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Introduction

The *gravity imager*, which will be developed under NEWTON-g and field-tested at Mt. Etna volcano, is composed by an array of microelectromechanical system (MEMS) *pixels* and an absolute quantum gravimeter (AQG). The main aim of the present document is to define the final configuration of the *gravity imager*, taking into account the environmental constraints and the gravimetric signature of volcanic processes highlighted in Deliverable 4.1, especially in terms of magnitude, timescale, detection zone and probability of occurrence of these processes. The first section of the present document defines the location, size and shape of this gravity imager. Section 2 describes the recorded data files produced by each sensor in the *imager* and the possible technologies to transmit data from the field to the data acquisition centre in the facilities of INGV-CT. In section 3, different complementary measurements which could be performed during the field test of the *gravity imager*, to better distinguish volcano-related from non-volcanic changes, are presented. Finally, the last section shows the different cross tests between MEMS and AQG which will be conducted before the deployment of the gravity imager.

1. Location, size of the pixels, size of the array, shape of the array of gravimeters

The gravity imager will be installed at elevations above 2000 m, in the summit zone of Mount Etna Volcano (figure 1, left). Harsh environmental conditions dictate that a great cure must be paid to different aspects of the deployment, i.e., installation of the sensors, power supply, data management and maintenance of the measuring system. Indeed, land cover mostly consists of volcanic ash and lava flows (figure 1, right) and, during the winter season (about 5 months) snow cover prevents the access to the summit, impacts the gravity measurements (figure 5 of deliverable D4.1) and degrade the efficiency of solar panels.

Figure 1: Summit road (left) crossing the active Craters of Etna and (right) land cover, mostly consisting of ashes and lava flows.

1.1 Insights from D4.1

The design of the *gravity imager*, to be developed in the framework of NEWTON-g, is partly based on deliverable D4.1 (Parameters definition for devices design). D4.1, issued under WP4, is meant to highlight the gravity signature of the volcanic processes, with a special focus on Mount Etna. In particular, the following key features of volcano-related gravity changes were discussed:

- Magnitude
- Timescale
- Detection zone

Observed gravity changes at Etna in the last ~30 years have been associated to several processes, including magma transport at depth, flow in the shallowest portion of the feeding conduits, gas segregation prior to lava fountaining, creation of fractures in the shallow layers (see Carbone et al., 2017 and D4.1). In particular, considering the results of past studies dealing with the gravity changes detected at Etna, five volumes within and below the volcanic edifice stand out as the most likely locations of mass changes, capable of producing gravity change measurable at the surface, within the timespan of NEWTON-g. Three of these locations are below the summit craters zone at elevations of 1500, 0 and -2000 m a.s.l., respectively. The other two locations are off-centered by ~3 km to the south and north along the S and NE Rifts, respectively, and at elevations of 1000 and 1500 m a.s.l., respectively. Figure 2 shows maps of gravity anomalies induced by mass sources in the above locations.

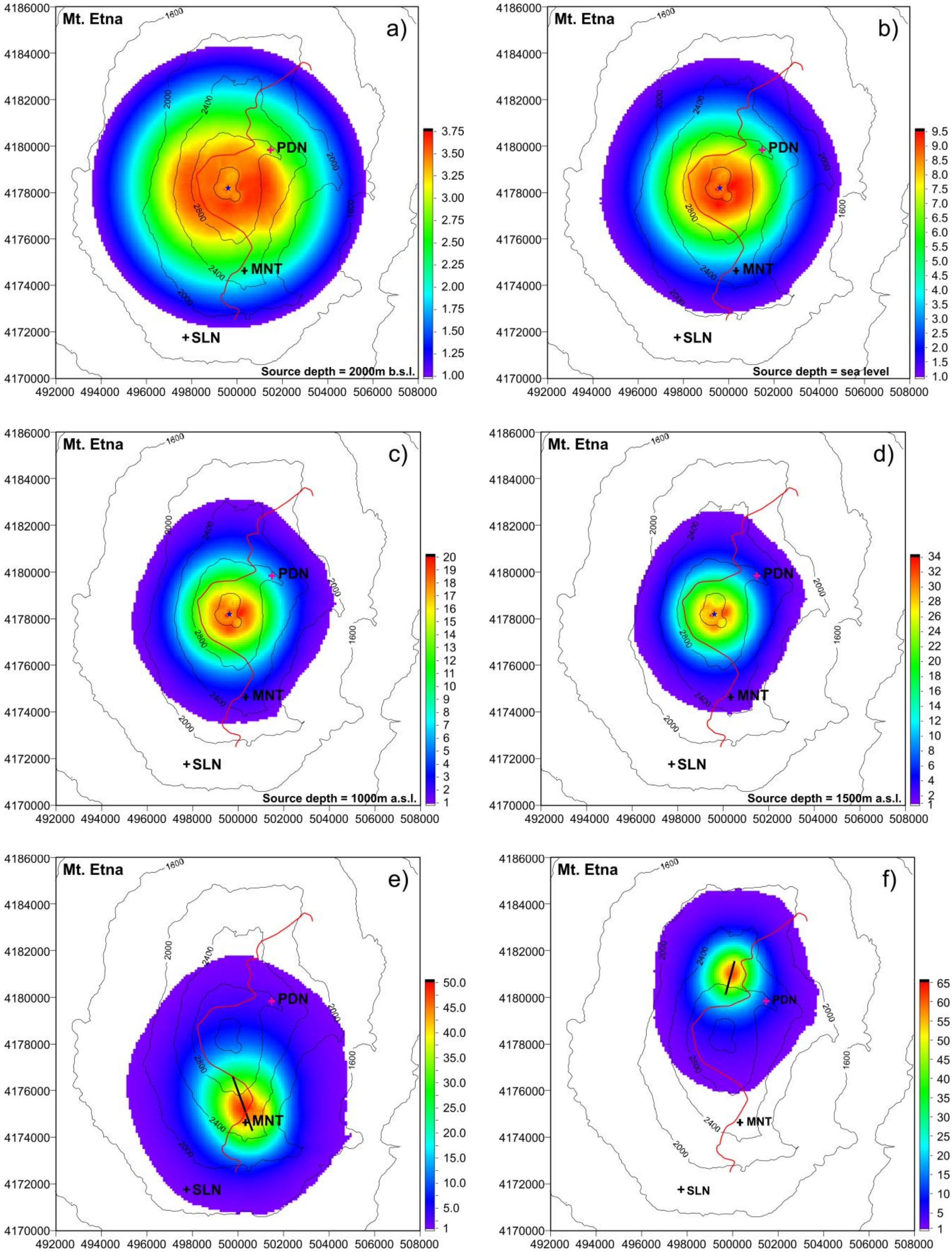


*Figure 2: Maps of Mount Etna showing positions of the gravity stations equipped with iGrav meters (SLN and MNT), of the Pizzi Deneri Volcanological Observatory and of the road crossing the summit craters zone (red track). a)-d) Gravity anomalies (in microGal) produced by a point source beneath the summit craters at different depths. In all cases, the same mass change (1.45 * 10^{10} kg) is assumed. a) source at 2000 m below sea level, b) source at sea level, c) source at 1000 m above sea level, d) source at 1500 m above sea level. e)-f) Gravity effect (in microGal) due to elongated mass sources (dikes) below the south and north-east slopes of Etna. e) (Budetta et al., Geophys. J. Int. 1999) Mass change of 2.5x10^{10} kg, source depth at 1000 m above sea level, f) (Carbone et al, JVGR 2003) Mass change of 1.5x10^{10} kg, source depth at 1500 m above sea level.*

Note that point (i.e., spherical) sources were assumed for locations below the summit craters, while elongated source were assumed in the cases of source locations along the rift zones. As shown in Fig. 2, the gradient of a gravity anomaly depends on the depth of the source. Very shallow sources generate local anomalies, only observable if the sensors are close to the active zone, while broader anomalies are induced by deeper sources.

1.2 Anticipated operational features

1.2.1 AQG

In order to properly design the gravity imager and, in particular, choose the location where the AQG will operate on Mont Etna, we have to anticipate the design of the AQG itself that will be developed in the frame of WP2. It is planned that the device will consist of 5 boxes for transportation, and only 3 boxes for operation (Figure 3), separate in two ensembles: a sensor head and a control unit. A cable links the two sub-systems. The two remining boxes will have to be stored in close vicinity for maintenance. The dimensions of the different sub-systems are not precisely determined yet, but the following figures of merit should be used:

- Laser system: base of 60 cm x 110 cm and height of 50 cm.
- Electronics and thermal control: base of 60 cm x 101 cm and height of 45 cm.
- Sensor head: cylinder with a diameter of 40 cm and a height of 80 cm.
- The maximal distance between the control unit and the sensor head is 15 m.

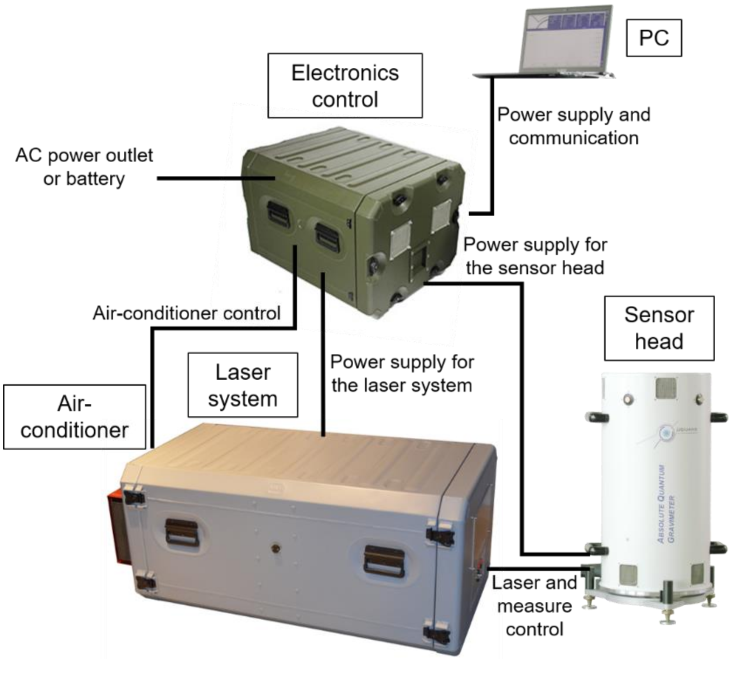


Figure 3: Schematic of the possible AQG design.

This gravimeter can be operated outdoors, provided that a solid and levelled installation surface is available. However, its operation and lifetime will be improved if it is protected from the sun and precipitations (rain, snow). In any case, it should not be exposed to temperatures out of the range of 0°C – 40 °C. Moreover, exposure to wind can cause vibrations which will degrade the measurement. Volcanic tremor may also induce unwanted effects, as discussed in section 1.5.

The total power consumption of the whole system is no precisely determined yet, but a range of 400 W to 800 W can be assume, depending on external temperature.

1.2.2 MEMS

The fully packaged MEMS device will be a cylinder with a base diameter of about 15 cm and a height of about 30 cm. Figure 4 shows the MEMS chip at the core of the device. Its power requirement is 5 W and the operating temperature range is not limited, as long as enough current is available to thermostat the device. In the context of this project, 75 MEMS will be produced, 30 for the deployment and 45 spares.

Figure 4: Picture of a MEMS sensor.

Concerning the environmental aspect, the MEMS do not need to be installed indoors, but they have to be accessible, and mounted on a solid surface. Each MEMS device will be fitted with a solar panel and battery storage. and will be mounted on a tilt stabilized platform, to avoid that tilting may affect the performances of the gravity sensor. Finally, as in the case of the AQG, the signal from MEMS devices is also expected to be affected by wind and volcanic tremor vibrations. Robustness to these factors will depend on many factors, including the sampling frequency.

1.2.3 Summarizing table

Operating features	**AQG**	**MEMS**
Operating temperature range	[0°C – 40°C] (Temperature range over which the 1 µGal resolution and stability is guarantee)	The MEMS device will be operated above ambient temperature. Whether this is stepped to reduce power consumption will depend on whether we are concerned by the tares in the data that will result from these steps.
Floor condition requirements	Concrete floor. Legs of the AQG directly set on the floor.	Solid base to mount the enclosure. It will need to be roughly level.
Typical power consumption	500 W	~5 W
Maximum power consumption	800 W for high external temperature	~5 W

Dimensions	Laser system: 50 cm x 60 cm x 110 cm Electronics and thermal control: 45 cm x 60 cm x 101 cm Sensor head: Height: 80 cm Diameter: 40 cm Cable length max: 15 m	Height: 30 cm Diameter: 15 cm
Weight	Sensor head:40 kg Control unit: 2 x 40 kg (without air-conditioner)	Sensor head: <1kg Tilt platform and electronic readout: ~2kg
Required footprint on the ground	2 m^2	< 30 cm x 30 cm

Table 1- operating features of the pixels of the gravity imager.

1.3 Location and size of the gravity imager

1.3.1 Location of the absolute reference pixel (AQG)

The choice of the installation site of the AQG is guided by the geophysical objectives of the *gravity imager*, the operating features of the instrument, and the logistical constraints set by the harsh environmental conditions in the summit zone of Mount Etna during a typical year.
In order to optimize the position of the AQG on Etna, we firstly need to consider the gravimetric signature of the volcanic events. This information is provided by D4.1 and briefly recalled in this document.
We describe below the choices that have been shortlisted so far.

- Pizzi Deneri Volcanological Observatory (PDN); altitude: 2800 m

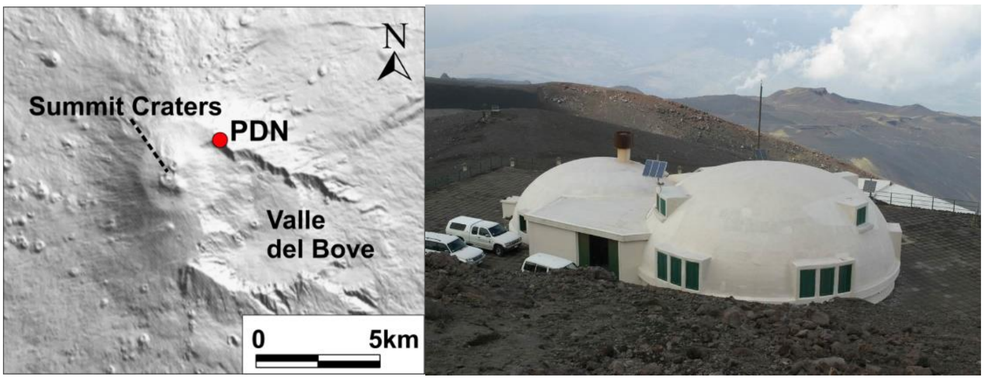


Figure 5: map of Mount Etna volcano showing the position of PDN (left). A photo of the observatory is shown on the right.

This location is the closest from the summit craters (distance is ~2500m; Fig. 5, left), so the sensitivity to volcanic events should be the strongest. It can be accessed by all-terrain vehicles through the summit road (Fig. 1), except during winter season, when it can be only accessed by snowcar or helicopter. We can thus assume that it would be difficult to provide

maintenance of the instrumentation during this period of the year. The temperature inside the building vary in a range between ~0 and ~10 °C (deliverable 4.1).
The site has indoor space with a concrete floor (Fig. 5, right) to shelter the AQG and a GPS station is in the close vicinity. However, this location has no power supply available and no internet connection. The deployment of the AQG at this site, would imply the need to set up a system that can produce more than 500 W of electrical power per day and to use a wireless or cellular connection to transmit the data.
Continuous gravity measurements through spring gravimeters have already been accomplished at this site, during intervals ranging from several months to a few years (Carbone et al., 2017). Nevertheless, establishing a new absolute station with continuous monitoring at PDN would be a great asset for the surveillance of Mount Etna in general.

- La Montagnola (MNT); altitude: 2600 m

Figure 6: map of Mount Etna volcano showing the position of MNT(left) and photo showing the hut at La Montagnola, with the summit active craters in the background (right)

The Montagnola is a site accessible nearly all year long, ~3500m SE of the summit crater, and featuring mains electricity (Fig. 6). A hut and a semi-underground concrete box of ~1m^3 (Fig. 7) are available at this site to host the instrumentation. Unfortunately, to install the sensor head in the box and the lasers and electronics systems in the hut is not feasible, due to the too long distance (23m) between the two structures. The installation of the AQG on this site would thus require the building of a new semi-underground concrete box closer to the hut. Assessment of the cost of this infrastructure is needed before deciding whether this solution is feasible or not. Moreover, the temperature was never recorded neither in the hut nor in the box. It is unlikely that the temperature goes negative, but there is still a non-negligible risk that needs to be taken into account. Concerning the hut, it would be possible to install a thermosetting system, while in the concrete box this is hardly feasible.

Figure 7: Google Earth screen shot of the hut and the box (left) and inside of the concrete box (right)

An iGrav superconducting gravimeter is already in operation at this site, so we could benefit from another gravity measurement point if the AQG is installed elsewhere. On the contrary, if this site is chosen, cross validation tests could be accomplished using the signal from the two high-precision gravimeters. A GPS/seismic station, belonging to the INGV-CT monitoring network, is available ~300 m away, which can be used to spot important ground deformation. Furthermore, a weather station will be soon installed at MNT.

- Cable car arrival station, altitude: 2500 m

This location is inside the cable car arrival station (Fig. 8), so the main issue is the noise coming from the engine of the cable car, human activities (the site is visited by hundreds of

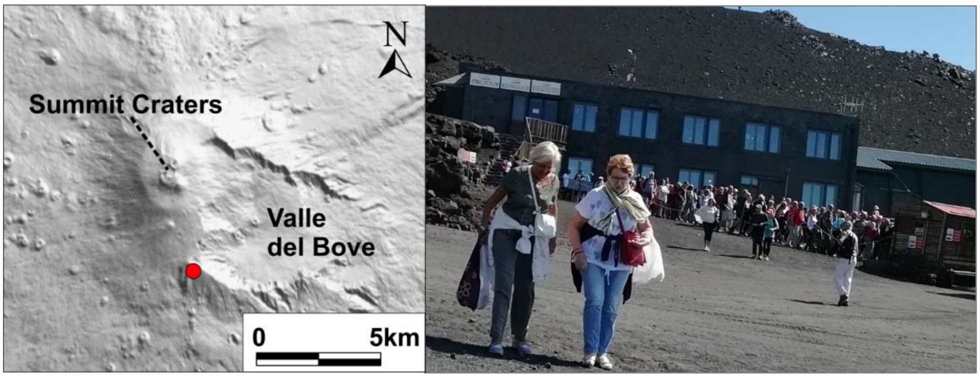


Figure 8: map of Mount Etna showing the position of the cable car arrival station (left) and photo of this site (right).

turists daily) and cars. Despite these drawbacks, the environmental conditions are interesting, since the temperature in the room is quite well controlled, there is space, the floor condition appears to be good and there is the availability of mains electricity.

- Serra La Nave (SLN); altitude: 1730 m

SLN is an auxiliary location on Mount Etna. Although it is ~6500m from the summit craters, hence not ideal for what regards sensitivity to volcanic activity, this site features appealing advantages so it is considered as a good candidate for preliminary tests and storage. Indeed, the instrumentation could be installed in the facilities of the Serra La Nave astrophysical observatory (1730m a.s.l.), managed by the Italian National Institute for Astrophysics (INAF). Installation space is available, with concrete floor, main power supply and access to the Internet. This site already hosts an iGrav gravimeter managed by INGV-CT and a weather station managed by INAF. A seismic/GPS station (INGV-CT network) is also available 30m from the installation site of the iGrav.

1.3.2 Summarizing table

Site	**Advantages**	**Drawbacks**
Osservatorio Pizzi Deneri (PDN) Alt. 2800 m	- Space - Close to the crater - Meets AQG temperature range - Floor conditions	- No power supply - No internet - Very difficult access for maintenance in winter
Montagnola (MTN) Alt. 2600 m	- Power supply - Close to the crater	- Not enough space inside the hut, box of 1m² outside

	- Floor conditions - Internet connection - Easy access for maintenance	but too far for the cable length of the AQG
Cable car stop close to MTN Alt. 2500 m	- Temperature well controlled - Power supply - Floor conditions - Space - Close to the crater - Easy access for maintenance	Noise due to the engine, crowds, cars
SLN Astrophysical Observatory Alt. 1730 m	- Indoor - Good floor - Easy power supply - Easy road access - Data connection	Far from sources

Table 2 - Overview of the possible installation sites for the AQG

In conclusion, important information is still missing and the final decision on the installation site for the AQG cannot be taken at the present stage. Indeed, an estimation of the number and cost of solar panels and batteries required for the AQG has to be done to validate the possibility to install at PDN. Concerning MTN, quotations for (i) an additional concrete box closer to the hut and (ii) thermosetting systems in the hut and concrete box are required, in order to be conclusive on whether the AQG can be installed at this location or not.

In the hypothesis were the conditions are fulfilled for all the sites, we present our choice for the location of the AQG:

- First choice: PDN
- Second choice: MTN
- Third choice: Cable car stop

If, for any reason, the first choice cannot be met in the course of the project, the consortium shall go for the second choice, and so on.

1.3.3 Location of the relative pixels (MEMS) considering the logistical aspects

The inter-node distance and the location of the MEMS devices are a compromise between logistical constraints and the results of the numerical simulation performed by the GFZ team, aimed at retrieving the best configuration for the MEMS array (i.e., the configuration that would allow to precisely detect the mass sources likely to activate in the time window covered by the field-test at Etna).

Concerning the harsh environmental conditions in the summit zone of Etna, it will be necessary to protect the MEMS devices using waterproof plastic boxes. There are 10 seismic/GPS stations managed by INGV-CT (semi-underground concrete boxes of 1 m^3) in the area where the gravity imager will be installed (squares in Fig. 9; only 5 boxes in the summit part, above 2500 m), which could be used to protect the MEMS devices. The temperature inside these boxes vary between 0°C and 25°C (deliverable 4.1). However, most MEMS gravimeters will be installed elsewhere to allow a better coverage of the summit area of Etna and improve the space resolution of the array.

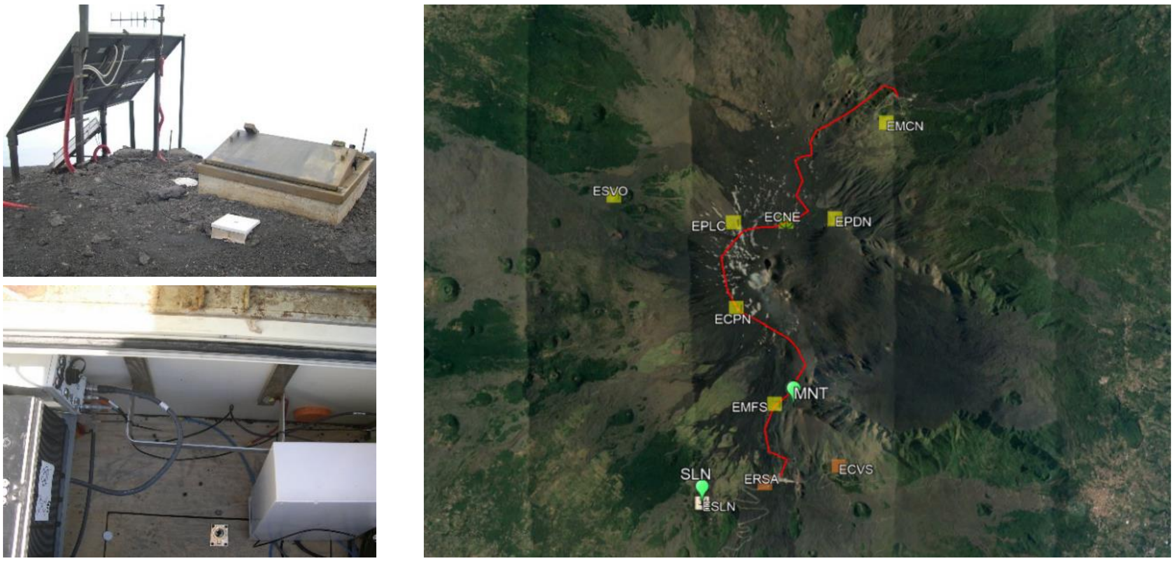


Figure 9: One of the semi-underground concrete boxes hosting the seismic/GPS stations in the INGV-CT monitoring network (left top and bottom) and map of Mt Etna with the location of the existing seismic/GPS stations close to the summit.

Hence, in the context of WP3, we will design and develop protecting boxes that will be installed in locations chosen on the grounds of the geophysical objectives of the gravity imager, the operating features, and the logistical and environmental constraints for operation at Mount Etna during a typical year.

With regard to the last point, deployment along the summit road (read track in Figs. 2 and 9) would permit an easier access to the chosen sites, especially as far as maintenance is concerned. Indeed, this presents the advantage to facilitate the maintenance of the 30 operational points during the 2-year field-test interval and to reduce the risk to have many points not working for extended periods. A solid and flat base, such as the top surface of a lava flow or a rock big enough to be stable, must be then searched in the close vicinity of each chosen installation point along the road. However, in some cases, it will be probably necessary to go relatively far from it to find a satisfactory installation base.

1.3.4 General considerations on the network design

Discrete gravity measurements have been performed at Etna by INGV-CT over the past 30 years, along a network of ~70 points and using standard spring gravimeters. This information provides a clear view of the most likely positions of mass sources that could induce gravity changes relevant to the aims of NEWTON-g.
On the grounds of the results outlined in D4.1, and the environmental constraints in the summit zone of Etna, several geometries were suggested for the network design during the 1st project workshop, held in Postdam on 9 and 10 October 2018 (see D5.2). A summary of this discussion is reported in the following. It is important to note that the Valle del Bove area can only be accessed on foot and thus it is better not to consider this area when searching for the best configuration of the MEMS pixels.

<u>Possible geometries of the MEMS array:</u>

- Stations distributed along three or more straight lines bifurcating from the summit, along or bisecting the fracture zones.

- Few pixels on each 500 m elevation slice all around the volcano.
- Points distributed along a spiral-like path.
- North-South linear profile passing through the summit craters zone, in addition of an almost circular line at elevation of ~2000m.This geometry could follow existing roads.

GFZ pointed out that inter-station distance should be smaller close to the summit and larger away from the summit. An inter-node distance of ~500m should be considered according to the results of deliverable D4.1, since it enables to spot most of the mass sources deduced by past studies (Carbone et al., 2017). Concerning geometries that do not follow the road, INGV pointed out that the access might be difficult to certain points, which could prevent maintenance and increases the risk to have many points not working for extended periods. It was also noted that more than one MEMS device could be installed at the same point, at least in sites where there are GPS/seismic stations of the INGV-CT monitoring network that could host the pixel, in order to improve the quality of the signal, at the expense of the spatial resolution.

The relative positions of the MEMS array and AQG is also a factor to take into account. Indeed, if the AQG is installed in a position close to the summit (e.g., PDN) and a volcano-related change occurs, the AQG should spot it. Hence, if a MEMS records a change that is not observed through the AQG, that is likely an instrumental effect. Conversely, if a cluster of MEMS is much closer to the craters than the AQG (in the case it is installed at MNT, or, worse, at SLN), it will be more difficult to tell a real change from an instrumental effect.
Possible ways to calibrate the relative MEMS devices through the AQG include (i) using the tide model provided by the AQG and (ii) performing measurement with the AQG at the sites where key MEMS pixels are installed to directly check the performances of the MEMS array. In this case, a solid base for the AQG as to be anticipated near the MEMS stations.
At the end of the Potsdam meeting it was agreed that GFZ would perform a calculation, aimed at retrieving the sensitivity of various network configurations, that is their capacity to detect gravity changes expected to occur in the summit zone of Etna. The final configuration of the MEMS array will be thus chosen also on the grounds of the results from this calculation.

1.3.5 Shape and size of the gravity imager considering the results from the simulations

In order to constrain the he optimal design of the gravity imager, the GFZ team has worked on a code to identify the network configuration(s) that minimizes the uncertainties associated with the inferred location and intensity of possible events of mass change during the timespan of the field-test at Mt. Etna. Estimating what sources might become active during the 2-year field-test interval is challenging, as magma transport and storage at Etna occurs in complex and constantly evolving ways. One possible approach is to consider the most relevant gravity changes during the last ~30 years (the period of time over which gravity measurements are available for Etna) and consider redundant mass source as the most plausible sources of gravity change in the near future. Published studies involving the inversion of gravity changes observed at Etna indicate five locations, within or below the volcanic edifice as good candidates for potential mass changes in the near future (see Fig. 2). They were thus used to run the resolution tests aimed at checking the network performance.
We addressed the problem of identifying the optimal network design by using the genetic algorithm, which is a nonlinear optimization method. The main assumptions and constraints in the optimization procedure are summarized below:

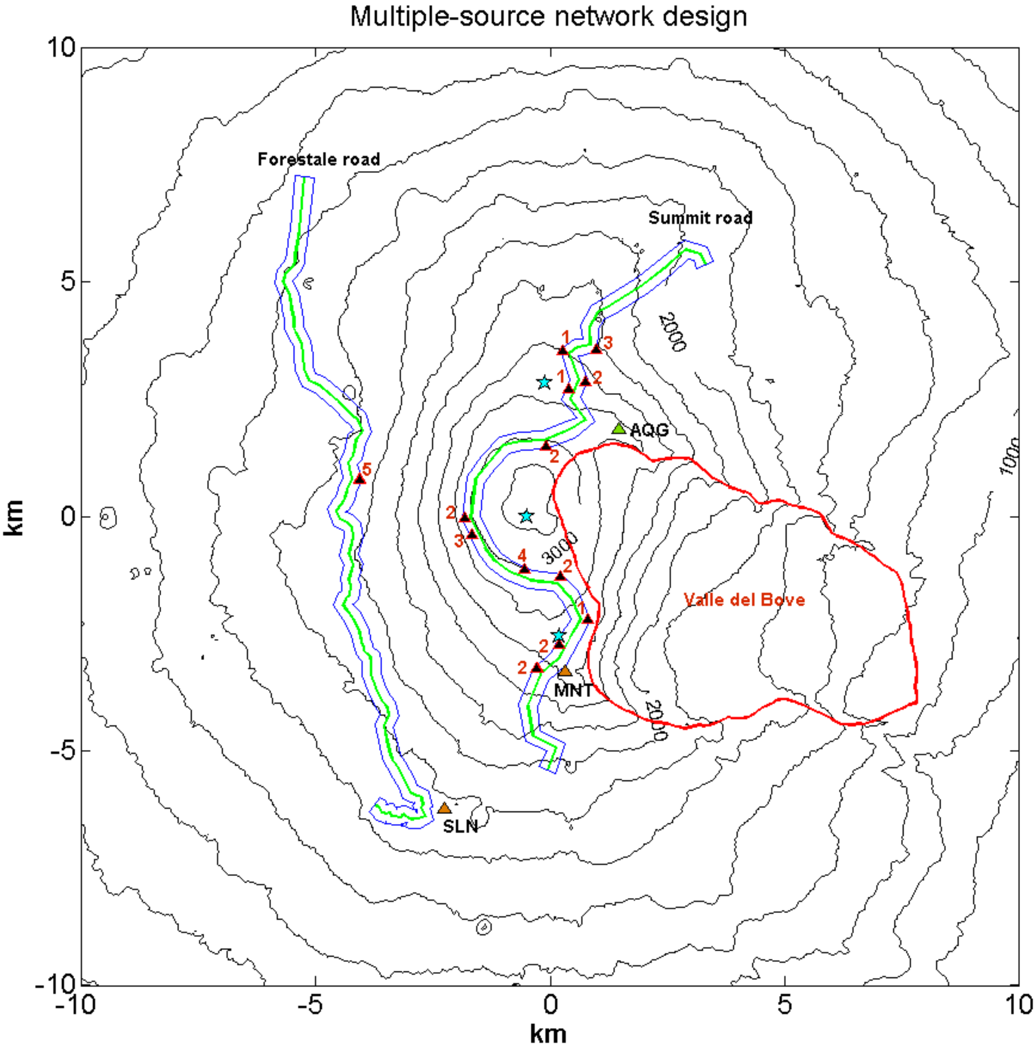


Figure 10: The optimal network configuration of 30 MEMS gravimeters (black triangles) after 50000 iterations. The iGrav gravimeters (at SLN and MNT stations) are represented by orange triangles. The AQG (green triangle) is located at the PDN station. Green and blue lines show the summit and Forestale roads and their 200-m sidelines, respectively. The red polygon is the outline of the Valle del Bove. The stars represent the 5 estimated most likely sources of mass change (3 vertically aligned sources below the summit). The red numbers next to the black triangles show how many MEMS have been clustered together by the algorithm (because of the scale of the figure they are seen as a single triangle).

- The gravity measurements have been previously corrected for other effects, including surface deformations.
- Five potential locations of mass change are assumed and approximated as point sources, thus their associated unknown parameters are the 3-D coordinates and the amount of mass change
- The sources of mass change may only become active one at a time
- The iGrav gravimeters (MNT and SLN stations) and the AQG (at PDN station) are fixed stations of the optimal network configuration.
- 30 MEMS instruments, constitute the "optimizable" part of the network
- We use the nominal standard deviations of 1, 5 and 10 microGal for the iGrav gravimeters, the AQG and the MEMS gravimeters, respectively.

- The observational errors conform to the Gaussian distribution and the covariance matrix of observations is a diagonal matrix composed of the variances (squares of standard deviations) of measured gravity at each station.
- The cost function of the optimization is defined as the weighted sum of traces of the covariance matrices of the five point sources (the trace of a square matrix is the sum of the components on the main diagonal.)
- All the stations are constrained to be within 200 m from the summit road (Figs. 2, 9 and 10) and Forestale road (Fig. 10).
- Due to logistic issues, the stations are not allowed to be placed in the Valle del Bove area.

The genetic algorithm scheme firstly generates an initial population of random configurations of MEMS gravimeters. Then, for each configuration, the covariance matrices of the five point sources are computed and, subsequently, the costs are calculated. The covariance matrices of the sources are functions of the network configuration and the covariance matrix of observations. As the next step, through genetic operations of natural selection, pairing, mating and mutation (see Holland, 1975), which are guided by the configurations' costs from the previous step, a new population of network configurations is generated. Repeating this procedure, the cost of the best configuration decreases as a monotonic function and after a certain number of iterations the calculations converge to an optimal solution.

We performed several tests considering the five locations individually or in groups. The "optimal' network configuration changes case by case. Here we propose the configuration obtained for the group of five sources (Fig. 10), as we think it is a good compromise between allowing for more potential locations of mass change at deeper levels and focusing on relatively shallow processes that are more likely to be measurable.

General "lessons" learnt from this procedure:

- The best configuration illustrated in Figure 10 is a compromise between allowing for more potential locations of mass change at deeper levels and focusing on relatively shallow processes that are more likely to be measurable
- The outcome of the optimization are clusters of MEMS gravimeters at most of the stations. The MEMS sensors in each cluster in Figure 10 appear as just one station in map view, because the distances between the MEMS in a cluster are often shorter than ~100 m. It appears that the algorithm favors a lesser number of stations with higher precisions over uniformly distributed MEMS at sparse points. The last issue needs further consideration to assess whether the model assumptions are fully justified.
- Stations on the Forestale road are needed to detectsources deeper than ~1 km b.s.l.

1.4 Power supply

Different solutions have been considered for power supply in sites where mains electricity is not available.
Regarding the MEMS, at each chosen location a power supply of ~5W per device should be supplied during several months, including winter seasons. A solution involving solar panels and batteries appears to be the most suited, even though maintenance will be needed in winter to remove the snow cover from the panels. Alternative solutions, such as fuel cells would probably be too expensive and overkill for this application.

Regarding the AQG, as stated in sections 1.3.1 and 1.3.2, its installation at the Pizzi Deneri volcanological observatory (PDN), which does not have mains electricity, would require a power supply system based on solar panels and batteries and/or fuel cells. A preliminary market survey showed that a solution based on fuel cells exceeds the available budget (the cost is on the order of 20 k€). Precise calculations have to be performed to assess the exact characteristic of the power system based on solar panels and batteries that would be needed to run the AQG at PDN, taking into account that the operating temperature range of the AQG could be shifted, in order to decrease its power consumption. The feasibility of installing the AQG at PDN depends on the results of the above calculations.

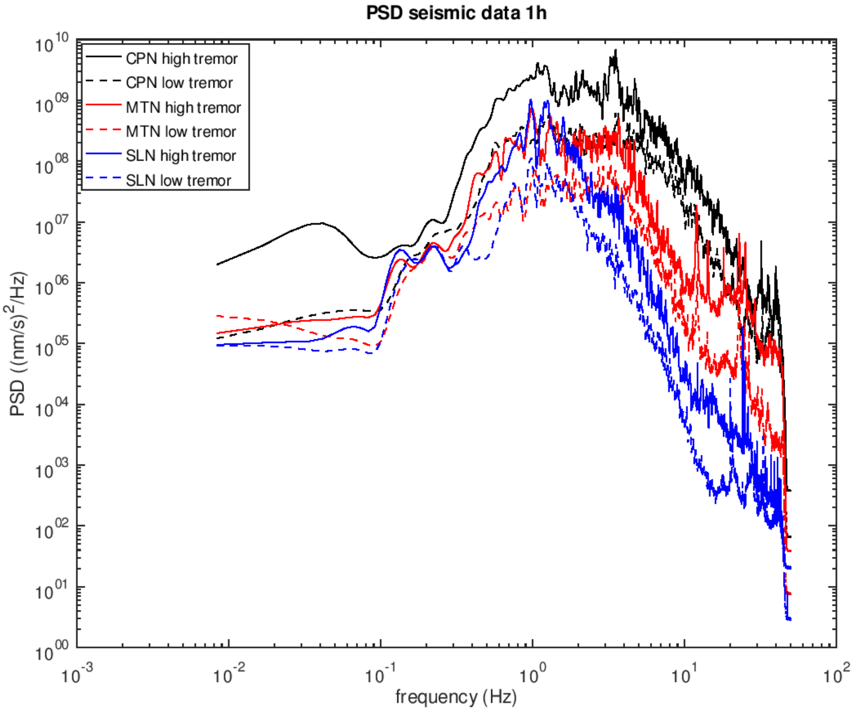
1.5 Comments on Volcanic Tremor

For both MEMS and quantum gravimeters, the characteristics of volcano-related seismic noise is an important parameter to be considered. This parameter is usually referred as *volcanic tremor* and can be described by the Power Spectral Density (PSD) of the ground acceleration noise. Such acceleration noise (inertial component) is recorded by gravimeters along with the measurement of *g* (gravity component) and can lead to a significant reduction of the sensitivity of the instrument. One thus has to assess what is the typical spectral content of volcanic tremor at Mount Etna, where the gravimeters will be deployed during the phase of field-test. We consider two typical situations: volcanic tremor during periods of quiet volcanic activity and during eruptive periods.

The PSDs in Fig. 11 were measured by three seismic stations (CPN, MTN, SLN) at different locations on Mount Etna. For each station, we consider two raw data sets which correspond to 24-hour continuous recordings: one relates to high volcanic tremor and the other refers to a quiet period. For each of these two raw data sets, we select a typical 1-hour long subset. As a result, each of the three stations is characterized by two 1-hour long datasets (quiet volcanic activity and eruptive activity).
The seismometers record velocity. Hence, we plot two PSD for each final data set: PSD of velocity (Fig. 11 top) and PSD of acceleration (Fig. 11 bottom; calculated as the derivative of the velocity), to be consistent with the output of the gravimeters.

The seismometers that were used to record the data feature a high-frequency cut-off at 40 Hz, and a low-frequency cut-off at 0,05 Hz. The PSDs show that most of the volcanic tremor signal is carried by frequencies around a few Hz, regardless the station that is considered. The amplitude of the volcanic tremor decreases quickly below 1 Hz, but remain quite high above 10 Hz. We see that, during paroxysmal phases of the activity, the amplitude of the volcanic tremor can increase by one order of magnitude, in the frequency band between 1 Hz and 10 Hz. As expected, we see that the closer to the summit craters, the higher the amplitude of the volcanic tremor.

These spectra show that volcanic tremor deserves to be carefully taken into account during the design of the gravimeters, to optimize their sensitivity as far as possible. Intense volcanic activity could significantly affect the quality of the measurements for both MEMS and Quantum gravimeters.



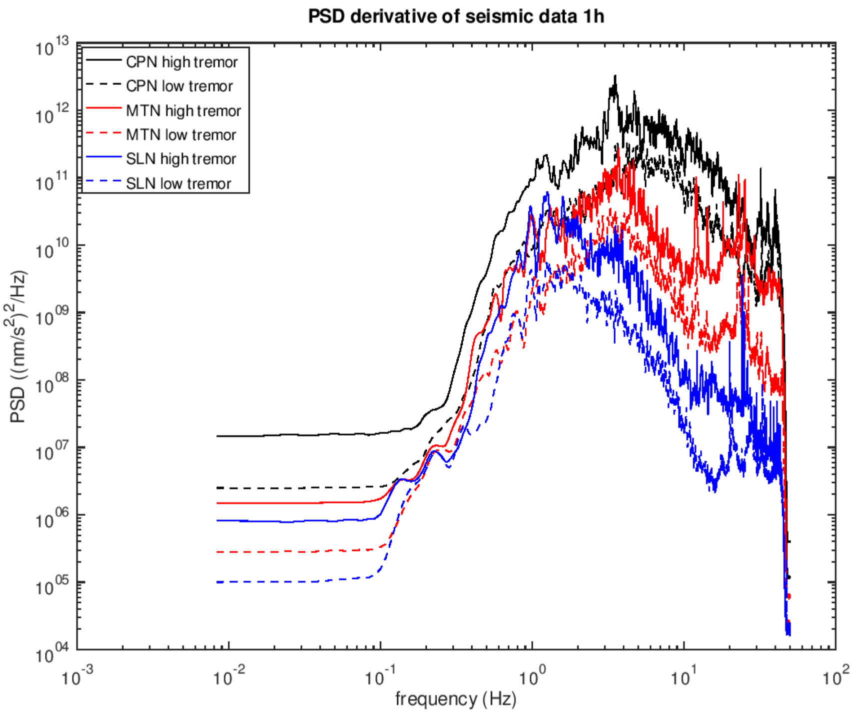


Figure 11: PSD of velocity (top) and PSD of acceleration (bottom), by taking the derivative of the velocity, recorded by three seismic stations (CPN, MTN and SLN) in condition of high and low volcanic tremor during one hour.

2. Data transmission

2.1 Data flow

Data recorded by the gravimeters in the field need to be collected and sent to INGV-CT for processing. To this end, two approach are possible. Either each gravimeter sends its data to INGV-CT directly, or a server installed close to the deployment area gathers the data and then sends consolidated data packets to INGV-CT. After discussion among the members of the consortium, it has been established that the first option is more suitable. Indeed, failure of the collecting server in a remote location during a period of reduced accessibility would imply the risk of losing data from all the pixels in the imager during a given interval.

2.2 Data format

The characteristics of the data produced by the different gravimeters are summarized in the following table.

Data features	**AQG**	**MEMs**
Data rate	2 Hz	Few Hz to few seconds
Number of parameters to be sent for each packet	- 25 in the raw data file - 39 in the 10-min averaged data file	~10
Data size (per day)	~25 Mo per day	~4 Mb per day for 1 Hz data rate
Data format	.csv	Normally .txt
Total data size for the array (per day)	~40 Mo (~320 Mb) for 30 MEMS deployed	

Table 3- Characteristics of the datasets produced by the two types of gravimeters

2.2.1 Data produced by the AQG

The AQG has an acquisition rate of 2 Hz and the data are recorded in 2 main .csv files, one with the raw data, which has a size of 25 MB per day and one with the 600 s averaged data, which has a size of ~50 kB per day. In these files, we record the following parameters: time, raw vertical gravity, tilt, external temperature, temperature at different locations inside the AQG, atmospheric pressure, and laser polarization. We also record different corrections applied to the measured gravity value, e.g., corrections of the quartz, tilt, pressure, earth tides, polar motion, ocean loading and finally we record the estimated corrected gravity value. In addition of these main files, there are two annex files, an info file, with a size of 2 kB, and a file with PSD.

2.2.2 Data produced by the MEMS

Concerning the MEMS data, the acquisition rate is 10 Hz to few seconds and the size of the recorded file is ~4 Mb per day for an acquisition rate of 1 Hz. Around 10 parameters will be recorded, and no pre-processing will be done on-site by the MEMS devices, hence only raw data will be sent to INGV-CT. The nature and exact number of complementary parameters recorded by the MEMS device will be defined later, taking into account the effect that increasing the number of parameters to be acquired may have on the battery life. In any case, parameters that could be needed to correct the gravity signal, e.g. tilt and ambient temperature have to be considered.

2.3 Communication

The following approaches have been proposed:

- UMTS (a network of mobile phones with SIM cards)

This approach presents the advantage to allow direct data transfer to Catania from any point in the array, provided that there is sufficient cellular coverage. INGV recently performed a test along the southern part of the summit road, using conventional cellular phones and a UMTS modem. In most of the points that were checked the cell coverage resulted to be good enough.

- LORAWAN

In the context of NEWTON-g, the communication protocol LoRaWAN may be of interest, since its application appears to be suitable for the MEMS network. Indeed, this technology was developed by the community of Internet of Things and is designed for connected objects. The main advantage is the low power consumption, but in return transmission rate is low compared to alternative solutions. In our case, it should be sufficient for the MEMS, but not suitable for the AQG. Finally, one should verify that the transmission range is long enough to suit the aims of the projects.

- WIFI

Points where there is not cell coverage could be linked to close points where the cell coverage is sufficient through WIFI connections. Data would be then sent to Catania from the collecting point through cellular connection.

- Storage on SD card

The consortium agreed that storage on SD card will be implemented by default, for redundancy purposes. Moreover, in the case where the data cannot be transmitted, they will be stored locally, hence allowing data transmission at a later time (if the signal is intermittent), or in-situ download from the SD card.

The different communication approaches are summarized in the following table:

Data transmission	**Advantages**	**Drawbacks**
UMTS	- Good transmission rate - Good coverage	- Relatively high power consumption
LORAWAN	- Low power consumption	- Low transmission rate (cannot be used for the AQG) - Transmission range to be defined carefully on the Mount Etna volcano
WIFI	- High transmission rate	-
SD card	- Back up storage	- Data collected on-site

Table 4- Data characteristics produced by the two types of gravimeters

In conclusion and based on the discussion above, we choose UMTS as the first choice for data transmission. If for any reason the first choice cannot be met at some locationss, the consortium shall consider the above alternative solutions.

2.4 Comments on time-stamping of the data

A time reference will be needed to synchronize all the data. The easiest solution consists in fitting each point (both MEMS and the AQG) of the network with a GPS module/antenna for time-stamping. Cheap GPS chips should be sufficient for this application. Conversely precise determination of possible ground displacement will require reference to the GPS station in the monitoring system of INGV-CT.

3. Complementary measurements

Complementary parameters have to be measured to distinguish volcano-related from other possible gravity changes. Many parameters are already recorded by the stations in the monitoring system of INGV-CT (seismicity, infrasonic signal, ground deformation, etc.), so it is not needed to perform redundant measurements. At some kay points in the MEMS array hydrological parameters will be measured, in order to assess changes in the local water balance that could affect the gravity field. We envisage that the same acquisition/transmission system fitted to the MEMS “pixels” will be used to handle the data from the hydrological sensors.

4. Cross tests

As soon as possible, UNIGLA will perform multiple tests with the MEMS devices in Scotland, aimed at validating the device performance and specifications. Both sensitivity and stability of the devices will be investigated, as well as environmental ruggedness. Preliminary tests will be performed indoor, while further performance checks will be carried out outdoor, under harsher environmental conditions. A standard spring relative gravimeter will be used as a reference, to validate the data from the MEMS.
During the spring or summer 2019, we plan to perform some tests with MEMS device at Mt. Etna, at different distance from the active craters, aimed at evaluating the performance of the devices against possible perturbations, such as the volcanic tremor.

On its side, MUQUANS will also verify the operation of the AQG outside the building in Talence, in a harsh environment with strong temperature and humidity variations. The best scenario would be to also bring an AQG to Mt Etna in 2019, in order to anticipate the impact of local environmental conditions on the device.

Finally, some preliminary tests will be performed with the AQG and the MEMS devices before the shipment to Sicily, in order to anticipate the final operation of the gravity imager as a whole. These tests could be done at the facilities of MUQUANS in Talence.

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