Muon and Muogravimetric Tomography as new tools in geophysics

1. Identificação do projeto/Project description
2. Instituições envolvidas/Institutions and their roles
3. Componente Científica/Scientific Component
    3.1. Sumário / Summary info (5000)
    3.2. Descrição Técnica / Technical Description info
        3.2.1. Revisão da Literatura / Literature Review info (6000)
        3.2.2. Plano de Investigação e Métodos / Research Plan and Methods info (10000)
        3.2.3. Tarefas / Tasks info (4000 each)
        3.2.4. Calendarização e Gestão do Projeto / Project Timeline and Management info
            3.2.4.a Description of the Management Structure (3000)
            3.2.4.b Milestone List (300 each)
            3.2.4.c Timeline
    3.3. Referências Bibliográficas / Bibliographic references info (30 items)
    3.4. Publicações Anteriores / Past Publications (5 items)
4. Equipa de investigação/Research team
5. Outros projetos/Other projects
6. Indicadores previstos/Expected indicators
7. Orçamento/Budget
8. Justificação do orçamento/Budget rationale (600 each)
9. Ficheiros Anexos/Attachments

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Outdoor field experience with autonomous RPC based stations
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Summary (4970/**5000**)

One of the central purposes of geophysics is to accurately and easily capture the physical properties of structures under the Earth´s surface and their spatio-temporal distribution. Any improvement on efficiency that science and technology can supply in this regard is a victory for Geophysics. Conventionally the density distribution inside geological bodies is mapped by means of gravimetry data inversion, an ill-posed problem strongly affected by non-uniqueness and instability.

Such instabilities can be canceled by incorporating complementary data from a different method sensitive to density: and Muography can take this role. Muons are particles produced by cosmic rays, arriving in large numbers from all directions in the sky with a known flux. Muons are able to penetrate through hundreds of meters of material in straight lines, allowing the formation of absorption images like those of X-rays. Muon tomography has had a strong worldwide development in the last decade, with applications ranging from the control of nuclear materials smuggling to geological exploration, including civil engineering and archaeological searches.

The goal of this project is to introduce Muon Tomography as a tool for subsurface geophysical surveys, and to develop the corresponding analysis methods to unveil the density distributions. Beyond the use of muography as a stand-alone technique, the project aims to develop 'muon-aided' gravimetry, by using muography data a priori to break the degenerated solutions from stand alone gravimetry, and most importantly to develop the joint gravimetry-muography sub-surface surveys, where a new joint inversion of the density matrices is key.

The physical structure used to test and validate all methodologies will be the Lousal mine (Grândola-Portugal). The mine galleries offer an adequate infrastructure for deploying a geophysical muon survey, allowing different observation scenarios. Geophysical and geodesic surveys will be done with ICT (Évora) equipment and a rented micro-gravimeter. The muon telescope is based on state-of-the-art RPC detectors, developed by the LIP team.

The project is composed by five interconnected tasks that will guide it from the geophysics and muonic surveys at the Lousal Mine, to the experimental data processing and analysis, and the development of methods for joint inversion of gravity and muography, it includes R&D in instrumentation and a focus on research dissemination. Task 1 is devoted to plan and

implement the experimental surveys and develop a database to archive and manage all data and results of the project; Task 2 is devoted to the muon data taking, simulation and analysis; Task 3 will develop and implement the theoretical and computational methodologies for inverting the results of muon surveys, and for the joint inversion of muon and gravity surveys; Task 4 is dedicated to the upgrade of the existing muon detectors; and Task 5 is centered on outreach and dissemination activities.

The LouMu project emerges from a multidisciplinary research team of earth and particle scientists, armed with the knowledges and technologies becoming to execute the proposed plan, that has been working for 2 years in a pilot project, and joins areas of expertise already existing in Portugal:

- Cosmic ray muon specialists, who participate in leading experiments, with experience in analyses and simulation;

- A worldwide leading group on Resistive Plate Chambers (RPCs), particle detectors which combine high precision, portability, low cost and robustness, outrunning most other technical solutions used in muon telescopes;

- A group of geophysicists who will assess the precision of muon imaging and tomography in comparison to standard techniques, like gravimetry; and propose innovative methods to combine both, boosting the accuracy-cost ratio for geophysical prospection.

- A group of experts in outreach activities for Earth sciences, and in general science and technology non-formal education and popularization, focusing on sharing of know-how and creative ideas from research.

To achieve the long term goal, this projects aims at the following objectives:

- Develop the techniques to produce Muon and Muogravimetric sub-surface tomographic (3D) images;

- Progress on reaching ready-to-use apparatus and analysis software, which can be used together with other more standard geophysical survey techniques;

- Disseminate Muon and Muogravimetric Tomography among academia, society and companies to open and explore new interdisciplinary projects;

- Study a real case scenario in an underground mine in Lousal, and form muographs (2D) and muon tomographs (3D) to identify features of interest for geological and geotechnical applications.

The chosen site is a non-active mine, well mapped and surveyed, ideal to test the capabilities of muography and muon tomography. The mine has become a public science centre, providing ideal conditions also for dissemination for the general public.

Literature Review (5644 / 6000c):

Several geophysical methods have been developed and employed in the last years in order to image the internal structure of the earth, capturing the spatiotemporal distribution of the physical properties of sub-surface. Their main objectives are to evaluate natural resources, understanding the dynamical behavior of the surface and inner earth and to mitigate natural and human hazards. These methods are globally designed as Geophysical Tomography (or Geophysical imaging). The appropriate methodology to develop a 3D model depends on the geological complexity, the physical property to be mapped and the available data. Gravimetry is one of those geophysical methods that provide information on the density structure of the Earth's subsurface.

Recently, a new technique named muography (image using muon rays) has been developed to map the internal density profiles of volcanoes (e.g. [AMB11],[LES12], [BAG14],[TAN15], to image reservoirs (e.g. [LUM01]) and discern time-dependent fluid flow in hydrology (e.g. [KEN16]), injection wells (e.g. [KER14] and carbon sequestration (e.g. [ZHA12), or for investigation of hidden cavities (e.g. [CIM19]).

Muography is based on measurements of the absorption of the atmospheric muon flux inside a target material. The attenuation of the muon flux can be used to infer the integrated density along muon trajectories crossing the area of exploration. The atmospheric muon flux is produced constantly by cosmic rays, which interact with the atomic nuclei of the atmosphere and produce around 70 muons / ($m^2 \cdot s \cdot sr$) after a particle cascading process. The energy and angular spectrum of muons are obtained by direct measurements in open air, or can be reliably calculated using comprehensive simulations of the particle cascading process [COR98] and propagation through material [GEA03]. They are routinely used to to self calibrate the detector response and later obtain information on the primary cosmic ray and particle interactions at very high energy in AUGER [CAZ12],[CAZ16].

Several options exist for cosmic ray muon detection. One of these are Resistive Plate Chambers (RPCs), widely used particle detectors in high energy physics experiments [AIE04, BEL09], and an emerging technology for cosmic ray detection [AIE06, LOP14, MAR18]. RPCs present a high detection efficiency (> 99%) and temporal resolution (< 100 ps). The readout can be segmented to obtain sub-millimeter spatial resolutions at low cost, which make them ideal for image large objects with muons. In addition, advances obtained in the last few years allow the RPC to operate outdoors under harsh conditions which makes them suitable for field operation in geophysical surveying.

Since both muon tomography and gravimetry are geophysical methods that provide direct information on the density structure of the Earth's subsurface (gravity and muon attenuation depend both on integrated column mass) it is natural to compare both and also to combine them.

The greatest advantage of muography is its high spatial resolution compared with other geophysical methods - in particular with gravimetry [NIS17] -, whereas its main limitation comes from geometrical constraints, as the muons must pass the targets between their point of creation up in the atmosphere and the detection. Thus, the muon telescopes must point up to the sky, in a direction always above the horizon.

The strong non-uniqueness of the models obtained by the geophysical surveys applying inversion methods is an intrinsic limitation of the gravimetric methods [TAR05]. Traditionally, this limitation can be partially overcome by introducing a priori information or imposing physical constraints to the model. The Integration of these geophysical datasets is complicated by the fact that, whereas gravity measurements depend linearly on density, observables such as seismic wave speeds and electrical conductivity are complex functions of density, temperature, composition, porosity, and saturation [COL07]. Muography data can either replace or be used together with gravimetry data.

One key element of our project to imaging a density distribution is to simultaneously treat gravimetric and muographic data. Some previous work demonstrated the potential improvements to be gained by jointly inverting both data sets (DAV12] [JOU14], [JOU15],[NIS14],[NIS17],[ROS17],[LEL19]. However, there has yet to be a thorough investigation of different numerical approaches for formulating the joint inverse problem.

The two measurements are also affected by different systematic uncertainties that are difficult to model [LIO00],[ROS17],[LEL19]. While for gravimetry these have been more thoroughly studied, for muography it is important to incorporate the uncertainties related to the muon fluxes and muon multiple scattering, telescopes resolutions.

Our teams have been working together towards this project, which is based on an already existing muon telescope, taking data on a well known - and accessible - mine, as explained in the following sections.

Research Plan and Methods (9610/10000c)

The goal of this project is to bring the Muon Tomography for subsurface geophysical surveys, (such as mines, tunnels or caves), and develop the corresponding analysis methods to unveil the density distribution of a given volume. Beyond the use of muography as stand-alone geophysical survey technique, the project aims to develop 'muon-aided' gravimetry, by using muography data as a priori to break the degenerated solutions posed by stand alone gravimetry, and most importantly to develop the joint gravimetry-muography sub-surface surveys, where a new joint inversion of the density matrices is key.

A fundamental requirement to properly develop the project is the availability of a physical structure which combines a suitable morphology with geological diversity, easy access and adequate facilities. It is the structure needed to test and validate all methodologies. The Lousal mine (Grândola-Portugal) is located on the NW flank of the vast geographical area known as the Iberian Pyrite Belt (IPB). The mine was active between 1900 and 1988 for the exploration of massive sulfides, especially pyrite. The exploration was made from the surface down to about 500 m deep. After the mining activity was abandoned, the Lousal Mine complex was re-qualified for scientific outreach activities, a mission that today it assumes under the name of "Centro Ciência Viva do Lousal – Mina de Ciência". With the support of this Center, the mine galleries offer adequate infrastructure for deploying a geophysical muon survey in an underground setting. The best experimental conditions are assured, namely access to a gallery ranging from ~12 to 20 m deep, and allowing to configure different scenarios for observation.

The present project will use muon telescopes made of state-of-the-art RPCs, resulting from the technology transfer from other LIP projects, namely MARTA [MAR18] the Pierre Auger Observatory and TRISTAN [BLA19].

The first testing prototype, called MiniMu, has been operated in the Lousal Mine since the beginning of 2019 to test the logistics of gas feeding and recovery, and of the remote control of data acquisition and transfer. MiniMu has been integrated in the Lousal Ciência Viva general visits circuit (https://www.lip.pt/LouMu/). The muon telescope to be used in the project, named CorePix, was made at LIP-Coimbra in the end of 2019 and consists of four squared RPC planes with an active area of approximately 1 m^2. Each of the detection planes is made up of a multigap RPC with two gaps of 1 mm defined by 2 mm glasses, which allows to obtain efficiencies close to 100%. These are assembled together in a mobile structure with a variable distance between the planes, that can be changed from 25 to 0 cm. The wheel axis used for the movement of the structure is also used for tilting the structure allowing an inclination of up to 30 degrees (in relation to the vertical axis).

Three of these planes share the same readout planet: a central core of 7 x 7 squared pads (pixels) covering 10% of the total area, which gives a spatial resolution of around 10 mm . The rest of the area is read by 15 pads and strips of various widths and lengths, in order to test other readout strategies with a lower resolution/area ratio.. A fourth plane has 64 parallel strips fully covering the active area, providing higher granularity (15 mm) in one dimension.

Each readout plane is connected to 64 electronic channels in a front-end-electronics, based on the MAROC ASIC, developed by LIP-Lisbon [MAR19]. An FPGA-based trigger system and a mini-computer is used for signal acquisition [MAR18b]. The total charge of each channel is digitized and available for analysis. Each chamber is accompanied by the necessary subsystems for its operation: HV power supply, gas distribution/collection, LV controlled power supply and I2C environmental sensor system, and can be operated remotely.

The CorePix muon telescope has been taking data since January 2020 in the detector laboratory in LIP-Coimbra having carried out the basic function tests, namely: efficiency and spatial resolution measurements as well as muon tracking capability The telescope can be easily reconfigured – decreasing the distances between planes to increase/decrease the acceptance/resolution , – and portable to provide extra 2D images of the building. The sensitivity of the muographic results to the actual 3D structure of the building will be tested for a future 3D tomographic inversion. The importance of parameters like the temporal variability of the open air flux and its symmetries will be studied.

CorePix telescope will be placed in the mine in Autumn 2021, (see timeline), where data taking and analysis present new challenges. The muon flux is decreased, increasing the need to control electronic noise and other backgrounds. In addition long term performance must be assured with careful monitoring. Changing the muon telescope position or configuration presents more limitations and will need careful planning.

A three-dimensional full geophysical model of the Lousal mine (LGM) structure between the gallery and the surface, obtained from data of different well-established geologic and geophysical methods is a fundamental methodological issue: a) In the configuration phases it will point to the interesting regions the muon data taking, and help set up the inversion strategy for muon and gravimetry data, and b) is to be used in the evaluation phases of sensitivity and validation of the resulting tomographic model. ICT has the human and instrumental resources for creating this model. Preliminary geophysical campaigns at Lousal have identified the specifications for the next measurements.

Synthetic geophysical model (SGM) describing the mine and detailed simulations of the passage of the muon flux through those models will be performed. This will allow comparison of real to simulated muography, and the production of contrast muography by the ratio of real to simulated ones, where deviations from unity will pinpoint the regions where SGM differ from reality by overdensity or underdensity.

The development of general tools to invert the muographic data accounting for different degrees of geophysical constraints to obtain a 3D, tomographic density structure of the mine will be investigated. A detailed gravimetric survey of Lousal will be also conducted during the project. Muography data will be used to constraint the gravimetric inversion, as well as a method to invert jointly the muography and gravimetry data. All the different systematic uncertainties will be accounted for, and the sensitivity of muogravimetric tomography as well as gavimetry constrained by muography will be assessed with real data.

Finally all the data of Lousal will be released, while the methods set the basis for future use.

The project is divided in three interconnected tasks that will lead to the muon tomography of the Lousal mine, providing also the improved results combined with complementary information, namely with joint inversion of muography and gravimetry data. The developed methods are of more general interest than just mapping the Lousal mine, and will set the procedures for future use of RPC muon telescopes for tomography of determining subsurface densities. Two extra tasks complement the project by upgrading the RPC muon telescopes, and by identifying new uses within geophysics, and for other applications.

Task 1 is devoted to plan and implement the experimental surveys that involve the collection and processing of data used in the project, including those necessary for the production of the Lousal Geophysical reference Model (LGM); and the planning of the Micro-gravimetry surveys and Muon data collection.

Task 2 is devoted to the muon data taking, simulation and analysis and will deliver the muography reconstruction. It will provide the calculation of the needed exposures to achieve the desired signal to noise ratio and help schedule the data taking for the different campaigns identified in Task 1. The muographic (2D) reconstruction of over and under-densities with respect to synthetic 3D reference models (SGM) will be obtained, using just muon data.

Task 3 will develop and implement the theoretical and computational methodologies for inverting the results of muon surveys, and for the joint inversion of muon and gravity surveys. These will be tested by simulation of the muon propagation through synthetic 3D models, before applying it to real muon data of the mine. Sensitivity and resolution analysis will be implemented and followed in different strategies for inversion of data, from local methods profiting the linearity of the direct problem to other global methods, all of them implemented in a High Performance Computing (HPC) environment. The final performance of the methodology will be assessed by comparing the reconstructed density distributions with the preexisting information available.

Task 4 is developed in parallel, using input from Task 2, and is dedicated to the upgrade of the existing detectors. Possible limitations of the present detector in terms of logistics and performance are taken into account in the present planning. But, by the end of the project, a user friendly muon telescope will be available.

Task 5 is centered on the creation of a community for developing muon tomography for geophysics, and also other applications, and particularly to the training of experts on this new technology. Since the project is located in a science center, it will naturally have a strong component with creation of short and long term contents of outreach for the general public.

TASK 1: Geophysical Surveys and Production of LGM

(~3843/4000)

This task aims to plan and implement all experimental surveys that involve the collection, processing and management of data used by muon tomography and by the joint inversion to be developed. It involves many actions integrated in four main activities.

Activity A – Geophysical reference model

From the compilation of all the existing geological and geophysical information (mechanical drill holes, electrical resistivity data, and other information that remained from almost a century of mining exploitation) the preliminary model of the structure above the Waldemar gallery will be produced. This model will determine future geophysical campaigns, planned in order to clarify the main information gaps verified.

Next, will be performed a multi-sensor geophysical survey, composed by electrical resistivity / conductivity, ground penetrating radar, electromagnetic induction and seismic refraction methods. To complement the multi-sensor geophysical records, a laboratory analysis of the physical properties (electrical resistivity, density, propagation speed of the P and S waves and dielectric constant) from the main rocks found on the ground above the Waldemar gallery, will be made.

Finally, the distribution of the physical properties revealed by the different sensor types and laboratorial determinations, will be integrated using a data fusion routine to create the final 3D Geophysical reference model of Lousal (LGM).

Activity B – Micro-gravimetry survey

To characterize the gravity field on the surface with the accuracy required to infer the density distribution in the near-surface investigations (in a few tens of meters) a high-density micro-gravity survey (mesh with few meters between adjacent nodes) will be implemented, covering the region over the mine galleries. Complementary, due the topographic corrections required, a high definition georeferenced Digital Surface Model (DSM) and the accurate location of gravity measurement sites will be produced, using Imagery acquired by unmanned Aerial Vehicle (UAV) and a differential GNSS survey data. After the gravity recording points are located and marked, gravimetric measurements will be made using a high resolution microgravimeter (~ 0.1

microGal). All the processing steps of the gravity data corrections to obtain the complete Bouguer anomaly used in 2D/3D inversions will be produced in this activity, by an adequate routine process, as the GravProcess of [CAT15].

Activity C – Planning the Muography survey

The geophysical reference model will be used to propose the baseline for the muon data acquisition, identifying the best positions for the location of the muon telescope and the resolution targets to achieve for different structures. As the results from gravimetry and muography are obtained, these will be re-evaluated, and new targets will be set so as to extract the most refined information up to the end of the project.

Activity D – Lousal Digital Database (LDD)

The data and results produced in this project will be integrated and managed in a open source database, the Lousal Digital Database (LDD), that encompass a range of tools to the storage, management and display all compiled and produced geological, geophysical or muographic data, photos and video records from the scientific actions carried out under the scope of the project, and developed models.

The LDD is a tool that will allow significant geophysical interpretations based on management of 3D models and their associated data. As it integrates all data produced and results It will be a virtual research environment for the documentation and analysis of the Lousal mine. To reach this, the database will be mounted on an open source software with database management and 3D visualization capacities and all data and results of the project will be normalized and introduced in this system.

TASK 2: Muon Telescope Analysis (3898/**4000**)

This task is devoted to muon simulations, data taking and analysis. The final goal is to provide real and simulated muographs.

A. A. Muon data taking

The telescope prototype has been acquiring data in different positions and configurations in the Detector Lab in Coimbra since the beginning of 2020. It will be commissioned in Lousal in Autumn 2021. It will be placed in a mobile structure, for easy repositioning.

The default configuration is to have the four planes aligned with vertical separations of 25 cm, but this can be changed and the full structure tilted, to focus on specific structures. The detectors are autonomous and can compensate variations on ambient temperature and pressure, keeping the signal gain constant.

The data obtained is displayed online at Lousal, for outreach purposes, relying on basic selection and reconstruction, and transferred to LIP for detailed analysis.

B. B. Muon simulations

During the first half of the project, this task is to provide the simulation tools to produce open air cosmic ray fluxes by means of existing parameterizations and of air shower physics simulations, and also the flux of outgoing muons after the passage through the 3D density distributions of materials.

A detailed Geant4 simulation is being developed, where all the relevant characteristics of muon propagation are considered, including the tracking of secondary particles they might produce and give rise to a signal in the telescopes.
The description of geometry and materials is provided by means of a customizable GDML file, where all geometrical forms and composition can be provided by means of a small set of basic elements. This will allow the inclusion of the reference geological models with increasing detail.

C. C. Coimbra muograph reconstruction

Firstly, we'll use the data acquired in the Detector Lab to construct a muography of the Coimbra building, allowing us to test the full chain of data analysis methods and to measure systematic uncertainties that can affect the image reconstruction.

The first step is to identify muon tracks (defined as collinear hits in the 3 planes, eventually using a 4th plane as an extra veto, providing 10 mm resolutions) and to reject those events attributed to electrons, electronic noise, muon decays and other possible physics backgrounds.

The direction of the clean tracks will be reconstructed on a 2D angular histogram, or muogram. The symmetry of the building can be explored to create preliminary 3D images, reflecting the depth of the walls, floors or other objects crossed by the muons in each direction.

D. D. Lousal muograph reconstruction

Attenuation maps will be obtained by the ratio of this image with respect to the image expected in open air. Refinements to get rid of remaining noise and uncertainties of the open-air muon flux due to space-weather or local variations will be studied and applied at a later step.

Later, the same methods will be used to analyse the data acquired in the Lousal Mine site, to obtain cleaned 2D maps of muon directions. The muon flux is smaller, the energy of the surviving muons higher, and the multiple scattering must be carefully calculated. Simulated muopgraphs will be generated using the SGM which then can be used to compare to real data muographs or to produce contrast muographs by means of the ratio of the observed.

TASK 3: Tomographic and Muogravimetric inversion (2577/4000)

In this task we develop the basics of the muon and gravity density inversion in 3 different ways: imaging only with muons, using muons as input a priori data for conventional inversion of gravity data, and finally imaging with gravity and muon data jointly.

For that we will develop numerical methods to perform joint inversion of gravity anomaly and muon data in order to obtain 3D density subsurface models. The reference model, the data of gravimetric anomaly and of muonic origin, as well as the a priori information (geophysical and geological) will constitute the inputs for the development of this task.

The main activities will be:

A.1 Development of an integrated methodology for the simultaneous calculation of anomalies in the gravitational field and muon flow depending on the distribution of density on the sub-surface (muogravimetric forward problem). In this topic we will approach the numerical resolution of the direct problem through two parameterizations (discretization of the Earth volume of interest): the classic one, considering a rectangular or cubic mesh and the alternative, using the natural reference of the muography, the spherical coordinate system.

A.2 Development of numerical methods for single and joint inversion of gravimetric and muonic data (least-squares inversion, bayesian methods and Monte Carlo methods) will be tested using parallel computing implemented in a HPC environment.

B. Standard Tomographic inversion methods will be adapted for the case of muons and applied to the muographic data of Lousal.

C Sensitivity analyses, or synthetic reconstruction tests will be employed for assessing the solution robustness of the tomographic method. Spatial resolution tests will be performed and multiple receptor positions will be tested in order to evaluate the density discrimination and penetrating ability of the method.

Evaluation of the effect of the introduction of a priori information (geophysical and geological data) in order to increase the quality of inversion. Realistic survey scenarios will be implemented from degradation of the level of spatial and temporal data sampling as well as the amount and quality of a priory information introduced

D. Finally, the methodologies developed will be applied to the data collected in the Lousal Mine site and the tomographic results will be compared with the LGM. Production of a Lousal Muogravimetric geophysical Model (LMM)

E. The possible advantages of muo-gravimetry will be analyzed by comparison with tomographic methods. Acquisition costs, data acquisition limitations, spatial resolution of the obtained models, calculation time and usability by the geophysical community will be the parameters to be analyzed.

TASK 4: Muon Telescope enhancements & R&D (3676/4000)

CorePix telescope is a fully functional prototype, however, optimisations are foreseen taking into account the experience gained on its field operation and the requirements set in the connected tasks.They include, on the one hand, field operation optimization, with the incorporation of sealed RPCs and low power consumption control unit and, on the other hand, the increase of image quality, by strategies to enhance the spatial resolution with scalable (in area) solutions. These will allow to shorten the exposure time (by increasing the active area) to perform true tomographic images improving dramatically the image quality. All these improvements will boost the use of this technology in the geophysics community.

The task is organized in the following activities:

Activity A) Field operation optimization

RPCs are gaseous detectors that require a continuous flow of gas to operate, which is supplied by a gas system (including a reservoir, distributor/controller and recovery gas systems), that complicates field operation. In recent years the LIP team has produced versions of these detectors that can be operated with a very reduced gas flow. The LIP group is pushing forward in this line, and has developed a sealed RPC (no gas flow) which is patent pending, and preliminarily shows similar performances.

This new development will be adapted to the specific case of muon tomography, making special emphasis in the robustness and portability of the detector and on the response under changing environmental conditions such as temperature and atmospheric pressure.

We foresee that a detection plane with sealed RPC technology will be integrated in the existing telescope and its performance compared to the other planes in real data taking conditions during the project.

On the other hand, the control and processing system used in the prototype will be upgraded to reduce the power consumption and allow running on batteries powered by solar panels. In this sense, the entire control and processing system will be embedded in a single low power consumption unit that will allow a much more robust and compact system.

Activity B) Readout optimization for high quality muographic images

The prototype incorporates three planes with a core pad matrix (pixels) providing high spatial resolution although not scalable in area (due to associated cost) together with pads and strips with different areas. A fourth plane is equipped only with strips in order to test other readout strategies. We will investigate the performance of the area equipped with pads and strips with different areas as well as the fourth plane with the existing front-end electronics.

We will pursue the development of a new readout plane in two main lines: the simultaneous readout using perpendicular strips and/or the grouping of acquisition channels. In the first case we will either add a perpendicular strip readout plane in the bottom or sample it with criss-crossed metal electrodes. In the second case the idea is to use a codification such that the signal of several strips can be combined in a single electronic channel, without loss of information. The developed readout will be tested in existing RPCs in the Laboratory and then implemented in the field, extending the present prototype

In addition, a new front end electronics (FEE) that allows reading bipolar signals will be pursued. The FEE which is used in the prototype, only allows reading signals from one polarity which limits the possibility of using the two polarities generated by the RPCs. A new FEE capable of reading both polarities will provide more sensitivity and versatility in the design of a new readout plane.

Task 5 - Public awareness, outreach and dissemination of results (3988 / 4000)

This task will be led by the Lousal Science Center team, who are experts in science and technology non-formal education and popularization, in close contact with the other experts in the project. It focuses on sharing of know-how and creative ideas from research to public audiences (and vice-versa), fundamental to raise awareness for applied science and proposed technologies; for the transference of knowledge to other research settings; and to establish fruitful networks.

Activity A – Building a Muon Tomography Community in Portugal

5.A.1 – Knowledge and Data Transfer: the Lousal Digital Database will be designed to be used in the course of the project, and to be later included in public repositories. It will provide the geoscience community with access to the final muon tomography and geophysical results, pre-existing technical information about the mine, geological mapping and core samples characterization, and all detailed data from the surveys and final analyses in Tasks 1 and 3.

5.A.2 - Muography for Geophysics and Beyond: since muography applications can range from engineering to archaeology, the experience in operation of the muon telescope and its upgrades (Tasks 2 and 4), as well as of the muographic analysis, will be shared beyond the geoscience community. Towards the end of the project, we will organize an international workshop at the project site at Lousal.

5.A.3 - Training of University Students: aiming to progressively include Muography as a new standard technique in geophysics and geosciences in general, training of the future experts on this technology and associated methodologies is crucial. We will actively search for candidates for MSc and PhD studies, and engage students in physics, geosciences and engineering in short internships, for all the tasks of the project.

Activity B – Sharing with the general public and schools

5.B.1 - Guided visits to LouMu: visitors will have the opportunity to see the muon telescope in operation at the Waldemar underground mining gallery. An explanatory panel will be installed next to it, and a large-sized tablet will display results and monitoring data. These elements are fundamental for project dissemination, but also as a communication tool for the guided visits to the gallery.

5.B.2 - Non-formal educational activities: we will carry out science educational activities for high-school students related to muography, general geophysics and particle physics subjects, both at Lousal and surrounding schools. We will develop strategies for the data to be explored by students, aiming to involve local schools in the monitoring and analysis of the telescope, and to integrate the LouMu data in existing programs, such as the IPPOG's Masterclasses Hands on Particle Physics.

Activity C – Fostering knowledge at the *Mine of Science* - Lousal Science Center

5.C.1 – A muography interactive exhibit will include a spark chamber detector, built at LIP, allowing the visualization of real cosmic muons. It will include interactive tools to explain the basics of particle physics, cosmic ray muons and tomography applications. Monitoring data collected by the LouMu muon telescope will be displayed in a large-sized screen, giving visitors the opportunity to explore real-time results. The exhibit will be installed at the "Shower of Science" exhibition building, next to an already existing unit dedicated to gravimetry. Its production will imply the development of scientific contents, software, design and the manufacturing of an attractive assembly suitable for outreach purposes, robust enough to be handled by undifferentiated public.

5.C.2 - Information panel and LCD display: the project's objectives, instruments and expected achievements will be presented in a large information panel to be produced and installed at the main lobby. As the project proceeds, all progress will be documented and shared on an LCD display at the entrance, accessible to over 22,000 annual visitors at Lousal Science Center.

General dissemination (2931/3000)

Being a pioneering project on muon tomography in Portugal, significant efforts will be put on sharing its results and advances with the scientific and academic community. In addition to the publications and communications in conferences dedicated to muography, geophysics, particle physics and instrumentation, and science education and communication, we will address seminars at various National Universities, starting with Coimbra, Évora and Lisbon, and the results of the project will also be made available in the most useful formats for future use in other research settings.

Mainly, but not exclusively, through the Lousal Science Center team, the creation of a set of new interactive exhibitions, and other popularization and non-formal education activities are integral parts of the project. Those efforts are described in a dedicated task for dissemination (Task 5). Actually, scientific culture popularization activities directed to teachers, high-school students, families, tourists, and other adult visitors to the Lousal Science Center have already started: the prototype MiniMu is integrated in the guided visits, which occur every day with schools and general public, a bilingual LouMu leaflet is available for all the visitors, and dedicated visits have been integrated in Ciência Viva summer programs and teacher training actions in 2019.

We want to foster a local public network, engaging local players and community with the scientific and educational objectives of the project: we will approach all possible stakeholders at local and regional scale; the news of the project will be shared with thematic websites and local/regional press; team members will disseminate the project results during regionally-wide initiatives, in conferences, thematic meetings, high-school events, etc.

A LouMu project's website will be created as a partnership between the ACCVL (webmaster entity), LIP and ICT-UE. The website will be hosted at the LIP official website (http://www.lip.pt/LouMu/), linked to the Lousal Science Center and ICT-UE websites. The site will provide updated information, in Portuguese and English, on the project's progress and results, and will remain active beyond the project's end. It is envisaged to constitute a working tool at the service of the project partners, and simultaneously a communication channel between the partners and the public.

We also foresee a video documentary to provide general information about the research and outreach work developed during LouMu - the first project that aims to foster muon tomography in Portugal. It will be built on photos and short clips of video taken during the field work, and drone footage made during the geophysical campaigns, to emphasize the main results of the project and provide vectors for future research and applications. The documentary will allow the project members to extend the seeds left by this project long after it reaches an end.