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POTENTIAL FOR THE APPLICATION OF A GRAVITY SENSING TECHNOLOGY FOR THE IMPROVEMENT OF THE ASSESSMENT OF SEISMIC HAZARDS

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ABSTRACT

Earthquakes of great magnitude are of great concern due to their high potential of damage and destruction of the *systems of objects* and *actions* of the affected communities. This work considers the recent progresses in the understanding of these events, particularly focusing on the co-seismic gravity variations. The challenges in empirical research in the field are analysed under the perspective of two variables: the *reliability* and the *precision* of the information about the risk. The research method consists of literature review and documentary research focusing different technologies in gravity sensing, including one in development at the University of Aberdeen. It is discussed if this technology could support the activities of the technical body in seismology.
Keywords: Earthquakes, co-seismic gravity sensing, gravity-sensing technologies.

Introduction: recent progress in the study of co-seismic gravity anomalies

Earthquake events change the distribution of mass in the Earth's crust, and this can be perceived by precise gravity sensors in the surface. Imanishi et al (2004) indicate two simultaneous effects involved: there is a variation in local gravity acceleration due to "the apparent addiction or subtraction of Earth's mass [and due to] a change in the distance [from the equipment] to the center of the Earth".

The first observation of co-seismic gravity changes was made in the 1964 Alaska earthquake (Barnes, 1966), however, the results were a matter of debate for decades due to the long period between measures and possible drifts from the equipment. Only during 1998 Mt Iwate Earthquake, reliable readings indicating co-seismic gravity change were observed, using an absolute gravimeter (Tanaka et al, 2001). This latter observation – of -6±1 microgal (1gal=100m/s^2) at 3km epicentral distance and 8 days period before and after the single earthquake event – confirmed the theory that gravity changes can be connected to earthquakes, encouraging further theoretical and empirical studies about the occurrence of this phenomena in different scenarios and how to address the inverse problem (obtain information about the seismic activity from the gravity signal).

Numerous models were developed to improve the knowledge about these co-seismic gravity changes in the near and far-field (ref. to earthquake source), enabling researchers to better understand the geophysical mechanisms in action during and after earthquakes. Using these models, associations were made possible between the gravity-change simulations and observational data, including patterns of stress accumulation and crustal deformations, thus allowing the development of improved risk scenarios.

Some of the most referred models are Sun & Okubo (1993) and Sun & Okubo (1998), the first related to surface gravity changes due to point displacements and the second due to finite faults, hence comprehending both the cases of far and near-field. The models indicates that

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co-seismic gravity change readings are expected to be below few hundreds of microgal (from the scenario of 1964 Alaskan earthquake (M_w=9.2)), typically remaining in the order of few microgal in events such as the 1998 Mt Iwate Earthquake (M_w=6.1), which agrees with observations (Tanaka et al, 2001).
These results, however, may represent a challenge for current empirical research, once the magnitude of the measure in the order of few microgal, is close to the precision level of modern devices, as it will be detailed in this study.

Current state of technology
Four different technologies are considered in empirical research in surface gravity variations: mass-spring gravimeters, superconducting gravimeters, optical interferometry gravimeters and cold atoms gravimeters.
Mass-spring gravimeters measure the gravity acceleration using the amount of stretch in a spring due to the weight of a probe mass. Modern devices have the advantage of being portable and cheap compared to the other gravimeters. Superconducting gravimeters, on the other hand, use the equilibrium between a magnetically levitated superconducting sphere in the presence of a field produced by persistent currents from superconducting coils. Comparatively, the stability of the supercurrents act similarly to a perfectly stable spring (Goodkind, 1999), and the consequences are much higher precision and smaller drifts with superconducting gravimeters than with common spring gravimeters.
However, both devices are subject to instrumental drifts, requiring periodic calibration. Such drifts may bring questions about the model used for data correction (i.e. if drift was considered linear, exponential etc., and the adopted parameters) as well as the time between re-calibrations. This is particularly critical for mass-spring gravimeters, due to the large values of its instrumental drifts, reaching up to miligals per month (as it will be detailed in Table I). It means that instrumental drifts reduce the *reliability* of the information, according to the definition:

> Reliability (n.):
> 1. The ability of [something] to be trusted to work well or to behave in the way you want them to;
> 2. The likelihood of an information being correct
> (Collins dictionary, 2014)

In optical interferometry and cold atoms gravimeters "the calibration is referenced to the wavelength of light used in the interferometers" (McGuirk, 2001), which, in turn, is locked to very stable atomic transitions, usually from Cesium or Rubidium. It implies that these devices do not have instrumental drifts, thence being referred *absolute gravimeters*. However, even without instrumental drifts, these devices may as well be susceptible to other types of influences (further described in Table I) that can also affect the *reliability* of gravity information.
Optical interferometry gravimeters assess local gravity using the data of displacement over time from a free-falling corner cube in vacuum and obtaining the gravity acceleration of the cube. These displacements are precisely determined using a Mach-Zehnder optical interferometer, enabling commercial devices to reach microgal precision (Niebauer et al, 1995).
Cold atoms gravimeters are still mainly objects of research, but recent comparisons have showed that they can achieve even higher precision than optical interferometry gravimeters in

the same integration time (Gillot et al, 2014). These latter operate using matter-wave interferometry of cold atom clouds, and many experimental setups possible, being the atomic fountain, which the cloud makes an upwards and free-fall movement, one of the most promising. Equipment such as the Rubidium atomic fountain gravimeter in development at the University of Aberdeen might soon reach the target accuracy of 1μgal or less (Wang, 2010).
The Table I, next, compares the precision (as given by manufacturers and researchers) and the factors that may negatively affect the reliability of the information produced by these four devices. The comparison indicates cold atoms gravimeters as a promising technology that may replace the use of optical interferometry gravimeters in future, due to its expected improved precision and progress in reducing factors affecting reliability. Relative gravimeters remain important, once superconducting gravimeters can reach the higher precision of the four, and mass-spring gravimeters are still more adequate for simple applications and development of gravity networks due to its low cost and portability.

Table I: Comparison between the four different technologies in surface gravimetry

		Relative Gravimeters		**Absolute Gravimeters**	
		Mass-Spring Gravimeter (reference device: gPhone)	Superconducting Gravimeter (reference device: iGrav)	Optical Interferometry Gravimeter (reference device: FG-5)	Cold Atoms Gravimeter (reference devices: LNE-SYRTE CAG and target for Aberdeen CAG (under development))
Precision	Precision[1]	Up to 1 μgal	Up to 1 ngal (with a 1-2years integration time) 0.05 μgal for 1 min averaging	15 μgal/$Hz^{1/2}$ (reaches 1 μgal in 4 min, 0.1 μgal in 6 hours	1 μgal in less than 100s, possibility of 0.2 μgal in less than 2000s
	System noise	< 6 μgal/$Hz^{1/2}$	0.3 μgal/$Hz^{1/2}$		< 3 μgal/$Hz^{1/2}$
	Agreement between gravimeters			1 - 8 μgal	
Factors affecting *reliability* of the information	Drift (μgal/month)	300-1500	0.5	-	-
	External factors	Vibration, temperature, Weather	Vibration (causes offset), weather	Vibration[2], weather	Vibration[3], weather
	Internal factors	Degradation of the spring system	Maintenance (especially cooling system and offsets)		Coriolis effect, laser aberrations[4]

[1]: **As described by the manufacturers in the sources below**
[2]: Superspring damping mechanism prevents most issues, **undesired v**ibration may **occur for high drop rates**
[3]: Recent **progress with active systems is designed** to prevent vibration issues. The internal syste**m is isolated from this problem**
[4]: **There is a work in p**rogress to model Coriolis contribution over the cold atom cloud and in instrumentation to reduce aberrations.

Source: Systematized by the authors, using information from Micro-g LaCoste (2007), GWR Instruments (2009), Niebauer et al (1995), Wang (2010) and Gillot et al (2014).

Conclusion

Earthquake events pose a great threat to a considerable fraction of human society, due to the potential of these events in disrupting communities in a very short space of time, typically in the order of minutes. Three factors are comprised in this disruption: the direct risk that earthquakes present to the physical integrity of people, occasioning in a possible elevated number of injured and deaths during an event; the damage or destruction of the whole *system of objects* (Santos, 1998, p.90) that physically compose the space, effectively creating the disaster scenery; and the damage or destruction of the whole *system of actions* (*ibid.*, p.91) that may be previously related to the destroyed objects in terms of conferring them meaning and functionalities which either ceased to be compatible with the new reality or should be drastically reinterpreted. It means that, within the space of few minutes, an earthquake event can create a disaster with long-lasting social, economic and health consequences and reach catastrophic levels, as exemplified by the 2010 Haitian earthquake and other events.

The risk analysis of earthquakes, however, is particularly delicate, once it has not yet been identified a completely reliable earthquake precursor which could be used to predict the occurrence of these events (International Commission on Earthquake Forecasting for Civil Protection [ICEF], 2011), and even the triggering mechanisms of earthquakes are still objects of research (Prejean and Hill, 2013). Therefore, the *technical environment* often makes use of probabilistic models based on the information provided by a set of different types of measurement – from minor seismic activities to underground Radon emissions. One of the types of measurement that have gained importance in the latter years is the monitoring of gravity anomalies, because it may indicate patterns of stress accumulation and crustal deformations which can also support the understanding of the triggering mechanisms.

Considering this, this study summarized some of the latest scientific and technological advances about the performance of four different technologies in gravity sensing used to analyze co-seismic events. We hope this contribution to be able support the *technical-operative community* in taking the best technical decisions in earthquake hazard monitoring for the near future.

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