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Experiences with Narrow Line Potassium Magnetometers and "SuperGradiometers"

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Optically pumped magnetometers are, with the exception of Helium 3, based on electron spin resonance of their valence electron.

They all exhibit high sensitivity (in pT range), relatively high speed of measurement (up to some 10-20 times/sec) but they also have some adverse characteristics like dead zones (the magnetic field can neither be aligned with the sensor axis nor at 90^0 towards it or the signal just disappears) and substantial heading errors, partially due to wide ESR spectral lines and in case of alkaline group lumped together composite spectral line.

Potassium has a special place in this group having widest spacing between its spectral lines and a regime of operation where they are isolated from each other and very narrow. Potassium has standard dead zones but greatly reduced heading error and unsurpassed sensitivity in sub-pT (femto-Testa or micro gamma) range. Its spectral line can be as narrow as 0.1nT and its sensitivity better than 0.1pTpp or 0.02pTrms for 1 reading per second.

Working with Very High Sensitivities

When dealing with enormous sensitivities like those, one can test the instrument only in differential (gradiometric) mode. In this mode, most temporal field variations - from global ones to regional - influence both sensors the same way, and only local changes, disturbances will be registered.

The ultimate status of potassium magnetometer/gradiometer features can only be shown (examined) in entirely static conditions. We use observatory-like conditions with stable pillars carrying the sensors where overwhelming moving errors can be suppressed and/or eliminated.

For example, potassium has a heading error of less than 0.1nT (Cs has typically 1nT or more) for a sensor - magnetic field orientation change from 5^0 to $85^{0.}$ Assuming a linear change, the sensitivity is more than $1pT/^0$ (i.e. original sensitivity will be disturbed by only 0.1^0 tilt of the sensor). Similarly, if the natural gradient between the sensors is only 1nT/m, we should be able to "see" sensor movement of less than 0.1mm.

Well, what's the sense of pursuing such a very high (and potentially impractical) sensitivity?

For moving measurements, this sensitivity enables us to resort to fast operations with many readings per second, say 10-20 or even 50. Noise increases with speed of measurement to 3/2 potential (i.e. for twice the speed), meaning that we have a $2\sqrt{2}$ increase of noise. Therefore, fast readings will have practical noise levels of some pT or even fractions of nT.

For static measurements full sensitivity can be utilized. Potassium Supergradiometer can detect some 10mg of steel at 1m distance or 10 tons of steel at 1km distance plus.

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Development Directions

Our development has therefore pursued two directions:

Ground and airborne exploration with relatively small sensors, fast readings and practical sensitivities of some tens of pT. For smaller sensors the line widths are higher, typically 1nT.

Aware of a relatively large heading error even for potassium, we have designed ground exploration gradiometers with sensors keeping the same orientation even in uneven ground - a pantograph type of mechanics.

Either horizontal or vertical gradiometers are suitable for fine archaeological work, unexploded ordinance detection or even detailed geophysical exploration. For positioning we use differential GPS either using local base station with post processing or in real time or OmniSTAR type of corrections in real time.

The instruments (i.e. model GSMP-30G) achieve about 10pTpp noise level for 10 readings/sec; their only weakness is moderate tolerance of gradients of some 2000 nT/m.

For static measurements, we have reached maximum sensitivities using what we refer to as a potassium “Supergradiometer”. Using 15 cm diameter sensors, we can produce spectral line widths down to 0.1nT in regimes of low light and relatively low potassium vapour pressure. An auxiliary voltage controlled oscillator is locked to the lowest frequency spectral line of potassium.

The average period of its frequency is determined and the corresponding magnetic (field) induction calculated to 11 digits (1fT) resolution. Motorola Cold Fire microprocessor is used for computation. Although we are dealing with gradiometers, the time reference for average period measurements must be of very high quality - high stability and especially low spectral noise.

The system can be tested by measurement of another stable time base frequency brought to both channels simultaneously. This kind of experiment gave us some 0.05pTpp noise, just about low enough for this particular supergradiometer. So far our best results gave 0.1pTpp noise for a 1 sec running average updated 20 times per second (Nyquist band pass of 0.5Hz) and in an observatory environment.

This is about 15fTrms noise per channel, which in turn, is about 2.5 times worse than theoretical sensitivity of the sensor itself determined by Professor Alexandrov (who conducted the original theoretical work in the potassium field) and his team.

SuperGradiometer Applications and Future Directions

So far, we have 2 fields of application for the supergrad: one is military - hunting of moving ferromagnetic objects, especially underwater ones and the other is an attempt to monitor piezomagnetic properties of rocks in earthquake prones areas, along geological faults.

We shall try to use short base gradiometers (say 50m spacing of sensors) to avoid cultural and other regional magnetic events. In this configuration an anomaly of 1nT generated 10km away will translate into 15pT gradient anomaly, so we should be able to detect equivalent total field anomalies of some 20pT short term.

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At this point, we are awaiting long-term experimental results with the Supergradiometer. Theoretical reasoning predicts long-term stability of some 10 pT. 2 three-sensor systems are being installed in Israel, along the Dead Sea fault, as researchers seek to use super sensitive measurements for earthquake monitoring and prediction applications. This area is very convenient for experimenting since we have a high incidence of relatively small earthquakes - some 20 per year.

Other static measurements may include volcanology and monitoring of temporal variations of magnetic field at observatories, precise determination of magnetic properties of the samples of different materials etc. Very fast determination of components of magnetic field may be done by delta I delta D method of field biasing. Up to 10 readings per second could be achieved with the sensitivity better than 0.1 nT, but we are now exceeding the scope of this talk.