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APPLICATION OF OPTICAL PUMPING TECHNIQUES TO STUDIES OF GEOMAGNETIC GRADIENTS.

**

The Particular Case of "Seaside Effect".

**

(Thesis)

by

Jean Mosnier

(France)

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Thesis presented to the
Faculty of Sciences, Univ. of Paris
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INTRODUCTION*

The study of variation in time of the Earth's magnetic field has been carried out for a very long time in all the observatories of the world. Naturally, the quality of measurements depends on the quality of the material being used, and the very important technical advances achieved in magnetometry for the last twenty years have resulted in a considerable increase in the volume and quality of observations.

- Apart from the very slow secular variation, the existence of three distinct categories of phenomena are detected in a natural magnetic agitation [1]:

- A daily variation depending on local time, i.e. on the position of the Sun with respect to the site of observation. It is produced by the modification of ionization in the upper atmosphere under the action of solar shortwave radiation (far ultraviolet or soft X-rays). In our regions its amplitude easily attains 50 γ.**

- A rapid or very rapid agitation engulfing phenomena whose periods vary from several minutes to several hundredths of a second and which are frequently of pseudo-periodical nature. The amplitude of these "magnetic

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* [Only the Introduction and the Geophysical Applications of the method are presented here in translation].

** $1\ \gamma = 10^{-5}$ oersted

pulsations" decreases rapidly with frequency. It may attain 1 γ for periods of the order of one minute and drops to a few hundredths of γ for higher frequencies.

- An intense and disorderly disturbance occuring during the arrival into the upper atmosphere of a mass of charged particles from the Sun and lasting sometimes for several days. It overlaps the preceding phenomena but its amplitude is such that it transforms their entire aspect, especially in the higher latitude zones.

Measurement Devices. It is obvious that depending on the frequency band one intends to investigate, the aspect of the phenomena and the performance required of measurement devices vary considerably.

For instance a magnetometer designed to measure daily variations must possess a high long-term stability. On the contrary, a high sensitivity would be useless. These conditions are more or less satisfied in magnetic variometers [2,3] such as the La Cour variometer, still used in numerous observatories. On the other hand, because of the smallness of the phenomenon instruments intended for studying rapid variations should be highly sensitive (0.001 γ). In this field the best results are obtained with induction devices. Let us assume, for instance, that the vertical component Z of the Earth's magnetic field varies by dZ in a time interval dt. Then, an induced electromotive force appears in a loop of a horizontally place surface S which is proportional to S dZ/dt*. Since this emf is very weak (10^{-9} V per m^2 for $dZ/dt = 1\ \gamma/s$) in order to obtain measurable voltages it is necessary to give to S values exceeding thousands of square meters. Therefore, the loops are cumbersone devices which are very sensitive to spurious voltages (50 c/s in particular) and to vibrations, and they are rather seldom used. [4].

The induction device yielding the best results derives from the "fluxmeter rod" conceived by Selzer in 1957 [5]. The induced circuit comprising tens of thousand of spires is wound around an elongated core made of a very highly-permeably ferromagnetic alloy. Thus, even for low dH/dt** values, appreciable emf are obtained that must then be only integrated. It is clear that only the component of the perturbation field parallel to the axis of the device is capable of inducing a voltage in the circuit. Therefore, it becomes possible to study any component of the Earth's field by merely giving an adequate direction to the rod.

Recently this type of magnetometer underwent numerous improvements tending

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* Then an integrating device makes it possible to determine the value of Z.

** In geophysics it is customary to designate the horizontal component of the Earth's field by the letter H. Letters Z,D,F designate the vertical component, the declination (expressed in γ) and the entire field, respectively. However, we will frequently use letter H to designate a magnetic field with any kind of direction. In case of doubt, we will always indicate when we mean the horizontal component.

mainly to increase the passband [6][7]. Owing to a galvanometric simplification combined with reverse feedback flux technique, Gendrin and Stefan [8] were able to attain the remarkable sensitivity of 0.0005 γ.*

However, following World War II, the progress achieved first in the nuclear and then in the electronic field of magnetic resonance, has made it possible to renovate to a considerable degree the methods for measuring the Earth's magnetic field. As a matter of fact, variometers and induction devices suffer from a common weakness which is the extremely relative nature of their responses. The considerable dispersion of their characteristics and effects of external physical factors, and of temperature in particular, render very difficult the comparison of the results of two devices based on different principles. Magnetic resonance which links field measurement to that of the frequency of a nuclear or electronic precession eliminates the majority of these drawbacks. No wonder, therefore, that devices based on this principle were readily accepted in numerous circumstances and all the more so since, besides the absolute nature of the measurements, their performance is greatly superior to that of ordinary variometers and tends to approach that of the induction devices.

The common trait of all the magnetometers utilizing magnetic resonance is that they are sensitive only to the modulus of the total magnetic field F and not to its direction. As a result, when vector $\vec{F}$ varies under the action of a disturbing field $\vec{\Delta F}$, only the $\vec{\Delta F}$-component, parallel to $\vec{F}$, is accessible to these devices, the normal components modifying $\vec{F}$ only to second order approximation. Therefore, we are dealing with a special type of variometers in which the virtually invariable direction of observation is that of the field. We shall subsequently refer to this subject again.

Comparison of Variations at Two Points.

Whatever the perfection of the device used, the knowledge of the perturbation field $\vec{\Delta F}$ and its variations in time at a point A becomes really interesting only when it is confronted with other data concerning other related phenomena (solar activity, state of the ionosphere, the tellurian field etc) or with the knowledge of the perturbation field at another point B. Let us dwell more particularly on this second case.

Assume that the origin O of a specific magnetic event is located in the ionosphere at an altitude of 100 or 200 km. It is evident that when the two stations A and B are very close, the resulting perturbation on the ground is evidently identical for both stations. However, in a first approximation, this remains true also when the stations are only moderately distant from each other, say, so long as AB remains distinctly inferior to AO. For instance, at two points distant by 20 to 30 km from one another identical variations in

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* The "Flux Gate" magnetometers which also use high-permeability cores but in a nonlineary region of the B (H) characteristic of the material can be ranged in the same category. During the last war, these devices served for the detection of U-boats and, consequently they were provided with numerous improvements. However, their sensitivity remains rather low, being of the order of 0.5 γ.

$\vec{\Delta F}$ should be observed.

However, actually the indication provided by a magnetometer on the ground does not exactly reflect an ionospheric disturbance. The ground being a conductor, any variation in the vertical component Z will induce in its thickness a system of electric currents whose distribution in depth is governed by the standard laws of electromagnetism.* The magnetic field induced by this system of currents is combined with the ionospheric effect and what is finally observed on the ground is their resultant.

The simultaneous determination of the magnetic and tellurian (ground) allowed L. Cagniard [9] and his disciples to determine the distribution of ground resistivity in depth by means of some simplifying hypotheses.** However, it should be noted that in the case of a ground consisting of infinitely extended homogeneous and horizontal layers, the effects produced by induced current sheets at the points A and B of the surface are identical. Consequently, the observed global perturbation remains the same for both stations.

Things are quite different when tellurian current distribution is different at A and B for instance, under the action of an electric conduction discontinuity of the ground. In this case, the magnetic variations registered at A and B will not be identical provided the thickness of the discontinuous layer is not too small as compared with current penetration depth. Such a situation is frequently encountered in the vicinity of coasts because of the considerable departure between the conduction of salt water and that of the adjacent grounds. The magnetic anomaly associated with this phenomenon has been known for some time as the "seaside effect" [10] but its study remains difficult for reasons which will be outlined later on. The final aim of this thesis is to experimentally determine the characteristics of this effect at one point of Brittany coastline.

As already stated, the study of the seaside effects was difficult. As a matter of fact, the application of the differential method implies the necessity to entirely think over the problem of equipment. With the exception of very improbably cases of total absence of correlation between the variations observed at stations A and B, the difference between signals $S_A - S_B$ is much smaller than the signal itself. Magnetometers adequate for studing S_A or S_B separately, may prove inadequate to measure $S_A - S_B$ for lack of sufficient sensitivity. This observation relates particularly to devices intended for registration of slow variations in spite of the high amplitude of the phenomena, for in this case skin thickness is very deep and the sea effect is insignificant.

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* For a given frequency, the intensity decreases exponentially with depth, but in this case, owing to the relatively high resistance of the ground, "skin thickness" is very great. In the case of slow phenomena it exceeds several tens of km.

** This "magneto tellurian" sounding method is at the present time very much in use especially in petroleum prospecting.

Therefore, the first problem raised by the study of the seaside effect is the development of high-sensitivity magnetometers, provided, however, with a passband sufficiently extended toward the lower frequencies. The already mentioned magnetic resonance devices possess the required characteristics but at the time we started our investigations their commercial availability was still rather limited. An important part of our work consisted in developing a magnetometer with optical pumping in the potassium vapor that would be adequate in geophysical investigations.

The principles on which this attainment was based are presented in Chapter I which places our study within the framework of the available devices. Chapters II and III desribe two types of magnetometers one of which is especially suitable for registrations from fixed stations, while the other can be used in easily portable stations. Chapter IV contains a detailed study of the light sources while Chapter V sums up the performances that have been achieved.

Chapter VI deals with another category of magnetometers. As we have seen, optical pumping devices measure only the perturbation field component ΔF, which is parallel to $\vec{F}$. To observe ΔF in another direction it becomes necessary to change also the direction of the main field. In this manner it is possible to measure the horizontal component H by nullifying the vertical component Z by a compensation field $Z' = -Z$. The operation is facilitated by the fact that an eventual variation if Z' affects the value of H only second order approximation when Z' is very close to $-Z$. In the same way one would obtain a measurement of Z by nullifying H. On the other hand, measurement of declination D is more complicated. It implies an a priori compensation of F, similar to those already mentioned, and the formation of a stable and homogeneous auxiliary field perpendicular to the magnetic meridian, in which resonance would be effected. The complexity of the experiment is thus obvious. However, for want of a more suitable equipment, this technique was actually applied [11] [12].

Taking advantage of the recent improvements in magnetic variometers, and especially by using the field operation method [13] [14] we have attempted to improve still more their performances so as to bring them to the same level as that of optical pumping devices. Chapter VI describes the means utilized to develop a sensitive declinometer and the first results obtained.

The use of the differential method raises an ultimate experimental problem, namely that of signals comparison between stations. All the results obtained to date were achieved separately on paper or on magnetic tape and compared later on. It is evident that this method is valid only when each station disposes of hourly signals sufficiently accurate, to subsequently ensure a perfect synchronization. Even in this case, the interpolation between two successive registrations remains more or less uncertain. This is the only practicable method when the measurement stations are very distant from each other, but when the distance between the magnetometers amounts to only few tens of kilometers it is preferable to centralize the data at one and the same point where they are registered simultaneously on the same device. This operation implies the existence of stable radioelectric connections capable of transmitting very low frequencies. The corresponding equipment is commercially available but for reasons of economy we have preferred to manufacture it ourselves and in some cases even to study novel solutions. Chapter VII deals with the problems raised by the transmission and with the solutions that we were able to contribute.

The foregoing analysis makes it clear that the very important role played by the problem of equipment within the program as a whole has up to now prevented the exploitation of all its possibilities. Chapter VIII deals with the geophysical results obtained to date. However, they are, in fact, only a beginning in the application of this novel tool of research.

N.B. Translation of Chapters I through VII is not presented
The entire work consists of 183 pages.

Translated by
Mr. Daniel Wolkonsky
August 2, 1968
Revised by
Dr. Andre L. Brichant

ALB/ldf

GEOPHYSICAL APPLICATIONS

As of 1964 our equipment was sufficiently evolved from the technical viewpoint to make it utilizable in the field and applicable to specific geophysical problems. Research then undertaken is still pursued at present, at least as regards magnetomarine phenomena, so the results assembled in the following pages have yet to be considered as provisional.

Besides a few isolated measurements in the Vosges in 1964, the experimental program was unfolded in two stages.

1. Study of Magnetic Correlations in the Massif Central

As already pointed out at the begininng of this thesis, comparison of magnetic variations at two points allows us to outline the local anomalies likely to perturb tellurian currents in depth. Experiments carried out in the Massif Central in 1964 and 1965 had for objective the determination of the optimum correlation rate that could exist between the observed variations at two stations under the best possible geologic and magnetic conditions.

This implies that measurements are performed in a thinly populated area, any urban concentration being a source of magnetic disturbances often quite considerable. Moreover, one must choose as far as possible a region geologically homogenous and constituted of poorly conducting soils (which decreases the intensity of induced currents) and sufficiently distant from the sea. Finally it must be devoid of large-scale magnetic anomalies. In this last case the direction and amplitude of the perturbation field are indeed varying from one point to another as a function of soils' magnetic susceptibility. In the extreme cases the magnetic gradient is such that it may hinder the normal operation of the magnetometer*.

We found these favorable conditions just about assembled in the high plains to the southeast of the Massif Central. The "Causse Mejean", a subdesertic plateau of about 400 m^2 area separated from the neighboring regions by the deep canyons of the Tarn and of the Jonte, seemed to be perfectly convenient for such an attempt.

A first series of measurements performed with the aid of free-precession prospecting magnetometer allowed us to make sure that no important magnetic accident existed in the entire area of the plateau. In no case has the large-scale magnetic gradient gone over 5γ /km, once corrected for the effect of the ground.

To the contrary, we have encountered everywhere an important vertical gradient that could exceed 100 γ/km in extreme cases in the immediate vicinity of the ground. This is visibly ascribed to the existence in the most superficial layers of ferromagnetic materials.

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* see J.Geoph. Res., 67, No.5, p.1889

However, from the moment the probe is placed at a few decimeters of height, this gradient attenuates to become practically negligible toward one to two meters. By carefully prospecting a region it is possible to find zones of a few square meters where the gradient does not exceed 5 γ/m in any direction, where the magnitude of the field is close to average values obtained in the neighborhood.

Under such conditions, said to be favorable, we have installed five stations on the "Causse Mejean". The principal of them, situated on the Chanet airfield, included a reference magnetometer, the radio receivers and the registration apparatus, the other four being portable stations equipped with one magnetometer and its transmission system. Their distribution relative to that of the Chanet was as follows:

Stations	Direction	Distance
Deidou	East	3 km
Mas de Val	West	3.5 km
La Croix Blanche	West	11 km
Nivoliez	South	3 km

Geologically the "Causses" constitute a sedimentary basin, the thickness of which may reach 2000 m, resting on a granitic base. Taking into account the average limestone resistivity (about 30 ω. x m), one may see that the penetration depth of tellurian currents in case of slow phenomena (for example, of pseudo-period greater than 10 sec) exceeds very considerably the thickness of the sediments and, by way of consequence, the current distribution will be mostly influenced by the structure of the base. A preliminary tellurian study performed with the help of nonpolarizable electrodes made of silver chloride has shown the existence at the Chanet station of a strongly privileged direction of the tellurian field from SW to NE. A similar study carried out at Deidou has also shown a polarization of the field *), but this time along WSW-ENE. Furthermore, if the time variations of the telluric field at the two stations offer very great analogies, their identity is by no means the rule. One may observe, in particular, notable divergences between the directions of the tellurian field at a given moment between the Chanet and Deidou. One could thus have anticipated a mediocre correlation of magnetic events.

Experience has entirely rejected these forecasts. We have operated in the following manner: the magnetic signal obtained at Deidou and transmitted by radio to the Chanet is opposed to the local signal, upon demodulation, so as to obtain the value of the perturbation field ΔF and the difference local (ΔF) — Deidou (ΔF) on a dual recording device. Postulating the identity of very slow variations (which was subsequently well substantiated), more particularly of the diurnal variation, we tried to suppress the latter on the differential recorder. Once this result achieved, the gain of the modulation-demodulation chain was exactly of 1. We also saw outright the disappearance of the aggregate magnetic phenomena on the difference, which characterizes a complete correlation, of which the limit naturally remains determined by the background noise of the apparatus.

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*) "polarization" stands for that anisotropy in the telluric field distribution.

In the case of Florac experiments it is of the order of 0.1 for a very brief lapse of time and of 0.2 to 0.3 for an average time of 2 to 3 hours. Repeated attempts failed to make obvious any smallest difference between the two stations. The situation was identical in all other cases. Fig.1 shows, for example, a thrity minute registration taken down between le Chanet and the Mas de Val station in a magnetoquiet period. Only local magnetic events, such as the passage of a car at some distance, appear clearly on the difference.

We must thus admit that magnetic variations are dependent on very broadly distributed factors, since the correlation remains total even for the most distant stations. To the contrary, the variations observed by us in the telluric field are attributable, at least in part, to more superficial causes, probably to "wandering currents" of rather remote origin, but not producing important magnetic effects.

Having tested all our apparatus on the ground at once and having made certain that the total correlation of magnetic variations at two not too distant points was in all favorable cases a hypothesis of reasonable operation, we attempted to apply the differential method to the study of certain phenomena related to the presence of the sea.

2. Study of Magnetomarine Effects

The sea is capable of modifying the terrestrial magnetism by way of two distinct mechanisms. On the one part it acts upon the distribution of tellurian (ground) currents, thus upon the "internal" part ΔF of the perturbation field by its very presence *). On the other hand, the motions of water, as a conductor in the terrestrial magnetic field, induce electric currents constituting a source of a new category of perturbations.

The resistivity ρ of sea water is about $0.25\ \omega \cdot \times$ m, thus 10^2 to 10^4 times weaker than that of surface rocks. An electromagnetic wave will induce in the ocean a system of currents quite different from that produced on the solid ground. These currents having a tendency to close inside the conducting water masses, one may see that the magnetic variation really observed will be dependent on the depth and on the shape of the sea. One may expect, in particular, to observe in the vicinity of a sea coast certain anomalies. By sea coast we naturally must understand the limit, beyond which water conductance becomes weak by comparison with that of the underlying ground. One is aware of the fact that the penetration depth P of induced currents, i.e., the "skin thickness" expressed by the relation

$$P\ (\mathrm{km}) = \frac{1}{2\pi} \cdot \sqrt{10\,\rho\ (\omega \times \mathrm{m}) \cdot T(\mathrm{s})}$$

For a phenomenon lasting 500 sec, this depth is nearly 5 km. One thus may see that in case of slow magnetic variations only deep seas can play an important role. The seaboard is then identified with the edge of the continental shelf, which in case of Brittany is located at some 100 km west of the coast itself. One may observe that this circumstance is not particularly

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We shall call this first manifestation "static" effect, though in reality we have to do with electromagnetic phenomena.

favorable to measurements and that the "seaside" effect would probably be easier to bring about in the region of Nice where 2000 meter bottoms are very near the coast. In return in the Morbihan we have benefited of implantation facilities in a site relatively quiet from the magnetic standpoint. We installed there two permanent stations, one being exactly on the seaboard in the Ker Neveste Fort, put at our disposal by the Admiralty, the other at twenty-five kilometers inland near the Grandchamp village NW of Vannes (see the map). The Ker Neveste station included two optical pumping magnetometers, a radio instalation capable of receiving "signal" channels independently of the regular telephone communication service, graphic or eventually magnetic records and a stockpile of material sufficient to assure the placement of the apparatus on the spot (see photograph XXI of the original text). The Grandchamp Station (plate XXI of the original text) just as the subsequently installed mobile units, were equipped more summarily.

As was done previously by us in Florac, the implantation of stations was preceded by a magnetic prospecting designed to detect eventual local anomalies. The Grandchamp station proved to be a particularly quiet and uniform site, where the gradient often descends below 1 γ/m. The Ker Neveste station was found to be somewhat less effective, but its magnetic conditions remained nevertheless equivalent to those encountered in the Massif Central.

There we performed also, as in Florac, a certain number of terrestrial (ground) field measurements. These disclosed the existence of total polarization at both stations, the privileged direction being perpendicular to the average seaboard direction, as could have been foreseen. This direction is very constant at Grandchamp and a little less constant at Ker Neveste, but its variations in time do not seem to be obviously linked with marine phenomena.

The magnetic measurements include a series of high-response registration (20 mm/γ or more) but of relatively short duration (generally below 24 hours) on one part, and a prolonged registration of about five consecutive weeks performed during the summer of 1967, but with more reduced sensitivity (2 mm/γ). The principal results are related to the static aspect of magneto-marine phenomena. However, we shall rapidly consider the problem of water movements.

Waves and ocean swells are susceptible of producing weak magnetic fields Indeed, water molecules are not immobile, though reference is made here to stationary oscillations, but describe circles, whose amplitude decreases with depth. Crews and Futterman [15], Warburton and Caminiti [16] performed theoretical calculations leading to the possibility to forecast the effects of gamma order at sea level, naturally variable as a function of waves' height and length, Weaver [17] has shown that long-period swells could exert a much more marked influence and produce a field of several gammas at 100 meter depth. Maclure, Hafer and Weaver [18] could check experimentally the accuracy of the forecast orders of magnitude. As a consequence of the existence of a vertical gradient of about 0.025 γ/m, measurement can be accomplished only with the aid of a magnetometer stabilized at a specific given height, thus either resting on the bottom, or uncoupled from the surface motions. Not

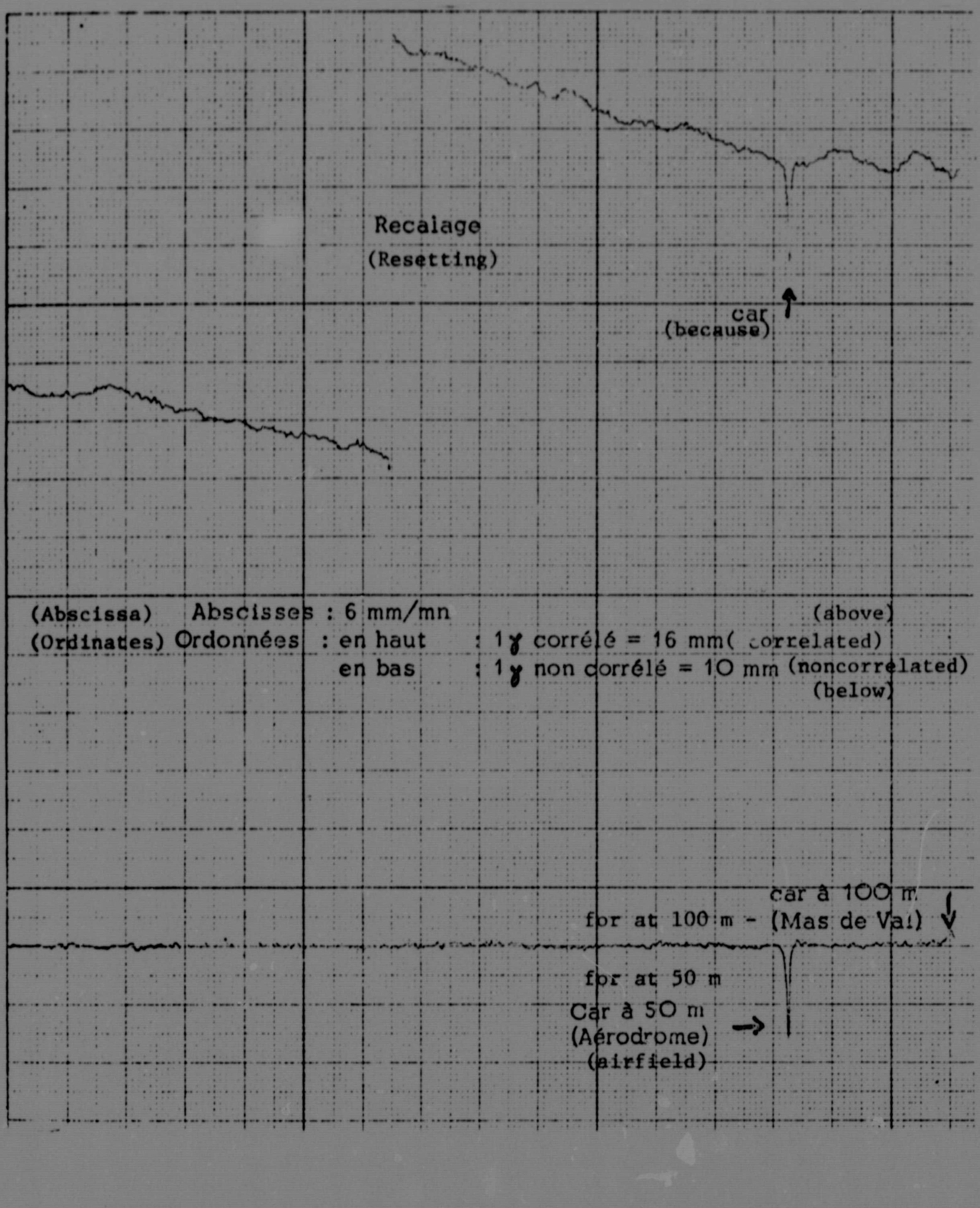

Plate XVIII. Magnetic correlations between the Chanet station and Mas de Val on the "Causse Mejean being in possesion of such an apparatus as yet,* we could not conduct experiments in this field.

Water motions accompanying tides and currents are also susceptible of producing electromotive induction forces and, consequently, of perturbing the ground or magnetic fields. The ground or telluric influence is certain and was often signaled by Schlich and Patriat [19] who attribute to the tide or to the tide current the difference observed between the values of the magnetic field measured at the Ouessant island and at the continental station of Plabennec. This difference, of which the amplitude reaches 3 γ, varies in time with a semi-diurnal period. We attempted to make conspicuous an effect of the same type ascribable to the current produced by the tide in the Morbihan Gulf. To that effect, we installed at Ker Pen Hir, near Locmariaquer (K P H on the plate XIX), at about 800 meters from the mouth of the gulf, a portable station equipped with a frequency operating magnetometer. Its readings were compared during high tide period for several consecutive days, with those of a similar magnetometer set at Ker Neveste. Owing to favorable magnetic conditions these devices operated in a particularly satisfactory fashion, especially during the night. However, the result was negative. No six-hour period phenomenon ascribable to tide effect could be revealed and the difference between the two magnetometers remained constant with a precision to ± 0.05 γ. The current influence, provided it exists, should thus be at most of such an order. We believe that the weakness of the effect is due to the particular configuration of the Morbihan Gulf and to the great resistance of the underlying granitic formation. There, the current lines have a tendency to close under water, thus to more or less annihilate their effects in the symmetry plane where the station was placed (Fig.VIII,1).

It may also be that the variation observed by Schlich is partially attributable not to an indirect current effect, but to the influence of the sea on the diurnal variation, on which we shall dwell further.

Other comparative measurements performed this time between Ker Neveste and Grandchamp have shown that night variations at the two stations were identical with an approximation to ± 0.5 γ. (Plate XXII represents the simultaneous field registration at Ker Neveste (2 mm/γ), at Grandchamp (∿ 1.5 mm/γ), and of the difference betwen the two stations (5 mm/γ) during three consecutive nights). This proves that the movements of water accompanying tides in the Quiberon Bay have a negligible influence at the coastal station. The hypothesis of a more important but entirely correlated effect must be here ruled out on account of the relative proximity of water masses in motion. In return, the influence of the sea is manifested in other circumstances, which we now shall examine.

The first experimental verifications of the existence of a "seaside" effect go back some ten years. Parkinson has studied in 1959 and subsequently in 1961 [20-1] the direction of the perturbation field $\Delta\vec{F}$ for a certain

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* An undersea magnetometer capable of operation at some 20 meter depth, is currently being realized.

Geographic Distribution of Morbihan Stations

Plate XIX

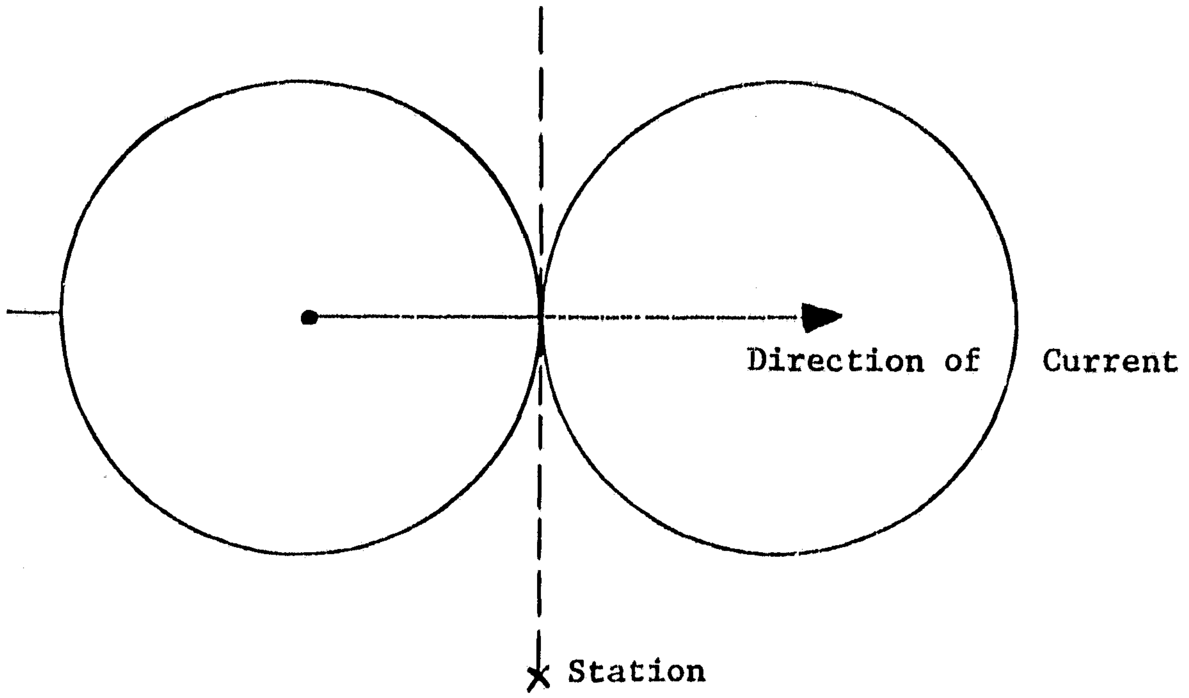

Fig. VIII 1

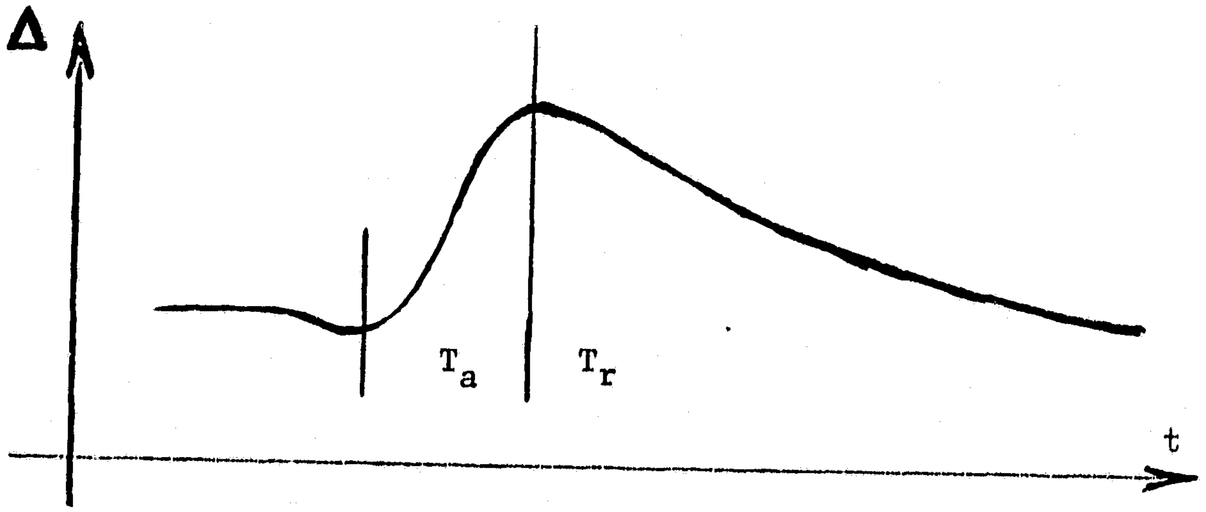

Fig. VIII 5

number of geophysical events of 5 to 60 minute average duration. He noted that this field was most often situated inside a privileged plane, whose direction could be materialized by a vector. The chart of Parkinson vectors established for Australia shows they all are perpendicular to the coastline and directed toward the sea. Analogous conclusions were reached by Schumaker in California (1964), Lambert & Canon [22] in the Vancouver region.

Other experiments carried out by Zhigalov in 1960 in the Arctic Ocean show that the ratio $\Delta Z/\Delta H$ decreases regularly as the sea depth increases; thus in open sea the perturbation field tends to become horizontal. Registrations performed by Duffus et al on the Vancouver Island (West Canada Coast) allowed hin to compare the magnetic field variations at two stations, of which one is coastal and the other at 20 km inland.* These experiments have shown that the amplitude of very slow phenomena was sensibly the same in both cases, but notable divergences appear as soon as the duration of perturbations was down below 300 seconds. For pseudo-periods of the order of 20 sec, the perturbation fields' amplitude ΔF** is greater at coastal station than at the island station by a factor of 2.5. This ratio may attain 20 if the distance between the stations is of several hundred kilometers [24]. Le Borgne et al [25] obtained analogous results by comparing the magnetic variations in Corsica with those at Chambon la Forêt. Schlich, Patriat and Ronfard [26] make case of important difference between St Jean Cap Ferrat, on the Mediterranean coast Draguignan at 40 km inland and a marine station situated off Hyères Islands For pseudo-periods of less than one hour the amplitude of variations at Saint Jean Cap Ferrat is always superior to those of Draguignan. Their ratio may vary from 1.2 (for T = 1 hour) to 3 (for T = 5 min), the marine station offering an intermediate behavior.

These results may be satisfactorily interpreted starting from theoretical models. Rikitake [27,28] Weaver [29] Dosso [30] and other authors have studied the system of currents induced by an electromagnetic wave in a medium with different conduction discontinuities. Calculation allows us to foresee a reinforcement of the vertical component of the perturbation field in the immediate vicinity of the shore, this effect attenuating rapidly above the sea and much more slowly above ground.

We have attempted to make this phenomenon conspicuous by utilizing optical pumping-magnetometers sensitive to the $\vec{\Delta F}$ component parallel to the total field $\vec{F}$. To that effect we made on the registrations the choice of a certain number of perturbations, of which the durations, drawn up in echelon from twenty seconds to one hour***. For each of them we have determined the amplitude ratio at Ker Neveste and Grandchamp and computed the average of the values attained for events of close durations. We may then plot the curve representing the variations of the mean amplitude ratio as a function of phenomenon's duration (Fig.VIII,2). Its general shape is very similar to that obtained by Schlich or by Duffus, but the value of the ratio of coastal to continental station for a given period is slightly lower than that observed by Duffus and decidedly lower than the one given by Schlich. We believe that this is due to the existence of the continental plateau, the true conduction descontinuity then being shifted to a certain distance from the coast. Experiments between Ker Neveste

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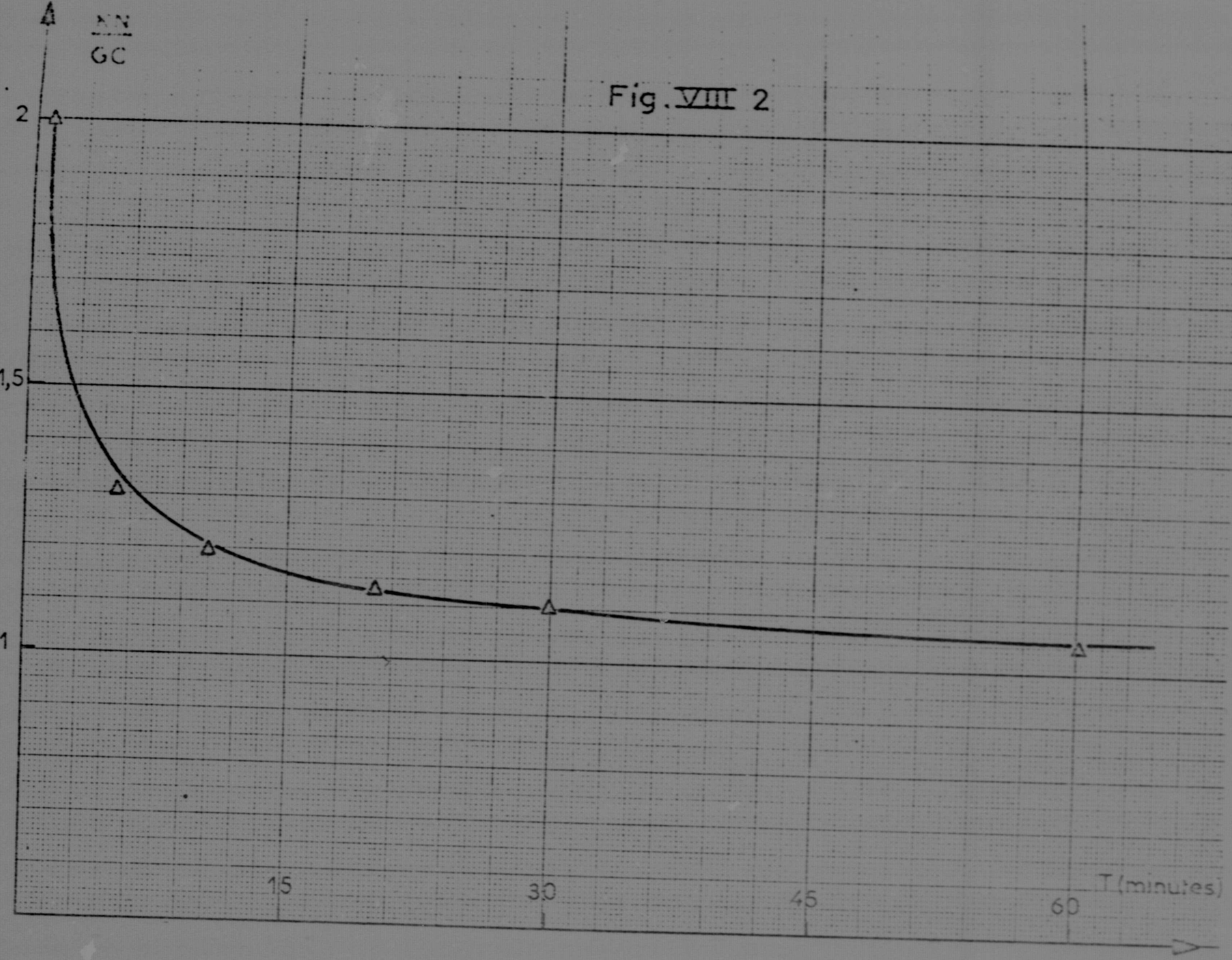
* [23] DUFFUS, SHAND, WRIGHT, NASMYTH & JACOBS: Jl of Geoph. Res. 64, No.5 p.581 (1959)

** Computed after values of X and Z by Duffus.

*** See next page

Fig. VIII 2



and Belle-Ile-en-Mer should allow us to make this interpretation more precise in the near future.

The sea effect is thus manifest on average-period phenomena; it is of the order of one to two hours. However, we must take notice that when the period increases, the ratio of variations at two stations, one marine and the other ground station, does not always approach the unity. Thus, for example, Schlich [19] points to the fact that the amplitude of duirnal Sq-variation in Mediterranean, has a value 1.4 times that measured at Draguignan. Hill and Mason had observed as early as in 1962 [31] that the Sq-amplitude at the English Channel entrance could be double of that measured on the solid ground and that a strong semi-diurnal component appeared in the difference; according to the authors, this component should be attributed to tidal currents. Still more recently, Malin [32] drew attention to the abnormal amplitude taken by the lunar magnetic variation at a coastal station of British Isles; this is probably due to the induction phenomena in the Atlantic.

Thus, it seems that the sea is indeed suceptible of playing an important role in the terrestrial magnetism, even for variations with periods of 12 hrs or more, although in this case the depth of electric currents' penetration into the matter is of several tens of kilometers.

Several authors undertook to resolve the theoretical problem of induction produced in the ocean by the diurnal Sq-variation, Rikitake [33] in particular, who must, however, involve the anomalies of conductivity in the mantle in order to explain certain peculiarities of the magnetic field in Japan. Roden [34] considered mostly the influence of the water layer, whereas Lambert and Ganer [22] estimate that the influence of the mantle prevails from the moment the period exceeds thirty minutes. This viewpoint is shared by Coode and Tozer [35] who try to link the seaside effect to mantle deformation below the ocean. The condition at limit and the models utilized naturally vary from author to author; however, for most of them it does not seem that induction phenomena in the sea water only are sufficient to explain the Sq-anomalies.

The precision of observations made by us in Brittany on the behavior of the diurnal variation was a great deal hampered by stations' remoteness from the continental shelf. In fact we found practically identical variations, the departure between magnetometer readings never exceeding 2 γ. We noted, however that the amplitude of Ker Neveste was very slightly superior to that at Grandchamp. Part of the effect is perhaps attributable to coastal magnetometer drift, the latter operating in very unfavorable thermal conditions (more than 20° differences from day to night), but we think that a residual difference of about 1 γ, due to natural causes, persists. This difference is too small to enable one to study systematically its origin, but it is very likely that we have to do with a reflection of Sq-enhancement perpendicularly to the continental shelf. The influence of the sea on certain slow magnetic variations is indeed certain.

** Plate XXIII represents a segment of registration clearly illustrating the influence of phenomenon frequency. The slow drift visible in the upper registration is completely obliterated on the difference (below). In return, rapid pulsations are clearly visible on it.

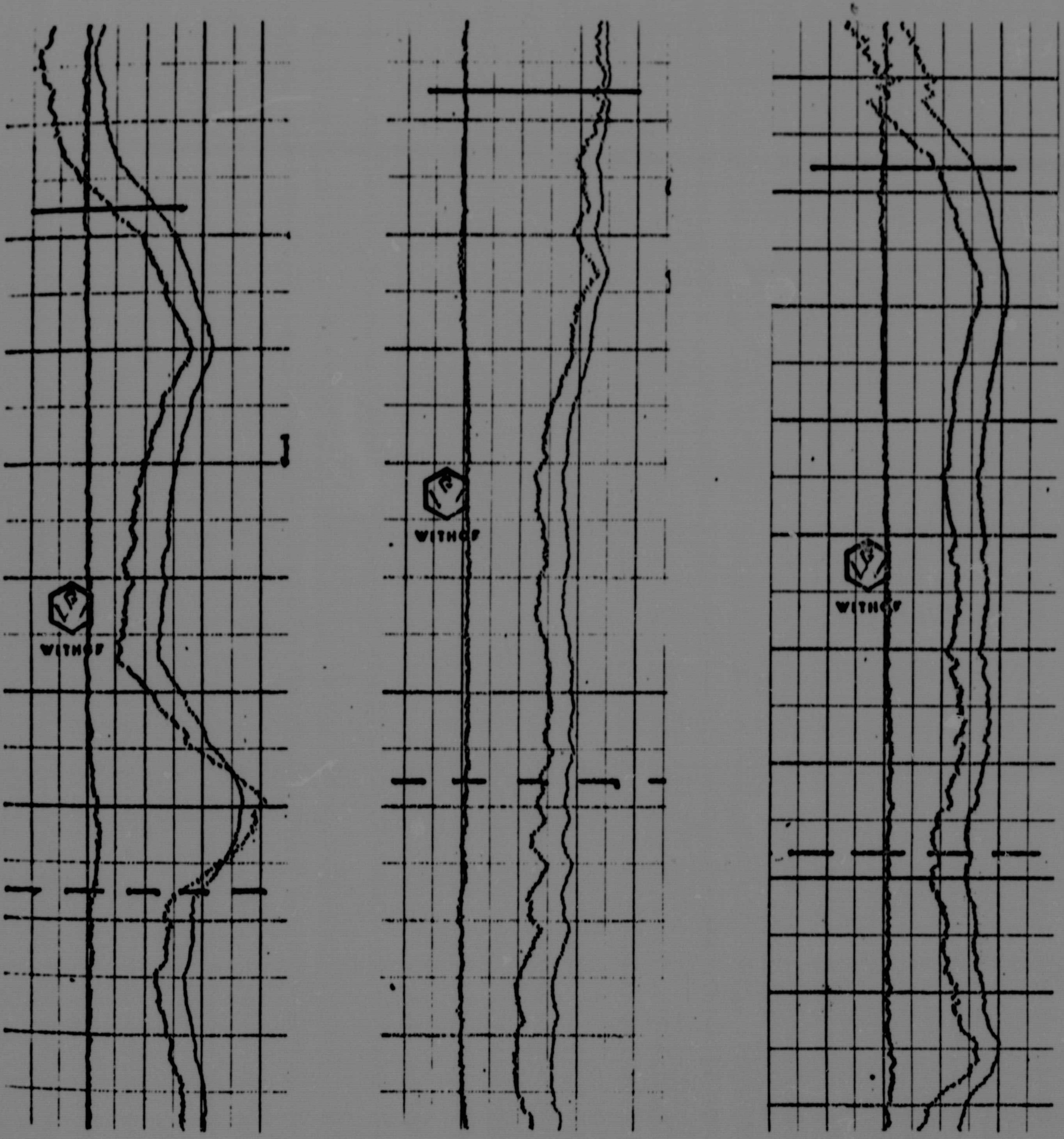
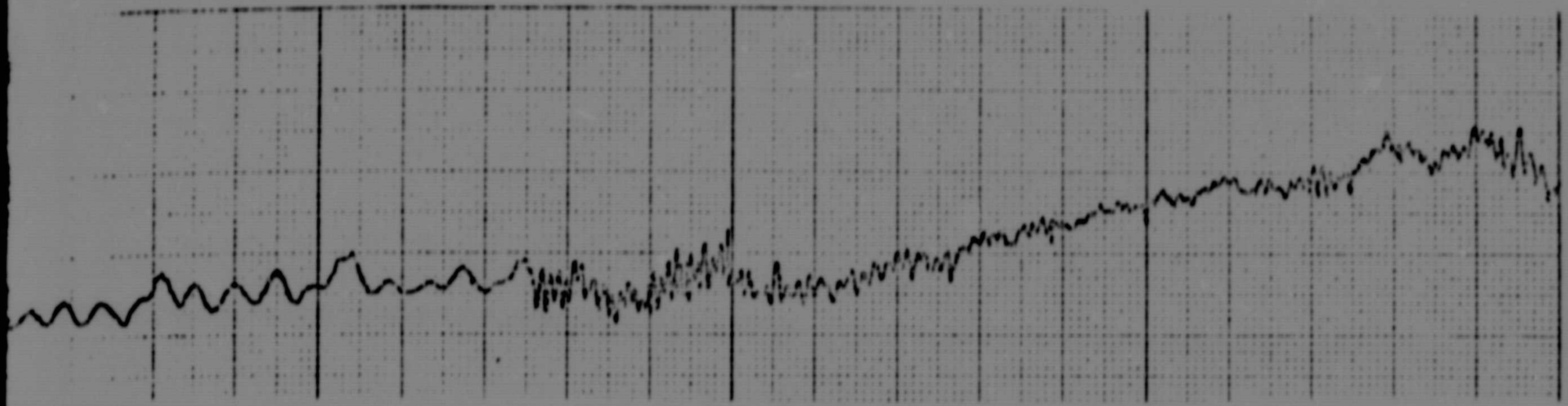


Plate XXII. Comparison of geomagnetic variations between Ker Neveste and Grandchamp



Abscisses : droite 3 mm/mn (right)
(Abscissa) : gauche 12 mm/mn (left)
Ordonnées : haut Σ 4 mm/γ (upper)
(Ordinates) : bas Δ 16 mm/γ (lower)

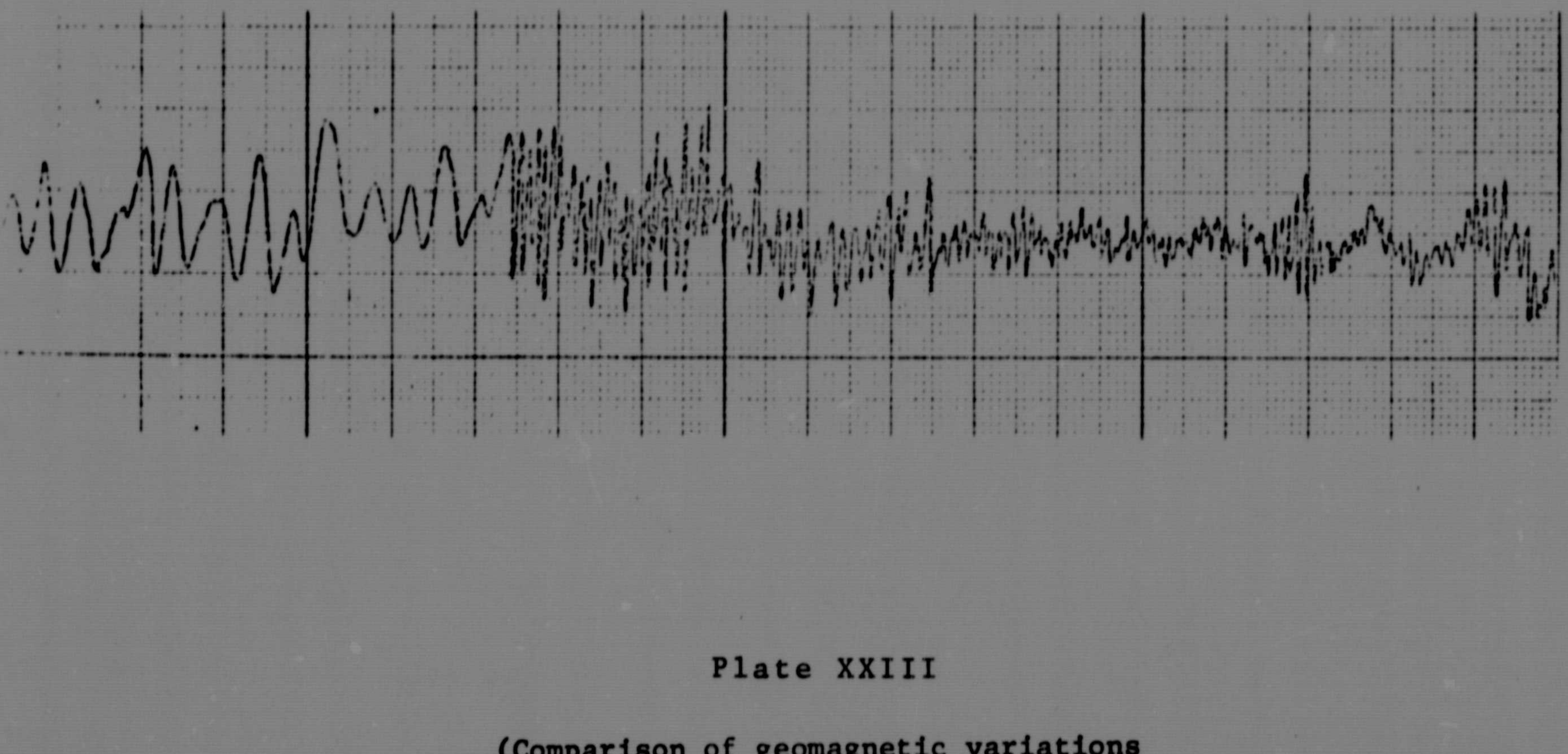


Plate XXIII

(Comparison of geomagnetic variations
between Ker Neveste and Grandchamp)

We convinced ourselves of this fact by comparing the mean diurnal variation during the spring tide period, usually observed during neap tide. Fig.VIII,3 shows that the Sq-values are notably different in both cases, though the mean value of the terrestrial field remains unchanged. In return it seems that the intensity of the terrestrial field during the night is systematically higher in period of syzygy-tide (Fig.VIII,4).

It is probable that the phenomena observed in Brittany are amenable to the same theoretical intepretations as the aggregate of "seaside" effects already referred to. However, we should like to draw attention to another mechanism also likely to produce magnetic anomalies in the vicinity of the coast.

It seems to be currently extablished that the origin of currents responsible for Sq-variations and lunar effects must be searched for, at least partially, in the motion of charged particles under the action of winds or ionospheric tides. The ionosphere motions attributable to gravitation forces have been known for a fairly long time [36] but their study has been recently the subject of a large number of works. Matshushita [37], Martyn [38], Appleton [39], Maeda [40,41], among others, have signaled the existence of ionospheric tides and shown their close relationship with the terrestrial magnetism. We may thus admit that the bulk of magnetic effect observed in the ground are in direct connection with the displacement of charges at the levels of E- and F-layers between 100 and 150 km altitude.

However, an appreciable fraction of the field is still being produced by the system of induction currents in the thickness of the ground. Chapman estimates it at about 40% of the total and this figure must be considered as a minimum, since all experimental data serving to establish it are provided by ground stations. These currents exert in their turn a breaking and repulsion force on the movement of charges engendering them; these are weak above ground but much more considerable above the sea. Thus the sea-ground discontinuity ought to be attended by a variation in the density and height of the ionosphere, contributing to the creation of a magnetic anomaly. We are obviously confronted here with a simple hypothesis, presently not resting upon any experimental verification. We hope to be able to make it more precise in the near future.

To close, let us mention that we observed on a few rare occasions small variation (1 to 5 γ), whose manifestations at Ker Neveste and Grandchamp were shifted in time by 5 to 10 minutes. They are translated by the appearance on the difference of a signal having the shape of an asymmetric dispersion curve, (Fig.VIII,5),*the appearance phase T_a being of a few minutes and that of restoration T_r - much longer. (In the extreme case T_r reached seven hours). These effects can in any case be attributed to the apparatus. They are possibly due to the passage, above the stations of an ionospheric disturbance of feeble dimensions, moving at a speed of 40 to 80 m/sec, which is a realistic value. However, we currently still lack a satisfactory explanation to offer for these phenomena.

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* see page 13

Fig. VIII 3

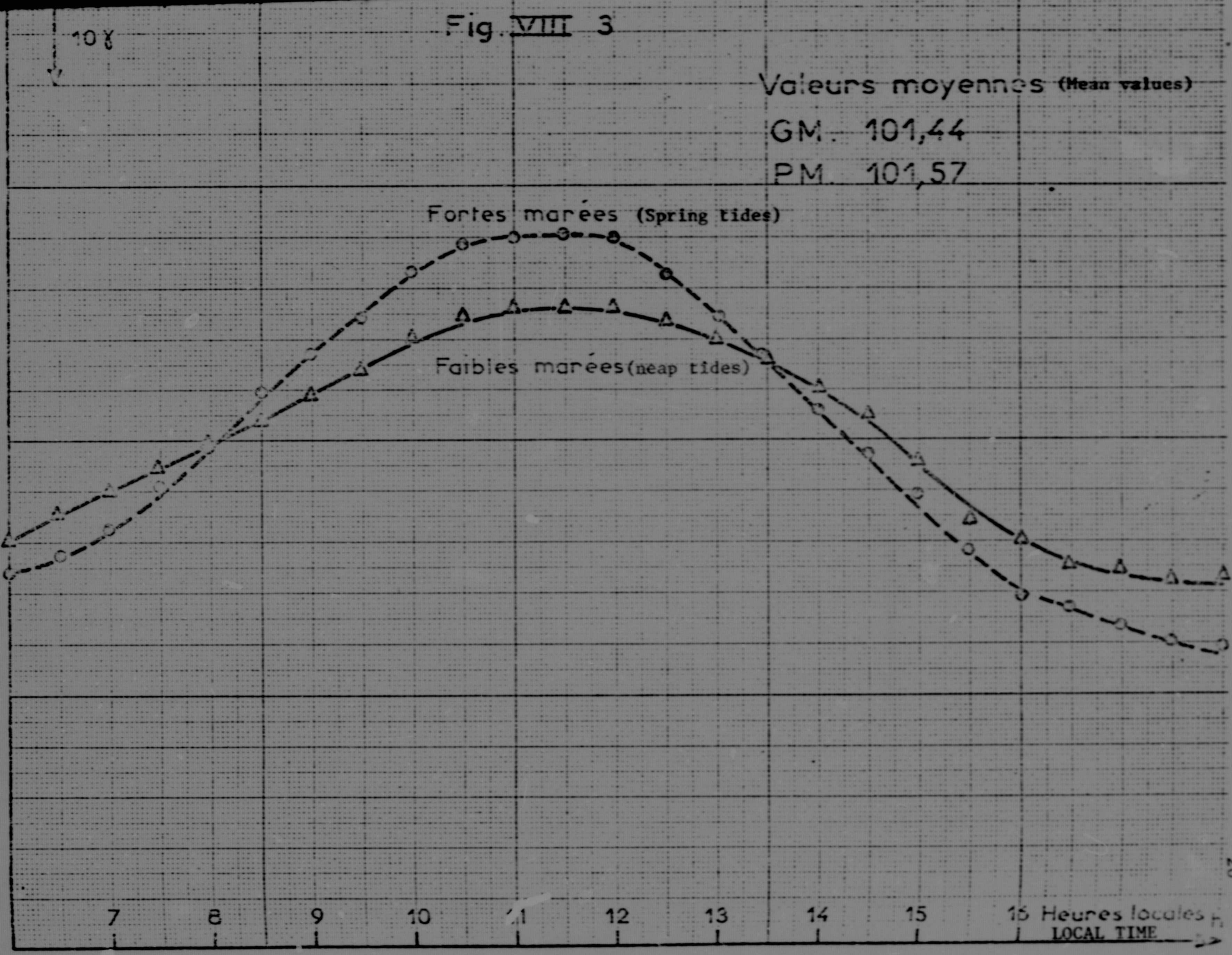
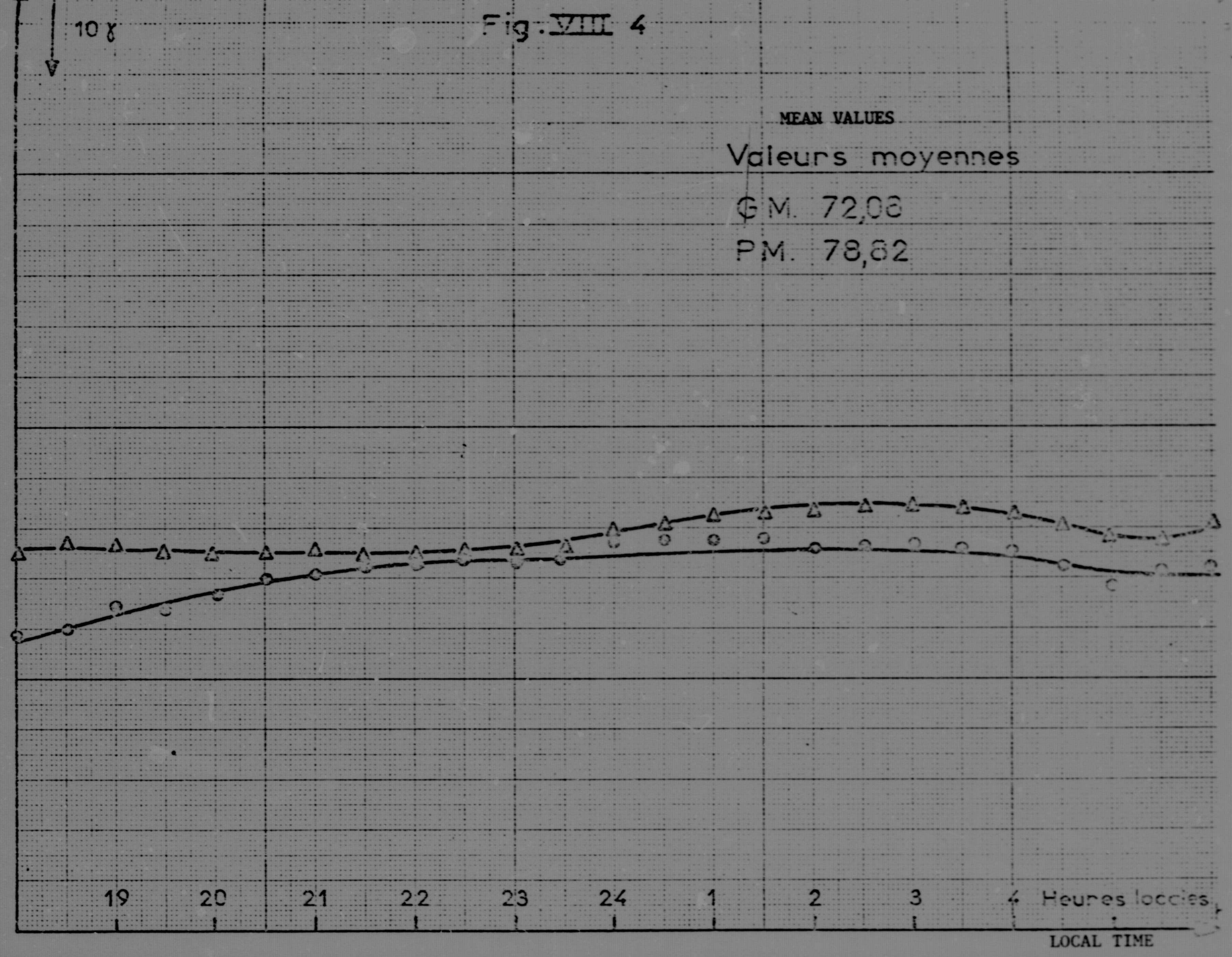

10 γ
Valeurs moyennes (Mean values)
GM. 101,44
PM. 101,57
Fortes marées (Spring tides)
Faibles marées (neap tides)
7
8
9
10
11
12
13
14
15
16 Heures locales h
LOCAL TIME

Fig. VIII 4


10 γ
MEAN VALUES
Valeurs moyennes
GM. 72,08
PM. 78,82
19
20
21
22
23
24
1
2
3
4
Heures locales
LOCAL TIME

CONCLUSION

At the end of this study we are in a position to summarize the results obtained as follows:

By utilizing the magnetic resonance of potassium atoms oriented by optical pumping, we succeeded in developing a magnetometer capable to measure the Terrestrial field with great precision. One of the versions realized is a field-subject apparatus that lends itself particularly easily to graphic registration. Another, frequency-operating model, allowing the displacement of the magnetic collectors, thus facilitating signal transmission. These magnetometers allow us in either case to render more conspicuous the relatively rapid events (from 10 sec. to 10 min.) of 0.03 γ amplitude and the slower events (1 to 10 hours) of about 0.1 to 0.2 γ amplitude. Taking into account the manner in which we define their response, they appear to us as being equivalent to industrial magnetometers based upon the same principle. They are probably not as practical to use, nor are they as dependable, but their use in the field has shown that they nevertheless constitute quite an operational material.

Parallelwise to optical pumping research we have been led to set in order a magnetometer provided with an operating magnet capable of studying weak variations of declination ΔD. For want of prolonged utilization one still may not prejudge of final performances of these devices. The results obtained during the first tests show, however, that they broadly outclass all other magnetometers of same type. The sensitivity obtained is from 0.01 to 0.02 γ at short-term and from 0.02 to 0.05 γ at long-term, i.e. better than that of optical pumping devices.

In order to achieve an instant comparison of magnetic variations we have also developed appropriate means of radiocommunication. This led us to set up a conversion system "voltage-frequency-voltage" of very great stability in time and to construct several emitters-receivers in the 150-160 Mc/sec frequency band. Owing to these elements, entirely realized at the "Laboratoire de l'Ecole Normale Supérieure, we could achieve a telemeasurement network capable of operation during several weeks, without incident, thus perfectly convenient for prolonged registrations of the terrestrial field.

This aggregate has been effectively used for the study of the terrestrial field and its relations with the sea. A first series of measurements performed in the Massif Central served as a global test of the equipment and could show that the temporal variations of the field were absolutely identical at two moderately distant (10 km) stations from one another. A second series of tests having taken place in Brittany in 1966-1967 allowed us to verify that this identity ceased to exist in case of a coastal and ground station mutually distant by 30 km. We could notice that the correlation ratio rose with the duration of events and became practically equal to unity for periods of several hours. We also noted that tides did not affect the difference between the two stations, that is, the effect of water movements, at least in the case of Brittany, endowed with a large continental plateau, was very reduced.

Likewise it was not possible to make evident a magnetic phenomenon accompanying in an assured fashion the tide currents in the Morbihan Gulf.

In return a prolonged registration has shown the existence of an important lunar influence on the amplitude of diurnal variation. This effect, observed by various authors, is generally attributed to the existence of reduced currents in the sea. We believe that it could also be in relation with ionospheric tide phenomena.

***** THE END *****

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Volt Technical Corporation
1145 19th Street, N.W.
Washington, D.C. 20036
Telephone: [202] 223-6700 X-36,37

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