

## On a seismic prospecting method in propagation of endogenous microseismic waves

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**Abstract.** It is shown that seismic prospecting as regards endogenous microseismic waves gives much promise, which is confirmed by graviprospecting practice. It was found that the spring gravimeter has some properties of a high-quality resonant microseismometer not taken into account earlier. These properties are used non-deliberately in highly effective empirical gravimethod called “GONG”. The emphasis is made on the importance of creating special resonant prospecting microseismometers, and a method for applying them to the seismic prospecting of oil and gas deposits is proposed.

### Introduction

The experience gained by the Russian and the world geophysics shows that endogenous microseismic waves (EMS-waves) permanently rise from the Earth’s interior. They represent a stationary or a piecewise stationary random process with a continuous frequency spectrum ranging from several hertz to, at least, first kilohertz. The mean square amplitudes of the EMS-waves usually lie in a nanometer or a lower range.

The nature of these waves has not been well-established, although several reasonable versions have been proposed. It is considered, for instance, that the EMS-waves are a response to distant earthquakes or hurricanes. A no less plausible version that the EMS-waves result from fracturing and other types of irreversible deformation that take place in rocks as a consequence of the tidal events and other global processes also deserves attention. It is probable that there can be these and other reasons for the EMS-waves not yet known. It may be that the ever-present gravitation can play the key role here. In the corpuscular theory of gravitation, one variant of which is briefly outlined in [1], waves of such a kind are quite possible. However, this is the subject of a separate serious investigation.

In any case, the EMS-waves must manifest all properties of a classical wave process: refraction, reflection, polarization, scattering, dissipation, interference, and diffraction. Passing through an inhomogeneous geological structure, the EMS-waves generate complex microseismic fields on the daily surface, which contain information about buried inhomogeneities. If a microseismic field is measured (and today this is an important problem in the EMS-waves prospecting), the extraction of data does not present any difficulties. A necessary theoretical basis has been accumulated in seismology and

acoustics. One only has to apply the available developments to the problem of prospecting in the EMS-waves, and this is a task of the future.

Here one should point out the following important fact. Microseismic fields formed on the daily surface are a noise-type mixture of harmonics of different frequencies, amplitudes, and phases. And such fields, most likely, do not have any bright contrasts that could serve as direct features of prospecting. To extract data of prospecting, it is necessary to subject microseismic signals to a narrow-band frequency filtration. This procedure resembles that of radio reception and is an indispensable technological part of prospecting in the EMS-waves.

Now let us dwell on the experience gained by predecessors. In 1982, M.A. Sadovsky and A.V. Nikolayev [2] analyzed and generalized all the real positive material accumulated by that time with much effort by means of wide-band serial seismometers. They concluded that the method of prospecting in the EMS-waves shows much promise. It is noted in [2], *inter alia*, that the first encouraging sounding of an oil deposit by the EMS-waves was made in 1959 on the Maili-Su deposit in the Fergana Valley. (The authors refer to [3].)

Later, in 1984, the authors [4] organized a 30-day session of continuous recording of microseismic noise above the explored Amangeldy gas deposit in Muyunkum sands. The recordings were taken by eight Cherepakha stations equipped with three-component seismometers SM-3 arranged along a 9-km profile. The operating frequency range of the seismometers was from 0.7 to 16 Hz. The processing of the material included: selection of realizations with the least noise of the surface origin; filtration of selected realizations at several reference frequencies in the range from 0.2 to 2.5 Hz; a comparison between stations of spectral amplitudes. As a result, some peculiarities of the deposit boundaries were revealed.

The fact is this undertaking did not have an adequate development. No method of prospecting in the EMS-waves that could be widely used in the field practice is available to this day. In our opinion, the main reason for this is the absence of sufficiently sensitive, precise, and noise-immune microseismometers. The standard wide-band Golitsyn seismometers do not quite meet these requirements. It is probable that the insensitivity band of wide-band devices caused by the Coulomb friction is commensurable with a level of informative EMS-waves and that the biggest part of these waves, except for rare maxima, is not sensed by a seismometer. The behavior of an oscillatory system such as seismometer in the presence of dry friction is described in detail in [5, 6]. It is shown that with a force of friction exceeding an active external force, the system inevitably comes from any initial state to the state of rest, and remains in this state for a long time.

A problematic question of how the insensitivity band can be considerably narrowed and the useful signal enhanced simultaneously, was principally

solved in the experimental gravitational physics [7]. For this, wide-band devices should be abandoned, and narrow-band resonant mechanical receivers with a high  $Q$ -factor be used. The  $Q$ -factor is a universal indicator of the quality of a receiver and its ability to sense weak signals. In addition, it is desirable to have a high  $Q$ -factor to suppress external and internal noise of the receiver. (The  $Q$ -factor value of mechanical oscillators designed for the trapping of relativistic gravitational waves reached to date [8] is  $\sim 1.7 \cdot 10^8$ .)

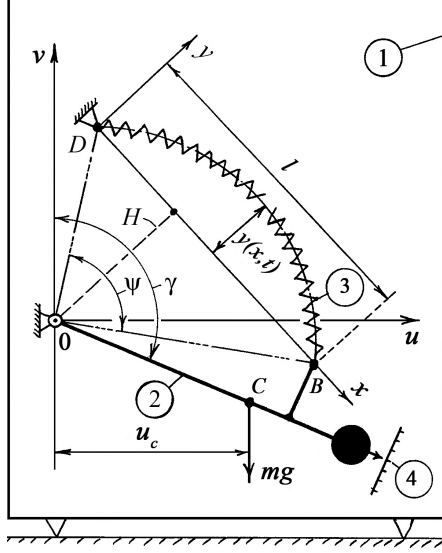
A Course on Resonant Receivers of the EMS-Waves was included in the programme of the School headed by Professor L.N. Rykunov (the Moscow State University) long ago. Dr. Yu.O. Starovoit [9] constructed several resonant microseismometers on the basis of SM-3 devices. Each of the devices was adjusted to its own frequency in the range from 25 to 40 Hz; the  $Q$ -factor value being within 100–150; the effective sensitivity with allowance for the internal noise of amplification paths was  $10^{-13}$  m. With the help of these devices, a 100-day recording session of the EMS-waves was performed on the basis of the CSO “Obninsk” enterprise. Information about the structural regularities of the EMS-waves important for seismology was obtained.

In 1990, an attempt was made [10] to develop a resonant microseismometer tuned within a frequency of 15–40 Hz. A mass on a flat spring was a device sensitive element. The  $Q$ -factor of the model, judging from the registogram of damped oscillations, did not exceed  $Q \approx 50$ –70.

As a matter of fact, the production of serial certified microseismometers of the resonant type has not been started yet. Therefore, the prospecting in the EMS-waves could remain on the previous ineffective level of good intentions if it were not for one surprising fact in gravimetry and graviprospecting. The spring-type gravimeter turned out to have the unforeseen properties of quite a good resonant microseismometer capable of working in the EMS-waves. It has also been found that it is a microseismic signal from the gravimeter that has long been used although unndeliberately but rather effectively in the wide-spread graviprospecting method GONG to be considered below.

## 1. A microseismic signal of the spring-type gravimeter

The spring-type gravimeters have different constructions but the same general scheme [11]. A physical pendulum with a horizontal axis of rotation held by the main spring (Figure 1) is a sensitive element of any gravimeter. The space or the time variations  $\Delta g$  of gravity bring about a change in the angular coordinate  $\gamma$  of the pendulum. The operator changes the tension of the other less rigid measuring spring using a compensatory screw, and brings the pendulum back to the zero-point. The angle of rotation of the compensatory screw is the measure  $\Delta g$ . (The screw and the measuring spring are not shown in Figure 1).



**Figure 1.** Scheme of the gravimeter (derivation of formulas for a pseudo-gravitational signal): 1) vacuum-treated frame; 2) pendulum; 3) the main spring; 4) a control device of zero point;  $y(x, t)$  are the transverse sags of the spring axial line in the figure plane

Thus, in the process of measurements, a distance  $l$  between the immobile end  $D$  and the mobile end  $B$  of the main spring is kept constant and equal to a certain quantity  $l_0$ . In addition,  $l_0$ , the angular coordinate  $\gamma_0$  and the linear coordinate  $u_{c0}$  of the center of mass  $C$  of the pendulum; the focal length  $H_0$  of section  $DB$ ; and the spring visibility angle  $\psi_0$  correspond to this basic state of the gravimeter. Let  $m$  and  $J$  be a pendulum mass and its moment of inertia with respect to the rotation axis, respectively,  $b = \sqrt{J/m}$  is the radius of inertia;  $\chi$  is a spring force under tension;  $g_0$  is the calibration value of gravity (the constant of a device). Then the tension of the main spring in the ground state is

$$N_0 = \frac{mg_0 u_{c0}}{H_0}. \quad (1)$$

Using the perturbation method, we obtain the following formula for the frequency of small free oscillations of the pendulum around the coordinate  $\gamma_0$ :

$$p_0 \approx \sqrt{\frac{H_0^2 \chi}{J} + g_0 \frac{u_{c0}}{b^2} \eta_0}, \quad (2)$$

where

$$\eta_0 = \text{ctg } \psi_0 - \text{ctg } \gamma_0 - \frac{H_0}{l_0}. \quad (3)$$

The expression for the mechanical sensitivity of the pendulum in the vicinity of the angle  $\gamma_0$  has the form

$$\theta_0 = \left( \frac{\partial \gamma}{\partial g} \right)_0 \approx \frac{m u_{c0}}{m g_0 u_{c0} \eta_0 + \chi H_0^2} = \frac{u_{c0}}{b^2 p_0^2}. \quad (4)$$

If necessary, the force of a spring can be determined in the following way:

$$\chi = \frac{J p_0^2}{H_0^2} \left( 1 - \frac{g_0 u_{c0} \eta_0}{b^2 p_0^2} \right) = \frac{J p_0^2}{H_0^2} (1 - g_0 \theta_0 \eta_0). \quad (5)$$

The sought for pseudo-gravitational signal of microseismic origin is formed in the gravimeter mainly due to transverse (the string-type) resonant oscillations of the main spring. For further reasoning it is convenient to use an auxiliary system of coordinates  $\{x, y, z\}$  with the origin at a point  $D$ ; the axis  $x$  of this system passing through point  $B$ , and the axis  $z$  being perpendicular to the plane. Under the action of microoscillations of the points  $D$  and  $B$ , the spring axis in the case of steady-state oscillations will be sagging according to a law  $r = r(x, t)$ , where  $r = \sqrt{y^2 + z^2}$  and  $t$  is the time. If we use the string theory, we have

$$r(x, t) \approx \sum_{k=1}^{\infty} A_k \sin \Omega_k x \cdot \sin(\omega_k t - \varphi_k), \quad (6)$$

where  $k = 1, 2, 3, \dots$  are numbers of harmonics;  $A_k$  are amplitudes;  $\Omega_k = k\pi/l_0$  are the wave numbers;  $\omega_k = c\Omega_k$  are the time frequencies;  $c = \sqrt{N_0/\mu}$  is the linear propagation velocity of transverse perturbations of the spring along its axis;  $\mu$  is the linear mass of the spring; and  $\varphi_k$  are the phase delay angles.

Additional tension of the spring resulting from transverse sagging (6) is

$$\Delta N = \chi \left[ \int_0^{l_0} \sqrt{1 + \left( \frac{\partial r}{\partial x} \right)^2} dx - l_0 \right] \approx \frac{\chi}{2} \int_0^{l_0} \left( \frac{\partial r}{\partial x} \right)^2 dx = \Delta N_\xi - \Delta N_t.$$

The term  $\Delta N_t = \frac{\chi l_0}{8} \sum_{k=1}^{\infty} \Omega_k^2 A_k^2 \cos 2(\omega_k t - \varphi_k)$  is a variable part of tension, which does not essentially affect the pendulum motion due to its inertia. In the worst case, the force  $\Delta N_t$  creates a weak blurring of the control index.

The term  $\Delta N_\xi = \frac{\chi l_0}{8} \sum_{k=1}^{\infty} \Omega_k^2 A_k^2 = \frac{\pi^2 \chi}{8l_0} \sum_{k=1}^{\infty} k^2 A_k^2$  is a constant for this set of harmonics. It is this term that is transformed into the sought-for pseudo-gravitational signal of an imaginary decrease in the gravity being measured:

$$\xi = -\frac{\Delta N_\xi}{N_0} g_0 = -\pi^2 E \sum_{k=1}^{\infty} k^2 A_k^2, \quad (7)$$

where

$$E = \frac{\chi H_0}{8ml_0 u_{c0}} = \frac{p_0^2 b^2}{8l_0 H_0 u_{c0}} (1 - g_0 \theta_0 \eta_0) = \frac{1 - g_0 \theta_0 \eta_0}{8l_0 H_0 \theta_0}. \quad (8)$$

The foregoing are common expressions. They are applicable to gravimeters of any geometry and any depth of astaticism. At  $\eta_0 = 0$ , a particular case discussed in [12] follows from (8):

$$E = \frac{p_0^2 b^2}{8l_0 H_0 u_{c0}} = \frac{1}{8l_0 H_0 \theta_0}. \quad (8a)$$

At  $\eta_0 = 0$  and  $H_0 u_{c0} = b^2$ , we obtain a very simple expression devoted to  $\xi$ -signal [13]:

$$E = \frac{p_0^2}{8l_0}. \quad (8b)$$

Now, let us explain the mechanism of excitation of transverse oscillations of a spring. This is a two-fold mechanism: a) parametric excitation by longitudinal forces at the ends of a spring; b) inertial excitation from transverse vibrations of the ends of the spring.

Let us consider one particular case of inertial excitation as an example. Let (see Figure 1) the ends  $D$  and  $B$  of a spring move in an absolute reference system parallel to the axis  $y$  from the same law

$$Y_D(t) = Y_B(t) = Y(t).$$

It is necessary to determine the transverse sags  $y(x, t)$  of the axial line of the spring. To do this, let us replace the spring by a string having the same linear mass  $\mu$  and the same tension  $N_0$ . This replacement is admissible if a diameter of the spring is small as compared to its length and if the bending stresses in the spring do not play a leading role.

Using conventional procedures of string theory (see, for instance, [14, §17]), we obtain the following equation:

$$\frac{\partial^2 y}{\partial t^2} + 2n \frac{\partial y}{\partial t} - c^2 \frac{\partial^2 y}{\partial x^2} = -\frac{d^2 Y}{dt^2}, \quad (9)$$

where  $2n = \nu/\mu$ ;  $\nu$  is a viscous resistance factor.

Equation (9) is a classical wave equation with a dissipative term and the right-hand side. Its solution for the steady-state condition at  $Y = a \sin \omega t$  has the following form:

$$y = \sum_k A_k \sin \Omega_k x \cdot \sin[\omega t - \varphi_k(\omega)], \quad (10)$$

where  $k = 1, 3, 5, \dots$ ;  $A_k = a\beta_k(\omega)$ ;

$$\beta_k = \frac{4}{k\pi} \cdot \frac{\omega^2}{\sqrt{(\omega_k^2 - \omega^2)^2 + 4n^2\omega^2}}, \quad (11)$$

$$\varphi_k = \arctg \frac{2n\omega}{\omega_k^2 - \omega^2}, \quad \omega_k = k\omega_1, \quad \omega_1 = \frac{\pi}{l_0} \sqrt{\frac{N_0}{\mu}}.$$

Thus, in the case of parallel-identical motions of the ends of a spring, odd harmonics of transverse oscillations are excited. (Even harmonics will apparently occur at parallel-opposite perturbations when  $Y_D = -Y_B$ .)

The amplifying and filtration properties of the spring with respect to external perturbations  $Y(t)$  are reflected in the amplitude frequency characteristics (AFC)  $\beta_k(\omega)$ . As  $\omega = 0$ , they all take the zero value. At  $\omega \rightarrow \infty$ , each function  $\beta_k(\omega)$  finitely approaches from above the individual limit,

$$\beta_k(\omega \rightarrow \infty) = \frac{4}{k\pi}. \tag{12}$$

At  $\omega = \omega_k$ , all functions  $\beta_k(\omega)$  reach one maximum value

$$\beta_m = \frac{4}{\pi} \cdot \frac{\omega_1}{2n}. \tag{13}$$

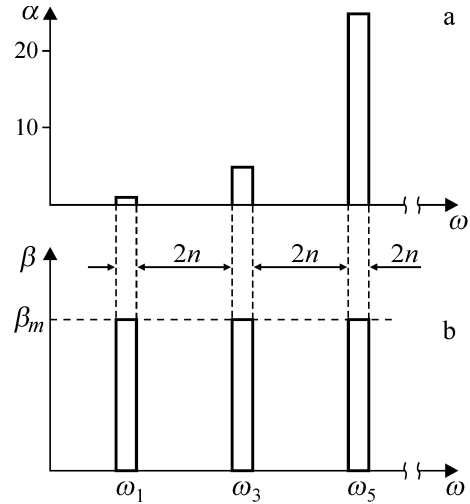
The conventional pass bands obtained with the help of the horizontal section of the functions  $\beta_k(\omega)$  at the level  $\beta_m/\sqrt{2}$  are also the same for all  $k$  and equal to

$$\Delta\omega = 2n. \tag{14}$$

Thus, the following  $Q$ -factor corresponds to the first tone of the spring oscillations:

$$Q_1 = \frac{\omega_1}{\Delta\omega} = \frac{\omega_1}{2n} = \frac{\pi}{4}\beta_m. \tag{15}$$

The  $Q$ -factor of higher tones increases proportional to numbers of harmonics as  $Q_k = kQ_1$ . For calculations, the total AFC of the spring sags can be schematized using a sequence of the uniform Heaviside maxima corresponding to the frequencies of odd harmonics (Figure 2b). The pseudo-gravitational  $\xi$ -signal has an AFC of a similar structure: in the same frequency bands there are maxima whose amplitudes  $\xi_{mk} = \pi^2 E a^2 \beta_m^2 k^2$  abruptly increase as  $k$ -numbers increase. (This tendency, however, is not preserved at rather high frequencies when the influence of bending stresses in the spring is beginning to emerge.) Figure 2a shows a graph  $\alpha(\omega)$  of a schematic AFC, normalized on  $\xi_{m1} = \pi^2 E a^2 \beta_m^2$ .



**Figure 2.** Schematic AFCs of a pseudo-gravitational  $\xi$ -signal (a) and transverse sags of the gravimeter main spring (b)

If a gravimeter is affected by random stationary microseisms with a continuous frequency spectrum, then

$$\xi = -\frac{16E\omega_1^2}{n} \sum_k k^2 S(\omega_k) = -\frac{16E}{n} \sum_k S'(\omega_k), \quad (16)$$

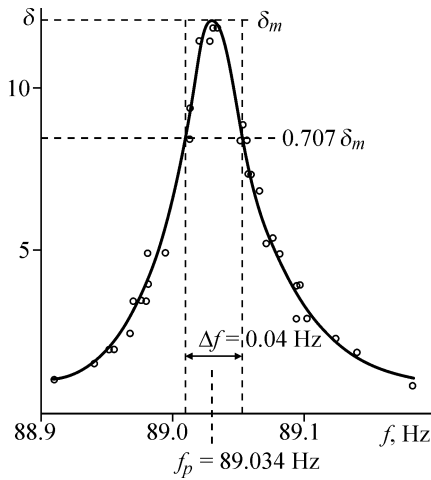
where  $S(\omega)$  and  $S'(\omega)$  are, respectively, spectral densities of microseismic displacements and microseismic velocities, oriented across the axis of the main spring.

According to (8), the coefficients  $E$  of different-type gravimeters, must, generally speaking, be different. Hence,  $\xi$ -signals from (7) and (16) for different-type gravimeters under the same microseismic action must have different values. It will be shown below that this very important conclusion has been well confirmed by the field survey.

According to the test data of the gravimeters GNUK-B and GNUK-C in monochromatic acoustic fields,  $\xi$ -signals are traced on many resonant frequencies in the range from 35 to 4500 Hz. Sometimes it is very difficult to observe  $\xi$ -signals with a positive sign. However, such signals, probably caused by the string oscillations of a wide-band spring, are of minor importance. Such resonant effects, both negative and positive were first observed by V.G. Budanov as early as in 1977 in gravimeters tests on a vibrostand of his own construction [15].

A real AFC of a harmonic of  $\xi$ -signal recorded in the process of acoustic tests of a certain device is presented in Figure 3. In this case, the  $Q$ -factor of the system is  $Q \approx 2200$ .

Thus, the spring-type gravimeter has the properties of a high- $Q$  multi-band resonant microseismometer. In terms of automation theory, the gravimeter is structurally arranged as a battery made of several filters operating in



**Figure 3.** GNUK-B gravimeter No. 01. Amplitude–frequency characteristics of a pseudo-gravitational  $\xi$ -signal in the vicinity of the resonant frequency  $f_p$  of one form of string oscillations of the main spring:  $f$  is cyclic frequency,  $\Delta f$  is conventional transmission frequency, and  $\delta$  is the deviation of the reference index in divisions of the device optical scale



parallel and independently with one rather narrow pass band  $\Delta\omega = 2n$  and a fairly large (of order  $10^3$  and higher) amplification factor. The following unforeseen operations are realized spontaneously in the gravimeter: reception of microseismic perturbations by the main spring; high- $Q$  multichannel filtration of input perturbations; multiple resonant amplification of filtered signals owing to the microseisms energy; detection of amplified signals; formation of a pseudo-gravitational  $\xi$ -signal; undesirable (but inevitable) summation of  $\xi$ -signal with a purely gravitational signal  $\Delta g$ ; monitoring of the sum  $\sigma = \xi + \Delta g$  on the gravimeter output.

## 2. Experience in prospecting of EMS-waves by gravimeters

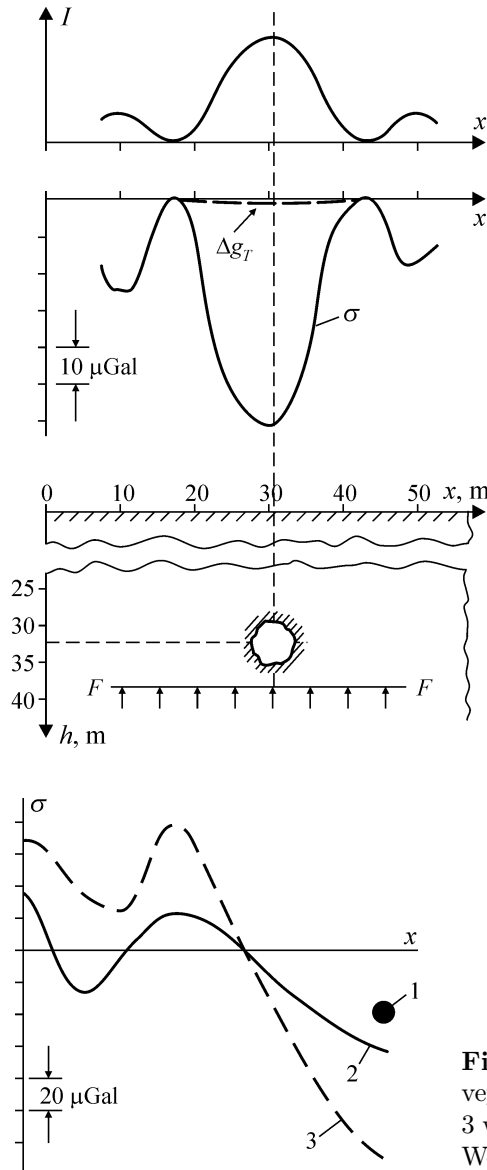
By today, two wave phenomena in the field graviprospecting have been tested nondeliberately but successfully. One of them is the EMS-waves diffraction on small-size “non-transparent” bodies, and the other one is focusing of the EMS-waves by lens-shaped anomalous objects.

### 2.1. The EMS-waves diffraction and graviprospecting

A diffraction pattern on the daily surface is created by waves, whose lengths are commensurate to the dimensions of a buried scattering body. The necessary condition of clear diffraction is the host rocks homogeneity.

In 1986, Z. Fajklewicz, Polish geophysicist, reported about strange gravimeter signals with clear signs of wave diffraction [16]. As a matter of fact, these signs were not noticed by the author and other specialists. The sources of the observed anomalies were small karstic caverns 5–10 m in diameter at a depth of  $h = 6$ –35 m. Figure 4 shows a cross-section of one of the caverns and associated gravimetric profile, in which a linear trend was eliminated. The observed signal  $\sigma$  turned out to be almost two orders of magnitude larger than the gravitational anomaly  $\Delta g_T$  from the cavern that is theoretically possible. In other words, the microseismic component  $\xi$  dominates in the signal  $\sigma$ . On the profile  $\sigma(x)$ , there are two lateral minima in addition to the main one. This is a necessary sign of wave diffraction; the signal  $\sigma(x)$  is, as it should be, an original qualitative inversion of the intensity  $I(x)$  of ground microoscillations under diffraction conditions.

A group of Moscow geophysicists, headed by K.E. Veselov, performed a detailed gravimetric survey [17] on three test sites assigned to newly-erected buildings. The methodological novelty of this survey was in that several different-type gravimeters were simultaneously used. The first test site ( $80 \times 120$  m) is located between workshops of the plant in the settlement of Tovarkovo of Tula region. The following two gravimeters were used: GVT No. 11 and Worden–Master No. 1. The other two sites are located in the center of Moscow. Four gravimeters of the GVT and the GNU-K types were used.



**Figure 4.** Gravimetric profile over a BH-10 karstic cavern taken by Worden–Master device (according to Z. Fajklewicz): at the bottom is a cross-section along the cavern center;  $FF$  is the front of the EMS-waves;  $I(x)$  is the conventional intensity of a microseismic field formed on the daily surface due to the EMS-waves diffraction on the cavern;  $\sigma(x)$  are real gravimeter recordings;  $\Delta g_T$  is a theoretical gravitational anomaly from the cavern

**Figure 5.** Results of microgravimetric survey over adit 1 in Tovarkovo. Profiles 2 and 3 were taken by GVT device No. 11 and the Worden–Master device No. 1, respectively

Underground hollows were detected during the survey on all the three sites in spite of significant external noise. The profiles taken in Tovarkovo over an abandoned adit, located at a depth of 28 m (see Figure 5) are impressive. A purely gravitational signal from the adit was less than  $5 \mu\text{Gal}$ . However, the GVT device with the oscillation frequency of the pendulum  $p_0 = 0.04 \text{ Hz}$  showed an anomaly  $\sigma \approx -60 \mu\text{Gal}$  over the adit, and a less sensitive ( $p_0 = 0.11 \text{ Hz}$ ) Worden–Master gravimeter showed an anomaly  $\sigma \approx -130 \mu\text{Gal}$ . Thus, the observed anomalies  $\sigma$  are again represented

mainly by the microseismic components  $\xi$ . They are in full agreement with the theory of  $\xi$ -signal. According to (8), the coefficient  $E$  and the signal  $\xi$  of a less sensitive gravimeter (all other factors being equal) must be greater than those of a more sensitive one. This effect clearly manifested itself clearly both in Tovarkovo and on the two Moscow sites. The profiles in Figure 5 have, like the Fajklewicz profiles (see Figure 4), lateral minima. This again indicates to the diffraction-wave nature of the observed effects.

On the whole, publications [16, 17] are, in our opinion, brilliant examples of the use of the EMS-waves diffraction in field exploration.

In addition to the diffraction on compact objects considered, there is also an edge diffraction of large geological formations. The edge diffraction can also possess important prospecting features. The limited volume of this paper, however, does not enable us to dwell on this interesting issue.

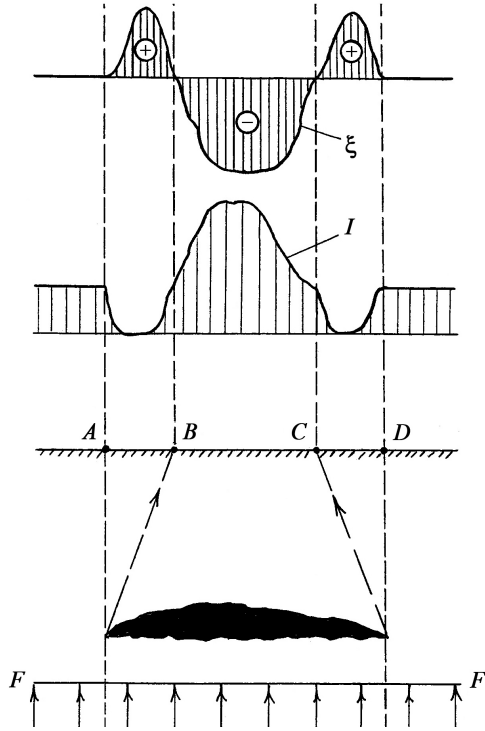
## 2.2. The EMS-waves focusing and GONG methods

By analogy with optics, one can point out three main conditions needed for the EMS-waves focusing: 1) a buried focusing body must be lens-shaped with horizontal spreading; 2) the wave velocity in a lens must be much smaller than in the host rocks; and 3) the lens dimensions must be considerable larger than the length of focused information-bearing waves.

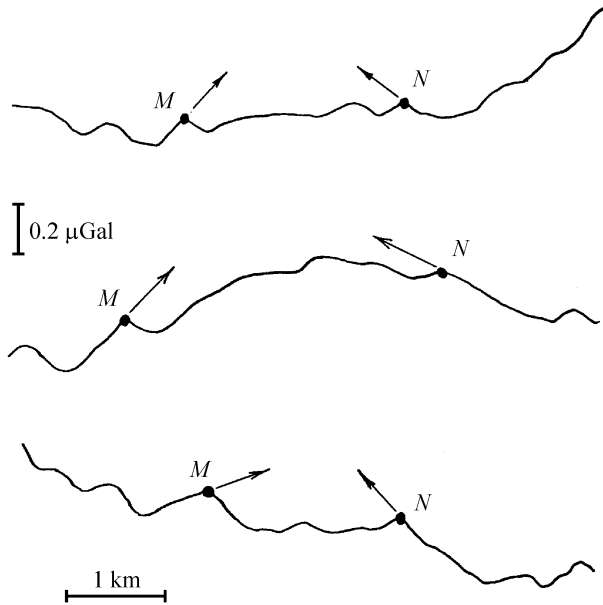
The water and oil deposits located under domes to some extent satisfy these requirements. Of course, real lens-shaped geological structures have geometrical and structural defects on which especially short EMS-waves are scattering. However, the spectrum has always waves that have more or less clear focusing (Figure 6). Such waves create the following pattern on the daily surface. Outside the contour  $AD$  of the deposit, the intensity  $I$  of microseisms is equal to its typical background value. The waves, focused by the lens, come into the central spot  $BC$ . Here, the intensity  $I$  of microseisms is higher than the background. And in the microseismic shadow zones  $AB$  and  $CD$ , the intensity  $I$  is smaller than that of the background. (Theoretically it is possible that  $I = 0$ .)

The reaction of a good microseismometer to this should be a signal similar to the profile with the intensity  $I$ . However, the response of the spring-type gravimeter is specific. A negative pseudo-gravitational signal  $\xi$  that is equal to some background value, is formed outside the deposit. It is taken for the zero reference point. In the quiet zones  $AB$  and  $CD$ , there must be positive maxima (with respect to the background) of  $\xi$ -signal. In the central spot, however, where the intensity of microseisms is higher than that of the background, a negative  $\xi$ -signal is formed.

Thus, positive maxima of  $\xi$ -signal, with their external sides, can always and independently of the lens depth correspond to its contour. Between the positive peaks, there must be a dip of  $\xi$ -signal to the negative values.



**Figure 6.** A scheme of EMS-waves focusing by a lens-shaped anomalous body:  $FF$  is the wave front;  $I$  is the intensity of microseisms on the daily surface;  $\xi$  is a pseudo-gravitational signal of the spring-type gravimeter. In microseismic “shadow” zones  $AB$  and  $CD$ , the gravimeter responds to a deposit by signals that are positive with respect to the background, in the zone of stronger oscillations  $BC$ —by negative  $\xi$ -signals



**Figure 7.** Three real gravimetric profiles over oil deposits. According to I.N. Mikhailov, the points  $M$  and  $N$  correspond to the deposit boundaries; this turned out to be the case in reality

The prospecting features have been surmised in the above-mentioned empirical graviprospecting method GONG [18, 20]. I.N. Mikhailov, the author of the method, noticed these features long ago, and thoroughly analyzed a bulk of the original graviprospecting data. The GONG method has been tested on many deposits. Its high efficiency has been confirmed: the reliability of predicting the contours of hydrocarbon deposits reaches 85–95 %. In fact, the GONG method does not predict the depth of deposits, although there are some data for this. For instance, the size of the central spot  $BC$  (see Figure 6) clearly depends on the lens depth. It is most likely that this aspect of the method will be developed in the future.

At first glance, the technology for interpreting graviprospecting profiles with the use of the GONG method is very simple. One has to find informative positive maxima and instantly map the deposit contour. Figure 7 shows three real profiles [19] with the authors' interpretation. It should be noted that only highly qualified specialists can identify informative peaks. Here the correlation of prospecting features on adjacent profiles plays an important role.

### 3. “Gravitational absorption” hypothesis

According to [20], I.N. Mikhailov thinks the nature of anomalous signals used in the GONG method to be associated with “gravitational absorption”. This non-newtonian phenomenon, also termed as “gravitational shielding effect” (GShE), was predicted by Le Sage’s theory of gravitation and discovered in 1919 by K. Majorana<sup>1</sup>. Repeated measurements in a unique special experiment [21] have shown that the weight  $W$  of a test ball of mass 1274 g always decreases by  $\Delta W = (0.98 \pm 0.16) \mu\text{g}$  if this ball is surrounded by a symmetric mercury shield of thickness  $\sim 8.4$  cm. K. Majorana found that the shielding index of gravitation forces at a level  $h \approx 6.7 \cdot 10^{-12} \text{ cm}^2/\text{g}$  corresponds to a weight defect  $\Delta W$ . Also, he theoretically determined the upper limit of this index as  $h_{\text{lim}} \approx 7.6 \cdot 10^{-12} \text{ cm}^2/\text{g}$ . (In any experiments and estimates we must have  $h < h_{\text{lim}}$ .)

Unfortunately, in some cases, as in [20], there are erroneous interpretations of the Majorana effect and a very free treatment of the physical concepts of Le Sage’s theory. To avoid such errors, researchers should always know the following.

Majorana’s GShE is currently the only well-established non-newtonian phenomenon. As a matter of fact, up to now no one has managed to repeat

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<sup>1</sup>Quirino Majorana (1871–1957), Professor, Academician, and President of the Association of Italian Physicists. His scientific interests include experimental (general and gravitational) physics, gravitation theory, and cosmogony.

Taking this opportunity, we would like to mention that the sound “j” in scientist’s name should be pronounced as the Russian “й” or the English “Y” in the word “Yes”. In book [22, p. 220], the foreign readers are specially informed about this.

experiments from [21] with the same scheme and in such a faultless realization. Even subsequent K. Majorana's experiments were less successful and accurate than his first experiment [21]. There was no definite criticism of some methodological and technical mistakes of K. Majorana. K. Majorana's opponents criticized his working hypothesis, which was far from being perfect, but not his experiments and the weight defect, not found there. In so doing, as a thorough analysis shows incorrect extrapolations, resulting in wrong conclusions about errors in the experiment, were used [21].

However, a strict mathematical search [1] has shown that a) Majorana's GShE can be observed in many reliable experiments made at different times by different researchers to determine the non-newtonian gravitational constant  $G$ ; b) The weight defect which was in fact observed ( $\Delta W \approx 1 \mu\text{g}$ ) to be detected in the experiment [21]. Thus, the Majorana effect has been indirectly strongly confirmed in many independent  $G$ -experiments; c) the existing dramatic disagreement between  $G$ -values, obtained in geometrically non-identical experiments, is a natural consequence of a conventional interpretation with no allowance of the non-newtonian Earth's background. After the introduction of appropriate corrections, the variance of experimental  $G$ -values is multiply decreased and  $G$ -values are compactly grouped around the mathematical expectation

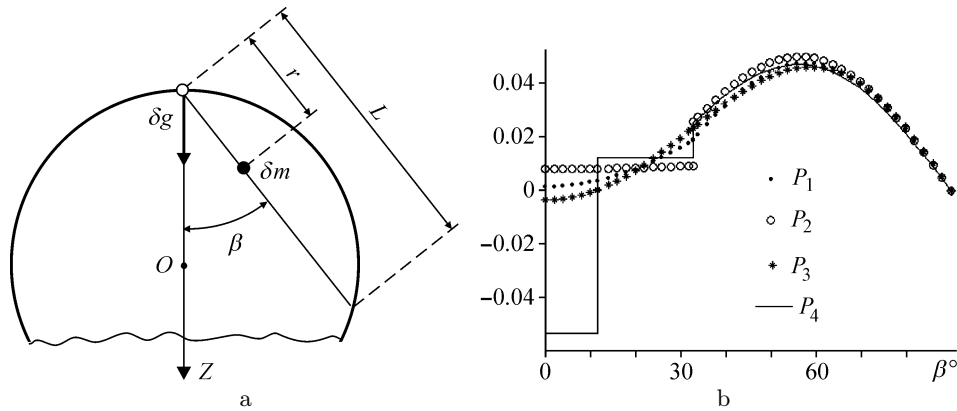
$$f = 6.76 \cdot 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}.$$

One should consider the parameter  $f$  as a "true" gravitational constant and the newtonian  $G$ -values as its substitutes.

Le Sage's theory provides some concepts, directly associated with gravi-prospecting. For instance, Le Sage's formula for acceleration generated on the Earth's surface by a buried elementary excess mass  $\delta m$ , located at a distance  $r$  from the observation point (Figure 8a) has the following form:

$$\delta g = f \frac{\delta m}{r^2} [1 - P(\beta)] \cos \beta, \quad (17)$$

where  $\beta$  is the angle between the line of action  $L$  and the direction  $Z$  to the Earth's center;  $P(\beta)$  is a dimensionless function with allowance for the absorption of Le Sage's gravitons in the Earth's body and a possible radiation of endogenous gravitons from the deep interior. In the absence of radiation, the function  $P(\beta)$  has the meaning of probability of absorbing gravitons piercing the Earth along the chord  $L(\beta)$ . Figure 8b shows the functions  $P(\beta)$  obtained in the above-mentioned computer analysis of  $G$ -experiments. In all the four versions, dips of the ordinates  $P$  are observed in a wide vicinity of the zero argument. These dips are a sign of a possible radiation of endogenous gravitons. They are presumably generated in the liquid core. In the version  $P_4$ , there is also a sign of radiation from the interior core: here the curve  $P_4(\beta)$  covers the domain of negative values.

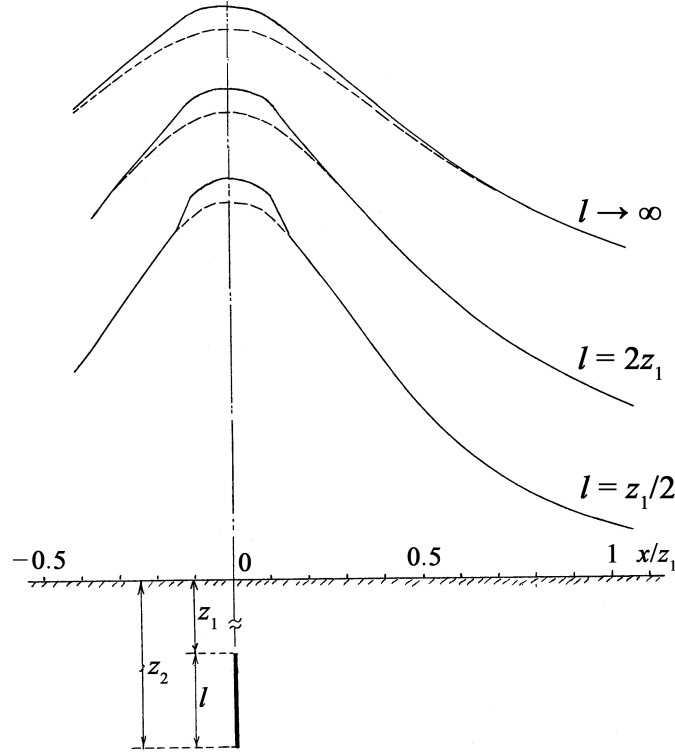


**Figure 8.** Left: notation of parameters in Le Sage's expression (17) for the acceleration  $\delta g$  caused by the elementary excess mass  $\delta m$ ;  $O$  is the Earth's center. Right: four versions of the function  $P(\beta)$ , obtained by a special analysis of independent  $G$ -experiments. The versions  $P_1$ ,  $P_2$ , and  $P_3$  were presented earlier in [1]

From the form of the functions  $P_i(\beta)$  one can conclude that in any case the difference between Le Sage's and newtonian signals of gravitation cannot exceed  $\sim 5\%$ . Test calculations with simple models of anomalous bodies have shown that Le Sage's gravitation does not manifest clear prospecting features. In most tests, Le Sage's and the newtonian gravitational profiles actually coincide. The only exception are column-shaped bodies in the version  $P_4$ . In this case, Le Sage's profiles have a typical secondary maximum (Figure 9).

The detected graviton radiation cannot explain the anomalies existing, for instance, in the Fajklewicz theory or the GONG-method. Even a special target gravimetric experiment did not reveal the radiation to be sufficient for this purpose. The experiment was carried out in the winter of 1989 on a geodetic station of "Borovoye". A rigid steel tripod with a table for the control gravimeter GNUK-B was installed on a certified monolith. A 1077 mm high column with a diameter of 154 mm and a mass of 228 kg consisting of 15 lead cylinders was assembled and disassembled just under the gravimeter. They were manufactured, calibrated, and weighted in the Siberian Research Institute of Metrology. The calculated newtonian signal from the column was  $7 \mu\text{g}$ . Test measurements with the column and without it were made at the night time, that is, at a minimal man-made noise. The gravimeter values, within its precision, turned out to be the same as the calculated newtonian value.

However, the final argument that excludes any gravitational versions of the above-mentioned anomalies is the existence of that very phenomenon, which was observed in Moscow and Tovarkovo [17]. None of the gravita-



**Figure 9.** Normalized gravity profiles on the Earth's surface by massive vertical sections  $l$  of different lengths: solid line—calculation on the basis of Le Sage's version  $P_4$ ; dotted line—calculation on the basis of the newtonian law, i.e., at  $P = 0$

tional theories (in particular, Le Sage's theory with its GShE) can explain a systematic difference in the reading values of different-type gravimeters working in parallel. Hence, there remains only one microseismic version.

In conclusion, let us present another very important concept of Le Sage's theory. This is the following expression for gravitation on the surface of a spherically symmetric celestial body:

$$g_0 = \frac{2\pi f}{h} \int_0^{\pi/2} P(\beta) \sin \beta \cos \beta d\beta = \frac{2\pi f}{h} \int_0^1 P(\tau) \tau d\tau, \quad (18)$$

where  $\tau = \cos \beta$ . It turns out that the parameters  $g_0$ ,  $f$ , and  $h$  and the function  $P$  are closely interrelated. Therefore, one cannot arbitrarily change or specify an element of this "quartet" without tracing what happens to the others. It follows from (18) that

$$h = \frac{2\pi f}{g_0} \int_0^1 P(\tau) \tau d\tau. \quad (19)$$



At  $P = 1$ , that is, in the case of a body with a finite diameter but an infinite mass that is absolutely “non-transparent” for gravitons, we obtain the following limiting expression:

$$h_{\text{lim}} = \frac{\pi f}{g_0}. \quad (20)$$

Let us assume, in the same way as K. Majorana in [21], that our Sun ( $g_0 = 2.74 \cdot 10^4$  Gal) is close to “non-transparency”. Then at the above-mentioned  $f = 6.76 \cdot 10^{-8}$  CGS, we obtain an estimate that is almost the same as Majorana’s one,  $h_{\text{lim}} = 7.75 \cdot 10^{-12}$  cm<sup>2</sup>/g. Substitution into (18) of the values  $P = 1$ ;  $f = 6.76 \cdot 10^{-12}$  and  $h = 6.3 \cdot 10^{-12}$  (obtained in [1]) will enable us to find the value of gravitation that is maximally possible within Le Sage’s theory,

$$g_{\text{lim}} = \frac{\pi f}{h} \approx 3.4 \cdot 10^4 \text{ cm/s}^2. \quad (21)$$

According to modern concepts (see, for instance, [24]), the Universe has certain objects (white dwarfs) for which  $g_0 \gg g_{\text{lim}}$ . This calls for a new revision of both Le Sage’s theory and the physical principles used in astronomy when interpreting of observation data. The situation is difficult but not hopeless. If we speak only of Le Sage’s theory, it has a wide potential for improvement, without a radical change.

We hope that the material of this section will help specialists to avoid inaccurate practical applications of Le Sage’s theory and the K. Majorana effect, and no hasty judgements about them will be made.

To conclude, a few words about a very interesting phenomenon: “constricted directional effect” noted by I.N. Mikhailov. According to his data, which are worth another look, informative GONG-signals of gravimeters are traced within the cone limit, having a vertical axis and central angle  $\approx 15^\circ$ , the latter being approximately equal to the angle of sight of the lower boundary of the Earth’s liquid core. In our interpretation, the effect in question is supposed to mean that informative EMS-waves received by the spring gravimeter are generated somewhere in the vicinity of the Earth’s core.

## Conclusion

The possibility of prospecting in endogenous microseismic waves has been clearly proved by the graviprospecting practice. The fact is that the spring-type gravimeter has unforeseen properties of a high- $Q$  multiband resonant microseismometer capable of working in the EMS-waves. The gravimeter can detect the effect of focusing of passing the EMS-waves by lens-shaped hydrocarbon deposits. This effect is used undeliberately but very successfully in the well-known method “GONG”. The gravimeter also detects a pattern of

diffraction of passing the EMS-waves by small-size anomalous bodies. There are many examples of successful prospecting of such objects.

The gravimeter, however, is not the best device for measuring the EMS-waves. It is very difficult to see and identify an informative microseismic component on gravimetric profiles. An experienced interpreter manages to do this. However, in this case, the prospecting information is often incompletely used.

Thus, the first task on the way to creation of a practically applicable method of prospecting in the EMS-waves is the development of high- $Q$  resonant microseismometers and appropriate devices.

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