

Long range magnetic localization- accuracy and range study

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Abstract. Undersurface localization systems are accuracy demanding application. Localization methods used for common position estimation in open space or in building cannot be used since they are usually based on RF signal transmission or satellite navigation. Magnetic localization methods are usually the only usable solution. Horizontal directional drilling is one of accuracy demanding application where the operator needs to know exact position of the underground unit with respect to a given point on the surface. Long range surface magnetic localization system will be presented in this paper. This paper will summarize achievable accuracy of magnetic localization and maximal range with respect to given localization error. First results measured with presented system will be presented as well as results from FEM modeling. The influence of target distance, magnetic sensors noise, orientation sensor accuracy and surrounding material will be evaluated and considered in this work.

1. Introduction

Increasing number of horizontal directional drilling jobs caused demand for high accuracy systems that are able to follow exactly planned track of the drill also in industrial or urban agglomerations. There are several systems for precise drill-head underground guidance. In principal we can differ following navigation and guidance approaches:

1.1. *Electronic compass + inclinometers with dead reckoning algorithm*

This method is not very precise since the accuracy of magnetometers is strongly limited[1][2]. Such system usually measures geomagnetic field of the Earth and estimates actual azimuth, pitch and roll. The other disadvantage is that vicinity of any soft or hard iron near the magnetic sensor will cause unpredictable error which is dependent on mutual alignment of Earth's magnetic field vector and the drill head. Advantage is that these systems can be designed for very small bore diameters down to 2 inches and they are quite cheap in comparison to others. Such systems are used for short drills with low demand on accuracy of the tract and exit point position.

1.2. *Optical gyro + inclinometers and dead reckoning algorithm*

Because of the high accuracy of optical gyroscopes they can be easily used for high accuracy orientation measurement (azimuth 0.02°)[3]. Optical gyros are used for orientation estimation and can be recalibrated (northseeking calibration) during the job several times so long time drift will not cause a problem. The accuracy of such system is very high and on the drill with total length of 2.5km the

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accuracy of exit point might be better than 2.5m. That disadvantage of these systems is price of optical gyroscope and dimensions. These systems are used for longer drills or drills in industrial or urban agglomerations where high accuracy is necessary.

1.3. Surface unit localization

The unit is localized with respect to given point on the surface. The working principle is very similar to localization of two underground systems[5]. The accuracy of unit itself doesn't need to be that high since the precise position is estimated during the drill job and drill track is corrected in order to match the planned route. Localization methods are mainly based on magnetic methods with surface coil or low frequency radio beacons in downhole unit and radio receiver in walkover surface unit. The beacons have limited accuracy and range and in higher depths the localization is very inaccurate. In this contribution we will focus on the localization using a surface coil for localization of downhole unit with magnetometer sensors.

This paper describes third configuration with surface excitation coil and downhole magnetometer system. System localizes downhole unit with respect to surface coil.

2. Method and unit description

The localization system consists of a surface transmitting coil and downhole unit with two magnetometers. The excitation surface coil generates square wave magnetic field with high amplitude ($N=1500$, $d=20\text{cm}$, $I=20\text{Ap-p}$, 1Hz) and given time pattern. This signal is measured by both magnetometers in downhole unit. According the known model of surface excitation coil processing algorithm estimates the position of magnetometer with respect to the surface coil (X,Y,Z). Model geometry is shown in figure 1.

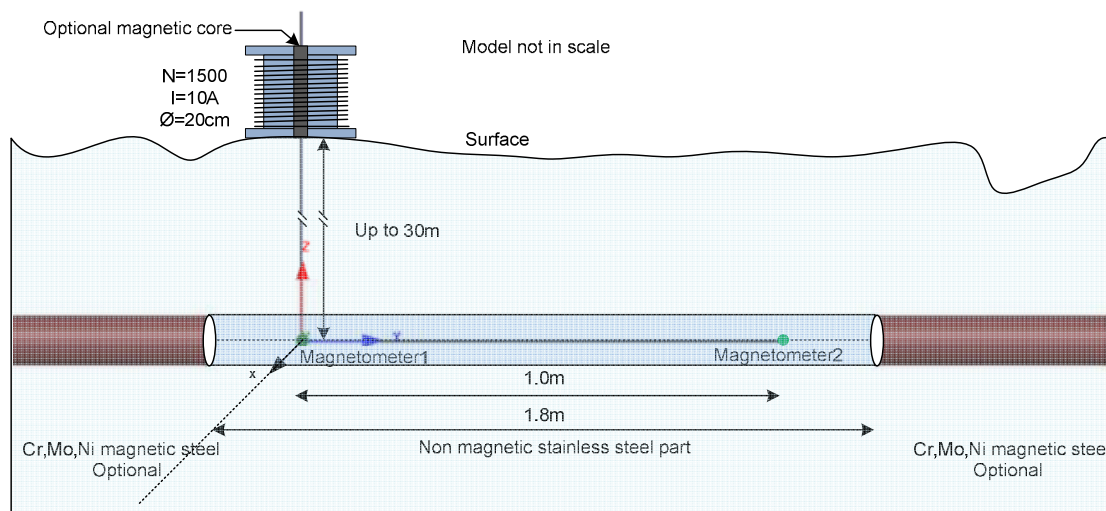


Figure 1. Measurement geometry.

The model of the coil is in far distance described using classical equation of magnetic dipole[4](1).

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \left(\frac{3\mathbf{r} \cdot (\mathbf{M} \cdot \mathbf{r})}{r^5} - \frac{\mathbf{M}}{r^3} \right) \quad (1)$$

Where $\mathbf{B}(\mathbf{r})$ is magnetic field vector, \mathbf{r} is vector representing position in the space with respect to the magnetic field source with magnetic moment \mathbf{M} .

Magnetic field drops with the cube of the distance to magnetic dipole source (surface coil). We can identify following sources of potential errors in magnetic localization according described method and perform sensitivity analysis of each source

Input parameters to the data processing algorithm are following:

Magnetometer data – accuracy and noise of the magnetic sensor

Orientation sensors (roll, pitch & azimuth) – accuracy and noise of the orientation sensor

The influence of these parameters to final position estimation algorithm were investigated.

3. Results

The accuracy of magnetometer orientation is important parameter which can lead to unpredictable errors that are related to mutual orientation of the surface coil and magnetometers. Figure 2 shows position error dependency with respect to overall distance to magnetic source and orientation sensor precision. Three different error values of orientation sensor accuracies are considered 0.01 deg in green, 0.1 deg in blue and 0.5 deg in red color line. Accelerometers used to estimate pitch and roll are quite precise today and can achieve accuracy of 0.5° with appropriate system calibration [1],[2]. The situation with azimuth is much worse. Azimuth accuracy below 0.5° is not easily achievable with magnetic sensors [1] and therefore optical gyroscopes are much better choice as azimuth orientation sensor.

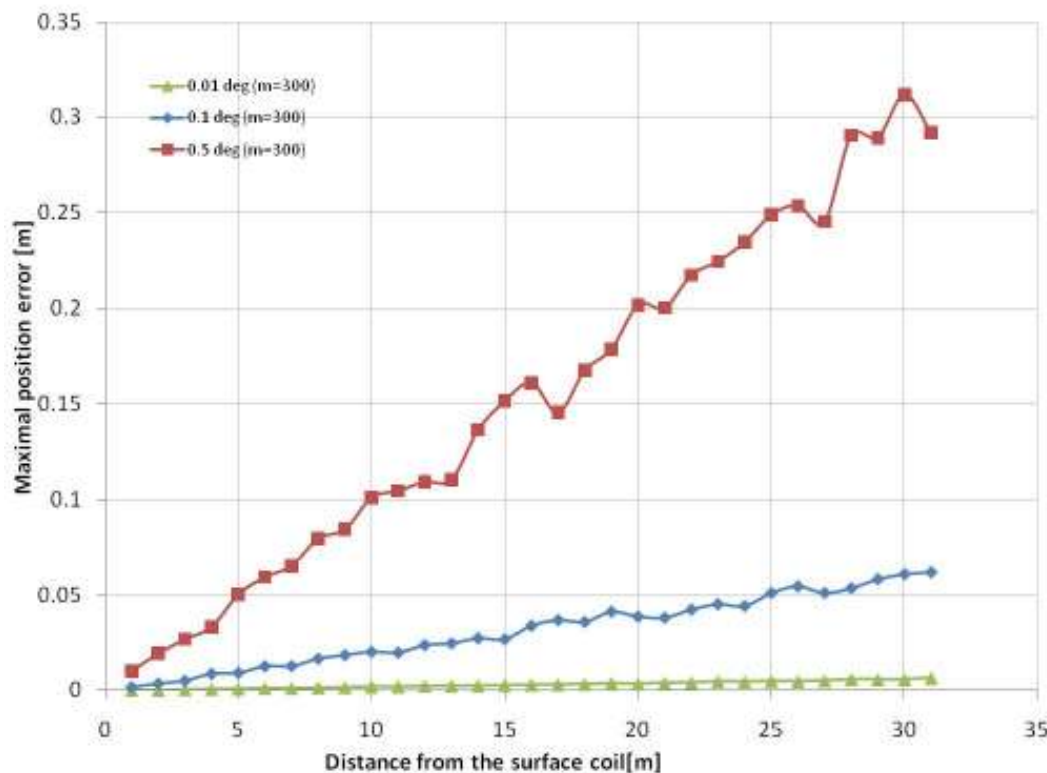


Figure 2. Localization accuracy with respect to distance from target and accuracy of orientation sensor.

The influence of the magnetic sensor noise is shown in figure 3. Also three different sensor noise levels were considered $0.01nT_{p-p}$ in green, $0.1nT_{p-p}$ in blue, $1nT_{p-p}$ in red line. It is clear that noise level of magnetic sensor has crucial influence on accuracy of the whole system. High accurate sensors (fluxgates) with low noise has to be used in order to minimize the contribution to final position error. Presented system uses three axis fluxgate magnetometer with noise level of 12 pT RMS/Hz. Nevertheless if we consider the whole 24-bit ADC magnetic data processing chain we will end-up

with noise value closer to 30pT. Obviously the influence of the sensor noise increasing with distance to surface coil (decreasing of magnetic signal to noise ratio).

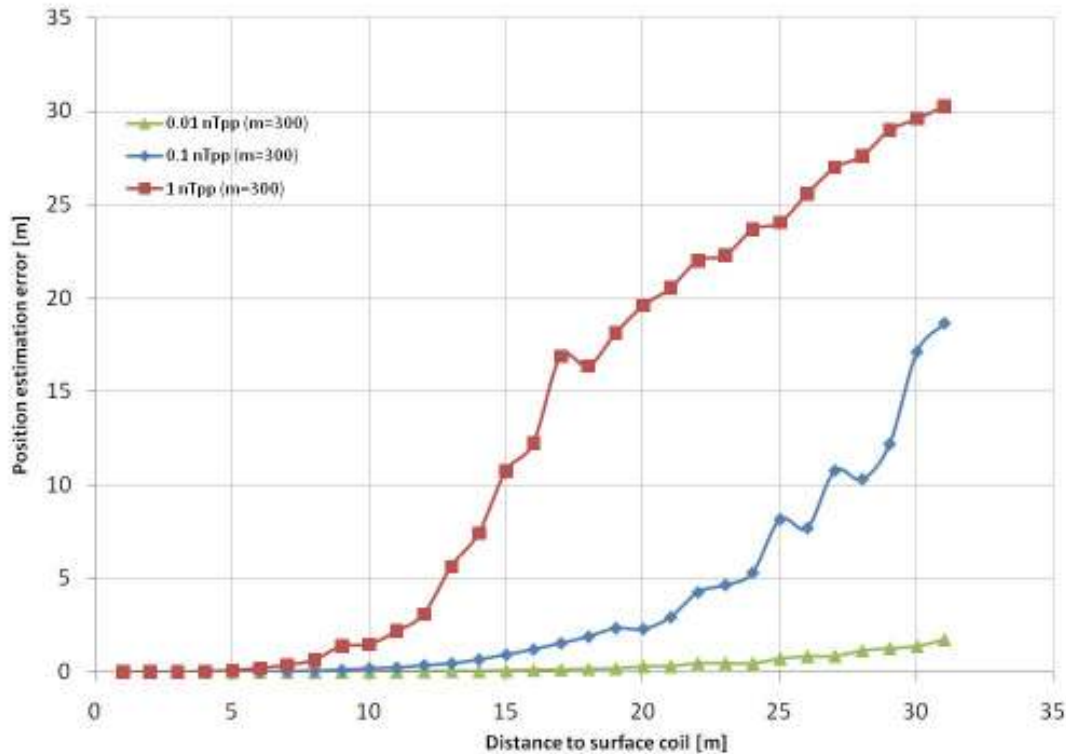


Figure 3. Influence of magnetic sensor noise to final positioning accuracy.

It has to be pointed out that presence of any magnetic material in close vicinity of the magnetic sensors can ruin the position accuracy. Therefore it is necessary to keep magnetic sensors in non-magnetic environment also in case of horizontal underground drilling even if all other components of the drill chain are magnetic. The model situation is shown in figure 4 where presence of magnetic material (long steel magnetic pipes) 40 cm far from magnetic sensors cause deviation of magnetic field vector in order of degrees. In such situation the estimation of position using general dipole model according equation (1) fails or the accuracy of position drops dramatically. Detailed characterization of this influence and possible compensation of the magnetic material presence is above the scope of this paper and will be evaluated separately.

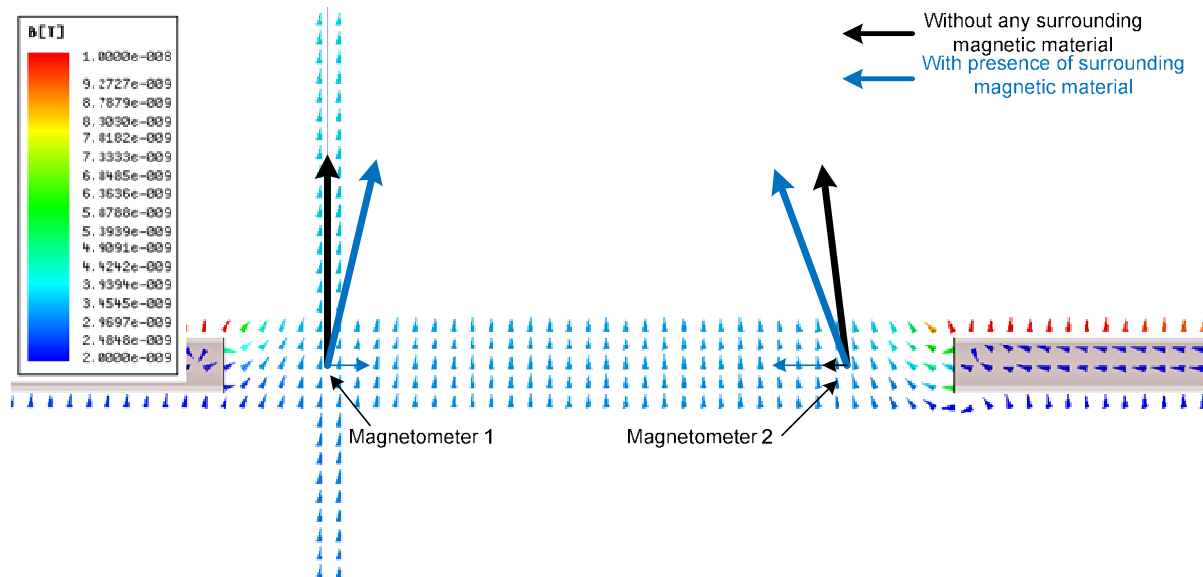


Figure 4. Model situation - Influence of magnetic material in close vicinity of the magnetometer. Same geometry as in figure 1

The accuracy and overall performance of the nonmagnetic system without presence of disturbing magnetic material was verified during real measurement. The measurement was done in area with low magnetic disturbances. The inspected depth Z range was up to 28 m, Y range was up to 8m and X range was 2m. Different mutual orientation between magnetometers and surface coil were tested also. We compare the position calculated from magnetic localization with the real measured position. Total error vector \vec{E} is calculated (2) and its magnitude (3) presented in figure.

$$\vec{E} = \vec{R}_{real} - \vec{R}_{calc} = [X_{err}, Y_{err}, Z_{err}] \quad (2)$$

$$|\vec{E}| = \sqrt{X_{err}^2 + Y_{err}^2 + Z_{err}^2} \quad (3)$$

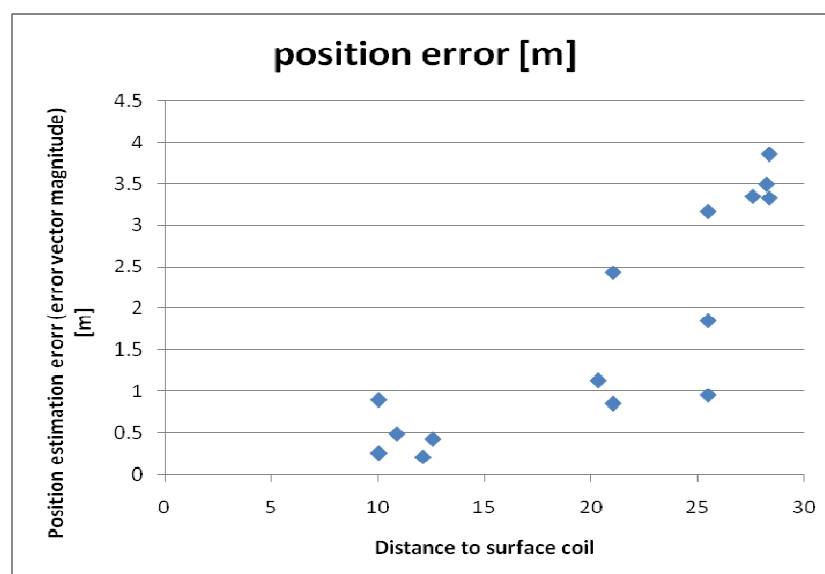


Figure 5. Total position error of real system with respect to distance to surface coil.

4. Conclusion

We use magnetic localization system simulation model to estimate the influence of sensor noise as well as orientation sensor accuracy to final accuracy of position estimation. It was shown that orientation sensor accuracy has much lower influence compared to sensor noise influence which is a range limiting factor. The influence of the magnetic material was shown in one model situation and was pointed out that it can ruin the algorithm precision if not compensated. It has to be noted that orientation sensor influence as well as magnetic material influence strongly depends on mutual position of the excitation coil and magnetometer. Real system was used to verify precision also in long distances (28m range). Surprisingly also in 28m range the precision of estimated position is still below 4m.

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