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Capability assessment and challenges for quantum technology gravity sensors for near surface terrestrial geophysical surveying

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ABSTRACT

Geophysical surveying is widely used for the location of subsurface features. Current technology is limited in terms of its resolution (thus size of features it can detect) and penetration depth and a suitable technique is needed to bridge the gap between shallow near surface investigation using techniques such as EM conductivity mapping and GPR commonly used to map the upper 5 m below ground surface, and large features at greater depths detectable using conventional microgravity (>~5 m below ground surface). This will minimise the risks from unknown features buried in and conditions of the ground during civil engineering work. Quantum technology (QT) gravity sensors potentially offer a step-change in technology for locating features which lie outside of the currently detectable range in terms of size and depth, but that potential is currently unknown as field instruments have not been developed. To overcome this, a novel computer simulation was developed for a large range of different targets of interest. The simulation included realistic noise modelling of instrumental, environmental and location sources of noise which limit the accuracy of current microgravity measurements, in order to assess the potential capability of the new QT instruments in realistic situations and determine some of the likely limitations on their implementation.

The results of the simulations for near surface features showed that the new technology is best employed in a gradiometer configuration as opposed to the traditional single sensor gravimeter used by current instruments due to the ability to suppress vibrational environmental noise effects due to common mode rejection between the sensors. A significant improvement in detection capability of 1.5–2 times was observed, putting targets such as mineshafts into the detectability zone which would be a major advantage for subsurface surveying. Thus this research, for the first time, has demonstrated clearly the benefits of QT gravity gradiometer sensors thereby increasing industry's confidence in this new technology.

1. Introduction

Geophysical surveying is widely used for the location of subsurface features and is of key importance for civil engineering (Metje et al., 2011), archaeology (Wynn, 1986), mineral exploration (Watson et al., 1998), environmental studies (Styles, 2012), in the petroleum and hydrocarbon industry (Berger and Anderson, 1981; Finch, 1985) and for unexploded ordinance management (Butler et al., 2002). In civil engineering, it is vital to be able to accurately locate hazards in the near surface prior to construction, as well as assess the condition of the ground in order to reduce the risks of unforeseen or unknown ground conditions when breaking ground or building foundations. This reduces the risks due to excavation as well as saving project costs through reduced Health & Safety impacts and mitigation procedures.

Commonly used geophysical techniques such as ground penetrating radar (GPR), electromagnetic (EM) conductivity, electrical resistivity and seismic methods have been successfully used to locate underground features in the near surface (Table 1). However, these “active” techniques rely on the transmission of generated signals such as EM waves into the ground, which have a limited penetration depth due to the spreading of the signal with distance and attenuative ground conditions. An alternative is to use “passive” technologies such as magnetic or gravity surveying which rely only on being able to measure the potential field generated by the target of interest and to distinguish it from the regional field and signals from other features above or below the ground.

In addition to the signal from the buried target, these instruments also measure noise (defined as spatially and temporally varying signals other than that from the target of interest) which compromises their detection capability and stems from 3 main sources;

1. Instrumental noise stemming from the instrument itself which tends to vary as a function of time. Examples include variation in the

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orientation of the instrument (e.g. tilt on gravimeters, sensor headings on magnetometers), drift on the sensor and electronic flicker noise from the instrumental electronics.
2. Environmental noise stemming from vibrations and signals from the movements of the planets and seas. These typically vary as a function of both time and spatial location. Examples include tidal signals, changes in atmospheric pressure, vibrational noise from traffic and microseismic noise from ocean waves in microgravity measurements and the presence of changing magnetic fields such as those produced by power cables or moving traffic in magnetic surveying.
3. Location based noise caused by the position of the instrument. These are static as a function of time but vary according to the location of the instrument. Examples include near surface signals from iron debris and buildings in magnetic surveying, and latitude noise, height of the sensor and signals from surrounding buildings and terrain in microgravity surveying.

These geophysical techniques are therefore limited by the resolution of current instruments (which causes quantization errors for small signals) as well as the magnitude of other noise signals and capability to remove them through survey strategy and processing. Details of the potential capability of a wide range of geophysical techniques in terms of horizontal and vertical resolution, and the factors which compromise them in terms of noise are given in Table 1.

In order to gain some idea of how well existing technologies perform in field conditions, experienced operators were consulted and asked for their experience of the performance of the different techniques in terms of the minimum size objects which could be detected in ideal but realistic conditions. Fig. 1 shows the limitations for detection in idealised conditions for four of the most commonly used existing technologies (GPR, Electrical Resistivity, EM conductivity mapping and conventional microgravity) for civil engineering surveys based on spherical features of different diameters buried at a range of depths below the ground surface. These anomalies are taken to have detectable material contrasts which would be typical for expected targets using each technique. For instance, the microgravity and resistivity anomaly is represented by a spherical void whereas the electrical resistivity and EM conductivity anomalies are represented as clay bodies within chalk. In civil engineering ground investigation studies, targets range from pipes and cable ducts with diameters of 0.1–1.2 m in the upper few metres, to larger features such as mineshafts, caves and pingos, which can be several metres in diameter and lie at greater depths of up to 50 m. Whilst it can be seen that these techniques perform reliably for shallow targets and electrical resistivity and conventional microgravity are useful for large targets at depth such as large voids, it is apparent that a large number of smaller objects (<2 m in diameter) at moderate depths (below 10 m) are currently outside the range of detection (see shaded area). It should also be noted that these detection ranges are in optimal conditions and in certain ground conditions, penetration depths could be significantly less. It is therefore apparent that a technique is needed to bridge the gap between the ability to detect large objects at depth and detailed near surface observation.

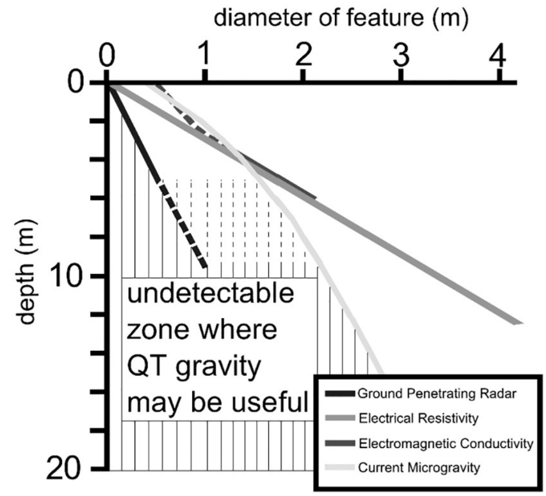

Fig. 1. The detection limits of four different geophysical techniques for spheres with perfect geophysical contrasts of different diameters and depths.

One possible solution to this problem may be to improve the sensitivity of the existing microgravity instruments which, even with long

Table 1
The resolution in the horizontal and vertical directions, depth of penetration and compromising factors for different geophysical techniques.

Instrument	Resolution (H)	Resolution (V)	Depth penetration/detection resolution	Principal compromising factors that would reduce the ability to detect the target[a]
FDEM (e.g. EM31)	±1 m	n/a (upper 5-7 m)	Averages the properties of the upper ~3–7 m of ground	As sensitive to above ground conductivity contrasts (esp. any metal) as to below ground features; Strong local EM fields (e.g. power cables, transmitters, mobile phones)
TDEM (e.g. EM61)	±1 m	n/a (upper 3 m)	Averages the properties of the upper ~3 m of ground.	Strong local EM fields (e.g. power cables, mobile phones)
GPR	1/10 depth	1/10 depth	frequency dependent; e.g. 1GHz–1 m 400 MHz–2 m 100 MHz–6 m	Electrically conductive ground conditions may limit penetration depth; uneven surface may cause air gaps beneath the antenna which will compromise data clarity
Microgravity (e.g. CG5)	1/5 depth	1/3 depth	No depth restriction. 10 μGals (Equivalent to e.g. a 2 m cylinder void at 8 m depth)	Vibration noise; soft/unstable ground; strong free-earth oscillations;, rapidly varying topography; inversion to determine the position and nature of the causative body requires a simple geometry, and little or no other signals in the data. Horizontal resolution dependent upon body geometry and survey design. Vertical resolution often requires additional constraints from other geophysical or investigation data.
Magnetic total field/ gradiometry (surface)	1/5 of depth	1/3 depth	No depth restriction. 0.1 nT e.g. from soil variations associated with archaeological remains	As sensitive to above ground ferrous objects as to below ground ferrous objects; Lateral resolution dependent upon the signal to noise ratio, so will be compromised in areas of high magnetic variability (e.g. igneous geology, areas of high anthropogenic materials). Vertical resolution depends upon the causative body being an isolated feature of known geometry otherwise depth inversions are non-unique.

[a] All techniques seek to detect physical contrasts (density, elastic or electrical) between the target object and the surrounding ground materials. Greater contrasts are more easily detected, as are larger, shallower targets. Deeper, smaller and less contrasting targets are correspondingly more difficult to detect. All anomalies of interest may be masked by the signals/ responses generated by other features in the subsurface (or for some technologies also above surface) that may represent equivalent or greater contrasts, and which would therefore mask or compromise the signal detectable from the target feature.