



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 1 of 64

Development of Ground Penetrating Radar for Subsurface Ice Detection on Mars

Mars Advanced GPR for Helicopter Ice Sounding

“MAGHIS”

System Design Definition

PREPARED by : A. Cicchetti¹

CHECKED by : M. Cartacci¹, M. Mastrogiuseppe²

APPROVED by : A. Cicchetti¹

¹Istituto Nazionale di Astrofisica (INAF), Istituto di Astrofisica e Planetologia Spaziali (IAPS), Rome, Italy

²Link Campus University, Rome, Italy

Table of Contents

1	BRIEF OVERVIEW	3
2	PROJECT DESCRIPTION	4
2.1	SUMMARY	4
2.2	SCIENTIFIC CONTEXT	5
2.3	OBJECTIVES	6
2.4	INSTRUMENT PRELIMINARY STUDIES AND SW SIMULATION ACTIVITIES	8
2.5	INSTRUMENT OPERATIONS	11
2.6	TEST CAMPAIGNS	12
2.7	DELIVERABLES AND MILESTONES	13
2.8	WORK PACKAGES DESCRIPTION	18
3	GPR PARAMETERS DEFINITION	22
4	LINK BUDGET ESTIMATION.....	25
4.1	INSTRUMENT DYNAMIC ESTIMATION	25
4.2	DIGITAL BOARD THEORETICAL DYNAMIC ESTIMATION.....	29
4.3	INSTRUMENT GAIN AMPLIFIER ESTIMATION	30
5	RADAR SF-CW.....	31
5.1	DESIGN OF THE TRANSMITTED SIGNAL.....	34
5.2	CONSIDERATIONS ON HOMODYNE AND HETERODYNE DEMODULATION.....	36
5.3	RECEIVER NOISE FIGURE ESTIMATION.....	37
5.4	TRANSMISSION TIME ESTIMATION.....	40
5.5	ELECTRONIC CALIBRATION SYSTEM.....	41
5.6	LABORATORY TEST	43
5.7	INSTRUMENT DATA RATE AND VOLUME.....	46
6	RADAR FM-CW	47
7	INSTRUMENT SUMMARY TABLE	52
8	INSTRUMENT HIGH LEVEL ELECTRONICS	54
8.1	INSRUMENT PRELIMINARY LAYOUT	55
9	SELECTION OF COMPONENTS	56
10	ESTIMATION OF POWER CONSUMPTION AND WEIGHT	64

1 BRIEF OVERVIEW

The possibility of achieving fundamental knowledge about the geophysical characteristics of planetary subsoil, has recently led to the development of numerous remote sensing techniques. Among these, Ground Penetrating Radar (GPR) is an efficient and non-intrusive geophysical method that offers a successful approach to imaging and to obtaining important subsoil information.

The aim of this project is to propose an innovative stand-alone GPR to support future missions on Mars, both human and robotic for the identification of accessible local water-ice deposits located a few meters beneath the planet surface. Additionally, this system aims to facilitate the study of Earth's glaciers, thereby enabling INAF to play a key role in these challenging research.

The innovation lies in the optimization of the Geo-Radar, particularly its antenna, which is one of the most challenging components of the instrument. This miniaturization allows for its integration as a payload on an Unmanned Aerial Vehicle (UAV), such as a drone-helicopter.

2 PROJECT DESCRIPTION

2.1 SUMMARY

The present project is aimed at proposing an innovative GPR called: **Mars Advanced GPR for Helicopter Ice Sounding (MAGHIS)**, operating at UHF frequency ($300\text{MHz} \div 3\text{GHz}$), for the detection of buried water ice deposits at depth of a few meters beneath the Surface of Mars, which represent a strategic resource for both Mars exploration and the search for potential past and present forms of life.

This innovative technology will also find utility in studying the structure of Earth's glaciers. Glaciers are widely recognized as significant environmental indicators. By assessing variations in ice volume over time, it becomes possible to characterize the effects of ongoing climate changes and, consequently, the fluctuations in local water resources.

The originality of this project lies precisely in the miniaturization, allowing its integration as payload on Unmanned Aerial Vehicles (UAVs) for future missions to Mars, both manned and robotic. The successful deployment of the small helicopter, Ingenuity, aboard NASA's Mars 2020 mission has already demonstrated the feasibility of utilizing UAVs in the thin Martian atmosphere.

Furthermore, compared to current commercially miniaturized GPR systems, MAGHIS boasts superior signal quality management. This capability enables MAGHIS not only to determine the geometrical dimensions and depths of target of interest but also to analyse their composition.

2.2 SCIENTIFIC CONTEXT

The exploration of Mars is crucial in addressing fundamental questions about the universe, such as the existence of life beyond Earth and if habitable planets are common in the universe. These findings could significantly impact our comprehension of our place in the universe. Additionally, studying Mars can also provide valuable insights into the origin and evolution of rocky planets in our solar system. This can contribute to our understanding of Earth's own evolution.

Recognizing these imperatives, NASA, along with international partners: the Italian Space Agency (ASI), the Canadian Space Agency (CSA), and the Japan Aerospace Exploration Agency (JAXA), has entered into a statement of intent to advance a potential robotic International Mars Ice Mapper (I-MIM) mission. This initiative aims to identify accessible ice deposits for potential landing sites on the Red Planet.

Furthermore I-MIM will also provide a map of water-ice resources for forthcoming human expeditions. Mapping shallow water ice could also support supplemental high-value science objectives including the investigation of Martian climatology, geology, climatic variations and even the potential presence of life forms

Water ice stands out as a critical natural asset that could serve as a source of hydrogen and oxygen for fuel, as well as support backup life systems. Given the exorbitant costs associated with transporting water from Earth to deep space, harnessing local resources is imperative to sustain human surface exploration.

The present project MAGHIS, would be an invaluable tool in achieving and enhancing the objectives of missions like I-MIM, as well as other future spatial missions capable of hosting miniaturized UAV Radar technology. This innovative approach will also contribute to the study of terrestrial glaciers, which serve as significant environmental indicators.

2.3 OBJECTIVES

This ambitious objective will be achieved involving researchers in antenna design, as well as in the radar and geological fields and combining the flexibility of a UAV with the GPR technology.

Given the instrument's complexity and ambitious goals, it is necessary to accurately and in-depth define the requirements of the overall system, paying particular attention to the integration phase of the different subsystems and studying suitable electrical interfaces. It is then expected to carry out the definitive design and development of the prototype of the instrument, with a Technology Readiness Level (TRL) equal to 6, complete in all its parts but not yet suitable for integration on a Martian flying drone. However, the prototype will be suitable for flying in the dense Earth's atmosphere, using for example, the Exacopter-drone (DJI Matrice 600 pro) provided by Astronomical Observatory of Cagliari, facilitating the qualification test of the instrument's performance (see Fig 2.3.1, "PRESENT PROJECT").

Further project development will involve the miniaturization of the instrument, while adhering to the already established requirements, in order to reduce its weight and dimensions, thus making it compatible for flying on a drone for a possible future space mission on Mars. (see Fig 2.3.1, "FUTURE DEVELOPMENT").

The instrument design will prioritize high modularity for easy reconfiguration and modification, enabling resolution of potential integration test issues.

The innovative, highly efficient lightweight antenna poses the greatest challenge for the Geo-Radar. Due to its big impact on electromagnetic properties, only this component will be qualified for Mars flight.

The proposed prototype instrument will also benefit other INAF research groups interested in studies in the following areas:

- Characterization of soil and subsoil composition, investigation of geological structures, and stratigraphy.
- Study of terrestrial glaciers, crucial environmental indicators enabling characterization of ongoing climate change effects and local water resource variations.
- Identification of groundwater resources. The geo-radar drone can assist in locating aquifers and monitoring underground hydrogeological dynamics.



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 7 of 64

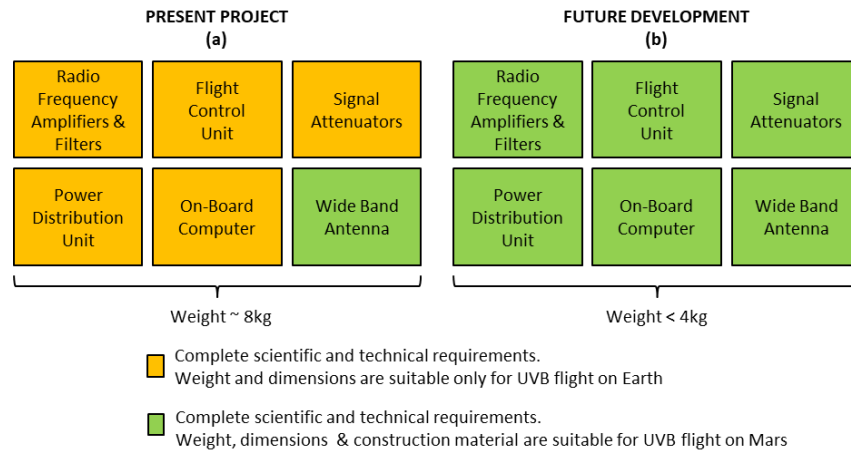


Figure.2.3.1 Project Milestones scheme

2.4 INSTRUMENT PRELIMINARY STUDIES AND SW SIMULATION ACTIVITIES

Regarding the most critical component of the project, the antenna, we have considered several models, in particular the Antipodal Vivaldi antenna with rectangular slots and circular terminations, exhibited highly promising characteristics. Measurements conducted using the Time Domain Reflectometry (TDR) technique, along with simulations using CST software, have underscored the feasibility of the proposed GPR system.

In particular, we have developed a preliminary prototype of this antenna, realized on an a cheap FR4 substrate [see Fig. 2.4.1], and published a paper[1] detailing its performance. In the Ground Probing Radar system under consideration, the antenna is connected to a TDR system, as illustrated in Fig. 2.4.2(a). The gain versus frequency profile of the antenna prototype is depicted in Fig. 2.4.2(b), demonstrating a good agreement between measurements and numerical simulations.

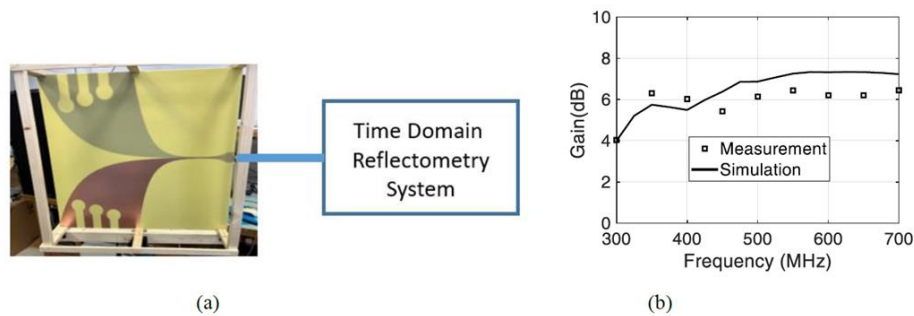


Figure.2.4.1 Antenna prototype (a) and antenna realized gain (b)

Initial measurements with real targets were conducted by placing the antenna in front of a metallic panel at distances of 120cm and 135cm. The transmission (TX) pulses were synthesized using the Time Domain Reflectometry (TDR) option available on the Agilent E8363C network analyser. The time-domain pulse responses are shown in Fig. 2-4-2. The first peak observed in the antenna response, occurring at approximately 3.3 ns, arises from reflections at the antenna mouth, while the subsequent peaks at 13ns and 15ns result from reflections off the metal panel. Considering the time delay introduced by the antenna, the second and third peaks correspond to distances of approximately 112cm and 142cm, with errors of 8cm and 7cm, respectively. Consequently, the radar system equipped with the proposed antenna demonstrates the capability to measure free-space target distances with errors of less than about 10cm, compatible with the system bandwidth of 400MHz.

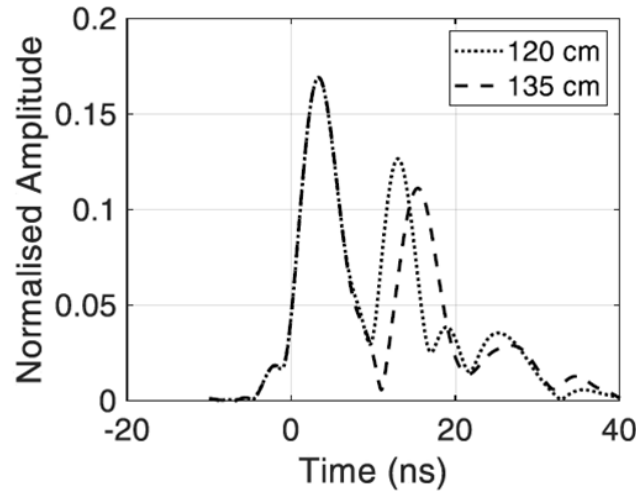
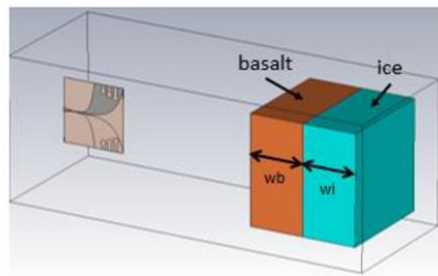
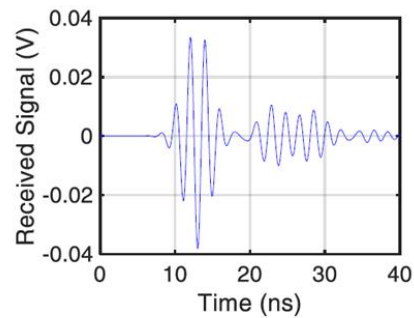


Figure 2.4.2. Antenna pulse response for 120cm and 135cm antenna-panel distances

To assess the performance of the proposed radar system on the Martian surface, a standard scenario was examined, considering an ice layer (with dielectric constant $\epsilon_r=3$ and conductivity $\sigma=0.0$ S/m) with a thickness of 50cm buried beneath basaltic rock (with dielectric constant $\epsilon_r=9$ and conductivity $\sigma=0.01$ S/m, with a thickness of 50cm) [refer to Fig. 2.4.3 (a)]. The GPR system was positioned at a distance of 2m from the planetary surface. The system's response at the antenna port was simulated using the full-wave CST Studio Suite software [see Fig. 2.4.3 (b)]



(a)



(b)

Figure 2.4.3. Investigated scenario (a) and plot of the pulse response of the antenna port(b).

The presence of reflections between the air and basalt, as well as between basalt and ice, is clearly evident in [Fig. 2.4.3 (b)], indicating that the radar's resolution is adequate to distinguish typical terrain stratifications.

The antenna we have developed will be further miniaturized by employing higher-performance materials that are qualified for space applications. While these initial tests have demonstrated the excellent performance of this antenna design, it is fundamental to explore additional solutions that may offer greater efficiency, lighter weight, and increased compactness. For instance, a class of lightweight spherical-axicon-like dielectric lenses, developed by the University of Rome “La Sapienza”, shows promise for enhancing broadband antenna performance [refer to Fig. 2.4.4].

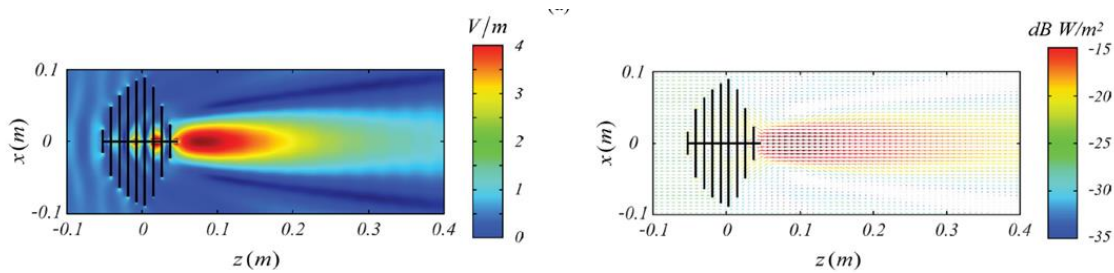


Figure 2.4.4. Spatial behavior of the x-component of the electric field and of the real part of the Pointing vector in the xz-plane for 8-disk lens, of permittivity $\epsilon_r = 10.2$

2.5 INSTRUMENT OPERATIONS

The radar signals are transmitted into the soil, and the reflected echoes, caused by variations in the electrical properties of the medium, enable identification of subsurface features. The on-board computer measures the time taken for a pulse to reach the target and for its echo to return to the receiver; this time delay provides information about the depth and location of the target. We have determined that a resolution of approximately 15cm is adequate for distinguishing the detection of shallow ice deposits.

The instrument emits and receives reflected signals up to a thousand times per second, which are then stored on digital memory and later retrieved for processing. The scientific data can be collected either in simple line scans or in a grid format, generating a 3D map of the Radar image. As radio waves travel through various materials such as debris, dust, and water-ice mixed with debris, each with distinct dielectric and conductive properties affecting radio wave propagation, it is crucial to perform an accurate analysis and calibration of the recorded signals.

To achieve a range resolution of 15cm in the medium (assuming a basaltic soil with a relative dielectric permittivity of 9) with a radar pulse duration of approximately 3ns, a radio frequency band of 400MHz is required. Additionally, to simplify antenna complexity and enable detection of features at mutual distances of 15cm to a maximum depth of 10m, a centre frequency of around 500MHz has been considered in our preliminary studies and simulations. Meeting the requirement of an 80% fractional bandwidth presents some challenges in antenna design.

The high-level hardware schematic of the instrument is shown paragraph 5.7, It includes a custom, highly efficient wideband antenna, radio frequency devices (TX and RX chains) for managing radar signals, a sophisticated single-board based on FPGA to command and control the entire system, including also the ADC/DAC for the radar signals generation and acquisition and a power distribution unit to supply power to all devices.

The Earth operating prototype will also incorporate a Flight Control Unit (FCU), composed by five sensors essential for georeferencing the scientific data collected by the instrument. The primary function of the FCU is to record the position and orientation of the antenna and a GPS sensor enables the recording of the position, including elevation information, while the tilt sensor and digital compass facilitate the recording of the antenna's inclination and orientation.

2.6 TEST CAMPAIGNS

An extensive test campaign will be planned to ensure the proper functioning of the instrument. Specifically:

LABORATORY TESTS. All radar devices will be connected and housed within a metal enclosure. The antenna will be substituted with a load impedance, and transmitted pulses will be directly injected into the receiver's front-end to assess the instrument's frequency response and generate calibration curves. These curves are essential for fine-tuning the hardware devices, especially in cases of significant non-linearity.

IN-SITU QUALIFICATION TESTS. A synthetic material, which simulates the dielectric constant of ice (presumably glass beads), will be buried at a depth of about one meter, as it shown in Fig.2.6.1. The deposit of simulated ice, will have a thickness of a few tens of centimetres and a diameter of about 2 meters. In these conditions we will verify that the Geo-Radar will be capable to record both the surface and subsurface echoes.

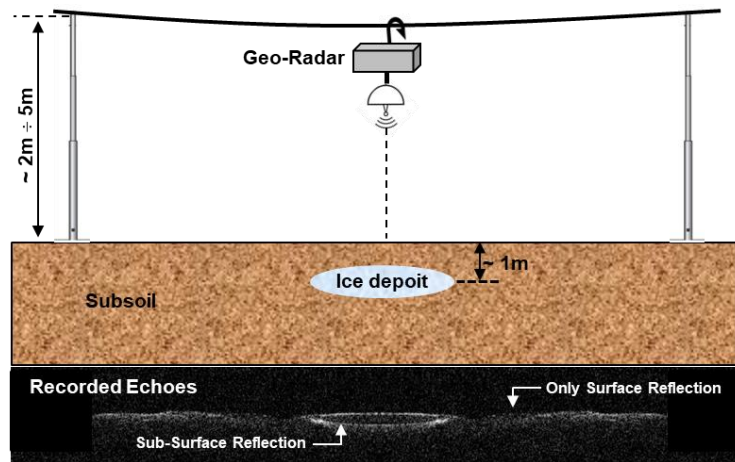


Figure 2.6.1. Artistic representation of the In-situ qualification test. The bottom panel shows an example of theoretical echoes visualization (radargram).

IN-SITU COMPATIBILITY TESTS CONDUCTED ONBOARD THE DRONE. The UAV, provided by INAF-OAC, utilized for carrying the instrument prototype, is an Exacopter “DJI Matrice 600 pro” equipped with a precise navigation system and accurate GPS positioning. Its purpose is to verify both the flight capabilities of the instrument and ensure that the electronic devices of the drone do not interfere with the radar.

2.7 DELIVERABLES AND MILESTONES

DELIVERABLES

1. **Models System Analysis and Hardwar architecture.** This document delineates the scientific objectives of the mission, explains the mathematical and theoretical models fundamental for instrument design, and outlines the architectural framework of the Geo-Radar hardware. Additionally, it encompasses the requisites of all electronic subsystems. The execution of this task will be managed by the personnel identified in WP02 (Scientific Requirement Definition)
2. **Instrument DES Requirements Description.** This document describes the Digital Electronic Section (DES) and the Software requirements, according to the instrument requirements defined in the “Models System Analysis and Hardwar architecture” document. This document will be written in collaboration with the external company chosen for DES implementation and by the staff listed in **WP03**(Digital Electronic Subsystem Design & Development).
3. **Radio Frequency Chains and Antenna Design Description.** This document describes the requirements for all commercial Radio Frequency devices, including antenna design, theoretical performance and simulation using SW tools and the final performances of the developed antenna. This task will be carried out by the personnel listed in **WP04** (Radio Frequency Design & Antenna Development), in cooperation with an external company to be selected for antenna development.
4. **Calibrations and Test Pans Description.** This document describes the overall system verification tests, required to validate radar performance and ensure the attainment of scientific objectives. This work will be executed by the personnel listed in **WP06** (Instrument Verification Tests).
5. **Instrument Data Format Description.** The aim of the document is to describes the Science and Housekeeping data formats essential for ensuring the usability of the dataset across Open Access repositories, including Zenodo (<https://zenodo.org>), OpenPlanetary (<https://www.openplanetary.org>), and GitHub (<https://github.com>). The task of defining these formats will be undertaken by the personnel identified in WP05 (Radar Signals Processing & Data Archiving).
6. **Geo-Radar prototype Delivery.** A full operative prototype of the Geo-Radar will be delivered complete of all its parts, described in this proposal, including the manufacturing of the innovative high efficiency lightweight antenna, the only component qualified to operate on Mars.

MILESTONES

Identification, through the study of scientific literature of areas on Mars located at medium latitudes, characterized by a higher probability of containing hidden shallow water ice deposits and being easily accessible.

Characterizing the distribution of near-surface Martian water from low to mid-latitudes has been identified as a key step in addressing critical knowledge gaps relevant to the design of the first human missions to Mars. Understanding the distribution of water is essential for achieving significant planetary science objectives, encompassing the planet's climate, geological history, and potential for past and present life. Simultaneously, the fundamental role of water in supporting human exploration guides the selection of landing sites toward regions with abundant reserves of accessible water. Therefore, understanding the presence and characteristics of water will not only inform decisions about future landing sites for Martian crews but also influence the scientific investigations conducted in those areas.

To achieve this objective, the International Mars Ice Mapper Mission (I-MIM) has been studied as a joint concept by the Italian Space Agency (ASI), the Canadian Space Agency (CSA), the Japan Aerospace Exploration Agency (JAXA), and the National Aeronautics and Space Administration (NASA). The primary aim of the mission is to characterize accessible near-surface water ice, within the uppermost 10 meters, and the geotechnical properties of its overburden in the mid to low-latitudes of Mars, in support of future human exploration efforts. The mission has been structured around the following three requirements:

- Identification and Extent of Water Ice.
- Accessibility of Water Ice.
- Assessment of Candidate Human Landing Sites [4].

To boost the development of I-MIM, NASA has initiated the Subsurface Water Ice Mapping (SWIM) on Mars project, dedicated to locating buried ice resources within the mid-latitudes. Employing a combination of orbital datasets and advanced data-processing methodologies, the SWIM project evaluates the probability of ice presence by analysing the coherence of various independent data sources [5].

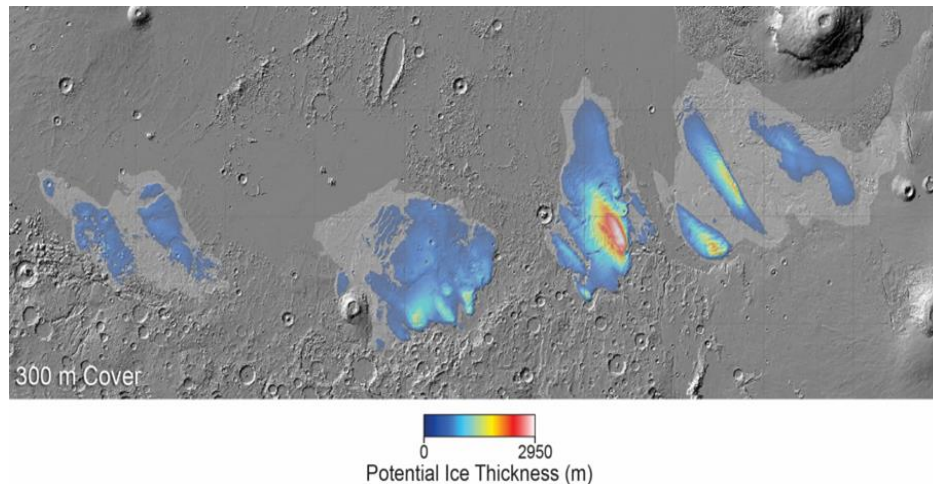
At mid-latitudes, the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS), which has been on-board the Mars Express ESA mission since 2003 and operated by INAF, has detected evidence of water ice layers [6] extending several kilometres beneath the surface. This discovery represents the largest concentration of water ice ever found in this region of the planet.

Radar signal collected over the Medusae Fossae Formation (MFF), near Mars's equator, exhibit a layered ice response similar to signals observed from Mars's polar caps, known for their abundant ice content.



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 15 of 64



CREDIT: Planetary Science Institute/Smithsonian Institution

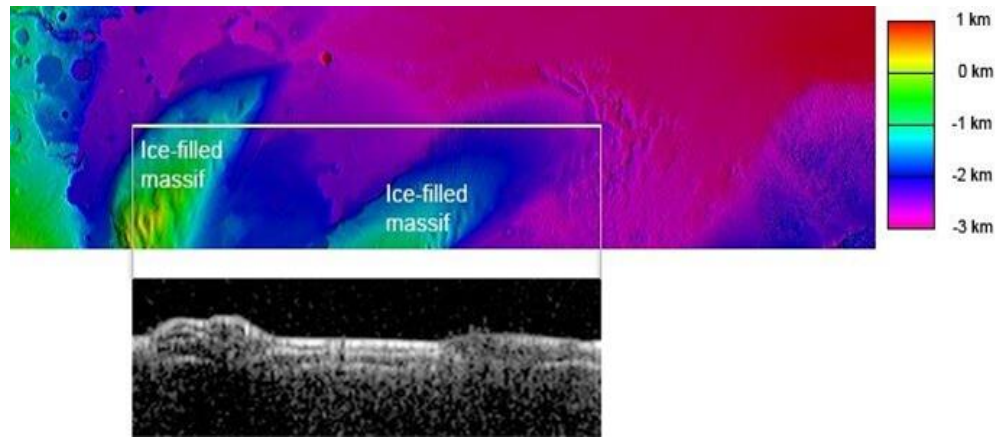
Figure 2.7.1. MFF Potential Ice Thickness distribution, from 0m (dark blue) to 3km (red-white)

Figure 2.7.1 shows Mars's Medusae Fossae Formation, characterized by a series of wind-sculpted deposits spanning hundreds of kilometres in width and several kilometres in height. These features are believed to be one of the largest sources of dust on Mars, obscuring what appears to be a substantial layer of water ice-rich deposits.

Figure 2.7.2 presents a coloured height map of Mars's surface, with a white horizontal line spanning two mounds separated by a valley. This feature corresponds to a narrow land area observed by MARSIS. The pop out below provides a closer look at the radar data collected by the instrument, unveiling the subsurface structure of Mars.

Analysis of the radar data indicates that beneath a substantial layer of dry material, likely composed of dust or volcanic ash, the mounds contain deposits of water ice.

Another two interesting areas of Mars, at mid latitude that are compatible with the objectives of this project are **Arcadia Planitia** and **Utopia Planitia**.



CREDIT: Planetary Science Institute/Smithsonian Institution

Figure 2.7.2. Mars Express radar image (black and white) showing layers of dry material and possible ice in the MFF below the surface

These recent discoveries underscore the significance of conducting further in-depth studies of Mars's mid-latitude regions, which are not only more accessible to robotic missions but also potentially to human explorers. In this regard, integrating geo-radar onto a drone would enable a more precise and detailed analysis of the most promising areas for ice extraction.

Definition of the requirements and specifications of the Geo-Radar to achieve optimal performance in terms of ground penetration (including transmitted pulse duration, carrier frequency, and antenna characteristics) and high accuracy, tailored to the geological characteristics of the identified areas of interest.

In order to search for water ice in the Martian subsurface up to a maximum depth of 10m, a medium resolution of a few tens of centimetres is required. However, due to the low flight altitude of the platform (<10m), it will not be feasible to use energy-efficient frequency-modulated pulses (chirp), as the modulation of the large bandwidth necessary to meet the resolution requirement within the short duration of the transmitted pulses, dictated by the flight altitude, would be impractical. Therefore, the simpler pulse on carrier approach will be adopted, with a bandwidth of approximately 400MHz required to ensure a resolution of about 15cm.

The selection of the carrier frequency will involve a trade-off between the need to minimize antenna size and the requirement for adequate penetration capability (down to 10m).

	 INAF THECNO GRANTS	ISSUE: 04 Data: 06/10/2025 Page 17 of 64
---	--	---

Hardware and software design of all electronic devices, with particular emphasis on the antenna, which, due to its weight and dimensions, can be regarded as one of the most challenging and complex elements of the instrument.

All hardware devices, both Analog and Digital, will be constructed using pre-assembled commercial components. This approach will allow us to minimize costs and concentrate on the primary challenge of this project: developing a high-performance professional antenna suitable for deployment on a drone for flights on both Earth and Mars.

To minimize size and weight, the received echoes will not be demodulated on-board and then digitized, as was typically done in past missions. Thanks to modern signal conditioning devices, it is now feasible to utilize low-cost Analog to Digital Converter (ADC) devices integrated directly into the FPGA board, offering very high sampling frequencies. Given that the highest frequency will be around 700 MHz, a sampling frequency of 2 GHz will enable accurate signal reconstruction without aliasing, thus preserving all scientific information.

	 INAF THECNO GRANTS	ISSUE: 04 Data: 06/10/2025 Page 18 of 64
---	--	---

2.8 WORK PACKAGES DESCRIPTION

To optimize the work and allocation of funds, we have organized the tasks into six Work Packages (WP), as described below:

WP01 - Project Management

WP Unit: INAPS-IAPS
 WP Leader: **Dr. Andrea Cicchetti**
 WP Participants: None

Responsibilities of the Coordinator:

- Coordinate all scientific and technical activities of the team.
- Organize and chair periodic meetings.
- Allocate funds to the different units.
- Monitor the progress of each Work Package in accordance with the proposed activity plan.
- Coordinate the preparation of technical reports.
- Perform quality control on deliverables."

WP02 – Scientific Requirements Definition

WP Unit: INAF-IRA, INAF-OAA, INAF-IAPS, Roma Tre University
 WP Leader: **Dr Roberto Orosei**
 WP Participants: Dr. Pietro Bolli, Dr Cicchetti Andrea, Prof Elena Pettinelli, Prof. Roberto Seu,

WP Description and Main Tasks:

This scientific work package aims to define the overall system requirements. Thanks to the great experience gained over more than twenty years of operations with the MARSIS radar on-board the "Mars Express" mission and operated by INAF, with the primary objective to map the distribution of water and ice in the upper layers of the Martian crust, we will be able to develop precise models of the Martian surface and subsurface environment, considering key parameters that influence radar investigations. These parameters include soil electrical conductivity, subsoil dielectric constant (determined by evaluating the speed of the 'ground wave'), surface roughness (height of radiating elements from the surface), and concentration and distribution of chemical substances affecting radio wave propagation in the medium.

	 INAF THECNO GRANTS	ISSUE: 04 Data: 06/10/2025 Page 19 of 64
---	--	---

WP03 - Digital Electronic Subsystem Design & Development

WP Unit: INAPS-IAPS
 WP Leader: **Dr Andrea Cicchetti**
 WP Participants: Pierluigi Ortu

WP Description and Main Tasks:

The goal of WP03 is to define the digital hardware requirements necessary for commanding and controlling the entire system, as well as for generating and conditioning radar signals (Tx pulses & Rx echoes). To achieve this objective, we will utilize modern digital system-on-chip (SoC) RFSoc boards, which represent a new class of integrated circuits. These boards integrate multiple high-speed Analog to Digital Converters (ADCs) and Digital to Analog Converters (DACs), a powerful multi-core ARM processing system, and a large programmable FPGA into a single monolithic SoC. This integration eliminates the need for external data converters and enables more precise timing and synchronization. The RFSoc 4x2 board, in particular, offers a complete, ready-to-use system with a 6 GHz RF input bandwidth and two 14-bit DACs.

WP Note:

The detailed design and development of digital hardware will be undertaken by a qualified external company.

WP04- Radio Frequency Design & Antenna Development

WP Unit: University of Roma Sapienza and INAF-OAA
 WP Leaders: **Prof Renato Cicchetti and Prof Stefano Pisa**
 WP Participants: Dr Pietro Bolli

WP Description and main tasks:

This WP will primarily focus on designing an innovative, high-efficiency lightweight antenna, employing both numerical simulations and laboratory tests. We have conducted an extensive study and analysis of the most promising solutions for ground-coupled antenna systems proposed in the literature, with a particular emphasis on a compact and versatile "Vivaldi" antenna. Additionally, we have developed an initial prototype of the Vivaldi antenna using commercial materials that are not space-qualified, aimed at initiating preliminary real tests on the antenna's performance.

	 INAF THECNO GRANTS	ISSUE: 04 Data: 06/10/2025 Page 20 of 64
---	--	---

The simulations and tests of the final antenna's performance, selected for the project, will be a crucial activity conducted in collaboration with the personnel involved in WP06 (Instrument Verification Tests). This aspect is essential for accurately characterizing the transmission and reception properties of the complex designed system, considering all the unique features of the instrument. This includes factors such as the effects of mutual coupling between components in a realistic geophysical environment (including various sub-surfaces and scatters). Determining the propagation characteristics of typical waveforms radiated and received in complex scenarios, as well as establishing the antenna's radiation pattern, will be fundamental for assessing the instrument's potential.

WP Note:

Due to its unique design, defined specifically to meet the requirements of this project, the antenna manufacturing will be subcontracted to a qualified external company.

WP05- Radar Signals Processing & Data Archiving

WP Unit: INAF-IAPS
 WP Leader: **Dr Raffaella Noschese**
 WP Participants: Dr Marco Cartacci

WP Description and Main Tasks:

The primary objective of this WP is to develop a suite of processing tools to implement all the functionalities required for instrument data processing. This also includes the development of compensation functions needed to address any distortions caused by electronic devices.

Another important aspect to be addressed in this WP is the definition of the science data architecture. This architecture is essential for ensuring that the science and test data are compatible with well-known Open Access platforms, such as Zenodo (<https://zenodo.org>), among others.

We believe that the Geo-Radar science data will also be of significant interest to other research groups involved in the ground-penetrating radar field.

	 INAF THECNO GRANTS	ISSUE: 04 Data: 06/10/2025 Page 21 of 64
---	--	---

WP06 - Instrument Verification Tests

WP Unit: Roma Tre University
 WP Leader: **Dr Sebastian Lauro**
 WP Participants: Prof Elena Pettinelli, Pierluigi Ortu

WP Description and main tasks:

These experimental activities will be conducted in the "Laboratory of Earth and Planetary Physics" at Roma Tre University, which is unique in Italy and equipped with several instruments (LCR meter, Vector Network Analyzer, TDR Cable Tester) for measuring the electric and magnetic parameters of solid, liquid, and granular materials.

The laboratory is also equipped with an experimental setup comprising dielectric boxes that can be filled with granular material to simulate soil characteristics. A structure built above the box allows for precise positioning of the Geo-Radar antenna on top of the soil. This setup will be utilized to experimentally validate the principles proposed in this project and to demonstrate the ability to retrieve electromagnetic properties of materials, as well as identify subsurface discontinuities.

Multiple field campaigns will be organized to determine the maximum penetration depth, vertical resolution, and data quality of the proposed instrument.

The final phase of the experimental activities will be conducted on-site to evaluate the performance of the Geo-Radar by comparing results with those obtained using a commercial GPR available at the Roma Tre laboratory.

3 GPR PARAMETERS DEFINITION

To detect subsurface water ice on Mars within the first few meters of depth on Mars, a vertical resolution of about $R_d = 12cm$ is required in a medium with dielectric permittivity of $\epsilon_{r1} = 9$ (basalt)

$$R_d \sim 12cm$$

From the following equations, it is possible to derive the duration of the transmitted pulse for the pulsed-type radar and the radio frequency bandwidth.

$$R_d = \frac{v_r \cdot \tau_c}{2} = \frac{c \cdot \tau_c}{2 \cdot \sqrt{\epsilon_r}} = \frac{c}{2 \cdot B_c \sqrt{\epsilon_{r1}}} \quad (\text{eq. 3.1})$$

$$B_c = \frac{c}{2 \cdot R_d \sqrt{\epsilon_{r1}}} \quad (\text{eq. 3.2}) \rightarrow B_c = 400MHz$$

The fractional bandwidth is given by the following equation:

$$B_{\text{frac}} = \frac{B_c}{f_c} \rightarrow B_{\text{frac}} = 0.8 \quad (\text{eq. 3.3})$$

In principle, to limit circuit complexity, the fractional bandwidth should not exceed 0.5, but in this application a higher value (≈ 0.8) is necessary to meet resolution requirements.

The carrier frequency f_c generates an electromagnetic wave in air with a corresponding wavelength given by $\lambda_c = c/f_c$. When the wave propagates through a material with relative permittivity ϵ_{r1} , the wavelength is reduced and can be estimated as $\lambda = \lambda_c / \sqrt{\epsilon_{r1}}$.

To distinguish between two reflections from parallel planes (such as the top and bottom surfaces of a buried object), the separation between them must be at least one wavelength of the radar signal as it travels through the subsurface medium. This condition is illustrated in Figure 3.1 and can be expressed by the following relationship:



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 23 of 64

$$f_c \geq \frac{c}{2 \cdot R_d \cdot \sqrt{\epsilon_{r1}}} \geq 333\text{MHz (eq. 3.4)}$$

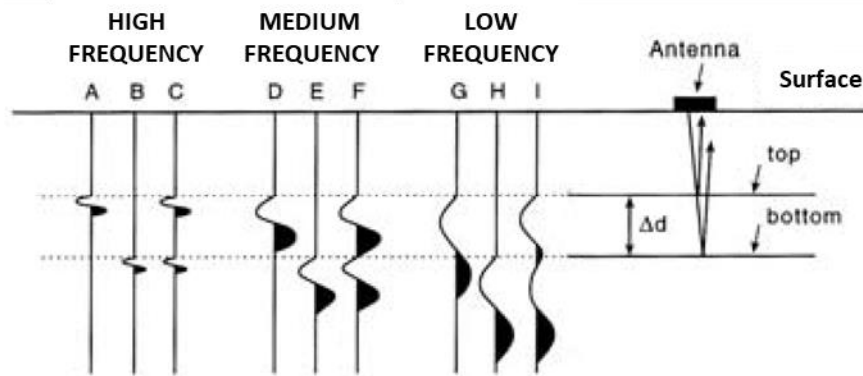


Figure 3.1. Propagation of radio waves in the medium

At high frequencies, the waves define both the top (A) and the bottom (B) of the interface. The wave resulting from these reflections (C) can resolve both interfaces because the distance between them (∇d) is greater than the wavelength.

The medium-frequency wave (D) defines both the top and bottom of the interface (E), and the resulting wave (F) can barely resolve both interfaces because the wavelength is close to ∇d .

The low-frequency wave defines the top of the interface (G), but since the separation between the two interfaces is smaller than the wavelength (H), the resulting wave (I) is the interference of two waves, and only the top of the interface is resolved.

When two interfaces are separated by a distance greater than one wavelength, two distinct reflections are generated, and the object can be resolved. For a buried flat surface, there are no wavelength-related issues. However, problems arise when the surface is highly irregular or undulating. If long-wavelength radar waves are used, reflections from buried surfaces generally appear very smooth. Therefore, surface irregularities smaller than a wavelength are not visible.

Accepting the design complexity introduced by the wide fractional bandwidth, the carrier frequency was fixed at 500 MHz, which balances penetration depth and antenna size

$$f_c = 500\text{MHz} (\lambda_c = 0.6m)$$

Another important aspect to consider is the antenna's far-field region, which, for the given carrier frequency, determines the minimum flight altitude of the instrument. The antenna maintains stable the electromagnetic characteristics, only when operating in the far-field zone, which begins at a distance approximately three times the wavelength of the radar signal:

$$\text{Antenna Far Field} \sim 3 \cdot \lambda_c \text{ (eq. 3.5)}$$

$$H_{\min} = 2\text{m}$$

4 LINK BUDGET ESTIMATION

In this chapter, the dynamic behaviour of the instrument is defined as a fundamental step toward achieving the planned objectives. Subsequently, the amplifier gains required to reach the desired power levels, for properly driving the receiver circuits are estimated, while taking into account the different sources of loss.

4.1 INSTRUMENT DYNAMIC ESTIMATION

The instrument dynamic range is given by the following equation:

$$\text{INST_DYN}_{\text{dB}} = P_{\text{RX,Max,dB}} - P_{\text{RX,min,dB}} \quad (\text{eq. 4.1.1})$$

$P_{\text{RX,Max}}$ Represents the maximum power level the instrument must handle without reaching saturation, which results from the coupling between the two antennas (TX/RX). However, in this project, a cancellation block will be tested to try to mitigate the effect of antenna coupling. Specifically, a Power Combiner Device sums the received signals with a phase-inverted (180°) replica of the transmitted signal, calibrated in power using a programmable attenuator. In this way, the contribution at time zero, caused by antenna coupling, will theoretically be cancelled, while echoes returning to the radar with a nonzero delay will remain unaffected. However, for conservative design the current link budget excludes it.

$$P_{\text{RX,Max,dB}} = P_{\text{TX,dB}} - AC_{\text{dB}} \quad (\text{eq. 4.1.2})$$

Where:

$P_{\text{TX,dB}}$: Power at the TX antenna input (antenna power supply).

AC_{dB} : Antenna coupling, to be considered positive and with a preliminary value of 30dB.

$P_{\text{RX,min}}$ Represents the minimum received echo power that the instrument can reliably detect and process under nominal operating conditions (flight altitude of 10 m with an ice target buried at a depth of 5 m), as illustrated in Figure 4.1.1

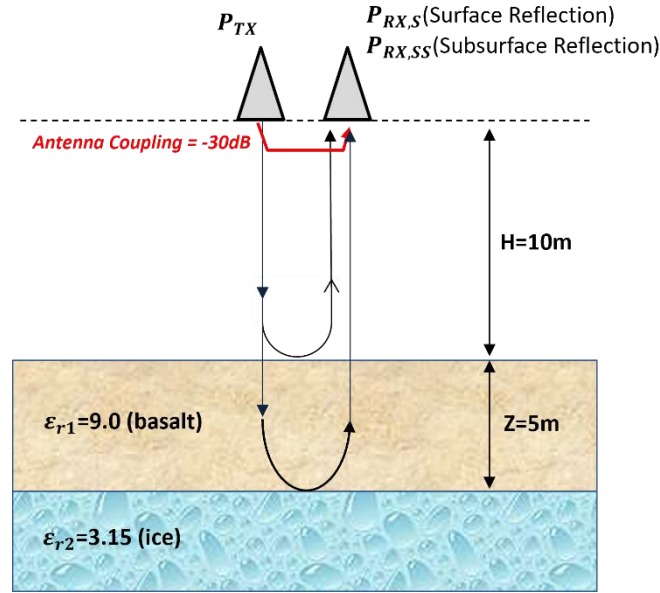


Figure 4.1.1 MAGHIS Observation Geometry

To determine the echo power levels, it is necessary to account for the attenuation caused by radio wave propagation both in vacuum and within the medium. For this purpose, the propagation model developed by Porcello et al. will be employed, which is applicable to smooth, parallel surfaces, as described by the following equations:

$$P_{RX,S} = P_{TX} \cdot \left(\frac{c}{f_c \cdot 8 \cdot \pi} \right)^2 \cdot \left(\frac{1}{H} \right)^2 \cdot |R_S|^2 \cdot G_{Ant}^2 \quad (eq. 4.1.3)$$

$$P_{RX,SS} = P_{TX} \cdot \left(\frac{c}{f_c \cdot 8 \cdot \pi} \right)^2 \cdot \left(\frac{1}{H + Z} \right)^2 \cdot (1 - |R_S|^2)^2 \cdot |R_{SS}|^2 \cdot \frac{1}{L_{Soil}} \cdot G_{Ant}^2 \quad (eq. 4.1.4)$$

$$R_S = \frac{\sqrt{\epsilon_0} - \sqrt{\epsilon_{r1}}}{\sqrt{\epsilon_0} + \sqrt{\epsilon_{r1}}}, \quad R_{SS} = \frac{\sqrt{\epsilon_{r1}} - \sqrt{\epsilon_{r2}}}{\sqrt{\epsilon_{r1}} + \sqrt{\epsilon_{r2}}} \quad (eq. 4.1.5)$$

$$L_{Soil} = L_{SS} \cdot Z \quad (eq. 4.1.6)$$

The value of the attenuation term, is given by the following equation

$$L_{SS} = 1,8 \cdot 10^{-7} f_c \sqrt{\epsilon_{r1}} \cdot \tan \delta \quad \left[\frac{dB}{m} \right] \quad (eq. 4.1.7)$$

Considering the worst-case scenario $\tan \delta = 0.02$ the following value was selected for defining the instrument link budget:

$$L_{SS/m} = 5.4 \text{ dBm (Two way travel time)}$$

where:

P_{TX} :	Transmitted Power (input of the transmitting antenna)
$P_{RX,S}$:	Received Power from the Mars's surface (output of the receiver antenna)
$P_{RX,SS}$:	Received Power from the sub-surface reflection (output of the receiver antenna)
f_c :	Carrier frequency
G_{Ant} :	Gain of the TX and RX antennas (it is assumed that the antennas are identical)
Z :	Penetration depth
R_S :	Fresnel surface reflection coefficient
R_{SS} :	Fresnel sub-surface reflection coefficient
L_{SOIL} :	Total attenuation of the subsurface at depth Z
L_{SS} :	Two-way attenuation in the basalt, as dB/m
ϵ_{r1} :	Dielectric permittivity of basalt
ϵ_{r2} :	Dielectric permittivity of water ice

By expanding the attenuation terms in equations 4.1.3 and 4.1.4, the following expressions are obtained:

$$EnvAtt_S = \left(\frac{c}{f_c \cdot 8 \cdot \pi \cdot H} \right)^2 \cdot |R_S|^2 \text{ (eq. 4.1.8)}$$

$$EnvAtt_{SS} = \left(\frac{c}{f_c \cdot 8 \cdot \pi \cdot (H + Z)} \right)^2 \cdot (1 - |R_S|^2)^2 \cdot |R_{SS}|^2 \cdot \frac{1}{L_{Soil}} \text{ (eq. 4.1.9)}$$

Considering the following values:

f_c :	500MHz
Z :	5m
H :	10m
L_{SOIL} :	37dB
ϵ_{r1} :	9
ϵ_{r2} :	3

It is possible to calculate the attenuations of the surface and subsurface environment:

$$EnvAt_S = 58dB$$

$$EnvAtt_{SS} = 97dB$$

By substituting them into the original equations and converting everything into dB, we obtain:

$$P_{RX,S,dB} = P_{TX,dB} + 2 \cdot G_{Ant,dB} - EnvAtt_S \quad (eq. 4.1.10)$$

$$P_{RX,SS,dB}(P_{RX,min}) = P_{TX,dB} + 2 \cdot G_{Ant,dB} - EnvAtt_{SS} \quad (eq. 4.1.11)$$

At this point, all the necessary elements are available to determine the instrument dynamics

$$INST_DYN_{dB} = P_{RX,Max,dB} - P_{RX,min,dB} = EnvAtt_{SS} - 2 \cdot G_{Ant,dB} - AC_{dB} \quad (eq. 4.1.12)$$

Considering a preliminary value of the antenna gain a 7dB, we obtain

$$INST_DYN_{dB} = 53dB$$

The following paragraph analyses the performance of the board *RFSOC(4x2)* in order to assess its compatibility with the instrument's dynamic requirements.

4.2 DIGITAL BOARD THEORETICAL DYNAMIC ESTIMATION

Assuming the use of an electronic board in the receiver, with the following characteristics:

- $V_{pp} = 1V_{olt}$, across a $100\ \Omega$ (nominal input peak-to-peak voltage)
- $N_b = 14$ (ADC quantization bits)

the following equations will then be used to calculate the dynamic:

$$P_{in_FULL_SCALE} = \frac{V_p^2}{2 \cdot R} = \mathbf{1dBm} \text{ (eq. 4.2.1)}$$

$$P_{in_MIN} = \frac{d_{Vp}^2}{2 \cdot R} = \frac{V_{PP}^2}{(2^{N_{bit}})^2 \cdot 2 \cdot R} = -77dBm \text{ (eq. 4.2.2)}$$

$$BORAD_THEORETICAL_DYNAMIC = P_{in_FULL_SCALE} - P_{in_MIN} = 78dB \text{ (eq. 4.2.3)}$$

According to board specifications and literature, the minimum detectable signal is **-55dBm** (SNR = 0 dB) or -49 dBm (SNR = 6 dB). This defines the lower bound of the system dynamic range

To avoid nonlinearities, only ~3dB below ADC saturation is used, yielding an effective system dynamic range of 53dB

The effective dynamic range of the instrument becomes:

$$\mathbf{BOARD_DYNAMIC = 53dB}$$

Concluding, the following values must be respected:

$$\begin{aligned} P_{in_ADC_max} &= -2dBm(\text{from antenna coupling}) \\ P_{in_ADC_min} &= -55dBm(\text{deepest echo at 5m}) \end{aligned}$$



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 30 of 64

4.3 INSTRUMENT GAIN AMPLIFIER ESTIMATION

In this paragraph will be estimated the overall gain of the instrument amplifiers in order to align the required instrument dynamic of 53dB with the available dynamic of 53dB of the RFSoc(4X2) board.

The total GAIN of the instrument's amplifiers will be primarily determined to prevent receiver saturation, which is most likely to occur due to the strongest signal generated by antenna coupling.

$$P_{RX,Max,ADC,dBm} = P_{0,DAC,dBm} - LOSS_{TX CH,dB} - AC_{dB} - LOSS_{RX CH,dB} + G_{Ampli,dB} \quad (eq. 4.3.1)$$

By expressing the equation in terms of the overall gain:

$$G_{Ampli,dB} = P_{RX,ADC,Max,dBm} - P_{0,DAC,dBm} + LOSS_{TX CH,dB} + AC_{dB} + LOSS_{RX CH,dB} \quad (eq. 4.3.2)$$

The value of $P_{RX,ADC,Max,dBm}$ is given by the maximum allowed signal to the ADC converter that is -2dBm and assuming the following values as a first approximation:

$$\begin{aligned} LOSS_{TX CHAIN} &= 2.25dB \quad (\text{Overall attenuation of the transmitting chain}) \\ LOSS_{RX CHAIN} &= 10.25dB \quad (\text{Overall attenuation of the receiving chain}) \\ P_{0,DAC,dBm} &= -9.5dBm \quad (\text{Power at the output of the DAC}) \end{aligned}$$

The overall gain of the amplifiers is: $G_{Ampli} = 50dB$

The required 50 dB gain is distributed across two stages: One 25 dB low-noise amplifier at RX input and a 25 dB power amplifier on the TX chain.

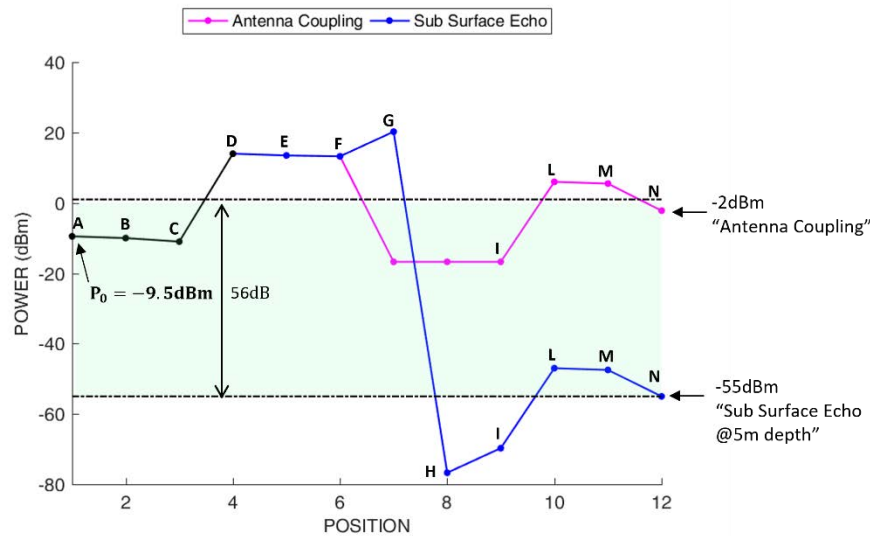


Figure.4.3.1 Main power levels at the key points of the instrument devices



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 31 of 64

5 RADAR SF-CW

This paragraph provides an overview of the Stepped Frequency Continuous Wave (SF-CW) technique, explaining its fundamental principles, operational methodology, and its significance in high-resolution radar and sensing applications:

$$B_c = F_{MAX} - F_{MIN} \quad (eq. 5.1)$$

The radar generates and transmits a finite number of distinct sinusoidal signals (tones) with constant amplitude and duration T_{tone} , spaced by discrete frequency steps Δf , ranging from F_{MIN} to F_{MAX} , as illustrated in Figure 5.1

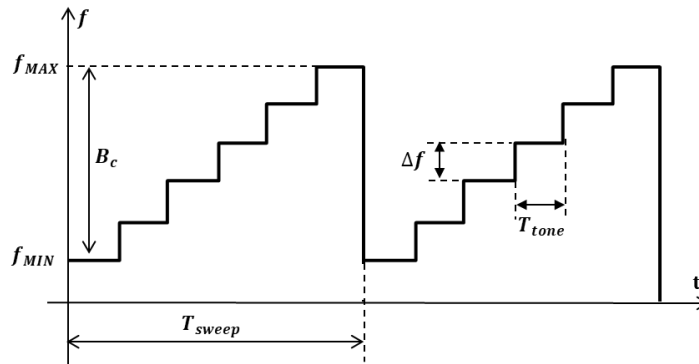


Figure 5.1 Transmitted waveform of the SF-CW radar.

The duration of tones T_{tone} must be sufficiently long to ensure that the frequency transition occurs only after the signal has travelled to the target at the maximum detectable range and returned to the receiver. Since this GPR operates on a drone flying just a few meters above the surface, the transmitted pulses and consequently the received echoes will cover a wide surface area. Additionally, considering a theoretical maximum flight altitude of 1000 meters, an unambiguous range of 1000 meters will be used for radar parameter estimation.

$$R_{NA} = 1000m$$



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 32 of 64

Knowing that

$$R_{NA} = \frac{c \cdot T_{tone}}{2 \cdot \sqrt{\epsilon_{r1}}} \quad (eq. 5.2)$$

Assuming propagation in a vacuum, the duration of the tone is given by the following equation:

$$T_{tone} > \frac{R_{NA} \cdot 2}{c} > 6.6us \quad (eq. 5.3)$$

Considering an adequate margin, the duration of the tone is:

$$T_{tone} = 10us \rightarrow (R_{NA} = 1500m)$$

Figure 5.2 instead shows the nominal operating scenario, i.e. flight altitude of 10m and maximum investigation depth of 5m.

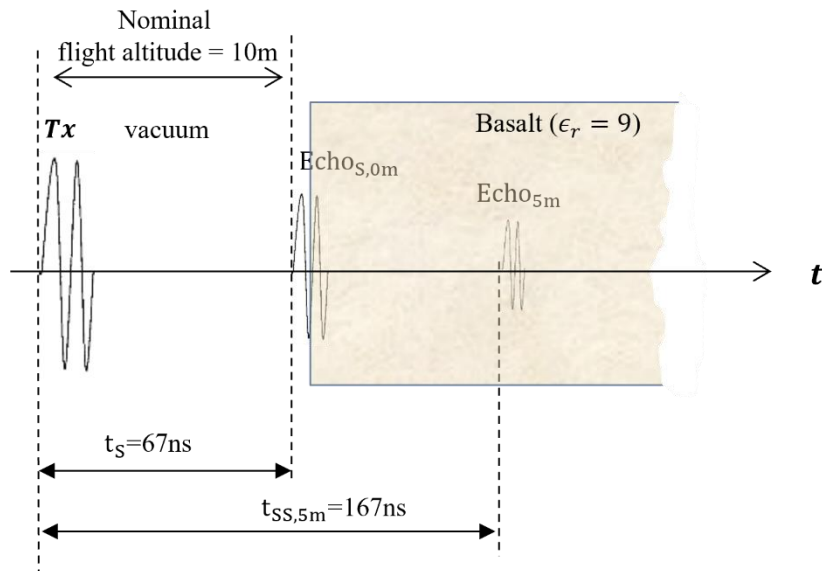


Figure 5.2 Nominal instrument timing

The receiver demodulates the collected signals by mixing them with a copy of the transmitted signal, sampling each tone in both amplitude and phase. The data is then converted from the frequency domain to the time domain using the inverse Fourier transform, reconstructing the range profile.

In SF-CW radars, the unambiguous range also depends on the frequency step Δf . A smaller frequency step results in a higher unambiguous range.

$$\Delta_t = \frac{1}{\Delta_f} \quad (eq. 5.4)$$

As a result, the unambiguous range is related to the frequency step by the following equation:

$$R_{NA} = \frac{c \cdot \Delta_t}{2} = \frac{c}{2 \cdot \Delta_f} \quad (eq. 5.5)$$

Considering $R_{NA} = 1000m$, the frequency step is given by the following equation:

$$\Delta_f \leq \frac{c}{2 \cdot R_{NA}} \leq 150KHz \rightarrow \Delta_f = \mathbf{150KHz} \quad (eq. 5.6)$$

5.1 DESIGN OF THE TRANSMITTED SIGNAL

The number of tones to be generated is calculated using the following equation, given that: $B_c = 400\text{MHz}$ and $\Delta_f = 150\text{KHz}$:

$$N_{tones} = \frac{B_c}{\Delta_f} = 2667 \text{ (eq. 5.1.1)}$$

To make the inverse Fourier transform more efficient, the nearest power of 2 to the calculated value is:

$$N_{tones} = 4096$$

Therefore the Δ_f becomes:

$$\Delta_f = 97.65\text{KHz} \rightarrow (R_{NA} = 1500\text{m})$$

Considering the effective frequency step of 97.67 kHz and a tone duration of 10 μs , the resulting non-ambiguous range is:

$$R_{NA} = 1500\text{m}$$

The duration of the sweep is given by the following equation:

$$T_{sweep} = N_{tones} \cdot T_{tone} \rightarrow T_{sweep} = 41\text{ms} \text{ (eq. 5.1.2)}$$

A higher number of tones increases the unambiguous range and shifts potential Hermitian replicas to non-relevant range bins. Additionally, it improves the integration gain of the IFFT, enhancing the effective dynamic range and penetration depth. However, a large number of tones slows down the instrument.

BEAT FREQUENCY AT THE MIXER OUTPUT

The Fourier Transform of a simple rectangle that represents the finite duration of the sinusoid (beat frequency) which maximum duration is T_{sweep} . The bandwidth occupancy, limited to the first two nulls of the Fourier transform, is:

$$B_{base} = \frac{2}{T_{sweep}} \rightarrow B_{base} = 49\text{Hz}$$

The beat frequency at the mixer output is given by the following relationship:

$$\frac{f_b}{B_c} = \frac{\tau}{T_{sweep}} \quad (eq. 5.1.3)$$

The frequency of the IQ components can be derived by expressing the time delay in terms of the target distance, while also accounting for the fact that the echo propagates through both vacuum and the medium.

$$f_{b,sub-surf} = \left(\frac{2 \cdot H}{c} + \frac{2 \cdot Z_{max} \cdot \sqrt{\epsilon_{r1}}}{c} \right) \cdot \frac{B_c}{T_{sweep}} \rightarrow \quad \mathbf{f_{b,max} = 1.7KHz} \quad (eq. 5.4)$$

The beat frequency due to the surface echo depends only on the drone's attitude and is given by the following equation:

$$f_{b,surf} = \left(\frac{2 \cdot H}{c} \right) \cdot \frac{B_c}{T_{sweep}} \rightarrow \quad \mathbf{f_{b,surf} = 0.7KHz} \quad (eq. 6.2)$$

The beat frequency due to antenna coupling is zero, since the time delay is negligible

$$\mathbf{f_{b,coupling} = 0Hz}$$

At the maximum nominal investigation depth of 5 meters, the beat frequency is 1.7KHz. This value will be used to design the cut-off frequency of the low-pass filter (LPF) in the numerical super-heterodyne demodulation.

It is important to note that the LPF cut-off frequency is not based on the maximum unambiguous range of 1500 meters, but rather on the actual maximum depth of investigation, which is 5 meters. This is because targets located 1500 meters from the radar are beyond the detection capabilities of the instrument due to power budget limitations and are therefore not of interest.

Defining the unambiguous range as 1500 meters for radar parameter calculation, while filtering out all echoes beyond 5 meters using the LPF, ensures that unwanted signals primarily from surface clutter at distances greater than 5 meters are not mistakenly interpreted as valid echoes. This prevents the occurrence of the Hermitian image effect, where an undesired echo appears at the position corresponding to the unambiguous range minus the actual delay of the distant target.



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 36 of 64

5.2 CONSIDERATIONS ON HOMODYNE AND HETERODYNE DEMODULATION

A superheterodyne receiver with $f_{IF} = 2.5$ MHz was selected, reducing harmonic distortion and improving balance compared to a homodyne design. This is achieved by mixing the received tones, with a copy of the transmitted signal, shifted by f_{IF}

A key advantage of this approach is that all received tones are converted to f_{IF} allowing the demodulator to operate at a fixed frequency, significantly reducing Hermitian distortion. Additionally, harmonic distortion is mitigated since the IF filter eliminates higher-order signal replicas, preventing artefacts in the range profile. While distortions may still arise in the intermediate frequency section, they can be compensated for in post-processing.

An intermediate frequency of $f_{IF} = 2.5$ MHz has been chosen, ensuring that mixing occurs with a frequency-shifted replica rather than a mirrored copy of the transmitted signal. Consequently, the beat frequency will range from 300MHz+2.5MHz to 700MHz+2.5MHz. The IF bandwidth depends on the number of transmitted tones and their duration, as illustrated in the following figure.

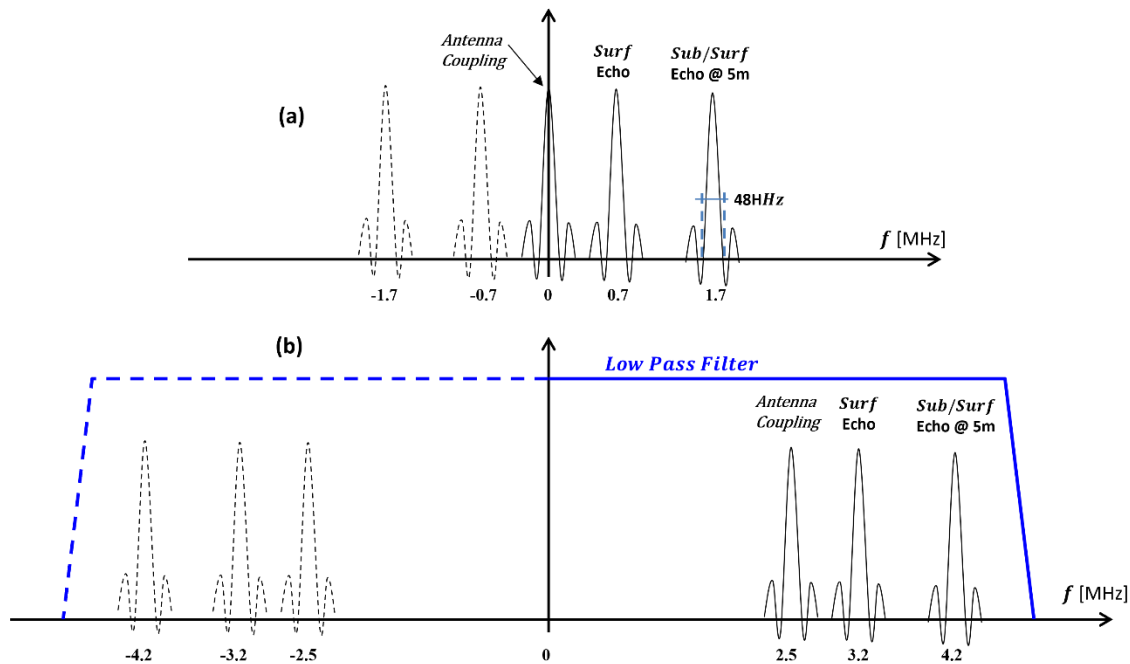


Figure 5.2.1 Bandwidth occupation after demodulation. (a) Homodyne demodulation. (b) Superheterodyne demodulation

After the demodulation process, carried out by the FPGA at the digital level, the frequencies return to their original positions, as shown in Figure 5.2.1(a)

5.3 RECEIVER NOISE FIGURE ESTIMATION

This section defines the maximum acceptable noise figure F_N for the receiver to meet the required SNR_{CMP} after processing (FFT Gain).

The SNR is imposed as requirement on a weaker signal, that is the one from 5m depth, as following:

$$SNR_{CMP,dB} = P_{SS,5m,dB} - N_{pk,dB} \quad (eq. 5.3.1)$$

$N_{pk,dB}$: The pick noise level

$P_{SS,5m,dB}$: Sub-surface reflection at depth of 5m

Making explicit for the noise, we obtain the following:

$$N_{pk,dB} = P_{SS,5m,dB} - SNR_{CMP,dB} \quad (eq. 5.3.2)$$

After processing, the power of the signal is increased by the FFT compression factor, as reported by the following equation:

$$N_{pk,dB} = (P_{SS,5m,dB} + RC_{dB}) - SNR_{cmp,dB} \quad (eq. 5.3.3)$$

$$RC_{dB} = 10 \cdot \log_{10} N_{tones} = 30dB$$

The conversion from effective noise to peak-to-peak noise is a simple multiplication by 6.6. In our case, the conversion is reversed, meaning the effective noise value is obtained by dividing the peak noise by 6.6 or, equivalently, by subtracting 16dB (since $20 \log_{10}(6.6) = 16dB$) from the peak noise value expressed on a logarithmic scale.

$$N_{pk} = 6.6 \cdot N_{RMS} \quad (eq. 5.3.4)$$

$$N_{RMS,dB} = N_{pk,dB} - 20 \cdot \log_{10} 6.6 \quad (eq. 5.3.5)$$

$$N_{RMS,dB} = N_{pk,dB} - 16 \quad (eq. 5.3.6)$$

$$N_{RMS,dB} = (P_{SS,5m,dB} + RC_{dB}) - SNR_{CMP,dB} - 16 \quad (eq. 5.3.7)$$

The RMS noise power level, can be expressed as following:

$$N_{RMS} = K \cdot T \cdot B_N \cdot NF \quad (eq. 5.3.8)$$

B_N is the equivalent noise bandwidth, determined by the low-pass filter placed after the intermediate frequency mixer.

$$(K \cdot T)_{dB} + B_{N,dB} + NF_{dB} = (P_{SS,5m,dB} + RC_{dB}) - SNR_{CMP,dB} - 16 \text{ (eq. 5.3.9)}$$

In an SF-CW radar, the equivalent noise bandwidth is determined by the low-pass filter placed after the intermediate frequency mixer. For a first-order filter with a time constant τ and a cut-off frequency f_t , such that, The equivalent noise bandwidth at intermediate frequency is given by:

$$B_N = \frac{\pi}{2} \cdot f_{t,IF} \text{ (eq. 5.3.10)}$$

Since we will not use a homodyne demodulator but a superheterodyne intermediate frequency demodulator, with $f_{IF} = 2.5MHz$, and considering that the beat frequency typically lies in the kHz range, we have chosen a low-pass filter after the mixer with a cut-off frequency of approximately $f_{t,IF} = 5MHz$.

Where f_t represent the cut-off frequency of the low pass filter after the Mixer. The equation (5.3.9) becomes:

$$(K \cdot T)_{dB} + \left(\frac{\pi}{2}\right)_{dB} + f_{t,dB} + NF_{dB} = (P_{SS,5m,dB} + RC_{dB}) - SNR_{cmp,dB} - 16 \text{ (eq. 5.3.11)}$$

Expressing $P_{SS,5m,dB}$ in dBm we obtain:

$$(K \cdot T)_{dB} + \left(\frac{\pi}{2}\right)_{dB} + f_{t,dB} + NF_{dB} = (P_{SS,5m,dBm} - 30 + RC_{dB}) - SNR_{CMP,dB} - 16 \text{ (eq. 5.3.12)}$$

It now possible to calculate the noise figure:

$$NF_{dB} = P_{SS,5m,dBm} - 30 + RC_{dB} - SNR_{CMP,dB} - 16 - (K \cdot T)_{dB} - \left(\frac{\pi}{2}\right)_{dB} - f_{t,dB} \text{ (eq. 5.3.13)}$$



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 39 of 64

$$NF_{dB} = P_{SS,5m,dBm} - 46 + RC_{dB} - SNR_{Cmp,dB} - \left(\frac{K \cdot T \cdot \pi}{2} \right)_{dB} - f_{t,dB} (eq. 5.3.14)$$

Assuming the following values:

$P_{SS,5m,dBm}$	= -70dBm
RC_{dB}	= 36dB
$SNR_{Cmp,dB}$	= 15dB
T	= 290K
$f_{t,dB}$	= 69dB
K	= 1.38e-23 (The Boltzmann constant)
T_e	= 290K (Receiver noise temperature)

$$NF_{dB} = 38dB$$

This seemingly absurd value indicates that the receiver's noise figure will not negatively impact the instrument's dynamic range. This is primarily due to the relatively shallow investigation depths (only a few meters below the surface) and the high value of the integration gain of the IFFT.

5.4 TRANSMISSION TIME ESTIMATION

By setting the equivalent noise bandwidth for the video filter on the in-phase and quadrature components (and thus for the receiver), it allows the calculation of the instrument's temporal efficiency and, consequently, setting the duration of each acquisition.

Still assuming a first-order filter for the filter after the MIXER, we can estimate the settling time in 5 time constants τ , which in this case corresponds to a time of approximately:

$$f_t = \frac{1}{2 \cdot \pi \cdot \tau} \quad (\text{eq. 5.4.1})$$

Considering the cut-off frequency of 5MHz, we obtain:

$$\tau = \frac{1}{2 \cdot \pi \cdot f_t} = 32\text{ns} \quad (\text{eq. 5.4.2})$$

Five times τ corresponds to 159ns, which would be the T_{lock} . Considering a good compromise between the acquisition duration and the integration time, a temporal efficiency of 0.8 has been set.

$$\eta = \frac{T_{int}}{T_{lock} + T_{int} + \tau} \approx \frac{T_{int}}{T_{lock} + T_{int}} = 0.8 \quad (\text{eq. 5.4.3})$$

$$T_{int} > \frac{\eta}{1 - \eta} \cdot (T_{lock} + \tau) \quad (\text{eq. 5.4.4})$$

Considering $\tau = 167\text{ns}$ (target at 5m of depth)

$$T_{int} > 1.3\mu\text{s}$$

having already chosen the tone duration at 10us, see (eq.5.3) this condition is largely satisfied

5.5 ELECTRONIC CALIBRATION SYSTEM

Radar calibration is essential because electronic systems' frequency response can vary in phase and amplitude, which impacts the acquired data. Since radar samples include both the scene response and the instrument's response, correcting these effects is crucial for accurate environmental characterization. This can be achieved by incorporating a calibration unit, which can be selected using RF switches, as shown in Figure 5.5.1.

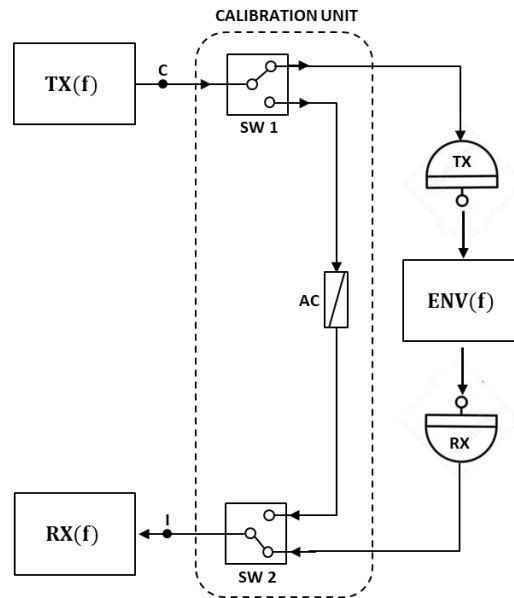


Figure 5.5.1 SF-CW Radar Calibration Unit

From an analytical point of view, the entire system can be described by the following mathematical functions:

- $TX(f)$ Transmitter frequency response (depends on the electronics)
- $RX(f)$ Receiver frequency response (depends on the electronics)
- AC Attenuator (can be considered constant with the frequency)
- $ENV(f)$ Scenario frequency response

By keeping the switches on the antennas, the entire system response is obtained:

$$ACQ(f) = TX(f) \cdot ENV(f) \cdot RX(f) \quad (eq. 5.5.1)$$

Switching on the calibrator, the frequency response obtained from this configuration is described by the following function:

$$CAL(f) = TX(f) \cdot AC \cdot RX(f) \quad (eq. 5.5.2)$$

Combining the two equations described above, it can be demonstrated that the calibration algorithm described in the following equation corrects the effect of the transmitter and receiver frequency responses, except for an amplitude scaling equal to the attenuation value on the calibration path.

$$\frac{ACQ(f)}{CAL(f)} = \frac{TX(f) \cdot ENV(f) \cdot RX(f)}{TX(f) \cdot AC \cdot RX(f)} = \frac{ENV(f)}{AC} \quad (eq. 5.5.3)$$

$$\frac{ACQ(f)}{CAL(f)} = \frac{ENV(f)}{AC} \quad (eq. 5.5.4)$$

Calibration significantly improves data quality, though it does not account for antenna/cable effects, which must be tested in controlled setups.

5.6 LABORATORY TEST

This paragraph aims to describe the tests conducted in a controlled environment, essential for the initial characterization of the instrument's performance, without the antennas connected. Figure 5.6.1 illustrates the architecture of the TEST UNIT block.

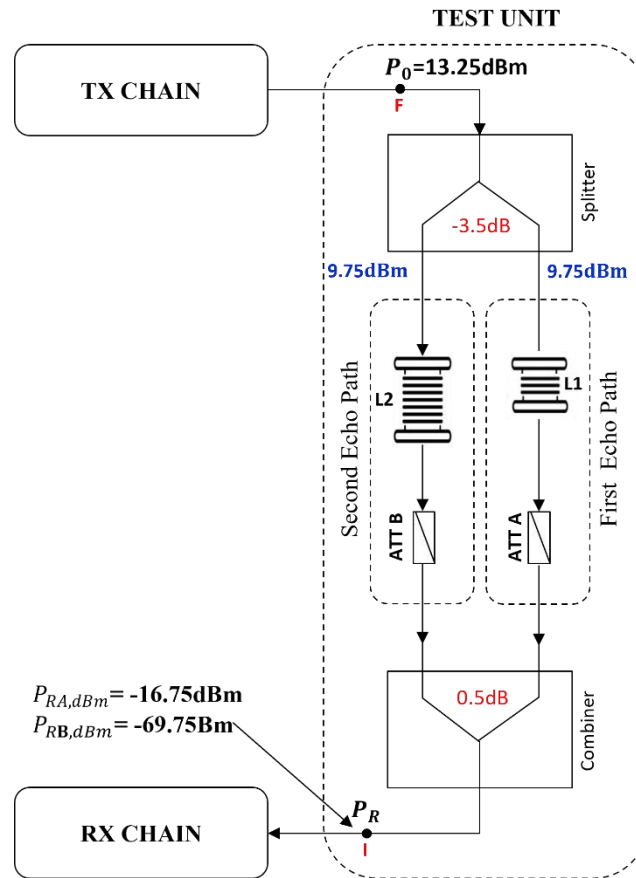


Figure 5.6.1 SF-CW Laboratory Test Configuration

Depending on the configuration of the two attenuators (ATT_A and ATT_B) and the lengths of the cables (L1 and L2) used to simulate echo delays, the following two tests will be conducted:

Assuming:

$CAtt_{dB/m} = 0.78dB/m$ Estimation of the RG316 cable loss, to be validated in laboratory

$SLoss_{dB} = 3.5dB$ Splitter loss, 0.5dB insertion loss and value in dB of the division by two of the Power

$CLoss_{dB} = 0.5dB$ Combiner Insertion loss

Test 1: Full Dynamic Performance Test

The purpose of this test is to evaluate the instrument's performance at 53dB of dynamic range, measured as the difference between the maximum signal generated by antenna coupling and the echo reflected by a subsurface discontinuity located at a depth of 5 meters.

The length of cable L1 is set to 0m to simulate the antenna coupling, while the length of cable L2 is set to 10m, that is the double of the nominal depth of 5m, to simulate the delay of the Echo.

the attenuators: ATT_A and ATT_B are calculated by the following equations, setting $P_{RA,dBm} = -16.75dBm$ (power level at the receiver due to the antennas coupling) and $P_{RB,dBm} = -69.75dBm$ (power level at the receiver due to the echo coming from 5m depth).

$$Att_{A/B,dB} = P_{0,dBm} - SLoss_{dB} - L2_m \cdot CAtt_{dB/m} - CLoss_{dB} - P_{RB,dBm} (eq. 5.6.1)$$

Test 2: Instrument Resolution Assessment

The aim of this test is to verify that the instrument is able to distinguishes two objects at a mutual distance of 15cm in a vacuum. The attenuators could be considered identical, while it is important to have a difference of 15cm between cable L1 and cable L2

The following table summarize the configuration of the attenuators and cables length of the three tests described above

Device	Test 1	Test 2
L1	0	L2-L1 = 15cm
L2	10m	
$AttA_{dB}$	26dB	$AttA_{dB} = AttB_{dB} = 40dB$
$AttB_{dB}$	71dB	

Table 5.6.1 Devices configuration for the laboratory tests



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 46 of 64

5.7 INSTRUMENT DATA RATE AND VOLUME

The instantaneous data rate is calculated by the following relation:

$$Data_{Rate} = \frac{N_{tones} \cdot N_{bit}}{T_{sweep}} = 1.4Mbs \text{ (175KBs)} \text{ (eq. 5.7.1)}$$

1GByte of raw data is collected in about 1.6Hr



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 47 of 64

6 RADAR FM-CW

This paragraph, outlines the radar design, based on Frequency Modulated Continuous Wave (FM-CW), which essentially consists of the beat between the received signal and a copy of the transmitted one. The beat frequency is proportional to the delay time τ of the received echo, as shown in the following Figure 6.1

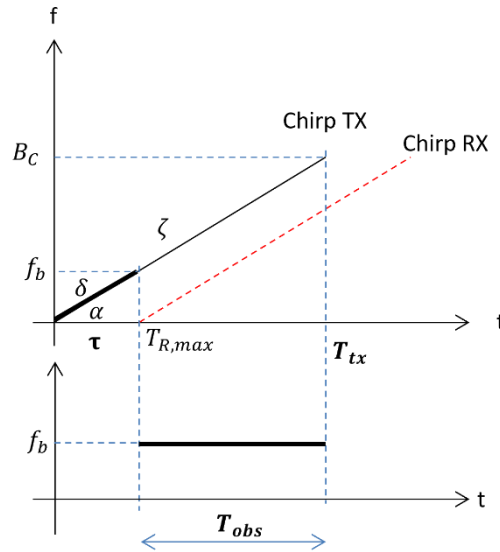


Figure 6.1 FM-CW Radar

The radar resolution depends on the transmitted bandwidth. To achieve a resolution of 12.5 cm in Martian basalt ($\epsilon_{r1} = 9$), or 37.5 cm in a vacuum, the required bandwidth can be obtained from the following equation:

$$B_c = \frac{c}{2 \cdot R_d \cdot \sqrt{\epsilon_{r1}}} \rightarrow B_c = 400 \text{ MHz (eq. 6.1)}$$

Also, for the FM-CW radar, the resolution does not depend on the duration of the transmitted pulse, but only on the transmitted bandwidth. However, the pulse duration must be much greater than the maximum expected echo delay, as highlighted by the following relation:

$$T_{R,max} = \frac{2 \cdot H}{c} + \frac{2 \cdot Z_{max} \cdot \sqrt{\epsilon_{r1}}}{c} = 167 \text{ ns} \rightarrow T_{tx} \gg 167 \text{ ns (eq. 6.2)}$$

Having assumed:

$H =$	10m	Drone flight altitude
$Z_{max} =$	5m	Maximum penetration depth
$\epsilon_{r1} =$	9	Dielectric permittivity of the mars sub-soil

Another important parameter, to take into account during the development of a FM-CW radar, is the slope (S) which the signal generator must be able to support, in order to modulate the required bandwidth. From Figure 6.1 it is easy to demonstrate the following relationship between the slope S and the other keys parameters:

$$S = \frac{B_c}{T_{tx}} = \frac{f_b}{\tau} \text{ (eq. 6.3)}$$

Where:

B_c :	Radar Band
R_d :	Range resolution
f_b :	Beat Frequency
τ :	Time delay of the received echo
T_{tx} :	Duration of the transmitted signal
ϵ_{r1} :	Dielectric permittivity of the mars sub-soil

The slope of the RFSoc (4x2) board can be configured within the following range:

$$S = 10^{13} : 10^{14} \left[\frac{Hz}{sec} \right] = 10MHz/\mu s \div 100MHz/\mu s$$

To avoid excessive stress on the board, the lower value will be used for this project:

$$S = 10^{13} \left[\frac{Hz}{sec} \right] = \mathbf{10MHz/\mu s}$$

Consequently, the duration of the transmitted signal is:

$$T_{tx} = \frac{B_c}{S} \rightarrow T_{tx} = \mathbf{40\mu s} \text{ (eq. 6.4)}$$

40μs is much greater than 167ns, so the condition of equation 6.2 is fully satisfied. The transmitted signal waveform will therefore have the shape shown in Figure 6.2

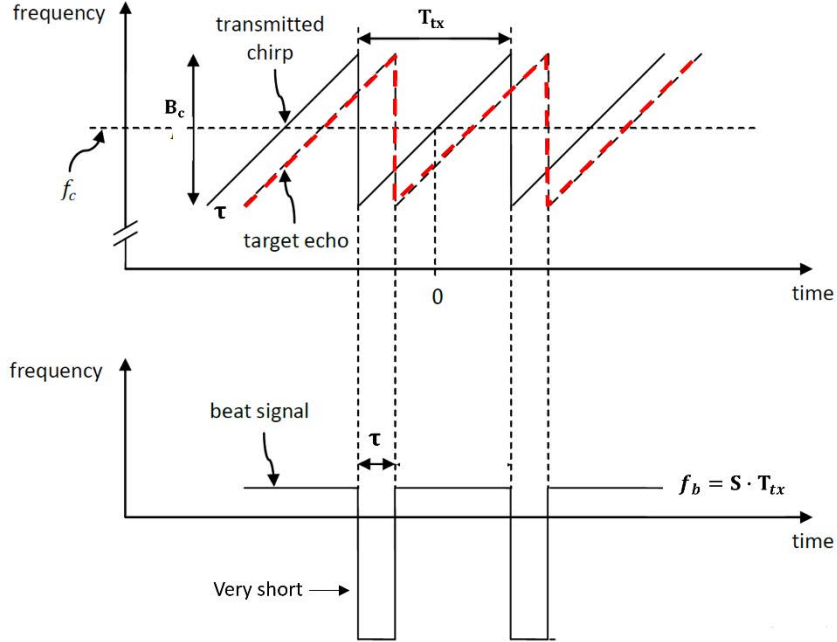


Figure 6.2 FM-CW Radar

The beat frequency, at the output of the mixer can be calculated by equation 6.3:

$$f_b = \frac{\tau}{T_{tx}} \cdot B_c \text{ (eq. 6.5)}$$

The maximum beat frequency, occurs for the echo coming from the maximum depth of 5m and given by the following equation:

$$f_{b,sub-surf} = \left(\frac{2 \cdot H}{c} + \frac{2 \cdot Z_{max} \cdot \sqrt{\epsilon_{r1}}}{c} \right) \cdot \frac{B_c}{T_{tx}} \rightarrow f_{b,max} = 1.7 \text{ MHz (eq. 6.6)}$$

The beat frequency due to the surface echo depends only on the drone's attitude and is given by the following equation:

$$f_{b,surf} = \left(\frac{2 \cdot H}{c} \right) \cdot \frac{B_c}{T_{tx}} \rightarrow f_{b,surf} = 0.7 \text{ MHz (eq. 6.7)}$$

The beat frequency due to antenna coupling is zero, since the time delay is negligible

$$f_{b,coupling} = 0 \text{ MHz}$$

The frequency increment Δf at each resolution step is given by the following equation:

$$\Delta f = \frac{2 \cdot R_d \cdot B_c \cdot \sqrt{\epsilon_{r1}}}{T_{tx} \cdot c} \rightarrow \Delta f = 25 \text{ KHz}$$

Where R_d is the resolution in the basalt which is 12.5cm.

All these considerations are illustrated in Figure 6.3(a). However, the beat frequency is not an exact copy of the transmitted signal, but a version shifted in frequency by a certain value f_{IF} , as shown in Figure 6.3(b) and explained in the previous sections.

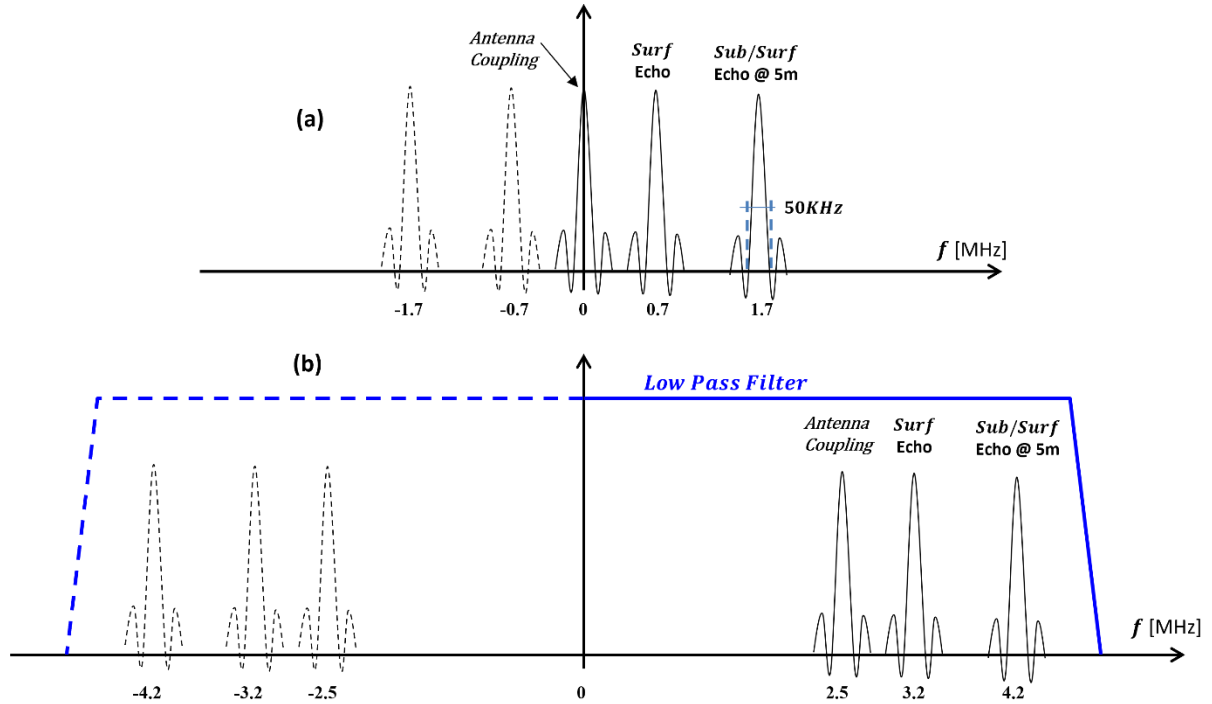


Figure 6.3 FM-CW Radar

After the demodulation process, carried out by the FPGA at the digital level, the frequencies return to their original positions, as shown in Figure 6.3(a)



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 51 of 64

BEAT FREQUENCY AT THE MIXER OUTPUT

The following figures shows the Fourier Transform of a simple rectangle that represents the finite duration of the sinusoid (beat frequency) which maximum duration is:

$$T = T_{obs} = T_{tx} - \tau = 40\mu s - 167ns = 39.83\mu s$$

The bandwidth occupancy, limited to the first two nulls of the Fourier transform, is:

$$B_{base} = \frac{2}{T_{obs}} \rightarrow B_{base} = 50KHz$$



Figure 6.3 Fourier Transform of a rectangle

7 INSTRUMENT SUMMARY TABLE

Summary Table			
Parameter	Value	UM	Description
ENVIRONMENT			
$\tan\delta$	0.02		Dielectric loss factor of the lunar soil
ϵ_{r1}	9		Dielectric permittivity of Mars basalt
ϵ_{r2}	3		Dielectric permittivity of pure ice
$L_{SS/m}$	5.4	dB/m	Two way travel time attenuation in the Mars Sub-Soil
$EnvAtt_s$	58	dB	Total environment attenuation from the Surface
$EnvAtt_{SS,Max}$	97	dB	Total sub-surface environment attenuation Maximum
INSTRUMENT REQUIREMENT			
$R_{d/vacum}$	37.5	cm	Vertical resolution in vacuum
$R_{d,\epsilon_{r1}=9}$	12.5	cm	Vertical resolution in the medium
$INS_DYN@10m$	53	dB	Instrument Dynamic for a 5m Detection Range
GENERAL RADAR PARAMETERS			
f_c	500	MHz	Carrier frequency
λ_c	60	cm	Wavelength of the carrier frequency
G_{Ant}	7	dB	Antennas Gain (TBC)
AC	30	dB	Antennas Coupling (TBC)
$LOSS_{TX CHAIN}$	2.25	dB	Total losses of the transmitting chain (TBC)
$LOSS_{RX CHAIN}$	10.25	dB	Total losses of the receiving chain (TBC)
G_{Ampli}	50	dB	Total gain of the instrument to ensure the desired performance.
$N_{0,RMS}$	-100	dBm	RMS noise level at the RX antenna output and considering the IF band
$N_{F,Max}$	38	dB	Maximum Noise Figure acceptable by the receiver
SF-CW PARAMETERS			
$R_{NA/vacum}$	1500	m	Unambiguous range in a vacuum, for radar design
Δf	98	KHz	Radar Frequency Steps
N_{toni}	4096		Number of tones in the SF-CW radar
f_{IF}	2.5	MHz	Intermediate frequency of the instrument
$f_{t,IF}$	5	MHz	Cut-off frequency of the intermediate frequency pass filter
T_{tone}	10	us	Single tone duration
T_{sweep}	41	ms	Sweep Duration
FM-CW PARAMETERS			
S	10	MHz/us	RFSoc(4x2) Slope
T_{tx}	40	us	Duration of the transmitted Chirp
$f_{b,max}$	1.7	MHz	Maximum beat frequency, in base band, due to echo from 5m depth
Δf	25	kHz	Frequency increment at each resolution step of 12.5cm in the subsoil
f_{IF}	2.5	MHz	Intermediate frequency of the instrument



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 53 of 64

DIGITAL BOARD CONFIGURATION (TBC)

V_{pp}	1	Volt	Nominal input voltage of the ADC (TBV)
N_{bit}	14		Number of bits of the ADC conversion
$P_{in_FULL_SCALE}$	1	dBm	Full-scale input power of the ADC
P_{in_MIN}	-55	dBm	Minimum input power of the ADC
$P_{R,ADC,Max}$	-2	dBm	Maximum input power to the ADC due to Antenna Coupling
$P_{R,ADC,5m}$	-55	dBm	Maximum input power to the ADC from the 5m depth of discontinuity
P_0	-9.5	dBm	Nominal power provided by the DAC (TBC)
REC_DYN	53	dB	ADC Dynamic Range



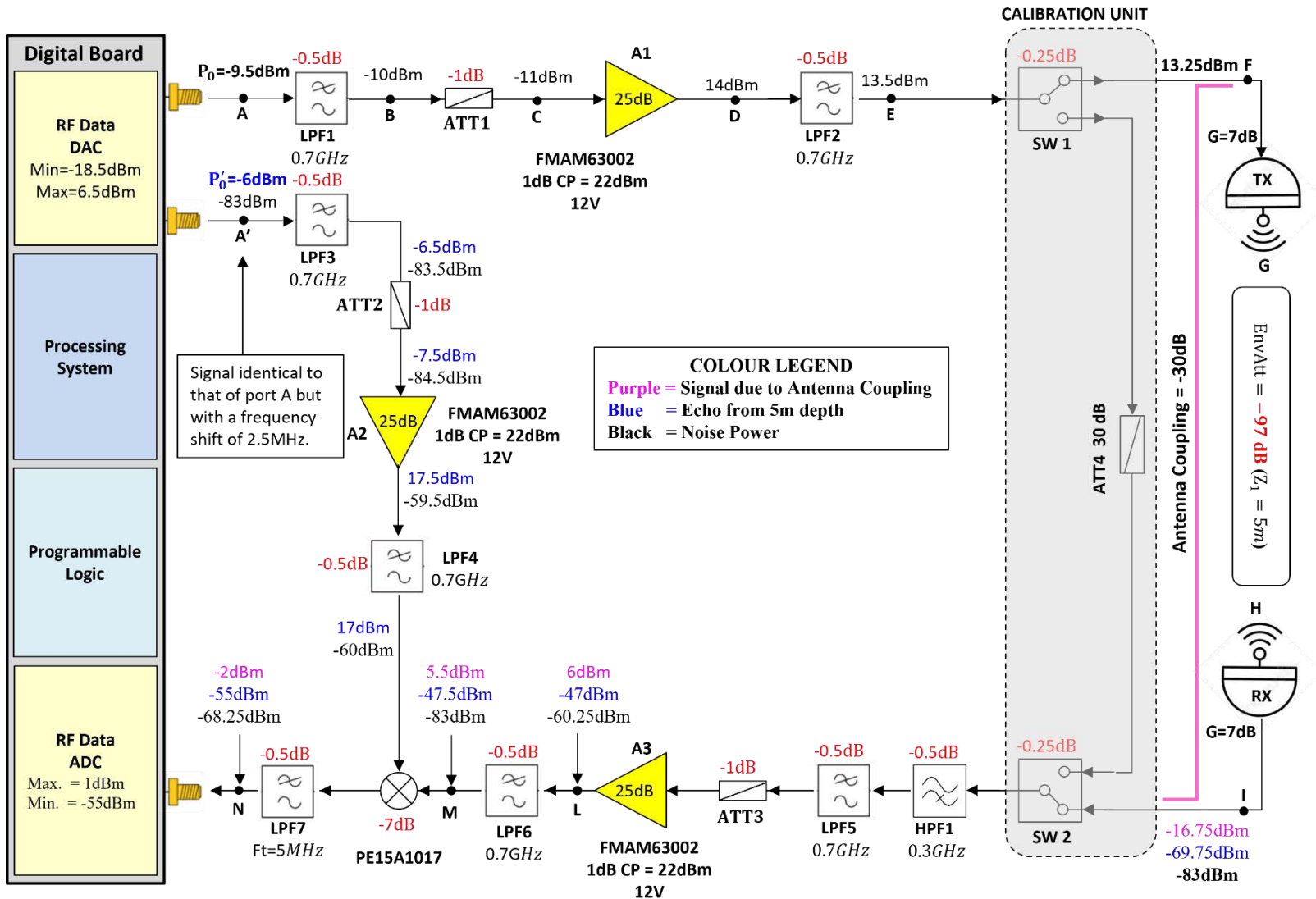
INAF THECNO GRANTS

ISSUE: 04

Data: 06/10/2025

Page 54 of 64

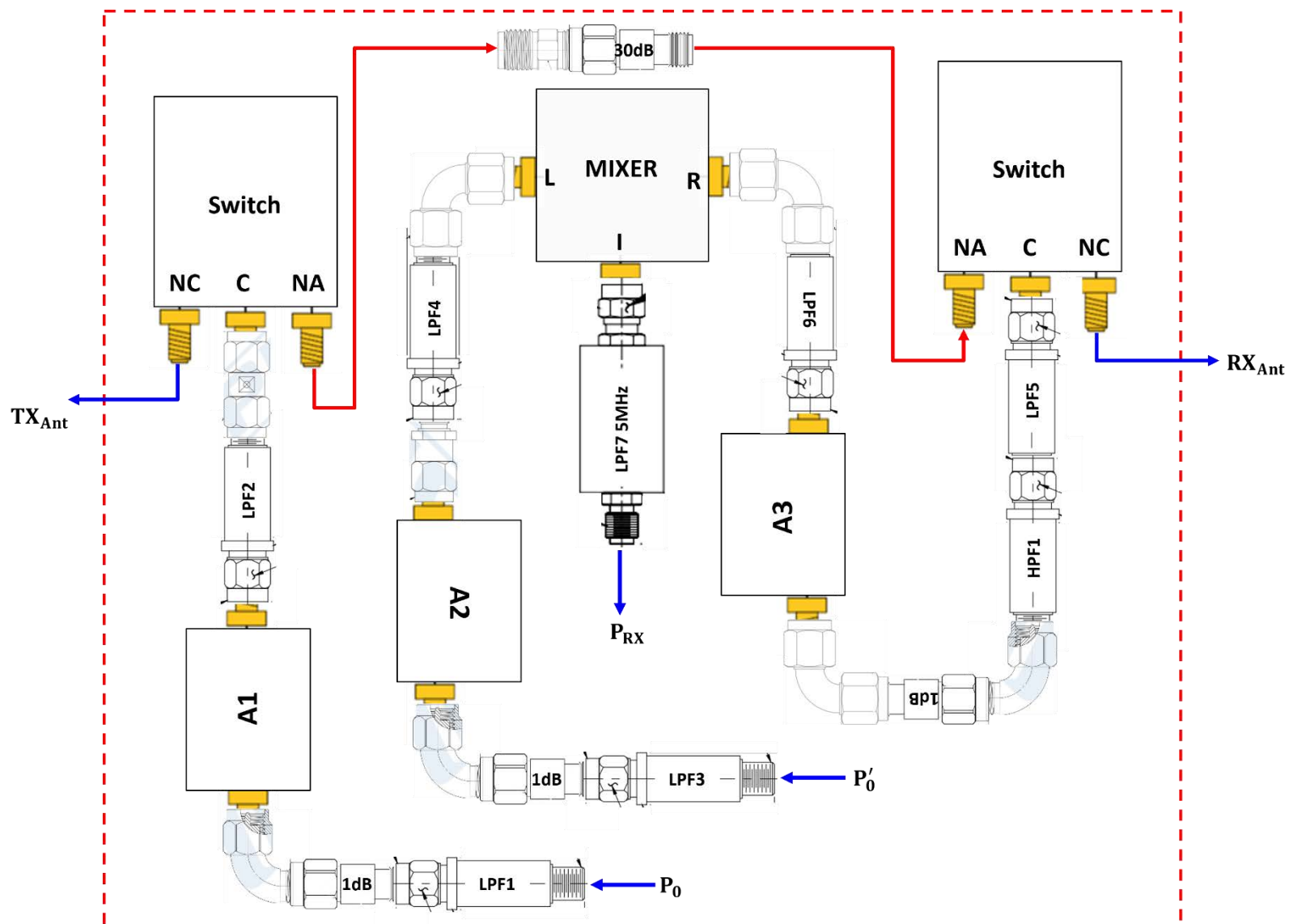
8 INSTRUMENT HIGH LEVEL ELECTRONICS





Page 55 of 64

INAF THECNO GRANTS





INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 56 of 64

9 SELECTION OF COMPONENTS

AMPLIFIERS (A1,A2,A3)

Manufacturer Product Number: FMAM63002
Manufacturer: Fairview Microwave
Description: LOWNOISEAMP 30MHZ-1.5GHZ P1DB SM
Link: <https://www.digikey.it/it/products/detail/fairview-microwave/FMAM63002/22223262>
Price: 229€

Electrical Specifications (TA=25°C, DC Voltage = 12Volts, DC Current = 150mA)

Description	Min	Typ	Max	Unit
Frequency Range	0.03		1.5	GHz
Small Signal Gain	23.5	25	26.5	dB
Gain Flatness		±0.5	±0.75	dB
Gain Variance at OTR*		1		dB
Output at 1 dB Compression Point	+21	+22		dBm
Output 3rd Intercept Point	+35	+39		dBm
Noise Figure		1.6	2	dB
Input VSWR		1.35:1	1.5:1	
Output VSWR		1.35:1	1.5:1	
Reverse Isolation		45		dB
Spurious			-70	dBc
Input Power (CW)			+30	dBm
Operating DC Voltage	10	12	15	Volts
Operating DC Current	140	150	180	mA
Operating Temperature Range	-40		+85	°C





INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 57 of 64

MIXER

Manufacturer Product Number: PE86X1021
Manufacturer: Pasternak
Description: Double Balanced Mixer Operating
Link: <https://www.digikey.it/en/products/detail/pasternak/PE86X1021/22166104>
Price: 765€

Electrical Specifications

Description	Minimum	Typical	Maximum	Units
RF Frequency Range	0.001		2.7	GHz
LO Frequency Range	0.001		2.7	GHz
IF Frequency Range	0.001		2	GHz
Impedance		50		Ohms
Conversion Loss		7	9.5	dB
LO to RF Isolation	17	38		dB
LO to IF Isolation	16	31		dB
RF Port VSWR		2:1	2.5:1	
LO Port VSWR		1.5:1	2.5:1	
IF Port VSWR		1.5:1	2:1	
Input at 3rd Order Intercept Point	+25	+27.8		dBm
RF Input Power			+13	dBm
LO Input Power		+17		dBm





INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 58 of 64

ANTENNA SWITCH

Manufacturer Product Number: R570312100
Manufacturer: Radiall USA, Inc.
Description: IC RF SWITCH SPDT 3GHZ MODULE
Link: <https://www.digikey.it/en/products/detail/radiall-usa-inc/R570312100/10521625>
Price: 213€

Electrical Specifications

RF CHARACTERISTICS

Frequency range : 0 - 3 GHz
Impedance : 50 Ohms

Frequency (GHz)	DC - 3
VSWR max	1.10
Insertion loss max	0.15 dB
Isolation min	80 dB
Average power (*)	240 W



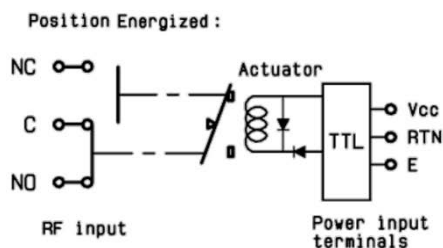
ELECTRICAL CHARACTERISTICS

Actuator : FAILSAFE
Nominal current ** : 250 mA
Actuator voltage (Vcc) : 12V (10.2 to 13V)
Terminals : solder pins (250°C max. / 30 sec.)
TTL inputs (E) : 2.2 to 5.5 V / 800µA at 5.5 V
- High level : 0 to 0.8 V / 20µA at 0.8 V
- Low level

MECHANICAL CHARACTERISTICS

Connectors : SMA female per MIL-C 39012
Life : 10 million cycles
Switching Time*** : < 10 ms
Construction : Splashproof
Weight : < 45 g

SCHEMATIC DIAGRAM



TTL input	RF Continuity
E = 0	C ↔ NC
E = 1	C ↔ NO



INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 59 of 64

LOW PASS FILTERS (LPF1, LPF2, LPF3, LPF4, LPF5, LPF6)

Manufacturer Product Number: CLPFL-0700
Manufacturer: Crystek Corporation
Description: RF FILTER LOW PASS 700MHZ INLINE
Link: <https://www.digikey.it/en/products/detail/crystek-corporation/CLPFL-0700/2339515?s=N4IgTCBcDaIOwBYEFoCMBmAbO5A5AlALoC%2BQA>
Price: 29€

FREQ (MHz)	INSERTION LOSS (dB)	Male Return Loss (dB)	Female Return Loss (dB)
0	0.04	46.40	46.37
15	0.05	40.77	40.44
30	0.11	36.97	36.96
45	0.10	34.71	34.56
60	0.13	33.06	32.93
75	0.13	31.82	31.69
90	0.18	30.92	31.03
105	0.15	30.22	30.19
120	0.16	29.65	29.86
135	0.16	29.37	29.46
150	0.21	29.12	29.31
165	0.21	28.97	29.15
180	0.24	28.97	29.41
195	0.23	29.21	29.53
210	0.22	29.50	29.83
225	0.24	29.83	30.56
240	0.25	30.52	31.20
255	0.26	31.22	32.43
270	0.27	32.25	33.87
285	0.26	33.25	35.76
300	0.27	34.28	38.87
330	0.30	35.38	42.16
405	0.36	27.06	27.30
450	0.41	22.91	22.85
510	0.51	18.75	18.59
585	0.69	14.66	14.53
705	1.39	8.77	8.73
810	3.85	4.05	4.08
900	7.78	1.74	1.76
1005	15.49	0.78	0.77
1245	33.66	0.24	0.20
1500	48.67	0.05	0.00
1755	41.69	0.02	-0.07
1995	40.50	0.04	0.00
2250	41.14	0.08	0.07
2505	41.63	0.19	0.16
2745	42.74	0.29	0.24
3000	44.32	0.39	0.31





INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 60 of 64

LOW PASS FILTER (LPF7)

Manufacturer Product Number: SLP-5+
Manufacturer: Mini-Circuits.
Description: LUMPED LC LPF, DC - 5 MHZ, 50
Link: <https://www.digikey.it/en/products/detail/mini-circuits/SLP-5/21727750>
Price: 51€

Typical Performance Data

Frequency (MHz)	Insertion Loss (dB)		Return Loss (dB)	Frequency (MHz)	Group Delay (nsec)
	$\bar{x}$	σ			
1.0	0.08	0.1	25.1	1.0	147.47
2.0	0.13	0.1	32.4	2.0	150.99
3.0	0.34	0.1	15.6	3.0	158.96
3.5	0.69	0.1	14.2	3.5	164.57
4.0	0.71	0.1	15.8	4.0	173.42
4.5	0.73	0.1	25.1	4.5	192.06
5.0	0.91	0.1	25.5	5.0	215.98
5.8	2.41	0.7	15.8	5.3	253.98
6.0	3.35	0.8	7.2	5.8	294.32
6.3	9.49	1.3	2.0	6.0	326.82
6.8	11.67	1.1	1.2	6.3	305.70
7.0	16.87	1.2	0.9	6.8	223.89
7.3	23.49	1.1	0.5	7.0	180.77
7.8	29.30	1.0	0.4	7.3	106.74
8.0	34.55	1.0	0.3	7.8	73.25
8.3	39.27	1.0	0.3	8.0	54.49
8.5	41.68	1.1	0.3	8.3	38.64
8.8	42.05	1.1	0.2	8.5	31.12
9.0	42.44	1.1	0.2	8.8	29.13
9.5	43.73	1.1	0.2	9.0	28.46
10.0	47.90	1.1	0.2	9.5	27.23
12.0	63.04	1.6	0.1	10.0	26.91
16.0	75.52	4.1	0.1	12.0	26.68
22.0	75.62	9.9	0.1	13.0	25.95
35.0	74.63	3.9	0.1	14.0	25.34
80.0	77.85	6.6	0.1	16.0	24.48
156.0	81.35	8.6	0.1	18.0	24.08
178.0	75.08	2.3	0.1	20.0	24.00
189.0	77.64	6.8	0.1	22.0	23.82
200.0	78.15	5.2	0.1	24.0	23.72





INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 61 of 64

HIGH PASS FILTER (HPF1)

Manufacturer Product Number: SHP-300+
Manufacturer: Mini-Circuits.
Description: LUMPED LC HPF, 290 - 3000 MHZ
Link: <https://www.digikey.it/en/products/detail/mini-circuits/SHP-300/21727619?s=N4IgTCBcDaIMoAkAKBaAzABgwahAXQF8g>
Price: 57€

Frequency (MHz)	Insertion Loss (dB) $\bar{x}$ σ	Return Loss (dB)	Frequency (MHz)	Group Delay (nsec)
10.00	70.05 4.53	0.11	100.00	1.52
100.00	67.77 0.48	0.08	125.00	1.84
125.00	56.38 0.52	0.14	150.00	2.14
150.00	45.47 0.61	0.17	159.00	2.24
159.00	41.59 0.66	0.17	160.00	2.25
160.00	41.15 0.66	0.18	161.00	2.24
162.00	40.29 0.67	0.18	162.00	2.25
163.00	39.86 0.67	0.18	163.00	2.28
164.00	39.43 0.67	0.18	164.00	2.29
170.00	36.88 0.71	0.19	170.00	2.45
180.00	32.65 0.77	0.21	180.00	2.69
190.00	28.46 0.84	0.26	190.00	2.94
200.00	24.28 0.90	0.33	200.00	3.32
210.00	20.10 0.98	0.44	210.00	3.84
220.00	15.91 1.05	0.61	220.00	4.59
225.00	13.82 1.08	0.75	225.00	5.09
230.00	11.75 1.10	0.96	230.00	5.69
231.00	11.35 1.11	1.01	231.00	5.81
232.00	10.94 1.11	1.07	232.00	5.94
233.00	10.53 1.11	1.13	233.00	6.08
234.00	10.13 1.10	1.20	234.00	6.22
235.00	9.74 1.10	1.27	235.00	6.36
236.00	9.34 1.10	1.35	236.00	6.50
250.00	4.46 0.85	3.58	250.00	8.29
300.00	0.49 0.02	23.84	300.00	4.35
400.00	0.32 0.03	32.34	400.00	2.02
500.00	0.27 0.03	27.26	500.00	1.31
1000.00	0.26 0.01	23.11	1000.00	0.52
2000.00	0.35 0.01	34.07	2000.00	0.35
3000.00	0.50 0.01	22.01	3000.00	0.33





INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 62 of 64

ATTENUATORS 1dB (ATT1, ATT2, ATT3)

Manufacturer Product Number: 0732870011
Manufacturer: Molex
Description: SMA M-F 18 GHZ 1DB ATTENUATOR WI
Link: <https://www.digikey.it/en/products/detail/molex/0732870011/25577776>
Price: 47€

SMA ATTENUATORS

18 AND 23 GHz
2 WATTS

SPECIFICATIONS:

Electrical:

Frequency Range _____ DC - 23.0 GHz
Standard Freq. Values _____ 18 & 23 GHz
Standard dB Values _____ 0-10, 12, 15, 20 & 30 dB
In 1 dB Increments

Attenuation Accuracy:	DC-18 GHz	18-23 GHz
1dB _____	±0.3 dB	±0.5 dB
0, and 2 - 6 dB _____	±0.3 dB	±0.4 dB
7 - 20 dB _____	±0.5 dB	±0.6 dB
21 - 30 dB _____	±0.75 dB	±0.8 dB

VSWR:

	DC - 4 GHz	4 - 8 GHz	8 - 12.4 GHz	12.4 - 18 GHz	18 - 23 GHz
@ 30 MHz _____	1.05:1 Max.	1.15:1 Max.	1.20:1 Max.	1.25:1 Max.	1.35:1 Max.
DC - 4 GHz _____	1.15:1 Max.	1.20:1 Max.	1.25:1 Max.	1.35:1 Max.	1.40:1 Max.

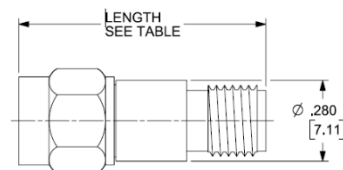
Input Power _____ 2 Watts Avg. @ 25°C
DERATED LINEARLY TO 0.5 WATTS @ +125°C

Peak Power _____ 250 Watts Max.
(5uSec Pulse, .05% Duty Cycle)

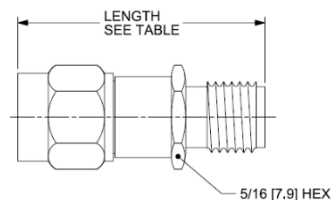
Impedance _____ 50 Ohms
Operating Temp Range _____ -65°C to +125°C

Mechanical:

SMA Connectors _____ Passivated Stainless Steel
Mates with MIL-STD-348
Conductors _____ Gold Plated Beryllium Copper



MALE/FEMALE WITHOUT HEX
SEE TABLE FOR CONFIGURATION OPTIONS



MALE/FEMALE WITH HEX
SEE TABLE FOR CONFIGURATION OPTIONS





INAF THECNO GRANTS

ISSUE: 04
Data: 06/10/2025
Page 63 of 64

ATTENUATOR 30dB (ATT4)

Manufacturer Product Number: 4882-6140-30
Manufacturer: Amphenol XMA
Description: ATTENUATOR, 2.92MM-M/F, 40GHZ, 1
Link: <https://www.digikey.it/en/products/detail/amphenol-xma/4882-6140-30/25971657>
Price: 162€

ELECTRICAL		SPECIFICATIONS		REVISIONS			
REV	DESCRIPTION	ECO #	DATE	APPROVED			
H	REVISED MARKING	16-080	4/12/16	T.KUHN			
J	REVISED MARKING LOCATIONS	16-166	8/4/16	T.KUHN			
K	ADDED 7 THRU 9 dB	18-117	8/1/18	T.KUHN			
L	ADDED 30 dB LENGTH - VIEW	20-020	2/10/20	T.KUHN			

FREQUENCY RANGE		DC - 40GHz
ATTENUATION		DC-26.5GHz 26.5-40GHz
0 TO 9 dB	±0.5 dB	±0.8 dB
10 TO 15, 20 dB	±0.6 dB	±1.0 dB
30 dB	±0.8 dB	±1.0 dB
VSWR		DC - 18.0 GHz <1.30:1
		18.0 - 40 GHz <1.40:1
POWER		@ 25°C SEE TABLE
		DERATES LINEARLY TO 10% @ 125°C
IMPEDANCE		50 OHMS
OPERATING TEMP RANGE		-55°C TO +125°C
MECHANICAL		
HOUSING		PASSIVATED STAINLESS STEEL IAW ASTM-A484 & ASTM-A582 ALLOY 303 COND A
CENTER CONDUCTORS		GOLD PLATED BERYLLIUM COPPER
ROHS COMPLIANT		
MARKING		
		PART LOOKS LIKE PRODUCT IMAGE ABOVE.
		PART MARKING ORIENTATION AND FORMAT AS SHOWN (CURVED SURFACE).
		dB = SEE TABLE FOR TWO DIGIT dB VALUE.
		REPLACE "X" WITH ONE DIGIT REPRESENTING POWER LEVEL FROM TABLE.
		MARKING TO BE AS LARGE AS POSSIBLE.
		YYWW EQUALS DATE CODE.

Technical drawing showing two views of the attenuator. The top view shows a side profile with dimensions: .87 ± .05 and .91 ± .05. The bottom view shows a top-down perspective of the connector. Marking areas are indicated with arrows pointing to the part number '4882-6X40-dB YYWW' and the manufacturer 'XMA'. A note specifies '0 - 20 dB ONLY' for the marking. A detail view of the connector end shows '281 FLATS'.



10 ESTIMATION OF POWER CONSUMPTION AND WEIGHT

<i>Device</i>	<i>Description</i>	<i>Voltage (Volt)</i>	<i>Current (Ampere)</i>	<i>Power Cons. (watt)</i>	<i>Weight (gr)</i>
Amplifier	A1 (Tx Ampli)	12	0.15	1.8	21
Amplifier	A2 (Mixer Dive Ampli)	12	0.15	1.8	21
Amplifier	A3 (Rx Ampli)	12	0.15	1.8	21
Mixer	Na	0	0	0	41(tbc)
Low Pass Filter	LPF1	0	0	0	22(tbc)
Low Pass Filter	LPF2	0	0	0	22(tbc)
Low Pass Filter	LPF3	0	0	0	22(tbc)
Low Pass Filter	LPF4	0	0	0	22(tbc)
Low Pass Filter	LPF5	0	0	0	22(tbc)
Low Pass Filter	LPF6	0	0	0	22(tbc)
Low Pass Filter	LPF7	0	0	0	42
High Pass Filter	HPF1	0	0	0	42
RFSoc Board	Digital Computer	12	2.5	30	400(tbc)
SWITCH	Tx Switch	12	0.25	3	45
SWITCH	Tx Switch	12	0.25	3	45
Straight Adapter	3 Pieces	0	0	0	45(tbc)
Curved Adapter	6 Pieces	0	0	0	90(tbc)
Attenuator	ATT1	0	0	0	40(tbc)
Attenuator	ATT2	0	0	0	40(tbc)
Attenuator	ATT3	0	0	0	40(tbc)
Attenuator	ATT4	0	0	0	40(tbc)
Total		12V	3.45A	41.4(35.4)W	1105gr