New Tools for Terrain Gravimetry
NEWTON-g
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Deployment of the system

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1. Introduction

NEWTON-g envisages the development of a new measurement system for gravity observations, the so-called gravity imager. This system is designed to allow the detection of gravity changes with unparalleled spatio-temporal resolution. The gravity imager includes sensors based on two complementary technologies: microelectromechanical systems (MEMS) and laser-cooled atoms (quantum technology). In particular, it consists of an array of MEMS-based relative gravimeters, (the "pixels" of the imager), anchored to an absolute quantum gravimeter (Carbone et al., 2020).

The implementation of NEWTON-g involves three main phases: (i) design; (ii) production, (iii) on-field application.

The 1st phase was completed during year 1 of the project and led to the accurate definition of the requirements and characteristics of the two sensor types and of the imager, as a whole (see D2.1 and Part B of the 1st Technical Report of NEWTON-g).

The outbreak of the COVID-19 pandemic and the lockdown measures taken as of March 2020, to mitigate its spread in all Europe's countries, severely affected activities during the 2nd phase of NEWTON-g (production; year 2). In particular, it was not possible to build and test the first prototypes of the MEMS gravimeter, due to the shutdown of facilities at the University of Glasgow, like the James Watt Nanofabrication Centre (JWNC) and the Kelvin Building, which are required for any R&D and fabrication of the device.

The above issue reverberated across the next phase of the project (on-field application) that was originally meant to start at the beginning of year 3 (summer of 2020). Indeed, due to the unavailability of MEMS gravimeters ready for installation on Mt. Etna, the consortium was forced to review the deployment plan agreed in February 2020, as described in the following sections.

This document presents the current (i.e., as of autumn 2020) status of production and deployment of the different components of the gravity imager and provides estimates of when the missing parts will be made available, thus allowing completion of the system deployment.

The document is organized as follows:

section 2 provides an overview on how the already executed deployment phases diverge from the original plan;

section 3 provides insight into the activities already carried out in the framework of the deployment of the quantum gravimeter (AQG-B03) at the Pizzi Deneri Volcanological Observatory (PDN);

section 4 provides insight into the activities already carried out in the framework of the deployment of the MEMS gravimeters on Mt. Etna;

finally, section 5 presents the expected timeline towards the complete deployment of the gravity imager.

2. Planned versus executed deployment during summer 2020

The original plan for the installation of the gravity imager at Mt. Etna was agreed by the consortium, in the framework of a meeting held at INGV-OE ("Pre-deployment meeting" 5 - 7 February 2020). The plan involved, by July 2020, the installation of (i) about 10 MEMS stations at the summit of Etna (elevations ranging between 2000 and 3000 m) and (ii) the AQG-B03 in the facilities of the Pizzi Deneri Volcanological Observatory (PDN; 2800 m elevation). The deployment of further MEMS sensors, which had meanwhile passed the final check at UNIGLA, was also scheduled for August and September 2020.

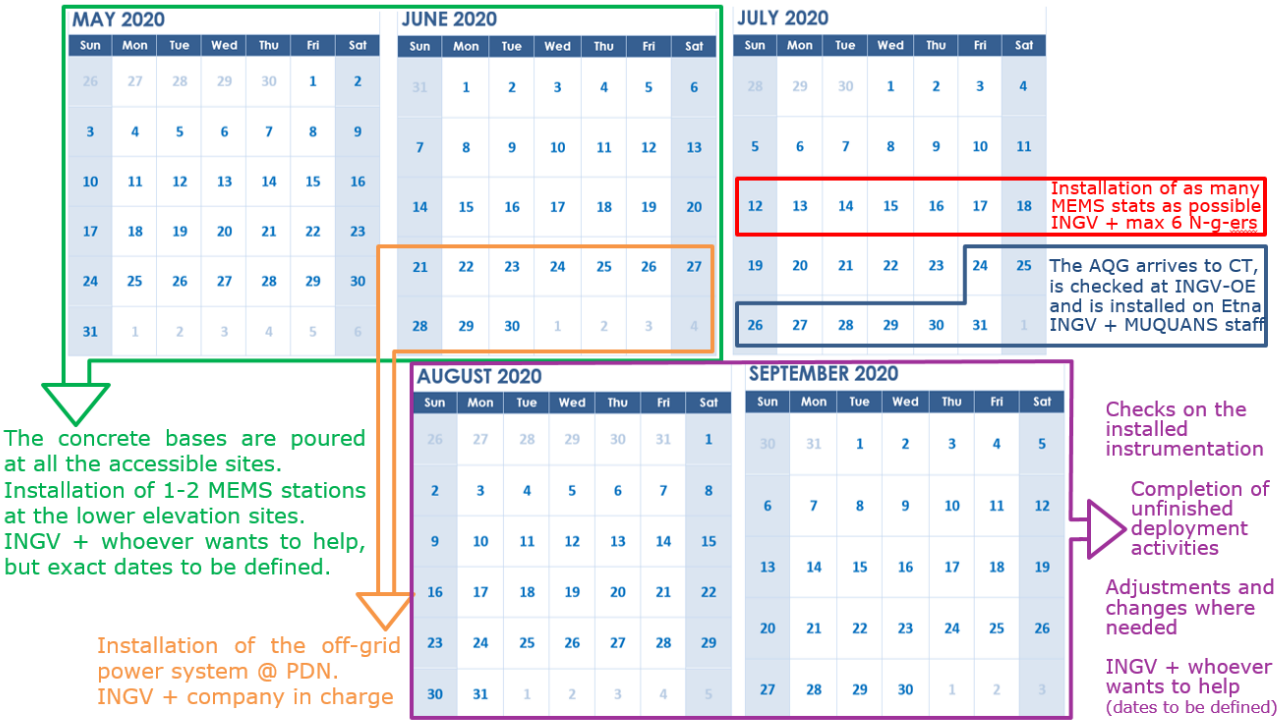

Figure 1 - Scheme outlining the plan for the deployment of the NEWTON-g gravity imager, that was agreed by the consortium in February 2020.

Unfortunately, due to the outbreak of the COVID-19 pandemic, it was not possible to complete, within the established timelines, most of the needed activities before the deployment of the gravity imager. That led to either delays in the execution of the planned phases of the deployment, or to the impossibility to carry out the scheduled activities. In particular:

- the installation of the off-grid power system to feed the AQG-B03 and allow continuous data acquisition at PDN was completed 3 weeks later than scheduled; hence, it was not possible to run any performance test before the installation of the quantum gravimeter;
- it was not possible to finalize the production of the first prototypes of the MEMS gravimeter and run laboratory and outdoor performance tests on them; hence we could not install any complete MEMS station up to the date of this writing.

Further details on the current status of the gravity imager deployment are provided in the following sections.

3. Deployment of AQG-B03 at PDN

3.1 Deployment of the power supply system

As reported in D3.3 (On-field infrastructures), continuous data acquisition through the AQG-B03 at the Pizzi Deneri Volcanological Observatory (PDN, 2800 m elevation, ~2.7 km from the summit craters of Etna; Fig. 2) requires an off-grid power supply system, able to ensure 500 W of continuous power. D3.3 provides full insight into the design of the off-grid power system that the consortium selected as the most suitable for the harsh ambient conditions at the installation site, especially during the winter time. This system employs solar panels (Fig. 3) and a diesel generator (Fig. 4, right), as the power sources, and a lithium-ion battery pack to store the power generated by the two sources (see D3.3 for details).

Figure 2 – The domes of the Pizzi Deneri Volcanological Observatory (right), in front of the summit craters of Mt. Etna (left).

The galvanized-iron structure to hold eight solar panels was deployed at PDN on 9 July (Fig. 3), while the other parts of the off-grid power system were installed during the second half of July, i.e., about three weeks later than planned (see Fig. 1). This delay was due to the impact of COVID-19 on the administrative procedures aimed to purchase all the materials and services needed for the installation of the off-grid system. In particular, due to the difficulties encountered by the administrative staff of INGV-OE in handling some steps of the procedures, while working from home during social isolation, 1 to 3 more months than originally planned were required to complete the procedures (see D3.3). As a consequence, the installation of the off-grid system was completed on the very same day as the continuous gravity data acquisition with AQG-B03 was started at PDN (31st of July), implying that it was not possible to carry out preliminary checks on the performance of the power supply system.

Figure 3 – Left: a phase of installation of the galvanized-iron solar panel structure at PDN on 9 July. Right: the structure after completion of the installation, with eight 350 W photovoltaic panels mounted on it.

That explains why several gaps affect the gravity time series from PDN during the first weeks after the installation of AQG-B03: hardware and software adjustments to the off-grid system were needed in order to ensure a smooth and continuous power flow to the load.
As detailed in D3.3, the off-grid power system installed at PDN includes, besides power sources and battery pack, two modules produced by SMA (Fig. 4, left), namely:

- a photovoltaic inverter (SMA Sunny Boy; mod.: SB3.0-1AV-41);
- a battery management system (SMA Sunny Island; mod.: SI4.4M-13).

Figure 4 – Components of the off-grid power system installed at PDN. Left: battery management system (SMA Sunny Island), in yellow, and photovoltaic inverter (SMA Sunny Boy), in red. Right: diesel generator.

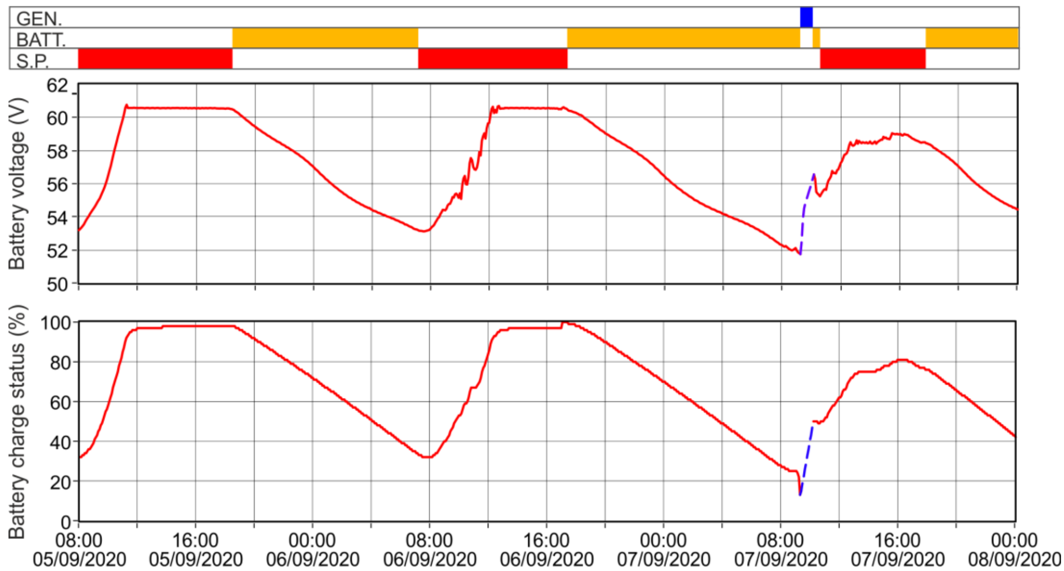

Figure 5 – Plots showing voltage (top) and status of charge (bottom) of the battery pack in the off-grid power system at PDN, during 2.7 days in early September 2020. The colorbar on top of the figure shows which element holds the load at different times (S.P. = solar panels, BATT. = battery pack, GEN. = diesel generator). In particular, after two days when the only exploited power source was the solar panels (5 and 6 September), due to adverse weather conditions, the level of charge of the battery dropped to the threshold (12%) at which the battery management system activates the diesel generator. The latter holds the load and charges the battery (dashed blue parts of the curves in the two plots) until the management system turns it off (level of charge off-threshold = 50%).

As explained in D3.3, the battery management system regulates the balance between energy fed to the grid and energy used by the load and automatically switches the powering/charging source between solar panels and diesel generator, depending on the solar power available at a certain time. An example of operation of the battery management system is presented in the plot of Figure 5 (5-min averaged data provided by management system itself).
The position of the different instruments that compose the off-grid power system installed at PDN is shown in Figure 6. Note that the diesel generator is at safe distance from and on a different floor with respect to the sensor head of the gravimeter, Hence, only a negligible instrumental effect is expected to arise from the ground vibration sourced from the diesel generator.

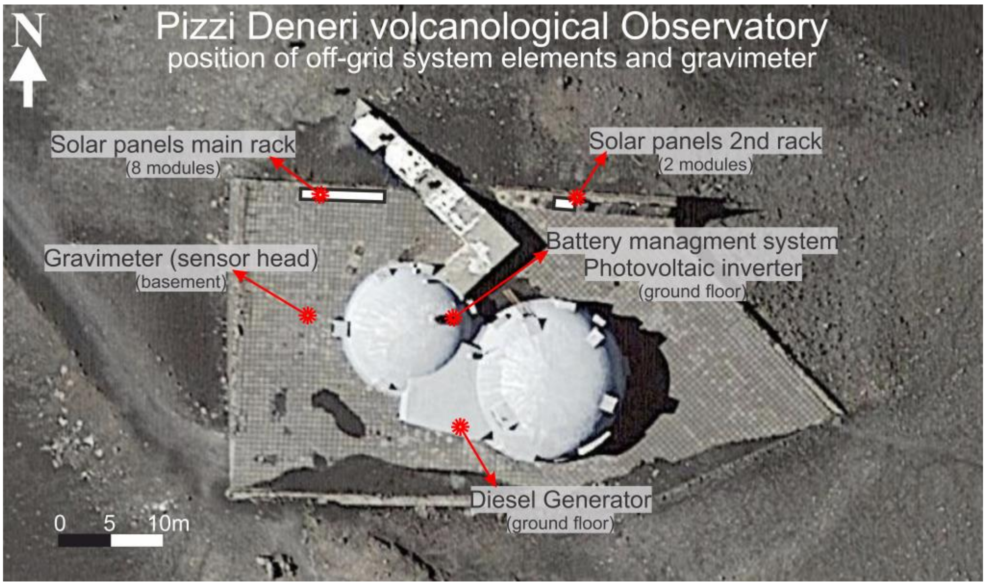

Figure 6 – Map view of the Volcanological Observatory of Pizzi Deneri showing the position of the different parts of the off-grid power system. Note that, besides the new solar panel structure (left), able to host 8 modules, another (pre-existing) structure (right) Is employed to host two more modules. Position of the sensor head of AQG-B03 is also reported.

3.2 Deployment of the AQG-B03

Figure 7 – Members of the INGV and MUQUANS teams during the installation of AQG-B03 in the Grav-Lab of INGV-OE.

The deployment of the AQG-B03 took place in two steps at the end of July 2020. After its shipment by truck, from the facilities of Muquans, in Talence (France), to the headquarters of INGV-OE (Catania, Italy), the device was first installed in the Grav-Lab of INGV-OE on 24 July (Fig. 1). The purpose of this preliminary measurement was twofold: (i) perform a check on the instrument to make sure that it was in proper operating conditions after the transportation from France to Sicily and (ii) establish a reference, in terms of sensitivity, for Sicily island.
Measurements in the Grav-Lab were accomplished under an average ambient temperature of 28°C. First, two different configurations were first tested, with and without rubber pads below the feet of the tripod that holds the sensor head of the gravimeter. Data inspection confirmed that a better sensitivity is obtained without the rubber pads. Successively, a continuous time series of gravity measurements (2 Hz rate) was acquired throughout two days. Results are presented in Figure 8. The 10-min averaged residuals and the Allan deviation both reveal a sensitivity of 550 (nm/s2)/$\sqrt{\tau}$ and a stability better than 2 µGal, after correction for a tide model generated by Tsoft, without ocean loading estimation. The noise level difference between days and nights (mainly due to urban noise) is highlighted on the standard deviation of the gravity residual signal (Fig. 8, bottom-left panel), as well as on the signal from the broadband seismometer installed side-by-side with the AQG (Fig. 8, bottom-right panel). Once the results obtained at this site were validated, the modules composing the gravimeter were packed and loaded in two pickup trucks of INGV-OE (Fig. 9), ready for transportation to the summit of Mt. Etna.

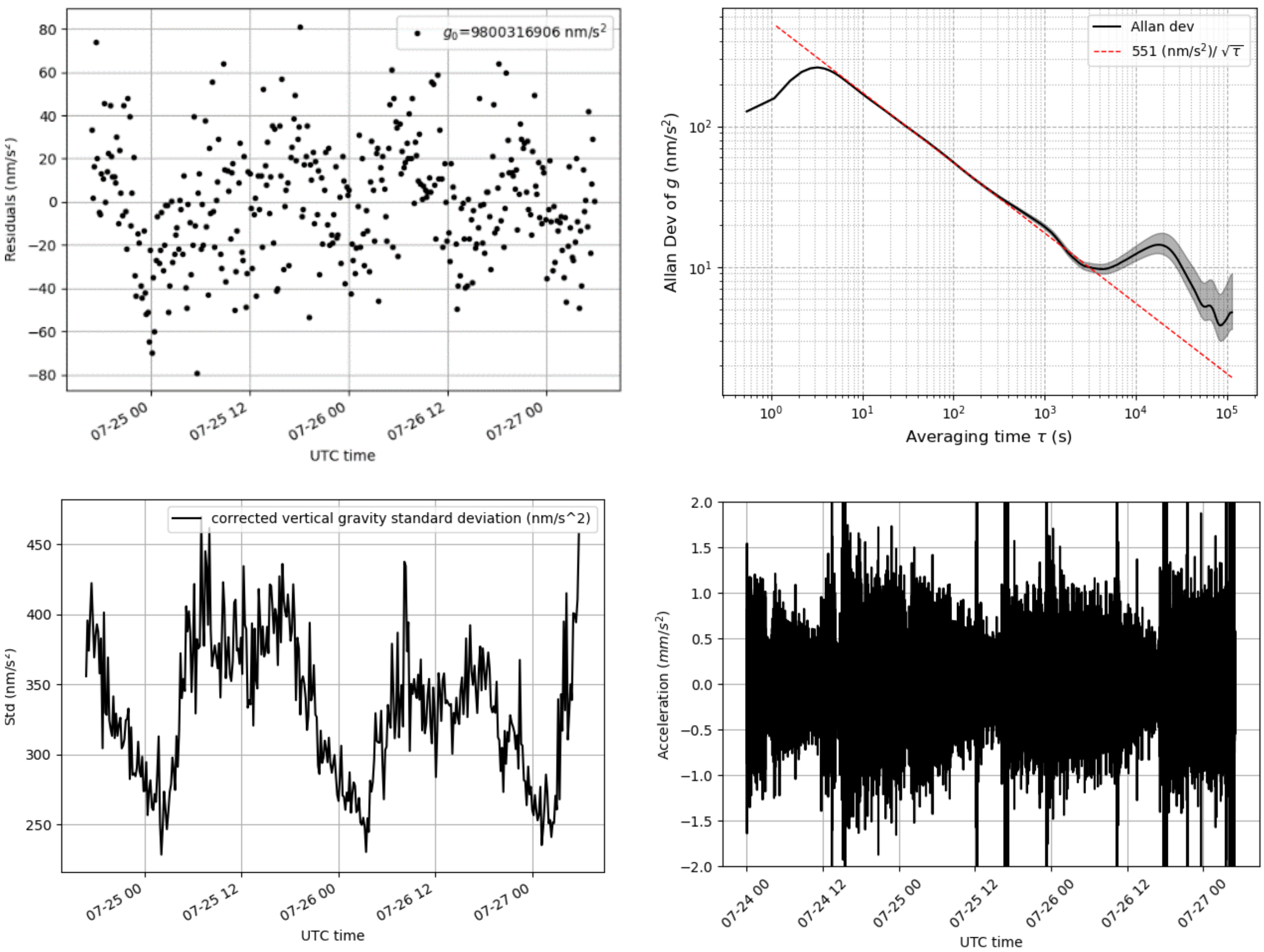

Figure 8 – Results from the two-day continuous gravity measurement at the Grav-Lab of INGV-OE. Top left: 10-min averaged gravity residuals, after correction for tidal effects, atmospheric pressure and tilt changes. Top right: Allan deviation of gravity residuals. Bottom left: 10-min standard deviation of the gravity residuals. Bottom right: seismic data from a broadband seismometer, installed side-by-side with the AQG-B03 (signal was converted in acceleration).

Figure 9 – The modules composing the AQG-B03 packed and loaded in the pickup trucks of INGV-OE, ready for transportation to PDN.

On July 28th, AQG-B03 was transported to PDN, at the summit of Mt. Etna. Four members of the INGV-OE team and two members of the Muquans team took part in the activities during that day. PDN is the facility closest to the summit active craters of Etna where the deployment of the AQG is feasible (see D2.1). This feature makes gravity measurements at this site more appealing from the scientific point of view than at other possible locations, even though the high level of volcanic tremor could lower the quality of the data. Indeed, given the fact that the amplitude of gravity changes measurable at a given point depends on the distance to the mass source, there is a higher chance to detect volcano-related anomalies at sites that are closer to the active structures. That is the main reason why PDN was preferred by the consortium to other possible installation sites for the AQG on Mt. Etna. More information on this subject can be found in D2.1.
From INGV-OE the road to PDN includes: (i) 35 km of motorway until the junction towards the village of Fiumefreddo; (ii) about 50 km of asphalted road between the village of Fiumefreddo and Piano Provenzana; (iii) 9 km of dirt track between Piano Provenzana and PDN (Fig. 10), accessible only to authorized means. The last part of the journey was particularly challenging since the dirt track is steep and rough, implying that the driving had to be very slow and smooth, in order to prevent damage to the most delicate parts of the AQG. That explains why the whole journey took about 5 hours!

Figure 10 – Transportation of AQG-B03 along the dirt track road between Piano Provenzana and PDN.

The PDN observatory is a building including (i) two interconnected dome-shaped shelters (Figs. 1 and 6) at ground floor and (ii) a large room at the semi-underground basement. The latter hosts a concrete pillar rooted in the rock underlying the building and detached from the building itself; this artifact is particularly suitable for gravity measurements as it is firm and stable and unaffected by vibration of the edifice during phases of strong wind. The sensor head of AQG-B03 was thus installed on this pillar. There are two entries to the room at the basement: a narrow spiral staircase connecting the ground floor to the basement and an old external door that is broken and thus currently unusable. Since one of the modules of the AQG (namely, the laser system) turned out to be too large to pass through the spiral staircase, the members of the INGV-OE and Muquans teams involved in the deployment decided to install the sensor head on the concrete pillar (basement), while leaving the laser and power supply modules in the corridor at ground floor (Fig. 11). That was possible thanks to the 15-m long cables connecting the sensor head to the laser module. The temperature in the basement was found to vary between 13°C (night) and 16°C (afternoon); hence, the insulation cover was installed on the sensor head, in order to limit thermal loss (Fig. 11).

Figure 11 – The sensor head of AQG-B03 on top of the concrete pillar in the basement of the PDN observatory, without (left) and with (center) the insulation cover. Right: laser and power supply modules in the corridor of the ground floor.

Once all the modules were properly installed, AQG-B03 was switched on, in order to allow thermal stabilization of its internal components during the night. A continuous gravity measurement was successfully started on the morning of 29 July. Some further tests were carried out during the following days and a wireless Internet connection was established, through the already existing Wi-Fi link of the observatory, to allow data transfer and remote control of the gravimeter. Once the installation was complete, continuous gravity data acquisition was started on 31 July, at a rate of 2 Hz. The time series recorded by the AQG between 31 July and 24 September is shown in Figure 12 (top). The gaps in the time series are mainly due to temporary failures in the power supply system that needed several hardware and software adjustments, during the weeks after its deployment, in order to reach the optimal configuration. Apart from those gaps, AQG-B03 has produced high-quality data, without loss of information, even during phases of high volcanic tremor. These phases correspond to increases in the standard deviation of the gravity residuals (Fig. 12, bottom right). After the subtraction of the correction terms (earth tide, atmospheric pressure and ground tilt effects), residual gravity changes with amplitudes in the order of a few tens of nm/s^2, can be recognized in the time series (Fig. 12, bottom left). These residuals could reflect underground mass changes driven by volcanic processes. No significant instrumental drift has been recognized in the time series from AQG-B03 at PDN so far.

Since AQG-B03 was installed at PDN, different levels of volcanic tremor amplitude have occurred and, up to date, the volcanic tremor has never lowered the quality of the gravity data towards the threshold requiring rejection. However, during phases of higher tremor, the sensitivity of the AQG is degraded. To evidence this aspect, we present a comparison of results obtained from the analysis of three 1-hour data sets, recorded under different ambient conditions: at Talence (France), in the facilities of Muquans, and at PDN, during phases of low and high volcanic tremor. Figure 13 presents the velocity power spectral density (PSD) for the three data sets. The PSDs calculated on data from Talence and PDN mostly differ over the 1-10 Hz range, while the PSDs calculated on data from PDN during phases of high and low volcanic tremor show the most important differences over the 10-100 Hz range. The estimated sensitivities are 550 nm/s2/√t at Talence, 800 nm/s2/√t at PDN during low tremor and 2500 nm/s2/√t at PDN during high tremor.

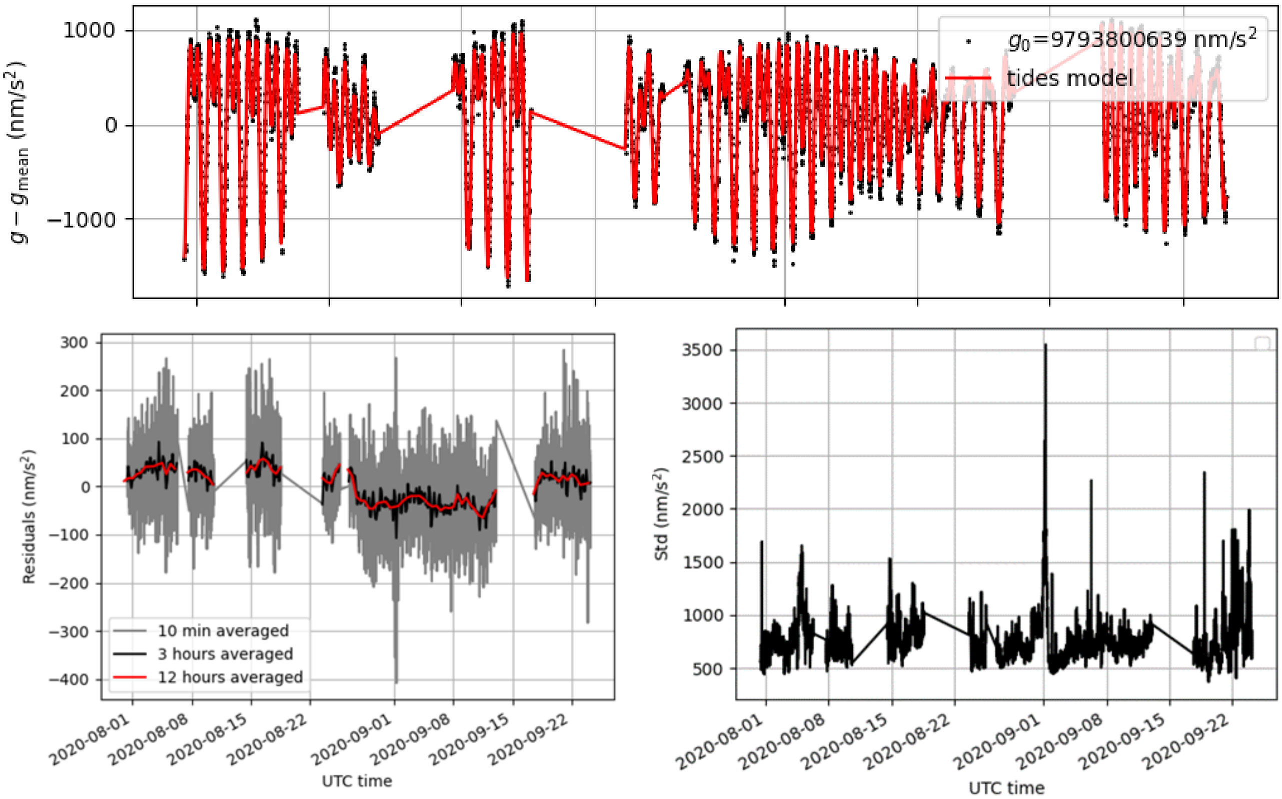

Figure 12 – Results of the measurements between July 31 and September 24. Top: 10-min averaged raw gravity measurements (black) and tides model (red). Bottom left: Residuals from the gravity measurement, corrected for tide model and atmospheric pressure, averaged over different intervals: 10 min, 3 hours and 12 hours. Bottom right: 10-min standard deviation of the gravity residuals.

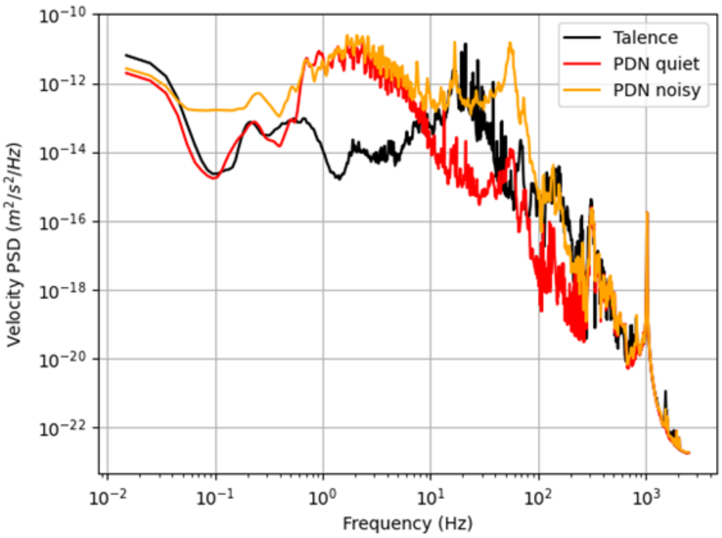

Figure 13 – Velocity power spectral densities (PSDs) calculated using data from the seismometer in the sensor head of AQG-B03, during operation at (i) Muquans facilities in Talence (black), (ii) PDN, during a phase of low tremor (red) and (iii) PDN, during a phase of high tremor (orange).

These data confirm the results of the simulations presented in deliverable D2.4 on vibration compensations. The anticipation of the risk on this subject, which led to the development of a new setup with a seismometer in the sensor head, thus enabled the AQG to perform measurement in an acceptable sensitivity range, in a volcanic environment, without loss of data during phases of high tremor.

4. Deployment of a MEMS station infrastructure

As reported in section 2 and detailed in the following sections, due to COVID-19-related delays, it has not yet been possible to get a prototype of a MEMS gravimeter ready for deployment at Mt. Etna. Nevertheless, the consortium decided to perform a field test on the complete infrastructure of a MEMS station, including power supply system and systems for data acquisition, local storage and transmission. In order to enhance the informative value of the test, it was decided to install the MEMS station at one of the higher elevation sites among those selected by the optimization algorithm which is described in Part B of the 1st Technical Report and in Nikkhoo et al. (2020). In particular, a site at 2650 m elevation was chosen, where ambient conditions during winter are expected to be close to the worst limit for the stations in the NEWTON-g's network. This will allow to spot and address possible unforeseen issues that may be driven by the harsh environmental conditions.

4.1 Preparation of the electronics case and sensor box

The final design of the modular infrastructure of the NEWTON-g MEMS gravity stations is described in D3.3 (On-field infrastructures). It consists of three main elements (i) the foldable steel structure holding the solar panel; (ii) the electronics case that contains the acquisition system, the router, the battery and the solar charge controller; (iii) the sensor box, hosting the gravity sensor (Carbone et al., 2020). D3.3 also presents in detail the design characteristics of the above three elements and the reasons that led to the choice of the components used to produce them.
The electronics case for the test MEMS station was assembled in the facilities of INGV-OE during September 2020. As stated before, the outbreak of COVID-19 impacted the administrative procedures aimed to purchase the needed components for the MEMS stations infrastructures and also delayed the delivery of certain materials that went out-of-stock during the lock-down period. As a consequence, it was not possible to complete the first electronic cases at an earlier time.

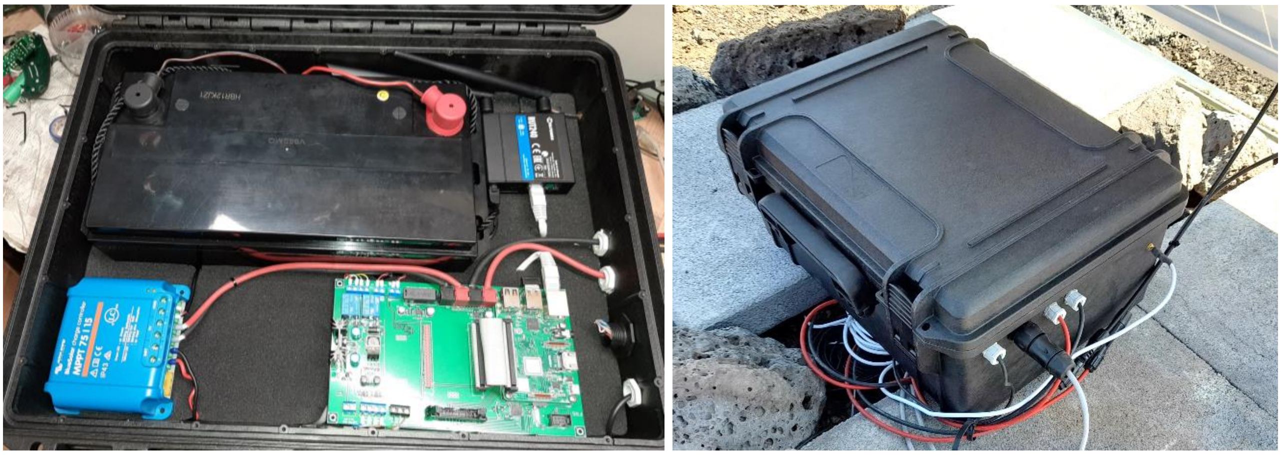

Figure 14 – Left: inside of the electronics case, with (a) battery (top-left); (b) router (top right); (c) solar charge controller (bottom-left) and (d) data-logging PCB board (FASEL-NEWTON-g board; bottom right). Outside connection (right side) are (from top to bottom): (1) to the router antenna; (2) from the solar panels; (3) from (signal) / to (power) the sensor box; (4) from (signal) / to (power) the soil probes. Right: view of the electronics case closed.

Two electronics cases (Fig. 14) were assembled, closely following the specifications outlined in D3.3 and we refer the reader to that document for details on the characteristics of the employed components. The most important module in the electronics case is the FASEL-NEWTON-g data-logging PCB board (bottom-right in the left panel of Fig. 14), which hosts: a Raspberry PI 3 model B+ (data acquisition and local storage), an ATMega328PB microcontroller (management of voltage/current sensors and soil-moisture probes), a BME280 sensor measuring air temperature, pressure and humidity, a voltage divider for battery monitoring and two current sensors. Another

BME280 sensor is mounted inside the sensor box and the signal from it is routed to the FASEL-NEWTON-g PCB board through an external cable that also routes the signal from the MEMS gravimeter to the electronics case and power from the electronics case to the sensor box.

During the pre-installation phase, two sensor boxes were also prepared for permanent installation in the field. After a thoughtful consideration of the alternatives available in the market, the consortium selected the Hoffman A181610PHC as the most suitable in terms of size, ruggedness and IP rating. The Hoffman A181610PHC box features an inner size of 456 x 405 x 263 mm, thus allowing to install a thick (a few cm) layer of insulating material inside it to protect the MEMS gravimeter from ambient temperature changes. The box also features resistance to a broad range of solvents, adequate impact resistance, and IP66 waterproof rating.

During the preparation phase, the bottom was partly removed from each sensor box (Fig. 15), in order to decouple the box from the gravimeter during installation and avoid transmission of shocks and vibrations of the external housing to the MEMS sensor. Furthermore, the panel connector for data and power exchange was mounted on each box (Fig. 15).

Figure 15 – Phases of preparation of the sensor box prior to installation in the field. A part of the bottom is removed (see text for details) and a panel connector is mounted on one of its sides.

4.2 Installation in the field

Preliminary design reliability checks that were performed in the field as of the summer of 2019 (see D3.2 for details) provided important indications on the characteristics of the selected components and solutions for the MEMS station and allowed to review some of the initial choices, toward the definition of the final configuration.

Figure 16 – A view of the first NEWTON-g's MEMS station infrastructure installed on Mt. Etna (site at 2650 m elevation).

The first complete MEMS station infrastructure, in its final configuration, was installed on Etna during the first half of October 2020 (Fig. 16). The installation site is located on the upper eastern flank of Mt. Etna, at 2650 m elevation and at a distance of 2.5 km from the summit craters (Fig. 17, left panel). As the first step of the installation, the concrete base for the sensor box was poured (middle and right panels of Fig. 17). Successively, the three main elements composing the station and the other accessory components were brought to the summit of Etna and installed at the selected site.

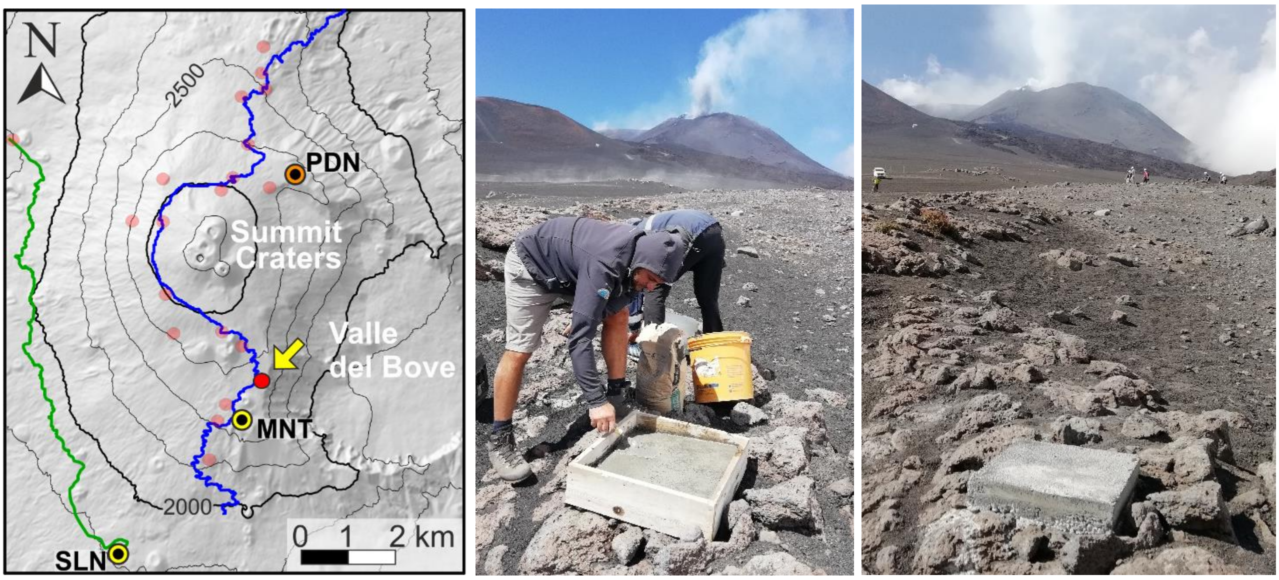

Figure 17 – Left: sketch map showing the position of the installation site of the MEMS station infrastructure (red dot evidenced by the yellow arrow). The positions of (i) the PDN Volcanological Observatory and (ii) the two stations equipped with iGrav superconducting gravimeters (MNT and SLN) are also indicated. Faded red dots indicate the possible position of the other MEMS stations forming the gravity imager. The blue and green tracks are roads accessible by authorized all-terrain vehicles. Middle and right: pouring of the concrete base and artifact after drying of the concrete. One of the craters in the SE Crater Complex is visible in the background.

Figure 18 – Left: the foldable galvanized-steel structure, holding the solar panel, installed at the summit of Mt Etna. It is one of the modules that compose the NEWTON-g's MEMS station infrastructure. Middle: four 50 x 50 cm, 20-kg concrete tiles are placed on the base frame of the galvanized-steel structure, in order to enhance its stability against wind. The electronics case is also placed on the base frame of the solar panel structure. Right: detail of the GSM antenna mounted on top of the solar panel structure.

As shown in the panels of Figure 18, the foldable galvanized-steel structure holding the solar panel, which is already quite heavy (75 kg, without the solar panel mounted on it), was further stabilized against strong wind through four concrete tiles (about 20 kg each) resting on its base frame (middle panel of Fig. 18). The electronics case is also placed on the base frame of the solar panel structure (middle panel of Fig. 18). The latter holds the antenna of the 4G/LTE router (right panel of Fig. 18).
The sensor box was screwed on the concrete base and sealed with waterproof mastic paste, resistant to temperatures between -40°C and +100°C. 50mm thick polystyrene sheets were installed inside the box to enhance thermal insulation (Fig. 19). Each MEMS station can be equipped with a changeable number of soil moisture probes. For the NEWTON-g gravity imager, Truebner SMT100 probes are employed (Fig. 20), which have been provided by GFZ, in the framework of project networking actions. This probe can measure the water content, permittivity and temperature of the terrain. It operates via the SDI-12 digital communication protocol, whereby the data logger (the ATMega328PB, in our case) requests data from the intelligent sensors; since each probe is identified with a unique address, a changeable number of probes can be installed at each site, without the burden of hardware changes to the data-logging PCB board. The probes are connected to the PCB board through a water-proof split box, outside the electronics case.

Figure 19 – Sensor box of the NEWTON-g's MEMS station. Left: The bottom of the box is partially removed before installation (see text for details). The sensor box is screwed on the concrete base and sealed with waterproof mastic paste. Middle: 50mm thick polystyrene sheets are used to enhance thermal insulation. Right: the sensor box after installation.

Figure 20 – One of the three soil moisture probes, which is part of the already installed NEWTON-g's MEMS station infrastructure, before it is buried in the volcanic ash at about 20 cm depth.

In the framework of the first installation of a MEMS station infrastructure at Mt. Etna, three soil moisture probes were deployed. They were buried in the volcanic ash surrounding the sensor box (Fig. 20), at a depth of about 20 cm and in a 120-degree configuration. The average distance between each probe and the sensor box is about 3 m.

4.3 Preliminary checks on data acquisition and transmission

The installation of the MEMS station infrastructure described in the previous sections is meant to check (i) the performance of its hardware components under the harsh environmental conditions at the summit of Mt. Etna, throughout the autumn and winter seasons, and (ii) the stability of data acquisition and transmission to the main collector host at INGV-OE.

As detailed in D3.3, data produced by the MEMS gravimeter and the other sensors in the MEMS station infrastructure are stored in the on-board 64GB microSD memory of the Raspberry module and are organized in three different families of ASCII files: (1) daily files with all the parameters in output from the MEMS gravimeter, acquired at a rate of 1 sample/sec, (2) monthly files of environmental parameters, acquired at a rate of 1 sample/min (ambient parameters inside the sensor box and data from the soil moisture probes); (3) monthly files of system state-of-health (SoH) parameters, acquired at a rate of 1 sample/min (battery voltage, current on load, temperature of the Raspberry CPU, etc.).

As of this writing, both the local data acquisition and the data transmission have worked as expected. In particular, the 4G LTE technology, employed for data transmission, has proved robust enough to allow regular data synchronization between the MEMS station and the central data concentrator at INGV-OE. Figures 21 and 22 show time series that were plotted from data in the "environmental" and "SoH" files, produced by the MEMS station.

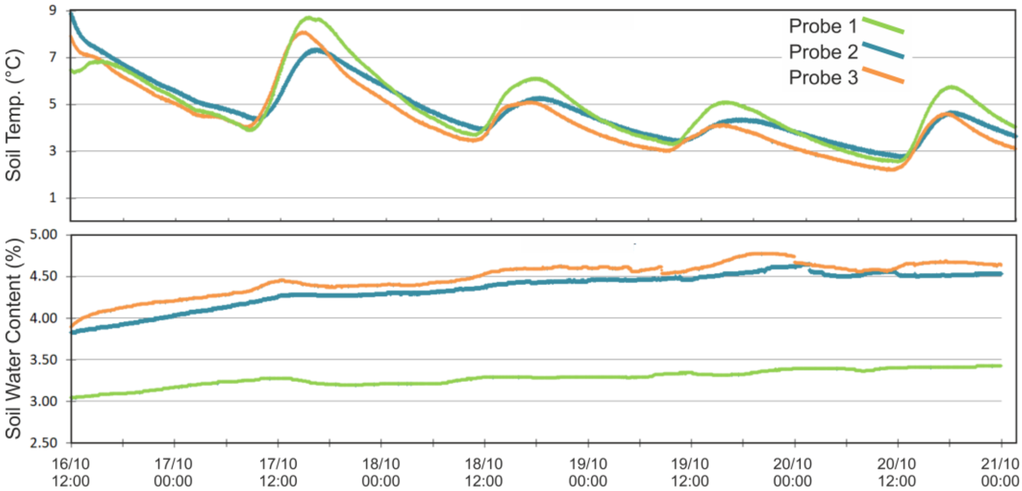

Figure 21 – Environmental parameters recorded through sensors (soil moisture probes, in this case) in the MEMS station infrastructure already installed on Mt. Etna

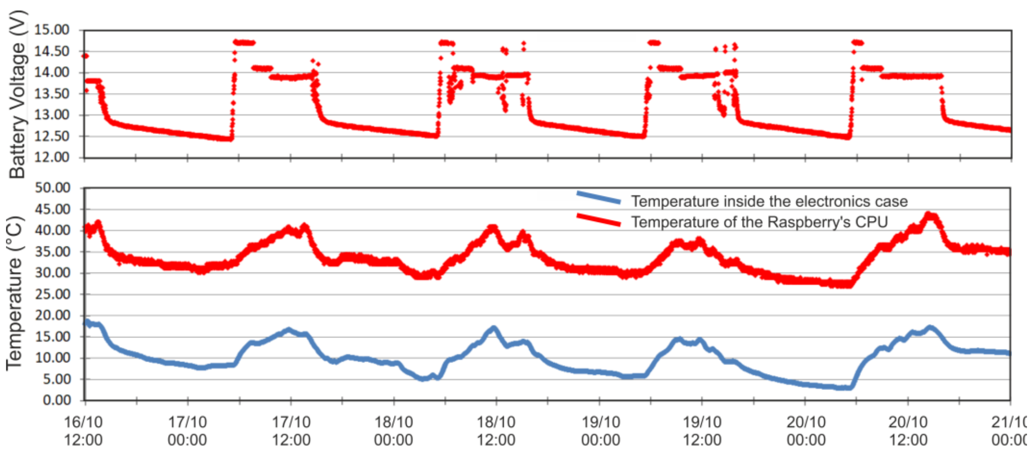

Figure 22 – SoH parameters recorded through sensors (ambient thermometer inside the electronic case and sensor on board of the Raspberry module) in the MEMS station infrastructure already installed on Mt. Etna

5. Expected timeline to complete deployment of the gravity imager

Deliverable 2.5 (MEMS device prototype) described the progress achieved by the UNIGLA team in developing a MEMS gravimeter, called Wee-g, in the framework of the NEWTON-g project. The same document, also reported on the significant impact that the COVID-19 pandemic has had on the ability for the UNIGLA team to carry out the necessary research, development and assembly of Wee-g. In D2.5, it was described that it could still be possible to deploy 1-2 MEMS devices onto Mt Etna before the end of 2020, followed by further deployment in 2021. The following two sections aim to describe the progress that has been made in the development of Wee-g since the submission of D2.5 and the challenges that are still present, due to current COVID-19-related restrictions.

5.1 State of progress of the MEMS gravimeter

Since previously reporting on the status of Wee-g in D2.5, it has been possible to conduct a significant level of R&D and testing, both within and outside UNIGLA facilities. Government and University enforced restrictions meant access to UNIGLA facilities was not possible until the end of July 2020, with limited access to the members due to building capacity restrictions and social distancing measures that are still in place as of this report. Access to the JWNC for fabrication and assembly of MEMS devices has also been significantly affected due to these on-going measures.

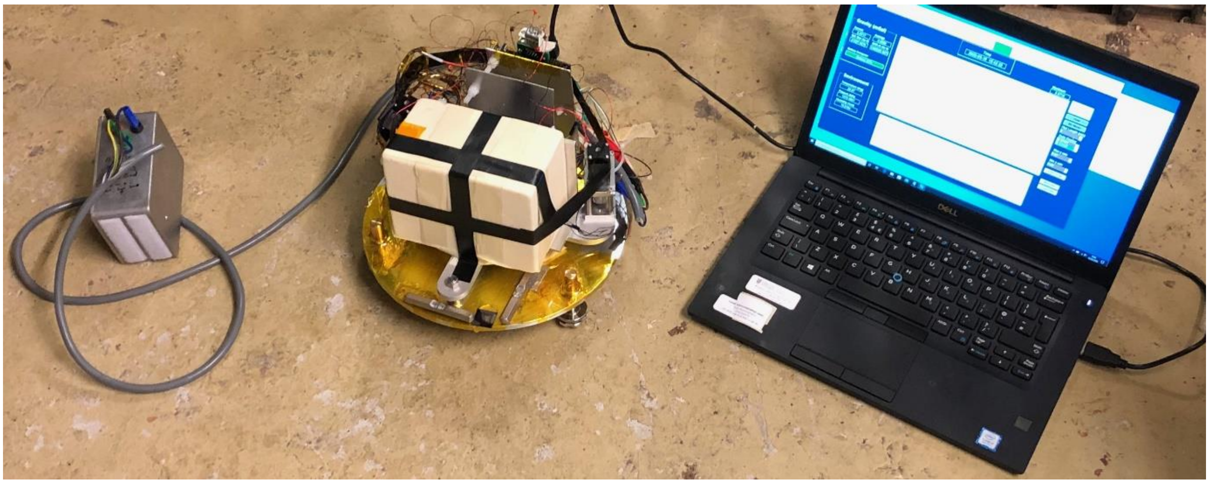

Figure 23 – Test rig set up that was reported in Deliverable 2.5.

Figure 24 – New test rig setup used for long-term testing of the MEMS gravimeter. The device is housed in a cylindrical enclosure, in order to better replicate the expected final set up.

An example of a change that has been made during this period is the addition of a temporary cylindrical enclosure for the test rig (previous and new test rig setups are shown in Figures 23 and 24, respectively). This is to better replicate the expected set up that would be used for future field tests and the final deployment.

The addition of a 4th heater servo into the enclosure was also made. Prior to this, heater servos were applied to the 3 thermal insulation layers that surround the package. The 4th servo aims to control the temperature of the air that is within the main enclosure that houses all the contents of the gravimeter. This has been achieved using a power resistor that has been placed on the inner wall of the enclosure. A small 12V fan is placed next to the resistor to circulate the air around the enclosure.

Long term testing within UNIGLA facilities, using the new setup (Fig. 24), has shown successful tracking of Earth tides (Figure 25), both in a quiet environment, with minimal temperature changes, as well as in a laboratory that is open to the outside air temperature changes and power generators (Fig. 26). Measurements during the month of August showed ambient temperature change within this environment of approximately 3 degrees

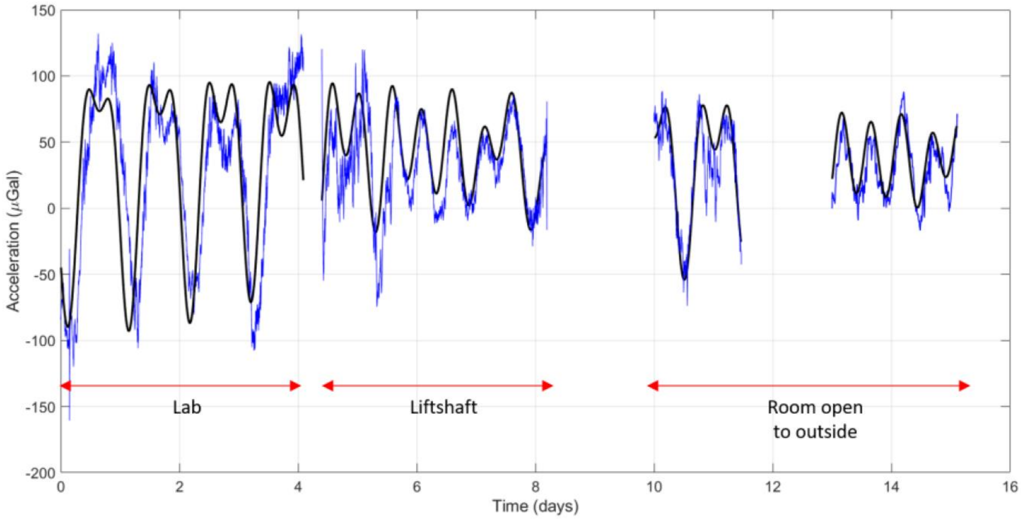

Figure 25 – Measurement of Earth tides in three different locations. The simulated data is shown in black, while the data from the MEMS gravimeter is shown in blue.

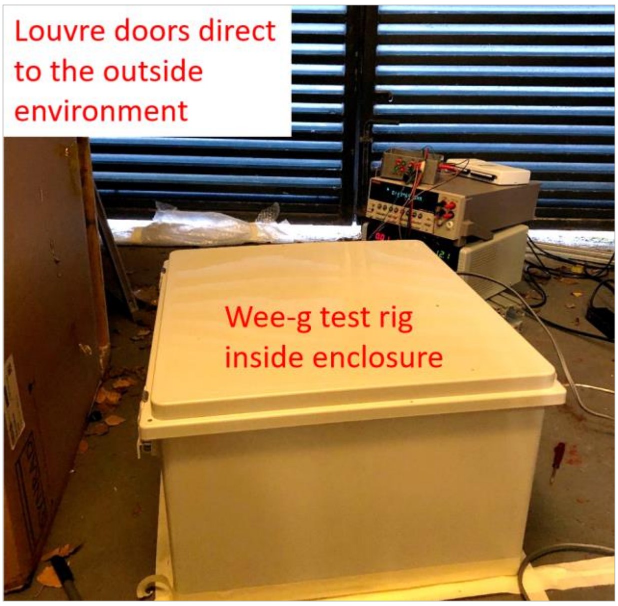

Figure 26 – Measurement setup where the Wee-g device is exposed to outside temperature changes.

During the tests in the open laboratory, the MEMS device was placed within the same plastic box that is used for installation on Mt Etna (Figs. 19 and 26).
Another change that is currently underway is the installation of an inclinometer onto the baseplate of the device. This will allow for a remote digital reading of the local tilt of the device through the GUI, to aid with the installation procedure, as well as monitoring tilt over time. Currently, bubble levels are installed when the device is sitting at its optimal position and are then referenced to when re-levelling the device to get it to roughly the optimal position. Fine tuning of the feet adjusters is then required to get it to the optimal position. The inclinometer, however, can be installed and fixed into place prior to the device being in its optimal position. The device can then be levelled to its optimal position and the offset of the inclinometer, shown on the GUI, can be logged. Relevelling of the device can therefore be carried out by adjusting the feet to match the logged offset, providing a more reliable reference than bubble levels.
UNIGLA has recently received the first prototype field enclosure from Wideblue, which is shown in Figure 27. Currently, the plan is to move the MEMS device from the test rig that has been used for long term testing, to the prototype field enclosure. It is envisioned that this field prototype would be sent to INGV for testing on Mt Etna before the end of the year. It should be noted that this prototype is not IP67 rated as the final production version would be; however, this should not be an issue since the MEMS gravimeter will be installed inside the waterproof sensor box to protect it.
Before being shipped to Italy, the performance of the field prototype will be checked at UNIGLA. Tests that are planned include (i) taking long-term measurements in the same environments where the previous rig setup was tested and (ii) performing discrete gravity measurements around the University campus, at locations where previous surveys were conducted with commercial gravimeters. Once these tests have been conducted, this unit would be delivered to INGV-OE.

Figure 27 – Prototype field enclosure for the MEMS gravimeter. It is similar to the final version, apart from some characteristics, including the waterproof rating.

Fabrication and assembly of MEMS devices in the JWNC (Fig. 28) is currently in progress. Kelvin Nanotechnology (KNT) is still contracted to make the MEMS layers and this is currently on-going. As mentioned, there are still restrictions in terms of ability to access the facility, due to capacity and social distancing restrictions in place. This has had the effect of increasing the amount of time it takes to go through the assembly process. At the moment, there are no indications that these restrictions will change soon; therefore, the consortium will need to take this factor into account for the definition of the timeline of devices production and installation on Mt. Etna.

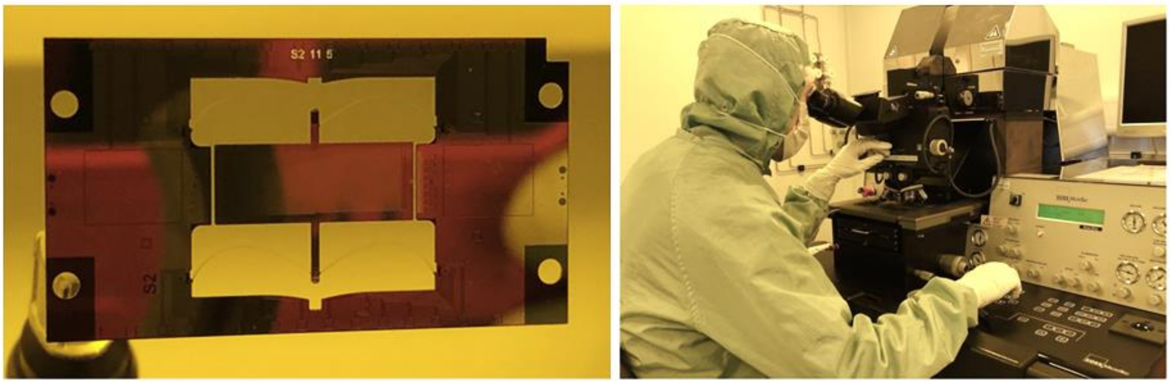

Figure 28 – Left: MEMS gravimeter. Right: Assembly of Wee-g at the JWNC.

Finalization of the device electronics is also in progress, with the hopes of freezing the design in the near future. Currently, the electronics is in a stacked formation as described in D2.5, though the aim is to merge the stack into one board with the ability to then use flex cables instead of manganin wires. Though this would not be implemented into the current field prototype to be delivered by the end of 2020, the plan is to achieve this improvement in the near future and implement it into the devices that will be sent to Italy at a later stage, for deployment on Mt. Etna.

5.2 Plan to complete the deployment

As mentioned in the previous section, the current goal is to get the field prototype of the MEMS gravimeter deployed onto Mt Etna before the end of the year. Currently, we are looking at the possibility of delivering the field prototype from mid-late November 2020, though there are still challenges that will need to be taken into consideration. Currently, the most serious challenge is the travel restrictions that are still in place for the UNIGLA team. As of writing this report, the University staff is still not allowed to travel abroad, and there are no indications that this would be changing in the near future. This implies that the UNIGLA team would not be able to personally deliver and install the field prototype at Mt Etna.

Failing this being an option when the time comes, delivery of the Wee-g would need to be made through a courier service, which presents its own challenges and risks. Previous discussions with Wideblue, the company in charge of producing the external enclosures for the MEMS devices, indicates that a Pelican-like case could be used for transportation, together with g-shock and orientation stickers, to ensure that the device is properly handled at all times by the courier. However, the risk is still present for the courier to mishandle the device during delivery.

The field prototype could be delivered with a spare MEMS package in the event that damage to the prototype occurs during transit. A separate shipping container will need to be organized to house the spare package, to avoid that the same mishandling during transportation damages both field prototype and spare MEMS package. It should be noted that useful tests can still be conducted with the Wee-g in the event of damage to the MEMS package during transit. Such tests can include long term thermal stability of the device, as well as tilt adjustment tests at the installation site.

A thorough user manual will also need to be written up by the UNIGLA team and passed on to the INGV-OE team, to ensure smooth installation and understanding of how to use all the features on the device and to debug issues that may occur.

The installation site on Mt. Etna for the MEMS field prototype will be chosen by the INGV-OE team, taking into account (i) the indications from the numerical algorithm for optimizing the configuration of the gravity imager, developed by the GFZ team (Nikkhoo et al., 2020), and (ii) constraints imposed by environmental issues, including reachability of the site at any time during winter to allow local debugging (only sites at lower elevation will be considered, where snow accumulation is not an issue).

In parallel to the above, fabrication and assembly of the devices will continue. After testing of the field prototype at UNIGLA, it is envisioned that the final design changes will be implemented, and the design of the device frozen for mass production by Wideblue. This would also allow the assembly of the enclosures to begin as parts are delivered to the company from their suppliers. Enclosures would be delivered to the UNIGLA team in batches as they are completed, to allow for testing of delivered enclosures to be carried out in parallel to assembly of further enclosures.
Assuming COVID-19 restrictions are lifted by the start of 2021 and UNIGLA members are allowed to travel again, deployment of the devices forming the gravity imager could potentially be carried out in batches through the year – ideally we would hope this would be during Q1 and Q2 of 2021. Failure for these restrictions to be lifted would mean the UNIGLA team would again be forced to go through a courier service for delivery of devices.
It must be kept in consideration that the possibility of a government enforced lockdown similar to that experienced earlier in the year is still a possible hurdle that could have an effect on the plans described above. Should that be the case, another revaluation of the deployment would need to happen.

To resume the above, the current timeline for deploying the first MEMS gravimeter field prototype and for starting the production of further Wee-g devices is as follows:

- Late October:
  - Testing of electronics to be installed into the field prototype.
  - Swapping of MEMS package from test rig to field prototype.

- Early November
  - Field tests and long-term measurements using the field prototype of the MEMS device; comparison with data from the device in the test rig setup.
    - Outdoor tests where previous gravity measurements were taken.
  - Assembly of additional MEMS devices for future enclosures.

- Mid-late November
  - Arrange delivery of field prototype to INGV-OE, for installation at a site on Mt. Etna, through UNIGLA team or through courier.
  - Feedback on field prototype to Wideblue to apply final changes needed to the enclosure before production of final design.

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