Mapping Subsurface Conductivity: Challenges and Progress in Italy's MARGE Project

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Abstract

In Italy, the **MARGE** initiative, an abbreviation for Geoelectromagnetic Risk Map for Central Italy, strives to create an extensive map of subsurface electrical conductivity by analyzing natural electric and magnetic fields.
Led by the Istituto Nazionale di Geofisica e Vulcanologia in collaboration with the University of Bari and the Institute of Environmental Analysis Methodologies at CNR, this project involves establishing measurement points distributed on a grid spaced approximately 50 km apart.
The MARGE project aims to gather broad-band and long-term magnetotelluric (MT) data, focusing on two primary objectives: utilizing magnetotelluric data to outline large-scale lithospheric structures in the central Apennines and developing maps of the geoelectric fields in central Italy to support Space Weather modeling and critical infrastructure vulnerability analysis.

Magnetotelluric (MT) surveys

Since 2023, a systematic MT measurement campaign has been underway in central Italy: induction broadband magnetometers and electrodes are used to simultaneously measure both the secondary electric (E) and magnetic (H) field in orthogonal directions N-S and E-W and along the vertical.
From the MT processing, the transfer function Z in the frequency domain is determined for each measurement site, from which two scalar quantities are derived that are real and frequency dependent: the apparent resistivity and the phase (*fig. 2*).

MT measurements: Challenges and enhancements

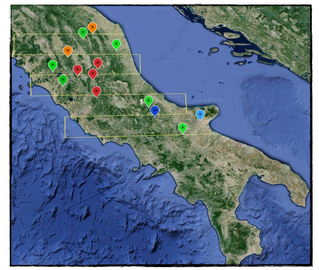
As part of the MARGE project, 12 Magnetotelluric (MT) surveys (*Fig. 1*) have been conducted in central Italy up to this point. However, the acquired data were not always of high quality due to significant contamination from electrical noise or external factors such as adverse weather conditions and cables damaged by grazing animals (*Tab. 1*).
Specifically, during our measurement campaigns, we encountered the following issues:

Electrical Noise
While it's recommended to place MT sites at least 15/20 kilometers away from electrical noise sources, achieving this in central Italy is particularly challenging due to the extensive railway networks.
In general, we aimed to identify sites at least 14 km away from electrified railway lines. However, we observed variations in the quality of measurements in terms of electromagnetic noise despite the equal distance from the railway lines. This suggests that the decay of the electromagnetic source is influenced by the geological characteristics of the site.

Adverse Weather Conditions
Rain and wind can disrupt the acquired electromagnetic signal by moving the electrical cables connecting the electrodes and magnetometers to the MT station. We attempted to address these issues by securing the cables to the ground and scheduling installations during periods of fair weather. However, there were instances of sudden downpours or exceptionally strong windy days that affected the quality of the recorded data. Enhancements in acquisition can be achieved by using thicker cables to better mitigate high-frequency noise and anchoring the cables to the ground.

Geomagnetic Storms
The commencement of measurement activities for the MARGE project coincided with a period of high solar activity, resulting in acquisitions occurring sometimes during geomagnetic storms. When this occurred, we still calculated the Z tensor referring only to the geomagnetically quiet period.

Data Analysis and Results



Quality	ID Survey											
	PIT	BLE	MGV	OCR	ORV	CAS	GUB	AML	RIE	PIE	COL	SER
High												
Medium												
Low												

Tab. 1 - Quality of data acquired in the MT surveys of the MARGE project.

Fig. 1 – Distribution of MARGE project sites where MT surveys have already been conducted. In green the 6 MT surveys with high quality. In orange the 2 MT surveys with medium quality and in red the 4 MT surveys discarded due to low results. In blue the geomagnetic observatory in Duronia (CB). In light blue the remote reference located on the Gargano promontory (FG).

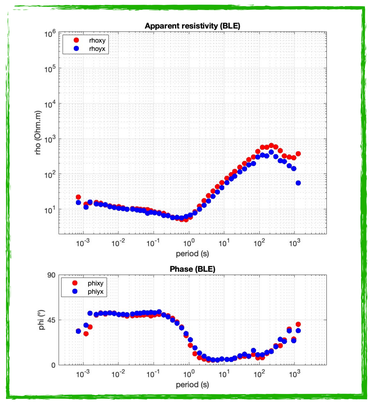


Fig. 2 – Survey BLE

***Fig. 2 – Survey BLE (Blera, Italy)**: example of a high quality survey. The top graph shows the apparent resistivity curve on a bilogarithmic scale that expresses the resistivity trend as the period and depth in the subsurface increase; the bottom graph on a semi-logarithmic scale represents the phase trend that varies continuously with frequency and resistivity changes with depth. The inflection point marks the transition in depth from the sedimentary basin (conductive sediments) to the resistive substrate.*

***Fig. 3 – Survey MGV (Montegiove, Italy)**: example of a medium quality survey. Apparent resistivity and phase curves of a MV site located close to electrical noise sources (railway network 11 km away).*

***Fig. 4 – Survey ORV (Orvinio, Italy)**: example of a low quality survey excluded from the MT database. Apparent resistivity and phase curves of an MT site located close to electrical noise sources (railway network 11 km away). The noise into the electromagnetic signal causes an anomalous slope and high values from the apparent resistivity curve.*

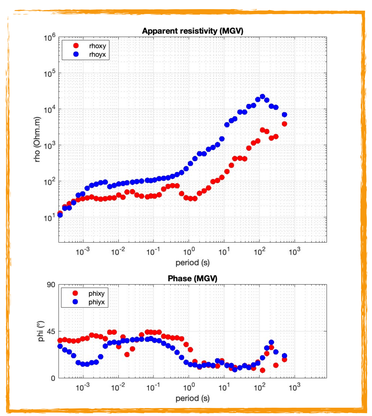


Fig. 3 – Survey MGV

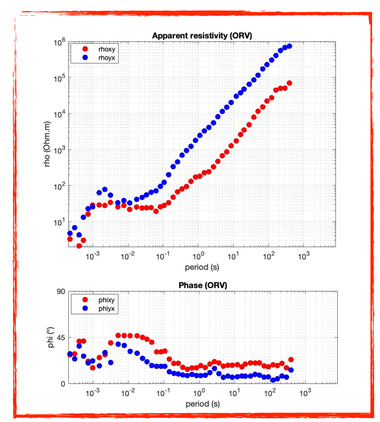


Fig. 4 – Survey ORV

Space Weather: Geoelectric field mapping

The primary aim of the MARGE project is to map geoelectric hazards in Italy, with a current focus on central Italy. Variations in the Earth's magnetic field can induce electric fields in the ground, which in turn can cause harmful currents through our power grids. The idea is to develop a model of the solid Earth's conductivity structure and surface impedance, and to map the geoelectric fields induced by magnetic storms. The results will provide a realistic insight into the nature of space weather disturbances at ground level, with a specific emphasis on Italy, particularly central Italy at the moment.

Indeed, if we know the impedance tensor Z within a period range of 1 to 10^5 seconds from previous magnetotelluric measurements or obtained from a high-resolution 3D electrical conductivity model calculated from a preliminary magnetotelluric survey, we can evaluate the electric fields induced by the magnetic storm without the need for continuous and prolonged electric field measurements at the MT site. In fact, the relationship between the impedance tensor and the magnetic and electric fields is as follows:

$$E_x(f) = Z_{xx}(f)B_x(f) + Z_{xy}B_y(f)$$

$$E_y(f) = Z_{yx}(f)B_x(f) + Z_{yy}B_y(f)$$

Therefore, once the tensor Z is known, the magnetic field can be approximated as the one measured, for example, at a geomagnetic observatory near the area of interest. The basic assumption is that the geomagnetic field propagates with a plane wave front in the frequency spectrum between 10^{-4} and 10^4 Hz, since at mid-latitudes electromagnetic sources are located at great distances from the measurement site. This implies the assumption that the magnetic field is uniform over large distances on the earth's surface (with a radius of 200-300 km from the MT measurement point) (*fig. 5 - 6*)

Magnetic field comparison

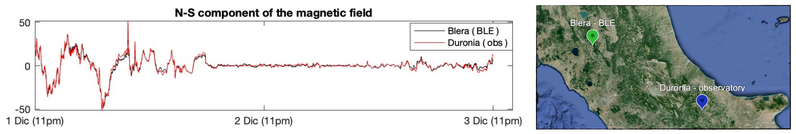


***Fig. 5** – Comparison of magnetic time series: in red, the magnetic signal acquired in the N-S direction from Duronia observatory (CB, Italy) with a fluxgate long period magnetometer and a sampling frequency of 1 Hz; in black, the magnetic signal acquired in the N-S direction at the MT site in Blera (VT, Italy), with a broadband source coil magnetometer and a sampling frequency of 32 Hz. Due to the different sampling frequency and the different instrumental sensitivity of the magnetometers at the two measurement sites, the magnetic signals were appropriately decimated, detrended and filtered before being compared. The geomagnetic storm event of 1 December 2023 is observed.*

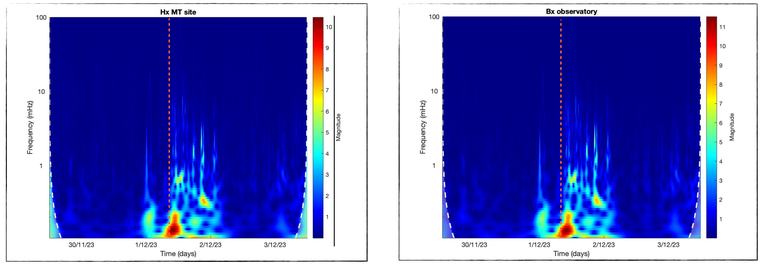


***Fig. 6** - Time-frequency graph shows the continuous wavelet spectrogram of the magnetic signal (left) in the N-S magnetic direction acquired at the MT site in Blera (VT, Italy) and the magnetic signal (right) in the same direction acquired at the geomagnetic observatory in Duronia (CB, Italy). The transition from blue to red represents an increase in energy, while the closed regions represent the geomagnetic disturbance (storm event on 1 December 2023). The dashed red line indicates the start time of the time section in Fig. 5.*
To compare the spectra of the signals obtained at the two locations, they were decimated and time-aligned.