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Planetary UAV GeoRadar Study

Issue 1, Rev 0

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1	**0**	07/02/2023	First Issue

1 SCOPE AND APPLICABILITY

The purpose of this project is to consolidate the Italian scientific competence about the geophysical features and composition of planetary surfaces and sub-surfaces in the solar system bodies and Earth itself, with particular interest in the exploration and characterization of the buried ice deposits, where bacterial primitive live could still exist.

This ambitious goal will be achieved involving Italian members of the main research groups in the fields of radar sounding and combining the flexibility of the Unmanned Aerial Vehicle (UAV) and the GPR technologies, that enable to image the subsurface structures and materials in impervious areas, providing also and additional solution for more efficient surveying.

With this proposal we intend to carry out the first phase of the project, that is focused on the design and development of the instrument with an high level of miniaturization and modularity, in order to allow the use of the drone as a flight platform, for the exploration and the study of the terrestrial glaciers, allowing at the same time to easily modify the technical design of the instrument if critical issues will arise. In order to fine tune and calibrate the GeoRadar we have identified several Alpine glaciers, such as the Carser and Sforzellina glaciers located in the Ortles-Cevedale Group (Central Italian Alps). They represent a good environment thanks mainly to the availability of many GPR surveys, acquired with traditional airborne radio echo sounding techniques; this will allow a more efficient calibration of the instrument.

A future development of the project, will consist of an additional integration of the instrument devices and antenna, using components and materials more compact and lighter, more suitable for operating on the other planets of the solar system and for a more intensive monitoring of the Earth's glaciers, to estimate the variation of ice volume, for a better characterization of the effect of climate change in progress.

2 INTRODUCTION

The possibility of achieving fundamental knowledge about the geophysical features of planetary surfaces and sub-surfaces has led in recent years to the development of many remote sensing techniques, most of which are based on the use of electromagnetic waves in various operational configurations. Among them, Ground Penetrating Radar (GPR) offers a well-established approach to achieve important information on the composition of sub-soil. We propose to develop a state-of-the-art, compact ground penetrating radar system whose small size, will make it a unique instrument that will be ideal for inclusion on future planetary missions and for the study of the Earth itself, allowing Italy to take a key role in this field.

Ground penetrating radars are low-frequency tools capable of penetrating below the surface and obtaining echoes from dielectric discontinuities in the subsurface. They are among the few remote sensing instruments capable of providing information on the interior of a planet. Two such instruments, MARSIS (on-board Mars Express ESA Mission) and SHARAD (on board Mars Reconnaissance Orbiter, NASA Mission), have been successfully built under Italian leadership and sent to Mars. Their observations provided insight into the geologic and climatic history of Mars that could not have been obtained otherwise.

GPR’s ability to provide high resolution subsurface geological structure leads to widespread geotechnical uses of GPR. Applications are wide ranging such as determination of bedrock depth, definition of soil stratigraphy, identification of features, location of buried groundwater and of particular interest for the overall international scientific community is to acquire a more complete knowledge of the shallow ice deposits, where bacterial primitive life may still exist.

NASA sent the first off-earth helicopter to Mars; the small drone helicopter was deployed in 2021 from the Mars 2020 rover, performing numerous successfully flights. NASA demonstrated that this technology demonstrator can fly safely, and provides better mapping and guidance that would give future mission controllers more information to help with planning travel routes and hazard avoidance, as well as identifying points of interest for the rovers. Unmanned Aerial Vehicle (UAV) may have a real future as low-flying scouts and aerial vehicles to access locations not reachable by ground travels.

In this frame, the present project is aimed at proposing an innovative miniaturized GPR for planetary subsurface sounding. Such a project, is based on a GPR operating at low frequency. The main innovation, compared to past Mars missions lies precisely in the miniaturization with the aim of using an UAV as flight platform to be proposed for the future missions to Mars and to the other planets as well, Earth included.

In order to exploit at best the instrument capabilities, a key step is the development of an innovative, miniaturized and lightweight antenna, to allow the use of the low frequencies requested to achieve high penetration capabilities in the medium.

At the moment, the available low frequency antennas, able to explore the medium at great depths, are characterized by weights and physical dimensions not suitable as a payload for light flight platforms such as the drone.

The other main distinctive feature of the project lies in the high scientific level results that will be achieved during the test and calibration campaigns of the instrument prototype, that will be conducted on Earth.
In this regard several alpine glaciers have been identified, where the ice structure and composition (mixture of water ice, debris and dust) and the rough topography, represent a scenario similar to the shallow Martina glaciers.
These information will allow to examine the ice structure, to understand the paleo-climate and perform an accurate estimation of the glacier ice volume. Glaciers, as is well known, represent one of the most significant "environmental marker", because through the estimation of the variation of ice volume, calculated over several years of measurements, will allow the characterization of the effects of climate changes in progress and consequently also the variation of local water resources.
Laboratory and field tests in different physical conditions will be also developed with the aim of calibrating the overall system.

3 SCIENTIFIC CONTEXT

Mars is today a cold, dry and sterile world with a thin atmosphere mainly made of CO_2. The geologic and compositional record of the surface reveals however that in the past Mars had a thicker atmosphere and liquid water flowing on its surface. For this reason, it has been postulated that life could have developed and that some primitive life forms may be existing even today. This possibility has led to the increase of an enormous interest in the red planet, and its exploration now involves all major space agencies in the world.

To define the best strategy for Mars exploration, NASA has created the Mars Exploration Program Advisory Group (MEPAG), formed by several tens of scientists from all over the world. To discover the life possibilities presence on Mars past or present, MEPAG has developed an exploration strategy known as "Follow the Water" (NASA, 2014). This would also be useful for choosing the site for the future human missions to Mars.

Following the water, requires an understanding of Mars current environment, through the study of the observed features such as dry river beds, the ice in the polar ice caps and the types of rocks that were formed only when water was present on the surface but also by searching for hot springs, hydrothermal vents or subsurface water reserves. These data will allow to understand if Mars once held a vast ocean in the northern hemisphere as some scientists believe, and how was Mars transitions from a watery environment to the dry and dusty climate it has today. Searching for these answers implies the study of geological and climate history of the planet to find out how, when and why Mars was subjected to the dramatic changes to become the forbidding planet we observe today.

For these reasons, Mars is currently one of the main objective of scientific interest in the Solar System exploration, with several space missions currently operating, such as Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter, Mars Science Laboratory, and several more planned for the near future, i.e. ExoMars Rover, Mars 2020. Italy is a major contributor to Mars exploration, providing several experiments on board the above-mentioned missions. In particular, Italy implemented the first two GPR still operating in orbit on Mars: MARSIS and SHARAD.

The Ground-Penetrating Radar is a geophysical method, also known as "radar sounding" that applies different radar pulses, frequencies and frequency band, according to the depth of required exploration in the medium. Higher is the frequency less is the penetration capability in the medium. In the Earth sciences, this technique has been used for more than five decades to study bedrock, soils, groundwater, and ice. The use of GPR in orbit, to study the subsurface of planetary bodies begun in 1972 with the Apollo Lunar Sounder Experiment (ALSE) on board the Apollo 17 (Porcello et al., 1974). The ALSE could operate at several different frequencies. At a frequency of 5 MHz it detected the base of a lava flow, 1.3 km deep. No other orbital sounder was flown until 2003, when the European Space Agency (ESA) mission Mars Express (MEX) carried the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) (Picardi et al., 2005) experiment.

MARSIS is a synthetic aperture radar sounder operating at 1.8, 3, 4 and 5 MHz and transmitting a 1 MHz bandwidth; achieving a vertical resolution of 150 m in free space, and a horizontal resolution of up to 5 km × 10 km. MARSIS has obtained its most significant results by detecting the presence of liquid water, trapped below the ice of the South Polar Layered Deposits (SPLD). Bright subsurface reflections were found within a well-defined, 20km wide zone centred at 193°E, 81°S. Quantitative analysis of the radar profiles collected between May 2012 and December 2015, shows that this bright feature has the dielectric permittivity >15, matching water-bearing materials (Orosei et al., 2008, published on Science) (see Fig. 1).

In Fig. 1(A) the radargram is a bi-dimensional colour coded section made of a sequence of echoes in which the horizontal axis is the distance along the ground track of the spacecraft, the vertical axis represents the two-way travel time of the echo, and brightness is a function of echo power. The continuous bright line in the topmost part of the radargram is the echo from the surface interface, whereas the bottom reflector at about 160μs corresponds to the SPLD/basal material interface. Strong basal reflections can be seen at some locations, where the basal interface is also planar and parallel to the surface. In Fig. 1(B) Red dots mark surface echo power values, while blue ones mark subsurface echo power. The horizontal scale is along-track distance, as in (A), while the vertical scale reports uncalibrated power in decibels (dB). The basal echo between 45km and 65km along track is stronger than the surface echo even after attenuation within the SPLD, therefore should be water.

In 2005, the SHAow RADar (SHARAD) was launched aboard NASA's Mars Reconnaissance Orbiter (Seu et al., 2007). SHARAD’s resolution is ten times better than MARSIS, owing to higher transmitted bandwidth (10 MHz), although the penetration depth, is about one tenth of that of MARSIS. The instrument has revealed a substantial amount of near-surface ice in Western Utopia Planitia (Stuurman et al., 2016) (see Fig.2). The reflectors are associated with layered mesas ~80–170 m thick. The value of 2.8 ± 0.8 for the dielectric constant of the material overlying the reflectors is consistent with a mixture of ice, air, and dust, containing a water ice volume up to 14,300 km3.

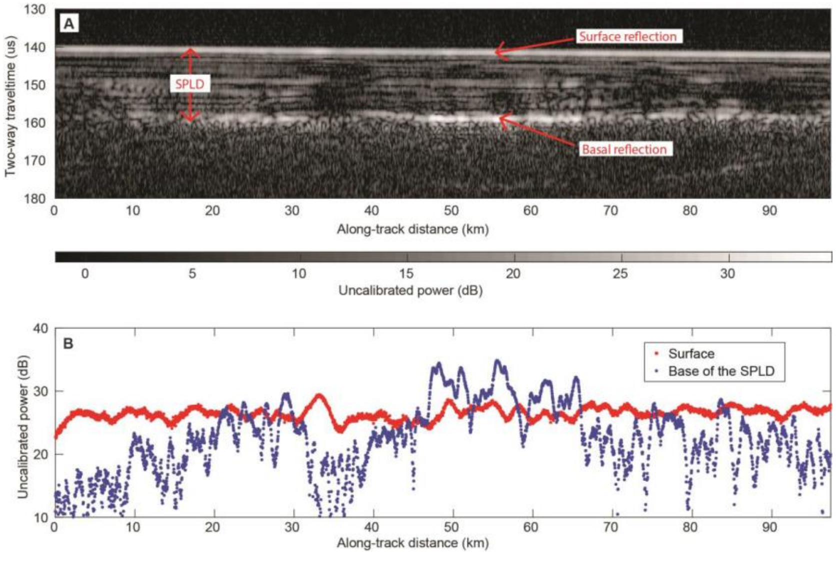


*Figure 1. Radar data collected by MARSIS. (A) Radargram for MARSIS orbit 10737. (B) plot of surface and basal echo power for the radargram in (A). Credits (*Orosei et al., Science 2008*).*

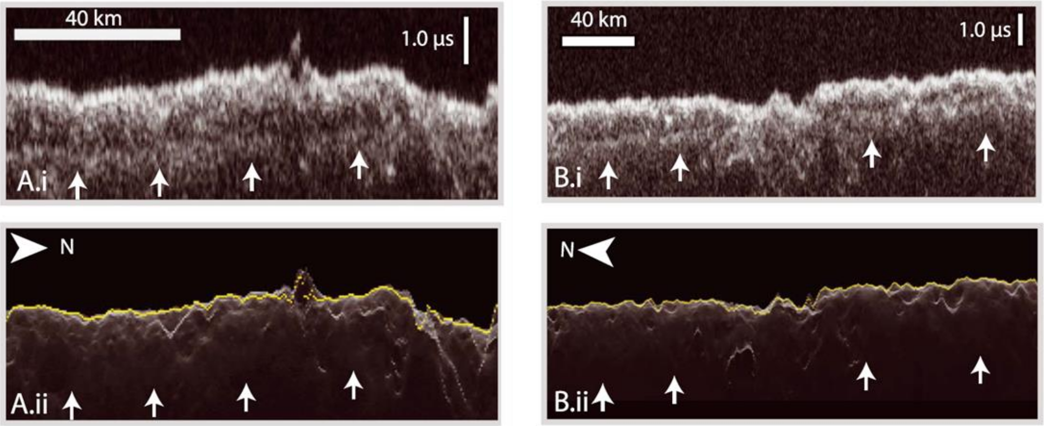


Figure 2. Examples of subsurface reflectors in western Utopia Planitia. (A.i) shows real SHARAD data for track 1346901. (B.i) shows SHARAD data for track 1389101. A.ii and B.ii show simulated surface return based on topography alone. Yellow lines in panels A.ii and B.ii is the Mars topography.
Credits (Stuurman et al., Geophysics. Res 2016).

Fig. 2Ai and Fig. 2B.i show real data collected by the SHARAD radar, respectively in the track 1346901 and 1389101, while Fig. 2A.ii and Fig. 2B.ii show the simulation of the radar surface returns based on topography alone. White arrows point to subsurface reflectors that are found in the real data but not in the associated simulations, this indicates that these are indeed real reflectors and not surface lateral clutter.

A surface penetrating radar, CONSERT (Comet Nucleus Sounding Experiment by Radio wave Transmission), was also onboard Rosetta mission. The 90 MHz bi-static radar investigated the internal structure of the comet nucleus through the measure of the time delay between transmitted (from Philae lander) and received signals (gathered by Rosetta orbiter) [Kofman et al., 2007].

In May 2008 the Phoenix NASA mission, landed inside the arctic circle of Mars (68.22°N, 234.25°E), during the northern spring. Phoenix was designed to verify the presence of subsurface water ice (P. H. Smith et al., 2008) that was previously predicted on the basis of thermodynamic principles and was mapped at low resolution (~500 km) within 1 m of the surface by using Odyssey's Gamma-Ray Spectrometer (GRS) instrument. A shallow ice table was uncovered by the robotic arm in the center and edge of a nearby polygon at depths of 5 to 18 centimeters (see Fig.3).
In late summer, snowfall and frost blanketed the surface at night; H2O ice and vapor constantly interacted with the soil. The soil was alkaline (pH = 7.7) and contained $CaCO_3$, aqueous minerals, and salts up to several weight percent in the indurated surface soil. Their formation likely required the presence of water.

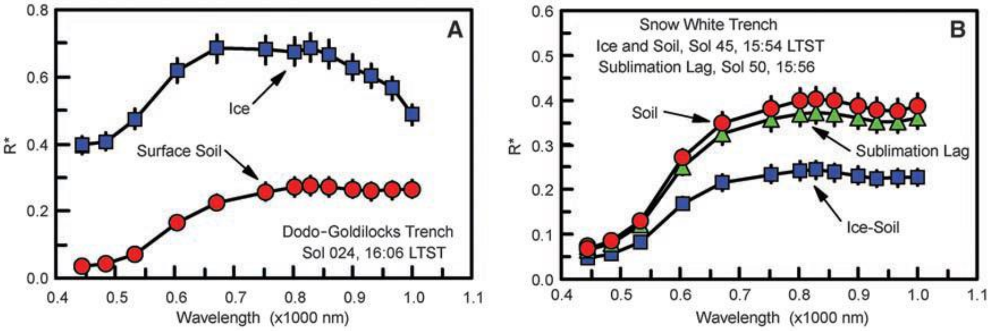


Figure3 Spectra reveal two different concentrations of ice mixed with soil. Error bars indicate 1s uncertainties. Credits (P. H. Smith et al., Science 2009).

In Fig. 3 (panel A) the Dodo Goldilocks trench matches high-albedo ice with a minor soil component (<2%) compared with nearby ice-free soil exposed in the trench bottom. Fig. 3 (panel B) shows the spectra in the Snow white trench correspond to low albedo ice with a major soil component, and nearby ice free surface soil exposed in the trench bottom and to the sublimation lag developed 5 sols later at the same location as the ice.

Observations and measurements from different satellites and rovers show that in the present climate on Mars, water mainly exists in large ice caps at the poles, in the ground as permafrost on the mid and high latitudes, and as frost patches and ancient glaciers scattered around the surface of the planet. Despite numerous studies of the Mars ice deposit, however, their internal structure and composition, remains still poorly understood; therefore developing innovative methods for filling these gaps is highly desirable.

High sensitivity, low frequency radar is an efficient tool to sound ice deposit that contain inclusions, map both deep and near-surface internal stratigraphy, and estimating the thickness of ice-sheet with fine resolution. Acquire a more complete knowledge of ice deposits close the surface is very important and could even be the trigger for a further ambitious new Mars mission, to drill into these buried ice pocket, like has been done for sub-glacial lakes in Antarctica on Earth (Vostok) where Scientist found evidence of bacterial life. To achieve these ambitious goals, the GPR system should make the measurements, as close as possible to the buried ice deposit, this is where drones come into play. They are lightweight and capable of flying autonomously with high precision and time efficient, owing to the small size, they can usually penetrate into constricted spaces and they can easily reach places that a nominal rover cannot do, due to rough terrain.

The correct functioning and the overall performance of the GPR system that we present here, will be verified and calibrated with a prototype installed on a drone on the alpine glaciers survey, where blocks, debris and the rough topography represent a scenario similar to that of buried glaciers near the surface of Mars. In this contest, we’ll also take advantages of this opportunity to investigate the internal structure and geometry of Alpine glaciers that are key components of local hydrogeological cycles and real time indicators of climate changes. Volume variations are primary targets of investigation for the understanding of ongoing modifications and the forecast of possible future scenarios.

These volume fluctuations can be traced by time-lapsed monitoring of the glacier thickness, for this reason a detailed reconstruction of the glacier bottom and surface morphology is however needed to provide total volume and reliable mass balance estimation.

Several alpine glaciers have been studied so far, with the GPR technology, among them the Careser glacier, located in the Ortles-Cevedale Group (Central Italian Alps) represents one of the most important frozen sector of Italian Alps. Over the years this glacier was also monitored by the glaciological campaigns performed by the “Comitato Glaciologico Italiano”. The Careser Glacier (Urbini el al. 2017) survey consists in approximately 5 km of profiles (see Fig. 4 c) covering the main parts of the glacier. All the flow lines, returned very clear bedrock reflections and practically no sign of backscattered energy areas (Fig. 4a). Fig. 4b represents, respectively, the ice thickness of BB’ profile (that includes the maximum recorded depth of about 80 m).

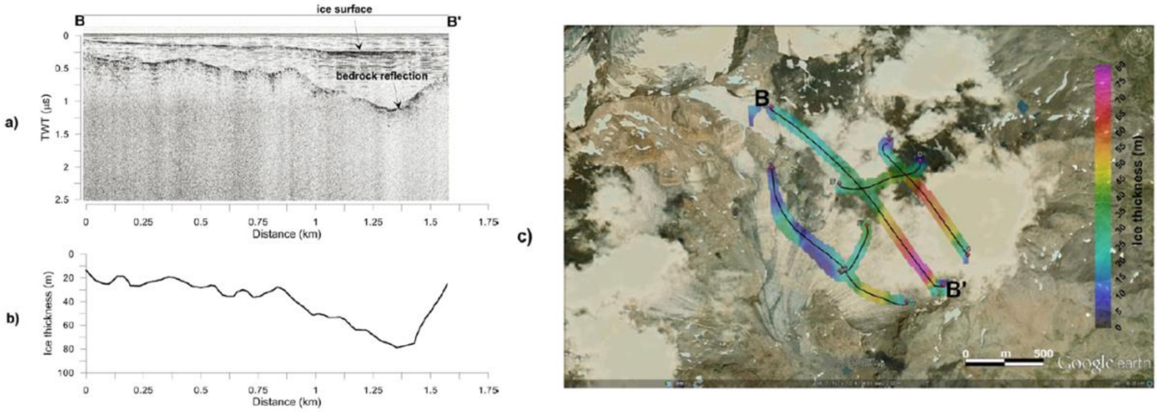


Figure 4. Example of profile recorded on the Careser Glacier: a) radargram; b) ice thickness along the profile; c) interpolated ice thickness dataset on Google Earth © map.
Credits (Urbini el al., Annals of Geophysics, 2017).

It is worth noting that the profiles acquired on the glacier are sparse compared to the total extension. The GPR on drone will be the best tool to improve the radar coverage, in order to mitigate the error on the ice volume estimation and above all to be able to monitor glacier elevation changes and mass balance, due to the deglaciation that cannot be explained only by natural climate variability (Dyurgerov M.B. and Meier M.F., 2000).

However, flying on the red planet is not easy, the thin atmosphere at the surface of Mars is the equivalent of being 30 km above Earth, well beyond the limits of terrestrial air vehicles, although the weaker gravity helps. At NASA’s Jet Propulsion Laboratory they have developed two pairs of rotor blades will spin in opposite directions at nearly 50 revolutions per second, a prototype has been tested in a chamber that mimics the Martian atmosphere.

A candidate in NASA New Frontiers competition would also send a robotic drone to Titan, Saturn’s largest moon. The four rotors drone would be able to perform detailed explorations of the moon’s various terrains, including its seas of hydrocarbons. This means that new GPR applications on drone can open new means of investigation in the solar system planets.

4 OBJECTIVES

. The proposed GPR is based on the propagation of electromagnetic (EM) waves within a frequency range between approximately 50MHz and 200MHz allowing a penetration depth of about 50m, while the radar signal bandwidth of 100MHz, will guarantee a range resolution in the ice, of about 1m. The radar signals are transmitted into the glacier and the reflected echoes are returned to the receiver, allowing the imaging of the subsurface features. The on-board computer measures the travel time taken for a pulse to reach the target and for its echo to come back to the receiver. This time provides target depth and location (see Fig.5). The radar unit emits and receives reflected signals up to a thousand times per second; these signals are stored on digital media and later downloaded for the on-ground processing and analysis. The Data can be collected in simple line scans to determine the thickness of the target or in a grid format which will produce a 3D map of the image. Since radio waves travel through many different materials, contained in the glacier: water ice, debris and dusts, since all of them have different dielectric and conductive properties that affect the radio waves, it is fundamental to perform an accurate analysis of the recorded signals and a careful post processing is also needed to compensate for nonlinearities of the overall system.

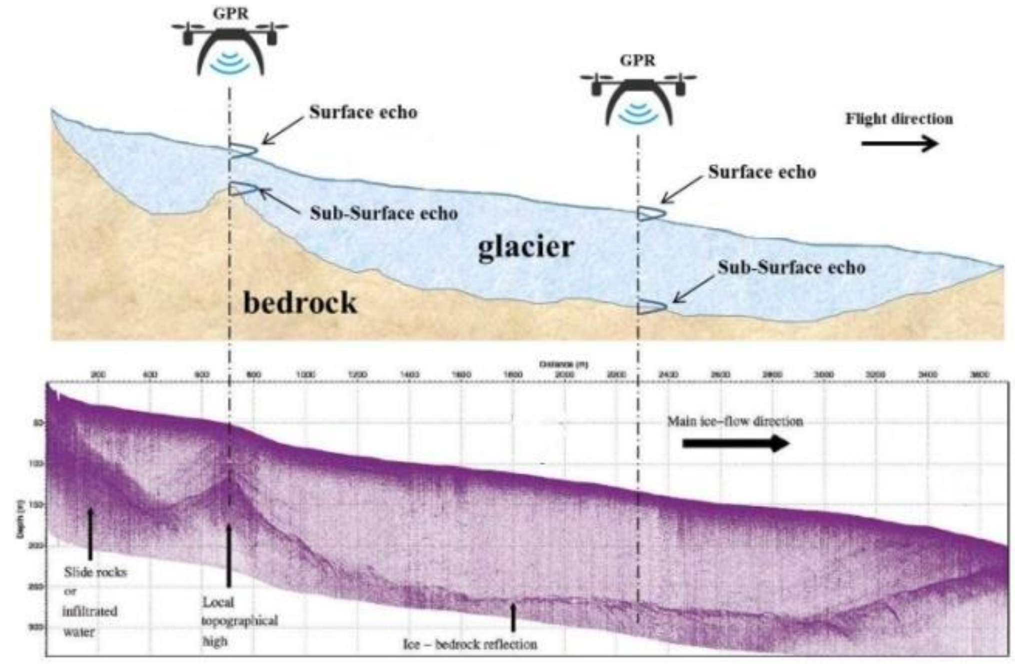


Figure 5. Artistic representation of the acquisition mechanism. Top panel shows a drawing of the glacier profile. Bottom panel shows real GPR data.

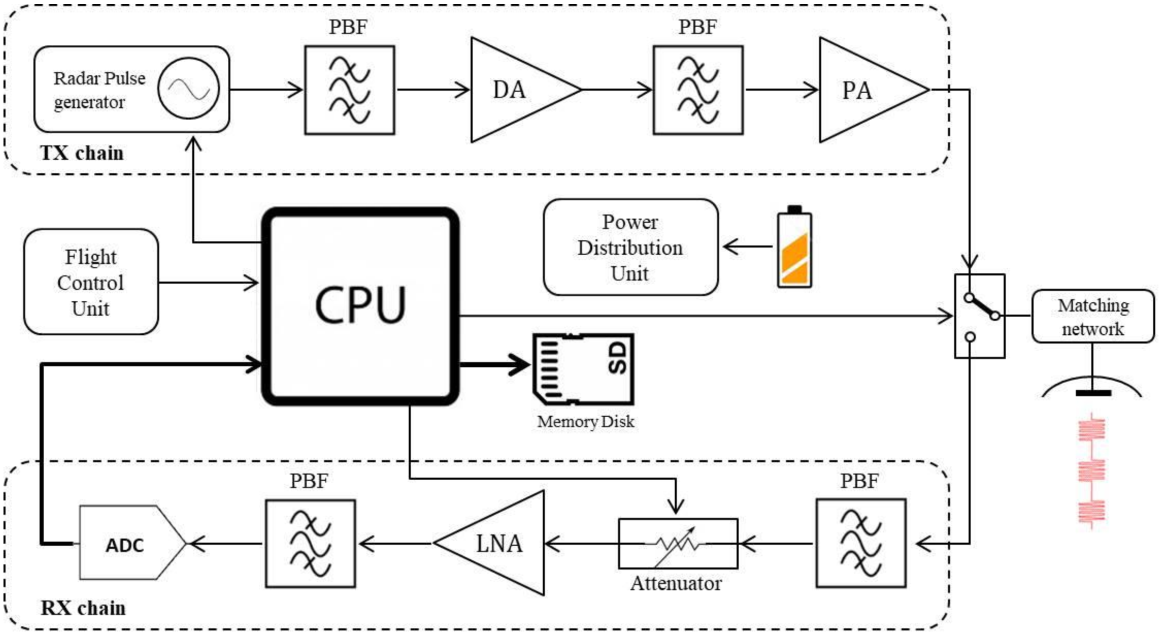


Figure 6. Instrument schematic block diagram.

The instrument hardware is shown in Fig.6. It consists mainly of a custom high efficiency wide band antenna, radio frequency devices (TX and RX chains) to handle the radar signals, a sophisticate single board acquisition computer with processing software to synchronize the overall system, a power distribution unit to supply power to all the radar devices, optimizing energy consumption from the on-board batteries and a Flight Control Unit for science data geo-referencing, composed of a GPS, an accelerometer on three axis and a laser altimeter. The UAV to carry the radar, could be an exacopter "DJI Matrice 600 pro" equipped with precise navigation system and accurate GPS positioning, it can be either flown manually or autonomously following a pre-defined track, with set speed and height above glacier to be repeated over the time in order to compare the ice volume variation.

5 TESTS AND CALIBRATION PLAN

Every verification activity is intended to provide verification and conformance to the requirements and will be described as a step by step procedure. The testing will be organized through the use of standard laboratory and a dedicated In-situ testing facilities, In particular:

- **Laboratory Tests**. All radar devises are wired and housed in a metal box. The antenna, will be replaced with a load impedance and the transmitted pulses are injected directly into the front end of the receiver with a coaxial cable, to determine the RF and digital gain of the sounder.

- **Anechoic Chamber Test 1**. Same configuration of previous tests, adding the antenna. The instrument will radiate power and a metal screen will be used to simulate a target.

- **Anechoic Chamber Test 2**. Same configuration of previous test, to verify the correction of eventually hardware deviation. The radar will be also operated simultaneously with an electromagnetic source of disturbances (i.e. Electrical engine to simulate the helicopter rotors).

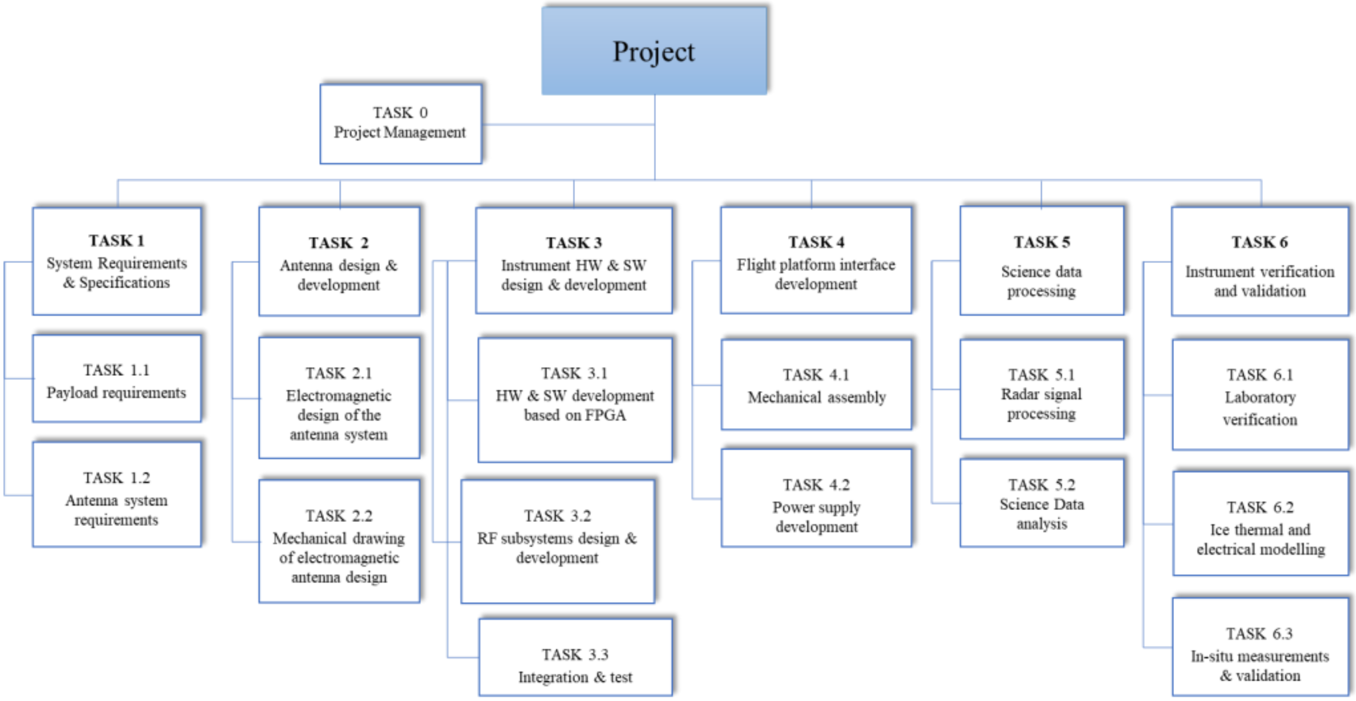
- **Anechoic Chamber Test 3**. Final qualification test.

- **In-situ Tests**, executed in different physical conditions, with the aim to verify the overall instrument performances. The radar will be hooked to a fixed support, a few meters from the ground and Ice will be buried underground, to simulate a real scenario.

Flight tests, the radar and its antenna are mounted as a payload of the drone, over a simulated target in different conditions (flight with a human operator) in order to verify the correct integration between the radar and the UAV. Moreover, these tests will allow to check the presence of possible drawbacks due to the drone trajectory stability and to solve them.

6 PROJECT BREAKDOWN STRUCTURE

The activities encompassed by this proposal are organized into TASKS included in the following Work Breakdown Structure (WBS):



6.1 TASKS DESCRIPTIONS

TASK0: coordination of all the scientific and technical activities of the team, verification of the state of advancement of each TASK in agreement with the proposed activity plan.

TASK1: definition of the overall system requirements from a functional point of view, considering the radar payload, the antenna system and the ground data processing.

TASK2: design and development of a miniaturized and lightweight broadband antenna.

TASK3: development of digital HW, firmware, and on-board software. Components integration testing, is also foreseen to verify the payload digital subsystem functionalities.

TASK4: design and development of the mechanical assemblies and the Power Distribution Unit. Payload verification and test.

TASK5: development of a set of processing tools for the implementation of all functionalities needed for the processing of the instrument data, including the compensation of the instrument devices distortions.

TASK6: Experimental support to all phases of the project from the preliminary study of the proposed GPR performance using commercial GPR, working in the same range of frequencies. This activity will regard both laboratory and in-situ tests in different physical conditions. The Laboratory experimental activities will be specifically devoted to characterize the electromagnetic properties of ice as a function of frequency, temperature and composition (presence of dust and salts in the ice).

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