REQUIREMENTS FOR OBTAINING HIGH ACCURACY
WITH PROTON MAGNETOMERS

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1.   DEFINITION OF ABSOLUTE ACCURACY

Absolute accuracy of a measurement is the difference between measured and true values. Obviously, nobody knows the true value, so we end up defining the limits we know the true value must be within.

Presently the limits of accuracy of measurement of the magnetic field of the Earth can be pushed to better than lppm. In a field of, say, 50,000nT this is better than 0.05nT.

However, there are numerous difficulties and conditions that must be fulfilled to obtain that kind of absolute accuracy. Parameters that are involved are:
- Gyromagnetic constant's accuracy
- Time reference stability and accuracy
- Method of measurement of the acoustic precession frequency in continuous and pulsed systems
- Signal-to-noise ratio of the precession signal
- Sensor cleanliness
- Presence of AC magnetic fields

In the Earth's magnetic field (0.2 - 0.6G) protons produce precession frequency between 850 Hz and 2.5 kHz. Spectral line widths of liquid sensors are anywhere from few nT to tens of nT. Spectral line widths (or decay time in pulsed systems) depend on temperature, gradient over the sensor and of course the type of liquid used. All liquids have a chemical shift due to local magnetic fields produced by the atoms of the particular molecule. Span of all chemical shifts is 10ppm. Gyromagnetic constant is usually given for water at 25°C. Water has about 3.5 ppm chemical shift related to tetramethyl silane the accepted reference for high resolution NMR.

Methanol, that we use in our sensors is about l ppm away from water. Kerosene, widely used liquid in proton precession magnetometers is a mixture of chemicals and its chemical shift is not known. Kerosene spectral line is very wide, about 15 nT (decay time is about 0.5 sec dependent on temperature).

2.   **GYROMAGNETIC CONSTANT**

The gyromagnetic constant relates the precession frequency and the magnetic induction or flux density. It is a real constant, i.e. the precession frequency of protons and the applied magnetic inductions are linearly related. Several institutions have been engaged in determination of the gyromagnetic constant:

NIST (USA) National Institute of Standards and Technology formerly NBS
NPL (UK) National Physical Laboratory
VNIIM (Russia) Mendeleyew Institute of Metrology, St.Petersburg
NIM (China) National Institute of Metrology
ASMW (former East Germany) Amt fur Standardisierung,
Messwesen and Wonenpufung, Berlin.

They came with their own results and accuracies, unfortunately often far apart from each other.

Presently we have gyromagnetic constants (γ) determined in high and low field. They differ by about 1.5ppm (results of different laboratories for higher field gyromagnetic constant differ between themselves by more than 4ppm.

Low field gyromagnetic constants that we may adopt as appropriate and convenient differ for NIST and VNIIM laboratories results by 0.7бppm. (NIST and VNIIM claim uncertainties of 0.11 and 0.36 ppm respectively).

Here is a complete list of reported results:

Low field	NIST	1986-8	267 515 427 (29) s^{-1}/T
	VNIIM	1987	267 515 630 (96) s^{-1}/T

Average value for low field is 267515528 s^{-1}/T ±0.74ppm $\gamma/2\pi$=4.25763665 kHz/G

High field	NPL	1973-4	267 515 030 (270) As/kg
	NIM	1988	267 515 410 (230) As/kg
	ASMW	1985	267 514 270 (210) As/kg

3.   TIME REFERENCE STABILITY AND ACCURACY

Measurement of frequency is one of the most precise measurements we can do, primary standards going into 10^{-13} or even better accuracy. In principle, therefore, there is no problem with the time reference for the counters measuring precession frequency. In practice, the situation is different. Due to higher costs and/or higher power requirements in the Observatory magnetometers we usually use temperature compensated or at best thermally stabilized crystal oscillators with long term (1 year) stabilities of lppm or similar. Latest development in global positioning systems allows for much better accuracies by locking or periodically referring magnetometer time bases to the GPS time standards. There are also radio stations emitting time. They could be used to calibrate magnetometer time reference.

Transient states of the most of the time references are very inferior to their steady state specs and one should exercise the precautions in sporadic and short-term measurements.

4.   METHOD OF MEASUREMENT

Proton precession frequency is of acoustic range and the measurement interval varies from a fraction of a second to few seconds. To achieve required resolutions of sub-ppm it is customary to measure the average period of the precession frequency and convert it to the frequency and the magnetic field.

Required accuracies are achieved by measuring precession frequency to a small fraction of one period down to only few degrees or even a fraction of 1 degree of phase shift.

This in turn means that the precession frequency must have a stable phase and good signal to noise ratio.

In continuous systems (of Overhauser type only - standard proton magnetometers are only of pulsed type) the signal is constantly present and the measurement of average time is much easier. However, self oscillating, continuous Overhauser magnetometer poses stiff requirements on phase-frequency conditions of the auxiliary electronic circuits constituting the oscillating system with the sensor. Any parasitic phase shifts of the precession signal by the electronics will be compensated by an opposite phase shift at the proton spectral Iine.

Phase shift at the spectral line means frequency shift of the proton oscillator. There is a 90° phase shift over the entire spectral line width. If line width is 3nT, this means frequency shift of 0.033nT per one degree of phase shift.

Moreover, as line width changes with the temperature or parasitic magnetic field gradient, over the sensor, the frequency shift will change too causing variations in reading due to temperature and magnetic field gradient.

In pulsed systems the decaying signal can cause several problems:
True zero crossing times of the exponentially decaying sinusoidal signal are all at zero and 180 degrees of phase. However, it is not unusual to have a small deviation from the zero voltage in any zero crossing detector. In this case, the phase shift of the "zero" detection will depend on signal amplitude and will increase as the amplitude decreases. Since we measure an average precession period, this shift causes an error in measurement of magnetic field. This error depends on the decay time of the precession signal i.e. spectral line width and therefore on temperature and gradient over the sensor.

Second mechanism for phase shift variations is based on dual pick-up coils that are connected in series opposition in order to suppress far source electrical interference such as atmospheric noise etc.

Due to a self capacity of the windings the two coils may have slight differences in selfresonance, i.e. different phase shifts of the picked up proton precession signals. Vectorial addition of the two phase shifted signals is subject to a phase variation in case of unequal decay times of the components. Decay times may be different due to different gradients over the two halves of the sensor or due to a temperature gradient over the sensor.

5.   **SIGNAL - TO - NOISE RATIO**

Limited S/N ratio will make measurement of the average period uncertain. Relative accuracy or repeatability of measurement, a prerequisite for absolute accuracy, depends to a large extent on S/N ratio of the obtained precession signal. Obviously, an effort must be made to use all the available information from the noisy precession signal, therefore usually all the zero crossings are taken and used for calculation of the result.

6.   SENSOR CLEANLINESS

Obviously, any ferromagnetic inclusion in the sensor or its immediate vicinity may influence the field and cause erroneous result.

7.   PRESENCE OF AC MAGNETIC FIELDS

AC magnetic fields caused by power networks or similar may modulate measured magnetic field and cause errors. AC fields collinear with the main magnetic field vector can be averaged out, but the fields perpendicular to the main vector get rectified because of nonlinear vectorial addition. The summ is a square root of the summ of squares of the components. Fortunately this summation greatly suppresses smaller of the two components. For example and AC component of 100nT at right angle to the main field will produce only 50pT offset in the field of 50,000 nT (or lppm).

CONCLUSION

Proton magnetometers, although theoretically of higher absolute accuracy, require tender care if the highest accuracy is ever to be achieved. Similar considerations apply for other candidates for the highest absolute accuracy of measurement such as potassium. (Potassium also exhibits nonlinearities in frequency-field relationship).

Fortunately for the magnetic observatories it is much more important to have repeatability of the results than the highest absolute accuracy. The reason for this is a substantial spatial distribution of local magnetic fields that masks the absolute accuracy and makes it virtually of academic importance.

The highest absolute accuracy of the magnetic field measurement has a metrological importance, but very little beyond this.