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A continuously operating proton precession magnetometer for geomagnetic measurements

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ABSTRACT

This paper describes a magnetometer for high precision total field intensity measurements at geomagnetic observatories and for geomagnetic surveys.

The output is a continuous proton precession signal with frequency directly proportional to field intensity. The signal is obtained from a circulating liquid containing protons having a long time of relaxation. The magnetization is acquired in a strong magnetic field between the poles of a permanent magnet. The time of magnetization and the necessary size of the magnet are greatly reduced by filling the pole gap with steelwool. From the magnet the liquid flows through a narrow tube to the field detector where the precessing protons induce electric currents in the signal coil.

The paper contains evaluation of optimal values of various design parameters.

INTRODUCTION

The proton free precession magnetometer was introduced by Packard and Varian (1954) as an instrument to measure weak magnetic fields. It is widely used for geomagnetic measurements and is amply described in many textbooks.

The instrument produces signal with frequency directly proportional to the strength of the magnetic field, but the signal decays and disappears in a few seconds. It is reestablished by a temporary strong magnetic field within the field detector while the magnetic field measurement is discontinued.

Many attempts have been made to construct continuously operating proton precession magnetometers for geomagnetic measurements. Under the direction of G. Bene methods were developed using the principle of the magnetic resonance spectrometer for obtaining a continuous proton precession signal in the earth's field, but this instrument suffers from a very weak intensity (Rocard, 1957).

The double resonance or Overhauser effect in a liquid can be used to improve the signal strength (Abragam et al., 1957). Initially the main difficulty of this method was the instability of the chemical used for the double resonance, but recently such magnetometers have become commercially available.

Skripov (1958) developed a method where a circulating liquid is magnetized in a strong electromagnet from where it runs to the field detector. This method has been used for total magnetic field intensity recording at a geomagnetic observatory (Grivet, 1960). It can give a very strong signal but the usefulness of the equipment is hampered by the heavy magnet.

The various possibilities for using nuclear magnetic resonance for measuring the earth's magnetic field have been discussed by Bonnet (1961).

The magnetometer described in this paper has been constructed at the University of Iceland in a continued effort to improve the free precession magnetometer built there in 1959 (Gardarsson and Sigurgeirsson, 1960). The method used is that of Skripov with a circulating liquid.

PRINCIPLE OF OPERATION

Fig. 1 is a schematic drawing illustrating the operation of the magnetometer. Water or other

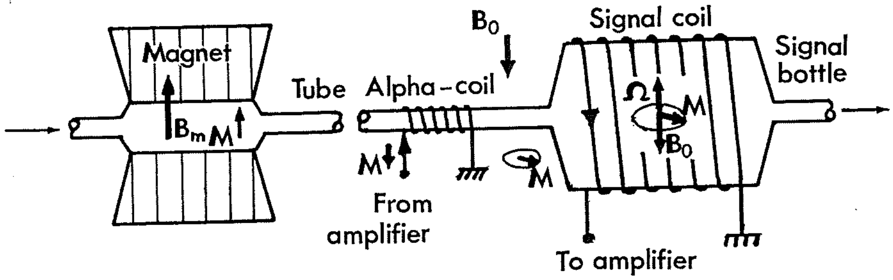

Fig. 1.
The principal parts of the magnetometer.

liquid containing protons is pumped through a strong magnetic field between the poles of a magnet. Here the protons are aligned and the liquid acquires magnetic polarization **M** in direction of the strong field $\mathbf{B}_m$. When the liquid leaves the magnet the change in magnetic field is so slow that the direction of **M** follows adiabatically the direction of the magnetic field. At some distance from the magnet the direction of **M** is the same as that of the earth's field $\mathbf{B}_o$, which we, to simplify our description, assume pointing straight down. From the magnet the liquid flows through a narrow tube to the field detector. Before entering the signal flask it goes through a small coil (the alpha-coil) which turns the direction of **M** 90° and leaves it pointing in a horizontal direction. After that, on the way to and inside the signal flask, **M** precesses around the direction of $\mathbf{B}_o$ and induces current in the signal coil.

For quantitative description of **M** we choose to use the modified Bloch's equation (Abragam, 1961, p. 53)

$$\frac{d\mathbf{M}}{dt} = \gamma \cdot \mathbf{M} \times \mathbf{B} - \frac{\mathbf{M} - \chi \cdot \mathbf{B}}{T} \qquad (1)$$

where $\gamma = 2.67513 \cdot 10^8 \text{ m}^2 / \text{wb} \cdot \text{s}$, is the gyromagnetic ratio of the proton, measured in water with an accuracy of one part in million (Bender and Driscoll, 1958), χ is the susceptibility of the protons in the liquid and T is a time constant characteristic for each liquid. χ can be calculated theoretically as $\chi = n \cdot \gamma^2 h^2 / (16 \pi^2 k T)$ (Abragam, 1961, p. 2). Here n is the number of protons per unit volume of liquid, h is Planck's constant, k Boltzmann's constant and T the absolute temperature. In Bloch's equation **B** may be time-dependent ($\mathbf{B} = \mathbf{B}(t)$), but in a constant field $\chi \cdot \mathbf{B}$ is the equilibrium value for **M**.

Possible deviations from the behaviour described by eq. (1) will be discussed under the description of apparatus.

If we assume the field of the magnet to be homogeneous and the liquid enters the magnet with practically zero magnetization, the **M** vector will start growing in the direction of $\mathbf{B}_m$ according to the equation

$$\frac{d\mathbf{M}}{dt} = - \frac{\mathbf{M} - \chi \cdot \mathbf{B}_m}{T} \quad \text{while } \mathbf{M} \times \mathbf{B}_m \text{ is zero.}$$

The solution to this equation is
$\mathbf{M} = \chi \cdot \mathbf{B}_m (1 - \exp(-t/T))$.

The solution gives us the magnetization of the liquid when it leaves the magnet after having been exposed to its field for a time t. We assume that all parts of the liquid spend the same time in the magnet.

On the way to and inside the signal bottle the magnetization of the liquid is very much higher than its equilibrium value, $M >> \chi \cdot B$. This justifies a simplification of eq. (1) to

$$\frac{d\mathbf{M}}{dt} = \gamma \cdot \mathbf{M} \times \mathbf{B} - \frac{\mathbf{M}}{T} \qquad (2)$$

For making clear the content of this equation we introduce the vector $\underline{\Omega} = - \gamma \cdot \mathbf{B}$ and write $\mathbf{M} = M \cdot \mathbf{U}$ where **U** is a unit vector having the same direction as **M**. Inserting this in eq. (2) gives

$$M \cdot \frac{d\mathbf{U}}{dt} + \frac{dM}{dt} \cdot \mathbf{U} = M \cdot \underline{\Omega} \times \mathbf{U} - \frac{M}{T} \cdot \mathbf{U}$$

Equating vector components in direction of **U** gives

$$\frac{dM}{dt} = - \frac{M}{T} \qquad (2')$$

while components at right angles to **U** give

$$\frac{d\mathbf{U}}{dt} = \underline{\Omega} \times \mathbf{U} \qquad (2'')$$

These two equations are equivalent to eq. (2). The solution of eq. (2') is $M = M_o \exp(-t/T)$ which shows that the intensity of magnetization decays exponentially and is independent of how **B** varies as long as B is much smaller than M/χ. The quantity $M_o = \chi \cdot B_m (1 - \exp(-t_m/T))$ is the intensity of magnetization as the liquid leaves the magnet after a time t_m, and t is the time from this moment.

If the liquid flow is Q volume units per unit time and the flow is such that all parts of the liquid spend the same time in the magnet, this time is $t_m = V_m / Q$ where V_m is the volume occupied by liquid between the poles of the magnet. At the outlet from the magnet the magnetization is then

$$M_o = \chi \cdot B_m (1 - \exp(-V_m / V_o)) \quad (3)$$

where $V_o = Q \cdot T$ is the volume of liquid flowing in the decay time T. Making the same assumptions for the flow in the tube we find for the magnetization at the entrance of the signal bottle

$$M_1 = M_o \exp(-V_t/V_o) \quad (4)$$

where V_t is the volume of the tube. Assuming no mixing the mean magnetization of the liquid in the bottle is

$$M_b = M_1 (1 - \exp(-V_b/V_o)) \cdot (V_b/V_o)^{-1} \quad (5)$$

where V_b is the volume of the bottle.

Eq. (2'') describes how the direction of **M** changes. The unit vector **U** is rotated around the direction of the magnetic field by the rotation vector $\underline{\Omega} = -\gamma \cdot \mathbf{B}$. This vector can vary with time due to the time dependent magnetic field as well as a result of motion of the liquid in an inhomogeneous magnetic field.

When the liquid runs out of the magnet the protons are exposed to a decreasing magnetic field. This does not affect **U** as long as the field does not change its direction. If, as might be suggested by Fig. 1, the magnetic field decreases to zero and then grows in the opposite direction without ever turning, the magnetization does not change direction and remains pointing up, opposite to the earth's field. However, this only happens if the magnet is carefully aligned in the earth's field. Normally the magnetic field is not zero in any part of the tube and the protons running along with the liquid see it slowly turning towards the direction of the earth's field.

In order to see the effect on **U** of the turning of the magnetic field we look at **U** from a reference frame S' which is rotated by a rotation vector $\underline{\omega}$ at right angles to $\underline{\Omega}$, in such a way that in S' the direction of $\underline{\Omega}$ is fixed and can be taken as the z' axis. If we call the time derivative of **U** with respect to S' $(d\mathbf{U}/dt)'$ and in the fixed frame $d\mathbf{U}/dt$, we have $d\mathbf{U}/dt = (d\mathbf{U}/dt)' + \underline{\omega} \times \mathbf{U}$. Inserted in eq. (2'') this gives

$$(d\mathbf{U}/dt)' = (\underline{\Omega} - \underline{\omega}) \times \mathbf{U} \quad (2''')$$

This equation shows that in S' the time variation of **U** is governed by a rotation vector $\underline{\Omega}' = \underline{\Omega} - \underline{\omega}$, where $\underline{\Omega} = \Omega(t) \cdot \mathbf{k}$ is a time dependent vector on the z' axis (**k** is a unit vector in direction of z') and $\underline{\omega} = \underline{\omega}(t)$ is a time dependent vector in the (x', y')-plane. In the beginning, before the field starts turning, $\underline{\omega}$ is zero. This is also the case in the end, after the field has reached its final direction.

We now introduce the angle α between **B** and **M**. The angle between $\underline{\Omega}$ and **U** is then $\pi - \alpha$ and we have $\cos(\pi - \alpha) = \mathbf{k} \cdot \mathbf{U}$. From this equation and eq. (2''') we get $\sin\alpha \cdot d\alpha/dt = \mathbf{k} \cdot (d\mathbf{U}/dt)' = \underline{\omega} \cdot \mathbf{k} \times \mathbf{U}$ or $d\alpha/dt = \underline{\omega} \cdot \mathbf{E} = \omega \cos\varphi$, where $\mathbf{E} = \mathbf{k} \times \mathbf{U}/\sin\alpha$ is a unit vector in the (x', y')-plane and φ is the angle between $\underline{\omega}$ and **E**. The quantity ω is the size of the vector $\underline{\omega}$.

The final angle between **B** and **M** will be

$$\alpha = \int_{t_1}^{t_2} \underline{\omega} \cdot \mathbf{E}\, dt = \int_{t_1}^{t_2} \omega \cos\varphi\, dt \quad (6)$$

The time t_1 denotes the initial time before **B** starts turning and t_2 is the final time when **B** has reached its final direction.

From eq. (6) we conclude that

$$\alpha \leq \int_{t_1}^{t_2} \omega\, dt \quad (7)$$

which tells us that the largest possible value for α is the total turning angle for **B**.

If the rotation of the magnetic field is slow compared to the rotation of **M** in the field ($\omega << \Omega$) we get a better judgement of the upper limit of α by looking at **U** from a new reference system S'' which has a rotation $\underline{\omega}'$ with respect to S' in such a way that the z'' axis follows the direction of $\underline{\Omega}'$. The vector $\underline{\omega}'$ is in the (x'', y'')-plane. By repeating the same process as before we find $d\alpha'/dt = \underline{\omega}' \cdot \mathbf{E}' = \omega' \cdot \cos\varphi'$ where α'

is the angle between **U** and $-\underline{\Omega}'$, and **E**' and φ' in S'' correspond to the unprimed quantities in S'.

As we have $\underline{\Omega}' = \underline{\Omega}$ both in the beginning and in the end, we can write

$$\alpha = \int_{t_1}^{t_2} \omega' \cdot \cos\varphi' \, dt \qquad (6')$$

and conclude

$$\alpha \leq \int_{t_1}^{t_2} \omega' \, dt \qquad (7')$$

Thus α can not be larger than the total turning angle of $\underline{\Omega}'$ measured in S'.

If ω' is small we may go one stage further and find that α is not larger than the total turning angle for $\underline{\Omega}'' = \underline{\Omega}' - \underline{\omega}'$ measured in S'', and so on.

Evatluation of α from eq. (7') shows that it is easy to arrange the magnet so that **M** follows closely the direction of **B** as the liquid flows from the magnet to the alpha-coil. Entering the alpha-coil the magnetization of the liquid therefore has the same direction as the earth's magnetic field. While flowing through the coil it is exposed to the constant earth's field B_o and a small oscillating field $B_x = B_1 \cos(\Omega_o t + \varphi_o)$, where $\Omega_o = \gamma B_o$. As $B_1 << B_o$ the field intensity inside the coil is practically constant and equal to B_o. With reference to Fig. 2 we see that the rotation vector $\underline{\omega}$ only has the y-component

$$\omega_y = -(dB_x/dt)/B_o = \gamma B_1 \sin(\Omega_o t + \varphi_o)$$

The angle between the magnetization and the magnetic field, when the liquid has left the coil, can be found by using eq. (6)

$$\alpha = \int_{t_1}^{t_2} \underline{\omega} \cdot \mathbf{E} \, dt = \int_{t_1}^{t_2} \omega_y E_y \, dt.$$

As S' is here practically the same as S, we may take **E** as a unit vector rotating counterclockwise in the (x, y)-plane 90° ahead of the projection of **M** onto this plane as shown in Fig. 3. If $\Omega_o t$ is the angle from the x axis to the projection of **M** we have $E_y = \sin(\Omega_o t + \pi/2)$ and

$$\alpha = \int_{t_1}^{t_2} \gamma B_1 \sin(\Omega_o t + \varphi_o) \cdot \sin(\Omega_o t + \pi/2) \, dt$$
$$= \tfrac{1}{2} \gamma B_1 \sin\varphi_o \cdot \Delta t.$$

where $\Delta t = t_2 - t_1$ is the time which the liquid spends in the coil. For the integration we assume $\Delta t >> 2\pi/\Omega_o$. By choosing $\varphi_o = \pi/2$ we get $\alpha = \tfrac{1}{2} \gamma B_1 \cdot \Delta t$. Maximum signal in the signal coil is obtained when $\alpha = \pi/2$. This we get by choosing $B_1 = \pi/(\gamma \cdot \Delta t)$. If the earth's field is homogeneous in the space occupied by the alpha-coil and the signal bottle, the magnetization will at any time have the same direction in the bottle as at the outlet of the alpha-coil. If both alpha-coil and signal coil have the same orientation, as indicated in Fig. 1, the axial component of the magnetization in the signal bottle is in phase with **M** in Fig. 3 and the magnetic flux through the

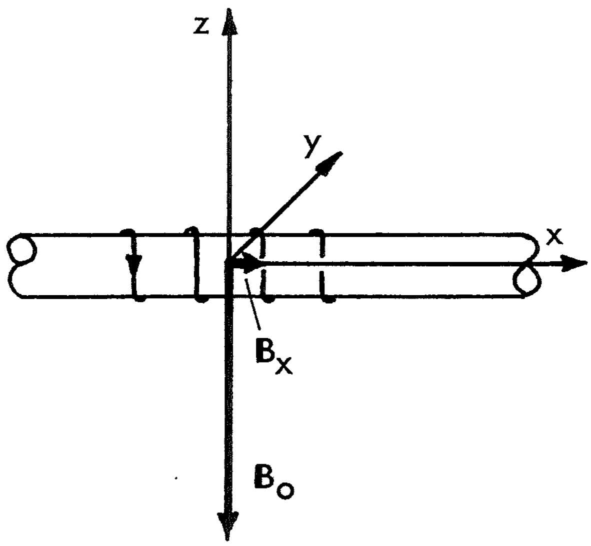

Fig. 2. The magnetic field in the alpha-coil.

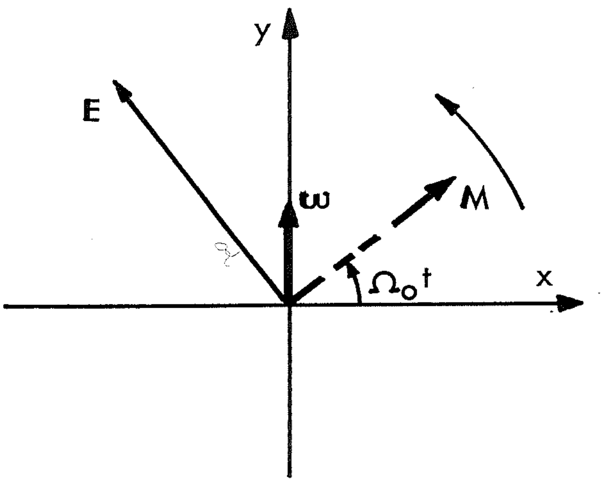

Fig. 3. Vectors used for calculating α in the alpha-coil.

signal coil can be written $\Phi = \Phi_o \cdot \cos \Omega_o t$. The e.m.f. induced in the signal coil is 90° behind the flux and can be written $e = e_s \cdot \cos(\Omega_o t - \pi/2)$.

The oscillating field in the alpha-coil, having the desired phase $(\Omega_o t + \pi/2)$, can be produced simply by amplifying this signal and applying it to the alpha-coil 180° out of phase. The current in the alpha-coil is then $i = i_a \cdot \cos(\Omega_o t + \pi/2)$ creating the field $B_x = (n/l_a)\, \mu_o i_a \cdot \cos(\Omega_o t + \pi/2)$ where n is the number of turns on the alpha-coil, l_a its length and $\mu_o = 4\pi \cdot 10^{-7}$ wb / A · m the permeability constant. Introducing the velocity of the liquid in the alpha-coil $v = l_a / \Delta t$ we get $\alpha = (n/2v)\, \mu_o\, \gamma \cdot i_a$. The current amplitude needed to give $\alpha = \pi/2$ is then

$$i_a = \pi \cdot v / (n \mu_o \gamma) \qquad (8)$$

The magnetization in the signal bottle is perpendicular to the magnetic field and induces maximum signal in the coil. If the angle between the axis of the alpha-coil and the earth's field is not $\pi/2$ but ϑ, the current amplitude should be increased by a factor $1/\sin\vartheta$.

A more conventional method for deriving eq. (8) can be found in textbooks on nuclear magnetic resonance (Abragam, 1961, p. 21).

DESIGN PARAMETERS

The magnet is the most critical part of the equipment. In order to get a strong signal we need, according to eq. (3), (4) and (5), a large B_m and V_m and a small V_t, which requires a large magnet and a field detector close to it. The size of the magnet tends to reduce the usefulness of the apparatus as it adds to the weight and disturbs the field at the place where it is to be measured.

Careful design helps to keep down the size of the magnet. The total volume of the magnet with its iron housing may be expressed as $V_I = c \cdot V_m \cdot B_m^2$ where c is a constant. A magnet should be designed for a certain flow of liquid in such a way that M_o, given by eq. (3), is as high as possible while V_I remains constant.

Using the expression for V_I to eliminate B_m from eq. (3) we get

$$M_o = c_1 \cdot (1 - \exp(-V_m / V_o)) \cdot (V_m / V_o)^{-1/2}$$

where $c_1 = \chi \cdot (V_I / cV_o)^{1/2}$ is a constant. M_o reaches maximum where we have

$\exp(V_m/V_o) - 1 = 2 \cdot V_m/V_o$ or at $V_m = 1.3 \cdot V_o = 1.3\, QT$.

For best results the magnet should be designed in accordance with this relation although the condition is not very critical. For this case the magnetization of the outflowing liquid is 73% of the saturation value, $M_o = 0.73\, \chi\, B_m$.

We see that a liquid with a long time constant requires a bigger magnet to produce the same magnetization as in liquid with a lower T if the flow rate is the same. However, if the flow is adjusted so that Q · T is the same, all design requirements are unchanged and we get the same signal strength provided both liquids have the same proton density.

An effective way to reduce the size of the magnet, and thus increase the usefulness of the apparatus, is to decrease the time constant of the liquid while it is inside the magnet. Reducing the time constant of the liquid by a factor of one hundred, only inside the magnet, makes it possible to obtain the same magnetization in a 100 times lighter magnet. This is accomplished by filling the magnetizing volume with fine grade steelwool. The large surface and tight packing of the steelwool causes the majority of the protons in the liquid to come in immediate proximity of the iron surface where they can freely exchange energy with the iron and get aligned in the field's direction. For the optimal value of the magnetizing volume we should therefore write

$$V_m = 1.3\, QT_m \qquad (9)$$

where T_m is the effective time constant for magnetizing the liquid at the conditions prevailing in the magnet.

Next we consider how the volume, V_t, and the length, l, of the tube, carrying liquid from the magnet to the signal bottle, should be chosen. This is tied to the magnetic disturbance caused by the magnet and to the properties of the pump.

The magnetic field disturbance at the location of the signal bottle should be kept within acceptable limits. If the magnet is of the type shown in Fig. 7, the disturbance from the permanent magnet and some of the soft iron effect can be eliminated by fixing small permanent magnets on the outside of the soft iron housing. The resulting disturbance should then be less than the disturbance caused by a sphere with infinite permeability having the same volume as the soft iron housing, V_I. This disturbance is

$$\Delta = 3\, B_o V_I / (4\pi l^3) \qquad (10)$$

where B_o is the earth's field and l the distance from the magnet to the signal bottle or the length of the tube carrying the liquid from the magnet to the bottle.

The disturbance can be decreased by decreasing V_I or increasing l but both tend to reduce the signal strength which is proportional to M_1 in eq. (4). Suppose that we have fixed our values for T, Q and M_1 and chosen a pump which produces a certain pressure. A part of the pressure drop occurs in the magnet and return tubes, but a certain pressure, p, will be available for driving the liquid through the tube from the magnet to the signal bottle. For turbulent flow the driving pressure can be expressed as

$$p = \psi \cdot \varrho \cdot v^2\, l/r \qquad (11)$$

where ψ is the resistance coefficient for turbulent flow of the liquid, assumed to be constant, ϱ the mass density of the liquid, v the mean velocity in the tube and r the radius of the tube.

Using the equations

$$Q = \pi \cdot r^2 \cdot v \text{ and } V_t = \pi \cdot r^2 \cdot l$$

to eliminate v and r from eq. (11) we get

$$p = \pi^{1/2} \cdot \psi\, \varrho\, Q^2\, V_t^{-5/2} \cdot l^{7/2} \qquad (12)$$

As the total magnet volume is proportional to M_o^2 we may write $V_I / V_{I\,min} = (M_o / M_1)^2$ where $V_{I\,min}$ is the magnet volume needed to produce the magnetization M_1 at the outlet of the magnet. According to eq. (4) we then have

$$V_I = V_{I\,min} \cdot \exp\,(2\, V_t/V_o) \qquad (13)$$

Using eq. (12) and (13) to eliminate l and V_I from eq. (10) gives

$$\Delta = \Delta_1 \exp\,(\, 2\, V_t/V_o) \cdot (V_t/V_o)^{-15/7} \quad (14)$$

where Δ_1 is independent of V_t.

In Fig. 4 we plot Δ/Δ_{min} from eq. (14) as a function of V_t/V_o. The minimum is at $V_t/V_o = 15/14$ but this requires a large magnet as seen from the plot of $V_I/V_{I\,min}$ of eq. (13). We see that Δ first starts increasing rapidly at V_t/V_o values below 0.5 so we have chosen $V_t = 0.7 V_o$. Here we have $\Delta = 1.2\,\Delta_{min}$ and $V_I = 4 V_{I\,min}$. For this value of V_t the magnetization is reduced by a factor of 2 in the tube, $M_1 = 0.5\, M_o$.

In our calculations we have assumed no restrictions on the distance between magnet and bottle as is the case for an observatory instrument.

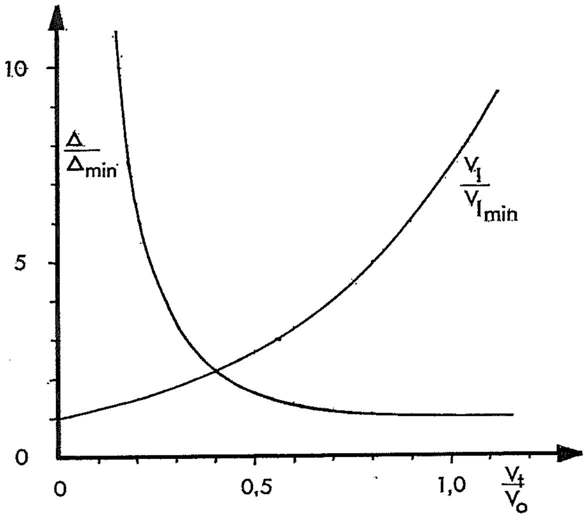

Fig. 4. Relative field disturbance at the detector, Δ/Δ_{min}, and relative size of the magnet, $V_I/V_{I\,min}$.

To find the most favourable size for the signal bottle we assume that we can expand or contract the bottle together with the surrounding signal coil without changing the shape. The signal, or the voltage induced in the signal coil by the precessing protons, will be proportional to M_b given by eq. (5) and to the area of the turns, so that

$$e_s = c\,(1 - \exp\,(- V_b/V_o)) \cdot (V_b/V_o)^{-1/3}$$

where c is independent of the volume of the bottle

With good amplifiers available, the signal strength itself is not important but rather the signal to noise ratio at the terminals of the coil. If the noise is only due to the unavoidable thermal agitation it is proportional to $R^{1/2}$, or to $(V_b/V_o)^{-1/6}$ as the resistance of the coil, R, is inversely proportional to the linear dimension. The signal to noise voltage ratio is then

$$e_s/e_n = c_1\,(1 - \exp\,(- V_b/V_o)) \cdot (V_b/V_o)^{-1/6}$$

where c_1 is independent of V_b. This is maximum if $\exp\,(V_b/V_o) - 1 = 6\, V_b/V_o$ or at $V_b = 2.9\, V_o$. The optimum value is not very critical. Thus at $V_b = V_o$ the signal to noise ratio has only decreased to 80% of its maximum value.

If the noise is predominantly external, due to an oscillating magnetic field, it should be proportional to $(V_b/V_o)^{2/3}$. The signal to noise ratio is then proportional to

$$(1 - \exp\,(- V_b/V_o)) \cdot (V_b/V_o)^{-1}$$

with maximum at $V_b = 0$, but at $V_b = V_o$ it has only dropped to 63% of its maximum value.

The overall result is that under all circumstances we are not far from the best obtainable signal to noise ratio if we choose $V_b = Q \cdot T$. According to eq. (5) this gives

$$M_b = 0.63 \cdot M_1$$

The size and shape of the signal coil should be chosen so that the signal to noise ratio is close to maximum. The signal amplitude is $e_s = \int E \cdot dl = \overline{E} \cdot l$ where E is the amplitude of the electrical field strength induced by the axial component of the magnetization, $M_b \cdot \cos \Omega_o t$, in the signal bottle and l is the length of the wire in the coil. $\overline{E}$ is the average value of E over the length of the wire. This is the same as the average value of E over the volume occupied by the coil.

The resistance of the coil is

$$R = l/(\sigma A) = l^2/(a \sigma V_c)$$

where σ is the conductivity and A the cross section of the wire, and a is the ratio between the volume of the conductor and the volume of the coil, V_c. Using this equation to eliminate l from the expression for e_s we get

$$e_s = (a \sigma R V_c)^{1/2} \cdot \overline{E} \qquad (15)$$

It is evident that the form of the coil should be such that inside it E is as high as possible, and that outside the coil E is everywhere lower than inside it. This means that the induced electric field should everywhere have the same value, E_s, on the outer surface of the coil while the inner surface rests on the signal bottle. The form of the coil is therefore determined by the equation

$$E = E_s \qquad (16)$$

valid for the outer surface.

According to eq. (15) the signal to noise ratio is proportional to $y = V_c^{1/2} \cdot \overline{E} = V_c^{-1/2} \cdot \int E dV = V_c^{-1/2} \cdot \int_0^{V_c} E_s dV.$

The integral can either be taken as volume integral of E over the interior of the coil or as a one dimensional integral of the surface field E_s considered as a function of coil volume, V. At the maximum we have

$$dy/dV_c = V_c^{-1/2} \cdot E_s - 1/2 \cdot V_c^{-3/2} \cdot \int_0^{V_c} E_s dV = 0,$$

or

$$E_s = 1/2 \cdot \overline{E} \qquad (17)$$

To get maximum signal to thermal noise ratio the size of the coil should be such that the field at its outer surface is everywhere half as big as the average field in the coil.

As an example we take a spherical bottle with radius r_b. The precessing protons produce a rotating magnetic dipole field around the bottle and we get

$$E = E_m \cdot (r_b/r)^2 \cdot \sin \theta$$

where

$$E_m = 1/3\, \mu_o \cdot M_b \cdot r_b \cdot \Omega_o \qquad (18)$$

is the maximum value for E at $(r, \theta) = (r_b, \pi/2)$, r is the distance from the centre of the bottle and θ is the angle between the axis of the coil and the direction of r.

According to eq. (16) the outer surface of the coil is given by

$$r = (E_m/E_s)^{1/2} \cdot r_b \cdot (\sin \theta)^{1/2} = r_o \cdot (\sin \theta)^{1/2}$$

while the inner surface is the sphere $r = r_b$ (wall thickness of bottle neglected). Fig. 5 shows an axial section through coils with different values of r_o/r_b.

To find a suitable size for the coil we calculate $y = V_c^{1/2} \cdot \overline{E}$ and plot y/y_{max} as a funtion of r_o/r_b in Fig 6. The relative signal to noise ratio, y/y_{max},

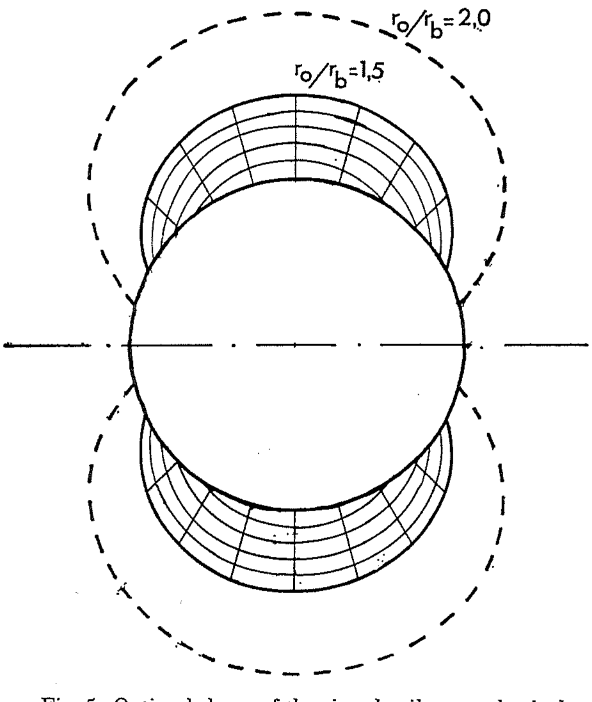

Fig. 5. Optimal shape of the signal coil on a spherical bottle.

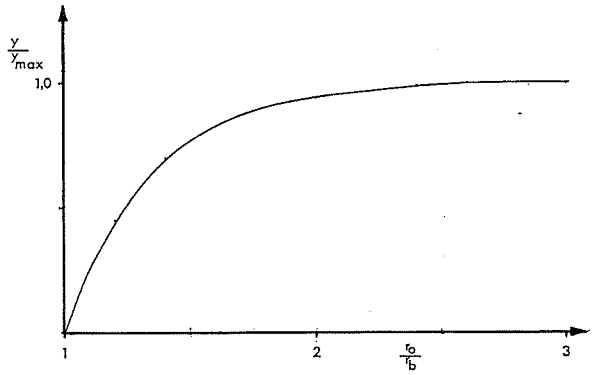

Fig. 6. Relative signal to noise ratio of signal coil.

reaches maximum at $r_o/r_b = 3$ where we have $\overline{E}/E_m = 0.22$, $E_s/E_m = 0.11$ and $V_c/V_b = 18$. For many applications it is inconvenient to have the coil so big, which also makes it rather sensitive to magnetic pickup noise. However, y has a very broad maximum and even at $r_o = 1.5\, r_b$ it is still as high as 78% of its maximum value. For such a coil we have $\overline{E} = 0.6\, E_m$ and $V_c = 1.5\, V_b$. Its shape is shown in Fig. 5. According to equations (15) and (18) this coil will give a signal with the amplitude

$$e_s = 0.15\, \mu_o\, \Omega_o\, (a\, \sigma\, R)^{1/2}\, V_b^{5/6} \cdot M_b \quad (19)$$

TABLE I

Preferred design parameters and theoretical performance.

Volume of magnetizing field	$V_m = 1.3\, QT_m$
Volume of tube	$V_t = 0.7\, QT_t$
Volume of signal bottle	$V_b = 1.0\, QT_b$
Volume of coil windings	$V_c = 1.5\, V_b$
Length of tube, l, as long as pump permits.	
Field disturbance $\Delta < 0.24\, (V_I/l^3) \cdot B_o$	
Theoretical signal amplitude	
	$e_s = 0.034\, \mu_o\, \gamma\, \chi \cdot B_m\, B_o\, (a\, \sigma\, R)^{1/2}\, (V_b)^{5/6}$

where M_b is given by equations (3), (4) and (5).

The main results of this section regarding design parameters and performance of a properly designed magnetometer are summarized in Table I. The design is intended to give a high signal to noise ratio and low field disturbance at the signal bottle. It is assumed that the distance between magnet and signal bottle can be increased at will and that magnetic disturbance from pump and pump motor can be eliminated by keeping them far from the bottle. In a portable magnetometer these conditions may not be met.

Values for signal coil volume and signal amplitude are evaluated on basis of a spherical signal bottle, but are likely to be similar for a cylindrical bottle if its length and diameter are comparable.

In Table I we have taken into account the possibility of having different time constants in the tube (T_t) and in the bottle (T_b) as influence from the tube wall may reduce T_t (Michel and Pfeifer, 1965), and T_b actually refers to the transverse time constant (Abragam, 1961).

DESCRIPTION OF APPARATUS

Three magnetometers have been built, one for stationary use at Leirvogur Magnetic Observatory and two for airborne use. The design parameters of the observatory magnetometer are similar to the values given in Table I and we shall limit our description mainly to this instrument.

The liquid.

Four different liquids have been used in the magnetometers: water, methanol, benzene and toluene.

The most important properties of these liquids for the present purpose are listed in Table II.

TABLE II

Properties of magnetometer liquids.

Liquid	N protons/m^3	χ Am/wb at 300° K	T sec 0° C	T sec 50° C	Viscosity poise 0° C	Viscosity poise 50° C	Density kg/m^3	Boiling point °C
Water (H_2O)	$6.7 \cdot 10^{28}$	$3.2 \cdot 10^{-3}$	1,7	6,0	$1.79 \cdot 10^{-2}$	$0.55 \cdot 10^{-2}$	1000	100
Methanol (CH_3OH)	6.0 · ,,	2.9 · ,,	6[1])		0.82 · ,,	0.40 · ,,	796	65
Benzene (C_6H_6)	4.1 · ,,	2.0 · ,,	11	32	0.91 · ,,	0.44 · ,,	880	80
Toluene ($C_6H_5CH_3$)	4.5 · ,,	2.2 · ,,	10[2])	18[2])	0.77 · ,,	0.42 · ,,	860	111

1) At 25° C $T_{CH_3} = 4.4$ s, $T_{OH} = 10.5$ s

2) At 0° C $T_{CH_3} = 8$ s, $T_{C_6H_5} = 12$ s
At 50° C $T_{CH_3} = 14$ s, $T_{C_6H_5} = 22$ s

Water is in many respects a favourable liquid for this use. The disadvantages are short time constant at low temperatures, freezing at 0° C and corrosive attack on magnet and steelwool unless special precautions are taken to prevent it. Benzene and toluene have long decay times but may be somewhat difficult to handle, especially when they are hot, because they dissolve most rubber and plastics materials. These liquids are electrical insulators and the flow can transport electric charges and cause high voltage and sparks at some points. This can be prevented by mixing alcohol in the liquid. Methanol has good properties for magnetometers of this kind and is used in our magnetometers today.

Desirable properties for the liquid are: high nuclear suceptibility (χ), long time constant (T) and low viscosity. The last two factors are related and usually improve by increasing temperature. Although T increases by increasing temperature, the time constant for magnetization in the magnet (T_m) will decrease as increased molecular diffusion in the liquid brings more protons in immediate contact with the steelwool. In the stationary magnetometer the temperature usually is about 50° C, but the airborne magnetometers are not heated and have in some cases been operated at temperatures as low as –10° C.

Due to the molecular structure the response of protons in methanol and toluene can not be described by a single time constant. In methanol at 25° C protons bound in CH_3 groups respond to the magnetic field with a time constant $T_{CH3} = 4.4$ s while those bound in OH groups have the time constant $T_{OH} = 10.5$ s. Here our previous calculations of the decrease of magnetization described by eq. (2') are not quite to the point, but they can still be a valuable guide in designing the apparatus when for T we use some average value between T_{CH3} and T_{OH}.

Most of the T values in Table II are taken from Landolt—Börnstein (1962). They apply to the pure liquids but there are several reasons why the effective values of T are lower. Dissolved oxygen and other paramagnetic impurities will decrease the time constant. Interaction with the steelwool in the magnet causes a huge reduction in T and interaction with the wall while the liquid is flowing through the tube may also cause some reduction. Finally, the decay of the precessing magnetization in the signal bottle may be faster than for longitudinal magnetization, especially if the magnetic field is inhomogeneous. This can be taken into account in the calculations by using different time constants in the tube and in the bottle as is done in Table I.

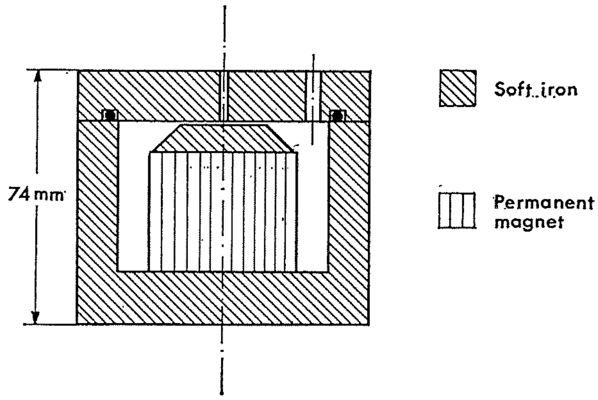

Fig. 7. The magnet.

The magnet.

The magnetizing field is produced by a permanent magnet made of Ticonal. It is cylindrical in shape, 3.5 cm long and 4.3 cm in diameter. It is surrounded by soft iron housing as shown in Fig. 7 which is an axial section through the assembly. The pole gap is only 1 mm and the pole diameter 2.5 cm. The magnetizing volume is thus $V_m = 0.5$ cm^3. The pole gap is tightly packed with about 0.5 g of fine grade steel wool (Silver Fleece, grade 000).

When the magnet has been assembled the Ticonal cylinder is magnetized by placing the entire assembly between the poles of a strong electromagnet which saturates the soft iron and the Ticonal cylinder. The resulting field in the pole gap is about 1 wb/m^2.

The magnet weighs 2.7 kg and has an outer volume $V_I = 420$ cm^3. According to eq. (10) the magnetic disturbance caused by this magnet at a distance of 4 m should be less than 10^{-10} wb/m^2 or 0.1 gamma units, provided the permanent magnetization has been compensated. At a distance of 1.5 m the disturbance is less than 1.5 gammas. Another magnet of the same shape, but only half as big, is used in the second airborne magnetometer where the field disturbance is less than 1 gamma. Here we have assumed $B_o = 5 \cdot 10^{-5}$ wb/m^2.

The liquid enters the pole gap from all sides and leaves it through the central opening at the top. On their way through the gap the majority of the protons in the liquid come in close enough contact with the surface of the iron threads to acquire immediately an equilibrium magnetization.

The Pump.

To secure a trouble-free long term operation of the apparatus it is of primary importance to have a reliable pump which does not contaminate the liquid. We have tried many different kinds with varying degree of success. For the stationary apparatus we are now using a membrane pump followed by a bellow to smooth out pressure pulses. The pump is of stainless steel with a teflon membrane and does not contaminate the liquid.

The bellow is elctrically heated. The hot liquid goes from it through a ceramic filter into the magnet. After 20 months of operation, pumping 13 cm^3/s of 50° C hot toluene against a pressure of 2 atm, the membrane had to be replaced.

In the airborne magnetometers we use small rotary pumps. In the first airborne magnetometer the pump is driven by an electric motor and in the second by an air turbine (Sigurgeirsson, 1970). They pump 5—10 cm^3/s of cold methanol against a pressure of 1—2 atm.

Tubes.

Teflon has proved to be a suitable material for the magnetometer tubing. Even at high temperatures it is not affected by any of the used liquids and it also seems to have favourable properties regarding interaction of protons in the liquid with the wall of the tube. Thus a comparison of the relaxation times for methanol at 25° C, flowing at a rate of 10 cm^3/s through tubes of nylon and teflon, gave 2.1 and 2.5 seconds respectively. Both tubes had an inner diameter of 3 mm.

The tube carrying the liquid from the magnet to the signal bottle has an inner diameter of 3 mm. In the observatory magnetometer the length of this tube is 4 m and its volume $V_t = 30$ cm^3. In the airborne magnetometers its length is about 1.5 m. The return tubes leading from the signal bottle to a reservoir for the liquid, contained in a glass flask, and from there back to the pump, have an inside diameter of 5 mm.

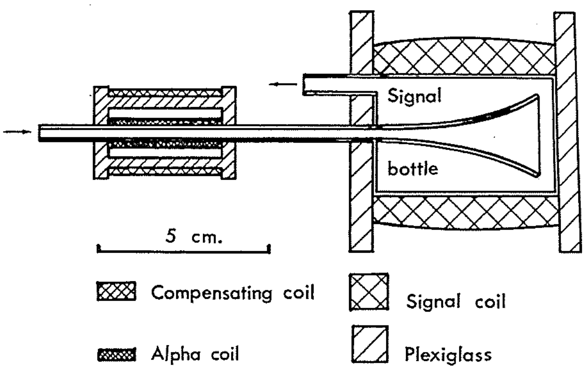

Fig. 8. The field detector.

The Signal Bottle.

The signal bottle is cylindrical in shape, 5 cm long and 3.5 cm in diameter, made of 1.5 mm thick glass. Its volume is $V_b = 44$ cm^3. The liquid enters the bottle axially through an internal funnel which reduces mixing and directs the flow through the bottle. The outlet is on top so the bottle does not collect gas bubbles. The signal bottle is shown in Fig. 8.

The Signal Coil.

The signal coil is wound directly on the signal bottle as shown in Fig. 8. It contains 5000 turns of lacquer insulated copper wire, 0.25 mm in diameter. The coil volume is $V_c = 70$ cm^3. About 55% of this volume is occupied by copper and 45% by the insulating material. The resistance of the coil is $R = 250$ ohm and the inductance $L = 0.65$ henry.

It is important to keep the signal coil free from magnetic impurities.

The Alpha-coil.

The coil contains 600 turns of thin copper wire tightly wound in two layers, either directly on the glass tube leading to the bottle or on a separate thinwalled pipe tightly surrounding the teflon tube. To eliminate direct magnetic coupling to the signal coil the alpha-coil is surrounded by a larger coil with about 30 turns. The effective number of turns is $n = 570$ as the same current goes in opposite directions through both these coils. Their position is shown in Fig. 8. The coil resistance is 20 ohm.

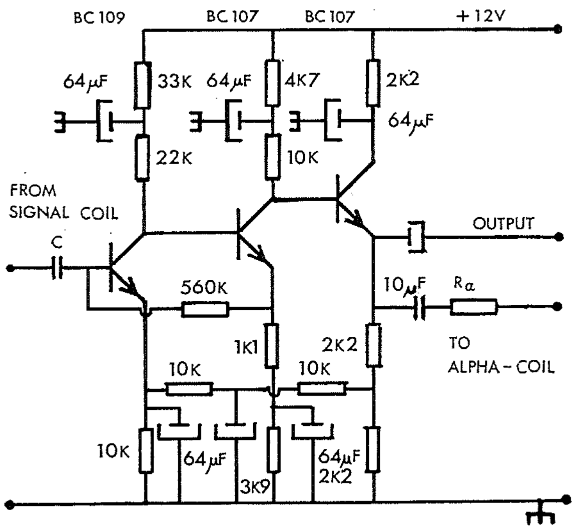

Fig. 9. The amplifier.

The Amplifier.

The amplifier consists of three resistance coupled silicon transistors. It has a voltage amplification of 1000 or 60 db. The input impedance is 4.5 kohm and output impedance 50 ohm. With the signal coil connected to the input the amplifier has a noise figure of 5 db. at a frequency of 2000 Hz.

Fig. 9 shows the diagram of the amplifier. The input condenser C is chosen so that it tunes the signal coil to a frequency corresponding to an average value of the magnetic field to be measured. At this frequency there is no phase shift in the input circuit and the output of the amplifier will supply current having the right phase for the alpha-coil if connections to the coils are made as shown in Fig. 1. The amplitude of the current in the alpha-coil is regulated by the varyable resistor R_a which normally is set to about 500 ohm.

Wide-band amplifier is used here to avoid phase shift resulting in frequency pulling. Improvement in signal to noise ratio can be achieved by reducing the frequency bandwidth in later stages of amplification.

TESTING AND PERFORMANCE OF THE MAGNETOMETER

The magnetometer has to be tested at a place with a homogeneous geomagnetic field. A place inside a laboratory will in general be unsuitable, as the gradient of field intensity should preferably be less than 10 gamma/m at the field detector. A sensitive magnetometer should be used to ensure that no magnetic material is in the neighbourhood of the signal bottle. To avoid external disturbance the field detector should be electrically shielded.

If the signal does not appear when the pump is started the following procedure is recommended:

a) Check the flow rate.
b) Disconnect the alpha-coil from the amplifier and feed it by current from an audio oscillator tuned to the proton precession frequency and giving a current amplitude in agreement with eq. (8).
c) When the proton precession signal has been found, reduce i_a to zero and increase it again until the signal reaches its first maximum. Compare the phase at the output of the amplifier and at the output of the audio oscillator. If the phase is opposite exchange the leads either to the alpha-coil or to the signal coil.
d) Load the amplifier with an impedance equal to that of the signal coil. Adjust R_a until the output current is the same as from the audio oscillator, both amplitude and phase. Connect the alpha-coil to the amplifier and the signal will remain the same.

For increased stability of operation it is advisable to set R_a to about half of the value which corresponds to maximum signal. This makes α about $3\pi/4$ instead of $\pi/2$ and reduces the signal strength by some 3 db.

Sometimes there may be large fluctuations in signal strength and the signal may even disappear for a while due to small grains of magnetic material carried by the liquid flow to the signal bottle, but this disturbance usually disappears when the pump has been operating for some time.

Table III lists the design parameters and the theoretical performance of the observatory magnetometer. It is designed for a flow of 10 cm^3/s and a time constant of 4.4 s for the liquid. Time constant for the liquid in the magnet is assumed to be 0.04 s. Methanol at 25° C is used as basis for the performance calculation.

The design parameters are close to the values listed in Table I assuming $T_t = T_b = 4.4$ s, so the

TABLE III

Design parameters and theoretical performance of observatory magnetometer.

Volume of magnet	V_I	$= 420\ cm^3$
Volume of magnetizing field . .	V_m	$= 0.5\ cm^3$
Magnetizing field intensity . . .	B_m	$= 1.0\ wb/m^2$
Volume of tube	V_t	$= 30\ cm^3$
Length of tube	l	$= 4$ m
Volume of signal bottle	V_b	$= 44\ cm^3$
Volume of signal coil	V_c	$= 70\ cm^3$
Relative copper volume in signal coil	a	$= 0.55$
Resistance of signal coil	R	$= 250$ ohm
Self inductance of signal coil . .	L	$= 0.65$ henry
Liquid flow rate	Q	$= 10\ cm^3/s$
Pressure drop in magnet	p_m	$= 1.3$ atm.
Pressure drop in tube	p	$= 0.4$ atm.
Nuclear susceptibility of liquid (Methanol at 25° C)	χ	$= 2.9 \cdot 10^{-3}$ Am/wb
Time constant of liquid	T	$= 4.4$ s
Number of turns in alpha-coil	n	$= 570$
Current amplitude in alpha-coil (for $\alpha = 3\pi/4$)	i_a	$= 33\ \mu A$
Calculated signal from coil . . .	e	$= 17\ \mu V$ rms
Amplifier voltage gain		60 db
Amplifier input impedance . . .	R_i	$= 4.5$ kohm
Amplifier noise factor		5 db
Signal to noise ratio at the output of a second amplifier with a bandwidth of 200 Hz		50 db
Error due to frequency pull . .	ΔB	$= -1.0 \cdot 10^{-4} \cdot \delta B$
Field disturbance from the magnet		$\Delta < 0.1$ gamma

expression for e_s given in the table or eq. (19) can be used for theoretical calculation of the signal amplitude. With $B_o = 5 \cdot 10^{-5}\ wb/m^2$ and $\sigma = 5.7 \cdot 10^7\ ohm^{-1}\ m^{-1}$ we get $e_s = 34 \cdot 10^{-6}$ V. This is the maximum amplitude corresponding to $\alpha = 90°$ but here i_a is chosen so that we get $\alpha = 135°$. This reduces the signal by a factor sin α and we get an amplitude of 24 μV or the r.m.s. value e = 17 μV. The output of the amplifier is then 17 mV r.m.s.

The theoretical r.m.s. value of thermal noise from the coil is $e_n = (4\ Rk\ T \cdot \Delta\nu)^{1/2}$ where k is Boltzmann's constant, T the absolute temperature and $\Delta\nu$ the width of the frequency band occupied by noise oscillations. Assuming this bandwidth to be 200 Hz we get $e_n = 2.9 \cdot 10^{-8}$ V and the signal to noise voltage ratio is $e/e_n = 590$ or 55 db. At the output of the amplifier the ratio is reduced to 50 db due to additional noise created in the amplifier.

Actually, the bandwidth of the system is much more than 200 Hz and should not be cut down for reasons to be mentioned later. At the output of the amplifier the signal to noise ratio is therefore considerably lower than the calculated value, which corresponds to what we get after the signal comes through a filter with a bandwidth of 200 Hz. The filtering is easily done in later stages of amplification. A bandwidth of 200 Hz corresponds to a magnetic field variation of 4700 gamma and should be sufficient to cover all magnetic storms.

With the prescribed flow of 25° C hot methanol the measured signal is only about one third of the calculated value. The main cause of the discrepancy seems to be a time constant for the methanol considerably shorter than 4.4 s which was assumed on the basis of Table II. Thus measurements of the time constant based on varying the length of the tube only gave 2.5 s. Using the corresponding $V_o = 25\ cm^3$ in eq. (4) and (5) and introducing the obtained value for M_b in eq. (19) brings the calculated signal strength in fair agreement with the measured value, although the theoretical value is still about 30% higher.

We have seen that our magnetometer does not comply with some of the assumptions of Table III and that its performance is inferior to expectation. A further study is needed to find the reason for this. However, the performance can be improved by raising the temperature. At 65° C the signal strength corresponds approximately to the value given in Table III.

ACCURACY

If a long time is available for the measurement, as f.inst. when hourly mean values of magnetic field intensity are measured, the signal frequency can be measured to a very high precision. This, however, does not represent the accuracy of the field determination.

In the first place the ratio between magnetic field intensity and proton precession frequency is only known with a certain degree of accuracy and may vary slightly from one liquid to another due to diamagnetic shielding of the protons (Laukien, 1958), but this will not be discussed here.

Secondly the magnetic field disturbance in the signal bottle due to the magnet will limit the accuracy of the measurement. This is evaluated in eq. (10).

A third possible cause of inaccuracy is that the signal frequency may deviate from the proton precession frequency. This happens if the precessing magnetization, $\mathbf{M}_1$, of the liquid entering the signal bottle is not in phase with the mean magnetization, $\mathbf{M}_b$, of the liquid inside the bottle.

Suppose that $\mathbf{M}_1$ is a small angle $\Delta\varphi$ ahead of $\mathbf{M}_b$ in the precessing rotation. We decompose $\mathbf{M}_1$ into a component, $M_1 \cos\Delta\varphi$, parallel to $\mathbf{M}_b$ and another component, $M_1 \sin\Delta\varphi$, perpendicular to $\mathbf{M}_b$. The parallel component maintains the size of $\mathbf{M}_b$ while the perpendicular component contributes to its rotation. Equation (5) is only valid if all magnetization inside the signal bottle has the same direction so here we get

$$M_b = M_1 \left(1 - \exp\left(- V_b/V_o\right)\right) \cdot \left(V_b/V_o\right)^{-1} \cdot \cos\Delta\varphi$$

The contribution of the perpendicular component to the angular velocity of $\mathbf{M}_b$ is

$$\Delta\Omega = QM_1 \sin\Delta\varphi / (V_b M_b) = \frac{tg\,\Delta\varphi}{T\left(1 - \exp\left(- V_b/V_o\right)\right)}$$

The outflowing liquid can also influence the rotation if its magnetization is not parallel to $\mathbf{M}_b$ but we assume that this influence is negligible.

The signal will have the angular frequency $\Omega = \Omega_o + \Delta\Omega$ where Ω_o is the proton precession frequency. Using the signal frequency instead of the true precession frequency results in a magnetic field intensity $B = \Omega/\gamma = B_o + \Delta B$. The error in the field determination is

$$\Delta B = \frac{tg\,\Delta\varphi}{\gamma T\left(1 - \exp\left(- V_b/V_o\right)\right)} \qquad (20)$$

One cause of the phase difference is misalignment of the alpha-coil relative to the signal coil. An angle between the axes of these coils (in the plane of precession) will cause the same phase difference between $\mathbf{M}_1$ and $\mathbf{M}_b$. In a properly designed field detector this angle can be kept within 1°, causing in our case an error of less than 0.03 gamma.

Another cause of phase difference is a phase shift in the electronic circuit conducting the signal from the signal coil to the alpha-coil. The phase shift in the amplifier itself and in the alpha-coil circuit is negligible. The signal coil with its internal resistance, the input condenser and the input impedance of the amplifier, all in series, will give a phase shift if this circuit is not tuned to the precession frequency. By adjusting the input condenser the circuit may be tuned to a frequency, $\Omega_a = \gamma B_a$, corresponding to the average field to be measured, so that the phase shift is less than 1°. If, however, the magnetic field changes to a value $B = B_a + \delta B$ this results in a phase shift given by

$$tg\,\Delta\varphi = -2L\,\delta\Omega / (R + R_i) = -2L\gamma \cdot \delta B / (R + R_i)$$

where L is the self inductance and R the resistance of the coil and R_i is the resistive input impedance of the amplifier. The phase shift is opposite the frequency variation and causes a frequency pull towards the tuning froquency. According to eq. (20) the resulting error in the magnetic field determination is

$$\Delta B = - \frac{2L}{T(R + R_i)\left(1 - \exp\left(- V_b/V_o\right)\right)} \cdot \delta B \qquad (20')$$

Inserting the numerical values from Table III we find

$$\Delta B = -1.0 \cdot 10^{-4}\,\delta B$$

Thus a field deviation of 1000 gamma from the average will cause an error of 0.1 gamma in the measurement.

A field gradient, dB/dx, between the alpha-coil and the signal bottle will also produce a phase difference $\Delta\varphi = \gamma\,(dB/dx)\,x_1^2 / 2v$ where x_1 is the distance between the alpha-coil and the bottle and v is the velocity of the liquid. However, this will not be important under typical observatory conditions.

The effect of an inhomogeneous magnetic field is not going to be treated here. We only mention that it shortens the effective time constant for the liquid inside the bottle and reduces its magnetic moment as phase differences arise between different parts of the liquid. (Laukien, 1958). In an inhomogeneous field the signal frequency will correspond to the field intensity at some point inside the signal bottle.

Our conclusion is that the magnetometer offers a possibility to measure the magnetic field with an accuracy of about 0.1 gamma, provided that the ratio between field intensity and precession frequency in the liquid is known with sufficient accuracy.

ACKNOWLEDGEMENTS

Many individuals have participated in the present study and much of the practical work has been carried out by students. In particular I should like to thank Dipl. Phys. Þorsteinn Halldórsson and Dipl. Ing. Björn Kristinsson for their active participation in developing the magnetometer. The electronic equipment has been tested by Vilhjálmur Þ. Kjartansson. All drawings are made by Marteinn Sverrisson.

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