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A new geomagnetic observatory at Livingston Island (South Shetland Islands): Implications for future regional magnetic surveys

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Abstract

A permanent geomagnetic observatory is always the ideal reference station for monitoring geomagnetic activity during airborne, marine or ground magnetic surveying, especially in Antarctica, where logistic difficulties are an important factor even for the deployment of temporary base stations. The utility of the magnetic observatory records for the correct reduction of the survey data is reinforced if both their spatial homogeneity and their particular anomaly biases are assessed. This, combined with data from the magnetic surveys themselves, can yield information on the crustal contribution to the Earth's magnetic field from a remote and poorly understood region. With these objectives in mind, we present a new geomagnetic observatory in the South Shetland Islands, where (because of the complex regional tectonic characteristics) magnetic surveys on one or another structure are conducted from time to time. An evaluation of the observatory representativeness and a look at the crustal magnetic anomaly ambience are also given.

Key words *geomagnetic observatories – magnetic surveys – magnetic anomalies*

1. Introduction

One of the main problems in the reduction of near-surface magnetic surveys for external and core field effects is the difficulty in finding standard geomagnetic observatories in the vicinity of the surveyed area. This difficulty is obviously enhanced in remote regions such as in Antarctica, and the common practice (not only in Antarctica) has been to temporarily deploy either a single, or better, a network of stationary magnetometers in the region of airborne or shipborne operations. In Antarctica, however, logistic difficulties are frequently an important factor, and it is not always possible to use the ideal reference station or base-station network and a compromise has to be made with survey accuracy (Maslanyj and Damaske, 1986). It is sometimes even difficult to obtain a sufficiently stationary platform for the recording magnetometers. These problems in reducing magnetic surveys for Antarctic external and core field effects are considered important enough to be included in the Antarctic Digital Magnetic Anomaly Project (ADMAP) and considerable space was dedicat-

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Mailing address: Dr. J. Miquel Torta, Observatori de l'Ebre, CSIC - Universitat Ramon Llull, c/ Horta Alta 38, 43520 Roquetes (Tarragona), Spain; e-mail: ebre.jmtorta@readysoft.es ed to them in a Project Workshop (see Chiappini *et al.*, 1998).

A new geomagnetic observatory that was deployed in Livingston Island (South Shetland Islands) in December 1996 is presented in this paper. Its three-letter code was established as LIV. It can be considered a standard geomagnetic observatory only during the austral summers (when frequent absolute observations are obtained), but it is maintained continuously to record all year round with a noteworthy stability. The continuous records are and will be very useful for any kind of geomagnetic study and, especially, as a reference level for the search for volcanomagnetic signals at the neighbouring Deception Island volcano (García *et al.*, 1997) or to correct magnetic surveys in the South Shetland Islands - Antarctic Peninsula region. This is particularly important now that the geomagnetic observatory of the Polish Arctowski Station (ARC) at King George Island concluded its operations during the first quarter of 1996 (W. Glegolski, personal communication).

There are, however, many pertinent questions that must be answered before the utility of such reference records can be accurately assessed (see, *e.g.*, Regan and Rodriguez, 1981). They include an evaluation of the spatial homogeneity of the various external field signals, *i.e.*, the extent of the capability of the observatory to mirror the changing field; or the effect of the terrestrial conductivity distribution. On the other hand, to reduce for the core field it is necessary to know the crustal component of the observatory or to rely on a global or regional main field model. In principle, since the region is immersed in a very complex magnetic anomaly structure and tectonically is one of the most active regions in Antarctica, those records are susceptible to contain an important anomaly bias and their variations may be not sufficiently representative to satisfy the assumption of regional uniformity of temporal variations of the geomagnetic field. Thus, a second important aim of this study is to attempt an assessment of the observatory representativeness. Thirdly, an inspection of a new anomaly map compiled for the Bransfield Strait region with regard to the influence of these anomalies on the observatory anomaly biases is presented.

2. The new observatory and its data

The geomagnetic observatory started its operations during the 1996-1997 Austral summer survey at the Spanish Antarctic Station Juan Carlos I. The station is located at Livingston Island, in the South Shetland Islands. The observatory was placed at 62°39′44″S, 60°23′41″W (52°6′15″S, 8°12′40″E Geomagnetic, according to the IGRF95; Barton, 1997), 19.4 m a.s.l. (fig. 1). The criteria for the selection of both the most appropriate site and the most suitable magnetic station, its characteristics, the method for the measurement of both the field variations and the absolute observations, the software designed for the data analysis, and its overall previous verification at Ebro geomagnetic observatory, are described in Torta *et al.* (1997a). In brief, the magnetic observatory (lodged in three non-magnetic and thermally isolated huts) is based on an automatic vector magnetometer, in which a Proton Precession Magnetometer (PPM), acting as the magnetic sensor, is adequately exposed to bias fields by means of two mutually perpendicular pairs of Helmholtz coils. When deployed, the coils are aligned to measure changes in Declination (D) and Inclination (I) ($\delta D/\delta I$ configuration), and total field (F) (Riddick *et al.*, 1995). Absolute measurements are independently taken with a fluxgate theodolite (often called *DI-flux* because D and I are determined using the instrument). Baselines and data for the first summer season are given in Torta *et al.* (1997b). The remainder of the 1997 records and the new baselines and data for the 1997-1998 survey have been published in a subsequent Bulletin (Torta *et al.*, 1998).

The closest geomagnetic observatory in operation in the region is Argentine Islands (AIA) at the former U.K. Faraday Station (this station was taken over by the Ukrainian Antarctic Research Centre in 1995 and renamed Vernadsky). The particular positions of AIA, ARC and LIV observatories, which are just on the meridional sector in which are located the geomagnetic poles, converts them as clear mid-latitude observatories in spite of their high geographical latitude (because the south magnetic pole lies in the opposite hemisphere). This is definitely an advantage with regard to magnetic surveys, since

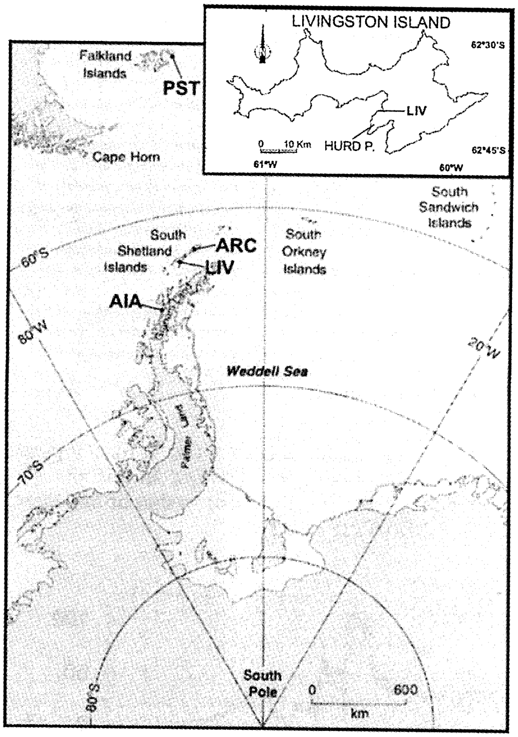

Fig. 1. Location of Livingston Island geomagnetic observatory (LIV) and neighbouring observatories in the region, identified by their IAGA code (Port Stanley, PST; Arctowski, ARC; Argentine Islands, AIA). ARC is closed at present.

the magnetic disturbances increase as the auroral zone is approached, sometimes making it impossible to judge whether magnetic anomalies are real or only appear as a result of non-appropriately corrected fluctuations in the external earth magnetic field, because of their huge amplitude and their important spatial heterogeneity (see, *e.g.*, Damaske, 1989).

On the other hand, and especially for ARC and LIV, they are observatories that lie close to one of the foci (the one with the largest amplitude and the only which corresponds to a minimum) of the four large regional total field anomalies caused by the non-dipole sources within the liquid core (Pesonen *et al.*, 1994). This means that the general criterion by means of which one assumes that the intensity of the magnetic field is of the order of 30000 nT at the equator and progressively increases towards the poles up to approximately 60000 nT is no longer valid along the way of the South America-Antarctic peninsula sector. In fact, at ARC and LIV average values are of about 36000 nT, which is a typical value on the geomagnetic equator. Moreover, these low values tend to decrease because of the negative annual change (the secular variation maps show also an isoporic focus on the area; Barton, 1997). Finally, the three observatories in the region suffer from important negative crustal anomaly biases, as will be seen in a following section. The combination of all these factors leads to an extraordinary decrease of the total field in this region.

3. Homogeneity of geomagnetic variations

Since essentially «the function of a magnetic observatory is to record the short and long term variations of the geomagnetic field in such a way that the information obtained is representative for a large area» (Wienert, 1970), it is always convenient to map not only the permanent magnetic field in the surroundings of the observatory but also its short-term variations. The first recommendation is fulfilled by resorting to both the main field and its Secular Variation (SV) charts (which can also include fields from large scale crustal anomalies, especially if they come from regional models; see De Santis *et al.*, 1999) and magnetic anomaly maps (see next section). But for many observatories, the second recommendation is not fulfilled, because of the implicit technical difficulties and the nature itself of the underground electrical conductivity distribution (Jankowski and Sucksdorff, 1996).

The homogeneity of the variations should be studied by analyzing simultaneous data from an array of magnetometers. This has not been attainable up to date for the case of Livingston Island observatory. The only simultaneous records at our disposal were only a month of data (15 December 1996 to 15 January 1997) from AIA. The next closest geomagnetic observatory in permanent operation is in the Falkland

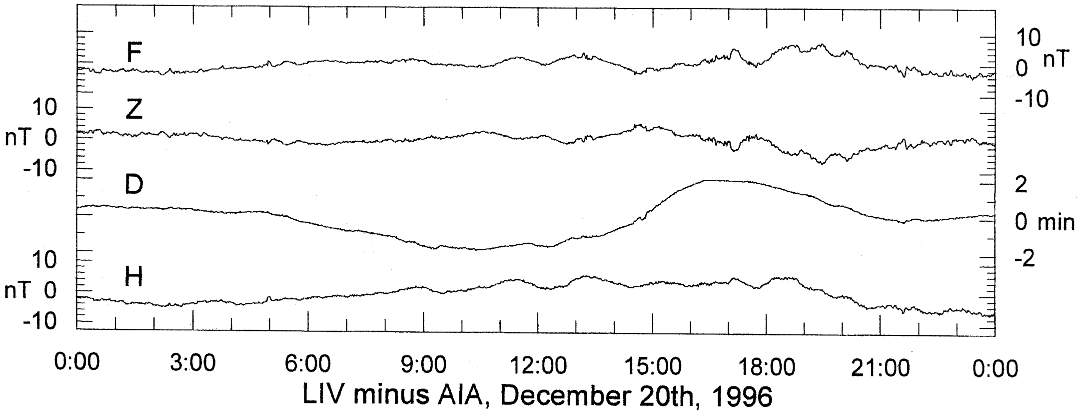

Fig. 2. Differences in the field elements between Livingston (LIV) and Argentine Islands (AIA) for a typical quiet day, computed from the variations with respect to the daily mean. Time is in UT hours. In this and the following two figures, the vertical scale of variation of D in minutes is set to be equivalent to that of the other elements in nanoTeslas, according to (*e.g.*, Wienert, 1970): $\Delta D(') = \Delta D(\text{nT})/H \cdot \sin 1'$.

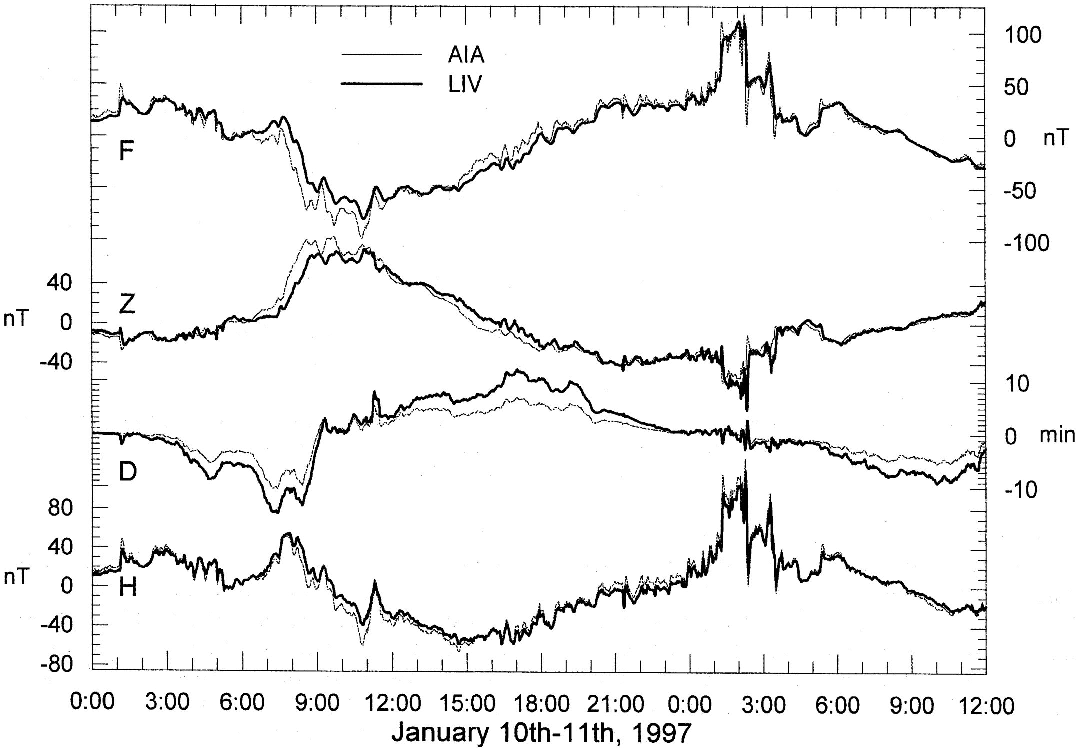

Fig. 3. AIA and LIV variations on 10th-11th January, 1997 with respect to the two-day mean (although only the first 36 h – when the most important disturbances occurred – are shown). Time is in UT hours.

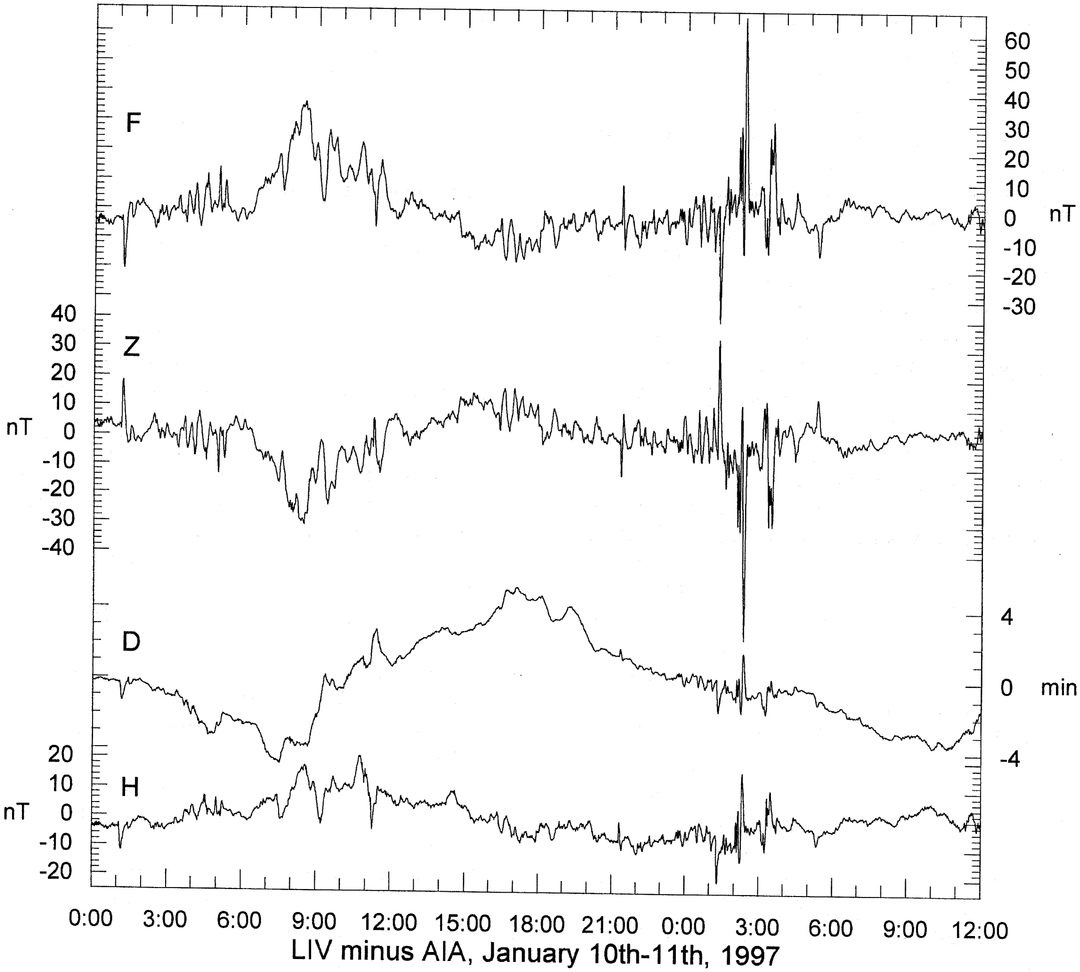

Fig. 4. Differences in the field elements between LIV and AIA for January 10th and first half of January 11th, 1997 (computed from the variations with respect to the two-day mean). The vertical scales are the same of fig. 2, but the horizontal axis has been compressed with respect to that of fig. 2. Time is in UT hours.

Islands, near Port Stanley, at about 1200 km from LIV. As the geographic longitude is about the same, data from the Falklands have been used for checks on the overall signs of the daily or shorter-term variations, or for correcting wrong timings in the case of GPS reception failures by the identification of universal events such as SSCs. However, the distance between both observatories is so large that the observed primary external fields are intrinsically different.

The comparison with the AIA data brought encouraging results with respect to the homogeneity of the variations of both LIV and AIA observatories, if we take into account that they are approximately 370 km far away. Typical differences in quiet days were of the order of ± 5 nT in *F* and *Z*, and slightly higher in *H* (± 6 nT) and *D* (± 2′). The 2.5° of difference in geographic latitude between both observatories is enough to detect the change in the shape and the current density of the overhead ionospheric current system which is responsible for the S_q daily variation, and this fact seems to have more influence in the horizontal components than in the vertical component. The range of the daily variation is maximum at the summer solstice, so the reported differences for the quiet-time variation are the highest to be expected. Some of the differences may be due to the non-cyclic variation, as a result of storm-time after-effects, which must be slightly different at both observatories. Therefore, the variation of the overall resulting difference is not always centred at zero. A representative example of the above described behaviour, corresponding to a typical quiet day ($A_p = 2$), is presented in fig. 2.

With respect to geomagnetic activity, the worst situation is expected to occur in the case of severe geomagnetic storms, like the well reported disturbance in the magnetic field of the Earth (*e.g.*, Joselyn and Peredo, 1997) which began on January 10, 1997, at 01:04 UT, and left it notably disturbed (with K_p ranging from 3- to 6o) till approximately midday of January 11 (at 01:16 UT of this day an important re-activation with another reported SSC appeared); the A_p of the two days being 32 and 18 nT, respectively. In fig. 3 the variations around the two-day mean including that event at AIA and LIV are jointly plotted, showing how the differences can increase in those special situations (difference values are given in fig. 4). Except in two almost instantaneous peaks, the total field differences in the most disturbed periods range between – 20 to + 30 nT. It has to be noted that sharp peaks might give rise to large differences, but they might be due to the different sampling at both observatories. Temporal discrimination in each figure is one minute, but while minute values at AIA were obtained by averaging 20-s instantaneous values, at LIV each *D* and *I* minute value is computed from the combination of two PPM readings shifted off by some seconds, and each *F* minute value from the average of another two readings, when it measures without polarizing the coils.

During periods of moderate activity ($A_p \approx 10$, and three hourly K_p index ranging from 1- to 4o) differences are not much higher than those reported above for quiet days. For the total field, which is the most required element with regard to magnetic surveys, we detect differences of about 8 nT peak to peak.

4. Magnetic anomalies

There exist several marine and airborne magnetic surveys covering the South Shetland Islands – Bransfield Strait – Northern Antarctic peninsula region (Parra *et al.*, 1984, 1988; LaBrecque *et al.*, 1986; Maslanyj *et al.*, 1991; Kim *et al.*, 1992). The most striking feature shown by these surveys is a high intensity magnetic anomaly broad belt (50-100 km width), termed as Pacific Margin Anomaly (PMA) or West Coast Magnetic Anomaly (WCMA), depending on the authors. This belt, extending along the Pacific margin of the Antarctic Peninsula, divides into two branches northeastward of Adelaide Island with one of them extending along the South Shetland Islands. It corresponds to an anomaly high in the total field, in excess of about 1000 nT, which seems to be caused by mafic and mafic-intermediate members of a linear plutonic complex (Garrett, 1990). Nevertheless, all three above mentioned observatories show important lows in this element with respect to the global models that range from about 500 to 1000 nT, indicating that the anomaly pattern is much more complex and/or that there are interferences from shorter wavelength constituents.

A detailed inspection of the anomaly contour maps which have recently been prepared as a result of the compilation made on behalf of the ADMAP (P. Morris, personal communication), however, shows how the anomaly highs are distributed along the Pacific margin of the islands, but in the Bransfield Strait margin -where Arctowski and Livingston Island observatories are located- lows dominate. This well defined wide magnetic low extends between the two branches of the WCMA, along the Bransfield trough, and there is a narrow positive signature in between which seems to correspond to an incipient rift along the Bransfield Strait (Parra *et al.*, 1984). The strong gradients on the northern coast of the Hurd Peninsula at Livingston Island (which delineate the steep passage from the South Shetland Islands branch of the WCMA to the Bransfield trough magnetic low) might explain the 1100 nT in the total field and the 2 degrees in declination biases that are observed at ground with respect to IGRF. Similar biases (although of smaller amplitude) were observed at ARC. These important magnetic gradients are interpreted (González-Ferrán, 1985) as originated by a series of longitudinal fractures parallel to the axis of the oceanic subduction trench.

To evaluate the anomaly biases that the above mentioned crustal signal produces in the observatory records we simply determined the mean value of the residuals derived by subtracting the values given by the IGRF models to the observatory annual means (see fig. 5). The anomaly biases estimated in this way do compare reasonably well with the values resulting from main field global models that incorporate the crustal biases as parameters of the models (by using satellite and surface data together). These

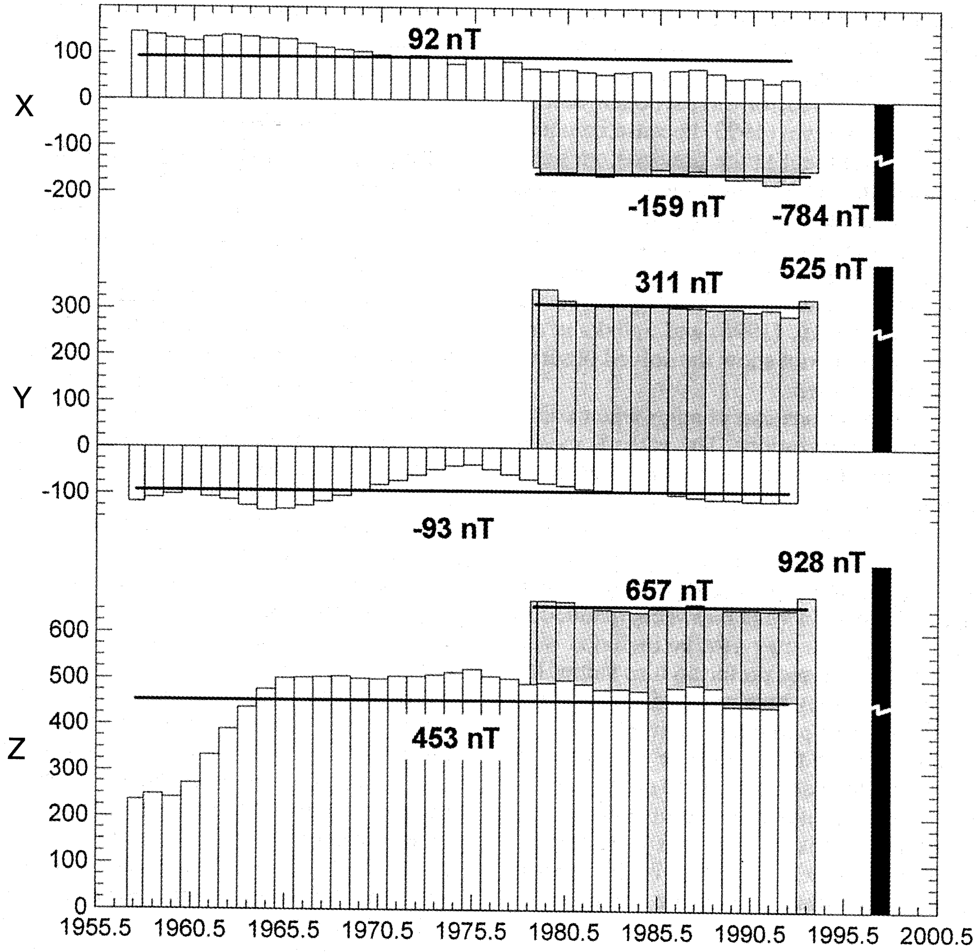

Fig. 5. AIA (white bars), ARC (grey bars) and LIV (black bar) residuals with respect to IGRF models (available observatory annual means minus IGRF). Solid lines and their labels indicate the overall mean value of the residual for each complete period and each component.

models have been routinely developed by the Goddard Space Flight Center of NASA (they are usually coded as *GSFC* plus the date of its preparation). Tables can be found for the anomaly biases solved for any of the geomagnetic observatories whose data were used for the model determination (Langel *et al.*, 1982; Langel and Estes, 1985; Sabaka and Baldwin, 1993). In the latter reference one can find a table with the values solved from various of those models for each observatory showing how, in fact, there exists preferred bias values even when using different parameterizations. Therefore, one can assume that those biases and ours (being very similar) provide a sufficient estimate of the observatory crustal signals. However, we do not trust the values solved for the particular model of Sabaka and Baldwin (1993) because incoherent biases with respect to the previous ones are solved for many observatories, such as ARC. This is comprehensible, the work being the first attempt to include the S_q variation in the modelling. Further and improved attempts, including also fields of magnetospheric origin, can be found in Langel *et al.* (1996) and Sabaka *et al.* (1997), but they do not show the solved observatory anomaly biases.

Observatory biases can change when using different parameterizations. The early S_q model of Sabaka and Baldwin (1993) included more parameters than the other models for which biases were shown in their table. This may explain part of the decrease in the bias they find at Arctowski. By including a separate parameterization for S_q, some of what had been included in the observatory bias may now be included with S_q. The fact that we see preferred bias values for the other models may be more a reflection of the similarities in their parameterization (degree 13 truncation of main field, little or no model of external field) than any constancy of bias values (M.E. Purucker, personal communication).

In any case, it is evident that the anomaly biases are particularly important in the vertical component, and those of LIV are certainly the largest ones of the three observatories in all three components. The signs of the vector crustal biases of ARC and LIV are coincident, reflecting that both observatories lie close to (but in the negative part of) the axis of separation of a dipolar elongated total field anomaly, as we can see in the magnetic anomaly map (the positive sign in the vertical component is explained by the main field values of Z being negative in the southern hemisphere). In addition to the WCMA, which is a regional feature and probably deep-seated, the magnetic effects of the topography (1700 m maximum relief and about 250 m of local relief) may be significant contributors to the determined observatory bias. While the rocks in the immediate vicinity of the observatory (turbidites) are not especially magnetic (A. Grunow, personal communication), Livingston Island as a whole is dominated by igneous rocks with magnetizations up to 4 A/m (Grunow, 1993).

5. Discussion and future perspectives

In the region under concern, typical maps reflecting magnetic anomalies due to geological sources use contour intervals of 100 nT or more. This means that under quiet or moderately active periods, the LIV magnetograms used as base-station records can be reliable at distances up to at least 300-400 km. The accuracy of the reduction can be further improved, or such a distance increased, if data from both LIV and AIA reference observatories are used. Differences between the survey location and each observatory can be calculated, and an interpolation procedure (with or without weighting) applied to determine the correction to be made at the measuring point, in a similar way to that employed for the reduction of repeat station data (Newitt *et al.*, 1996).

In the case of severe geomagnetic activity, some of the LIV-AIA analyzed differences in the vertical component (which are accordingly also reflected in the total field differences) are shown to be due to a phase shift in the most rapidly changing variations, which is likely to be caused by some heterogeneity in the conductivity of the upper crust strata, affecting the induced variations. However, we do not reject a different coast, island or peninsula induction effect. As stated in Section 3, however, the investigation of the electrical conductivity anomalies requires observations at some temporary measuring sites besides magnetic observatories already existing (Honkura, 1978), but this has not been attainable yet. A first attempt to relate LIV and AIA individual response functions could be made, but it is not clear that the result might be taken as representative, because the electrical conductivity of the crust and upper mantle is usually far from isotropic.

To confirm whether the measured anomaly biases are strictly of crustal origin, it is our intention to downward continue the anomalies compiled at airborne altitudes as well as to derive an estimate of the other elements. This will also serve to check whether the assumption of taking magnetizations parallel to the present field (Ghidella *et al.*, 1991; Suriñach *et al.*, 1997) is correct or not. On the other hand, the inclusion of the new geomagnetic observatory data in the derivation of global or regional models which incorporate a solution for the anomaly field at each observatory will provide a better estimation of the actual observatory anomaly bias.

There exist several methods for deriving all elements of the crustal magnetic field from total intensity observations (Purucker, 1990; Macmillan and Barraclough, 1990), the most promising ones being the equivalent point source inversion method (*e.g.*, Mayhew, 1979) and the application of filter operators (*e.g.*, Le Mouël, 1970). It would not be feasible, however, to apply the equivalent source technique directly to low-level aeromagnetic data because an enormous number of dipoles would be required (unless one is looking at a very small area). In the only reported attempt to apply the technique to data taken at altitudes much lower than those typical of satellite missions, an aeromagnetic survey was first upward continued by a conventional technique, and then the equivalent source technique was applied to interpret the regional field in terms of Curie isotherm variations (Mayhew, 1985). On the other hand, one would not want to fit data at a certain elevation using dipoles, then compute the field at a lower elevation in an attempt to «downward continue» the field, because this would probably lead to big problems because of the inherent instability of the method (M.A. Mayhew, personal communication).

Some tests with the determination of the appropriate filter operators and the use of the convolution operation in the space domain, by means of an adaptation of the program of Gibert and Galdeano (1985), have provided encouraging results (Macmillan and Barraclough, 1990). Analogously, either the space domain convolution of Bhattacharyya (1977) or the frequency domain transformation of Lourenco and Morrison (1973) should be adequate given the nature of the survey and its geomagnetic latitude.

For the correct comparison between the downward continued aeromagnetic data and the recent ground observations (or the upward continuation of the latter with the original aeromagnetic survey), one has first to translate the field to present epochs according to the regional secular variation pattern. Figure 6 indicates how

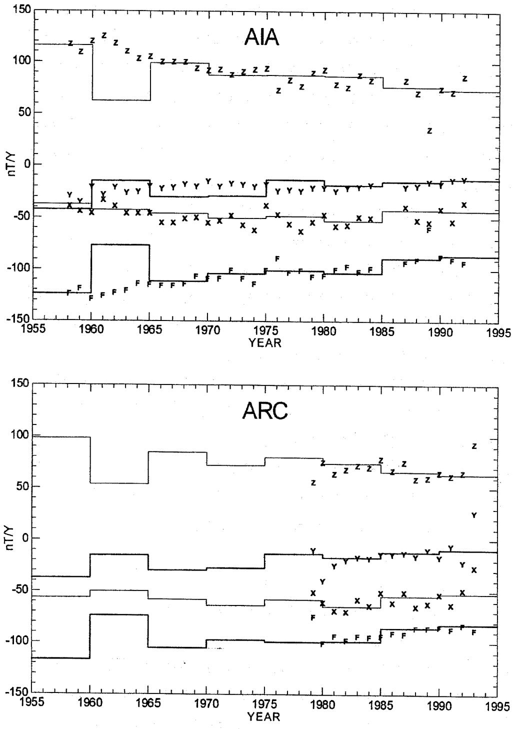

Fig. 6. Behaviour of the Secular Variation (SV) field measured at AIA and ARC for X, Y, Z components, and the total field F (indicated by the corresponding letters as symbols). The same behaviour, but synthesized from the different DGRF-IGRF models is plotted as solid lines.

the IGRF SV models behave fairly accurately in the area. It is, however, not equally precise for all the intervals (we recall that the IGRF SV is a constant function for each 5-year interval). The worst situation occurred for the 1960-1965 interval, due to the inefficiency of the DGRF 1960 to fit the actual AIA data. This is also manifested in the residuals plotted in fig. 5: the IGRF is becoming more precise after approximately 1980.5 (one expects residuals from the observatory annual means to be constant in time, if the unmodelled signals are only of crustal origin). This agrees with the general impression that the DGRF 1980, based almost entirely on data from the Magsat satellite, provided the best coefficients ever determined, and their influence in the successive revisions is still noticed. On the contrary, single one-year discrepancies in fig. 6 are probably due to errors in the observatory base-line determinations. Significant amounts of annual change manifested by the total field in the region, and accordingly by the horizontal and vertical intensities, are a result of the nearby isoporic focus which was already mentioned in Section 2.

The differences provided by the global models might certainly be reduced with the aid of a regional reference model for the main field and its SV, because they tend to represent regional distinct behaviours more accurately. A new task for ADMAP is to encourage the development of such a regional core field model for a variety of applications, including better determination of crustal magnetic anomalies. The inclusion of the Livingston Island observatory data will help to constrain it to realistically represent the magnetic field in the concerning sector.

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