"HELLENIC ARCHAEOMAGNETIC INTENSITY MASTER CURVE: Tentative results from spectral analysis"

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Abstract

The up-to-date reliable data of archaeomagnetic intensity for Greece and surrounding areas are specially analysed employing the Maximum entropy and best fitting by successive approximation methods.

The analysis revealed the possible existence of periodicities, superimposed to each other. The eminent ones are of ~8000 yr, ~1000 yr, ~700 yr, while other quasiperiods or occassionally interrupted ones were obtained for ~4000, ~1350, ~400 and 180-350 yrs.

The raw data are best smoothed by a 60 knots cubic spline appropriately chosen.

These preliminary results are critically discussed. The project is on going.

INTRODUCTION - REVIEW

The present work comprises from a short review of the archaeomagnetic dating (first section) and of spectral analysis of the Greek archaeomagnetic intensity master curve, searching for possible periodic variations.

Archaeomagnetism is a branch of geophysics devoted to the determination of the past geomagnetic field of the earth, incorporating periods which envelops the activities and development of ancient man even though the main subject of palaeomagnetism is actually reserved for geophysical and geological applications.

Strictly speaking, baked archaeological artifacts or structures such as, pottery, tiles, bricks, well-fired clays, ceramic kilns, belonging to the last 10000 years are considered suitable archaeomagnetic materials (Fig.1).

The establishement of archaeomagnetic curves from this material has been the main objective of world-wide work in this field. Therefore, archaeointensity (i.e. the ancient intensity of the earth's field) curves have been constructed for certain time periods for Bulgaria, Egypt, Mesopotamia, China, Japan, Australia, N.America, U.S.S.R., to mention only the main examples. Further information can be acquired in the up-to-date bibliography in Creer et al (1983), Runcorn et al (1982) .

Fortunately Greece has concentrated the bias of areal and temporal coverage due to the fact that it has an inheritance of wide and varied archaeological material most of which can be dated absolutely or relatively. (Fig. 1 and Fig. 2).

The Greek work, of course, does not stand separately from the above mentioned relevant work in the international field which provides comparative data.

The archaeomagnetic study of baked clays began towards the end of the 19th century with the work of Gheradi, Folgheraiter and Mercanton.

The foundations of the modern subject were laid by Emile Thellier and his students in the period 1930 to 1960. They described the basic magnetic properties of baked clay, developed sampling techniques and laboratory apparatus for archaemagnetic determination, as well as alternating field and thermal demagnetization techniques for the removal of secondary components of remanence.

Subsequently various workers in different parts of the world attempted to constract curves depicting secular variations in both direction and intensity until today, with the culminating efforts of Martin Aitken and his team at Oxford.

For archaeomagnetic dating, the secular variation curve needs to be calibrated with known-age structures for each region (within 1000 km distance) of the earth's surface. This age is provided by other dating methods e.g. thermoluminescence (TL) of ceramics, or carbon-14 of organic matter belonging to the cultural level of the pottery, of by archaeological means (style, epigraphy).

The accuracy of an archaeomagnetic reference curve really depends on the dating errors of the measured samples, thus giving to the method its relative character.

The error in the actual measurement is around 5% and this is limited by certain effects, amongst which are mineralogical changes, anisotropy, cooling rates, distorting fields, weathering.

So far, archaeointensity curves are more plentiful, while for the archaeodirection orientated samples are required that have remained undistrurbed since firing in the antiquity, that are difficult to find.

The errors in the directional measurements are systematic e.g. undetected tilts, and can be due to seismic activity, tectonic displacement of the ground, phenomena that change the initial coordinations of the sample.

Movements up-to 5° or so may well occur without recognition. Without such errors and with adequate sampling an accuracy of some 1-2° can be expected for stably magnetized materials corresponding to some ± 5 years, for times when directional changes were at similar rates as those observed in London and Paris during the last 200 years or so (Tarling, 1983). A more realistic estimate of the likely errors in any one stably magnetized site yields a potential precision of some ± 20 years, but higher or lower accuracy may occur when the rate of secular variations was higher or lower than that observed in western Europe.

The available statistical evaluation of either the precision of a mean direction or the scatter of directions about the mean depends on the total number of observations and the length of the magnetization vector, the latter being expressed as probability density of vector points on a sphere, a statistic based on a Fisher distribution, a_{95}, the smaller the a_{95} suggests that the mean has been more reliably estimated.

Serious errors can arise from the dating techniques used. Radiocarbon dating for example man be slightly in error when uncorrected for the dendrochronological correction, but may be drastically in error when old carbon is present. As with most techniques, the errors tend to increase with age, so the errors in C-14 become more significant on a scale of several hundred years for materials several thousand years old.

On the other hand the TL method, with a dating accuracy ± 5%, provides a high error with respect to the anticipated accuracy of the archaeologists, which is about a quarter of a century.

As better dated materials become available with refining of dating techniques (especially by C-14 or comparative typology) it is essential that they are incorporated into the extant master curves, therefore leading to a greater accuracy in archaeomagnetic dating techniques.

With these in mind, the direction curves can give a precise date say to within ± 20 years, as it is the case of inclination (I) and declination (D) variations in England from 1300 AD to 1800 AD.

The intensity curve gives a date within ± 10 years for some AD periods where the dating is precises (e.g. from epigraphic record on the Byzantine church itself) and ± 100-400 for earlier times.

The archaeomagnetic dating is not thus absolute, since the time-scale of the reference curve is based on existing archaeological chronology, but it is showing strong signs of being a potentially very effective dating tool in archaeology and/or Geology.

In the present work the archaeointensity data for Greece (72%) supplemented with some from Bulgaria, W.Turkey, Cyprus,(see Fig.4) are spectrally analysed (Xanthakis and Liritzis, 1986,Aitken et al 1989) The methods applied are :1) Successive approximation (SA) which serves as a basis to fourier analysis (Xanthakis and Liritzis, 1986, Xanthakis et al 1985) and ii) Maximum entropy special analysis (MESA), to search for possible periodic variations (Liritzis, 1986), and, iii) Smoothing by cubic splines in order to construct a type-curve.

The archaeointensity curve comprises of the most reliable measurements, according to written reports and of tight dating errors. For the AD period most measurements derive from a new project measuring bricks and tiles from Byzantine monasteries (Aitken et al 1989).

Although there are some more archaeointensity data in the literature for the Greek Balkan region their large age uncertainties made them unsuitable for the present purpose.

2. SPECTRAL ANALYSIS

2.1. Successive approximation method (SA)

This method works as follows: fitting of the data by an appropriate sinusoidal represent the large periodic term. Subsequently this period is subtracted from the raw data. The residuals are again fitted by sinusoidals of shorter periodic terms. The fitted periodic terms are combined and the standard deviation is calculated between the raw data and the best fitted curve.

This approach offers five advantages: i)locates the periods in the time-series, ii)measures their amplitudes, iii)locates change of phase, iv)infers of any combined effect of several periods (network of periodicities), and, v)it is characterised by a stepwise control of the analysis. Xanthakis and Liritzis (1986) presented this approach for first time. Their analysed data have by now been enriched and/or reassessed, the new analysis being presented herewith.

In Fig.1 the results of our analysis are explained as follows: In Fig.1a the small circles represent the original values of F^A/F^D ratios and the solid curve their average fluctuation. During the period apprx. 6000 B.C to approx.2000 BC the ratios are less than 1.0; that is, the ancient field $F^A < F^D$ today. While for the period 2000 BC till about 1900 AD the ratios are above 1.0 or $F^A > F^D$.

That is the archaeointensities (thereafter called AJ) follow a periodic variation of about ≃8000 years.

With the least squares method the amplitude of this period is defined, being 0.30 (6000 BC - 2000 AD).

Therefore, the computed mean variation of the ratios is illustrated analytically by the relationship:

$$\overline{(F^A/F^D)}^{com} = 1.05 - 0.30 \sin \frac{2\Pi}{8000} (T - 6200) \qquad (1)$$

The standard deviation (s.d.) of the differences $(F^A/F^D)^{meas} - (F^A/F^D)^{com.}$ is $\sigma = \pm 0.16$, for number of points N=140 (made from the averaging of 227 original data points).

This s.d is almost half the amplitude of the large variation, implying the existence of shorter periods as well.

Fig.1b show the differences (residuals)

$$W = (F^A/F^D)^{meas} - \overline{(F^A/F^D)}^{com.} \qquad (2)$$

There seams that these residuals are not distributed randomly in the considered period, instead exhibit periodic variation of ~1000, ~800, ~400 and ~200 years.

These shorter periods appear either complete or as quasiperiods, superimposing each other in some cases. The position and amplitude of these shorter periods are shown in Fig.1b.

Analytically the periodic variations of short duration are represented by the relationship (3).

$$W = \alpha_1 \sin \frac{2\Pi}{1000} T + \alpha_2 \sin \frac{2\Pi}{800} T + \alpha_3 \sin \frac{2\Pi}{400} T + \alpha_4 \sin \frac{2\Pi}{200} T \qquad (3)$$

Overall, the computed ratios are represented by the relationship.

$$(F^A/F^D)^{com} = eq.(1) + eq.(3) \qquad (4)$$

The degree of freedom is 68 (Table 1) and the s.d of the differences (measured-computed) was $\sigma = \pm 0.054$ or of the same order as the errors in the measurements.

2.2. Maximum Entropy Spectral Analysis (MESA)

In the frequency domain the maximum entropy power spectral analysis was applied which is essentially algorithms based on Burg (1968), Anderson (1974), Smylie et al (1973) (see also Barton, 1983).

The MESA essentially involves fitting an autoregressive model to the data based on the principle that the resultant estimate should be based on all the information in the actual record and assume the least possible amount of information about the series outside the observed record.

The physical meaning of the MESA spectrum is that the (power) spectral density function s(f)df represents the contribution to variance of components with frequencies in the range (f, f + df). The total area underneath the curve is equal to variance of the process. A peak (period) in the MESA spectrum indicates an important contribution to variance at frequencies in the appropriate region.

The choice of the order of the autoregressive process (m) is made such that $N/3 < m < N/2$ (Ulrych and Bishop 1975) and after Berryman (1978), where $m = 2N/\ln 2N$.

The MESA was applied to equeally spaced curves at 40,70, 100 years and split into several segments; 0-4000 yr, 0-5000 yr, etc. to 0-9000 years, and 9000-1000 yr, 9000-2000 yr, etc. to 9000-4000 years. Two subsets were also formed consisting of alternate data points.

Before the analysis, the raw data were detrended by substracting a cubic spline of 1 knot.

The results of the MESA analysis (Fig.3) revealed periodicities at 4000 ± 300, 1350 ± 50, 950 ± 50 and 700 ± 35 years, where the higher power was found.

A tendency for reappearing power at higher frequencies provides a possible existence of short periods between 180-340 years.

The most eminent period consistent in all subsets was the 900-1000 years.

3. DISCUSSION OF THE PERIODICITIES

The two methods differ in two periods, the 4000 and 1350 years, given by MESA. The 8000 yrs period is not shown by MESA but it is seen in the 1 knot cubic spline fitting of the data. (archaeointensity = AJ).

Though the periodicities observed at the AJ data set from Greece and surrounding areas are local periodicities associated with the drift, growth and decay of sources close to the sites, their resemblances with palaeointensity variations from Britain, France and N.America enhances their real existence as harmonics of the geomagnetic field (Creer et al 1982; Smith, 1985; Xanthakis and Liritzis 1989, in preparation).

As any differences between dipolar field and the real observed field are concerned within the lower order terms of the harmonic expansion of the geomagnetic field, the obtained periods probably represent the variation of the non-dipole field.

The drifting or stationary character of the growth sources can not be assessed here, since a longer record is needed that covers also other peaks appear to superimpose onto the long trend of ~8000 years period that is due to the dipole field.

The higher harmonics of the fundamental T = 4000 ± 300 years obtained with MESA otherwise harmonises with the non-sinusoidal character of the 4000 years, that would imply that this is a combination of varying in strength, but mainly of drift-rate, sources other than the main dipole source.

Assuming a fixed drift-rate of T_d = 950 years and two different growth rates of T_g = 10000 and 4000 years, than according to the theory of combining sinasoids any of the two other periods can be obtained. These are T_a = 867 and T_b = 1050 years, that both are found within the errors to be our 950 ± 50 year period. Assuming, furthermore a different T_g = 1450 years then the 1245 and 760 years are obtained that are approximated to our periods of 1350 ± 50 (by MESA) and 700 ± 50 years (by MESA and SA) respectively. The 200 yrs (180-220 yrs) period appeared somehow significant in the 2nd half of the record (4500-9000 yrs) for all the three even spaced curves, but not in the other subsets. This period is similar to the Nyquist frequency where a meaningful periodicity can be obtained. Apart from the fact that it is shown up scarcely (as shown by SA, Fig.1b) while its existence has been observed in other solar-terrestrial parameters nothing more can be said about its significance at present (Neftel et al 1981, Liritzis 1986). From to date, however, evidence (Cox, 1968; Crossley et al, 1986) the geomagnetic field is considered to result from a stochastic rather than a deterministic process.

Several parameters prevent a complete unfolding (decomposition) of the AJ spectrum from its composed frequencies.

These include: i)errors in the measurements, ii)phase changes/shifts and iii)unknown internal/external forcing oscillators.

Further work is required and this project is under development with the application of more spectral methods of analysis and of more tests (Xanthakis and Liritzis, 1990 in preparation).

4. FITTING THE ARCHAEOINTENSITY CURVE WITH CUBIC SPLINES

It is desirable to remove outlying data points from the analysed time series. One method of smoothing raw data set is to fit cubic splines. The advantage being that outliers have less effect on the shape of the smoothed curve than some other methods of smoothing (e.g. running means).

The question then arises as to the optimum choice of number of knots. We have used the method described by Clark and Thompson (1978) and Clark (1983) of removing a small proportion of the data points chosen at random before each smoothing and then calculating what is the residual between the smoothed curve and the actual point, thus constructing a family of curves for a particular number of knots.

The root mean square residual error of all the removed points (called the cross validatory mean square error, CVMSE) is calculated for the data column and then plotted against the number of knots.

This reveals the optimum number of knots required for smoothing as a broad minimum. The 60 knots have been chosen which minimize the degree of smoothing, whilst remaining safely within the broad minimum (Fig.4).

This kind of smoothing reduces any random noise, whilst optimising the information remaining. Such a smoothing aims also in the production of a type-curve, for the intensities, provided that the variations are of real rather than random nature. Such a curve helps the archaeomagnetic dating and provides a clearer picture of the geomagnetic field variation for modelling secular variations (Creer, 1983).

5. EPILOGUE

On the whole the accumulation of archaeomagnetic data is proceeding rather slowly but, so far, there are some reference curves, parts of which can be used for dating purposes (e.g. Greek master curve, Bulgarian, Near Eastern, Egyptian, Mesopotamian, Japanese). The dating accuracy, for certain time-spans, is competing with the accuracy of C-14 method and is higher than the TL method. The relatively quick measurement of archaeointensities gives to the method a potential for routine dating that it is hoped to be fully realized, eventually, for the whole period of interest and for many regions separately.

Besides the archaeological side, it must be pointed out the substantial information these data provide towards the elucidation of some geophysical problems in the recent past. We need to know about both the direction and magnitude of the geomagnetic field, if we are to correctly deduce past patterns of the non-dipole field and the symmetry of the ancient field.

The archaeomagnetic analysis of archaeological materials of known age provide an extremely useful resolution to the secular variation curves, that undoubtedly helps to answering some very basic questions such as a)the spatial and temporal variations of the geomagnetic field, b)the relative importance of the non-dipole to dipole field, c)the identification of "standing" and "drifting" non-dipole field sources, d)the typical lifetime of any given non-dipole, e)evidence of rapid changes in the field's strenght or direction, to mention a few. One approach to finding answers to some of these questions is to examine the characteristic properties of secular variations synthesized from computer models. Finally, the construction of standardized archaeomagnetic curves (archaeo-palaeomagnetic secular variation type-curves) of certain regions is important to ensure a high degree of detail obtainable from the data being analysed and thus accurately resolve archaeological problems.-

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TABLE 1

Coefficients α_1, α_2, α_3, α_4 and respective time interval T of the equation 3.

α_1	T
+0.25	3400 BC - 2400 BC
+0.20	750 BC - 250 BC
-0.15	100 BC - 1700 AD

α_2	T
-0.35	5850 BC - 5450 BC
-0.15	5350 BC - 4550 BC, 4250BC-3850BC, 1650AD-2050AD
+0.15	4500 BC - 4100 BC
-0.20	2600 BC - 2200 BC, 2200BC-1800BC

α_3	T
+0.30	5200 BC - 5000 BC
+0.20	4000 BC - 3600 BC
-0.20	1700 BC - 1500 BC
+0.15	3800 BC - 3700 BC, 3650BC-3550BC

α_4	T
+0.30	5800 BC - 5700 BC, 1250AC-1350AC
-0.30	3300 BC - 3200 BC
-0.20	950 BC - 750 BC, 650BC-550BC, 550BC-450BC, 400AD-500AD
-0.15	6950 BC - 6750 BC, 3150BC-3050BC, 950AD-1150AD, 1450AD-1650AD

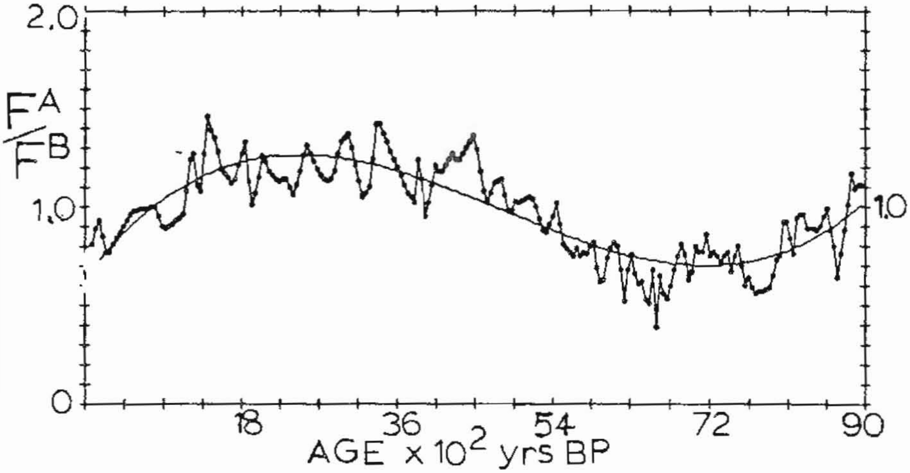

Fig.1 Archaeointensity spectrum equally spaced at 40 year intervals (●) and cubic spline IK (solid line).

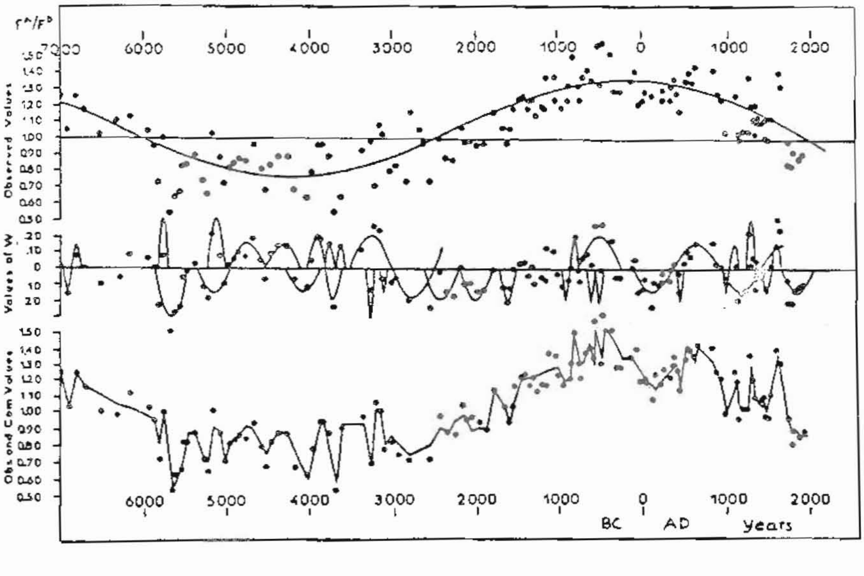

Fig. 2 a)Archaeointensities as ratios (F^A/F^D) versus time. Circles are the raw data and solid line represents the mean variation. b)Differences (residuals) of

$W = (F^A/F^D)^{meas} - (F^A/F^D)^{com}$. The solid lines are sinusoidal fittings of periods 200, 400, 800 and 1000 years. c)Raw data (●) and computed ratios (solid line) (see eq. 4 in the text).

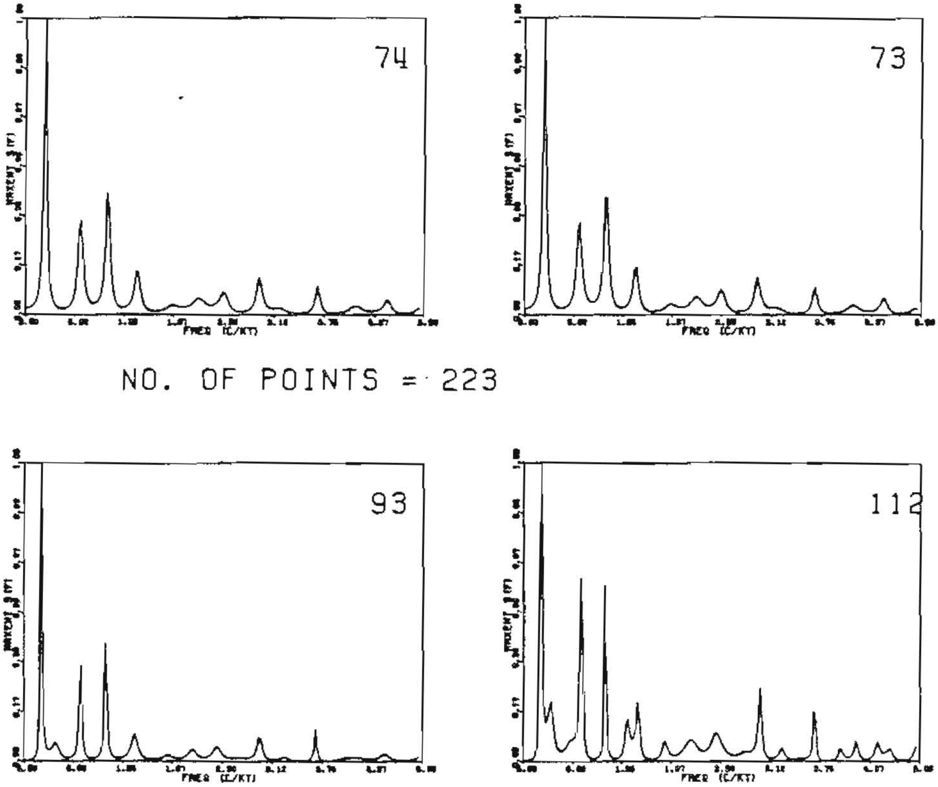

Fig. 3 Some characteristic MESA spectra for the time interval 0-9000 yrs and for different autoregressive order (m).

Fig. 4 Archaeointensity versus time since about 9000 years BP for Greece and the surrounding area. The intensity is represented by (F^A/F^D - mean), where F^A is the ancient intensity and F^D is the dipole field intensity assuming axial geometric symmetry at the site's latitude L, and

$$F^D = M/R^3\sqrt{4-3\cos^2 L},$$ M=magnetic moment=8X10'' Am' at present, R=Earth's radius at L.

The mean is taken as 1.

The data (+) are equally spaced at 40 years intervals. The superimposed (O) curve is the 60 knots cubic spline smoothed version.

This kind of smoothing reduces any random noise whilst optimising the information remaining.

The data are derived mainly from Greece (72%), supplemented by some from Bulgaria (18%) and Czechoslovakia, Poland, Hungary, Turkey (10%). More information can be obtained from (Aitken et al. 1983, Walton 1984, Kovacheva, Bucha in Creer et al. 1983. Liritzis and Thomas, 1980, Aitken et al 1989, Thomas, 1981).