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P. Vorob'ev, V. Ianovski, I. Okunev

INFLUENCE OF GEOMAGNETIC PERTURBATION ON RESONANT GRAVITATIONAL WAVE DETECTOR

Budker INP 96-19

НОВОСИБИРСК

Influence of geomagnetic perturbation on resonant gravitational wave detector

P. Vorob'ev, V. Ianovski[1] *and I. Okunev*[1]

The State Research Center of Russian Federation
"Budker Institute of Nuclear Physics SB RAS"
630090 Novosibirsk, Russia

Abstract

The level of background signals in modern cryogenic resonant mass gravitational wave antenna is discussed caused by (a) the geomagnetic field pulsations and (b) an atmosferic of very low frequency band, generated by a lightning flash. The analysis of our results show that the signals of this origin will generally exceed the signals from the gravitational wave sources. To suppress these artifacts in such gravitational antenna, it is necessary to use the magnetometer included as anti-coincidence protection and a system of magnetic screens.

PACS number(s): 04.80.N, 95.55.Y

e-mail: vorobyov@inp.nsk.su
e-mail: ianovski@lnpi.spb.su
e-mail: okunev@lnpi.spb.su

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[1] Petersburg Nuclear Physics Institute, Gatchina, Russia 188350.

1. Introduction

In the last years the problem of detection of gravitational waves of cosmic objects has moved to a qualitatively new level. The sensitivity of such detector as resonant-mass antenna, working at temperatures below 100 mK should reach for short bursts the range of $h \sim 10^{-21}$ [1, 2] and will come, in nearest future, close to the sensitivity of laser interferometer gravitational wave detectors, such as in LIGO/VIRGO and LISA experiments [3]. The transition of resonant-mass detectors to ultra low temperatures operation requires to investigate the influence of low-frequency electromagnetic noise on the gravitational wave antenna of this type.

The problem of electromagnetic background was discussed several years ago in an association with the results of J.Weber [4]. It was considered, that the background signals, registered by Weber's antenna, could be caused by an electromagnetic noise of geomagnetic origin. However Joseph Weber has experimentally demonstrated tolerance of his gravitational antenna to the electromagnetic signals of appropriate level as well as to high energy cosmic ray particles. Therefore this theme has not received further development.

Obviously, the influence of the noise of such origin on modern resonant-mass detectors like "NAUTILUS" [2] is qualitatively different due to, first, essential increase of the sensitivity of the third generation detectors, and, secondly, we deal with superconductivity of the material in these generation detectors at working temperature below 1 K. The veto systems there are practically in all gravitational detectors of the Weber's type for elimination of a cosmic ray background. However detailed analysis of narrow-band (bandwidth ~ 1 Hz) resonant antenna excitation by geomagnetic field pulsations and lightning flash was not performed and it is the main aim of this work.

2. Influence of the magnetic field pulsation

There are two mechanisms, linking the tension in a solid body of a gravitational antenna with the external magnetic field:

1. For frequencies around 1 kHz the skin thickness in aluminum bar is few mm, therefore the change of external magnetic field with this (sufficiently high frequency) produces the appropriate change of pressure, that can excite the gravitational antenna.

2. During the transition process in the superconducting state, the multiton Al bar (the resonant bar is a cylinder, made usually of the special alloy — Al 5056), can trap a significant part of a magnetic field flux of the Earth. For pure Al the transition temperature in the superconducting state is $T_c = 1.18$ K, and Al 5056 alloy becomes superconducting at $T_c = 0.925$ K [5]. Thus the external magnetic field pulsations will cause, by interaction with induced dipole moment of the bar, an appreciable tension in the antenna body.

We shall evaluate both effects in this paper. It goes without

saying that we have to take into account the external field suppression by the vacuum tank and by the system of conducting cryogenic shields of the gravitational detector.

We need to know the perturbation spectrum of the Earth magnetic field in the band around 1000 Hz. The magnetic field perturbations are determined in this band by the high-frequency tail of the geomagnetic field perturbation spectrum, caused, basically, by the interaction of the solar wind with the ionosphere, and by the low-frequency tail of the atmospheric spectrum. Here the term "atmospheric" denotes the transient field (electric or magnetic), generated by the lightning flashes, or by any subsidiary features of the flashes. The spectral density of the geomagnetic field variations S_H around 1 kHz is about 1×10^{-6} $\mathrm{A}\cdot m^{-1}\cdot \mathrm{Hz}^{-1/2}$ [6]. It is useful to recall, that at the Earth average latitudes the spectrum of the magneto-telluric field of the atmospheric has a maximum around 30 Hz [6, 7].

The evaluation of spectral density of the magnetic field perturbations is rather difficult in examined band at large distances, because the low-frequency tail contains peaks, associated with the resonant properties of a cavity "earth-ionosphere" — the Schumann resonances [8]. W. Schumann has predicted that the cavity formed between the earth and the lower ionosphere should resonate at certain frequencies, and that these resonances would be excited by the lightning flashes. The detailed theory of Schumann resonances is not simple, but observations gave for the first order of the resonance the value $7 \div 9$ Hz.

If we divide the frequency band from 5 Hz up to 2 kHz in to two sites, then for the first of them $5 \div 100$ Hz we can write [6]

$$S_H(f) \simeq 4\times10^{-7}\cdot f^{0.3}\,, \tag{1}$$

and for second, $100 \div 2000$ Hz

$$S_H(f) \simeq \frac{1}{f}\cdot 10^{-3}\,. \tag{2}$$

More detailed theory of geomagnetism, including the data on the magnetic field perturbations, can be found in [6, 9, 10, 11]. The top of the geomagnetic field perturbation spectrum — the frequency band above 1.5 – 2 kHz is connected, basically, with ionospheric processes and with the influence of the space radiation. The spectral density on these frequencies are, with 95% probability, below 1×10^{-8} A·m^{-1}·Hz$^{-1/2}$ [6, 11]. It follows from estimations Eq.(1,2), that the spectral density of the magnetotelluric field does not exceed 1×10^{-6} in all the interesting frequency band.

It is necessary to add some words about the magnetic field perturbation by the near lightning flash. Note, that the spectral density of magnetic component of the electromagnetic wave in ULF band strongly depends on the lightning flash distance and its orientation [12]. The current in lightning reaches $1 \div 2 \times 10^5$ A [12, 13], at distances more than 10 km it is not already a linear conductor with a current, which we use as the model only for valuation (as the field will fall appreciably faster). There is the well-known expression for the current distribution along the channel in double-exponential form [12]

$$i_t = i_0[\exp(-at) - \exp(-bt)]. \tag{3}$$

Here $a = 2 \times 10^4$ s^{-1}, $b = 2 \times 10^6$ s^{-1}.

For an incoming signal the spectral density $S(f)$ is defined by

$$S(f) \sim \frac{(a-b)}{\sqrt{(a^2+f^2)(b^2+f^2)}}\,. \tag{4}$$

We shall evaluate the value of the horizontal magnetic flux density of the thunderstorm H_{ts} now. In these circumstances H_{ts} is given approximately by [13]

$$H_{ts} \approx \frac{1}{4\pi R^2}\frac{dM}{dt} + \frac{1}{4\pi c R}\frac{d^2M}{dt^2}\,, \tag{5}$$

where R is the distance from the source, c – the speed of light. The "charge" moment at any time t is given by $M_t = 2\sum q_z z$, where the summation covers all elementary charge of magnitude q_z at height z.

If $R = 10$ km, and $I = 1 \times 10^5$ A, we can obtain now using Eq. (3, 4, 5)

$$H_{ts} \simeq \frac{I}{2\pi \cdot R} \simeq 1\,, \tag{6}$$

and the spectral density will be:

$$S_{ts}(f) \simeq 1 \times 10^{-3} \div 1 \times 10^{-4}. \tag{7}$$

It can be seen that the influence of the thunderstorms is approximately 3–4 orders of magnitude higher than the geomagnetic field variations.

Let the geomagnetic field H_{geo}, acting on a cylinder, consist of two terms: the constant component H_0 equal to the average intensity of the Earth field in a given place and $H(\omega)$, the variable part

$$H_{geo} = H_0 + H(\omega) \tag{8}$$

Here the value of the Earth magnetic field is $H_0 \simeq 40$ A·m^{-1}. For simplicity we shall consider the vector H_{geo} to be perpendicular to the cross section plane of the cylindric bar with area S, (however this is not an essential restriction). Then the force F of the geomagnetic field pressure on the detector end face is

$$F = \mu_0 H_{geo}^2 \cdot S = \mu_0\left[H_0^2 + 2H_0H(\omega) + H^2(\omega)\right] \cdot S, \tag{9}$$

where $\mu_0 = 4\pi \times 10^{-7}$ H·m^{-1} is the permeability of the empty space.

The first term in Eq.(9) corresponds to the static pressure of the magnetic field, which rises when we consider the superconducting cylinders only. In our case it is not of interest, since it deviates the resonant frequency very slightly. It is possible to neglect also the third term here, the electro-magnetic wave pressure, due to its very small value. As a result we receive

$$F(\omega) = \mu_0 H_0 \cdot H(\omega) \cdot S\,. \tag{10}$$

The force F describes here the action of the variable geomagnetic field on any detector or shield of a well conducting material, when the size of the antenna bar is much more than the skin-layer thickness on the resonant frequency. For resonant gravitational antenna from the superconducting material the force of the electromagnetic pressure at resonant frequency is determined by the same expression, as Eq.(10). It does not depend, whether the Earth magnetic field flux was trapped by the superconducting antenna bar, or it was completely superseded at cooling.

On the main frequency mode of the ultracryogenic resonance detector NAUTILUS [2] (about 1 kHz), the geomagnetic noise is rather small: $S_H\,|_{f=1kHz} < 10^{-6}$. The cross section area of cylindrical bar $S \simeq 1$ m^2. Therefore, the force of the electromagnetic pressure F_{em} (in 1 Hz bandwidth) by the action of geomagnetic noise can be roughly described as

$$F_{em} = \mu_0 H_0 \cdot H\,|_{1\mathrm{kHz}} \cdot S \simeq 1 \times 10^{-11}\ N. \tag{11}$$

And the magnetic perturbations by lightning flashes produces the force $F_{ts}(\omega)$

$$F_{ts}(w) = \mu_0 H_{ts}(\omega) \cdot H_0 \cdot S \approx 1 \times 10^{-7} \div 1 \times 10^{-8}\ N. \tag{12}$$

Let us compare the perturbations excited by the geomagnetic field variation with the signal from the gravitational wave. Just to simplify this task let the mass of the cylindrical bar be: $m =$ 1000 kg, length $L = 1$ m, cross-section $S = 1$ m^2, resonant frequency $f = 1000$ Hz and the bandwidth $\Delta f_d = 1$ Hz. And just to set the scale of estimates set the detector sensitivity $h = 1 \times 10^{-20}$. We shall evaluate the excitation of the conducting Al bar by geomagnetic field perturbations, leaving out the bar superconductivity (at zero freezing flux).

The value of F_g, acting on the bar body, is:

$$F_g(f_g, \Delta f_d) \simeq \pi \cdot mL \int f^2 \cdot Z \cdot df_d\,, \tag{13}$$

where f_g – the frequency of gravitational wave, Δf_d – the bandwidth of gravitational antenna and Z – the Fourier image of h.

For the gravitational burst of sine shape with duration of the packet of waves τ_g we have

$$Z = h \cdot \frac{\tau_g}{2} \left\{ \frac{\sin(f - f_g) \cdot \tau_g/2}{(f - f_g)\tau_g/2} \right\}. \tag{14}$$

After integration Eq.(13) over the bandwidth of the resonance detector with resonance frequency f_d we have

$$F_g \simeq \pi \cdot mLh \cdot f_d^2 \cdot \tau_g \cdot \Delta f_d \left\{ \frac{\sin(f_d - f_g) \cdot \tau_g/2}{(f_d - f_g)\tau_g/2} \right\}, \tag{15}$$

that in the presence of small frequency deviation $(f_d - f_g) \cdot \tau_g << 1$ makes

$$F_g \simeq \pi \cdot mLh \cdot f_d^2 \cdot \tau_g \cdot \Delta f_d \tag{16}$$

For short pulses of gravitation radiation, when $\tau_g \sim 1/f_d \sim 1\ ms$,we have

$$F_g \simeq 10^{-13}\ N. \tag{17}$$

Let us equate this value to the magnetic field pressure F_{mf}, that is necessary for reception of a comparable signal. We have

$$F_{gr} \simeq F_{em} = \mu_0 H_0 \cdot H(\omega) \cdot S. \tag{18}$$

Using this equation, we can find the corresponding estimate for H

$$H \simeq 1 \times 10^{-7}. \tag{19}$$

Comparison of Eq.(11,12) and Eq.(17) shows that the stress in the detector body due to its interaction with the geomagnetic field perturbations (and more, with the fields of near-by thunderstorm) will exceed the stress due to the gravitational wave-induced tide! Certainly, it is necessary to shield the antenna bar and to arrange a veto-system connected with the magnetometer.

3. Shielding

We shall estimate the shielding property of the vacuum tank and of the system of heat shields, surrounding the detector bar. The designs of the modern third generation ultracryogenic resonant antennae [2] require the vacuum tank and the cryostat walls of stainless steel, the cryogenic shields of copper.

Let the thickness of the skin-layer at the frequency ω be d and we get

$$d = \frac{c}{\sqrt{2\pi \cdot \sigma \cdot \mu \cdot \omega}}. \tag{20}$$

Then for the copper (at frequency 1 kHz) the skin thickness is about 1.5 mm, and for stainless steel becomes about 5 mm. In the case of the thickness of the wall $h > d$, the attenuation coefficient of the magnetic field k_1 is defined by [14, 15]

$$k_1 = C \cdot \left(\frac{S}{Ld}\right) \cdot e^{h/d}. \tag{21}$$

here C is a coefficient about 1, depending on the tank geometry; S – the cross-section orthogonal to magnetic field; L – the perimeter of this cross-section. In the case of $h < d$ we have the attenuation coefficient k_2 as

$$k_2 = \sqrt{1 + \left(\frac{2Sh}{Ld^2}\right)^2}. \tag{22}$$

It is interesting to note, that for the vacuum tank of stainless steel, and also for the copper heat shields h and d are the values of the same order of magnitude. For such case we shall make estimates for both, Eq.(21 and 22), at $h = d$. Let $S = 2$ m^2, $L = 6$ m, $d = 0.005$ m, then we have

$$\begin{aligned} k_1 &\simeq 300, \\ k_2 &\simeq 240. \end{aligned} \tag{23}$$

As it is seen from Eq.(23), these estimates are well agreed. Thus, the attenuation coefficient of the magnetic field for the detector vacuum tank is $200 \div 300$ on the frequency about 1000 Hz. However, the vacuum tank, also the thermal shields are, as usual, not continuous and contain flanges and other elements of design, hindering the induced currents. As the experiments show, the shielding factor (in the direction of field) appreciably drops for flanges with dimensions of the same order as the tank cross-section. The experimental values of the shielding factor k for flange with the rubber sealing joints are $k = 30 \div 300$, depending on design. Meantime for the metal sealing joints we have $k > 300$ and the demountable flange joint does not, practically, deteriorate the shielding properties of a vacuum tank. In the same time, the longitudinal cuts (along the cylinder copper heat shields), can reduce the shielding factor of a separate shield up to 10 times. The shielding factor of the multilayer shield is always lower, than the product of shielding factors of separate layers and is determined by its mutual arrangement and by the shield dimensions. Therefore the definition of the field reduction factor requires complex calculations or experimental measurements. However for multilayer heat shielding systems k is, to all appearance, always more than 100.

We have conducted also the actual measurements for 3 helium cryostats of slightly different types with the typical dimensions: length about 1.5 m, external diameter 0.5 m, internal diameter 0.3 m. Walls were: *aluminum alloy 3* mm+*copper* 2 mm+*stainless steel 1.5* mm. The stainless steel flange covers the top end of the cryostat. For our measurements the cryostat was placed in a special solenoid. The magnetic field was excited at the frequency 1000 Hz and was measured inside and outside of the cryostats by an inductive probe, which was sensitive only to the magnetic field. The probe signal was measured by the spectrum analyzer SK4-56, which was used as the high-sensitivity narrow-band selective voltmeter. It is clear, that the ratio of the magnetic field outside to the field inside the cryostat gives us the shielding factor. The shielding factor of the magnetic field was in the range between 300 and 500 for all the studied cryostats in our experiments.

4. Conclusion

Our analysis result show, that the tensions, connected with the geomagnetic field perturbation will surpass the gravitational wave influence. A good system of magnetic screens, that are able to ease an external magnetic field at frequencies near to the working frequency of the detector not less than three orders, is necessary in that case as minimum. Certainly, the best way to do it — to take into account at the detector design. It is necessary, practically, either compensate or shield the Earth field (by compensating coils or by the magnetic shields). The most natural way to suppress the magnetic background is to arrange the complete installation into the magnetic shield, so-called magnetic room. The last way is

more reliable, but it will be more expensive. Nevertheless, the 2–3 layer magnetic shield permits to suppress the earth magnetic field (and all its fluctuations too) not less than 3 orders of magnitude and more without any monitoring systems. However, note once more, that the modern gravitational detectors operate typically in the helium temperature range — below 1.8 K. Thus such detector needs a special cooling system with heat bridges and with broad cuts in the cryogenic shields and in the tank walls. All these elements of the installation construction can to deteriorate the magnetic shielding and to pass an electromagnetic damage, which can be the sources of the noise of nonstationary nature, additional to the fundamental sources of the noise in the detector [1]. In this context to suppress artifacts from close lightning flashes it is necessary,according to our results, to use a magnetometer system, which should be included as an anti-coincidence protection from false signals of terrestrial origin. In particular it is important for the near future gravitational measurements in coincidence with several ultralow temperature antennas - the AURIGA antenna, INFN Laboratori Nazionali di Legnaro near Padova, the antenna in preparation at the Stanford University and the NAUTILUS antenna of the Rome group.

To all this it should be added, that the antenna bar is making some noise during the cooling process due to relieving of the thermo-stress. The complete adiabatic change of magneto-telluric field can become a trigger mechanism that will provoke a false signal. The cause of such shakes is the removal of stresses, for which there was a potential barrier at usual temperature, and which were "captured" in local minima of potential stress energy.

Apparently, one more source of noise exists. It arises because of the strong magnetic coupling of the heat screen to the antenna bar, that could excite variable tensions in the antenna bar due to oscillations in the heat screen, caused by external perturbations, such as the acoustic vibration, electromagnetic field, etc. Thus all these will arise induced vibrations of the installation. The noise of such origin will be present, most probably, also in the gravitational wave detectors like VIRGO/LIGO [2, 3].

We will continue the study of both these sources of terrestrial origin noise in the gravitational wave detector.

We would like to express our gratitude to all the colleagues and friends who helped us in different ways during this study. In particular we thank Eugenio Coccia (Roma), Igor Kolokolov (Novosibirsk), Valentin Rudenko (Moscow). We also thank our friends Stanly Forgang and Gregory Itskowitch (Texas) for very efficient discussions. One of us (P.V.) thanks the "Cosmion" Center for financial support.

References

[1] *P. Astone et al.* Long-term operation of the Rome "Explorer" cryogenic gravitational wave detector, Phys. Rev. D**47**, 363 (1993).

[2] *E. Coccia.* Ultracryogenic gravitational wave experiments, Lecture given to the XII Int. School of Cosmology and Gravitation, Preprint LNF-93/059 1993.

[3] *M. Yevert et al.* Status of the Virgo experiment, Preprint LAPP-EXP 94-15, 1994;
Kip S. Torn. Gravitational waves, in*Proceedings of Snowmass 94 Summer Study on Particle and Nuclear Astrophysics and Cosmology*, Eds.E.W.Kolb and R.Peccei (World Scientific, Singapore, 1995); LANL e-print archive (gr-gc/9506086 , 30 June 1995).

[4] *A.F. Pisarev.* Problems of radiation and reception of gravitational waves, Particles and Nucleus **6**, 284 (1975).

[5] *E. Coccia and T.O. Niinikoski.* Sci. Insr. **16**, 695 (1983).

[6] The fluctuations of the earth magnetic field in ULF band, (Ed. M.S. Aleksandrov), Moscow, Nauka, 1972.

[7] *S.H. Ward.* AFMAG – Airborne and Ground, Geophysics, **24** (1959) 761.

[8] *W.O. Schumann.* Z. Naturf. **72**, 149 (1952).

[9] Geomagnetic pulsations. (Ed. B.A. Tverskoy), Moscow, Nauka, 1973.

[10] *Ya.L. Alpert, E.G. Guseva, D.S. Fligel.* Distribution of the low-frequency electromagnetic waves in the Earth-ionosphere guide, Moscow, Nauka, 1967.

[11] *V.M. Ianovski.* The earth magnetism, Leningrad, Leningrad Univ., 1978.

[12] Lightning. Physics of Lightning, v1 (Ed. R.H.Golde), Ac. Press, N-Y, 1977.

[13] *Ya.L. Alpert.* Propagation of radio wave and ionosphere, Moscow, Nauka, 1960.

[14] *G. Kaden.* The electromagnetic shields, Gosenergoisdat, Moscow, 1957.

[15] The constructing of UHF shields and devices (ed. A.M. Chernushenko), Moscow, Radio and Svyas, 1990.

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Влияние геомагнитных возмущений
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Budker INP 96-19

Ответственный за выпуск С.Г. Попов
Работа поступила 11.04. 1996 г.

Сдано в набор 19.04.1996 г.
Подписано в печать 19.04.1996 г.
Формат бумаги 60×90 1/16 Объем 0.8 печ.л., 0.7 уч.-изд.л.
Тираж 180 экз. Бесплатно. Заказ N° 19

Обработано на IBM PC и отпечатано на
ротапринте ГНЦ РФ "ИЯФ им. Г.И. Будкера СО РАН",
Новосибирск, 630090, пр. академика Лаврентьева, 11.