	−3.43
BSB	—	—	−0.6569	7.97	−1.4815	2.72

Fig. 5 — Table of the coefficients; for the i-th interval the secular variation can be determined by $df = (A_i\,(t\text{-}t_0) + B_i\,(t\text{-}t_0))$ where t_0 is, respectively, 1950, 1969, 1979, t is expressed in years and df in nT.

2.2 – *The IGRF80 secular variation model*

The secular variation terms included in the IGRF80 model are not usually suitable for secular variation synthesis over long periods of time. However, as the time interval involved in the survey is very small, both reference epochs being located in a period of known «normal» behavior of the field, it is to be expected that they would give a reasonable estimation of the secular variation of the total field.

The values obtained from the IGRF80 are compared in Fig. 6 to those that correspond to the differences previously calculated from the magnetic repeat array. It is clear that for most of the stations both values are small and there is a good agreement between them, usually within the error limits of this kind of measurements.

In the south, however, the results from the repeat magnetic array seem not reliable, as there is a difference of about 4 nT between the variation estimates of two stations (BSB and MRC) located very close to each other.

The analytic expression of the secular variation from the repeat network stations is less consistent in the south.

2.3 – *Misfit estimation*

From Fig. 1 it is clear that a small area of overlap exists around tie-line 44 allowing a check of the misfit between the two panels of the survey

Unfortunately, the azimuth of the flight lines is different for the two panels and so there are no points belonging to both panels. Consequently it is necessary to perform an adequate interpolation of the measurements points to get an estimator of the differences, free from regional variations.

In Fig. 7 we present a typical result of the observed misfit along the flight line 9.

The analysis of all lines shows the existence of a systematic north-south positive difference with an average value of 6.0 nT. This difference is probably connected to the reduction methods employed and is within the error limits of the method.

The final survey accuracy did not change significantly from one part of the survey area to the other. The cross errors and the

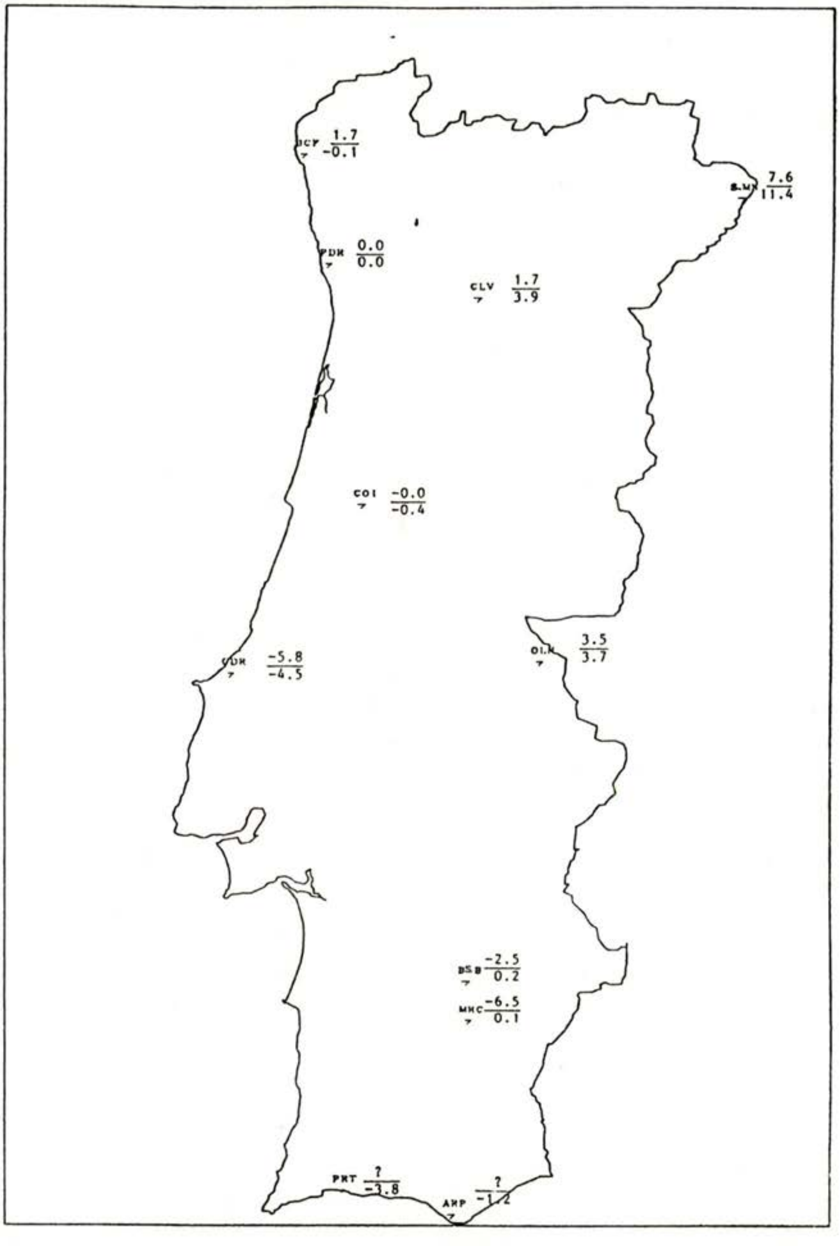

Fig. 6 — Differences between IGRF80 secular variation model (numerator) and the calculated values from INMG array of magnetic repeat stations (denominator) (nT).

uncertainty of the mean annual values for the Beja and Vila Real reference stations are quite similar. It is then justifiable to equally divide the average misfit between the two panels. This corresponds to a change of ± 3.0 nT in all field values.

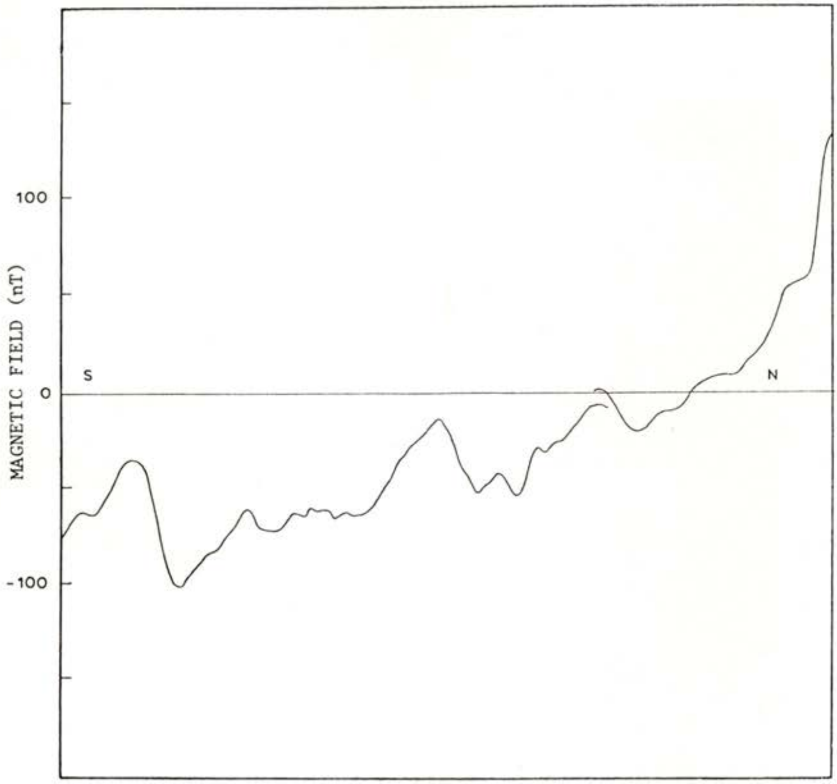

Fig. 7 — Fit of the northern and southern flight lines n.° 9.

After this translation all pairs of flight lines were slightly adjusted to assure a smooth transition along the overlapping area.

The final map is presented in Fig. 8.

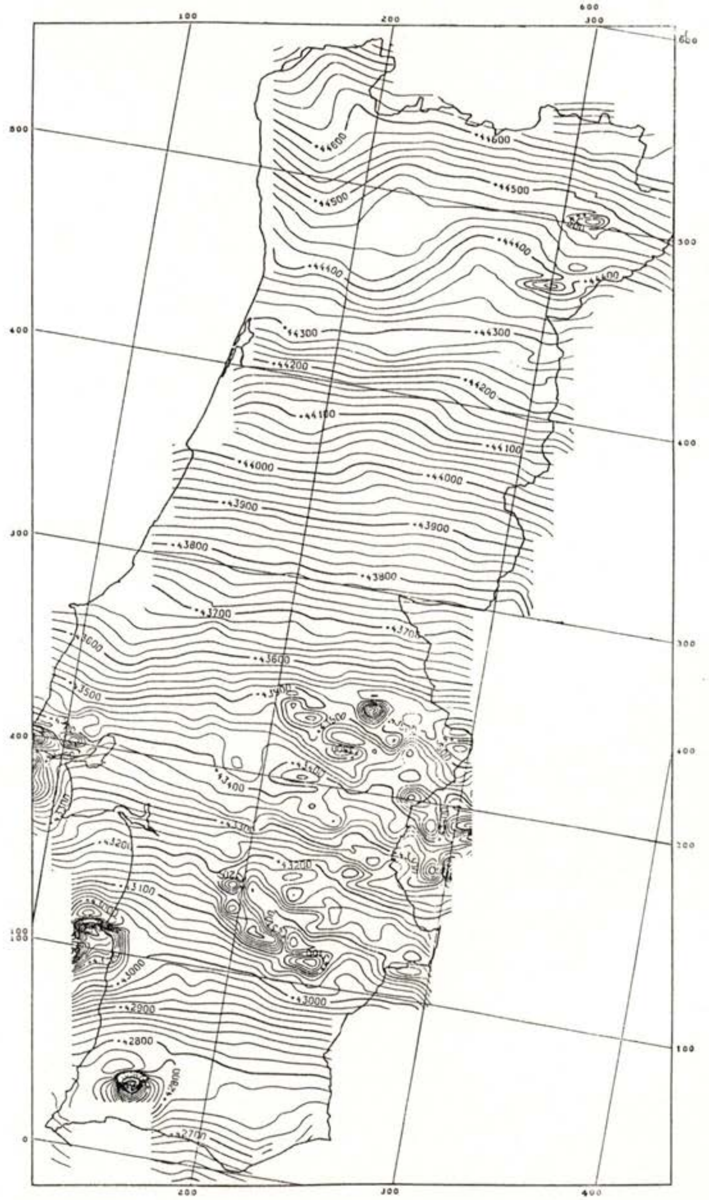

Fig. 8 — Total intensity magnetic field map for Portugal for the 1980.0 epoch and an altitude of 3000 m. Isovalues are plotted 20 nT apart.

3 – REPRESENTATION OF THE MAIN FIELD

The analysis of aeromagnetic data for the southern panel (Miranda et al.) mainly pointed out the implications of the lateral extension of the survey in the possibility of obtaining a realistic local expression for the main field. On the other hand it was assumed that the plan approximation to the measured data did not differ significantly from the IGRF80 model. Thus a slightly modified IGRF80 expression for the main field was adopted.

The addition of data for the northern panel modifies this picture: we have now a better knowledge of the north-south variation pattern of the geomagnetic field over Portugal. Now the relative importance of the southern anomalies for the numerical calculation is smaller. However, the relatively short longitudinal extension of the survey inhibits the clear description of the main field in this direction.

An orthogonal polynomial analysis of the survey data (Grant, 1957; Berezin et al., 1965) was carried out to detect the existence of a cut-off between the deep and the shallow components of the field. The normalized coefficients are partially listed in the table of Fig. 9 (a). As was already noted for the southern panel we cannot clearly identiy any gap between the two contributions.

x (E-W degrees)

0	1	2	3	4	5
0	4449441	867319	2133708	388194	150428
310364467	93932	4969347	1405616	1620564	31898
49201	702045	69534	896719	23009	1474
470723	7478	171204	459	6407	42460
10480	34459	143038	67226	55882	23398
12316	29811	4828	991	4777	11441
43965	6286	14755	1146	21874	881

(a) Normalized coefficients for the gridded data. Dimension of the matrix (55,18) corresponds a grid covering a rectangular area of 540 km by 170 km.

0	0	0	0	0
125556442	310364467	257936411	211921565	165135749
46802	49201	16146	233	12143
13361	470723	203701	72554	44151
16828	10480	30452	76732	53729
7311	12316	7306	355	6301
2859	43965	30293	781	2411
9647	10	12	4200	5
5907	31	14916	10204	3987
9611	1	945	6337	20144

(b) Values of the normalized coefficients for sucessive «windows» of dimensions (55,18), (51,18), (47,18), (43,18) and (39,18). We show only the polynominals in y (north-south) for the zero-order in x (east-west).

Fig. 9 — Table of the orthogonal polynomial analysis of the gridded data.

If we take successive nested windows of the matrix that represents the gridded data and perform again the orthogonal polynomial analysis we can detect a gradual change of the relative importance of the normalized coefficientes (see Fig. 9 (b)) avoiding the use of a high degree polynomial expression for the normal field.

The least squares first degree polynomial expression, which appears to be least sensitive to the contraints resulting from the small survey area, is:

$$F = 43770.0 - 0.14137 \times 10^{-3} \times (x - 200000) \\ + 3.73649 \times 10^{-3} \times (y - 300000) \;\; \text{nT}$$

where $(x - 200000)$ and $(y - 300000)$ represent the Hayford Gauss coordinates, in meter, referred to the cartographic «central point» of Portugal.

If we compare the IGRF80 with this approximation (see Fig. 10), as we did in the southern panel processing, we arrive of a different conclusion now; in spite of the very small difference between the mean values of both fields over Portugal (1.6 nT) there is a clear difference in the north-south gradient, mainly in the north. The choice between the two models remains difficult as we have no

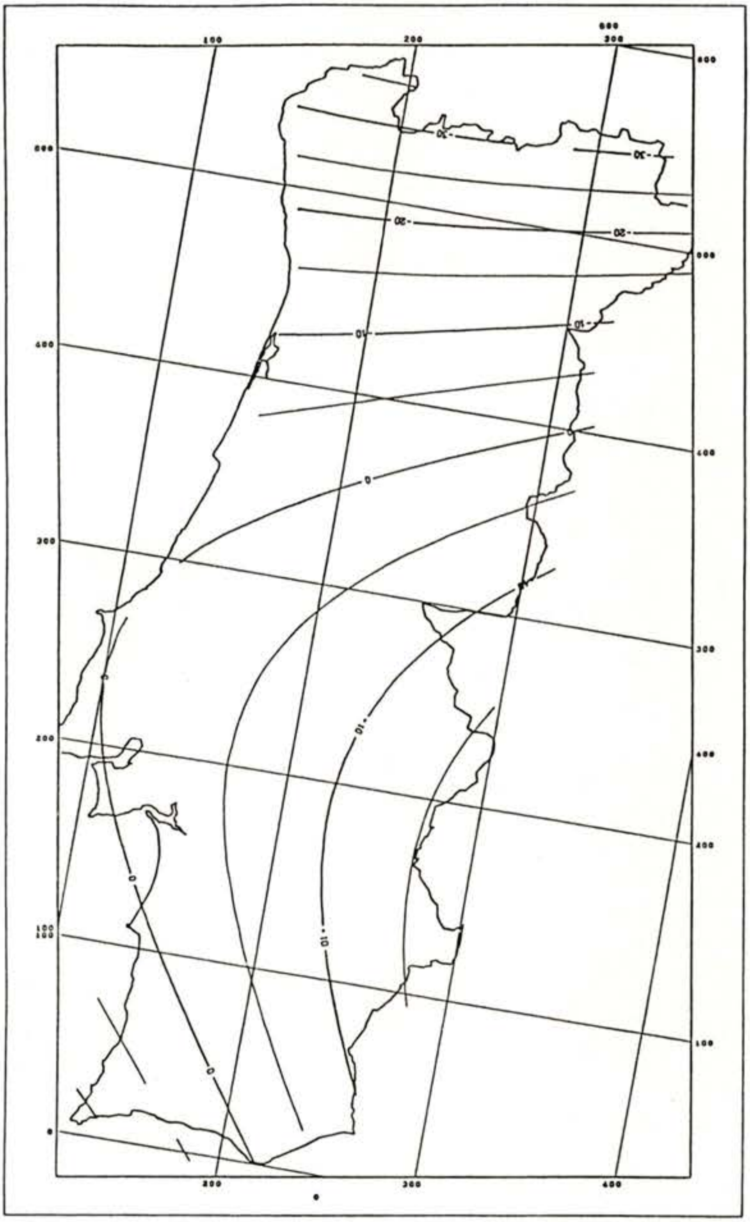

Fig. 10 — Difference between IGRF80 and a planar LS approximation of the survey data. Isovalues are plotted every 5 nT.

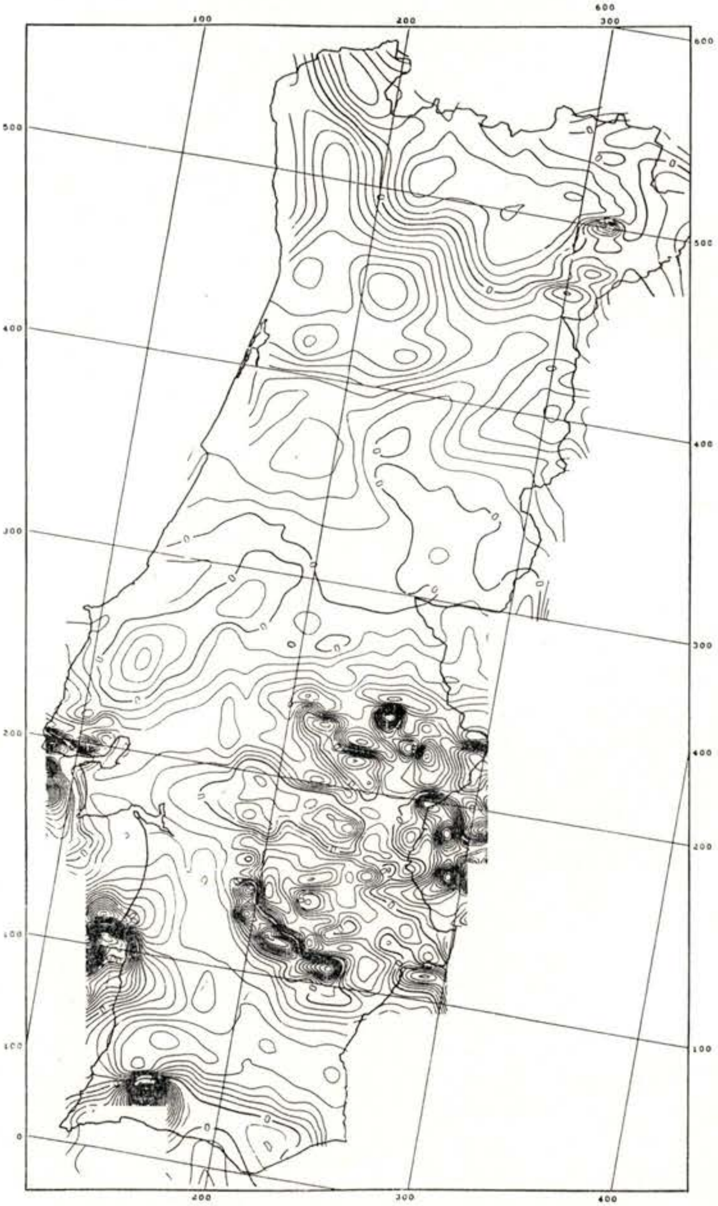

Fig. 11 — Aeromagnetic anomaly map for Portugal.

reliable information on the total intensity field over the rest of the Iberian Peninsula. While the Spanish aeromagnetic survey is not accomplished (and there is no equivalent available information from other sources, such as satellite — derived magnetic cartography) it is not possible to obtain a precise description of the main field.

The option for the IGRF80 as a normal field model appears to be the only coherent possibility as it is a well known model, also used as a reference for many other magnetic surveys. The misfit between the two models must be related in some way to the medium and large wavelength crustal anomalies that are not included in the global models (such as the IGRF) but whose wavelength (hundreds of kilometers) is of the same order of magnitude as this aeromagnetic survey.

The corresponding anomalies are presented in Fig. 11.

4 — ACCURACY OF THE SURVEY

The remarks made when discussing the accuracy of the southern panel of this survey are generally applicable now.

The proton precession magnetometer employed in the field operations has a nominal accuracy of ± 1 nT. The smoothing effect needed to filter the flight lines is similar for both panels although the distribution is a little larger for the northern panel because the field records of flight lines 25 and 27 are somehow disturbed as discussed above. The noise envelope can be so estimated as 2 by 3 nT.

Location errors over the land are not very serious where the cartography is updated, as an error of 50 meters in an area of large horizontal gradient (20 nT/km in the south but smaller in the north) causes an uncertainly of only 1 nT. There are some regions where the available cartography is old, and a greater error can be introduced because few terrain references are available for photo identification. We estimate the maximum location error as 3 nT over the land. However, this value can be greater over the sea, where the coordinates are interpolated or extrapolated.

The errors due to the variation of flight height and the non-homogeneity of the daily variation are roughly estimated from the residual cross errors. The two panels show a similar behavior and we can take 5 nT as a standard deviation of the cross error.

The new element that can be used to judge the final accuracy of the survey is the misfit between the two panels of about 6.0 nT. This is a measure of the uncertainty in the absolute values attributed to the reference stations (taking no account of any systematic error in Coimbra mean values) to which all data are reduced.

In conclusion, all the error sources produce a net uncertainty in the absolute values that can be roughly estimated at less than 10 nT. We must emphasize that the major part of this uncertainty is a smoothly varying quantity, distributed along the flight lines during the levelling processes, or an adding constant of the survey. Thus, the interpretation of the corresponding anomalies will not be biased by spurious or systematic effects.

We thank the Instituto Nacional de Meteorologia e Geofísica, the Força Aérea Portuguesa and the Laboratoire de Géomagnétisme of the Institut de Physique du Globe de Paris for all support needed to accomplish this work.

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