GROUND OVERHAUSER DNP GEOPHYSICAL DEVICES

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ABSTRACT

The NMR technology is widely used in a proton precession magnetometers of the Earth magnetic field intended for geological and geophysical exploration. The main method used in the devices is the Packard & Varian free precession method. Considerable improvement of the modern proton magnetometers reached by using the Overhauser dynamic nuclear polarization (ODNP). In this report we present modern ground magnetometer designs including those developed in QM Laboratory. As examples, meteorite Chelyabinsk LL5 investigations and noncontact magnetic defectoscopy gas pipelines are reported.

Modifications of ODNP vector magnetometers measuring both the field module and the absolute field components are another ODNP application to in magnetometer methods for geophysical exploration, magnetic observatories and oil applications related to directional drilling purposes. It is based on the usage of special bias FC magnetic fields at precession signal pick up with a subsequent calculation of field component.

Other examples of application ODNP and NMR of low magnetic field include oil well logging and cores exploration in which Overhauser magnetometers provide stability of the spin echo signals in the conditions of an unstable Earth magnetic field.

Keywords: overhauser vector magnetometer, dynamic nuclear polarization, meteorite, oil gas pipeline defectoscopy

INTRODUCTION

The proton geophysical magnetometers represent an example of high technology NMR technique usage to make precise total field measurements based on a world constant, proton gyromagnetic ratio. By the principle of operation, they enter a class of proton magnetometers which measurements are based on the relation of the free precession frequency ω of the substance nuclei to the modulus of induction of magnetic field $|\vec{B}|_0$:

$$\omega = \gamma|\vec{B}_0| \tag{1}$$

Four major designs of proton NMR geophysical magnetometers [1-3] performance are commonly used. The first is a well-known Packard-Varian scheme, where polarization is due to a field of approximately 100 Oe (10 Oe = 1mT). The second design is the Overhauser precession magnetometer. It is similar to the first one, but the polarization is produced by a field of tens Oe, while an effective polarization field is about thousands Oe due to Overhauser dynamical nuclear polarization (ODNP) effect. For the third and the fourth designs, the polarization and the registration are performed by the geomagnetic field. The signal is excited by short or continuous impulse based on the Salvy-Glenat scheme. The fourth approach is not field cycling (FC) technique as the polarization generated directly in the Earth magnetic field. The signal value for continuous devices is also larger compared to the proton magnetometers. At the values below 30 000 nT the signal abruptly drops and approaches the proton magnetometer signal because of physical construction and Overhauser radical DNP properties namely due to presence of two blocked ESR lines with opposite signs of DNP amplifying.

The methods of DNP factors calculation are well known at least for the basic radicals of the nitroxide types (NO•) having four or six quantum energy levels; the state of art can be found in the review [4].

For modern DNP substances of the Overhauser magnetometers, the spin Heisenberg exchange plays considerable role in interradical interaction allowing to reach maximum of DNP amplification factor. This effect is important for Overhauser magnetometer sensors. Effective width of ESR lines differ repeatedly T1s ≠ T2s which allows to improve essentially the HF power consumption and to create compact bias systems with a non-uniform field of polarization required for nonorientable (omnidirectional) proton Overhauser sensors. For the first time the effect of ODNP easy pumping was noted in the fundamental review of J. Potenza [5] for the free radical GALVINOXYL.

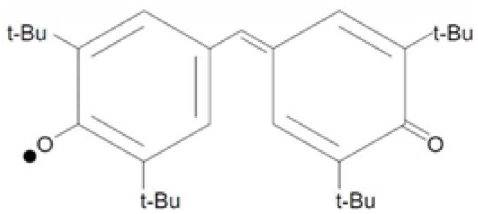

Figure 1. Radical GALVINOXYL having the effect of ODNP easy pumping

Unfortunately, this commercially accessible radical is a little stable (3-6 months). We develop similar radicals having high stability (5-10 years). ODNP magnetometers using these principles and substances are described further.

OEM Scalar proton Overhauser magnetometers POS-1 and gradiometer POS-2

Quantum NMR proton Overhauser magnetometers are well-known; they are widely used in the ground, marine, and borehole geological prospecting. The reason for such proliferation, as compared with other known magnetometers (like flux-gate, GMR, Hall) [6], is the measurement of the absolute value (length of the field vector), based on physical principles of sensors. Absolute scalar sensor does not require orientation in space and thus has no angular errors.

Since 1997 the Quantum Magnetometry Laboratory produces the magnetometers POS 1 using the processor Overhauser sensor technology (POS - Processor Overhauser Sensor). The POS operation principle is similar to standard proton magnetometers. Polarization by Overhauser effect in a bias DC-magnetic field (15-30 Oe strength) and alternating HF-field (frequency about 55 MHz) are used. Our development experience has shown that it is possible to avoid by this way of a sharp decrease of proton Overhauser signal in a range 20000-40000 nT and to exclude a systematic error stipulated by feedback circuit in other types of Overhauser magnetometers. This design variant has allowed applying a new stable substance with lifetime up to 10 years

Table 1. Specification of POS-1

Range of measurements, nT	20000-100000
Resolution, nT	0.001
Sensitivity, nT (RMS at 3 s cycle and at 1 s cycle	0.02 - 0.10
Accuracy, nT	±0.5 (0.1 under VNIIM option)
Gradient tolerance, nT/meter	up to 30000
Reading intervals, sec	1, 2, 3, …(5, 4, 3, 2 Hz option)
Data output	RS232 port
Power, VDC	10-15 (2-3 watt average)
Size, mm - head - electronics	∅70×120 160×90×60
Weight, kg	< 1.2
Operating temperature, °C	-30 … +60

The POS-1 metrological parameters are confirmed by comparative tests with in the lead scalar magnetometers [7]. The POS-1 is analogue widely known Overhauser magnetometers of GEM Systems. There are available a number of advantages, namely:

- A special algorithm of digital processing of the proton precession signal ensures high resolution and sensitivity of measurements with a simultaneous determination of the measurement error in the field's units (QMC). The unique parameter QMC (quality of measurement condition) is equals a standard deviation at a stable magnetic field. It allows by a convenient way to supervise of the noise, not optimum sensor orientation and gradient conditions.
- To increase of gradient tolerance the POS-1 monitors of the short signal and calculate the optimal time interval for measurement.
- Working volume of our Overhauser sensors OS-2 is record small (only 30*65mm), that allows to create compact bias systems for Overhauser vector magnetometers as by the users and in devices designed now by us.

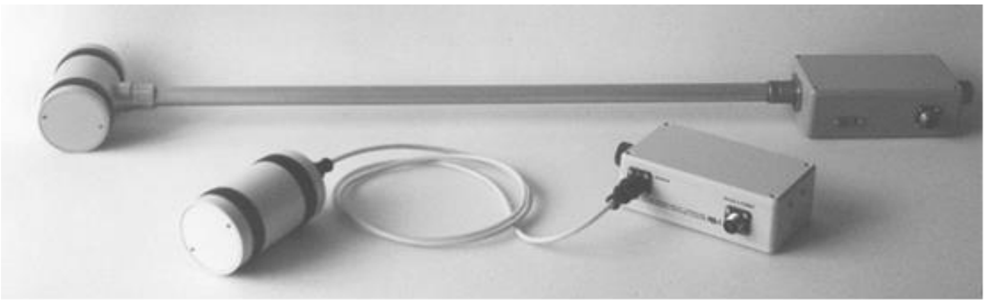

Figure 2. Appearance of the POS-1 soft and hard designs.

There is a POS-2 gradiometer option that is an upgrade of one-sensor POS-1. An additional LF-amplifier/HF-generator and a second Overhauser head with a cable extender are mounted. The POS technology and design allows applying various types of data loggers and software as RS232 protocol POS management are opened for users.

Interesting works to develop of a similar gradiometer design are spent by the Chinese researchers [8] and we are glad they refer us articles.

Ground survey Overhauser DNP magnetometer MMPOS and new using examples

The MMPOS is a scalar Overhauser magnetometer and/or gradiometer intended for ground precision geological survey. Mobile magnetometer consist of POS-1 or POS-1&2 and data logger DLPOS connected via RS232 port. All modes, necessary at ground geological survey are provided:

- Magnetic mapping with manual and semi-automatic input of point, line, time or from external GPS-receiver and data saving in non-voltage memory.
- Walking mode of continuous measurements with opportunity to mark of the point, line and GPS coordinates.
- Base station and test mode with calculation of average and RMS of 11 measurements.

Figure 3. Data logger DLPOS and transportation case of MMPOS-1gps soft design.

The POS and MMPOS are widely known in Russia of 15 years and successfully competing to the leader of the world market GSM-19 not only due to price but a number of advantages having. It is delivered abroad without military restrictions.

February, 15th, 2013 there was a unique event - the meteoric rain has dropped out on Chebarkul lake of Chelyabinsk region. Meteorite has been registered under a name Chelyabinsk LL5. Ice study of meteorite underwater crack using MMPOS-2gps was carried out and shows figure 4. Preliminary results demonstrated possibility of this technique to determine magnetic anomaly relation to meteorite fragment's mass. Article [9] describe analogue investigation refer us. GPS co-ordinates and depth have been defined also for divers that the 600 kilogramme fragment lifted.

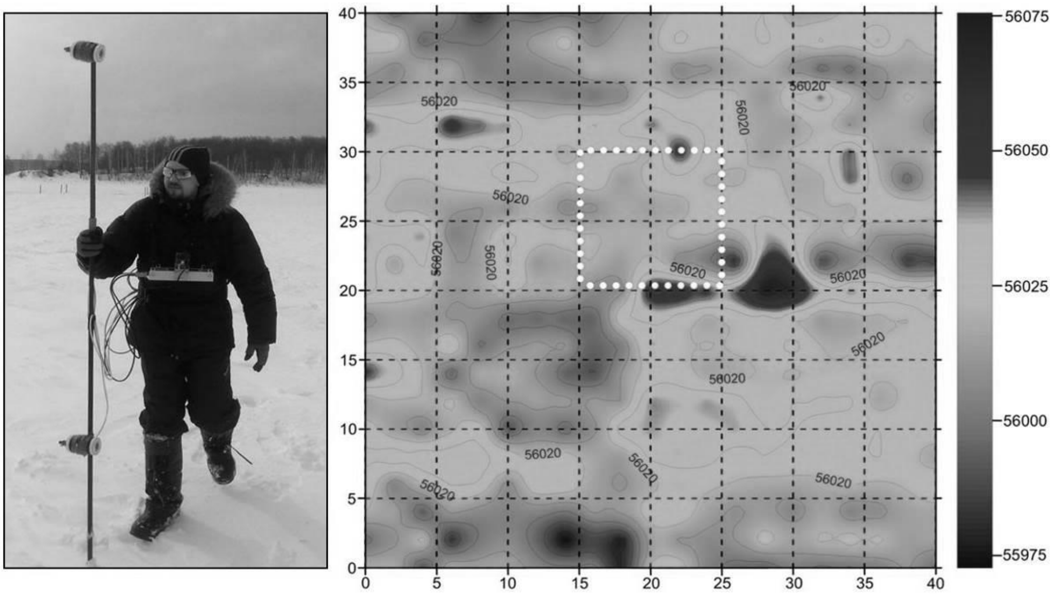

Figure 4. Mapping of meteorite Chelyabinsk LL5 by E.D. Narkhov with MMPOS-2gps.

The young wing of our QM laboratory develops of a perspective last 10 years in Russia direction of contactless magnetometer inspection and defectoscopy of the old oil and gas pipelines that is described in article [10] and presented on drawing 5**.**

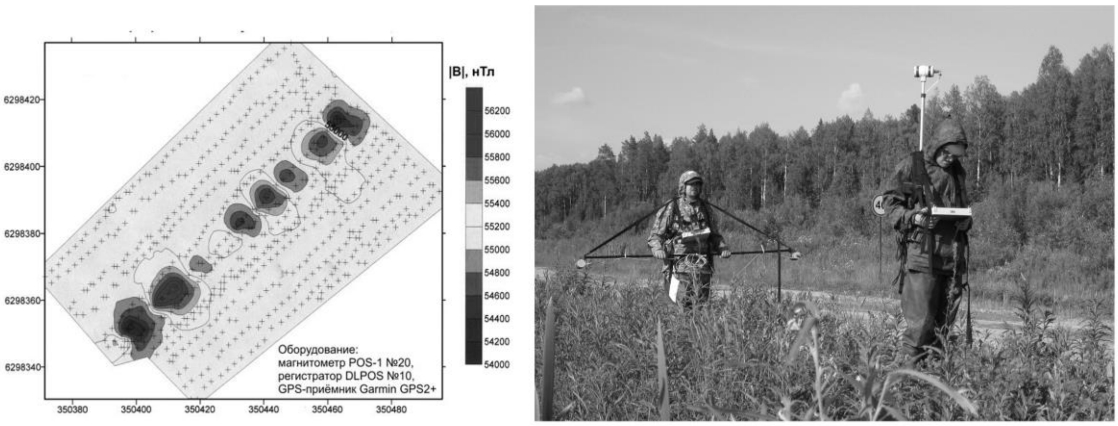

Figure 5. Mapping and inspection investigation of gas pipeline by MMPOS.

Such possibilities are provided by the record gradient tolerance and absolute accuracy of the POS magnetometers thanks to special algorithms of proton signal processing [11]. It is necessary to note that similar results can be reached of the commercially quantum Cesium magnetometers [12, 13] but they have high power consumption especially in cold conditions of Arctic regions.

New vector Overhauser IdDF magnetometers POS-3 and POS-4

Today, it is very impotent to monitor of the global geomagnetic field that are producing in frame of INTERMAGNET magnetic observatories. These observatories are typically configured with a vector fluxgate magnetometer to measure variation of the three orthogonal components, a scalar proton or overhauser magnetometers for measuring the total field and a fluxgate nonmagnetic theodolite to calibrate absolute value (base line D and I and components via total field F from a scalar proton magnetometer).

There is modern trend to create autonomous magnetic observatories for replacement these tools by single instrument, such as an overhauser vector magnetometer based on switched bias magnetic field. The vector proton magnetometers were developed practically simultaneously with the availability of the free precession proton NMR magnetometers and are known since about 70 years. The basic drawback of this type of magnetometers is the significant size of the magnetic coil systems (up to one meter), due to the requirements of low gradient of the bias fields and the significant size of the proton sensors. Figure 6a shows an example of such a system. The greatest success in design and introduction in observatory practice has been achieved by a joint project of GEM Systems Inc., Eötvös Lorand Geophysical Institute (ELGI), and Mingeo. The Figure 1b shows the bias system and one of its co-authors L. Hegymegi. Researchers Zhirov G. and Pack V. made a similar development in Kazakhstan and Russia in 1993 on the basis of the Braunbeck coil (figure 6c) using of the Overhauser sensor developed by the Quantum Magnetometry Laboratory of USTU (now UrFU).

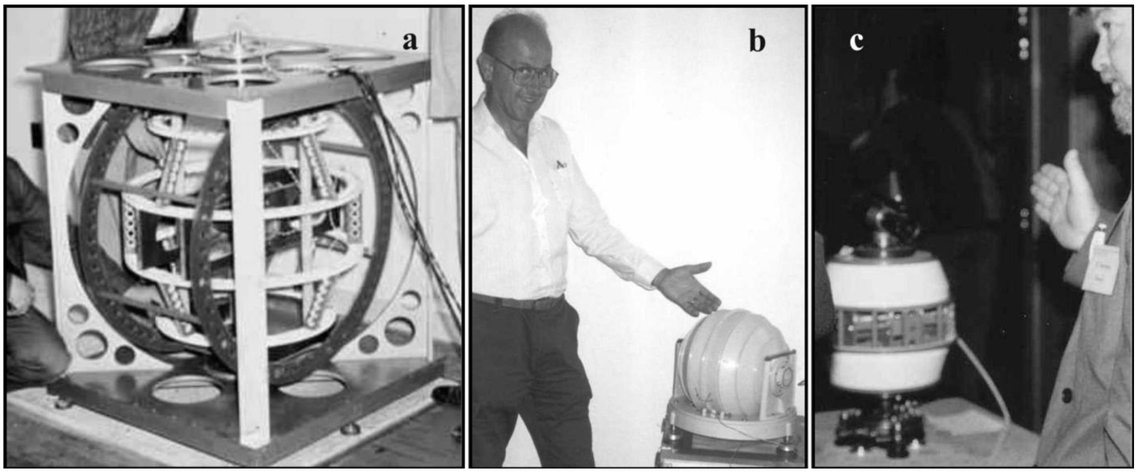

Figure 6. Old proton and modern proton overhauser vector magnetometers.

To measure the components of the geomagnetic field by a proton (scalar) magnetometer a number of methods are known. We investigate below the set-up based on the switching of bias magnetic fields (cycle + J, − J, J = 0) with the measurement of resulting total field [14]. Such scheme corresponds to our POS-3, which measures only vertical component Earth's field along to bias system axis. The bias system is made of the titanic cylinder, which levelled by two liquid levels of 10 angular second. The similar scheme to measure a full vector and the scalar field by switching of two currents in two perpendicular bias systems allows successfully. The device in figure 7 is shown.

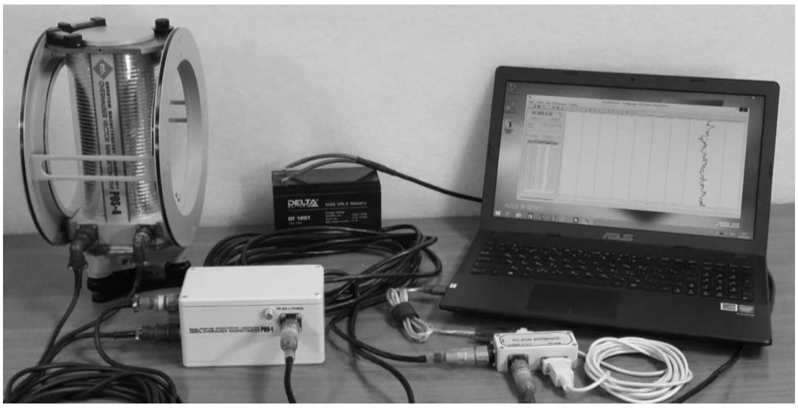

Figure 7. New DdIF magnetometer POS-4 for an autonomous magnetic observatory.

Oil nuclear magnetic logging and NMR relaxometry of the Earth magnetic field

Other examples of application of field cycling FC NMR of low magnetic field include oil well logging and cores exploration [15]. There are no problems to receive proton free precession and spin echo signals in the range of geomagnetic fields. On the other hand, a number of flaws of this logging method have prevented. The comparison with the NML methods based on permanent magnet has shown competitiveness of new NML SEGF technology - spin echo in geomagnetic field by a number of parameters, in particular there is a multiplied improvement of porosity sensitivity (up to 0,05% FFI at relaxation time T_2 of 0.3-3 sec. The basic perspective advantage of the SEGF technology is an opportunity to perform radial imaging with depth up to 0.5 m. Thus the radial imaging with the appropriate choice of a gradient field and parameters of the modified CPMG pulse sequence has appeared where ODNP magnetometers provide stability of the spin echo signals in the conditions of an unstable Earth magnetic field. An example of the spin echo signal from core 90 мм on figure 8 shown.

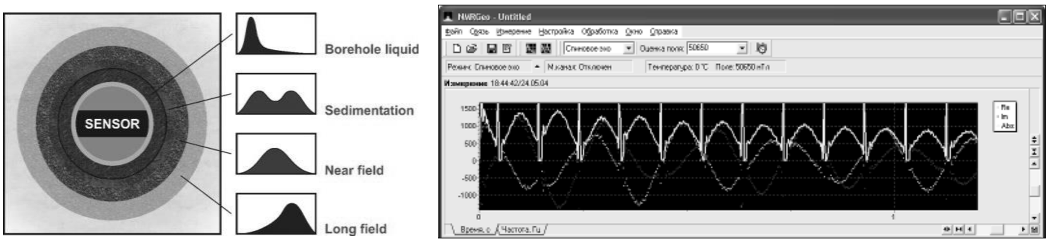

Figure 8. Sensor schematic and example of the stable multiple spin echo signals in both lab and ground tests of the model NML SEGF equipment was obtained.

CONCLUSION

Thus the high technology of the dynamic nuclear polarization and magnetometers are perspective and usefully for many areas of geology and geophysics. In this report shown that the scalar overhauser magnetometers, in particular MMPOS-2gps, due to the high sensitivity and gradient tolerance to investigate of a meteorite crack and to control magnetic state and mapping of the main gas pipelines are effective.

Thanks to new working substances the small-sized overhauser sensors, in particular the POS, the vector and module absolute geomagnetometers using a technique of the switching bias fields for future autonomous magnetic observatories are perspective. Such magnetometers for tasks related to directional oil drilling will be useful also.

The stable multiple spin echo signals of nuclear was obtained due to application of the precision Overhauser proton magnetometer for adjustment of RF-pulses frequency

Within the development of nuclear magnetic logging tools to reach a stable spin echo and radial imaging at use of the channel high-precision scalar magnetometry are shown.

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