**Laser Physics, v.6, no.2, p.244-251 (1996)**

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# Double-resonance atomic magnetometers: from gas discharge to laser pumping.

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**Abstract**

*The ultimate resolving power of the atomic frequency discriminator based on ESR of optically pumped potassium atoms was studied in quest of the best version of a Zeeman Earth field magnetometer. A perfectly resolved single line as narrow as 1 Hz was realized at signal-to-noise ratio not less than $10^4$ within pass-band from 0.001 to 1 Hz, providing the ultimate short-term sensitivity better than 10 fT/Hz$^{1/2}$. Laser pumping provides ~2 times better ultimate short-term resolution and a number of other technical advantages. The main source of systematic errors was found to be light induced resonance frequency shifts which was studied under laser pumping versus wave-length. The base line stability of the stationary installed magnetometer is expected to be of about 10 pT under lamp excitation and can be made much better in case of properly wave-length adjusted laser pumping. Though expected tilt-errors up to 0.1 nT can not be circumvented by laser pumping, they can be greatly suppressed in gradiometric mode of magnetometers application when two or more identical sensors are mounted on the common rigid frame.*

## 1. Introduction.

Measurements of magnetic fields with highest resolution become of great interest for many branches of basic and applied research. For instance, fundamental problem of upper limit of the neutron's electric dipole moment rests now on the accessible magnetic field stability. To surpass the present restriction it is necessary to provide the magnetic field resolution better than 1 pT within the pass-band 1Hz for accumulation time of about 100 sec. One of the most serious problem of magnetic prospecting is the problem of Earth's magnetic field variations. These variations can be effectively suppressed in the gradiometric mode of measurement, when at least two magnetometers are used separated by a fixed base. However, to meet the requirements of modern practice under condition of a restricted base length compatible with the on-board application, the resolution of the sensors should be better than 100 fT.

This order of sensitivity and even higher (better than 10 fT/Hz$^{1/2}$ r.m.s.) can be achieved with the use of modern optically pumped magnetometers (OPM) which are the subject of this paper. Such tremendous sensitivity is about 100 times higher than that revealed by commercial OPMs and about ten times better than the record sensitivity of the so-called Hanle magnetometer first demonstrated by the French group [1] a quarter of century ago. The Hanle magnetometer however, can detect only very weak field within the range limited by Hanle linewidth which was about 0.1 nT in [1]. In fact, it is a component magnetometer with analogue output which needs a calibration procedure. Unlike the Hanle magnetometer, the OPM using the effect of magnetic resonance measures the absolute magnitude of the magnetic field vector in a wide range of magnetic fields. In particular, the Potassium Narrow Line OPM

most effectively measures the module of a field stronger than 10 μT, with its resolution being independent of a field strength.

## 2. The main direction of efforts.

Below we give only a brief description of basic principles of the OPM operation. For more details see for example reviews [2] and references therein.

The atomic resonance magnetometers belong to the family of instruments based on Zeeman effect, the most known of them being proton precession magnetometer. They measure the frequency of a magnetic-dipole transition between magnetic sublevels of the ground or a metastable state of some polarized paramagnetic particles. The values of this frequency is related to scalar value of magnetic field via the relationship known from the theory or from experiment.

The magnetometer sensitivity defined as the smallest noticeable deviation $\Delta H_{min}$ of the magnetic field magnitude limited by the intrinsic noise of the device within a given frequency band is given by the obvious formula:

$$\Delta H_{min} = k\Gamma/(\gamma S_n), \qquad (1)$$

and is determined by three key terms:
*i*) by the frequency-to-field ratio γ (the frequency-vs-field dependence, in fact, is not always linear, but nonlinearity is usually extremely small as compared with the dominant linear term and, anyway, has nothing to do with the ultimate sensitivity);
*ii*) by the magnetic resonance line-width Γ;
*iii*) by the signal-to-noise ratio $S_n$ which is in turn proportional to total number of the particles N in the sample and to the polarization *p*: $S_n = \varepsilon p N$, where ε is a parameter, reflecting efficiency of monitoring method. (k in (1) is the form-factor which is of the order of unity).

While conventional proton magnetometers use a condensed medium of nuclear paramagnet, taking advantage of very high N and small Γ (with disadvantage of small γ and $p<<<1$), the atomic-resonance magnetometers use gas-filled sensors with about $10^{10}$ fewer particles but, in reward, three orders of magnitude higher γ and with dramatically higher product ε*p*. The change in the latter term is due to radical change of the methods of sample polarization and magnetic resonance monitoring. Conventional technique involves direct magnetic polarization and resonance monitoring through the absorption or emission of RF power by the sample. This technique, however, can not be applied to gases because of their low density. The atomic systems became competitive with condensed paramagnets after invention of Optical Pumping - Double Resonance method by A.Kastler and J.Brossel [3] which made it possible to achieve high magnetic polarization of the vapor (close to $p=1$) by means of optical pumping and to monitor with ultimate efficiency the RF-induced transitions via optical channel.

The OPM measures the resonance frequency of the induced magnetic-dipole transition between sublevels of some long-living atomic state with pure spin (electronic and/or nuclear) magnetic moment. This allows one to realize a long relaxation time of the magnetic moment and thus a narrow resonance line.

Speaking of OPM, we will characterize it by resolution $\Delta H_{min}(t)$ defined as the smallest distinguishable magnetic field excursion equal to root-mean-square random deviation of the instrument readings normalized to the pass-band of 1 Hz and averaged over the time interval t .There are several sources of noise limiting the OPM sensitivity. The influence of disturbing factors can be restricted to some extent by proper choice of measuring mode or of the measuring time. To begin with, each magnetometer reveals spurious variation of reading being

rotated even in perfectly uniform magnetic field. These tilt-errors are of crucial importance for on-board applications of magnetometer and are worthy of keen attention. We will assume below that the instrument is fixed in space.

Other sources of OPM errors can be divided into two groups. The first one contains only one fundamental source of noise - the shot-noise of a primary photo-detector. This noise limits the accuracy of localizing the resonance curve center. This noise is characterized by "white" spectrum, having equal spectral density at each frequency. This noise source produces no systematic errors.

The second group includes many different sources of systematic errors. Their nature is partly connected with parametric shifts of the resonance line under the influence of a number of factors including unavoidable effect of the measurement procedure upon the atoms. Spectral density of the corresponding random processes decreases rapidly with frequency and becomes smaller than that of the shot noise at a frequency $f_L$ of the order of 0.001 Hz. In other words, the parametric shifts are as a rule perfectly stable within the time intervals shorter than several minutes. So, it makes sense to introduce the ultimate "short-term resolution" (or "short-term sensitivity") $\Delta H_{min}$ revealed for accumulation times t <100 s and limited only by the photo-detector shot-noise. Longer observation reveals slow drift of the instrument reading. It is natural to refer to the value $\Delta H_{min}(\infty)$ at very long t as to the base line stability (or long-term resolution) .

The choice of one or other sort of atoms and type of OPM depends on priorities of measurement. The highest short-term sensitivity can be realized today using alkaline atoms. Alkaline vapors were historically the first object of optical pumping. Their optical absorption lines are located in the convenient visible and near infrared regions and three of them (Cs, Rb and K) have well resolved fine structure of the principle optical resonance $n^2S_{1/2}$ - $n^2P_{1/2,\ 3/2}$ making it easy to select the $D_1$ line most efficient for optical pumping. At the same time their magnetic resonance spectrum is very complex that creates problems for applications. The RF spectrum of any alkaline atoms consists of a number of closely spaced lines with separation depending on the magnetic field strength. Their overlap produces an uncertainty in true resonance position, the value of this uncertainty being dependent on the ratio between the line splitting and the line width. Two favorable asymptotic situations might be aspired:
i) when the line splitting is much less than the width of each line and all the components merge, producing a single strong almost symmetric line; ii) when the line width is much smaller than the splitting and one can deal with a single isolated component.

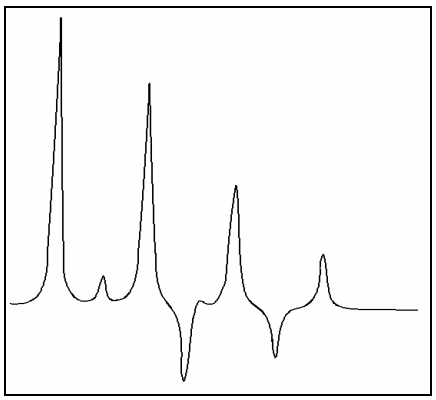


*Fig.1 RF spectrum of induced magnetic coherency of optically oriented $^{41}K$ atoms*

The situation close to the first one is realized in Cs vapor, where the line splitting is about 7 Hz in the average Earth's field 50 μT. Since the width of each component is usually ~50 Hz, the resonance absorption is characterized by a nearly symmetric composite line. Cs-OPMs are the most popular magnetometers. They have a good short-term sensitivity (about 1 pT) but their base-line stability never exceeds 1 nT even for most sophisticated versions [4], an ordinary instruments having errors of the order of 10 nT within the Earth's magnetic field range.

The opposite asymptotic situation can be realized with much more perfection using potassium atoms. Having the smallest hyperfine splitting of the ground state, they reveal well resolved RF spectrum starting from sub-Earth magnetic fields. Fig. 1 shows the RF spectrum of induced magnetic coherency of optically oriented $^{41}K$ atoms recorded at the fixed driving frequency 82 kHz, magnetic field being swept in the vicinity of 12μT. Four strong

positive peaks are attributed to F=2, $|\Delta m_F|=1$ transitions, two weak positive peaks correspond to the two strongest transitions of the same nature of admixing atoms of $^{39}K$, while the negative resonances are related to F=1, $|\Delta m_F|=1$ transitions of $^{41}K$. (Other components of the spectrum are too weak to be attributed under used resolution).

The line used in practice is the most isolated line F=2, $m_F=2 \Leftrightarrow m_F=1$, its resonance frequency $\nu_{21}$ being related to the magnetic field strength H by the expansion (true for any alkaline atom with nuclear spin 3/2) of the well known Breit-Rabi formula:

$$\nu_{21} = \gamma H - 3\gamma^{(2)}H^2 + 6\gamma^{(3)}H^3 - \ldots \qquad (2)$$

The resonance frequency $\nu_{10}$ of the nearest adjacent transition F=2, $m_F=1 \Leftrightarrow m_F=0$ is given by the same linear term but differs in higher-order terms:

$$\nu_{10} - \nu_{21} = 2\gamma^{(2)}H^2 - 12\gamma^{(3)}H^3 + \ldots \qquad (3)$$

$\gamma = f_j + f_i$ ; $\gamma^{(2)} = f_j^2/\Delta_{hfs}$ ; $\gamma^{(3)} = \gamma^{(2)}f_j/\Delta_{hfs}$ ; $f_i = g_i m_B/h$; $f_j = (g_j - g_i)m_B/h$

Here $g_j$ and $g_i$ are electronic and nuclear g-factors, $\Delta_{hfs}$ - zero-field hyperfine splitting of the ground state, $m_B$ is the Bohr magneton, h is the Plank constant. Admitting

$m_B/h = 1.39962575(48)\cdot 10^{10}$ Hz/T [5]

and potassium constants [6] for $^{39}K/^{41}K$:

$g_j = 2.00229421(24)$; $\Delta_{hfs} = 0.461719702/0.254013872$ GHz;

$g_i = -(1.4193489/0.7790600)\cdot 10^{-4}$ , we find:

$\gamma = [7.0046664(35)/7.0053385(35)]\cdot 10^9$ Hz/T;
$\gamma^{(2)} = (1.06327/1.93257)\cdot 10^{11}$ Hz/T$^2$; $\gamma^{(3)} = (1.6135/5.3306)\cdot 10^{12}$ Hz/T$^3$;

The absolute accuracy of $\nu_{21}(H)$ relation is limited first of all by uncertainty of material and fundamental constants $g_j$ and $m_B$.

The idea to use potassium in OPM rather than any other alkaline metal vapor is far from being the new one. The first application of potassium as a working medium for OPM is known since 1964 [3]. Still we do not think that all advantages of potassium were completely used. Analyzing the ultimate resolution of atomic frequency discriminator [7], we came to conclusion that potassium is the best element for OPM when the combination of the highest short-term sensitivity with high enough base-line stability is of interest. The greatest (among alkaline atoms) separation of adjacent RF resonances in potassium removes the problem of inter-resonances interference. As to its sensitivity, analysis of the relation (1) shows that as far as the photo-current shot noise remains to be the dominant source of fluctuations, the ultimate sensitivity $\Delta H_{min}(t)$ is proportional to $\Gamma_0^{1/2}$, where $\Gamma_0$ is the asymptotic line width of magnetic resonance as the pump light intencity approaches zero. At the same time the most significant systematic errors of OPM are proportional to $\Gamma_0$ or to $\Gamma_0^2$. So, the concept of "super-narrow" line became the main in our quest for super-magnetometer“. It should be noted that striving for an anomalously narrow line, we make at the same time a choice of general arrangement of OPM in favor of so-called $M_x$-system based on registration of transverse precessing magnetization $M_\perp$ [4]. Unlike $M_z$-system, it does not use frequency modulation of the driving RF field which would have been unrealistically slow in case of "super-narrow" line.

## 3. Line width of the potassium magnetic resonance and its ultimate resolution.

The line width $\Gamma$ is limited by the decay time $T_2$ of atomic RF-coherency or of transverse magnetization $M_\perp$. The regular (precessing) motion of atomic spin is broken down first of all by collisions of the potassium atoms with the cell walls. Two kinds of spin-preserving technique are widely known: with buffer gases and with inert coating of the cell walls. In the first case the spin-polarized atoms diffuse through specially selected atomic or molecular gas with a very low spin-relaxation cross-section. In the second case atoms freely fly from wall to wall which are covered by a special film, which provides extremely short resting time on the wall. Both approaches have their merits and problems. The main advantage of the first approach is associated with its technological simplicity and reproducibility. The second approach, although used for more than three decades, still keeps some feature of the "black magic". It does, however enable one to realize much narrower line width. The additional important advantage of a coated cell is related to the effect of motional narrowing of the magnetic resonance line: the sensor is to some extent insensitive to an inhomogeneity of magnetic field within the sensor volume. So, we concentrated our efforts along the line of coated cells.

Fig. 2 shows the set-up used for measuring the potassium magnetic resonance line width and its ultimate resolution. It comprises an ordinary one-beam $M_x$-scheme of optical pumping placed in stabilized magnetic field of variable strength. The stabilizer consists of large coil system with a self-oscillating Cs-OPM inside. It allows to limit magnetic field variations to within several pico-Tesla for interval of tens minutes.

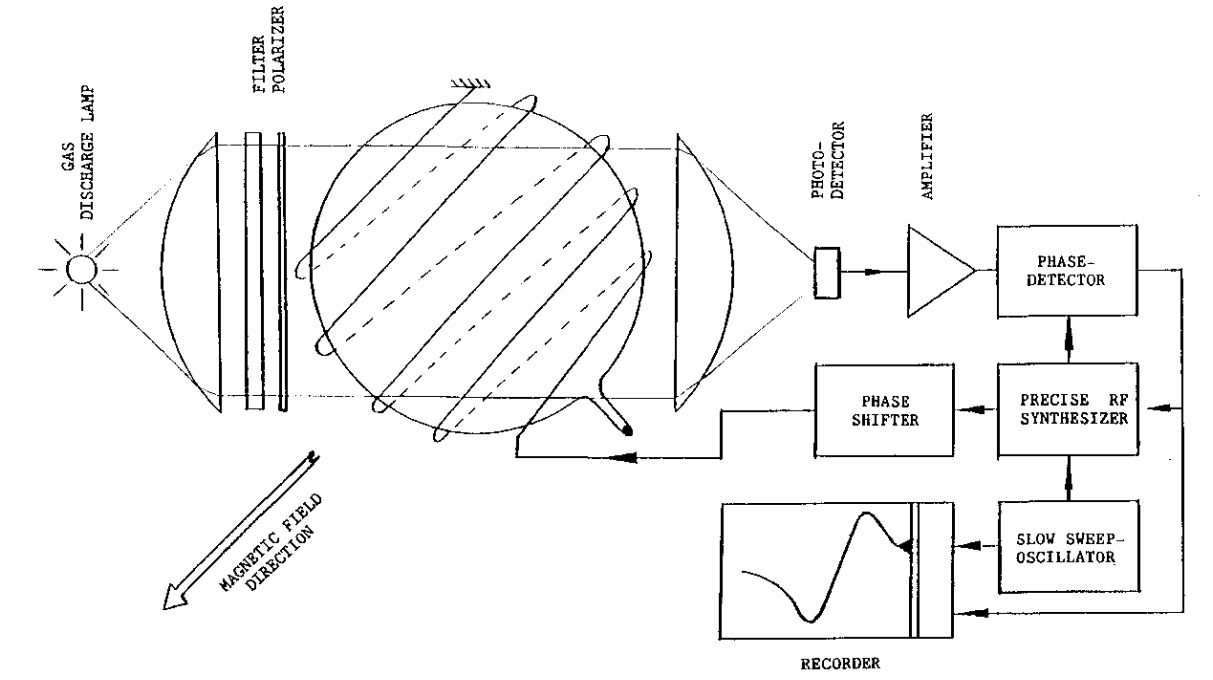



*Fig.2. Set-up used for measuring the potassium magnetic resonance line width and its ultimate resolution*

Resonance line was recorded using lock-in technique of $M_\perp$ detection: the pump light after passing the cell acquired amplitude modulation on the frequency of the driving RF- field. The corresponding signal of a photo-detector was led to the phase detector with the reference signal from the local RF-oscillator which fed RF-field inductor. The output signal as a function of the RF frequency gave a resonance line contour. Its shape depends on phase of the reference signal. While studying line width, the phase was adjusted to get the line in the dispersion-like

form. The line width Γ was assumed to equal the half frequency interval between two symmetric extrema of the line in the limit of very weak RF-field.

Fig. 3 shows the measured Γ as a function of pumping light intensity for spherical cell ∅15 cm at three different temperatures. Fig. 4 presents the function Γ(T) under very low intensity of pump light $I \Rightarrow 0$. Temperature broadening of the line is connected with the spin-exchange collisions.

As it follows from Fig. 3, the ultimate width $\Gamma_0$ is about 10 pT. It is predominantly related to the wall relaxation, all other ones being much less. Of course, there is an obvious way to unlimited narrowing of resonance line by simple increase of a cell dimension, because ultimate relaxation time (limited only by surface relaxation) is proportional to the cell dimension.

The realization of the smallest line width $\Gamma_0$ is possible only at very small signal intensity because of substantial reduction of pumping light intensity and vapor density. This regime is favorable to achieve the highest absolute accuracy. But if the highest resolution is wanted, the light intensity and potassium concentration should be greatly increased, the price being a corresponding line width increase. Since the resolution depends on both the signal strength and the line width (1), a certain compromise has to be reached. The problem is too complicated to be solved analytically. We used semi-empirical method based on considerations of our work [7]. They, in particular recommend to use unusually low pumping intensity and the vapor density.

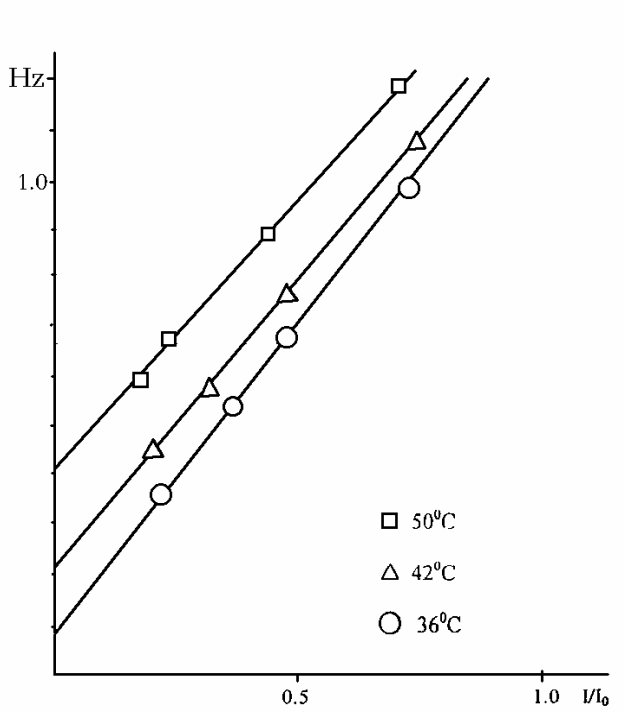



*Fig.3. G as a function of pumping light intensity*

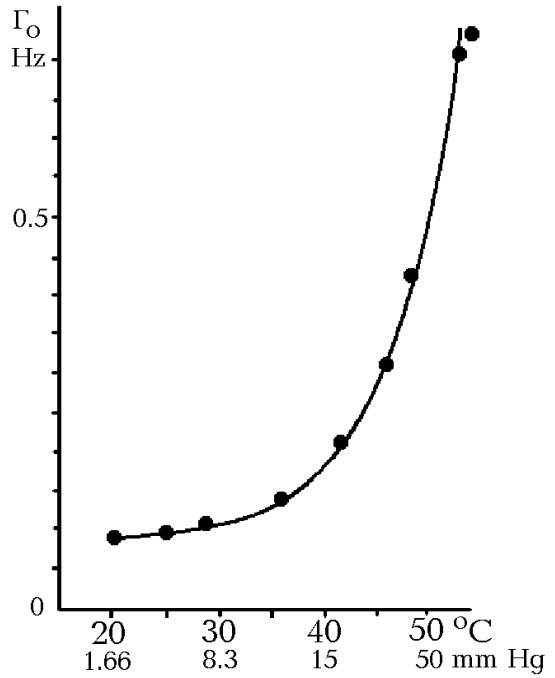



*Fig.4. G as a function of cell temperature under very low intensity of pumping light*

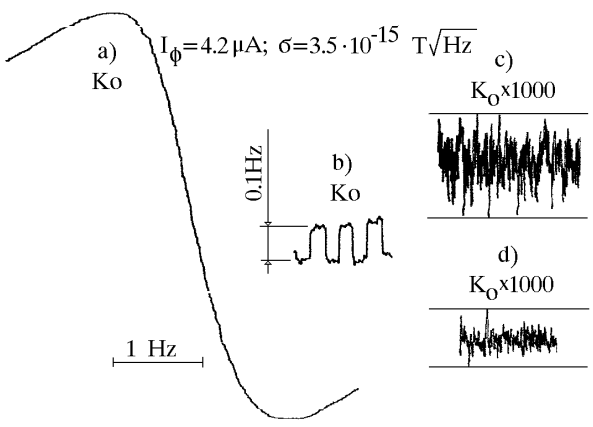
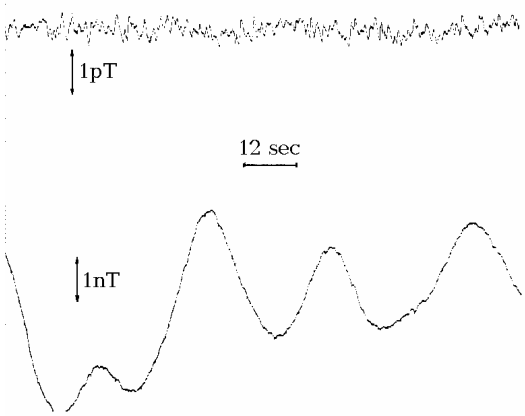


Fig. 5 illustrates the procedure of the ultimate resolution evaluation. The left trace (*a*) represents the central part of the strongest resonance line of potassium RF spectrum. The resonance was recorded by scanning the frequency of local oscillator in the vicinity of resonance. The visible noise of record originates from residual magnetic field instability. The resonance curve is twice broadened by the optimal RF-field saturation. The central part *b* of Fig. 5 shows the signal produced by meander excursions of reference frequency with amplitude 0.1 Hz. To estimate the intrinsic noise of this magnetometer model the RF field was switched off and amplification of the signal channel was 1000 times increased. The trace *c* gives an example of ~ 1 minute noise record. Peak-to-peak amplitude of noise is about 43 fT at integration time of 0.1s. It corresponds to the r.m.s. value of about 5.7 fT/(Hz)$^{1/2}$. The lowest noise trace *d* was recorded when the ight was switched off. This record demonstrates the contribution of an excess noise from electronic equipment which is low enough, decreasing the final resolution only by the factor of 1.2 as compared with the intrinsic resolution of the resonance (4.7 fT/Hz)$^{1/2}$.

*Fig. 5. The procedure of the ultimate resolution evaluation*

This experiment demonstrates the potential ability of atomic frequency discriminator. The practical realization of this ability is not an easy technical problem. One of the most obvious difficulties is connected with necessity to measure frequency with highest accuracy. The field resolution 10 fT corresponds to $0.7 \cdot 10^{-4}$ Hz frequency resolution. For Earth magnetic field it corresponds to the reference oscillator stability of around $10^{-10}$. It is very high though technically reasonable stability. In any case, this problem requires a careful attention.




The instrument realization of commercial potassium "super-magnetometer" is now being under development in GEM-Systems (Richmond Hill, Ontario)[1]. Fig.6 shows an example of short-term sensitivity test of one of the first instruments. The trace in the bottom shows the record (at 10 readings per 1 sec) of fast pulsation of the Earth's magnetic field in the Toronto region on July 27 1995. The upper trace displayed the difference of the two instruments reading, their sensors being separated by 2.5 m. One can see that the magnetic field variations turned out to be highly correlated at these two points, the difference being stable within 1pT. It means that root-mean-square deviation estimated for one instrument does not exceed 100 fT. But the nature of the remaining noise is not fully clear. It may include the magnetic gradient noise as well as the counting system noise. The contribution of the last one was evaluated as 100pT peak-to-peak.

*Fig.6. An example of short-term sensitivity test made using commercial potassium "super-magnetometer" by GEM-Systems*

## 4. On the laser pumping of potassium.

Laser pumping is widely considered as an obvious step towards more advanced OPM. These expectations are fully motivated relative to helium OPM, because only laser permits to excite selectively the single $D_0$ line of the triplet $2^3S_1$ - $2^3P_{0,1,2}$ with a great gain in pumping efficiency [8, 9], but they are justified only partly with respect to potassium. Computer

[1] Our colleague V.A.Bonch-Bruevich takes part in elaboration of the instrument sensor construction.

simulation [10] predicted only a modest (not more than twice) increase of resolution due to laser pumping: the single $D_1$ line excitation of potassium is accessible using an ordinary discharge lamp with interference filter, so that the gain in sensitivity arises only from the more efficient monitoring interaction of K absorption spectral line with much more narrow laser line. But lasers promises other pure technical advantage: the usage of laser makes it possible to send light to and from the sensor by means of fiber light-guides of almost unlimited length with obvious merit of reducing of the equipment magnetic influence. It also opens the prospects of gradiometer network development with many sensors pumped by a single laser source.

Two main problems should be solved to provide effective laser pumping: the frequency stabilization of laser light at the center of potassium $D_1$ line (769.9 nm) and suppression of the excess amplitude noise which is typical for laser sources.

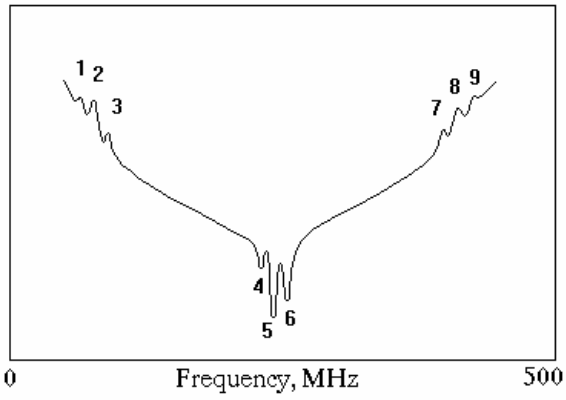



*Fig.7. Potassium Doppler-free saturated absorbtion spectrum of D1-line*

We succeeded in solving these problems using an extended cavity diode laser with external cavity[2]. To stabilize the laser frequency we used a narrow Doppler-free resonance of saturated absorption in an additional uncoated vapor cell $^{39}K$ [11, 12]. Two counter-propagating laser beams of almost the same intensity were sent through the cell and the absorbtion was detected in one of these channels. The typical Doppler-free spectrum for K (Fig.7) is more complicated than those for Rb and Cs [13] since both hyperfine splittings of the ground and first excited states are smaller than the Doppler width. The absorption dips appear due to the velocity-selective hyperfine pumping, while the peaks (which are cross-overs combining transitions from different sublevels of the ground state) result from resonant compensation of the optical pumping within the ground state hyperfine sublevels. The strongest peak at the line center (number 5, the "four level cross-over" [10]) was selected for stabilization of the laser frequency.

The excess amplitude noise of diode laser was attributed entirely to diode current fluctuation]. Both active and passive stabilization of the laser current have been applied to suppress the excess noise. The requirement for such suppression turned out to be quite reasonable in case of optical pumping of potassium: very narrow magnetic resonance line corresponds to low pumping intensity with a rather pronounced shot-noise.

The ultimate resolution under laser pumping has been measured using the same procedure as before: a discharge lamp at Fig.2 has been substituted by the end of laser excited light-guide (in fact, both measurement were made in one run). The laser light intensity was adjusted to reach the same width of the resonance. This intensity turned out to be ≈ 1.5 less which is natural because of much more narrow line width of laser. It lead to higher contribution of the back-ground noise of electronics. After its excluding, we get 2.7 times better ultimate sensitivity (about 1.8 $fT/Hz^{1/2}$) than that under lamp pumping. The gain turned out to be somewhat more than it was expected [10]. It could be attributed to non-optimal regime of the gas discharge lamp. But in fact, it demonstrates the additional advantage of laser pumping: it is always optimal as long as it is correctly tuned and not noisy.

[2] This part of the work was made in cooperation of the team of V.L .Velichansky (*the Institute of General Physics, Moscow*), which provided us with the very stable and compact tuned diode laser.

## 5. On systematic errors of a „super-magnetometer“.

The measured ultimate short-term resolution of potassium OPM must be realized in stationary measurement mode. Any on-board application will immediately meet the tilt errors problem. A direct experimental investigation of the problem is very difficult at sub-picaTesla level of sensitivity, requiring extremely uniform magnetic field. But almost all constituents of the combined tilt error can be evaluated without real instrument rotation.

In the extended list of the systematic errors the so called light-induced shifts greatly dominate (when the most important source of errors for alkaline metals - the interference of unresolved spectrum components - is suppressed).

Pump light shifts resonance line due to two different effects [3]. The first one is the optical Stark effect [14] proportional to the light intensity. Its frequency dependence is an odd function of the optical resonance detuning, so that pumping by a symmetrical spectral line centered at the absorption line do not produce any Stark shift. But in practice there is always some asymmetry of excitation, producing a residual shift. The natural scale of this shift is the resonance width Γ. The sign and value of the shift depends on many factors (like a cell optical density, an operation regime of a gas discharge lamp, the pumping light direction relative to the magnetic field), being as a rule not more than ~10% of light contribution to the line width $\Gamma_{light}$. For the line width ~1Hz it attains ~ 10pT.

The second contribution to the light shift is connected with the difference between Larmor precession frequencies of atoms in the ground and excited states. It is the so-called “coherency transfer effect” [15]. This part of the light shift is also linear to the light intensity. But its sign is definite (and negative for any alkaline atoms). The value of the shift is proportional to the magnetic field strength and depends on the pumping light direction. In practice this shift also amounts a part of $\Gamma_{light}$.

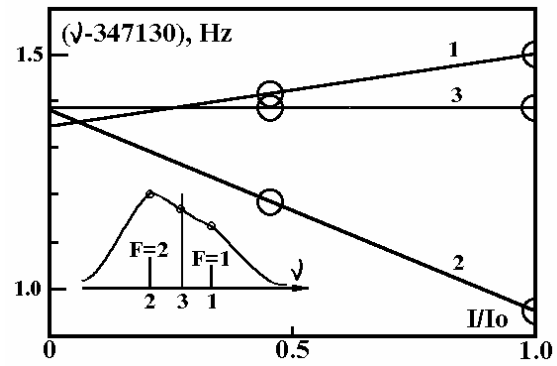



*Fig.8. $^{39}$K light shifts versus pump intensity. Three lines correspond three pumping light wavelengths.*

Fig.8 gives an experimental illustration of the light shifts versus pump intensity in case of laser pumping of $^{39}$K at $45^0$ between the pumping light beam and magnetic field direction. The intensity $I_0$ corresponds to about twice of the optimum intensity (providing the greatest short-term resolution, see Fig.10). The inset of the figure contains the calculated $D_1$ absorption line shape where three laser frequencies positions are marked. Being tuned to the position 2, that is to the center of the strongest hyperfine absorption component $4^2S_{1/2}$ (F=3/2) - $4^2P_{1/2}$ (F'=1/2, 3/2), the laser light produces no Stark shift, and the revealed frequency shift should be attributed to coherency transfer. At the position 3 almost perfect compensation of the two types of light the shifts takes place, and when laser is tuned to the weak hyperfine absorption component (frequency position 1) the Stark component of the light shift predominates. (In this particular experiment the frequency of the resonance $m_F = -2 \Leftrightarrow m_F = -1$ was measured).

Under lamp pumping, the Stark component of the light shift is about 10 times reduced while the coherency transfer contribution remains unchanged, being predominant. Its maximum value under the optimum intensity is about
30 pT and it is the most important source of systematic error.

All other sources of systematic errors contribute at the level of about 1 pT. It makes sense to mention specially the problem of “temperature shift“ of K-OPM readings which is very significant for an ordinary alkali-atoms OPM. The narrow-line K-OPM is in fact almost completely free of any temperature dependence. Direct investigation of a very small residual temperature shifts is hampered by slowness of such measurements and can be masked by long-term drifts and first of all by magnetic field instability. We observed small thermal effect, using special cell (d=85 mm) with the fifty-fifty mixture of the two isotopes $^{41}$K and $^{39}$K. Atoms of both isotopes "feel" the same magnetic field and any temporal variation of the latter can be completely excluded. The simplest approach consists in measuring the difference $\delta\Im$ of the principal resonance frequencies of the two isotopes which is 3000 times less sensitive to magnetic field than each frequency separately. But this difference can reveal some parametric frequency shifts not necessary equal for both isotopes. Fig. 9 shows $\delta\Im$ as a function of time when the heater of the cell was turned off. During 55 minutes the temperature dropped from $45^0$ to $30^0$ C, which was accompanied by a decrease of resolution and by deviation of $\delta\Im$ within 0.007 Hz (~1 pT). The experiment was carried out in stabilized field, so that any magnetic origin of the shift was out of question. It should be attributed to light shifts: both isotopes were excited by light of $^{39}$K lamp which is spectrally shifted by about half Doppler width relative to the center of the absorption line of $^{41}$K, producing much more pronounced AC Stark shift [14] than in case of $^{39}$K. Variation of the cell temperature was followed by variation of the average intensity and spectral profile of the pumping light which reflected in variation of $\delta\Im$. This experiment gives a right idea about limits of long-term stability of narrow-line K-OPM.

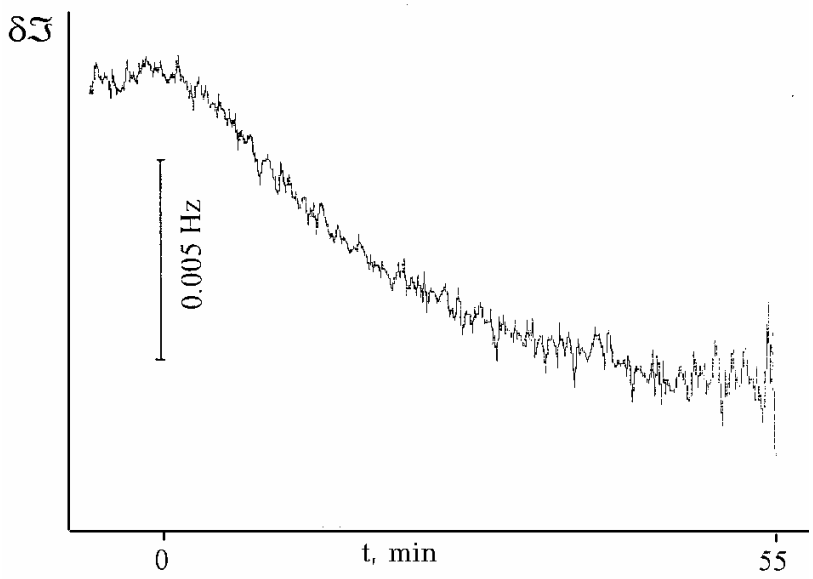



*Fig. 9. dÁ as a function of time during the cooling of the cell*

As was pointed above, all systematic errors should be revealed as a long-term irreproducibility (or a slow drift) of the instrument readings and as tilt errors even for short-term observation. Being mainly stipulated by light shifts, tilt errors can not be reduced by perfect light intensity stabilization (like long-term stability of a stationary installed instrument). But the tilt problem can be very much mitigated in gradiometer (differential) mode of measurement, using two highly identical instruments separated by a fixed base. The cancellation factor varies for different components of tilt errors. For instance, gyro-error [16] will be compensated perfectly, while light shifts can be compensated to the extent of identity of the pumping conditions for two sensors.

**6. Conclusion.**

It has been shown that a fast $M_x$-type narrow line potassium OPM can be realized with short-term (observation period ≤ 100 sec) resolution better than 10 fT/Hz$^{1/2}$ r.m.s. and base-line stability about 10 pT, using the paraffin-coated spherical cell of 15 cm in diameter. Under other regime of exploitation this device can provide base-line stability within ~ 1 pT and resolution of about 1 pT/Hz$^{1/2}$. Both base-line stability and ultimate resolution can be 2-3 times

improved in case of laser pumping. The most effective way of application seems to be in a gradiometer assembly.

**Acknowledgments.**

We were financially supported by ISF and in part by Russian Foundation of Basic research. E.B.Alexandrov additionally acknowledges the support of Alexander fon Humboldt-Stiftung. The authors are grateful to USA Geological Survey and personally to Dr. A.W.Green for interest to and support of the work.

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