



Absolute and Relative Gravity Measurements at Volcanoes: Current State and New Developments Under the NEWTON-g Project

F. Greco, D. Carbone, F. Cannavò, A. A. Messina, and G. Siligato

Abstract

Gravity changes associated with volcanic processes occur over a wide range of time scales, from minutes to years and with magnitudes between a few and a few hundred microGal. High-precision instruments are needed to detect such small signals and both time-lapse surveys along networks of stations, and continuous measurements at single points, are accomplished. Continuous volcano gravimetry is mostly carried out through relative gravimeters, either superconducting instruments, providing higher quality data, or the more widely used spring meters. On the other hand, time-lapse surveys can be carried out with relative (spring) gravimeters, that measure gravity differences between pairs of stations, or by absolute gravimeters, capable of measuring the absolute value of the gravitational acceleration at the observation point. Here we present the state-of-the-art of terrestrial gravity measurements to monitor and study active volcanoes and the possibilities of new gravimeters that are under development. In particular, we present data from a mini array of three iGrav superconducting gravimeters (SGs) at Mount Etna (the first network of SGs ever installed on an active volcano). A comparison between continuous gravity measurements recorded through the iGrav#016 superconducting gravimeter at Serra La Nave station (1730 m a.s.l.) and absolute gravity data collected with the Microg LaCoste FG5#238 gravimeter in the framework of repeated campaigns is also presented. Furthermore, we introduce the Horizon 2020 NEWTON-g project (New Tools for Terrain Gravimetry), funded under the FET-OPEN Research and Innovation Actions call, Work Programme 2016–2017 (Grant Agreement No 801221). In the framework of this project, we aim to develop a field-compatible *gravity imager*, including an array of low-costs Micro-Electro-Mechanical Systems (MEMS)-based relative gravimeters, anchored on an absolute quantum gravimeter. After the design and production phases, the *gravity imager* will be field-tested at Mt. Etna (Italy) during the last 2 years of the project.

Keywords

Gravimeters · Laser-cooled atom · MEMS

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1 Introduction

High-precision gravity measurements provide a powerful tool for volcano monitoring, since they highlight processes that induce bulk mass/density changes. This technique thus provides an important contribution to the understanding of the processes driving magma ascent during the preparatory phases of eruptive events.

In spite of its potential, volcano gravimetry is not widely adopted by research institutions and agencies in charge of monitoring active volcanoes. This depends on several factors, including: (1) the cost of instrumentation, (2) problems that are inherent with the use and deployment of instruments intended for laboratory conditions in the harsh environments that characterize the summit zones of most active volcanoes, and (3) difficulty in interpreting gravity changes that may result from volcanic processes, as well as hydrological effects (changes in the underground water mass), and instrumental artefacts. These difficulties are not insurmountable and efforts in a variety of volcanic settings highlight the value of time-variable gravimetry for understanding volcanic hazards, as well as revealing fundamental insight into the volcano dynamics (Carbone et al. 2017).

The Istituto Nazionale di Geofisica e Vulcanologia (INGV) has operated a relative gravity network for the monitoring of Etna volcano since 1986 (Budetta et al. 1989). The network has been developed and has evolved over the years and currently it consists of: (a) 71 benchmarks, covering an area of about 400 km², for relative gravity campaigns (LaCoste & Romberg model D and Scintrex CG-3M/CG-5 gravimeters were used over time); (b) three continuously running gravity stations equipped with iGravs superconductive gravimeters by GWR Instruments, Inc.; (c) 14 stations for absolute gravity (AG) measurements using the Microg LaCoste FG5#238. In all stations for AG measurements and in some stations for relative measurements, the vertical gravity gradient is also measured.

The whole Etna gravity network is routinely occupied every summer (in the same season of the year to minimize seasonal variation effects). More frequent measurements are carried out through relative spring gravimeters in some elements of the network (almost monthly along the East-West profile; Fig. 1; Carbone et al. 2009; Greco et al. 2010; Del Negro et al. 2013; Bonforte et al. 2017) or during volcano activities. Since 2007, several absolute field surveys have been routinely carried out at Etna volcano to check the long term gravity variations and to confirm the gravity changes obtained by relative measurements (Pistorio et al. 2011; Greco et al. 2012, 2015). To collect the absolute gravity data, the IMGC-02 absolute gravimeter (D'Agostino et al. 2008), developed by Istituto Nazionale di Ricerca Metrologica (INRiM, Italy), was used in the period 2007–2009. Since 2009 up to date the Micro-g FG5#238 absolute gravimeter is used.

In this paper, we present data collected with SGs and absolute gravimeters at Mt. Etna. Furthermore, we introduce the field-compatible *gravity imager*, that will be developed under the NEWTON-g project, including an array of low-costs MEMS-based relative gravimeters, anchored on an absolute quantum gravimeter. This measuring system will provide continuous imaging of gravity changes associated with variations in subsurface fluid properties, with unpar-

alleled spatio-temporal resolution and, consequently, with fundamental implications for risk management. We will deploy the new gravity imager at Etna volcano (Italy), where frequent gravity fluctuations, easy access to the active structures and the presence of a multiparameter monitoring system ensure an excellent natural laboratory for testing the new tools.

2 The Mini-Array of Three iGrav SGs at Mount Etna

Continuous gravity measurements have been successfully carried out at a number of volcanoes around the world using spring gravimeters. Nevertheless, these instruments do not provide reliable continuous data over intervals of weeks or more, because they are influenced by environmental factors and are subject to instrumental drift. Accordingly, most studies of continuous gravity at active volcanoes have focused on the analysis of changes over time-scales of minutes to a few days (Branca et al. 2003; Carbone et al. 2006, 2013, 2019).

An alternative to spring gravimeters for continuous measurements is given by superconducting gravimeters (SGs) that feature a much higher precision and stability than spring gravimeters. SGs are free from instrumental effects and thus allow to track even small gravity changes (1–2 μ Gal) over a wide range of time scales (minutes to months). However, even the most portable SGs (e.g., the iGrav[®] by GWR) are not ideal for installation in the vicinity of active volcanic structures. Indeed, they require AC power at the installation site and some kind of hut or vault to house the instrumentation (Carbone et al. 2019).

At Mt. Etna, the installation of a mini-array of three SGs (distances of 3.5–15.5 km from the active craters; Fig. 1) began in September 2014, when the iGrav#16 was installed in the facilities of the Serra La Nave (SLN) Astrophysical Observatory (1,730 m above sea level (asl); 6.5 km from the summit craters; Fig. 1). In the summer of 2016, iGrav#20 and iGrav#25 were also installed at La Montagnola hut (MNT; 2,600 m asl; 3.5 km SE of the summit craters; Fig. 1) and in the facilities of INGV – OE located in the village of Nicolosi (NIC; 720 m asl; 15 km SE of the summit craters; Fig. 1), respectively.

To our knowledge, these are the first SGs ever installed on an active volcano.

Signals from these instruments have shown hydrologically-induced components superimposed on gravity changes that are related to volcanic processes (Carbone et al. 2019).

Figure 2 shows the signals acquired in the period 23 July–05 September 2016 at NIC (top; iGrav#25), SLN (middle; iGrav#16) and MNT (bottom; iGrav#20) stations, after the corrections for the effect of Earth tides (Wenzel 1996), local atmospheric pressure variations (Merriam 1992), and polar motion (Hinderer et al. 2015), are accomplished.

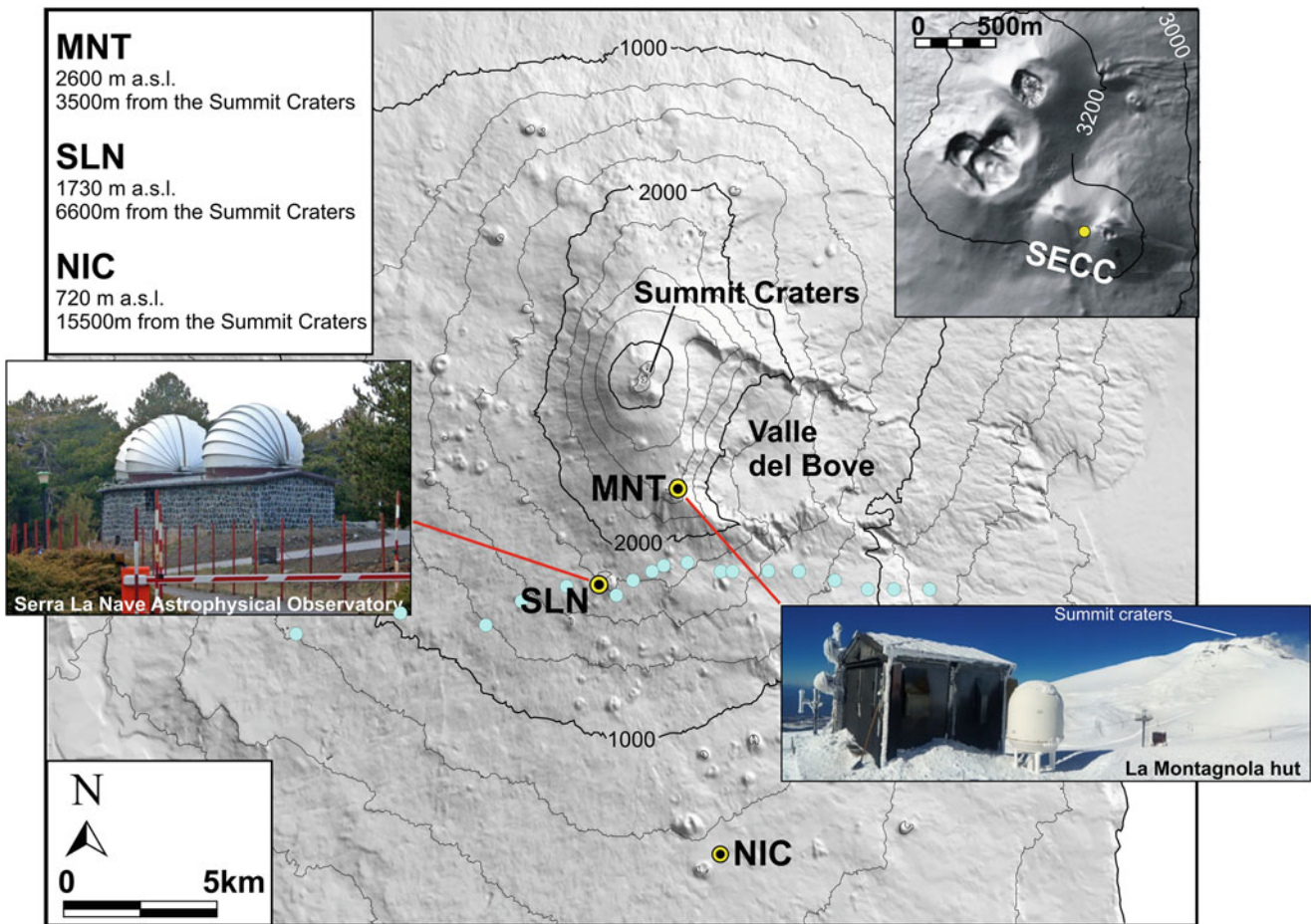


Fig. 1 Sketch map of Mt. Etna showing the mini-array of three SGs has been in continuous operation at Mount Etna since the summer of 2016. The stations belonging the East-West profile (blue circles) where

more frequent measurements are carried out through relative spring gravimeters are also indicated

The reduced signals show common anomalies over intervals of 10–15 days. In particular, a gravity decrease is observed in the signals from SLN and MNT stations during August 8–18. The MNT/SLN amplitude ratio during this period points to the activation of a mass source located a few kilometers below sea level.

Figure 2 also shows positive variations on time scales of the order of a few hours on the signal acquired at MNT (red arrows). Since these variations (average amplitude equal to about 2 microGal) are not present on the SLN and NIC signals and occur during heavy rainfall, they are most probably due to local hydrological effects.

station (the total error on AG measurements at this station is typically ± 3 microGal).

Once a linear fit, obtained through AG data, is removed, there is a good fit between the two data sets. Continuous gravity changes are within 1–2 microGal of gravity changes measured using AG at the same site. This comparison allows to estimate the long-term drift of the iGrav SG, which is of the order of 9 microGal/year (Fig. 3).

This example shows how repeated AG measurements and continuous gravity observations can be used together to get a fuller and more accurate picture of the temporal characteristics of the studied processes.

3 Comparison Between the Time Series from a SG and Absolute Gravity Data

Figure 3 shows a 56-month long time series from iGrav#16 SG (at SLN station), after removing the effect of Earth Tides, atmospheric pressure and polar motion. Figure 3 also shows absolute gravity observations (red points) at the same

4 New Tools for Terrain Gravimetry

Gravimetry is a powerful geophysical tool that, through sensing changes in subsurface mass, can supply unique information on the dynamics of underground fluids, like water, magma, hydrocarbons, etc. This is critically important for both resource management and risk reduction. In spite

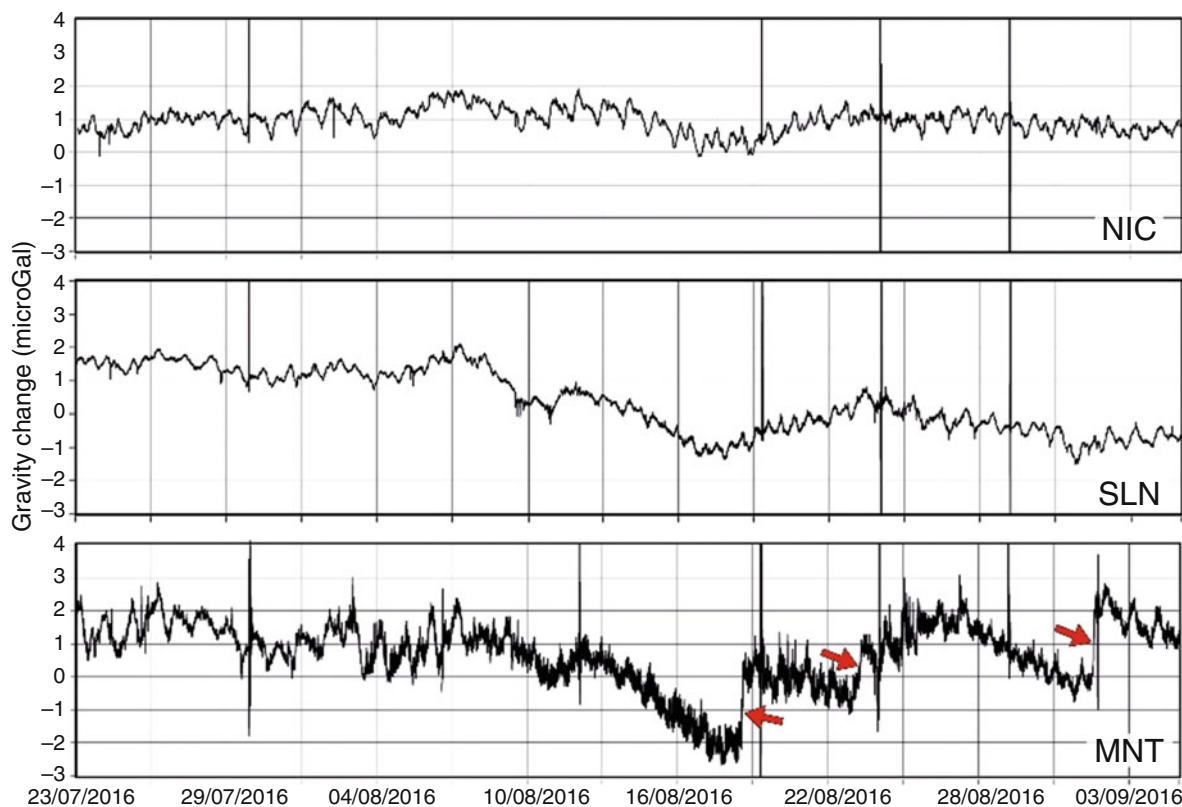


Fig. 2 Gravity time series from NIC (top), SLN (middle) and MNT stations during the 23 July to 03 September 2016 interval, corrected for the effect of Earth tides and local atmospheric pressure. The time series are also high - pass filtered (cutoff of 0.01 Hz)

of this potential, gravimetry is currently underexploited. Indeed, continuous gravity measurements have been rarely performed, owing to the fact that the available instruments are not well suited for continuous measurements under severe field conditions. In addition, the high cost of available gravimeters limits deployment to, at most, a few sensors in a given area, implying that the achievable spatial resolution is always lower than needed.

To overcome the current limits of terrain gravimetry, the NEWTON-g project, that received funding from the European Commission's Horizon 2020 programme, under the FET-OPEN 2016–2017 call, proposes the development of a new generation of gravimeters, based on MEMS and quantum technologies (www.newton-g.eu). MEMS technology will make possible the production of a device that is two orders of magnitude cheaper and lighter than currently available gravimeters. In the framework of NEWTON-g, one goal is focused on strategies to increase the stability of ordinary MEMS accelerometers, thus making them capable of measuring, beside inertial, also gravitational acceleration, with a sensitivity of a few tens of $\mu\text{Gal}/\text{hz}^{1/2}$ (Middlemiss et al. 2016).

The quantum gravimeter that will be developed under NEWTON-g will be the ideal complement to the MEMS devices. We expect that the new quantum gravimeter would: (a) measure the absolute value of the gravity acceleration

(absolute instrument), with a sensitivity and a stability at the μGal level; (b) perform continuous measurements at a high rate (2 Hz) over a long time interval (several years).

A network of low-cost MEMS gravimeters, anchored to the absolute quantum device, will form the so-called *gravity imager*, which will provide imaging of sub-surface mass changes with unparalleled spatio-temporal resolution (Fig. 4).

Once developed, the gravity imager will be field-tested at Etna volcano (Italy) during the last 2 years of the NEWTON-g project (summer 2020 – summer 2022). Insights from the gravity imager will also be used for volcanic hazards analysis, to demonstrate the importance of using gravity to face problems of societal relevance. A successful implementation of NEWTON-g will open new doors and represents a fundamental step that can move gravimetry into a cornerstone resource for geophysical monitoring and research.

5 Conclusions

Many geophysical phenomena are associated with mass transport and may induce gravity changes measurable at the surface over a wide range of time scales. Gravimetry can thus supply unique information on mass transport within the Earth system.

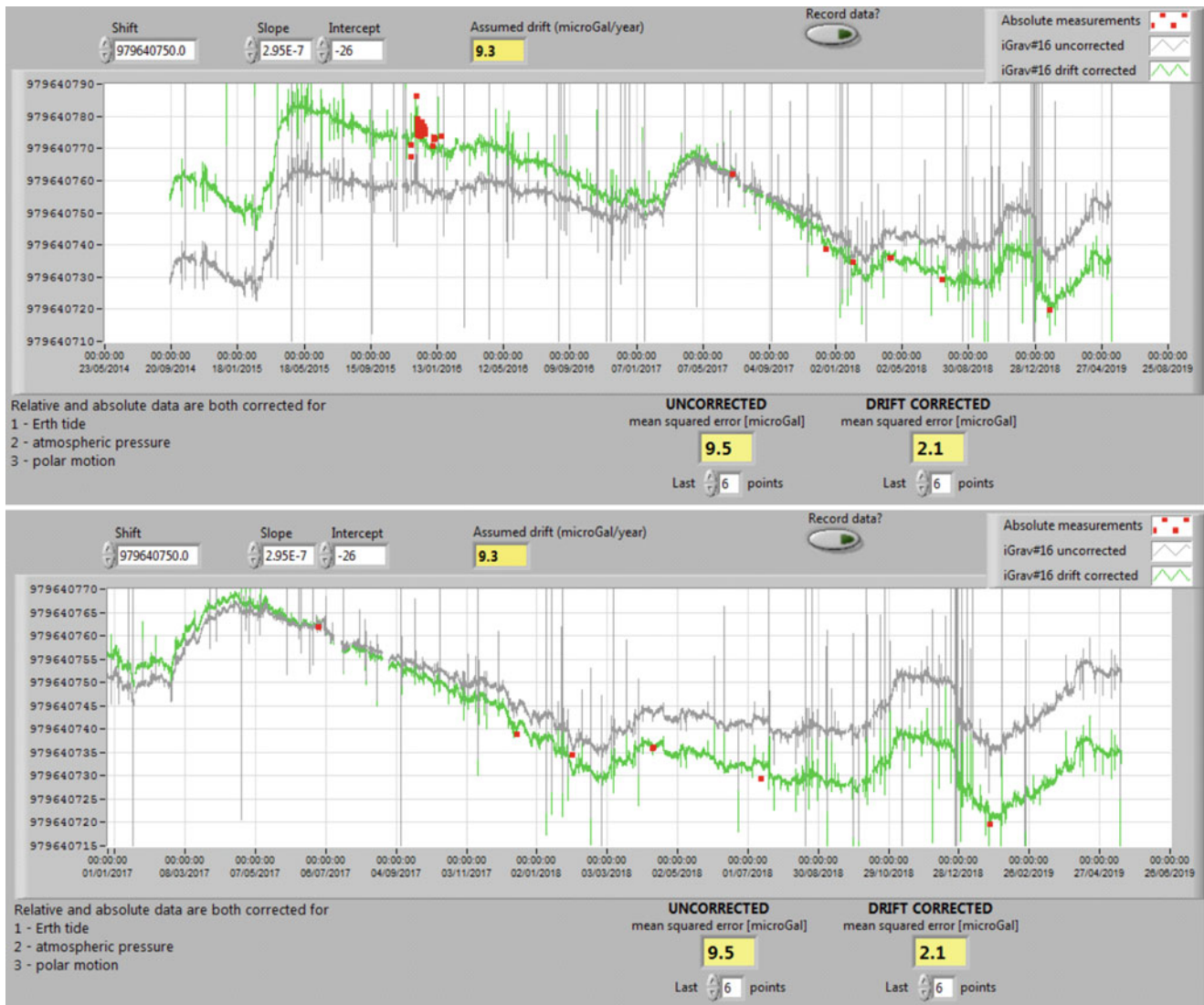


Fig. 3 (Top) time series from iGrav#16 at SLN station during the September 2014–April 2019 interval. Data are corrected for the effect of Earth tides, local atmospheric pressure and polar motion (grey signal). The time series is also high-pass filtered (cutoff of 0.01 Hz). The green

curve is the same signal, after correction for a linear trend deduced from the AG data (red points). (Bottom) same signals as in the top panel, but during the January 2017–April 2019 interval

Through the experiments accomplished at Etna during the past few decades many steps forward have been made towards the regular acquisition of high-quality gravity data. The main issues with continuous gravity measurements at active volcanoes is to obtain and maintain data to a suitable standard (as for quality and continuity) against an adverse environment (high altitude, inaccessibility for several months, lack of mains electricity for power, variable temperature, pressure and humidity, seismicity, corrosive gases) and using instruments which are intended for use under laboratory conditions.

The combined use of discrete (absolute and relative) and continuous gravity measurements is a unique tool both for studying the internal dynamic of a volcano and for surveil-

lance purposes. Such combined system has already allowed important conclusions to be drawn at Mt. Etna.

The state-of-the-art instruments are, in most cases, heavy, expensive, power-hungry and difficult to operate. This prevents the installation of dense networks of continuously running gravimeters, implying that suitable spatio-temporal resolution cannot be attained.

Less expensive and easier to deploy instruments will open new horizons for terrain gravimetry. In particular, the gravity imager that will be developed and field-tested under the NEWTON-g project will demonstrate the possibilities of a new generation of MEMS and quantum gravimeters, allowing a step that can turn gravimetry into a cornerstone resource for volcano monitoring and hazard assessment.

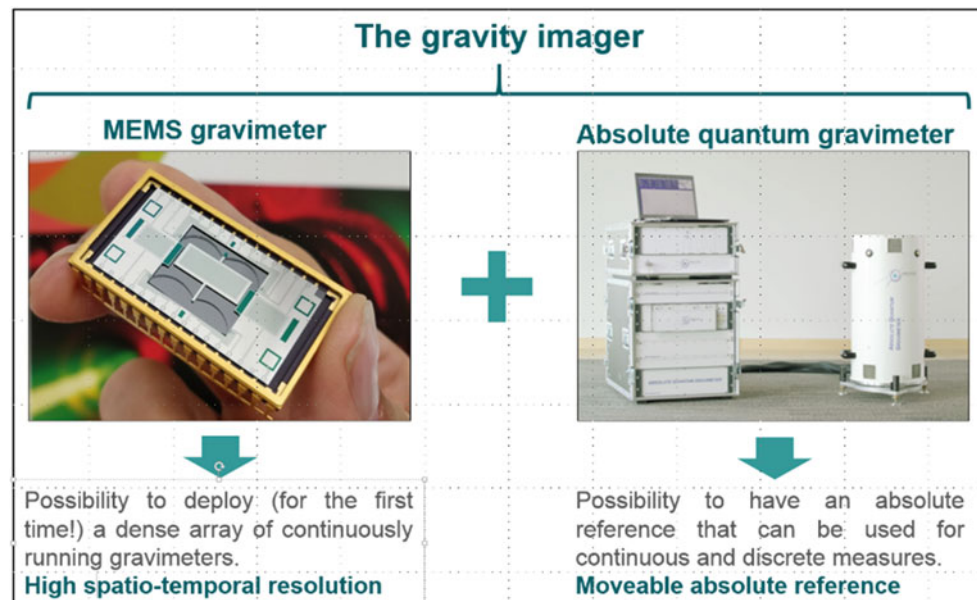


Fig. 4 The NEWTON-g *gravity imager* (currently under development) consist of an array of low-cost MEMS relative gravimeters, anchored to an absolute quantum gravimeter

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