

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO



Bistatic Synthetic Aperture Radar for Deep Space Remote Sensing

Pedro Ramos Costa

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Tutor: Sérgio Reis Cunha, PhD

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Abstract

This thesis goal is to study the possibility of imaging an asteroid's shape and its interior using a double orbiter synthetic aperture bistatic radar configuration. Ground observations provide precious information about asteroids. However, they cannot determine accurately the shape and composition of such extra terrestrial objects. Density and internal structure are naturally related with the determination of electrical properties of such an object.

Several space missions are migrating from a single-satellite to multiple-satellite configurations. Thus, exploring more flexible radar geometries for deep-space remote sensing can now be supported by the already available inter-satellite links. These were found to be precise enough at estimating baselines for the proposed experiment, even with an OCXO on board.

The proposed dual orbiter configuration provides the capability of inferring the electrical properties of "Didymoon" as well as determining the existence of monolithic structures, voids or interfaces between different materials. Synthetic aperture radar, in conjunction with ground penetrating techniques, allow the association between the object's shape and its electrical properties. Elevation information is obtained through the measurement diversity in a "Didymoon" cross-orbital direction, provided by the bistatic configuration. The proposed experiment, working in the S band ($f_c = 2.65$ GHz), was determined to enable a metric 3D resolution, and the capability of detecting a target with distributed reflectivity of $\sigma_0 = -20.2$ dBm²/m² at 4.5 m and $\sigma_0 = -59.9$ dBm²/m² at the asteroid surface within an 8 week period. The experiment is tightly integrated with a time-division ISL protocol, that allows the coordination between transmitter (CubeSat) and receiver (main satellite) spacecrafts. The average power consumption of the CubeSat, with a 50% power efficiency, is $P_{TX_{avg,acq}} = 1.9$ W in acquisition mode (21 minutes every 11.3 hours) and an average of $P_{TX_{avg}} = 0.058$ W throughout the entire mission duration (8 weeks).

An experimental setup was mounted, using the microwave analogy. In this way, a target with an electrical permittivity close to the asteroid's but with its dimension scaled with the working wavelength was chosen. The hollow target has a 2-layered structure, with an outer layer of fiber-glass and silicone rubber. A volume was generated in 3D using a matched-filter and a range-Doppler algorithm using MATLAB®. The layers are readily visible, within the limit of resolution, i.e. slightly less than 4.5cm.

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Pedro Ramos Costa

*“Mystery creates wonder
and wonder is the basis of man’s desire to understand.”*

Neil Armstrong

*“No member of a crew
is praised for the rugged individuality of his rowing.”*

Alfred North Whitehead

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Abbreviations and Symbols

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AIDA	Asteroid Impact & Deflection Assessment
AIM	Asteroid Impact Mission
APEX	Asteroid Prospection Explorer
ASPECT	Asteroid Spectral Imaging Mission
AU	Astronomical Units
BPA	Backprojection Algorithm
BPSK	Binary Phase-Shift Keying
BSAR	Bistatic Synthetic Aperture Radar
CASTAway	Comet and Asteroid Space Telescope – Away
CNSA	China National Space Administration
CONCERT	Comet Nucleus Sounding Experiment by Radio-wave Transmission
CS	Chirp Scaling
CSS	Catalina Sky Survey
CSS	Catalina Sky Survey
CT	Computerized Tomography
CubeSat	Cube Satellite
CW	Continuous Waveform
DART	Double Asteroid Redirection Test
dB	Decibel
DLR	German Aerospace Center
EADS	Astrium's TerraSAR-X
EM	Electromagnetic
ESA	European Space Agency
FeNi	Iron-nickel alloy
FeS	Ferrous sulfide
FFT	Fourier Transform
GNSS	Global Navigation Satellite Systems
GPR	Ground Penetrating Radar
GPS	Global Positioning System
IFFT	Inverse Fourier Transform
IFSAR	Interferometric Synthetic Aperture Radar
InSAR	Interferometric Synthetic Aperture Radar
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
IR	Infra-Red
ISAR	Inverse Synthetic Aperture Radar

ISL	Inter-Satellite Link
JAXA	Japan Aerospace Exploration Agency
LEO	Low Earth Orbit
LFM	Linear Frequency Modulated
LHI	Linear, Homogeneous, Isotropic
LIDAR	Light Imaging, Detection and Ranging
LINEAR	Lincoln Near Earth Asteroid Research
LNA	Low-Noise Amplifier
LO	Local Oscillator
LOS	Line of Sight
MANOS	Mission Accessible Near-Earth Object Survey
MarCO	Mars Cube One
MARSIS	Multi-frequency Orbital Sounding Synthetic-Aperture Radar Instrument
MEO	Medium Earth Orbit
MF	Matched Filter
MIMO SAR	Multiple-Input Multiple-Output Synthetic Aperture Radar
MIT	Massachusetts Institute of Technology
MTRC	Migration Through Range Cells
NASA	National Aeronautics and Space Administration
NEA	Near-Earth Asteroid Scout
NEAR-Shoemaker	Near Earth Asteroid Rendezvous – Shoemaker
NEO	Near-Earth Object
NEOCam	Space-based infrared telescope
NEOWISE	Near-Earth Object Wide-field Infrared Survey Explorer
NESZ	Noise-Equivalent Sigma Zero
OC	Ordinary Chondrites
OSIRIS-Rex	Origins Spectral Interpretation Resource Identification Security Regolith Explorer
OCXO	Oven-Controlled Crystal Oscillator
Pan-STARRS	Panoramic Survey Telescope and Rapid Reporting System
PBR	Passive Bistatic Radar
PFA	Polar Format Algorithm
PNA	Precision Network Analyzer
PRF	Pulse-Repetition Frequency
PRI	Pulse Repetition Interval
RADAR	Radio Detecting and Ranging
RCM	Range Cell Migration
RCMC	Range Cell Migration Correction
RCS	Radar Cross Section
RD	Range-Doppler
RDA	Range-Doppler Algorithm
RTT	Round-Trip Time
SAR	Synthetic Aperture Radar
SINEO	Spectroscopic Investigation of Near-Earth Objects
SIR	Signal-to-Interference ratio
SLAR	Side Looking Airborne Radar
SMASS	Small Main-Belt Asteroid Spectroscopic Survey
SMASSII	Small Main-Belt Asteroid Spectroscopic Survey II

SNR	Signal-to-Noise Ratio
TAG	Target Area Gain
TB-RDA	Tomographic Bistatic Range-Doppler Algorithm
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurement
TEM	Transverse Electromagnetic
TIE	Time-Interval Error
TomoSAR	Tomographic Synthetic Aperture Radar
TSX	TerraSAR-X
VNA	Vector Network Analyzer
WISE	Wide-field Infrared Survey Explorer

Chapter 1

Introduction

Human existence is far from brief. So is the perseverance of civilization. However, from a stellar timescale perspective it is, indeed possible to understand the small duration of our presence. Several threats pose against our longevity, not only from nature but also from ourselves. Above all, even with incredible recent technological breakthroughs, a big natural disaster could have devastating effects. Among all causes of natural disasters, asteroid impacts are one that we can predict and attempt to prevent. The Cretaceous/Tertiary event, believed to be a major responsible for the dinosaur extinction [2] and more recently, the Tunguska event [3] are examples of the possible magnitude of this threat, expressing the need for its mitigation. Recent studies have shown that although over 90% of the asteroids larger than 1km population is known, a smaller fraction of intermediate sized bodies (100-500m) is located. In fact, it is estimated that even asteroids of a few hundred meters can have country or continent impact [4][5]. Moreover, the impact rate of this asteroid category is from centuries to millenniums [5]. Therefore, a deeper understanding of the threat they pose and how to protect the future of civilization from it, is needed. In addition to further identification of this population, also more information regarding the geophysical properties of celestial bodies in this size range is needed.

Another asteroid aspect that has interested countries and space agencies is related to the utilization of its resources, i.e. asteroid mining. Our poor knowledge of asteroid properties, limits the proper prediction and design of tools for material extraction. Particularly, the mechanical properties at the surface and sub-surface, including regolith¹ properties. Spectral observations from the ground only provide useful information on the first microns of an asteroid surface, which prevents the determination of potential heterogeneities of its composition. It has also not been proven that meteorite material is representative of all the bodies in space [7]. Therefore, to understand the feasibility of extracting rare Earth materials from an asteroid, more information about its composition is necessary.

¹The term regolith refers to loose unconsolidated material that comprises the upper portions of the asteroid, as in [6]

1.1 Problem and Motivation

Until the age of space travel, very limited information could be obtained by the largest telescopes on Earth. With the help of the Earth-orbiting Hubble Space Telescope, small details on the surface of asteroids were finally possible to observe, although mostly remain fuzzy. Through radar imaging, it is possible to obtain better information about near-Earth asteroids (NEA) shape, orbital and rotational parameters. For physical properties, density is investigated. This is mostly determined by observation of binary asteroids. Orbital period of the second provides the system's mass while other observations provide volume. Porosity is estimated by comparison of the asteroid bulk density with meteorite analogs. The rotation rate, in conjunction with density, provide information about cohesion. However, current estimations are still inaccurate thereby contributing to the overall inaccuracy of present-day asteroid models. Indeed, validate and improve our knowledge about asteroids has motivated several fly-byes, orbital, landing missions from different space agencies. The first asteroid to be photographed in close-up was 951 Gaspra, in 1991 [8]. Since then, over ten missions have been launched with the ultimate purpose of exploring asteroids [9]. Recent and future efforts focus, alongside other objectives, on extracting the size and shape of asteroids and on analyzing surface and sub-surface properties. Being, the first typically referred to as asteroid topography and the latter as tomography.

Radar/Lidar missions provide the finest remote sensing alternatives for analysis of asteroids topography and tomography. In fact, there are still unresolved questions that could be answered by an analysis using remote sensing techniques [10], such as:

1. How are an asteroid's surface and sub-surface related?
2. What is the internal structure of a small binary asteroid?
3. What is the cohesion within this type of structures, formed in micro-gravity?
4. What are the properties of the regolith covering asteroid surfaces?

On the other hand, the space paradigm is changing, migrating from single-satellite approaches to multiple spacecraft arrangements. Deep-space missions are no exception. Examples are MarCO (Mars Cube One), the first CubeSat deep-space mission. The twin spacecrafts accompanied In-Sight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) successfully relaying its entry, descent and landing phase data in November of 2018 [11]. Another example emerges within the scope of an international cooperation, Asteroid Impact & Deflection Assessment (AIDA). The proposed ESA's Hera mission is intended to operate a multiple spacecraft arrangement in an asteroid remote sensing context [7].

Synchronization between all assets is crucial and, in deep-space solutions, absolute time references provided by Global Navigation Satellite Systems (e.g. GPS, Galileo) are not viable. Thus, to cooperate and coordinate actions, inter-satellite links are needed to provide the capability for spacecrafts to communicate and exchange information. This enables the exploration of multiple

spacecraft arrangements for remote-sensing. In particular, radar missions using separate transmitters and receivers can improve the diversity of the measurements and reveal hidden features of an observed scenario. In a deep-space context, this translates into an increased flexibility among spacecraft requirements.

1.2 Scope and Thesis Objectives

The problem addressed in this thesis is the surface and subsurface investigation of a near-Earth orbiter (NEO). The goal is to entail characteristics of state-of-the-art deep-space exploration, such as multiple spacecraft arrangements and radar remote sensing techniques. The objectives of this Thesis are as follows:

- Design a new waveform that is suitable for supporting close range characterization of the surface and subsurface of a NEO.
- Conduct experiments to assess the behavior of the developed waveform.
- Investigate an optimal acquisition geometry for a low-power and low-propulsion deep-space solution.
- Conduct experiments to evaluate the feasibility of the geometry for a tomographic characterization scenario.
- Develop a bistatic processing algorithm based on the three-dimensional frequency signal.

The results of this thesis will be useful to agencies working on the development of NEO characterization and synthetic aperture radar (SAR).

1.3 Document Structure

This thesis is organized as follows:

- Chapter 1, [Introduction](#) - The document begins with an overview of the problems faced in deep-space remote sensing, namely towards asteroids. These problems provide the motivations for this thesis.
- Chapter 2, [Literature Review and State of the Art](#) - This chapter discusses the evolution and description of radar signal processing techniques. It provides a theoretical basis for understanding bistatic SAR and ISAR processing, as well as tomographic bistatic SAR. A review of current solutions for characterization of near Earth objects and previous radar investigations are also given in this chapter.
- Chapter 3, [Radar Geometries for NEOs Surface and Subsurface Investigation](#) - This chapter gives a short overview of fundamental electromagnetic subsurface sounding concepts and surface and subsurface properties of asteroids.

- Chapter 4, [Bistatic Tomographic Synthetic Aperture Radar for Didymos Characterization](#) - The material presented in this chapter constitutes a novel deep-space acquisition method and a discussion about radar parameters optimization.
- Chapter 5, [Experimental Bistatic Tomographic Synthetic Aperture Radar](#) - An experimental setup using an asteroid model is presented, establishing a proof of concept for the proposed solution in the previous chapter.
- Chapter 6, [Conclusions and Further Work](#) - The thesis concludes by giving a summary of the contributions of this thesis and suggesting a few areas for future work.

Chapter 2

Literature Review and State of the Art

In this chapter, the state of the art regarding the most important topics related to this dissertation is presented. It is outlined as follows:

- [Radar and Synthetic Aperture Radar](#)
- [Bistatic Radar and Bistatic Synthetic Aperture Radar](#)
- [Bistatic Synthetic Aperture Radar](#)
- [NEO Characterization](#)
- [Summary and Main Conclusions](#)

2.1 Radar and Synthetic Aperture Radar

Like many inventions, radar is difficult to ascribe to an individual. However, the memorandum 'Detection and Location of Aircraft by Radio Methods' written, in 1935, by the physicist Sir Robert Watson-Watt, seems to be the most influential precursor to Radio Detection and Ranging (RADAR), as we know it [12][13]. As the name suggests, it consists in detecting and localizing targets. Essentially, its working principle is radiating electromagnetic energy from an antenna. A target, or targets, of interest, at a given distance to the radar, intercept some of the radiated energy and reflect it back. Some of that energy is re-radiated back, and these are the so-called echoes. A system with an antenna, amplification and signal processing is then required to retrieve information about the illuminated scene.

Nowadays, radar has applications in many different areas. An example is airport air traffic control and detection of aircrafts. Another examples are weather observation, space-born imaging or spacecraft ranging, the growing industry of the self-driving vehicles and more. The different requirements intrinsic to any industry or system help to maintain its relevance in the research community. Furthermore, radar adds valuable complementary information to optical sensors, since it works at different wavelengths and polarizations, hence revealing sometimes hidden features to other sensors. It is also independent of weather and, of course, daylight. Signal processing

techniques have allowed to surpass the physical limits of an antenna in terms of performance, which enabled the generation of products with radar image combinations.

Different types of radar have been defined, depending on a few key differentiator characteristics. For example, the signal transmitted can be a pulsed or continuous waveform (CW). In the first case, a signal, followed by an absence of transmission is transmitted and then received on a pulse-by-pulse basis. The processing of the received signal is done through match filtering, which can be achieved by correlating the transmitted with the received signal (auto-correlation principle [14]). Its continuous wave counterpart is broadcast without interruption. Its advantages are its distributed and steady transmission make it more easily detected. However, adequate isolation must be achieved between the transmitter and receiver to prevent them from jamming each other. Also, typically, CW radars have a operating shorter range and stricter auto-correlation requirements.

The transmitting and receiving antenna may be the same, or they might even be different pieces of hardware. Nonetheless, if both antennas are collocated, or the difference is negligible with respect to the intended target's range, the radar system is said to be mono-static. By contrast, when both are separated, the configuration is denominated as bi-static. There can be even the case where there are multiple transmitting and receiving antennas on multiple platforms. In this case, the employed term is multi-static.

Target location is done by measuring round-trip delay from the reflected signals in the simplest of radars, as in, for instance, the radar altimeter. This was actually the first concept associated with radar. But it was not long before other types of information, such as a target's closing velocity, started to be extracted from the Doppler frequency shifts of the echoes. It was then discovered that, by processing the Doppler shifts, finer resolution could be obtained in the along-track direction, i.e. the direction perpendicular to the range or beam direction. This technique is labeled Synthetic Aperture Radar (SAR). It allows a virtual placement of several smaller antennas in the along-track direction, increasing the obtained phase information from the scene, thus simulating the behavior of a perhaps unfeasible larger antenna [15]. In reality, this is enabled by the movement of the platform with respect to the target, while integrating several measurements from sequential (azimuth) positions in time. This basic principle is represented in Figure 2.1.

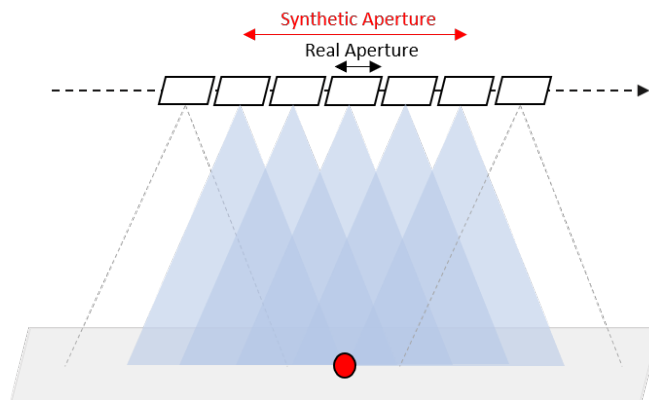


Figure 2.1: Synthetic Aperture Radar principle.

In a remote sensing context, the Synthetic Aperture Radar hopes to make an image of the scene it is illuminating. In fact, it has been the standard for the formation of aerial radar ground maps. An example is the famous Shuttle Topography Radar Mission [16]. Due to its simplicity regarding other topologies, historically mono-static configurations have been widely deployed. Having the same antenna for transmission and reception lowers the hardware costs and, at the same time, there is only one platform to track and synchronize.

Within SAR, there are several signal processing techniques that relate differently the data collected across the entire synthetic aperture. This data is commonly called "phase history data". A context scenario, where the radar is on-board of a plane, usually denominated Side Looking Airborne Radar (SLAR). The conventional operation of SAR, Stripmap Imaging Mode, is represented in Figure 2.2. In this case, the radar is point at the ground, using an antenna beam fixed to the platform. It focuses on a constant swath, i.e. centered at a fixed range throughout the azimuth sampling. The swath is then limited by the nearest range it can detect, i.e. the minimum unambiguous range, and its farthest range, determined by the maximum unambiguous range it can detect. To obtain broader widths, one can use a different technique, that goes by Scan SAR. In this

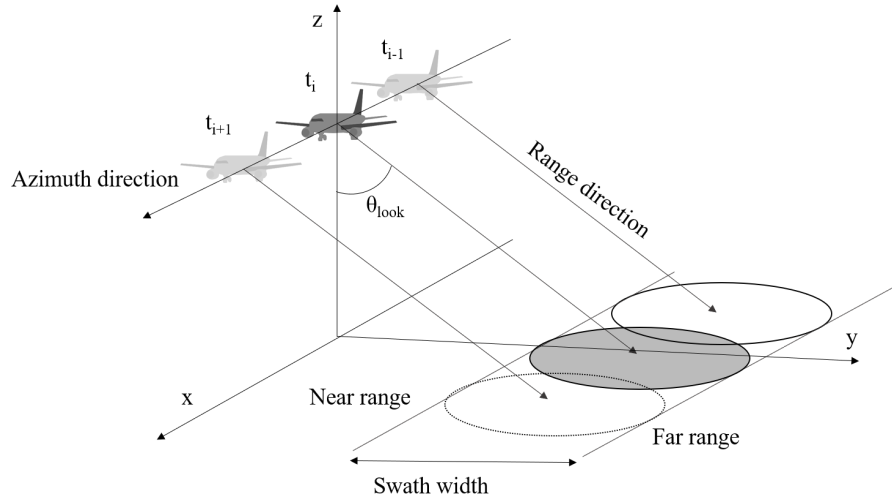


Figure 2.2: Side Looking Synthetic Aperture Radar. Plane at several aperture positions (t_i corresponds to mid-aperture time) and observing at an angle with the normal of the imaging surface of θ_{look} .

mode, the observation of a wide-area is possible due to elevation beam switching, i.e. variations of the look angle, θ_{look} , within the formation of the synthetic aperture. This generates several more strips, or sub-swaths, but it is also trivial to understand that they will have, individually, less observation time, hence coarser resolution. In Spotlight mode, the phase history is combined such that, throughout the entire synthetic aperture, the beam direction is adjusted to keep pointing at a specific target area. Thus, it grants a longer observation time than Stripmap or Scan SAR, which translates into a finer cross-range resolution. Another mode that has been exploited in a space-based context is the Interferometric SAR (InSAR or IFSAR). It uses two antennas whose

signals can be combined coherently if placed horizontally. This technique allows the perception of a target's motion and the determination of height if two targets are placed vertically [17]. This concept has been adopted recently in the TSX/TanDEM-X high-resolution interferometric SAR mission of DLR (German Aerospace Center) and partners. Two InSAR observational modes are possible. A bi-static and a mono-static configuration and it allows accurate digital elevation measurements [18][19]. The Space Shuttle is also an example of interferometric SAR. It works, however, on a different principle often referred to as Inverse Synthetic Aperture Radar (ISAR). In this case, the radar is considered stationary, while the platform movement is simulated by the target itself, whose relative velocity causes different Doppler shifts that can then be processed to generate an image.

2.1.1 Radar Basic Concepts

In this sub-section a brief explanation is presented about some of radar's fundamental concepts. The working principle of radar is complemented by some useful mathematical formulation regarding the target's echo and properties that can be obtained from it. The distance, R , from the radar's platform to a given target is intrinsically related to the speed of light, c , and the time between the transmission of a pulse and the reception of its corresponding echo, Δt_{2-way} .

$$R = \frac{c \cdot \Delta t_{2-way}}{2} \quad (2.1)$$

If the target exhibits a velocity component towards the radar, v_r , a Doppler frequency shift will be induced. In turn, this corresponds to a phase shift ϕ and consequently to a frequency shift f_D dependent on the radar's working wavelength, λ .

$$\phi = -\frac{4\pi}{\lambda} R \quad (2.2)$$

$$f_D = -\frac{2\pi}{\lambda} \frac{\partial R}{\partial t} v_r \quad (2.3)$$

The range resolution is defined as the minimum spacing between two objects so they can be differentiated. Therefore, the range resolution δ_r corresponds to the minimum interval between the reflections in two different objects without any overlap of the echoes R_{min} . This is defined by the pulse transmission time, τ :

$$R_{min} = \delta_r = \frac{c \cdot \tau}{2} = \frac{c}{2B} \quad (2.4)$$

For the case of a simple pulse, duration is inversely related to the pulse bandwidth, B . In fact, for more complex waveforms, the criterion of resolution commonly adopted in radar is the "3 dB" or "Rayleigh" Criterion [20]. Essentially, it is assumed that two targets can be resolved when they are separated, in time, such that the peak of the response of one target falls on the first null of the second target.

The maximum unambiguous range is defined by the interval of time in which it is possible to have certainty that the received pulse corresponds to the last emitted echo. This is clearly dependent on the Pulse Repetition Interval, PRI .

$$R_{max} = \frac{c \cdot PRI}{2} \quad (2.5)$$

Spaceborne applications, however, frequently entail working beyond the maximum unambiguous range limit due to the distance between the radar and the illuminated scene [21]. The solution passes by ensuring that adequate SNR is achievable within the range of interest and the unambiguous range constraint is adequately managed.

Another useful definition is the Radar Cross Section (RCS), commonly represented by the Greek letter, σ . This is an abstraction, that represents in a unique parameter, the target size, orientation, physical shape and material. It is the hypothetical area required to intercept the transmission power density at the target such that, if the total intercepted power was re-radiated isotropically, it would be received with the same power density at the reception that is actually produced [22]. In other words, it is a ratio between the incident power density P_0 and the power reflected P_r .

$$\sigma = \frac{P_r}{P_0} [m^2] \quad (2.6)$$

There are several techniques used to predict the RCS of a target. They can be exact techniques, which are typically only possible for a few geometries or numerical methods for low frequencies, or they can also be approximate techniques. These methods, such as Surface Integral or Ray Tracing Techniques, are typically also slow but more useful at high frequencies. Combinations between both techniques are typically used for higher performance [22][23][24][25].

The Radar Equation is a useful tool in the design of radar systems and has been consistently used in the literature [15][20][22][26]. Basically, it represents the fundamental relation between the characteristics of the radar, the target and the received signal, allowing the determination of a theoretical maximum range. For convenience, the Radar Equation can have multiple forms, depending on the type of input parameters that are available in a given system. The transmitter can be characterized by the power density P_D of a transmitting directional antenna, usually defined in its pointing direction. Hence, at a given range, R , for a mono-static configuration:

$$P_D = \frac{P_{TX} G}{4\pi R^2} \quad (2.7)$$

Being P_{TX} the transmitted power averaged over the pulse transmission time τ and G the transmitter antenna gain. The target itself can be described entirely by its RCS, from which the power is considered to be reflected omni directionally. Therefore, considering that the receiver has a directional antenna (i.e. with a small beam width) with an aperture with A_p area and an efficiency of $0 < \rho < 1$, such that its effective aperture is A_e .

$$A_e = \rho A_p = \frac{G \lambda^2}{4\pi} \quad (2.8)$$

Additionally, if the losses from the radar system (transmitter and receiver) are accumulated in a single parameter, together with the losses in the signal path (except free space losses) are accumulated in a single parameter, L . The power delivered to the radar is, given by a simplified version of the Radar Equation:

$$P_r = \frac{P_{TX} G \sigma A_e}{(4\pi R^2)^2 L} = \frac{P_{TX} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L} \quad (2.9)$$

To determine the Signal-to-Noise Ratio (SNR), at the input of the receiver, one has to consider the unwanted voltages in the radar operating bandwidth, i.e. noise. The input noise to the antenna is:

$$N_i = k T_s B \quad (2.10)$$

Where $k \approx 1.38 \cdot 10^{-23} m^2 s^{-2} K^{-1} kg$ is the Boltzmann's constant, B represents the noise bandwidth and T_s is the equivalent system's temperature at the antenna input. All things considered, it is possible to determine a still simplistic SNR version of the Radar Equation:

$$SNR = \frac{P_{TX} G^2 \lambda^2 \sigma}{(4\pi)^3 k T_s B R^4 L} \quad (2.11)$$

The final radar performance is determined also by the Signal-to-Interference ratio (SIR) or a combination of performance due to noise and interference (SNIR):

$$SNIR = \frac{P_{TX} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L} \frac{1}{k T_s B L + C + J} \quad (2.12)$$

Being J , the jamming, or purposeful interference, power and C , the clutter power, in other words, the scattering of the signal in a target that is not the one of interest.

2.1.2 Synthetic Aperture Radar Concept

Synthetic aperture Radar is a signal processing technique that enables high resolution in the cross-range (or along-track) direction by coherently processing consecutive echo data. The cross-range resolution is defined by the positions of the nulls in either side of the main lobe, i.e. when each wave source has a corresponding point that is out of phase. In a real aperture radar, the first null occurs when there is a $\lambda/2$ phase difference. Which means that, if the beam-width θ is small, the angle given by the radar and this two points can be further approximated to:

$$\sin(\theta) \approx \theta = \frac{\lambda}{L_{ant}} \quad (2.13)$$

Where L_{ant} is the diameter of the antenna aperture. If during the collected aperture, the relative positions of the surface do not change, then an analysis of subsequent pulses produces an intensified and high-resolution image. Moreover, there is a redundancy caused by the doubling of the phase shifts within the synthetic aperture. In other words, in the case of a sliding antenna, the first null occurs when there is a $\lambda/4$ phase difference for the two-way propagation with respect to

the sliding antenna element. This causes an improvement in azimuth resolution by a factor of 2. Therefore, in this type of SAR:

$$\sin(\theta) \approx \theta = \frac{\lambda}{2L_{SA}} \quad (2.14)$$

Where L_{SA} is the length of the synthetic aperture. The cross-range footprint dimension (or cross-range resolution, δ_{cr}), is given by the previously described angle and the distance the target is radar, such that, in the real aperture, and in the synthetic aperture case, respectively:

$$\delta_{cr} = \frac{\lambda}{L_{ant}} R \quad (2.15)$$

$$\delta_{cr} = \frac{\lambda}{2L_{SA}} R \quad (2.16)$$

Being so, the strip-map SAR resolution, in which the beam remains normal to the nominal flight path, can be obtained relating both the antenna element and the combined aperture over an integration time. It is trivial to understand from [Figure 2.1](#), that the combined aperture will be equivalent to the footprint of the antenna element itself. Thus, the cross-range resolution becomes:

$$L_{SA} = \frac{\lambda}{L_{ant}} R \quad (2.17)$$

$$\delta_{cr} = \frac{\lambda}{2L_{SA}} R = \frac{\lambda R L_{ant}}{2\lambda R} = \frac{L_{ant}}{2} \quad (2.18)$$

This brings some important implications. First, the cross-range resolution does not depend on either range or frequency. Secondly, to obtain the same resolution, antennas can be much simpler and, therefore, less expensive. The requirements regarding antennas are also relevant for other reason. From [Equation 2.4](#), it is possible to understand that range resolution is inversely related with bandwidth. Moreover, to obtain large bandwidths, high frequency antennas need to be used. However, they are small and thus, imply, in a real aperture radar, a coarser cross-range resolution. This technique enables to surpass this difficulties, whilst keeping the transmitted power lower, due to the processing gain, at the cost of a higher computation time.

Regarding the radar cross section σ , in an imaging context, the RCS is defined within the area of each pixel. In this way, for a given scatterer, its distributed target reflectivity σ_0 is then sampled by the area formed by the range and cross-range resolutions. In this way, the RCS becomes:

$$\sigma = \sigma_0 \delta_r \delta_{cr} \quad (2.19)$$

Typically, the distributed target reflectivity is only known for a nominal frequency f_n and it can be extrapolated for the intended operating frequency f from the reference frequency (f_n) value

$\sigma_{0,ref}$, by the following relation [21]:

$$\sigma_0 = \sigma_{0,ref} \left(\frac{f}{f_n} \right)^2 \quad (2.20)$$

2.1.3 Processing Gain

The SAR technique also improves the signal-to-noise ratio, differently for each dimension. In the range dimension, SAR's processing gain is typically the same as the obtainable in normal radars if pulse compression is used. This is essentially a modulation applied to the transmitted signal that also improves the correlation properties. It also lowers the requirements on the pulse transmission time that would be otherwise required for the same resolution. Accumulating pulses in azimuth can be seen as an integration. This means that the reflection power from the same scatterer will accumulate in the overall integration. Whereas the noise is modeled as a random process, thus not benefiting from an integration procedure. As a side note, it is adequate to refer that this azimuth processing benefit does not extend to fading related interferences, as they, unlike typical noise, do not possess a random nature.

2.1.3.1 Range Processing Gain

The gain in the range dimension $G_{r_{proc}}$ is related to the time-bandwidth product, $\tau \times B$. However, the effective pulse width of the radar decreases with respect to the transmitted one after data weighting or windowing. The range impulse broadening factor a_{wr} that represents the normalized bandwidth of signal processing window functions is thus added. Also, L_r , a reduction in SNR gain due to non-ideal digital matched filtering, is accounted for.

$$G_{r_{proc}} = \frac{a_{wr} \tau B}{L_r} \quad (2.21)$$

2.1.3.2 Azimuth Processing Gain

Azimuth processing is inherently geometry dependent. However, regarding its SNR gain, it is mainly related to the aforementioned averaging process. This can be expressed as the number of pulses N_{az} :

$$G_{az_{proc}} = \frac{N_{az}}{L_a} = \frac{PRF \lambda R}{2 \delta_{cr} v_{cr} L_a} \quad (2.22)$$

Where PRF is the pulse repetition frequency, or the inverse of PRI , pulse repetition interval. As in the range processing case, generally it is assumed that, due to non-ideal matched filtering losses, the factor L_a has to be included in Equation 2.22. The platform velocity in the cross-range (azimuth) direction v_{cr} drives the acquisition frequency and thus number of samples and azimuth aperture.

2.1.3.3 Final Image SNR

Grouping the SAR parameters into the Radar Equation from Equation 2.11, the signal-to-noise ratio of the final image SNR_{img} is:

$$SNR_{img} = SNR \times G_{r_{proc}} \times G_{az_{proc}} \quad (2.23)$$

It is also important to define a frequently used metric for evaluating SAR systems performance, the noise equivalent sigma zero $NESZ$. It is therefore a measure of the strength of the system noise in terms of the average power in the image domain that would result from an idealized distributed scatterer of the stated reflectivity [27].

$$NESZ = \frac{\sigma_0}{SNR_{img}} \quad (2.24)$$

Literally speaking, it is a measure of the idealized target distributed reflectivity that would be possible to image with an SNR of 1 (or 0dB).

2.1.4 Tomographic SAR Principles

Side-looking geometries that observe a given target area contain inherent 3D information within a single azimuthal aperture, represented in Figure 2.3 by Δ_s . This, however, corresponds to a single measurement for an azimuth-range pixel in the focused image. A three-dimensional azimuth-range-elevation reflectivity profile is thus embedded in each SAR generated image. Due to the common and consistent side-looking geometry of spaceborne SAR sensors, little orbital deviations or multiple sensor arrays can accumulate targets echoes within an elevation extent Δ_b . This technique is referred to as Tomographic SAR, or TomoSAR [28][29][30].

Generally, this extra dimension adds another aperture, that can be seen as an azimuth aperture on another plane. The resolution in elevation δ_{el} follows the exact same principle, given by the frequency at which the data is sampled.

$$\delta_{el} = \frac{\lambda}{2L_{SA_{el}}}R \quad (2.25)$$

Indeed, also the elevation aperture $L_{SA_{el}}$ increases the final volume signal-to-noise ratio by a factor of $G_{el_{proc}}$:

$$G_{el_{proc}} = \frac{N_{el}}{L_e} = \frac{PRF_{el}\lambda R}{2\delta_{el}v_{el}L_e} \quad (2.26)$$

Where v_{el} is the platform's elevation velocity, N_{el} is the number of accumulated elevation pulses and L_e are the losses in the elevation match-filtering process.

TomoSAR is tightly related with the concept of InSAR and it allows to resolve misinterpretations in SAR images caused by layover and foreshortening effects. It has been recently applied in several applications, such as canopy characterization in forests, urban environment and also from a space-based perspective, in for example DLR's and EADS Astrium's TerraSAR-X [31][32][29].

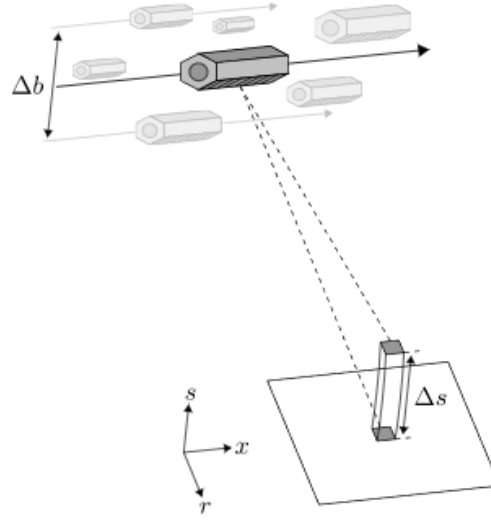


Figure 2.3: Layover phenomenon in side-looking SAR imaging. Range, azimuth and elevation axis are respectively r , x and s . Repeat-pass measurements within an elevation aperture of Δb allow to resolve multiple scatterers in the far-field toroid segment with elevation extent Δs [29].

2.2 Bistatic Radar and Bistatic Synthetic Aperture Radar

A radar whose transmitter's distance to the receiver is not negligible comparing with the intended observation area is denominated as bistatic. Periods of intense research about this type of radar have occurred intermittently [33]. Bistatic radar's usually measure the sum of the delay caused by the propagation path of the transmitter to the target, R_t and from the target to the receiver, R_r . They are related, as in monostatic radar a relation between the speed of light and its echo delay Δt .

$$R_t + R_r = c \cdot \Delta t \quad (2.27)$$

Jackson [34], through an analytical and geometric perspective over the bi-static radar scenario as shown in Figure 2.4, derives, for a given bistatic angle β , the area of a resolution cell in a plane.

Linear beam width W is equivalent to the product of range R and the $3dB$ beam width (one-way) B . It is assumed that the transmitter and the receiver have linear beam widths of $W_T = R_T B_T$ and $W_R = R_R B_R$, such that, in the range dimension:

$$\delta_r = \frac{1}{2} c \tau \sec(\beta/2) \quad (2.28)$$

And in the transverse dimension, or along track:

$$\delta_{cr} = \frac{\sqrt{2} W_T W_R \sec(\beta/2)}{\sqrt{W_T^2 + W_R^2}} \quad (2.29)$$

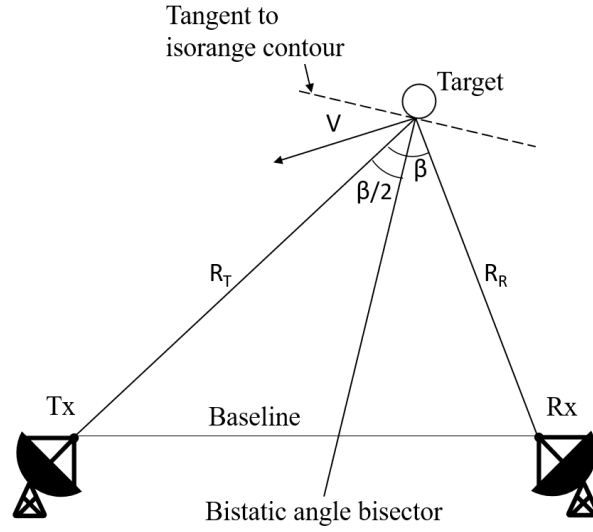


Figure 2.4: Bistatic Radar Scenario.

Where the pulse duration is τ and c , the speed of light. Thus, the area is given by $A_{cell} = \delta_r \delta_{cr}$. To note if the linear beam widths are considerably different, it is the smaller of them which is going to control the cross-range resolution. If the 3dB beam widths are comparable, this corresponds to the station closest to the target.

The bistatic version of the Radar Equation is:

$$(R_T R_R)_{max} = \sqrt{\frac{P_{TX} G_T G_R F_T F_R \lambda^2 \sigma_B}{(4\pi)^3 k T_s B (SNR_{min}) L}} \quad (2.30)$$

Where F_T , F_R , G_T and G_R are, respectively, the transmitter and receiver noise factor and antenna gains. Regarding this equation, the non co-location of transmitter and receiver have to be taken into account as well as the pattern propagation factors from transmitter-to-target and target-to-receiver. Furthermore, the bistatic RCS σ_B is not equal to monostatic RCS (backscatter). It is dependent on many factors such as look angle and surface roughness. It is often found to be close to the monostatic value measured along the bistatic bisector for small angles and rough surfaces [35][36], typically for $\beta < 5^\circ$ [37]. Also, considering the tangent of an ellipse with foci at the transmitter and receiver sites and passing through the target position orthogonal to the bisector of the bistatic angle is found to be a good approximation [37].

This type of radars have intrinsic advantages over mono-static configurations, which are described by Hanle [38]. They include: stealthiness, since the receiver location is not given away by the transmission; easiness of implementation of a continuous waveforms, since there are no isolation constraints; independent design of transmitters and receiver, i.e. no transmit-receive switch or duplexer is required. These devices are lossy, expensive, and heavy (important for airborne/space-based radar applications). Notwithstanding, a bi-static target detection and location are more complicated than mono-static. Firstly, for the matched filter operation, the transmitted waveform

(and its phase for a coherent processing) needs to be available at the receiver. Secondly, the conventional radar, estimate range and angle of arrival from a given echo. Such estimation is done, in bi-static radars, over a period of propagation corresponding to the distance from the transmitter to the target, R_T , and from the target to the receiver, R_R . Therefore, the receiver requires information about the transmitter's position, which usually implies an estimation. This synchronization can be done by reception and demodulation of the transmitted signal over the line-of sight, if available, or by the use of identical stable clocks aligned before the start of operations. Position data can be then obtained via a data link or from an intercept receiver and emitter location system.

There might be the case where saturation occurs at the receiver. This has to be accounted particularly when the transmitter is pointed directly at the receiver. In this cases there is the need to attenuate the signal at the reception. It can be done by Doppler filtering (reducing the influence of targets at specific relative velocities [22]), spatial nulling (for example, with side-lobe cancellation) or time gating (clearly only in pulsed signals) [33].

2.2.1 Bistatic Synthetic Aperture Radar

The Synthetic Aperture technique can also be applied to a bi-static configuration. It is enabled through the motion of one or both of the stations (or platforms). A first documented study about synthetic aperture using this geometry was published in 1977, by Teague [39], with the aim of observing wave scattering. A bi-static imaging configuration might reveal advantageous comparing to a mono-static due to the associated advantages of using bi-static radar exposed in section 2.2. Furthermore, a valuable advantage in the case of imaging is that this configuration might enhance different scattering patterns in detected objects and their materials, e.g. asteroid's ice will typically produce "volume scattering" at the reception and with rock, the more traditional surface scattering would occur. Actually, a bi-static geometry imaging also allows a reception of not only back scattered signal from a target, as in the mono-static case, but forward or side scatter can also be explored, depending on the geometry. This presents a solution for the distortions such as the observed in back scatter patterns in the cases of: a layover, i.e. when a target of height, for example a mountain, appears in the same range as a lower height target, i.e. a valley; or for example, a foreshortening, i.e. when sloped sides of a mountain are contracted in size because of slope and height of the first mountain [40].

For BSAR systems where the transmitter and receiver are moving, the cross-range resolution is [41]:

$$\delta_{cr} = \frac{\lambda R_T R_R}{L_T R_T + L_R R_R} \quad (2.31)$$

Where L_T is the paths or apertures traversed by the transmitter during signal transmission and L_R the path traveled by the receiver during signal reception.

An important note is the reduction in resolution for a BSAR system where one of the nodes is stationary. The azimuth/Doppler resolution reduces the bistatic aperture to half of the monostatic

aperture during the collection time. Thus, when the transmitter is stationary:

$$\delta_{cr} = \frac{\lambda R_R^2}{L_R R_R} = \frac{\lambda R_R}{L_R} \quad (2.32)$$

2.2.2 Synchronization in BSAR systems

The reference for both the local oscillator (LO) and pulse-repetition frequency (PRF) timing is provided by the master oscillator. Hence, frequency instabilities on the master oscillator output are magnified by frequency multiplication. Naturally, the same oscillator is used for both the transmitter and the receiver in monostatic SAR systems. This lowers the degradation of SAR images resulting from the oscillator phase noise, since it is the result of a first-difference operation on the LO with a time offset equal to the (in many cases negligible) round-trip range delay. This provides significant cancellation of the low-frequency components of phase noise in the master oscillator. However, for a BSAR system, the separation of the transmitter and receiver results in additional phase noise between the two systems instead of cancellation. Thence, the LO frequency stability requirement is much more stern in the bistatic case than monostatic SAR.

Weiss [42], after reviewing typical requirements for several bi-static radar missions, arrived to the conclusion that for time accuracy, or synchronization a typical requirement is a tenth of the transmitted compressed pulse width.

$$\delta t = \frac{\tau}{20\Delta t_{update}} = \frac{1}{20B\Delta t_{update}} \quad (2.33)$$

Where B is the frequency bandwidth, τ , the pulse width and Δt_{update} , the update rate of clocks. If the bandwidth, $B=100\text{MHz}$, and the clock update rate, $\Delta t_{update}=30\text{s}$, then the time stability has to be $\delta t \approx 1.67 \times 10^{-11}\text{s}$.

If the two clocks deviate too much, radar echoes could be lost due to the drift of echo sampling window. This case hardly occurs for current radars, however, each echo can be successfully received but be drifted because of clock timing jitter. That is, a scatterer at a specific range, at different azimuth positions, appear in other range bins. A typical requirement for BSAR is presented by Tian, Weiming et al. [43], based in the work of Cumming et al. [44]. From SAR imaging theory, they determine that the maximum quadratic phase error should be less than $\frac{\pi}{4}$, therefore:

$$\alpha < \frac{1}{f_c T_a^2} \quad (2.34)$$

Being α the frequency drift rate, f_c the central frequency and T_a the aperture time. It shows that it is unbearable to image scenarios with large aperture times, unless both clocks are somehow syntonized and synchronized within this timespan.

2.3 Bistatic Inverse Synthetic Aperture Radar

The synthetic aperture in radar is, by definition, generated by the relative motion of the target with respect to the radar platform(s). In conventional SAR or equivalently in BSAR, this relative motion is created by the movement of the platform itself. For many applications, however, it is more convenient that instead the target changes its aspect angle with respect to the radar. This is indeed the primary requirement to generate an ISAR image. ISAR has been widely investigated due to its obvious stealthy applications, focusing on airplanes or vessels. It is also quite useful for constrained imaging scenarios, which is the case of deep-space remote sensing.

2.3.1 Signal Model and Doppler Scenario

In this subsection, the received signal model is derived. A generic situation is presented in [Figure 2.5](#). The reference system T_γ was chosen so that the axis γ is aligned with the line of sight (LOS) direction of an equivalent monostatic radar for the bistatic geometry. A bistatic angle β is formed by the radar-transmitter and the radar-receiver LOS $\hat{\gamma}_T$ and $\hat{\gamma}_R$ unit vectors. A 3D rotation can be translated into a single vector by means of the rotational vector, Ω_T . In this case, Ω_R is a sum of the translational and angular rotation vectors Ω_{tr} and Ω_a respectively. An object possesses a translational motion by changing its position with respect to the observer (in this case, a radar). The change in the orientation of the object towards the radar creates a rotational motion. The projection along the plane orthogonal to γ (LOS), will generate the relevant rotation data for the BISAR image reconstruction. The rotational vector associated with this projection is Ω_{eff} . The imaging plane is centered around the origin O (assumed to be the rotating and thereby focusing point) and a generic point-target is represented by the letter P , at the distance of $|\vec{r}_P|$ and oriented in the direction of $\vec{r}_P$. The vectors $\vec{r}_T$ and $\vec{r}_R$ are, respectively, the transmitter-origin and receiver-origin vectors. ϑ is the angle between the bistatic bisector and the projection of P in the γOv plane.

After motion compensation, an ISAR echo $S_R(f, t)$ can be written as [\[45\]](#) for a scatterer :

$$S_R(f, t) = H(f, t) \int_V \zeta(\gamma) e^{-j\phi(\gamma, f, t)} dy \quad (2.35)$$

where

$$H(f, t) = \text{rect}\left(\frac{t}{T_{obs}}\right) \text{rect}\left(\frac{f - f_0}{B}\right) \quad (2.36)$$

$$\text{rect}(x) = \begin{cases} 1, & \text{if } |x| \leq 0.5 \\ 0, & \text{if } |x| > 0.5 \end{cases} \quad (2.37)$$

Where f_0 the carrier frequency, B the transmitted signal's bandwidth, $\zeta(\gamma)$ the target's reflectivity function and V the volume where $\zeta(\gamma)$ is defined.

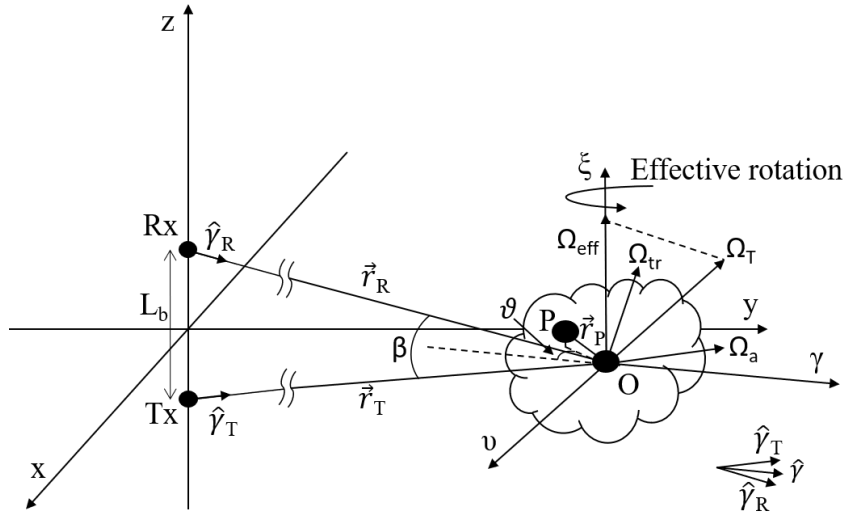


Figure 2.5: BISAR generic configuration.

The phase terms relative to the bistatic configuration can be written as:

$$\phi(\gamma, f, t) = 2\pi f \frac{|\vec{r}_T(t) + \vec{r}_P(t)| + |\vec{r}_T(t) + \vec{r}_P(t)|}{c} \quad (2.38)$$

Which is equivalent to [45]:

$$\phi(\gamma, f, t) = 2\pi f \frac{|\vec{r}_T(t)| + |\vec{r}_R(t)| + K(t)\gamma \cdot \hat{\gamma}}{c} \quad (2.39)$$

Where, approximately [46]:

$$K(t) = \left| \frac{\hat{\gamma}_T(t) + \hat{\gamma}_R(t)}{2} \right| = \cos(\beta(t)) \quad (2.40)$$

$$\beta(t) = \arccos(\hat{\gamma}_T(t) \cdot \hat{\gamma}_R(t)) \quad (2.41)$$

$$\hat{\gamma} = \frac{\hat{\gamma}_T(t) + \hat{\gamma}_R(t)}{|\hat{\gamma}_T(t) + \hat{\gamma}_R(t)|} \quad (2.42)$$

The Doppler shift can be divided in translation $f_{D_{Tr}}$ and rotational $f_{D_{Rot}}$ induced components.

$$f_D = f_{D_{Tr}} + f_{D_{Rot}} \quad (2.43)$$

The translational Doppler shift can be expressed as:

$$f_{D_{Tr}} = \frac{f}{c} \frac{d}{dt} [r_T(t) + r_R(t)] = \frac{f}{c} [v_T(t) + v_R(t)] \quad (2.44)$$

The rotation induced by Doppler is:

$$f_{D_{Rot}} = \frac{2f}{c} [\omega \times R_P(t)]_{Bisector} \quad (2.45)$$

The latter is usually referred to as Micro-Doppler. It is often characterized by a period frequency function of time and distributed around the translational Doppler frequency.

The pulse repetition requirements are associated with the maximum unambiguous range. In BSAR it is naturally dependent on the baseline length and is given by:

$$[r_T + r_R]_{max} = \frac{c}{PRF} \quad (2.46)$$

Monostatic configurations can produce an ISAR image by means of any available ISAR technique (an overview is given in the following section). Bistatic configurations, whilst employing the same signal processing techniques, require an attentive and meticulous adaptation for these standard techniques. Although the two received signal models differ only in their aspect angle and their radar-target focusing point distance, the bistatic ISAR image is inherently distorted by the bistatic geometry. This is revealed mathematically in Equation 2.40 by the term $K(t)$. Nevertheless, monostatic or bistatic ISAR images can and have been generated, even if its movement is not parametrized a priori [47][46][48].

2.4 Ambiguities in SAR and BSAR

2.4.1 Range Ambiguities

Range ambiguities in SAR are formed by the same mechanism as in conventional radar systems. In this case, the maximum unambiguous range defines the swath width W_s (Equation 2.47). This constraint is similar to the experienced by conventional radars.

$$W_s \leq \frac{c}{2PRF \sin \theta_{inc}} \quad (2.47)$$

Where θ_{inc} is the incidence angle, defined as the angle between the incident ray and the normal to the surface. In reality, even if the condition is respected, ambiguities will still exist due to echoes of targets within areas adjacent to the main swath or sidelobes of the range antenna pattern. The ambiguities resulting from this phenomenon appear in the ranges R_{amb} , equivalent to:

$$R_{amb} = R_0 + \frac{n \times c}{2PRF}, \quad n = \pm 1, \pm 2, \dots \quad (2.48)$$

2.4.2 Rectilinear Trajectory Azimuth Ambiguities

In the azimuth direction, ambiguities arise from insufficiently sampling the Doppler spectra. Let us consider the typical side looking strip-map SAR represented in Figure 2.6. The azimuth position

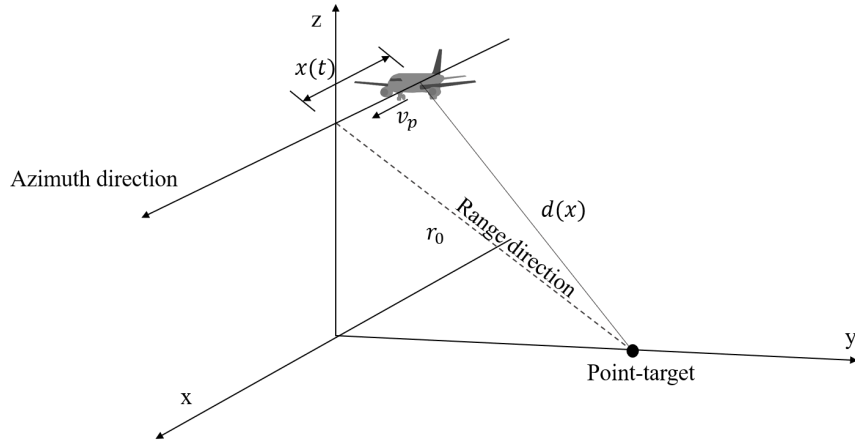


Figure 2.6: Side looking SAR rectilinear trajectory.

of the platform is fully described by:

$$r_0 = \sqrt{x_0^2 + y_0^2 + z_0^2} \quad (2.49)$$

$$x(t) = v_p \times t \quad (2.50)$$

Where (x_0, y_0, z_0) is the sensor position at the middle aperture point, v_p is the velocity of the platform and t is the time.

If a second order Taylor expansion is applied to the range equation for a point-target:

$$d(x) = \sqrt{r_0^2 + x^2} \approx r_0 + \frac{x^2}{2r_0} \quad (2.51)$$

Therefore, the azimuth phase variation is:

$$\phi_a(t) = -2 \times \frac{2\pi}{\lambda} r(t) \approx -\frac{4\pi}{\lambda} \left[r_0 + \frac{(v_p \times t)^2}{2r_0} \right] \quad (2.52)$$

Accordingly, the azimuth Doppler frequency is:

$$f_D(t) = \frac{1}{2\pi} \frac{d\phi_a(t)}{dt} \approx -\frac{2v_p^2 t}{\lambda r_0} \quad (2.53)$$

The maximum Doppler bandwidth is defined within the observation time T_{ap} . For the standard strip-map SAR [15]:

$$T_{ap} = \frac{L_{SA}}{v_p} \approx \frac{\lambda r_0}{L_{ant} v_p} \quad (2.54)$$

Replicas arise if the total Doppler bandwidth is not sampled, this is the so-called aliasing phenomenon. Sampling in the azimuth direction is determined by the *PRF* or the frequency at which

pulses are emitted. Therefore, the minimum operational *PRF* is constrained by:

$$PRF \geq B_D \quad (2.55)$$

$$B_D = f_D(t)|_{t=t_0-\frac{T_{ap}}{2}} - f_D(t)|_{t=t_0+\frac{T_{ap}}{2}} \approx \frac{2v_p}{L_{ant}} \quad (2.56)$$

The azimuth resolution is coarser if the *PRF* does not respect the above mentioned constraint as it is also determined by the Doppler bandwidth. In strip-map SAR [15]:

$$\delta_{cr} = \frac{v_p}{B_D} \approx \frac{L_{ant}}{2} \quad (2.57)$$

Which is according to the previously deduced in [subsection 2.1.2](#).

2.5 Image Formation Algorithms

Synthetic aperture radar techniques can make use of a focus filter to correct the distortions associated with the image formation process [15]. SAR image formation is inherently a two-dimensional process. The mathematical ideal method is the matched filtering (MF), performing as a maximum likelihood estimator for the reflectivity of targets in a scene. It can be implemented more efficiently as the backprojection algorithm (BPA)[49]. This is a two-dimensional time correlation techniques, as the back projection method that can be used to directly address the aperture resulting 2D transfer function. These methods, though precise, are very time-consuming, which is often an important resource for remote-sensing systems. For an image of N^2 pixels, the MF technique scales with $O(N^4)$ complexity and conventional BPA with $O(N^3)$.

On the other hand, frequency-domain algorithms, that separate the corrections to the signal's space-variant component into range migration and azimuth compression parts allow to explore the efficiency of the correlation methods available in the frequency domain at the expense of approximations. These typically achieve $O(N^2 \log_2 N)$ complexity, but may suffer from implicit algorithmic constraints, in exchange. The main differences among these algorithms fall within the implementation of the range cell migration correction (RCMC) or in the absence of it. The range-Doppler algorithm implements this procedure in the azimuthal frequency domain, which takes advantage of the intrinsic relation between range and Doppler history of any scattering object within the synthetic aperture. Compatibility across platforms and geometries, specifically ground applications, airborne and spaceborne require the implementation of more general algorithms. A factor of significant importance is the type of pulse compression, or modulation, that the radar system exploits. For an application intended to have higher Doppler tolerance, frequency modulations are, usually, better candidates. Earth-Observation applications, however, frequently entail working beyond the maximum unambiguous range limit due to the distance between the radar and the illuminated scene. To avoid the contamination of the SAR image with ambiguities, orbit customization (usually dictated by other criteria) and/or pulse repetition frequency (*PRF*) choice are crucial parameters [21]. *PRF*, however, is also often constrained by other requirements. Thus,

the complex nature of spaceborne SAR's design involves managing interference between sequentially transmitted pulses, in addition to ambiguities generated from the antenna's sidelobes. For a solution concerning this problem, orthogonal pulses properties bring several advantages [50]. In these cases, or in large MIMO SAR configurations, phase-coded pulses provide more flexible alternatives [51]. Also, waveforms other than chirps have been widely used by radars for planetary observations [52][53].

The most common approaches for on-board focusing of satellite SAR images are the Chirp Scaling (CS) algorithm [54] and the Range-Doppler (RD) algorithm [44]. The latter makes use of interpolation, that is usually a time-consuming operation, whilst the CS algorithm avoids it, by increasing the complexity of its implementation. Also, the CS is, inherently, a phase preserving algorithm. It assumes that the radar uses chirp modulation, i.e. linear frequency modulation. Additionally, range re-sampling and slant to ground range conversions can be conveniently incorporated in the RD algorithm. In terms of image quality, the fundamental difference is that in the RD case, the residual second term azimuthal phase component is neglected. The associated loss increases quadratically with range compression bandwidth and linearly with Doppler Centroid [55]. This, however, represents a negligible loss for the designed processor's intended application, that is not necessarily strict in terms of phase-preservation, unlike, for example, interferometric SAR. For spotlight imaging modes, the polar format algorithm (PFA) is also an usual choice [41]. It is relatively fast and is extremely useful for polar formatted data, due to its intrinsic formulation. It, however, does not correct for range curvature, thus imposing a scene-size limitation for non-distorted and focused data.

2.6 NEO Characterization

Pursuing more detailed knowledge of the physical characteristics of several representative Near Earth Objects (NEOs) has pushed the need to develop remote sensing techniques, since landing operations are usually more complex. It would also help the design and implementation of the mitigation techniques needed should an NEO threaten the planet Earth. Information on several aspects is necessary to fully characterize this extra terrestrial objects. Firstly, there is a difficulty on differentiating asteroids which will only come close to Earth and those that will actually hit. Depending on the number of observations, a more accurate estimation of the orbit is possible and, thus, a better trajectory and impact probability is delineated. Secondly, mass represents a measure of the kinetic, thus, impact energy. Thirdly, the size and density that relate to the structure and strength of an asteroid. Moreover, multiplicity and rotation period are also important characterizers. Surface properties as well, since they define the type of interaction possible with the NEO.

The most relevant data sources for the determination of orbit and impact probability are the space observatory Gaia mission from ESA, the NASA funded survey programs: MIT Lincoln Laboratory's Lincoln Near-Earth Asteroid Research (LINEAR), University of Arizona's Catalina Sky Survey (CSS) and Hawaii University's Panoramic Survey Telescope and Rapid Response System

(Pan-STARRS) [56][57]. Newly proposed solutions, such as the space-based infrared telescope NEOCam, as well as dedicated ground telescopes will be key for the next developments of the observations [57]. The determination of rotation, size and shape is also mainly monitored by NEOCam's mid-IR space mission and ground based optical/radar telescopes. Regarding surface properties, i.e. albedo, roughness and composition, photometry and spectroscopy methods are used for the characterization. Breakthroughs from Earth-based measured were enabled by observing different wavelengths and sky coverages by SMASS, MANOS, WISE (decommissioned in 2011 and reactivated as NEOWISE in Sept.2013) [58][59][60]. Density and internal structure are naturally related with the determination of electrical properties of such an object. To determine such parameters, usually one relies on educated guesses. Density is estimated from population while the structure information is typically a guess based on examples. However, for most population, a wide uncertainty characterizes our estimates. This is due to the scarcity of in-situ measurements and because the main source of relevant data is still radar and light-curves from telescopes. Radar echoes are extremely precise however, their power varies with the fourth root of the distance and the limited location of this stations pose relevant performance constraints to this option.

In the past, space missions have included a fly-by or rendezvous with an asteroid (see [61][1]), e.g. Galileo probe (NASA, 1989) to Jupiter that as a secondary mission included a fly-by to 951 Gaspra in 1991 and to 243 Ida in 1993; NEAR-Shoemaker (NASA, 1996) probe that flew-by 253 Mathilde in 1997 to 433 Eros 2000-2001; Deep Space 1 (NASA, 1998) to 9969 Braille in 1999; Stardust (NASA, 1999) a mission to recover interstellar dust and to investigate the comet Wild 2 in 2004 and 5535 AnneFrank asteroid in 2002; Hayabusa (JAXA, 2003) to the S-type asteroid 25143 Itokawa in 2005, the first asteroid sample-return mission; Rosetta (ESA, 2004) to 2867 Steins in 2008 and to the largest asteroid visited, 21 Lutetia, in 2010; Chang'e 2 (CNSA, 2010) to 4179 Toutatis in 2012; and lastly Dawn (NASA, 2007) rendezvous mission to 4 Vesta in 2011 and to the dwarf planet 1 Ceres in 2015, that terminated operations in Nov. 2018.

Currently, a fleet of spacecrafts for asteroid observation is operational, in cruise or in development. Examples are the sample-return missions OSIRIS-REx (NASA, 2016) to the B-type asteroid 101955 Bennu reaching proximity in 2018 [62] with expected return in 2023 and Hayabusa2 (JAXA, 2014) to the C-type asteroid 162173 Ryugu in 2018, expected to come back to Earth in 2020 [63]. Following the steps of previous sample-return missions, OSIRIS-REx and Hayabusa2 are an essential landmark for our understanding of asteroids composition, complementing future space-based surveys, e.g. CASTAway [64].

Other future asteroid missions have been proposed or are in development phases. This is the case of the NASA/Discovery missions, Lucy (expected launch in 2021) to visit Jupiter's Trojan asteroids [65] and Psyche (expected launch in 2022) to the metallic asteroid 16 Psyche [66]. A dual mission AIDA to the asteroid 65803 Didymos is expected to be launched in 2021 and 2023 [7].

Despite the fact that several asteroids have been subjects of close-by studies, the internal structure was never directly measured for any asteroid. Until now, it is only possible to infer what might

be their composition. However, considerable uncertainty remains regarding the internal structure of asteroids, even already visited ones, e.g. Itokawa [67]. Observed surface properties differ even within the same type of asteroids, e.g. Eros and Itokawa, revealing information about the regolith in their surfaces. Several incognito related to asteroids bulk constituents and regolith, porosity and homogeneity, relevant to understand the evolution of our solar system, remain unsolved. As a result, our current knowledge of asteroids would noticeably benefit from further close-by surface inspections and direct internal structure characterizations.

2.6.1 In-Situ Radar Systems for NEO and Planetary Characterization

To observe the NEO surface features, common optical imagery or lidar [62] provide high-resolution options. Moreover, thermal infrared observations supported the existence of regolith on asteroid surfaces. Nevertheless, to characterize the interior of a small airless body from sub-meter to a global scale, radar is certainly the most mature technique [1].

Future subsurface radar systems for asteroid characterization inherit valuable lessons from other NEO classes or planetary remote sensing missions. For instance, MARSIS was a multifrequency orbital sounding synthetic-aperture radar instrument contained onboard ESA's Mars Express [68]. It operates at an altitude of 250 to 800 km and in its subsurface mode, with operational frequencies ranging between 1.3 and 5.5 MHz. The free-space range resolution of the instrument was roughly 150 m. The MARSIS instrument was apparently capable of imaging over 1km within the ice-rich deposits beneath surface of Mars, probably imaging the basalt contact.

The CONSERT experiment on-board ESA's Rosetta mission had, as a primary goal, to investigate the interior of 67/P Churyumov-Gerasimenko comet [69]. Long-wavelength radio-waves (in the range of 86-94 MHz) were transmitted and received from a lander and an orbiter (Rosetta) bistatic radar configuration. Using pseudo codes and a ping-pong technique, the orbiter could accurately estimate, when the comet was inserted in the propagation path, the additional delay of a wave traveling through its interior. From the group delay of the main path, the mean permittivity of the comet nucleus was estimated. Thus, it was possible to derive electrical properties of the comet's interior constituent material. Size and homogeneity are obtained by analyzing the temporal and texture (volume scattering) characteristics of the received signal. The class of materials was identified from mean absorption measurements caused by the radiowave path loss within the comet [70]. This configuration exploits the low dielectric permittivity properties of comets (determined to be, in average, $\epsilon_r = 1.27$ [71]) that allow reasonable signal-to-noise ratio to be detected at the orbiter. Notwithstanding, the geometry was an important constraint in this scenario, since the lander position was not trivial to determine. The required triangulation was highly dependent on the accuracy of the Rosetta's orbit estimation, signal processing and re-synchronization processes resulting in RMS standard deviations of respectively 11 to 16m, 0.8m and 3.4m for the lander location [72].

A pertinent overview of the science requirements for observations of asteroid interior and regolith is given by Henrique et al. in [1]. The authors suggest that a bistatic (lander and orbiter configuration, inherited from CONSERT/Rosetta) or monostatic high frequency synthetic aperture

radar, as shown in Figure 2.7, are possibilities for future asteroid missions, namely for AIM/AIDA mission (currently called Hera).

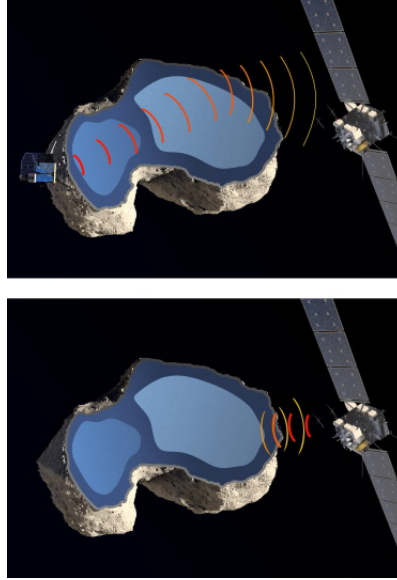


Figure 2.7: Bistatic (top) and monostatic (bottom) radar configuration for asteroid observation.

Herique et al. provide the results of simulations for a meter resolution in 3D with a dynamic range better than 20 dB (ambiguity ratio 20 dB) after 10 acquisitions in the monostatic case (operating at frequencies from 300 to 800 MHz). For the bistatic, less power is needed since the propagation path is reduced. The proposed frequency is also lower. However, the resolution is significantly coarser.

In [73], an overview and a discussion of the ambiguity and radar geometry as well as synthetic aperture parameters for the system proposed in [1] applied to the binary asteroid system Didymos is given. The operational scenario for the monostatic radar is constrained by link budget to 10 km of nominal distance and an operational scenario of 1 km up to 35 km. The movement of the satellite along the direction of the orbit of Didymos secondary forms a rectilinear synthetic aperture. Then, combining several passes of Didymos secondary and a few mm/s along the direction orthogonal to the one of the previously described movement allow the 3D tomography operation. The satellite placement out of the equatorial plane resolves some of the North-South ambiguity.

2.6.1.1 DART and Hera missions

Didymos is the target asteroid of the Asteroid Impact and Deflection Assessment mission (AIDA) mission. AIDA is an international collaboration between NASA and ESA, that are responsible for the Double Asteroid Redirection Test (DART) and Hera missions, respectively. Howbeit independent, both missions are mutually supporting each other in the first ever mission to a binary asteroid system [7][74].

	<u>Bistatic Radar</u>		<u>Monostatic Radar</u>
	Orbiter	Lander	
Frequency (nominal)	50 – 70 MHz		300~800 MHz
Frequency (extended)	45 – 75 MHz		up to 3 GHz
Signal modulation	BPSK		Step frequency
Resolution	10 – 15 m (1D)		1 m (3D)
Polarization	Circular (AIM)	Linear (Mascot)	Tx: 1 Circular Rx: OC and SC
Tx power	12 W		20 W
Pulse repetition	5 s		1 s (typical)
Sensitivity	Dynamic = 180 dB		$NESZ = -40 \text{ dB m}^2/\text{m}^2$
Power max/mean	50 W/ 10 W	50 W/ 10 W	137 W/ 90 W
Typical Data	1 Gbit	0.3 Gbit	300 Gbit

Table 2.1: Main characteristics of the bistatic low frequency radar and the monostatic high frequency radar from [1].

DART is a NASA mission whose primary objective is to impact the small moon, Didymoon, of a binary asteroid system. The goal is to perform the first asteroid deflection test and observe the outcome from ground-based observatories [7]. Hera is an ESA mission whose objectives are: to determine the momentum transfer by the hypervelocity impact of DART and the resulting effects on Didymoon's surface; and to carry, deploy and operate the two CubeSats in interplanetary space (ASPECT and Juventas) along with a main spacecraft while performing a spectral characterization of a small body. Remarkably, it will perform close-proximity operations in the vicinity of the smallest asteroid ever visited. Radio science, seismology, gravimetry and volatile detection are among the secondary scientific objectives [7]. The European mission concept is illustrated in Figure 2.8.



Figure 2.8: Hera mission concept. Mother-ship orbits the asteroid system alongside APEX and Juventas CubeSats [75].

The following instruments form the payload of the different spacecrafts in Hera mission [7]. The asteroid framing camera, used for science imaging, guidance, navigation and control. It has

an image scale of approximately 1 m/pixel. Observations of Didymoon's surface, in particular its craters will be performed with down to a few cm/pixel resolution by two 6U cubesats. The 3-D shaping of Didymoon's surface, the asteroid's surface topography (highlands, ponds and small scale features) are among the requisites that a LIDAR in the essential payload has to fulfill. Also, the instrument will support the study of surface chemical and mineralogical properties through measurements of intensity on albedo returned. Additionally monostatic high-frequency radar described in [Table 2.1](#), whose mission is to map the spatial variation of the regolith texture was proposed to fly aboard the Juventas CubeSat. Its requirements entail obtaining information on surface and sub-surface layers up to a depth of 10 – 20 m. It is intended to also support bi-static radar measurements offering better resolution and sensitivity (at frequencies in the S-band of around 2.5 to 3 GHz) compliant with Arecibo and Goldstone ground stations.

2.7 Summary and Main Conclusions

From the previous exposed content it is possible to extract some pertinent conclusions to guide this dissertation.

- Multiple small spacecraft configurations are starting to be adopted in deep space missions.
- Radar signal processing techniques have achieved maturity. In particular, bistatic synthetic aperture radar can enhance imaging detail with respect to a mono-static configuration case due to exploration of different types of scattering from objects/materials.
- The performance of bistatic radar is mainly geometry dependent. Bandwidth increases resolution, but poses a constraint to clock stability for synchronization.
- The interior of an asteroid was never directly measured.
- A SAR configuration for 3D imaging was already developed and tested for other satellite missions.
- The possibility of performing asteroid topography and tomography, tightly integrated with inter-satellite communication systems, remains unstudied.

Chapter 3

Radar Geometries for NEOs Surface and Subsurface Investigation

The necessary knowledge and the state of the art solutions that address the same problem as this dissertation, were exposed on the previous chapter. Considering this, an overview of the background related to surface and subsurface scattering of radar signals is presented. Additionally, the transition from state-of-the-art solutions to the proposed one is detailed in the final sections of this chapter.

Asteroids present an important section of near Earth orbiters (NEOs) and it is very likely that in the future they are mined for materials. Extracting information from its subsurface would also be extremely beneficial for our understanding about our Solar System. Additionally, the majority of asteroids in the asteroid belt possess radar properties that might enable its exploration with an adaptation from conclusions of this thesis. Therefore, asteroids were the NEO selected as a case-study for this thesis.

3.1 Asteroids in Near-Earth Orbits

The process of transformation of protoplanetary particles into planetesimal or planetary sized bodies is still puzzling. Near-Earth asteroids are essential to our understanding of the history and formation of the Solar System [43][76]. In 1973, a simple lettered classification system for asteroids was developed by the astronomers Chapman and Morrison based on narrow-band spectrophotometry with polarimetric and radiometric albedo measurements [77]. They supported the conclusion that asteroids fragments found on Earth were non-representative of the observed population by finding a correlation between these properties and the respective asteroid probable composition. Earlier classifications were based only on reflectance properties which only enabled the differentiation between "darker" carbonaceous and "brighter" rocky types. More recently, during the second phase of the Small Main-Belt Asteroid Spectroscopic Survey (SMASSII), 1447 asteroids were analyzed by Bus and Binzel with a higher spectral resolution howbeit disregarding albedo [78]. It created a basis for the taxonomic Bus-DeMeo classification. Using principal component

analysis and visible features to characterize the asteroid received spectrum in visible and infrared wavelengths the study expanded and clarified the previous classification [79]. The 25 identified taxonomic types key are visually summarized in the web-based Bus-DeMeo classifier [80] into: S-Complex, C-Complex, X-Complex and End Members. The first three categorizations correspond to siliceous (stony), carbonaceous and metallic objects, respectively. The later correspond to rarer identified members with more extreme spectral signatures.

Binzel (et al.) have estimated that 2/3 of NEOs fall in the S or Q-complex category [81], being roughly 40% belonging to the first taxonomic type and 25% to the later. Regarding Mars crossers, approximately 65% are identifiable as belonging to the S-complex category. In fact, despite its abundance in near-Earth orbits, the Q-complex type (also ordinary chondrite-like¹) remain unobserved in the main belt [78]. S-type is the typical classification for objects with absorption features due to pyroxene and olivine [83], which are characterizers of ordinary chondrites (OC). In fact, the link between S-type asteroids and ordinary chondrites has been long discussed and a growing data set and source region models continues to build this connection [81]. Recent studies on the diversity of the NEA populations and samples from Itokawa revealed that OC are the dominant minerals in most asteroids and their characteristic absorption features can be used to determine their abundances [84][85].

Ordinary chondrites are classified into the H, L and LL chemical groups based on composition and mineralogical parameters such as mol% Fa of olivine and mol% Fs of low-Ca pyroxene [84]. H chondrites possess the highest concentration of iron and metal while LL chondrites possess the lowest. L chondrites are intermediate between H and LL in these properties, but somewhat closer to LL [86]. An illustration of the modeled cross-sectional planes of these asteroids and their nucleus, mantle and crust, depending on their parent main body composition, is represented in Figure 3.1.

Despite containing similar material, asteroids present a much lower density than its meteorite analogs [88]. As to the reason behind it, there is no certainty. Observed features from [67] also suggest that Itokawa is composed of a few hundred meter blocks of fractured shards with about 20% porosity with a maximum of 26%. The regolith covers approximately the first half meter and a porosity of about 35-40%. However, other explanations for the observed features are possible. It is also viable that one rubble pile lobe is attached to a monolithic lobe [1]. Hence, to resolve ambiguities, there is a need for direct measurements of the subsurface properties.

3.1.1 Didymos 65803, A Binary Asteroid System

Didymos 65803 (1996 GT) is an Apollo NEO², first discovered in 1996 by Joe Montani on a Spacewatch program [89]. In 2003, Arecibo radio telescope observations confirmed the existence of a secondary body [90]. Hence its name Didymos, Greek for "twins".

¹Chondrites are stony (non metallic) meteorites typically composed by chondrules (spherical, millimetre sized, silicate formed by flash heating within the solar nebula)[82].

²Earth-crossing NEAs with semi-major axes larger than Earth's (named after asteroid 1862 Apollo).

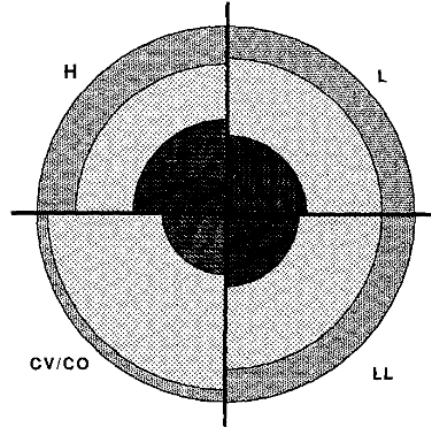


Figure 3.1: Schematic cross-section of four different asteroids originary from main bodies with composition and mineralogies corresponding to H,L, LL and CV/CO chondrites². Relative volume fractions of: FeNi FeS core, olivine mantle and pyroxene-feldspar crust [87].

² CV-CO are contained in the carbonaceous chondrite group.

The primary Didymos body was initially classified as belonging to the Xk taxonomic type[78]. However, aggregating data from the Spectroscopic Investigation of Near Earth Objects (SINEO) to the previously obtained by SMASSII, de León et al. categorized the asteroid as S-complex [91]. More recently, Dunn et al. associated its spectral response to an L/LL ordinary chondrite-like composition [84]. Didymos binary asteroid system's physical properties and orbital parameters are summarized in Table 3.1.

Heliocentric semi-major axis	~ 1.64 AU
Heliocentric eccentricity	~ 0.384
Heliocentric inclination (ecliptic)	$\sim 3.41^\circ$
Primary rotation period, P_p	(2.26 ± 0.0001) h
Secondary orbital period, P_{orb_s}	$(11.920 + 0.004/-0.006)$ h
Separation between primary and secondary, S_{PS}	$1.18 + 0.04-0.02$ km
Mean diameter of the primary, D_p	0.780 km $\pm 10\%$ (3σ)
Mean diameter of the secondary, D_s	(0.163 ± 0.018) km
Secondary (shape) elongation a_s/b_s and b_s/c_s	1.2 (Assumed)
Bulk density of the primary, ρ_p (Secondary assumed to be similar)	2100 kg $m^{-3} \pm 30\%$
Total system mass, $M_T=M_p+M_s$	$5.28 \pm 0.54 \times 10^{11}$ kg

Table 3.1: Known physical properties of Didymos binary system. Heliocentric orbital elements given at epoch 2457000.5 (2014-Dec-09) [92][90][93].

From combined radar and photometry data, the binary system was estimated to be composed of a more elongated (assuming an ellipsoidal-cluster model) secondary body (informally called Didymoon) and a more polyhedron-like primary body, as represented in Figure 3.2. The secondary body is assumed to be in a tidal lock or 1:1 spin-orbit resonance, i.e., its rotation is synchronous

with its revolution around the primary, $P_S = P_{orbs}$ [92]. By analyzing thousands of light-curves and data retrievals from deep-space explorations missions such as Hayabusa2 or OSIRIS-REx as well as standard terrestrial granular media, Walsh has concluded that evidence points at a rubble-piled structure for most asteroids [94]. In other words, gravitational bound piles of rocks. This has, in fact, been used as a standard in the modeling of these systems and appears to fit our current knowledge regarding these quasi-planetesimal structures [95]. In particular, Didymos primary rubble-pile could maintain its shape at the observed spin rate within the observed bulk density uncertainty with a highly size-heterogeneous configuration, using the model developed by Zhang et al. [95]. In an imaging radar context, this is most likely observable as different interfaces for a given image slice, as in a classical ground penetrating radar (GPR) image. Such as the different type of materials, also the void (or filled with a different type of smaller aggregates) spaces in-between the largest components can be differentiated.

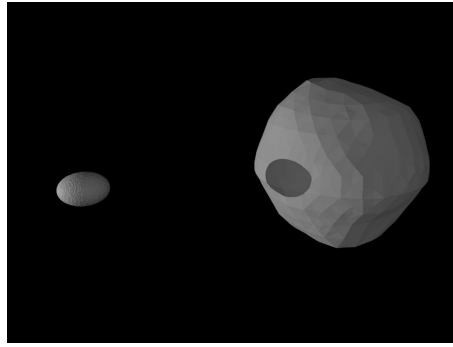


Figure 3.2: Didymos and Didymoon preliminary shape model from combined radar and photometry 2003 data [92].

As discussed in [subsubsection 2.6.1.1](#), the Didymos binary asteroid has been the focus of considerable research for the purpose of an on-development deep space mission. This has the advantage that its physical properties have been detailed within acceptable margins for the design of feasible real systems. Being a binary system itself is attractive to test new deflection techniques, but can also benefit other purposes, such as exploring in-situ deep-space novel observation techniques. Furthermore, to study an S-complex asteroid ensures that the results from this study can be applicable to a large fraction of the likeliest potential. Its likely resemblance with L/LL ordinary chondrites in terms of composition, brings yet another advantage for the use of radar imaging techniques. A high concentration of metallic objects, which are usually quite reflective, would undermine the ability of imaging lower scatterers and/or penetrating in the subsurface. Didymos primary, similarly to Didymoon, is most likely a "gravitational bound pile of rocks". Therefore, estimated porosities of S-type asteroids at close range [67] and Didymos [1], complemented by a structural arrangement such as described in [87][95] and illustrated in [Figure 3.1](#) (L/LL chondrites), enables, with acceptable resolution, the penetration within the sub-surface layers along with a topographic mapping of the surface. For the above mentioned reasons, Didymos was chosen as a target asteroid of this dissertation's study.

3.2 Surface Scattering of Radar Signals

3.2.1 Wave Theory

For completeness, an introduction to basic properties of electromagnetic waves is presented. There is no intent to insult anyone's intelligence, but rather to clearly define the framework of ideas for subsequent discussions. An electromagnetic (EM) wave is a self-propagating wave consisting of electric and magnetic fields whose intensities follow a sinusoidal pattern. The direction of propagation of an EM wave is perpendicular to both of these fields. In turn, they are perpendicular among themselves. The distance from one crest to the next crest of the sinusoidal pattern is said to be the wavelength λ of such a wave. Its frequency f is the number of waves that passes a given point per unit time.

Let us consider the complex notation for an EM field described by a plane and monochromatic wave:

$$\vec{E}(\vec{r}, t) = \vec{E}_0 e^{j(\omega t - \vec{k} \cdot \vec{r} + \phi)} \text{ [V/m]} \quad (3.1)$$

$$\vec{H}(\vec{r}, t) = \vec{H}_0 e^{j(\omega t - \vec{k} \cdot \vec{r} + \phi)} \text{ [A/m]} \quad (3.2)$$

The EM field is characterized by the its electric field $\vec{E}$ and magnetic field $\vec{H}$ vectors. Where the angular frequency is $\omega = 2\pi f$ and ϕ is a phase shift. The amplitude $\vec{E}_0$ (analogously to the magnetic field case) is given by:

$$\vec{E}_0 = E_0 \hat{u}_x + E_0 \hat{u}_y + E_0 \hat{u}_z = E_0 \hat{p}_e \quad (3.3)$$

Being the wave vector $\vec{k} = k_x \hat{u}_x + k_y \hat{u}_y + k_z \hat{u}_z = k \hat{a}_n$ and the position vector $\vec{r} = x \hat{u}_x + y \hat{u}_y + z \hat{u}_z$. The direction of propagation is given by $\hat{a}_n$ and k is the so-called wavenumber. A wave is said to be polarized in the direction of its electric field, or polarization vector $\hat{p}_e$. By considering Maxwell equations in a lossless linear, homogeneous, isotropic (LHI) medium, it is possible to relate the electric and magnetic fields in a wave equation of the Alembert type [96].

$$\nabla^2 \vec{E} = -\frac{1}{v^2} \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \quad (3.4)$$

$$\nabla^2 \vec{H} = -\frac{1}{v^2} \frac{\partial^2 \vec{H}}{\partial t^2} = 0 \quad (3.5)$$

Where a relation between the medium's electric permittivity ϵ and magnetic permeability μ determine the speed of the propagating EM wave, $v = 1/\sqrt{\epsilon\mu}$. These physical quantities are usually referred relatively to the free-space (where $\epsilon_0 \approx 1/(36\pi \times 10^9)$ F/m, $\mu_0 = 4\pi \times 10^{-7}$ H/m, for which the speed (of light in vacuum) is $v = c = 299792458$ m/s) case. For that, the concept of relative electric permittivity ($\epsilon_r = \epsilon/\epsilon_0$) and relative magnetic permeability ($\mu_r = \mu/\mu_0$) is used. For harmonic solutions, a physical meaning can be given to the wavenumber. It is the spatial

frequency of a wave, measured in cycles per unit distance or radians per unit distance, since

$$k = \omega\sqrt{\epsilon\mu} = \frac{2\pi}{\lambda} = -j\gamma \quad (3.6)$$

Where γ is the propagation constant of the wave. A refractive index can also be defined as:

$$n = \sqrt{\epsilon_r\mu_r} = \frac{c}{v} \quad (3.7)$$

Also, from Maxwell equations, the concept of wave impedance arises. It can be shown that for lossless LHI media, the wave impedance η is:

$$\eta = \sqrt{\frac{\mu}{\epsilon}} \approx 120\pi\sqrt{\frac{\mu_r}{\epsilon_r}} \quad (3.8)$$

Resulting from the relationship between magnetic and electric field intensities.

$$\vec{H} = \frac{1}{\eta}(\hat{a}_n \times \vec{E}) \quad (3.9)$$

A medium is said to be dispersive when the dielectric properties and therefore refractive index of a medium vary with frequency. If the medium absorbs energy from the wave, the electric permittivity and consequently the refractive index constant become complex (real + imaginary). The real part is related with the wave velocity and the imaginary part to the wave absorption. This is equivalent to saying that the media is lossy. If the damping of the vibrating dipole moments is not considered in the dielectric constant, in a LHI medium, then:

$$\epsilon = \epsilon' - j\epsilon'' = \epsilon'(1 - j\tan\delta) = \epsilon'\left(1 - j\frac{\sigma}{\omega\epsilon'}\right) \quad (3.10)$$

$$n = n' - jn' \quad (3.11)$$

Where $\tan\delta$ is the medium's loss tangent, ϵ' and ϵ'' are, respectively, the real and imaginary part of the permittivity ϵ and σ is the conductivity. If n varies with frequency, a medium is said to be dispersive, which is the equivalent of saying that a lossy medium is dispersive. The propagation constant is, now:

$$\gamma = \alpha + j\beta = j\omega\sqrt{\mu\epsilon}\sqrt{1 - j\frac{\sigma}{\omega\epsilon}} \quad (3.12)$$

Attenuation resulting from lossy media is incorporated in the constant of attenuation α and β is the phase constant, that dictates the phase velocity of the wave, which, in the general case, depends on ω . A useful definition for comparing the behavior of diverse media or even the same medium at different frequencies is the penetration depth δ . In the most general case [97],

$$\delta = \frac{1}{\alpha} = \frac{1}{\omega\sqrt{\mu\epsilon}} \left[\frac{1}{2} \sqrt{1 + \frac{\sigma^2}{\epsilon^2\omega^2}} - 1 \right]^{-1/2} [m] \quad (3.13)$$

As it is possible to infer, the penetration depth decreases with an increase in frequency. It is however important to denote that in any way this is a physical quantity that represents the exact penetration depth of a wave, given that it intrinsically depends on its energy.

Indeed, in radar we are usually interested in the energy transported by a given wave. The Poynting theorem based upon the work of Maxwell's theory of energy can be translated into an integral form, thereby resulting

$$\oint \vec{S} \cdot d\vec{s} = -\frac{\partial}{\partial t} \int_V \left(\frac{\mu}{2} |\vec{H}|^2 + \frac{\epsilon}{2} |\vec{E}|^2 \right) dv - \int_V \sigma |\vec{E}|^2 dv \quad (3.14)$$

Where $\vec{S}$ is the Poynting vector and it represents the instantaneous power density per unit area normal to the direction of electromagnetic wave propagation, usually expressed in units of Watts per square metre.

$$\vec{S} = \vec{E} \times \vec{H} \quad [W/m^2] \quad (3.15)$$

The instantaneous or average flux-density P_{med} in a given area A , are obtained by integrating $\vec{S}$ over a given target area, as follows.

$$P_{avg}(\vec{r}) = \int_A S_{avg}(\vec{r}) \cdot dA \quad [W] \quad (3.16)$$

Where S_{med} is the instantaneous power density per unit area integrated over the time T . Which, for transverse electromagnetic (TEM) waves (normal behavior in unguided media), yields a constant value. Only dependent on the electric field's magnitude and on the real part of the medium's wave impedance (which is purely real if the medium is lossless):

$$S_{avg} = \frac{1}{T} \int_T \vec{S}(\vec{r}, t) dt = \frac{1}{2} |\vec{E}|^2 Re \left\{ \frac{1}{\eta_*} \right\} \hat{a}_n \quad (3.17)$$

For a radar system, this expression leads to the radar equation, derived in [subsection 2.1.1](#).

The interaction of electromagnetic radiation with matter is simply described by three different mechanisms. The incident radiation upon a surface must either be transmitted through it, reflected from the surface, or be absorbed. The absorption is, as aforementioned, related with the losses of such media, i.e. the surface is opaque to the incident radiation. Transmission represents portion the incident wave that passes through matter. Reflection occurs when the surface is smooth relative to wavelengths, usually determined using the Rayleigh roughness criterion [98]. Mirror-like surfaces are called specular reflectors. On the other hand, rough surfaces relative to wavelengths create scattering (diffuse reflection). In these cases, EM waves velocity and wavelength are not affected but the wave is instead redirected more unpredictably. From boundary conditions for the electric and magnetic fields at an interface between medium 1 and medium 2, the expressions of the Fresnel reflection $r_{1,2}$ and transmission $t_{1,2}$ coefficients can be derived in both vertical and horizontal polarizations. In other words, in case the electrical field is perpendicular to the incidence plane and in case it is parallel. Circular or elliptical polarizations are a combination of both components. Since for most dielectric media (excluding ferromagnetic material, $\mu_r = 1$) then, for

smooth surfaces, in the horizontal polarization:

$$r_{1,2}^H(\theta_i) = \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} = \frac{\sqrt{\epsilon_{r1}} \cos \theta_i - \sqrt{\epsilon_{r2} - \epsilon_{r1} \sin^2 \theta_i}}{\sqrt{\epsilon_{r1}} \cos \theta_i + \sqrt{\epsilon_{r2} - \epsilon_{r1} \sin^2 \theta_i}} \quad (3.18)$$

$$t_{1,2}^H(\theta_i) = \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_i + n_2 \cos \theta_t} = \frac{2\sqrt{\epsilon_{r1}} \cos \theta_i}{\sqrt{\epsilon_{r1}} \cos \theta_i + \sqrt{\epsilon_{r2} - \epsilon_{r1} \sin^2 \theta_i}} = 1 + r_{1,2}^H(\theta_i) \quad (3.19)$$

And for the vertical polarization:

$$r_{1,2}^V(\theta_i) = \frac{n_1 \cos \theta_t - n_2 \cos \theta_i}{n_1 \cos \theta_t + n_2 \cos \theta_i} = -\frac{\epsilon_{r2} \cos \theta_i - \sqrt{\epsilon_{r1}} \sqrt{\epsilon_{r2} - \epsilon_{r1} \sin^2 \theta_i}}{\epsilon_{r2} \cos \theta_i + \sqrt{\epsilon_{r1}} \sqrt{\epsilon_{r2} - \epsilon_{r1} \sin^2 \theta_i}} \quad (3.20)$$

$$t_{1,2}^V(\theta_i) = \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_t + n_2 \cos \theta_i} = \frac{2\sqrt{\epsilon_{r1} \epsilon_{r2}} \cos \theta_i}{\epsilon_{r2} \cos \theta_i + \sqrt{\epsilon_{r1}} \sqrt{\epsilon_{r2} - \epsilon_{r1} \sin^2 \theta_i}} = \frac{n_1}{n_2} [1 - r_{1,2}^V(\theta_i)] \quad (3.21)$$

Where n_i and ϵ_{ri} are the i^{th} medium refractive index and electrical permittivity. The local incidence angle θ_i is defined by $\cos \theta_i = -\hat{k}_i \cdot \hat{n}$, being $\hat{n}$ the vector normal to the surface. The transmission angle θ_t and the reflection angle θ_r , also defined normal to the surface, can be described by Snell-Descartes laws and thus:

$$\theta_r = \pm \theta_i \quad (3.22)$$

$$n_2 \sin \theta_t = n_1 \sin \theta_i \quad (3.23)$$

The incident electric field at the interface E_{i0} , is related to the reflected E_{r0} and the transmitted E_{t0} , simply by:

$$E_{r0} = r_{1,2} E_{i0} \quad (3.24)$$

$$E_{t0} = t_{1,2} E_{i0} \quad (3.25)$$

As a note, often for rough scattering, a slightly different expression is given for the transmission coefficient, because $r_{1,2}^V$ is replaced by $-r_{1,2}^V$ [96]. An interesting property is that, at media boundaries, more energy is reflected when the difference in electrical permittivities is higher. The same thought can be expressed by thinking in terms of the wave impedance. Energy tends to transmit well in media with similar wave impedances and otherwise, the contrary tends to occur. Intuitively, in radar, the reflected (in most cases scattered) wave is the obtained measurement.

A more detailed derivation of formulas contained in this subsection as well as pertinent literature concerning electromagnetic wave theory can be consulted in one of the following references [97][98][99].

3.2.2 Propagation of Radar Signals

When a radar signal scatters from a given surface, its nature is affected by the properties of the surface itself. In remote sensing applications where surface properties are of interest, the actual measurements is given by the change in the signal relative to a calibration source. Surface spectral imprint is therefore embedded in the spectrum of the reflected wave.

When an electromagnetic wave propagates through a multi-layered media, the reflected wave contains contributions not only respective to the reflected energy from the first boundary, but it also contains contributions from the other layers' reflections (and reflection loops). Fortunately, in radar, these contributions are associated with a time-stamp. Therefore, the different layer contributions can usually be isolated, providing their size is larger than the radar's resolution.

Different types of scattering were conveniently determined for natural surfaces and objects. The already mentioned specular and quasi-specular, associated with smooth surfaces. Using the Lambertian scattering model, to an observer, an object appears the same regardless of the observer's angle of view [98]. That is naturally often not observed in natural surfaces and only valid as a first approximation. In general, an object or in radar terms, a target's reflectivity, is a function of the incident and observed angle. Backscattering refers to the portion of the incident EM wave that is reflected back to its incoming direction. By opposition, forward scattering is related to the portion scattered in the same direction as the incident field (different from the transmitted wave).

In monostatic radar, the measurements translate the backscatter of a given target. Thus, it is evident that bistatic radar, by definition, allows to gather different information about the same analyzed scenario. Furthermore, at steep angles (incidence angle less than 20 degrees), in rough surfaces, most of the emitted pulse is scattered in random directions so that the total backscatter measured by the antenna is lower than from a smooth surface at the same angle [98]. Changing the incidence angle and comparing how the backscatter changes with different angles allows to map distinct types of surfaces. Equivalently, by keeping the illumination angle steep and varying the bistatic angle it is possible to determine different features of surfaces. As a side-note, targets with dimensions close to the incident waves wavelength (typically ten times bigger or smaller) exhibit, dominantly, the so-called resonance or Mie scattering [100] and cause the propagating wave to lose coherence. Whereas as encountering targets with dimensions much smaller than the wavelength, waves propagate as in perfect homogeneous media. In these cases, the so-called Rayleigh Scattering predominates.

In plain English, aggregates of sand and a monolithic structure would exhibit similar behaviors. Specifically, low signal spreading and similar texture, which in an imaging context would result in a clear interface. Permittivity, spatial variability, signal spread from the larger blocks and other gathered data would then make possible to constraint the measurements. Hence, an unbiased extrapolation of the interior of complex structures like asteroids, it is important to explore different acquisition geometries.

Two fundamental scattering properties of a target are its reflectivity and the reflectance. Reflectivity measures the fractional amplitude of the reflected electromagnetic field while reflectance

refers to the fraction of incident electromagnetic power reflected at an interface. Thus, reflectance is the square of the magnitude of the reflectivity, implying that the first is a real number, whilst the latter can be complex. These two concepts are therefore intrinsically embedded in the definition of a target's radar cross section (RCS), presented in [subsection 2.1.1](#), which is, of course, also frequency-dependent.

The operating frequency is thus an essential tuning parameter for a radar performing a specific function. For example, a choice to detect ice layers within the Earth's surface would necessarily be a lower frequency than the chosen to detect rain droplets. At the same time, frequency is also constrained by [Equation 3.13](#) (qualitatively) as by other factors. Indeed, a more detailed study about this parameter choice will be presented bearing NEO characterization in mind.

An overview of the microwave frequencies used conventionally by radars is shown in [Figure 3.3](#), providing a quantitative sense about the possible working wavelengths of the proposed system (in vacuum). As detailed, radar operating wavelengths range from a few mm to m. Larger

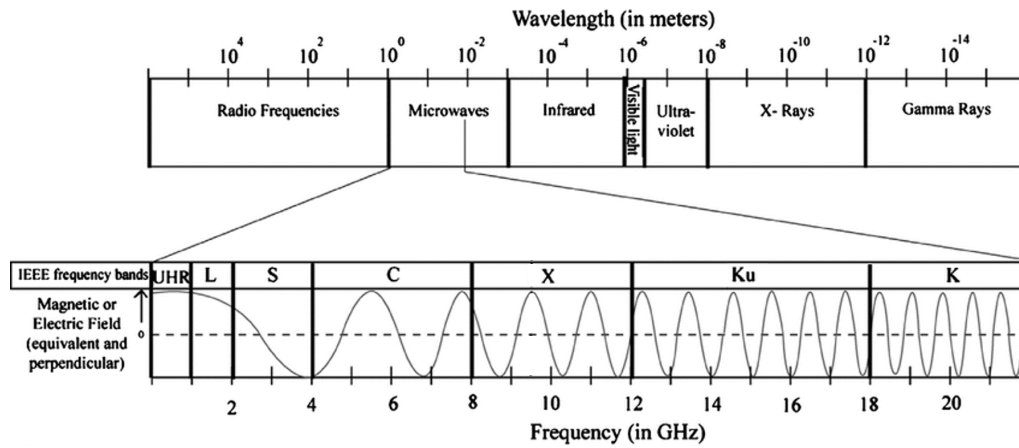


Figure 3.3: Electromagnetic spectrum and radar bands (frequency and wavelength in vacuum) [101].

wavelengths are equivalent to coarser azimuth resolutions for conventional radars or non-stripmap SAR's (refer to [Equation 2.13](#) and [Equation 2.14](#)).

Ground penetrating radars (GPRs) are usually set to operate close to the Earth's surface. This is due to the power budget challenges to penetrating the ground itself. In an asteroid observation scenario, landing a probe successfully in its surface is not a straightforward task. Hence, the GPR concept is more prone to be applied using orbital remote sensing techniques. The surface characteristics, such as landmarks (craters, ponds, etc) determined with about 1m of resolution allow to determine the mass of Didymoon with the expected accuracy [7]. Furthermore, the size and mineralogy of the grains and macro-porosity can be associated with the spatial variation of the regolith texture. Radar geometries capable of the required high-resolution imaging are discussed in the following section.

To summarize, attenuation in a given surface is related to its electrical properties, such as its electrical permittivity, as seen in the previous subsection. Surfaces can be dispersive, i.e. its

electrical behavior changes with frequency. Moreover, the overall attenuation at a given frequency entails not only contributions from simple reflections but from scattering, which itself changes with frequency. Guiding attenuation models exist for the penetration in an S-type asteroid surface [1]. However, attenuation due to scattering itself in the asteroid case is hard to estimate. Notwithstanding, when the scatterers are numerous at a dimension comparable to the wavelength, attenuation becomes significant. Therefore, attenuation itself provides information about internal structure. This is clearly only valid for nearby examinations, where this subtle differences become relevant. As a result, the close-by characterization of an asteroid with an unknown internal structure certainly benefits from studies at different wavelengths. For a more detailed understanding of this trade-off, an example is provided. Following the definition for rock sizes based on Wentworth's work [102] from the authors of [92], "pebbles", "cobbles" and "boulders" represent surface particles with size ranges in intervals of 4 mm–6.4 cm, 6.4 cm–2.56 m, and >2.56 m. Frequencies in the range of 300-600MHz would be sensitive to cobbles with dimensions of close to half a meter. Frequencies closer to 3GHz would be able to detect the presence of small "cobbles" or maybe even "pebbles", increasing the capability to characterize regolith.

3.3 Overview of Didymos surface and subsurface radar investigation

Some of the trade-offs between monostatic and bistatic radars are detailed in [section 2.2](#). In the considered application, the fact that high-resolution radar imaging requires a precise time synchronization naturally gives an advantage over a deep-space monostatic configuration. However, the exploration of different features of the scenario and a reduction in complexity and constraints associated with a simultaneous transmitter and receiver radar module appeal to the advantages of a bistatic configuration. Withal, trajectories to form the synthetic apertures necessary to obtain the required high-resolution and penetration are thoroughly exposed in this section.

This discussion will be directed towards the characterization process of the binary asteroid Didymos 65803 (1996 GT) for geometry-based concerns. Didymos primary and secondary asteroids will be hereinafter referred to as Didymos A and Didymos B for simplicity. Planned operations European component of the AIDA mission, summarized in [7] and details concerning [103].

Regarding the bistatic case, NEO subsurface remote sensing was successfully attempted in the past, as detailed in [subsection 2.6.1](#) or in [69]. It also has allowed the determination of a mean electrical permittivity and restrained the possible composition of the comet to a narrow set of possibilities [71]. In [73], a similar solution to image the subsurface of Didymos is proposed. This solution, however, has tight constraints regarding the landing location of the spacecraft or its orientation and it can take years to estimate accurate positions [72]. The availability of solar power is strictly dependent on the landing site. Howbeit, this cannot be restrained with absolute precision due to the uncertainty associated with the current knowledge about the asteroids surface characteristics. Under the assumption that other topologies could be explored to achieve subsurface penetration of a few meters with a close-to metric 3D resolution, an orbital solution was

considered.

3.3.1 Bistatic radar comprising satellites in the same orbit phased at 180° to one another

For completeness, let us consider exactly the same transmitter and receiver scenario as proposed in [69] and in the bistatic case from [73]. However, in this case, the role of the lander is fulfilled by one of the orbiters. Let us also consider that, in the simplest of forms, they both orbit the asteroid in the same orbital plane, at a same velocity V , separated by a bistatic angle of $\beta = 180$. One could draw an immediate correlation with a computerized tomography (CT) scan, if familiar with the procedure. CT scans are used to create images of organs, bones and other tissues. It uses X-Rays and combines several observations from different angles by moving the transmitter and/or receiver arrays, usually in a circular trajectory. The satellite situation resembles at least a rudimentary CT scan technique since, lately, rotating arrays of transmitters and receivers are typically used.

If one were to use Equation 2.28 to further characterize this radar topology, it is clear that the range and cross-range resolution becomes undefined using the conventional bistatic radar definition (as it was expected for $\beta = 180^\circ$).

$$\delta_r = \frac{1}{2} c \tau \sec(\beta/2) = \infty \quad (3.26)$$

$$\delta_{cr} = \frac{\sqrt{2} W_T W_R \sec(\beta/2)}{\sqrt{W T^2 + W_R^2}} = \infty \quad (3.27)$$

Indeed, a different approach might be useful in this particular radar configuration. In essence, it is equivalent to the simple transmitter-receiver situation in line-of-sight. The measurable quantities are delays, amplitudes and wave coherence. Moreover, radio waves do not leave the transmitter in a perfectly narrow beam, and are not received from a single tiny point. Fresnel ellipsoids (or zones) mathematically describe this physical phenomenon. To calculate the radius of the n th Fresnel zone on a surface perpendicular to the propagation path, the following equation holds as a good approximation [104].

$$F_n \simeq \sqrt{n\lambda \frac{R_1 R_2}{R_1 + R_2}} = \sqrt{\frac{n\lambda R}{2}} \quad (3.28)$$

Where $H = F_1$ is the height of the first Fresnel radius and $R_1 = R_2 = R$ is the equal distance between each spacecraft and the observed asteroid, as Figure 3.4 illustrates (not at scale). To note that the chosen configuration has equidistant satellites from Didymos primary or secondary since it yields the better resolution.

Assuming that the relevant reflected energy is contained within the first Fresnel zone, ambiguities would be governed by the volume of the first ellipsoid. Essentially, an object could be resolved within twice the first Fresnel radius $2H$. In other words, the incident beam in the surface of Didymos would illuminate regions that could arrive with the same delay at the receiver. This is easily understandable by considering the two extremes in one direction, at a distance H and

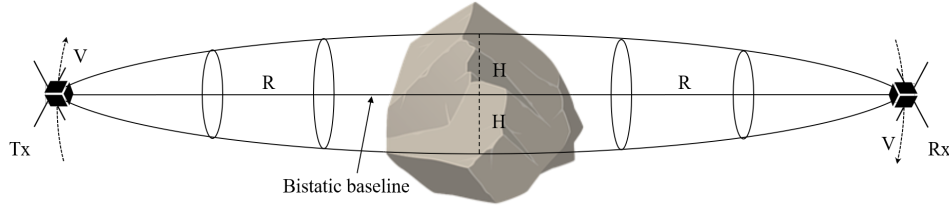


Figure 3.4: Bistatic geometry for characterizing Didymos (CT scan-like). Transmitter and receiver in the same orbit phased at 180° to one another, moving with an equal velocity.

noticing that the path lengths to the transmitter and to the receiver are equal, generating the same delay. CT scans, beside working at a few meters at most, make use of sharp X-ray beams. For example, at a distance of $R = 2m$, using the lowest frequency in the X-ray portion of the spectrum, 30 petahertz (3×10^{16} Hz), the resolvable distances are $2H \approx 0.28$ mm. Thereby being able to image small parts of the human body.

Most operations in the Hera mission will be performed at a distance of $R = 10$ km [7]. Thus, let us begin by considering a scenario where this experience could be co-existent with most of the planned course of action. For a frequency of 2.7 GHz and a distance of $R = 10$ km, the first Fresnel radius is $2H \approx 47$ m and for a frequency of 1 GHz at the same distance is $2H \approx 77$ m. This would be, of course, assuming that there is enough signal-to-noise ratio for a correct reception at the end of the link. Considering the Didymos system, this type of resolutions would roughly be admissible for Didymos A (whose Diameter is estimated to be about 780 m). To detect a 5% variation in the mean porosity along a propagation path equivalent to transversing Didymos A requires a resolution better than 60m. Whereas for the Didymos B case, a satisfactory resolution would be of 15 m.

The attenuation model from [1] for the Didymos asteroid was considered. Therefore, the path loss within the internal structure of the body L_{PLD} is:

$$L_{PLD} = 0.091f \sqrt{\epsilon'_r} \tan \delta d \text{ [dB]} \quad (3.29)$$

Where f is the operating frequency (MHz), ϵ'_r is the real part of the relative electric permittivity of the asteroid, $\tan \delta$ the loss tangent and d is the path within the asteroid (m). Based on Looyenga's mixture formula [1], for S-type asteroids without porosity, ϵ'_r ranges between 7 and 5 and the maximum loss tangent is $\tan \delta = 0.01$. Thus, considering Didymos' relative electric permittivity real part $\epsilon'_r = 5$ and a loss tangent of $\tan \delta = 0.008$, the attenuations for penetrating Didymos A and B are $L_{PLDA} = 3428$ dB and $L_{PLDB} = 716$ dB for $f = 2.7$ GHz, respectively. For $f = 300$ MHz, these values become approximately $L_{PLDA} = 381$ dB and $L_{PLDB} = 79.6$ dB.

To deal with every aspect, a situation where the transmitter and receiver are located at $R = 750$ m from asteroid's center of mass was analyzed. This corresponds to approximately half the distance between both the primary asteroid body and the secondary. Considering that distances

where spacecrafts are located between the primary and secondary bodies, it is important to assess the possibility of dust and boulders existing in the working environment. From identified binary asteroids formation mechanisms, it is possible that mass transfers occur. However, Didymos is considered to be in a spin-lock rotation in formation, thereby being clear of any major mass transfer [92]. It is also estimated that Didymos, despite rotating considerably fast, can be below the escape velocity, so lifted particles will not escape. Instead, they will orbit the body for a given time and rejoin the primary at a different location or attach to the secondary. The survival time of small particles is also small due to radiation forces. Therefore, it can be assumed that no risks pose for relatively close observations of the primary. That said, for example, for a frequency of 50MHz, the first Fresnel radius is $2H \approx 95\text{m}$ at this distance and the asteroid path attenuation is $L_{PLDA} = 63\text{dB}$. An analysis over a range of 10 to 500 MHz is shown in Figure 3.6. It is possible to observe that sufficient resolution $2H = 60\text{ m}$ is obtained at a working frequency of 125 MHz for which the path loss within the primary is $L_{PLDA} = 159\text{ dB}$. In this case, the free space path loss following the Friis equation [105] is:

$$L_{FS} = 20\log_{10}\left(\frac{4\pi \times 2R}{\lambda}\right) = 78\text{dB} \quad (3.30)$$

This percentage of signal loss was not possible to translate into reasonable signal-to-noise ratio, even after processing. Specifically, considering a 10W transmitter, antennas of 1.4m of diameter, a receiver bandwidth of 8MHz and processing gain of around 100dB [69]. As for the signal noise, ITU recommendations regarding galactic noise were followed to retrieve the equivalent noise temperature [106]. Evidently, only the galactic noise is of interest in this case. Furthermore,

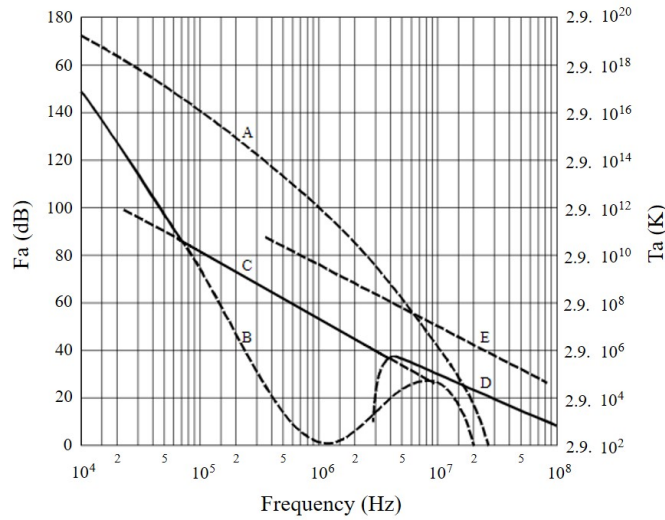


Figure 3.5: External noise-equivalent temperature t_a and factor f_a from 10kHz to 100MHz, considering several noise sources: A-atmospheric noise upper threshold; B-atmospheric noise lower threshold; C-man-made noise at quiet receiving site; D-galactic noise; E-median business area man-made noise [106].

it dominates the equivalent system temperature, thereby mainly influencing the system's noise.

Considering as a rough estimate a noise equivalent system temperature of $T_S = 2.9 \times 10^3$ K, a signal-to-noise ratio (SNR) below -10 dB was obtained.

For a distance of $R = 300$ m to the secondary, the necessary resolution is not achieved for frequencies up to 500 MHz (Figure 3.7). Neither it is achievable within acceptable attenuation levels, since for the intended resolutions, a frequency of 800 MHz is needed. In this case, the accumulated free space and asteroid path loss is $L_{PL} = L_{FS} + L_{PLDB} = 86 + 212 = 298$ dB. This results in an even lower SNR (below -30 dB).

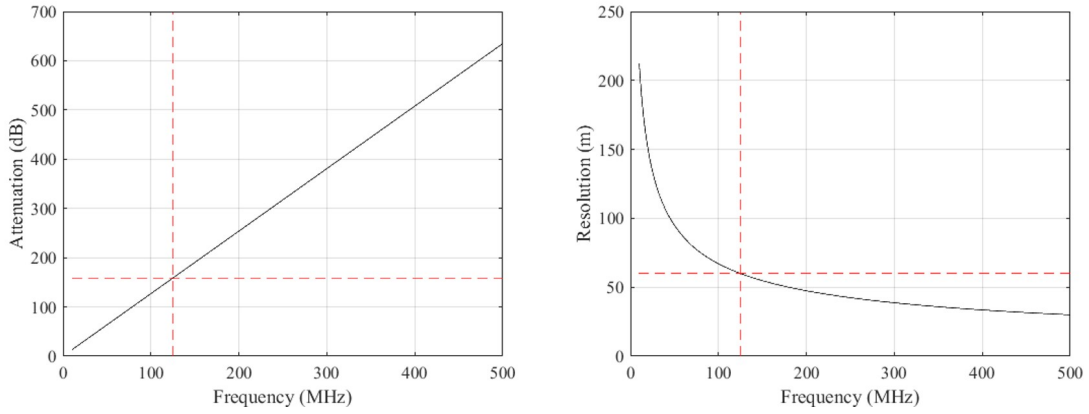


Figure 3.6: Bistatic $\beta = 180^\circ$ - Didymos A path loss (considering a loss tangent $\tan \delta = 0.008$ and a relative electrical permittivity of $\epsilon'_r = 5$) and associated resolution (given by the Fresnel ellipsoid) at $R=600$ m.

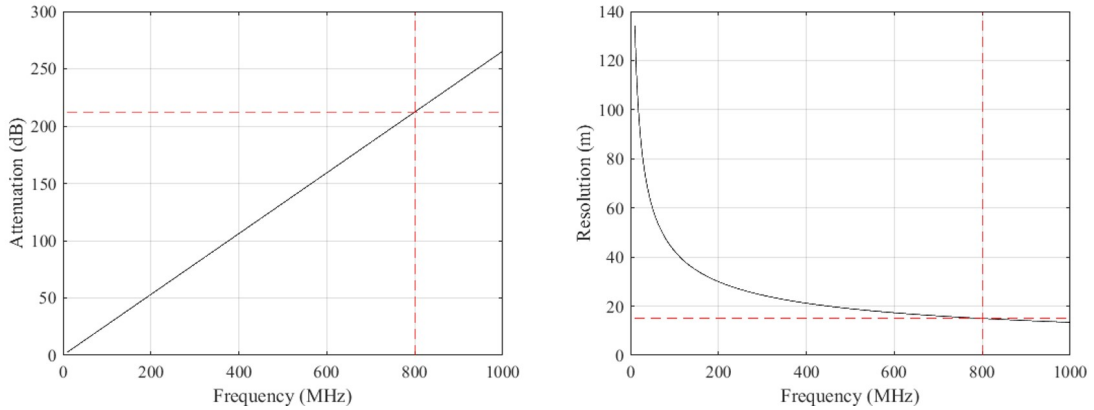


Figure 3.7: Bistatic $\beta = 180^\circ$ - Didymos B path loss (considering a loss tangent $\tan \delta = 0.008$ and a relative electrical permittivity of $\epsilon'_r = 5$) and associated resolution (given by the Fresnel ellipsoid) at $R=300$ m.

This solutions would also bring strict operational requirements in terms of spacecraft trajectories, requiring propulsion capability from both spacecrafts. Moreover, following the current

planning of Hera's mission, DART will impact Didymoon's surface creating ejecta whose properties are still uncertain to a large degree [92]. Another aspect to consider is that the distances considered would also represent the closest orbital approach to an asteroid or close to it. The record so far is held by OSIRIS-REx that orbited Bennu asteroid at 680m in June 2019 [107]. In general, mission limitations regarding power and size dictate the in-feasibility of overcoming the total percentage of signal loss.

Chapter 4

Bistatic Tomographic Synthetic Aperture Radar for Didymos Characterization

Remote sensing techniques to characterize the interior of NEOs using radio-frequency technology can be split into two main groups. The measurements can be conducted across the NEO, by having a sensor on opposite sides of the body and analyzing the transmitted wave. Measurements across the celestial bodies, however, are characterized by low resolution, given the bistatic baseline restrictions. Moreover a dual-orbiter solution reveals unfeasible within Didymos asteroid's and AIDA's mission limitations (refer to [subsection 3.3.1](#)). Instead of measuring the effect of propagating through the entire asteroid, imaging techniques, in particular SAR, can be used for subsurface investigations, providing there is enough signal-to-noise ratio. Moreover, beside imaging, delays and received power can be related to the complex dielectric properties or roughness of the asteroid [108]. In a SAR perspective it is essential to provide the capability to characterize any heterogeneities beneath the surface including the detection of possible cavities. Furthermore, the compositional heterogeneity, spatial and size distribution of such constitutive blocks shall be possible to determine. A geological map imaging spatial variability, layers or embedded monolithic blocks might allow linking the surface to deep interior properties. This is pivotal for sampling site selection and contextualization and for the purpose of the asteroid deflection and mining programs. To fulfill this scientific goals, a metric resolution is necessary [1].

The following study was aimed at determining an optimal configuration for a one or two-satellite arrangement that could fulfill this criteria. Likewise, particular attention was given to a sensor arrangement working at higher frequencies, since it could provide increased versatility and benefit data retrieval from the Arecibo Observatory [1].

Synthetic aperture radars design entail explicit trade-offs that must be managed carefully for any given scenario. Let us introduce first a bistatic configuration, analyzed within the scope of Hera mission. The proposed sensor geometry is shown in [Figure 4.1](#). Two nearby orbiters, separated by a bistatic angle of β were considered. For simplicity at demonstrating the concept, they

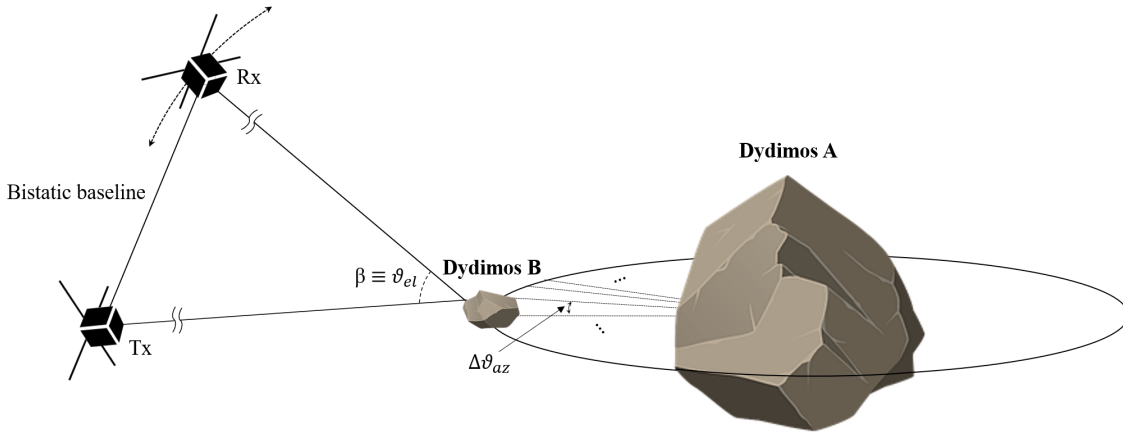


Figure 4.1: Bistatic 3D SAR geometry for characterizing Didymos.

are located at the same distance and in orbital planes at different "latitudes" of the asteroid. To promote compatibility and reduced mission requirements imposition, only solutions requiring low power and propulsion budgets, specially concerning the CubeSats, were considered relevant. In particular, a solution where the satellite can be orbiting the asteroid (an already explored capability [107]), instead of flying by it, was explored. This is possible if, for example, Didymos A rotation or Didymos B translation (and rotation) movements are exploited. For signal-to-noise ratio purposes, further detailed in this chapter, Didymos B was chosen as the target celestial body. The acquisition principle explores robust SAR techniques such as a variation of the regular ISAR and strip-map SAR to provide 3D resolution. By orbiting its main body, the secondary Didymos permits the accumulation of pulses as if the radar was moving itself (assuming that the satellites orbital velocity is negligible compared to the orbital velocity of the asteroid's natural satellite). The range direction is defined, as usual, as the direction of line-of-sight of the equivalent monostatic radar. Indeed, this is the direction in which the radar produces meaningful constant phase planes thereby understanding targets correctly. The 3D capability is formed on top of this conventional ISAR working principle by accumulating several Didymos B's passages and integrating information in an orthogonal direction to the ISAR imaging plane. Each passage corresponds to an orbital period, to which the satellites, if orbiting in the opposite direction, is summed or subtracted its orbital velocity contribution.

Earth-like orientation planes were defined for this solution. Hereinafter, azimuth will be referred as the direction along the orbit of Didymos B. Furthermore, we define the secondary's orbital plane as the zero-latitude of the asteroid and incidence angle as the angle between a sensor and its target. As aforementioned, in the radar's range dimension, resolution depends solely on bandwidth for pulsed compressed radars. In the elevation and azimuth dimensions, resolution is proportional to the operating wavelength and the number of accumulated pulses contribute to the overall synthetic aperture, thereby increasing resolution. This is naturally related to the total time spent in acquisition modes but it is also affected by how frequent the measures are. Within the 3

dimensions, the worst resolution usually dictates the resulting image resolution in the others. Several operational limitations were imposed on this solution so that it could be relevant for a feasible deep-space mission. ESA's Hera mission is already in development phase, possessing already detailed some of these constraints. For compatibility with other planned operations, a distance of 10km between both satellites and the asteroid was chosen [7]. Furthermore, a period of 8 weeks was considered the maximum duration for this mission as it was the timespan of operations for the ASPECT CubeSat within the scope of AIM's mission (Hera precursor) [103]. This is an important constraint as it limits the achieved accumulation of radar pulses in elevation and therefore the possible resolution and signal-to-noise ratio.

4.1 Radar Parameters

4.1.1 Frequency Selection

The frequency is definitely an essential parameter for SAR systems. Its relevance is accentuated even further by the subsurface penetration required. Low-power solutions are again also a crucial requisite. Therefore, the frequency must emphasize the asteroid characteristics but at the same time allow restricted power consumptions. Synthetic aperture radar processing gain can be explored to overcome the low-signal with respect to the level of noise that may characterize an already constrained scenario. Being able to compensate the high losses associated to higher frequencies, transmissions in the S-band (above 2 GHz) were considered. This provides a more versatile solution with respect to the previously studied ones and to promote the data retrieval from Arecibo observations.

4.1.2 Pulse Compression

Pulse compression is indeed necessary to achieve fine resolutions while avoiding the transmission of extremely short signals that require considerably more instantaneous power and faster switching devices. Continuous-wave radars can provide more signal-to-noise ratio but imply a ceaseless transmission and allocation of resources. On the other hand, pulsed radars can be flexibly allocated within spare resources of the inter-satellite link (ISL). Moreover, pulsed signals allow to explore the asteroid reflections with respect to complex signals, which is not the case for real signals from continuous wave radars.

A large bandwidth, B , is required to obtain a finer range resolution (Equation 2.4). However, it cannot be increased indefinitely, since it is intrinsically related to the system's capability of maintaining coherency throughout the entire transmission time (τ). Whenever a transmission happens, for example, input voltage fluctuations can cause small variations in the local oscillator frequency. This subtle input voltage scintillations could occur not only due to transmissions but due to other on-board instruments, for example. The system is clearly more vulnerable the longer it is transmitting. To not undermine the measurements, we constrained the so-called time-bandwidth product

of $B \times \tau$ to 2000, constraining the pulse compression gain. As a result, a larger bandwidth also means less signal-to-noise ratio in the received signal (Equation 2.11).

Furthermore, the signal modulation choice is crucial for an optimized assessment of the asteroid's properties. A summary of the performances of implementing the most often used waveforms for pulsed radars is given in [109]. Phase-coded implementations usually provide better clutter rejection. Also, most coded waveforms provide lower range sidelobes. However, at the range compression stages, windowing functions can be used to trade between range sidelobe level and resolution [52]. This is not needed whilst using phase-coded waveforms, neither is the associated signal-to-noise ratio loss. Furthermore, the phase-coded waveforms exhibit sinc-type spectra while the spectrum of linear frequency modulated (LFM) signals is narrowband. Hence, the bandwidth of the transmitted signal is maximized and consequently better range resolution can be obtained [52]. Additionally, fast algorithms for high-spatial resolution imagery or phase preservation are substantially easier to implement with chirp waveforms. Chirp signals are inherently more Doppler tolerant than coded waveforms and thus also less susceptible to degradation due to the Doppler spread of the targets [53]. The waveform properties and their relevance for planetary and asteroid observation missions can be found in [52] and [53] as this technique was used to produce range-Doppler images of the near-Earth Asteroid (162421) 2000 ET70 using Goldstone radar system. Coded waveforms have also been used exhaustively in planetary radars [52][53].

Phase-coded waveforms are generating by modulating the transmitted carrier with phase modulation techniques such as Barker codes or polyphase codes. Barker codes, for instance, are binary-phased codes, also called as perfect code sequences, as they give equal amplitude time sidelobes. Therefore, they require no amplitude weighting for sidelobe suppression. The longest Barker code is 13-bit length. In chirp (LFM) waveforms the transmitted carrier is frequency modulated with a linear ramp signal. The transmitted signal has a frequency that varies linearly within a certain bandwidth. These modulation types increase the transmitted signal bandwidth with respect to an un-modulated radar by a factor equivalent to the time-bandwidth product.

Large bandwidths are required for small range resolutions, as explained in Equation 2.28, since:

$$\delta_r = \frac{c \sec(\beta/2)}{2B} \quad (4.1)$$

For a collocated transmitter and receiver, to obtain a metric resolution, a bandwidth of around $B = 150\text{MHz}$ is needed. This can be a wide bandwidth for the receiver to handle. To avoid the imposition of constraints to the receiver hardware or software, a sampling frequency of $f_s = 60\text{MHz}$ is assumed. This means that the maximum useful bandwidth transmitted per pulse is around $B = 60\text{MHz}$. This yields a resolution of $\delta_r = 2.5\text{m}$, which is not acceptable for the science measurement requirements for asteroid interior and regolith structure, detailed in [1].

4.1.2.1 Stepped Chirp Waveform or Stepped Phase-Coded Waveform

Independently of the type of modulation used, techniques to form wider bandwidths with limited receiver available bandwidth can be employed [110][111]. If several pulses are transmitted with

smaller but adjacent bandwidths, they can be processed together to form an equivalent to a wider-bandwidth one (Figure 4.3 and Figure 4.2).

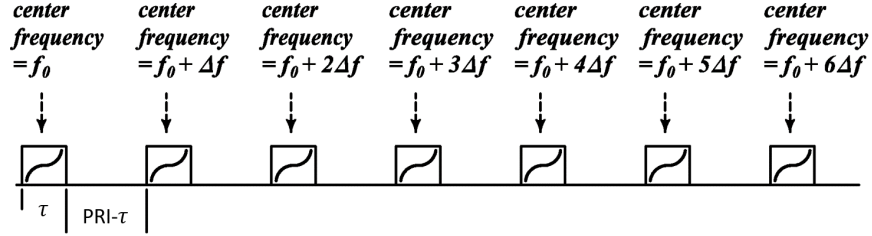


Figure 4.2: Wide-bandwidth waveform resulting from the combination of several smaller bandwidth pulses - time domain [110].

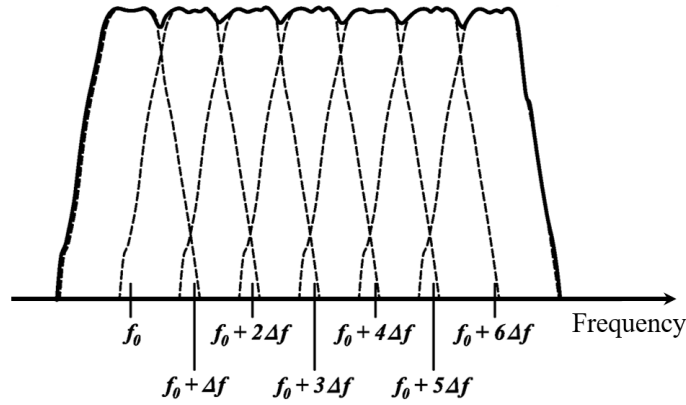


Figure 4.3: Wide-bandwidth waveform resulting from the combination of several smaller bandwidth pulses - frequency domain [110].

Specifically, for almost stationary scenarios, this techniques are susceptible of use with little need for additional corrections. The sub-waveforms do not need to be transmitted in order (i.e. Costas Code waveform), thus enabling opportunistic transmission optimizing the radar system telecommunication resource utilization. Disadvantage of the stepped chirp or stepped phase-coded waveforms are that the radar's time budget is worsened and all frequencies must be received before any range bin can be imaged. Nevertheless, higher resolution can be obtained, as well as better signal-to-noise ratio, using this technique.

4.2 Radar System Overview

A general 6U CubeSat was considered as one of the two link ends and a larger spacecraft with propulsion capability was considered at the other end. To demonstrate the feasibility of the underlying SAR concept, no emphasis was given to state-of-the-art microwave elements.

4.2.1 Transmitter and Receiver Selection

The data relay to Earth is expected to be assured by the larger spacecraft. If the receiver is a CubeSat, a percentage of the ISL capacity is needed for transmitting data to the main spacecraft. Furthermore, the receiver has to be in an active mode for a more extended time than the transmitted, since alongside the data, in bistatic SAR, it is useful that the direct echo is received. For this reasons, in this work, the receiver is envisioned to be the main spacecraft and the transmitter one of the CubeSats.

4.2.2 Transmitter Power and Efficiency

Needless to say that the feasibility of a space system is strictly dictated by the amount of resources needed comparing to the available. Power is often generated in deep space using solar panels, of limited size and it has to sustain all experiments. Indeed, the power consumption of a given on-board experiment or equipment is mission critical. The transmitted power was assumed to be at most a few Watts. Specifically, an average power of less than $P_{Tx_{avg}} < 2 \text{ W}$ was considered. This constraint entails a trade-off between the transmitted pulse peak power P_{TX} , the pulse repetition frequency PRF , the pulse duration τ , since:

$$P_{Tx_{avg}} = P_{TX} \left(D + \frac{1-D}{5} \right) \quad (4.2)$$

$$D = \tau \times PRF \quad (4.3)$$

Additionally, a percentage of 20% of the cycle not used for transmissions is added to the duty cycle D to account for the energy consumption in transition phases. A remark is given in the scope of the power efficiency of the transmitter. It is assumed that the transmitting system has a power efficiency of about 50%.

4.2.3 Transmitter and Receiver Antennas

Antenna arrays of 20x20cm (the size of 2x2 of the CubeSat faces) was considered for both transmitter and receiver. Neglecting the array aspect and its sinc pattern, the gain of a directional antenna can be related to its area, as in [subsection 2.1.1](#).

$$G_T = G_R = \frac{4\pi A_e}{\eta_a \lambda^2} = \frac{4\pi \rho A_p}{\eta_a \lambda^2} \quad (4.4)$$

Being the effective aperture considered approximately equal to the physical aperture $A_e \approx A_p$. The antenna losses were considered to be of $\eta_a \approx 1.58$ (2 dB). Additionally, the gain of the transmitting antenna G_T and the antenna at the receiver G_R were assumed to be equal.

4.2.4 Noise Performance

The noise present in a radio system can be attributed either to an external or to internal sources. External sources affect the system uniquely dependently on what the antenna itself is actually receiving. This factors include: atmospheric noise; man-made noise; interference by other users (in the same or in adjacent channels); and galactic (or cosmic) noise, resulting from thermal bodies (such as the Sun, the Moon, or even the Earth) in the background of the antenna's beam and side-lobes. The noise generated by components inside the receiver are classified as internal sources. This is a result of random processes. At a more fundamental level view, they can be result of: thermal vibrations that naturally occur in any component at a temperature higher than absolute 0, denominated as thermal noise; shot-noise, more specifically random fluctuation of charge carriers in an active device; recombination of charge carriers (flicker or 1/f noise); or quantum noise, caused by the discrete or quantized nature of charge carriers and photons.

For the receiver itself, the whole system can be modeled through a cascade of two-port networks, each with its specific gain (or attenuation) and equivalent temperature. Another important concept worth mentioning is the noise figure,

$$F = \frac{S_i/N_i}{S_o/N_o} \quad (4.5)$$

It relates the input signal to noise ratio with the output one. Therefore it is always equal or higher than one, since the output ratio is always equal or higher than the input, being the first the case of a lossless two-port network. On Earth, usually a reference of $T_0 = 290K$ is considered. Hence, for the case of a lossy passive 2-port network [112]:

$$F = 1 + \frac{(L-1)T}{T_0} \quad (4.6)$$

Being T the physical temperature of the lossless two-port network, usually we can assume it to be in thermal equilibrium with the Earth itself, which simplifies Equation 4.6 to $F = L$.

Assuming that there are no attenuating factors, such as the atmosphere or rain, the equivalent noise temperature at the receiver is:

$$T_{ant} = \eta_a T_{cosm} + (1 - \eta_a) T_0 \quad (4.7)$$

Where η_a are the antenna losses. As computed above, the antenna temperature represents all effects related to the external noise factors and the internal sources are modeled through the receiver's equivalent temperature, T_r . At this point, the system's equivalent temperature T_s and noise power N_s is:

$$T_s = T_{ant} + T_r \quad (4.8)$$

$$N_s = kBT_s \quad (4.9)$$

In this study, we have considered frequencies within the cosmic window (from about 1 GHz to 100 GHz). The expected noise temperature is thus, considerably low, arguably below 3k (refer to curve B of Figure 4.4). Furthermore, if the system's noise temperature is high enough, the external sources contribution are negligible. In this case, the system temperature is approximately mainly dependent on the receiver temperature $T_S \approx T_R$. A typical low-noise amplifier (LNA) exhibits a noise figure of $F = 3$ dB. Excellent LNA's can go below $F = 0.5$ dB. As usually the system temperature is referred at the antenna input, it is also necessary to consider the losses between the antenna and LNA in the noise figure. To focus on the processing gains stemming from the novel pulse accumulation technique and not determine additional system requirements, a low performance system with a $F = 5$ dB noise figure was considered. Moreover, the receiver was assumed to be a lossy network for exaggeration, thereby creating losses at the level of its noise figure $L_r = F_r = 5$ dB.

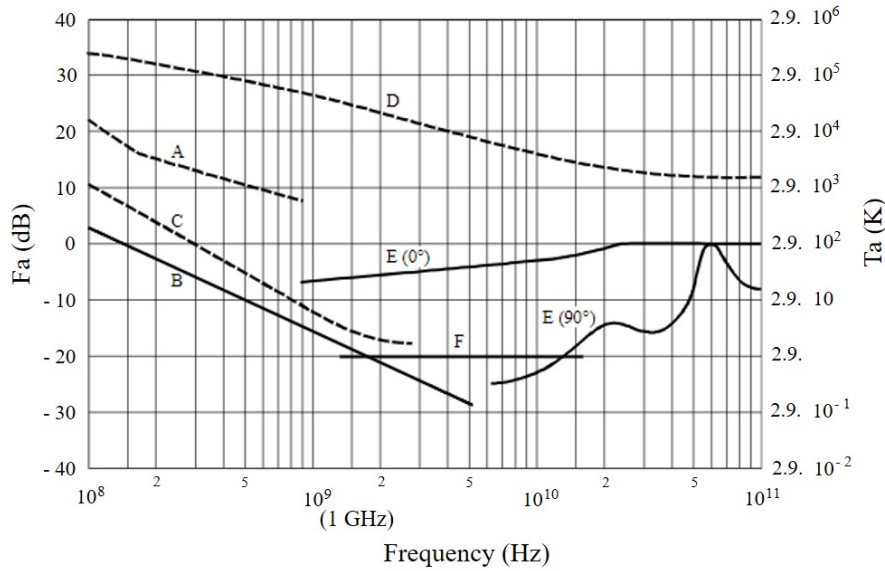


Figure 4.4: External noise-equivalent temperature t_a and factor f_a from 100 MHz to 10 GHz, considering several noise sources: A-estimated median business area man-made noise; B-galactic noise; C-galactic noise (toward galactic centre with infinitely narrow beamwidth); D-quiet Sun ($1/2^\circ$ beamwidth directed at Sun); E-sky noise due to oxygen and water vapour (very narrow beam antenna), upper curve, 0° elevation angle, lower curve, 90° elevation angle; F-black body (cosmic background), 2.7k [106].

4.3 Geometry and Aperture Parameters

To determine the optimal geometry, one might consider also other factors affecting the overall performance of any solution. First, it is important to establish what the radar can actually measure. Radars emit a signal, which if in a far field region the curved waves can be approximated by uniform plane waves. In a mathematical perspective, this allows the definition of planes of

constant phase, where the amplitude is constant and so is the internal product between the wave vector and the position vector $\vec{k} \cdot \vec{r} = \text{const}$. This implies that the projection of $\vec{r}$ in the propagation direction $\hat{a}_n$ is constant. In other words, that is the equation of fields perpendicular to $\hat{a}_n$ and that is what a radar sensor measures. In a bistatic scenario, the measured physical quantity is instead the combination of both transmitter and receiver position vectors. Put differently the dot product between both vectors. Therefore, the resolution is also coarser in this scenario. Another aspect is the loss of penetration for large bistatic angles, which in the proposed acquisition system translates into a larger incidence angle for one of the satellites. This solution does improve the ability to reduce ambiguities due to a non-beam limited scenario comparing with a monostatic working at small incidence angles. Hence, the sensor, located at approximately 9 km from Didymos B, for any transmitted pulse, would receive echoes from its whole surface unless the beamwidth was below roughly 0.5° , where it would become beam limited. This is a very directional antenna, which is a highly demanding size/frequency requisite. In a non-beam limited case, at zero incidence angle, echoes from the upper and lower part of Didymos B's surface could not be distinguished. The bistatic can make use of non-collocated transmission and reception to resolve points in Didymos's surface while exploring more flexible incidence angles.

From the physical parameters of the asteroid summarized in Table 3.1, the following selection of relevant information is considered:

- Diameter of Didymos A, $D_P = 780 \text{ m}$
- Separation of Didymos A and B, $S_{PS} = 1180 \text{ m}$
- Didymos B Orbital (equal to Rotation) Period, $P_{orbs} = P_S = 11.92 \text{ h}$
- Diameter of Didymos B, $D_S = 163 \text{ m}$
- Didymos B shape elongation $a_s/b_s = 1.2$ and $b_s/c_s = 1.2$.

From the relation among distances between celestial bodies (S_{PS}) and their orbital periods (in this case, P_{orbs}) expressed by Kepler's third law of planetary motion, it is possible to deduce Didymos B angular velocity. Neglecting the orbit eccentricity and the gravity pull of the satellites towards Didymos B and Didymos A towards Didymos B, it is possible to formulate Kepler's third law as:

$$GM_{DA} \approx \left(\frac{2\pi}{P_{orbs}} \right)^2 S_{PS}^3 \approx 35.225 \text{ m}^4 \text{ s}^{-2} \quad (4.10)$$

Being M_{DA} the mass of Didymos A and $G = 6.674184 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ the gravitational constant. In fact, it is possible to deduce any orbiter's angular velocity providing the orbit radius R is known. The same can be said for the orbital velocity. Thus, the following parameters were determined for Didymos B and for an orbiting satellite at $R = 10 \text{ km}$ from the asteroid's center of mass:

$$\omega_{SAT} = \frac{v_{SAT}}{R} \approx \sqrt{\frac{GM_{DA}}{R^3}} \quad (4.11)$$

$$\omega_{DB} = \frac{v_{DB}}{S_{PS}} \approx \sqrt{\frac{GM_{DA}}{S_{PS}^3}} \quad (4.12)$$

- Didymos B Angular Velocity, $\omega_{DB} \approx 0.146 \text{ mrad/s}$
- Didymos B Orbital Velocity, $v_{DB} = \omega_{DB} S_{PS} \approx 0.173 \text{ m/s}$
- Satellite Angular Velocity, $\omega_{SAT} \approx 5.94 \text{ } \mu\text{rad/s}$
- Satellite Orbital Velocity, $v_{SAT} \approx 0.0594 \text{ m/s}$.

To note that the spacecraft's orbital period in a gravitationally bound orbit of $R = 10 \text{ km}$ radius is nearly two weeks. It is assumed that it is possible to determine Didymos B's translation direction and thus that it is possible to control the relative period of Didymos with respect to the sensor arrangement.

Regarding the transmitter and receiver module separation (in elevation), for the bistatic approach, angles of more than $\theta_{el0} > 20^\circ$ were considered so that the features detected from the asteroid terrain are with high probability different than those gathered via a monostatic approach.

A final remark on the roles of both spacecrafts is hereby presented. One of the orbiters is envisioned to possess a vertical velocity component. It is likely that it is simpler to artificially generate it. The main spacecraft is also expected to possess higher propulsion capability. Therefore, it is envisaged to be responsible for the function of creating the elevation aperture, while one of the CubeSats might be at the other link end. This is not meant to be understood as a prohibitory statement if one decides to adopt any other configuration, but rather a pondered guess taking into account this specific deep-space mission constraints.

4.4 Resolution vs Ambiguities in the Generated Volume

Beyond fine resolution, resolving replicas is a stringent necessity for an image to be clearly focused within a target area. An overview of the requirements for a non-distorted output image is provided in this section.

4.4.1 Range Ambiguities

The main provenience of range ambiguities can be avoided if the swath width W_s accommodates the target area. Expressly, in mathematical language:

$$W_s \leq \frac{c}{2PRF_{az} \sin \theta_{inc}} \quad (4.13)$$

Where PRF_{az} is the azimuth pulse repetition frequency and θ_{inc} is the incidence angle. A PRF_{az} below approximately 7.5 pps (pulses per second) requires the swath width to be lower than 20 km, which is comfortably within the requirements to image the Didymos system at $R = 10 \text{ km}$.

4.4.2 PRF Constraint and Obtained Resolution Derivation for Circular Orbital SAR and ISAR

If the radar is not moving on a straight path, but instead in a circular one, the PRF constraint is altered. For a more rigorous baseline for the design of a SAR system of the kind, a meticulous analysis is hereinafter detailed on this topic. The minimum pulse repetition frequency for a given velocity (which also permits to conclude the maximum velocity for a certain PRF) was analytically determined for the orbital trajectory scenario. Consider the geometry presented in [Figure 4.5](#).

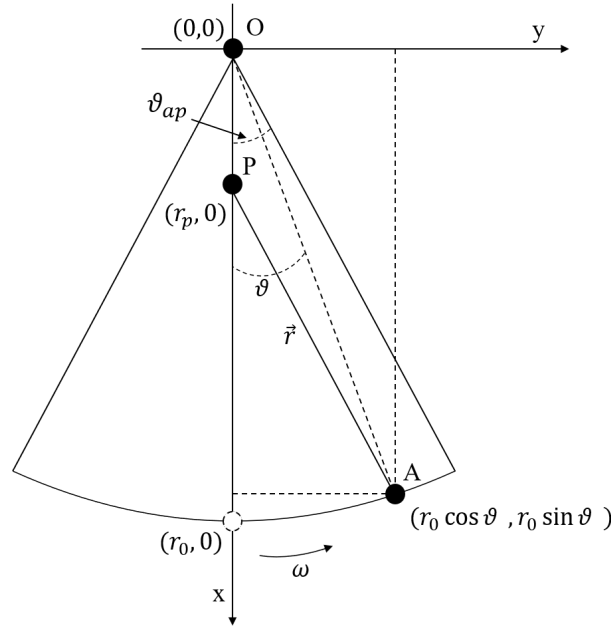


Figure 4.5: Radar orbital trajectory geometry (SAR).

The minimum pulse repetition frequency is determined by the maximum Doppler bandwidth that might exist in a given scenario. Let us start by determining the range equation that determines the echo received by a radar located at A resulting from a target at the point P. The distance between two points in this vector space d or in other words the L_2 norm of the vector $\vec{r}$ is determined by simple geometry.

$$\begin{aligned}
 d(\vartheta) = |\vec{r}|_2 &= \sqrt{(x_{r_A} - x_{r_P})^2 + (y_{r_A} - y_{r_P})^2} \\
 &= \sqrt{(r_0 \cos \vartheta - r_p)^2 + (r_0 \sin \vartheta)^2} \\
 &= \sqrt{r_0^2 + r_p^2 - 2r_0 r_p \cos \vartheta}
 \end{aligned} \tag{4.14}$$

Where (x_{r_A}, y_{r_A}) and (x_{r_P}, y_{r_P}) are the coordinates for the point A and P respectively. The distance from the center of rotation to the radar is given by r_0 and to the point P by r_p . The angle ϑ formed

by the radar and the center of rotation can be described by:

$$\vartheta = \vartheta_i + \omega t + \frac{1}{2} \frac{d\omega}{dt} t^2 \quad (4.15)$$

Where ω is the angular velocity and t is the interval of time corresponding to each ϑ . The total aperture length is defined by the arc formed by the total rotation $2\vartheta_{ap}$. We assume that the angular velocity is constant. This is generally valid, if the angular acceleration is negligible during the considered interval of time, for which case, the scene is sampled uniformly. Otherwise, an interpolation was necessary. We assume that the synthetic aperture is formed from $-\vartheta_{ap}$ to ϑ_{ap} , hence the initial angle is $\vartheta_i = -\vartheta_{ap}$ rad. Thus, $\vartheta = \omega t - \vartheta_{ap}$ and the synthetic aperture induced phase $\phi(t)$, wavelength λ dependent, along the aperture is:

$$\phi(t) = -2 \times \frac{2\pi}{\lambda} d \{ \vartheta(t) \} = -\frac{4\pi}{\lambda} \sqrt{[r_0 \cos(\omega t - \vartheta_{ap}) - r_p]^2 + [r_0 \sin(\omega t - \vartheta_{ap})]^2} \quad (4.16)$$

Consequently, the Doppler frequency f_D is:

$$f_D = \frac{1}{2\pi} \frac{d\phi(t)}{dt} = -\frac{2}{\lambda} \frac{d}{dt} \left[\sqrt{[r_0 \cos(\omega t - \vartheta_{ap}) - r_p]^2 + [r_0 \sin(\omega t - \vartheta_{ap})]^2} \right] \quad (4.17)$$

This can be solved using the chain rule:

$$\frac{d\sqrt{u}}{dt} = \frac{d\sqrt{u}}{du} \frac{du}{dt} \quad (4.18)$$

Being $u = (r_0 \cos(\omega t - \vartheta_{ap}) - r_p)^2 + (r_0 \sin(\omega t - \vartheta_{ap}))^2$. Thus, the resulting formulation is:

$$\frac{\frac{d}{dt} \left\{ [r_0 \cos(\omega t - \vartheta_{ap}) - r_p]^2 + [r_0 \sin(\omega t - \vartheta_{ap})]^2 \right\}}{\sqrt{[r_0 \cos(\omega t - \vartheta_{ap}) - r_p]^2 + [r_0 \sin(\omega t - \vartheta_{ap})]^2}} \quad (4.19)$$

Using two other chain rules of the form:

$$\frac{d \sin^2 v}{dt} = \frac{dk^2}{dk} \frac{dk}{dv} \frac{dv}{dt} \quad (4.20)$$

$$\frac{d \{ \cos(v) + \beta \}^2}{dt} = \frac{d\chi^2}{d\chi} \frac{d\chi}{dv} \frac{dv}{dt} \quad (4.21)$$

Where $k = \sin(\omega t - \vartheta_{ap})$, $\chi = \cos(\omega t - \vartheta_{ap}) - r_p$ and $v = \omega t - \vartheta_{ap}$. In this way, the azimuth Doppler frequency, as a function of time, becomes:

$$\begin{aligned} f_D &= -\frac{2 \{ 2r_0^2 \omega \sin(\omega t - \vartheta_{ap}) \cos(\omega t - \vartheta_{ap}) - 2r_0 \omega \sin(\omega t - \vartheta_{ap}) [r_0 \cos(\omega t - \vartheta_{ap}) + r_p] \}}{\lambda \sqrt{[r_0 \cos(\omega t - \vartheta_{ap}) - r_p]^2 + [r_0 \sin(\omega t - \vartheta_{ap})]^2}} \\ &= -\frac{2r_0 r_p \omega \sin(\omega t - \vartheta_{ap})}{\lambda \sqrt{[r_0 \cos(\omega t - \vartheta_{ap}) - r_p]^2 + [r_0 \sin(\omega t - \vartheta_{ap})]^2}} \end{aligned} \quad (4.22)$$

With the following approximations being possible for small angles, each degrading the precision of the expression.

$$f_D \approx -\frac{2}{\lambda} \frac{r_0 r_p \omega \sin(\omega t - \vartheta_{ap})}{r_0 \cos(\omega t - \vartheta_{ap}) - r_p} \approx -\frac{2}{\lambda} \frac{r_0 r_p \omega (\omega t - \vartheta_{ap})}{r_0 - r_p} \quad (4.23)$$

Therefore, the minimum PRF is equal to the maximum Doppler bandwidth B_D . In other words, the Doppler shift variance from the beginning to the end of the aperture cannot be higher than the sampled frequency, or:

$$\begin{aligned} B_D &= f_D(t)|_{t=t_0-\frac{T_{ap}}{2}} - f_D(t)|_{t=t_0+\frac{T_{ap}}{2}} \\ &= -\frac{2}{\lambda} \frac{r_0 r_p \omega \sin(\omega T_{ap} - \vartheta_{ap})}{\sqrt{[r_0 \cos(\omega T_{ap} - \vartheta_{ap}) - r_p]^2 + [r_0 \sin(\omega T_{ap} - \vartheta_{ap})]^2}} \end{aligned} \quad (4.24)$$

Where T_{ap} is the total observation time. To uncover resolution, one can look at the variation of range as a function of the angle ϑ and constrain it using the Nyquist sampling theorem. An infinitesimal phase variation can be re-written as a function of ϑ and an the angle step $\Delta\vartheta$, as:

$$\begin{aligned} d\phi &= -\frac{2dr}{\lambda} = -\frac{2}{\lambda} \frac{dr}{d\vartheta} \Delta\vartheta \\ &= -\frac{2}{\lambda} \frac{r_0 r_p \sin \vartheta}{\sqrt{(r_0 \cos \vartheta - r_p)^2 + (r_0 \sin \vartheta)^2}} \Delta\vartheta \\ &\approx -\frac{2}{\lambda} \frac{r_0 r_p \sin \vartheta}{r_0 \cos \vartheta - r_p} \Delta\vartheta \lesssim \frac{1}{2} \end{aligned} \quad (4.25)$$

The phase variation has to be below one half for the worst case scenario in a given scene, in order to fulfill the sampling requirements [15]. Put differently, the imaged scene must be sampled at more than twice the distance of half wavelength. The largest phase shift is expected to be at the extremes of the trajectory, i.e at angles ϑ near $-\vartheta_{ap}$ or ϑ_{ap} , being the Doppler-centroid in the mid-trajectory point. Angle-wise, this is equivalent as the total angle variation across the aperture ϑ_{ap} . This implies that:

$$\Delta\vartheta \lesssim \frac{\lambda(r_0 \cos \vartheta_{ap} - r_p)}{4r_0 r_p \sin \vartheta_{ap}} \quad (4.26)$$

Therefore, the resolution can be constrained to:

$$\Delta r \approx r_p \Delta\vartheta \lesssim \frac{\lambda(r_0 \cos \vartheta_{ap} - r_p)}{4r_0 \sin \vartheta_{ap}}$$

An useful way to compare this result to the aperture formed by a straight trajectory is to relate the results with the length of the straight aperture L , given that:

$$L = 2(r_0 - r_p) \sin \vartheta_{ap} \quad (4.27)$$

In this way, the resolution along the synthetic aperture's direction can be expressed as:

$$\Delta r \lesssim \frac{\lambda(r_0 - r_p)}{2L} \frac{(r_0 \cos \vartheta_{ap} - r_p)}{r_0} \quad (4.28)$$

$$< \frac{\lambda(r_0 - r_p)^2}{2r_0 L} \quad (4.29)$$

The first part of Equation 4.28, resembles the typical SAR resolution (given in Equation 2.16):

$$\Delta_{r_{linear}} = \frac{\lambda}{2L} R \quad (4.30)$$

Whereas in this case comes improved by a factor of approximately:

$$\Delta_r = \Delta_{r_{linear}} \left(\frac{r_0 \cos \vartheta - r_p}{r_0} \right) \quad (4.31)$$

In fact, for ISAR, some of this derivations are still valid. Figure 4.5 represents an adapted version of Figure 2.5, where the collocated transmitter and receiver are rotating along an arc centered in O and the target is kept still. This version is represented in Figure 4.6. In this case, the range

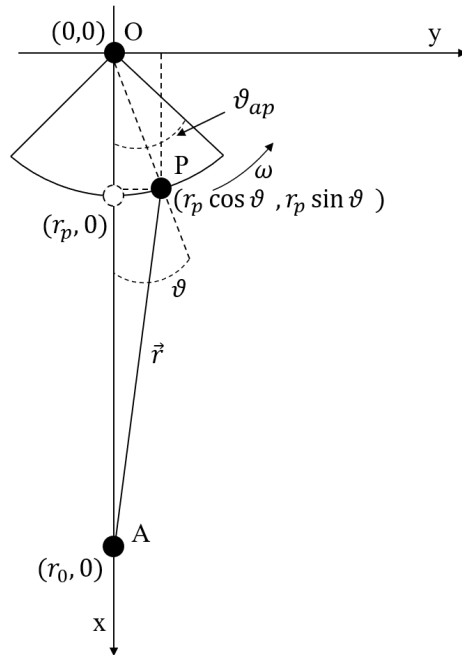


Figure 4.6: Target orbital trajectory geometry (ISAR).

equation yields:

$$\begin{aligned}
 d(\vartheta) = |\vec{r}|_2 &= \sqrt{(x_{r_A} - x_{r_P})^2 + (y_{r_A} - y_{r_P})^2} \\
 &= \sqrt{(r_p \cos \vartheta - r_0)^2 + (r_p \sin \vartheta)^2} \\
 &= \sqrt{r_0^2 + r_p^2 - 2r_0 r_p \cos \vartheta}
 \end{aligned} \tag{4.32}$$

It is important to note that the result is indeed the same as in the SAR scenario and so are the constraints regarding ambiguities. The only exception being in the definition of the straight aperture length, that is in ISAR formed by the target. Thus, straight aperture length L is:

$$L = 2r_p \sin \vartheta_{ap} \tag{4.33}$$

Therefore, rearranged in terms of L , Δr_{inv} the resolution along the synthetic aperture for ISAR is:

$$\Delta r_{inv} \lesssim \frac{\lambda r_p}{2L} \frac{(r_0 \cos \vartheta_{ap} - r_p)}{r_0} \tag{4.34}$$

$$< \frac{\lambda (r_0 - r_p)}{2L} \frac{r_p}{r_0} \tag{4.35}$$

4.4.3 Azimuth Resolution and Ambiguities

As deduced in the previous subsection, the Doppler bandwidth due to a circular orbital-like motion can be calculated, in azimuth or elevation direction, as follows. The azimuth pulse repetition frequency is typically chosen to be higher than the azimuth Doppler bandwidth $B_{D_{az}}$ by a factor K_a . In this work, K_a was chosen to give a 10% margin to account for the azimuth matched filter sidelobes.

$$PRF_{az} \geq K_a B_{D_{az}} \tag{4.36}$$

$$B_{D_{az}} = -\frac{2}{\lambda} \frac{RS_{PS} \omega_{SS} \sin(\omega_{SS} T_{ap_{az}} - \vartheta_{ap_{az}})}{\sqrt{[R \cos(\omega_{SS} T_{ap_{az}} - \vartheta_{ap_{az}}) - S_{PS}]^2 + [R \sin(\omega_{SS} T_{ap_{az}} - \vartheta_{ap_{az}})]^2}} \tag{4.37}$$

Where $T_{ap_{az}}$ is the total aperture time for each elevation pass, covering the angle aperture of $2\vartheta_{ap_{az}}$, $\omega_{SS} = \omega_{DB} \pm \omega_{SAT}$ is relative angular velocity between the azimuthal plane where the satellites are located and Didymos B. There is a plus-or-minus sign since the satellites might be orbiting the asteroid center of mass in the same direction of Didymos B or the opposite. Similarly, the resolution in azimuth is:

$$\delta_{az} \approx S_{PS} \Delta \vartheta_{az} \lesssim \frac{\lambda (R \cos \vartheta_{ap_{az}} - S_{PS})}{4R \sin \vartheta_{ap_{az}}} < \frac{\lambda (R - S_{PS})}{4R \sin \vartheta_{ap_{az}}}$$

Being $\Delta \vartheta_{az}$ the step in azimuth. At $R = 10$ km, at a given operating frequency, the azimuth resolution decreases with an increase of azimuth aperture (for small angles). At a frequency of 2.2 GHz, a sub-metric resolution is obtained with an aperture of approximately $\vartheta_{ap_{az}} = 1.72^\circ$. In this

case, the minimum azimuth pulse repetition is $PRF_{az_{min}} \approx 0.058$ pps. It is important to highlight that if the pulse compressed is implemented using stepped chirp or stepped phase-coded pulses, the minimum pulse repetition frequency is multiplied by the number of pulses combined. Thus, if a combination of, for example, four pulses is used, the effective azimuth pulse repetition frequency is, in reality, $PRF_{eff,az_{min}} \approx 0.235$ pps.

4.4.4 Elevation Resolution and Ambiguities

The "pulse repetition" in elevation is actually representative of the frequency at which an azimuth aperture occurs. Within the scope of the proposed geometry, this is equivalent to the inverse of Didymos B's orbital period (assuming no movement from the satellite). If the angular motion in azimuth of the sensors is considered:

$$PRF_{el} = \frac{1}{P_{orbs} \pm P_{orbSAT}} = \frac{\omega_{SS}}{2\pi} \quad (4.38)$$

Being P_{orbSAT} the orbital period of the sensor arrangement. If the satellites azimuthal plane's angular velocity is considered negligible in comparison with the angular velocity of Didymos B, then:

$$PRF_{el} \approx \frac{1}{P_{orbs}} = \frac{\omega_{DB}}{2\pi} = 2.33 \times 10^{-5} \text{ pps} \quad (4.39)$$

The same requirements regarding the elevation Doppler bandwidth B_{Del} have to be respected while configuring the aperture in this dimension. In this case, however, the pulse repetition PRF_{el} is essentially predefined by geometric constraints. Therefore, the tuning parameter is instead the sensor's orbital (or angular) velocity in elevation ω_{el} . The tolerance factor K_{el} is chosen, similarly to in the azimuth case, to give a margin of 10%.

$$PRF_{el} \geq K_{el} B_{Del} \quad (4.40)$$

$$B_{Del} = -\frac{1}{\lambda} \frac{RS_{PS}\omega_{el} \sin(\omega_{el}T_{ap_{el}} - \vartheta_{ap_{el}})}{\sqrt{[R\cos(\omega_{SS}T_{ap_{el}} - \vartheta_{ap_{el}}) - S_{PS}]^2 + [R\sin(\omega_{SS}T_{ap_{el}} - \vartheta_{ap_{el}})]^2}} \quad (4.41)$$

The total aperture time is $T_{ap_{el}}$ over an angular aperture of $2\vartheta_{ap_{el}}$. In fact, the mission duration is roughly dictated by the total elevation aperture time and therefore, further in this document, special attention will be given to it. The resolution in this dimension is given by:

$$\delta_{el} \approx S_{PS}\Delta\vartheta_{el} \lesssim \frac{\lambda(R\cos\vartheta_{ap_{el}} - S_{PS})}{2R\sin\vartheta_{ap_{el}}}$$

Where $\Delta\vartheta_{el}$ is the angle step in elevation. Additionally, as in the proposed bistatic configuration the elevation aperture is ensured by a single satellite, the Doppler bandwidth is only half of the monostatic and bistatic with a moving transmitter and receiver cases. This has the same effect in resolution, which is only half as in the previously mentioned configurations. Hence, twice the angular aperture ($\vartheta_{ap_{el}} = 3.44^\circ$) must be covered to obtain a metric resolution. On the other hand,

the maximum angular (or orbital) velocity to avoid ambiguities for a given PRF_{el} is the same, since the resolution and Doppler bandwidth are intrinsically binded.

$$\delta_{el} = \frac{\omega_{el} S_{PS}}{B_{D_{el}}} \quad (4.42)$$

The maximum satellite orbital velocity constraint can thus be extrapolated from the above expression.

$$v_{SAT_{el}} = \omega_{el} R = \frac{\delta_{el} B_{D_{el}}}{S_{PS}} R \quad (4.43)$$

Therefore, if the satellite arrangement's azimuthal movement is considered negligible, for a metric resolution and after the applied tolerance:

$$v_{SAT_{el}} = \frac{\delta_{el} PRF_{el}}{S_{PS} K_e} R \approx \frac{1 \times 2.33 \times 10^{-5} \times 10^4}{1180 \times 1.1} \approx 0.180 \text{ mm/s} \quad (4.44)$$

4.5 Mission Duration

The management of ambiguities in azimuth and elevation deeply impact the mission time and operational constraints. The total mission T_m duration is:

$$T_m = \left(N_{el} + \frac{2\vartheta_{ap_{az}}}{360} \right) [P_{orb_S} \pm P_{orb_{SAT}}] \quad (4.45)$$

Where N_{el} is the number of elevation compressed pulses, given by:

$$N_{el} = \frac{2\vartheta_{ap_{el}}}{\omega_{el} (P_{orb_S} \pm P_{orb_{SAT}})} \quad (4.46)$$

If the elevation orbital velocity is $\omega_{el} = 0.1988 \text{ rad/s}$ (i.e. the maximum velocity to respect the ambiguity constraint at $f = 2.65 \text{ GHz}$) aperture in elevation is $2\vartheta_{ap_{el}} = 5.47^\circ$ and the aperture in azimuth is $2\vartheta_{ap_{az}} = 11^\circ$, the total mission duration is 56 days, 8 hours and 7 minutes or, more practically, 9 weeks. Within the scope of Hera mission this is beyond the maximum time established earlier in this chapter. The expected time-line for the ASPECT CubeSat also envisions a commissioning period in the beginning of the mission and a contingency period in the end of the mission [103]. As the previously proposed timespan of operations for the tomographic experiment not only does not allow a margin but is beyond the defined maximum time, an alternative for reducing the mission duration is discussed. In fact, a possibility to reduce the mission time without sacrificing the quality of the output image is to artificially decrease the relative orbital period between Didymos B and the azimuthal plane of both sensors. This is equivalent to artificially generate an azimuthal orbital velocity component to the sensor arrangement, in the opposite direction of Didymos B's orbit. Howbeit, there is an inherent limit for how much the sensor's azimuthal orbital velocity can be increased and still keep the configuration under study. Put simply, it is necessary to ensure that the satellites do not escape the gravitational influence of Didymos. This

limit is determined by the well-known escape velocity $v_{SAT_{esc}}$.

$$v_{SAT_{esc}} = \sqrt{\frac{2GM}{R}} \quad (4.47)$$

For an orbit of radius $R = 10$ km and for a $GM_{DA} = 35.225 \text{ m}^4\text{s}^{-2}$, the escape velocity is $v_{SAT_{esc}} = 83.9$ mm/s. This is indeed the same for any orbit with $R = 10$ km, as it is also the case as the "vertical" orbit performed by one of the satellites in the elevation direction. However, in this dimension, the maximum velocity is determined by the requirement previously described for an aliasing-free image. To reduce the mission duration, it is proposed that the satellites possess an azimuthal orbital velocity component lower but close to the escape velocity, for example $v_{SAT} = 80$ mm/s, contrary to Didymos B translational motion direction. In this case, the mission duration is 55 days, 13 hours and 44 minutes, which even though represents a decrease of approximately a day in total mission time, can be important for the integration with other experiments. In this case, for example, mission completion is still within 8 weeks time.

4.6 Further Enhancing the Subsurface System Performance

A ground penetrating radar (GPR) for asteroid investigation require overcoming the deterioration suffered by the transmitted signal at any interface inside the asteroid itself on top of the free-space losses.

4.6.1 Free-space and Asteroid Path Loss

The free-space path loss can be determined following the Friis equation [105] as:

$$L_{FS} = 20 \log_{10} \left(\frac{4\pi \times 2R}{\lambda} \right) \quad (4.48)$$

The two-way path loss within the internal structure of Didymos L_{PLD} can be modeled as [1]:

$$L_{PLD} = 2 \times 0.091 f \sqrt{\epsilon'_r} \tan \delta d \text{ [dB]} \quad (4.49)$$

Where f is the operating frequency (MHz), ϵ'_r is the real part of the relative electric permittivity of the asteroid, $\tan \delta$ the loss tangent and d is the path within the asteroid (m). Based on Looyenga's mixture formula [1], for S-type asteroids without porosity, ϵ'_r ranges between 7 and 10 and the maximum loss tangent is $\tan \delta = 0.01$. A body with 40% porosity is chosen as representative of Didymos [1]. Consequently, its relative electric permittivity real part is expected to range between approximately 4 and 5 and the loss tangent is roughly $\tan \delta = 0.008$.

The two-way path loss along Didymos B for multiple frequencies is shown in Figure 4.8.

Another aspect yet to consider is the incidence angle. The path loss within the asteroid is ultimately altered by this factor and to present a trustworthy result it must be considered. The worst case is when the satellites are further apart. That is when a full elevation aperture is considered,

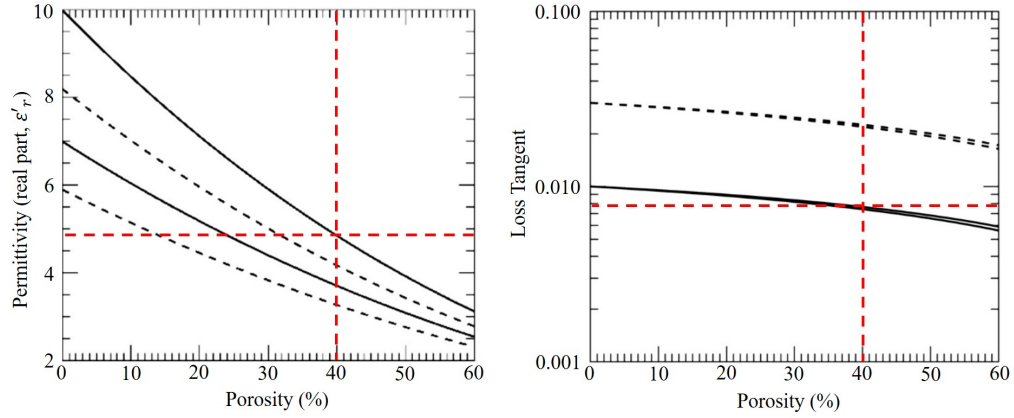


Figure 4.7: Real permittivity and maximum loss tangent versus porosity for S-type (solid lines) and C-type asteroids (dashed lines) based on Looyenga mixture formula. Dashed red vertical and horizontal lines mark the values for a body with 40% porosity [1].

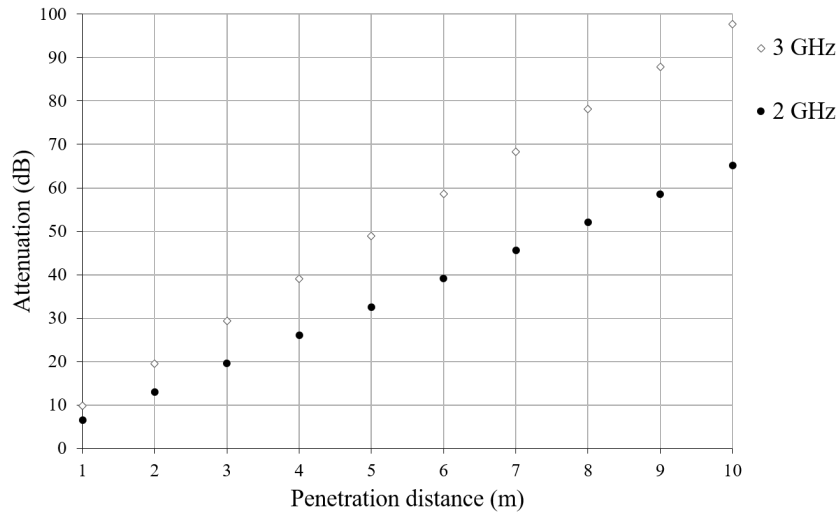


Figure 4.8: Two-way propagation losses within Didymos B for 2GHz (darker dots) and for 3GHz (lighter dots).

along with the initial elevation offset. Let us assume an angular elevation aperture of $2\vartheta_{ap_{el}} = 5.47^\circ$ and an initial elevation offset of $\vartheta_{el_0} = 25^\circ$. The resulting worst case incidence angle is $\theta_i = 2\vartheta_{ap_{el}} + \vartheta_{el_0} \approx 0.484 \text{ rad}$. Using the Snell-Descartes law (Equation 3.23), and assuming that the asteroid is a non-magnetic media ($\mu_{r_{DB}} = 1$):

$$\theta_t = \arcsin \left(\frac{\sqrt{\epsilon_{r_{fs}} \mu_{r_{fs}}} \sin \theta_i}{\sqrt{\epsilon_{r_{DB}} \mu_{r_{DB}}}} \right) = 0.210 \text{ rad} \quad (4.50)$$

Being, respectively, the electrical permittivity and magnetic permeability of free-space $\epsilon_{r_{void}} =$

$\mu_{r_{void}} = 1$. This means that the vertical penetration distance can be formulated as:

$$d_{pen \text{ vertical}} = \frac{d}{\cos \theta_t} = 1.0224 \times d \quad (4.51)$$

This difference might seem negligible but might account for a reduction of signal-to-noise ratio of almost 1dB at merely 5 meters of penetration for the considered asteroid properties.

4.6.2 Resolution Fine Tuning

Since the volumetric resolution is determined by the coarser resolution of all the dimensions, one could erroneously conclude that the optimal scenario would be to design the radar system for the same resolution in all dimensions. Nonetheless, this is not the case for every situation.

Speckle confers a random aspect to SAR generated images or volumes, but may not be considered as a simple noise. It is, in fact, tightly related to the measurement principle and to the inherent contribution of multiple scatterers within each resolution cell. The resulting integrated response is random in phase and amplitude and is shown to follow a Normal distribution over homogeneous areas. Averaging different perspective samples, i.e. different azimuth or elevation samples, also provides a simple low-pass filter-like filter, reducing the speckle granular effect in the final image. Therefore, if the resolution in this dimensions is smaller than the range resolution, they can be combined coherently. Essentially, by means of an averaging process thereby improving the output signal-to-noise ratio by an azimuth/elevation averaging gain, respectively $G_{I_{avg,az}}$ and $G_{I_{avg,el}}$.

Whilst generating the final output images/volume, an additional processing step is needed for its correct visualization, if the resolutions differ of more than the size of an azimuth/elevation pixel. Since range resolution is coarser than the cross-range or elevation resolution, the aspect ratio of the illuminated area will end up incorrect without any correction. This factor affects the perception of the images/volume itself and must, therefore, be corrected. The chosen method for solving this problem is to average consecutive azimuth or elevation samples, as a final processing step, until all resolutions are equivalent. In this way, the patches, or pixels (voxels¹), from the image are approximately quadrangular (cubic) and, thus, more eagerly understandable by a human brain.

Nevertheless, reducing the resolution brings a nefarious effect to the target area gain. In essence, the intensity of the distributed target reflectivity σ_0 is by definition amplified by the pixel dimensions for each SAR image generated by an azimuth aperture (i.e. for each elevation sample). The target area gain (TAG) is given by:

$$TAG = \frac{4\pi\delta_r\delta_{az}}{\lambda^2} \quad (4.52)$$

Fundamentally it represents the gain of an equivalent antenna with the dimensions of the image's patch. This is complementary to the definition of target reflectivity discussed in [subsection 2.1.1](#). However, this apparent gain for coarser resolutions is occluded by the inherent principle of obtaining a coarser azimuth resolution. This is that the aperture itself is smaller, thus less pulses are

¹Voxel is the volume-equivalent of a pixel. It represents a value on a regular grid in three-dimensional space.

accumulated, resulting in less azimuth compression gain.

$$G_{az_{proc}} \approx N_{az} = \frac{2\vartheta_{ap_{az}} PRF_{az}}{w_{SS} L_a} = \frac{\lambda PRF_{az}}{\delta_{az} w_{SS}} \quad (4.53)$$

Therefore, the effect of coarser or finer azimuth resolutions in *TAG* is compensated by $G_{az_{proc}}$, therefore, the only real contribution to the output SNR is created by the averaging process initially described in this subsection.

4.6.3 Pulse Bursts for Coherent Averaging

The losses experienced by subsurface penetration might demand additional signal processing compensation. Considering typical deep-space missions energetic and size constraints, the combination of several observations within the same azimuth/elevation bin provide a rather useful and efficient solution for increasing the signal-to-noise ratio. This improvement can be translated (in dB) in terms of the total number of range profiles averaged as $10\log_{10} N_{coh}$.

The aforementioned operation allows the integration of over $N_{coh} > 100$ pulses due to the low relative velocity in azimuth. However, it brings also an energetic constraint, since there is an underlying increase in the pulse duty cycle, since the effective pulse repetition frequency PRF_{eff} is increased by a factor of N_{coh} , as:

$$P_{Tx_{avg}} = P_{TX} \left(D + \frac{1-D}{5} \right) \quad (4.54)$$

$$D = \tau \times PRF_{eff} \times N_{coh} \quad (4.55)$$

It is readily understandable from the previous equations that specially when the duty cycle is low, it is much more beneficial to increase the number of coherently accumulated pulses, than the transmitted peak power. The previous statement is correct providing that, naturally, it is indeed possible to transmit the amount of pulses envisioned and that the pulses are transmitted in a burst, which ideally abolishes considerable alterations to the transition phases.

4.7 Time Synchronization and Guidelines for a Possible Communication Protocol

Synchronization constraints related to frequency drift impose limitations on the measurement accuracy. The intervals between the echo window and the PRF of the receiver should be a fixed value to preserve a stable phase relationship. If there is a time synchronization error, scatterers will not preserve the expected position within the echo sampling window (or pulse repetition interval) in subsequent azimuth/elevation pulses. Consequently, the phase relation of the sampled data would be destroyed. It is thus mandatory that both clocks are synchronized and syntonized and that the update time is sufficiently brief. Otherwise, a harsh requirement is imposed on the on-board clock, which is typically not reasonable for deep-space applications. Moreover, it is crucial that

their update times are shorter than a complete azimuth aperture, since the proposed scenario takes advantage of exactly the substantial time Didymos B requires to perform a full orbit. Additionally, low SNR situation caused by the transmission of a radio wave through the asteroid demands a coherent accumulation to obtain better detection properties. Moreover, it is mandatory that the measurements occur inside the deduced aliasing free time framing.

Spacecraft coordinates its navigation and operations by means of an inter-satellite communications system. A proposed time line is discussed in this section. Assuming a time-multiplexed protocol is used for communications, in which every second is divided for example in 20 slots (Figure 4.9). This is the equivalent as 50ms per time-slot. Let's say the first slot is associated with a packet exchange between spacecrafts to determine the link state and perform ranging and time synchronization operations.

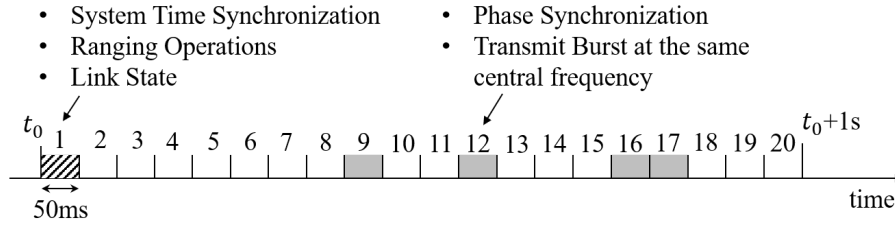


Figure 4.9: Possible time-multiplexed protocol.

4.7.1 Time Synchronization and Syntonization

Timekeeping ability requirements are hereby presented for establishing the requisites regarding the internal clocks. Timekeeping ability is derived from the modified Allan Deviation [113]. It is sometimes also called the time-interval error (TIE) due to frequency drift that comes associated with a time since being synchronized and syntonized. The time stability capability of several clocks is shown in Figure 4.10.

Following the requirement for time stability for bistatic radar presented in subsection 2.2.2 and given by [42]:

$$\delta t = \frac{1}{20B\Delta t_{update}} = \frac{1}{20 \times 50MHz \times \Delta t_{update}} \quad (4.56)$$

If the update time Δt_{update} is 1s, coincident with the ranging operation, the needed timekeeping stability of the on-board clock becomes $\delta t = 1ns$. This is reasonable for available space-rated clocks, such as oven-controlled crystal oscillators (OCXOs), as shown in Figure 4.10.

Assuming an architecture as described would enable an accurate positioning at every second, which is sufficient recognizing that the dynamics of the scenario are relatively slow and predictable to some extent. This mechanism can provide synchronization even when the experiment

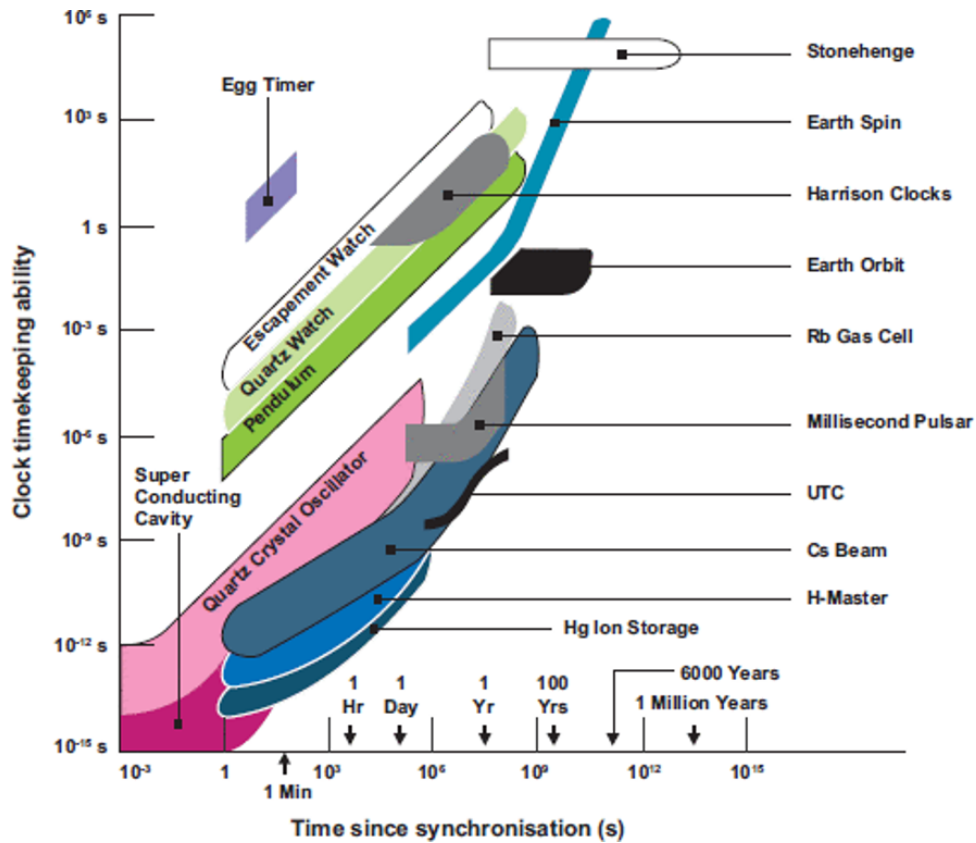


Figure 4.10: Comparison of the timekeeping stability of clocks as a function of time since being synchronized and syntonized [42][113].

is not transmitting pulses and therefore during the entire elevation aperture. Phase synchronization amongst each transmitted pulse, however, can even be updated more frequently. This is due to the direct wave received at each transmission whose expected sharp peak after the matched filter operation (Figure 4.11) is sufficient to provide the necessary time-reference [114][115].

4.7.2 Time-frames for Pulse Bursts

A transitory period is typically a characterizer of a change in central frequency for a transmitter or receiver system. Thenceforth, it is in advantageous that this periods do not occur often. The transmission of a pulse burst for improving the signal-to-noise ratio at the receiver certainly benefits from the exploiting the full system capacity in terms of number of transmitted pulses. However, the intrinsic trade-off with the power consumption has to be carefully managed. It is proposed that bursts at the same central frequency are transmitted at a single time-slot, allowing for transition phases amongst the same time-slot, if they are in the order of ms.

Let us assume that the transmitter is far enough from the receiver, that the latter does not saturate whilst receiving the direct wave. In this case, pulses can be transmitted sequentially, providing that no range ambiguities arise in the output image. The underlying problem is illustrated

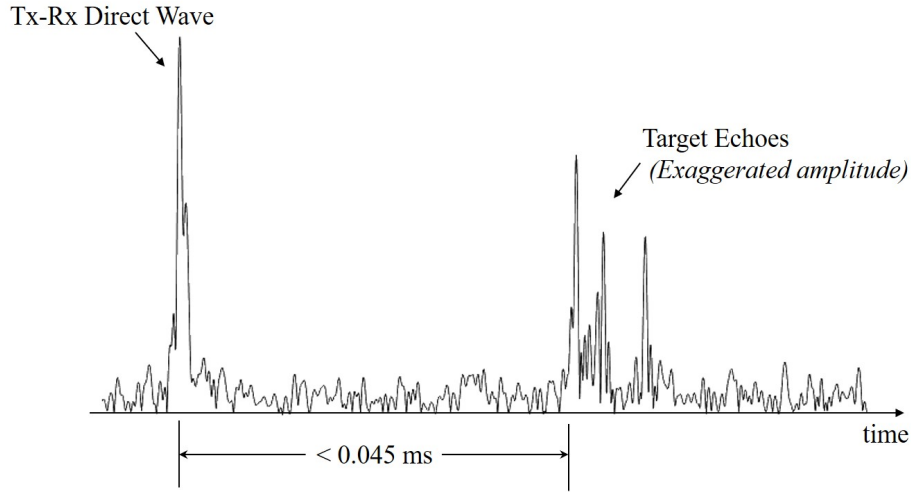


Figure 4.11: Expected received signal from Didymos asteroid after the matched filter operation for orbiters at $R = 10$ km, initial elevation angle $\vartheta_{el_0} = 25^\circ$ and azimuth aperture angle of $2\vartheta_{ap_{az}} = 11^\circ$.

in Figure 4.12. Firstly, there is an intrinsic delay between the transmission and reception due to the

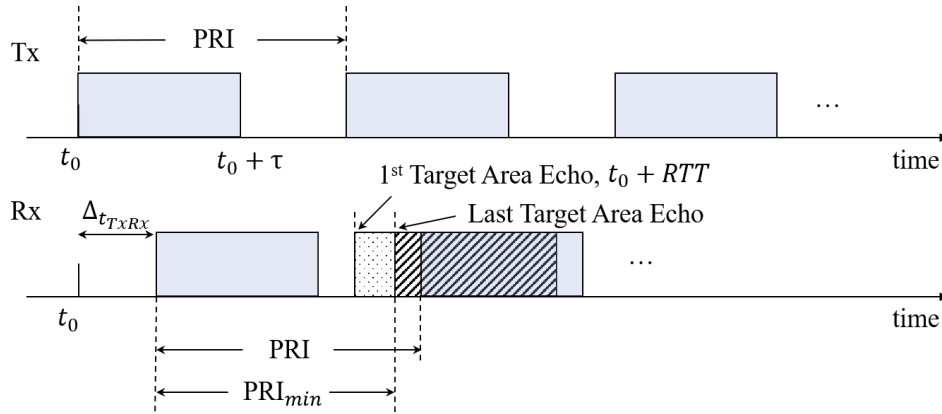


Figure 4.12: Minimum PRI to avoid range ambiguities due to the next transmitted pulse in a burst (Considering a pulse duration τ of less than the difference between the round-trip time RTT and the separation in time between the transmitter and receiver $\Delta_{t_{TxRx}}$).

bistatic configuration. To respect the condition regarding the time-bandwidth product presented in subsection 4.1.2, we consider that the pulse duration τ is less than the difference between the round-trip time (RTT) and the separation in time between the transmitter and receiver $\Delta_{t_{TxRx}}$. For satellites at an orbit with $R = 10$ km radius, initial elevation offset $\vartheta_{el_0} = 25^\circ$ and an elevation aperture of $2\vartheta_{ap_{el}} = 5.47^\circ$, the maximum distance between satellites is $d_{SAT-SAT} \approx 4.794$ km. This is the equivalent to a difference of $\Delta_{t_{TxRx}} \approx 15.98 \mu s$ in time. The pulse round trip time is determined by the distance to Didymos B, which is, for the mentioned conditions equivalent to at least $RTT \approx 58.84 \mu s$. The target area echoes are expected to last, in the worst case, roughly $\Delta_{t_{Target}} \approx \frac{2(D_S + D_P + S_{PS})}{c} = 14.2 \mu s$. A safety margin is considered and this value is assumed to be

$\Delta_{t_{Target}} = 20 \mu s$. If the PRI is less than PRI_{min} , then the next pulse overlaps in time with the target area echoes. This also limits the number of pulses that is possible to accommodate in a 50 ms time-slot. For a pulse of duration $\tau = 40 \mu s$, the minimum time between transmitted pulses is $PRI_{min} = 60 \mu s$. If the number of pulses in a burst is $N_{coh} = 150$, the total burst duration is at least $\Delta_{t_{Burst}} \approx 9 ms$, which can still be comfortably accommodated within a time-slot duration.

4.7.3 Effective Pulse Repetition Frequency Constraint

Allocating a time-slot for a single central frequency burst results in the necessity of designating an equal number of slots to the experiment as the number of pulses used to form a high-resolution wide-bandwidth pulse (discussed in [subsubsection 4.1.2.1](#)). Withal, having an effective pulse repetition frequency in azimuth higher than one pulse per second ($PRF_{eff_{az}} > 1 pps$), results in an impossibility of using the reasoning behind the protocol shown in [Figure 4.9](#) without further adaptation. In addition, the ISL does have to be transferring control data or data originated by other experiments. Thus, there is also a reasonable limit of time-slots that can be readily available for the bistatic experiment. For simplicity, we consider the $PRF_{eff_{az}} = 1 pps$, which enables a single slot for each frequency and we also consider a maximum of 4 accumulated pulses for the intended high-resolution. Therefore, the experiment is presented as permanently consuming 4 time-slots at every second while functioning. For an azimuth aperture of $2\vartheta_{ap_{az}} = 11^\circ$ and an azimuthal velocity of the sensor arrangement of $v_{SAT} = 80 \text{ mm/s}$, this is equivalent to approximately 21 minutes at every 11.3 hours. Further optimization regarding this constraint can be done bearing the actual ISL protocol and requirements in mind.

4.8 Data Rate and Volume

Considering the combination of narrower bandwidth pulses to generate a high-resolution wider-bandwidth pulse, the sampling frequency can be under $f_s = 100 \text{ MHz}$, which is acceptable for deep-space technology available [\[116\]](#). The duration in time of Didymos B is:

$$\Delta_{t_{DB}} \approx \frac{2D_S}{c} = 1.1 \mu s \quad (4.57)$$

At a sampling frequency of $f_s = 60 \text{ MHz}$, this corresponds to 64 samples. However, if a stepped waveform is used, there are 64 samples for each narrow bandwidth pulse. If 4 pulses are used, Didymos B is fully represented in 256 samples. Considering the target area as the Didymos asteroid, echoes are expected to last, in the worst case, roughly:

$$\Delta_{t_{Target}} \approx \frac{2(D_S + D_P + S_{PS})}{c} = 14.2 \mu s \quad (4.58)$$

In this case, for a single pulse, there are 850 samples of interest. For the intended high-resolution, the data is contained in 3400 samples. As in BSAR, the peak location is also relevant for phase synchronism within each pulse, some samples around the peak can also be collected. If 20 samples

are collected around each pulse's peak, then an additional 80 samples are required at each effective pulse repetition.

The data rate can be extrapolated from the pulse repetition frequency, along with the previously calculated duration of the target area in samples. Considering the total Didymos system and the direct wave, if the wide-bandwidth pulse repetition frequency is $PRF_{eff_{az}} = 1$ pps, then the data rate (in Ksps) is:

$$Data\ Rate = \frac{(\Delta_{t_{target}} + N_{peak})N_p f_s PRF_{eff_{az}}}{1024} = \frac{3480}{1024} \approx 3.40\ ksps \quad (4.59)$$

Being N_p the number of narrow-band pulses used to form the high-resolution one and N_{peak} the number of stored peak samples.

The volume of generated data is naturally dependent on the observation time T_{obs} . The latter is given by:

$$T_{obs} = \left(\frac{2\vartheta_{ap_{az}} N_{el}}{360} \right) [P_{orbs} \pm P_{orb_{SAT}}] \quad (4.60)$$

Being $2\vartheta_{ap_{az}}$ the azimuth total angle aperture, in degrees. If $2\vartheta_{ap_{az}} = 11^\circ$, the number of elevation pulses is $N_{el} = 118$ and the azimuthal orbital velocity of the satellites is $v_{SAT} = 80$ mm/s, then the total data generated (in Msamp) is:

$$Data\ Volume\ (Msamp) = \frac{Data\ Rate\ (Ksps) \times T_{obs}(s)}{1024} = \frac{3.40 \times 149339}{1024} \approx 496\ Msamp \quad (4.61)$$

If each sample occupies 4bytes, 2 for each the real and imaginary parts, then the Data Volume can be also expressed as:

$$Data\ Volume\ (Gbit) = \frac{Data\ Volume\ (Msamp) \times 32}{1024} \approx 15.49\ Gbit \quad (4.62)$$

From which, the data corresponding to some samples around the pulse for synchronism and Didymos B is about:

$$Data\ Volume\ DB(Gbit) \approx 1.50\ Gbit \quad (4.63)$$

This amount of data generated is reasonable for an asteroid remote sensing mission [1].

4.9 Summary of the Proposed Geometry and System Parameters

Previous sections established relations among key parameters for surface and subsurface investigations of Didymos. A compiled version of the radar system and geometry parameters is shown in [Table 4.1](#). The resolution possible to obtain with the selected parameters is approximately metric in the three-dimensional space. It is, in fact, dictated by the elevation aperture, as it is possible to notice from the following equations.

$$\delta_r \lesssim \frac{c \sec(\vartheta_{el0} + 2\vartheta_{ap_{el}})}{2B} \approx 1.03\ m \quad (4.64)$$

Radio	Frequency (nominal)	2.65 GHz
	Signal Modulation	Stepped Chirp or Phase-Coded
	Bandwidth Pulse (Sweep)	50 MHz (200 MHz)
	Pulse Duration (Sweep)	40 μ s (160 μ s)
	Sample Rate	60 MHz
	Pulse Repetition	1 s (0.25 s)
	Power Tx	4 W
Geometry	Distance (nominal)	10 km
	Elevation Initial Offset	25°
	Nadir Angle	0°
Signal Processing/Geometry	Azimuth Aperture	11°
	Azimuth Orbital Velocity	80 mm/s
	Elevation Aperture	5.47°
	Elevation Velocity	0.1977 mm/s
	N coherent sums	300

Table 4.1: Radar Parameters for the tomographic bistatic synthetic aperture radar

$$\delta_{az} \lesssim \frac{\lambda(R \cos \vartheta_{ap_{az}} - S_{PS})}{4R \sin \vartheta_{ap_{az}}} \approx 0.26 \text{ m} \quad (4.65)$$

$$\delta_{el} \lesssim \frac{\lambda(R \cos \vartheta_{ap_{el}} - S_{PS})}{2R \sin \vartheta_{ap_{el}}} \approx 1.04 \text{ m} \quad (4.66)$$

For an angle aperture of $2\vartheta_{ap_{az}} = 11^\circ$, number of pulses accumulated in azimuth is $N_{az} = 1242$. For the elevation case, the number of accumulated pulses is $N_{az} = 118$ for an aperture of $2\vartheta_{ap_{el}} = 5.47^\circ$. The nadir² angle was chosen to be zero.

The mission duration is:

$$T_m = \left(N_{el} + \frac{2\vartheta_{ap_{az}}}{360} \right) [P_{orb_S} \pm P_{orb_{SAT}}] \quad (4.67)$$

Where T_m is the mission duration and results in 55 days, 13hours and 44minutes or, equivalently, a time-span of 8 weeks. Over this period, the experience shall be functioning in radar mode for the observation time for each azimuth aperture $T_{obs_{az}}$, in seconds:

$$T_{obs_{az}} = \left(\frac{2\vartheta_{ap_{az}}}{360} \right) [P_{orb_S} \pm P_{orb_{SAT}}] \approx 21 \text{ min} \quad (4.68)$$

This observation time must be repeated at every $P_{orb_S} \pm P_{orb_{SAT}} \approx 11.3 \text{ hours}$. The observation time throughout the entire mission is:

$$T_{obs} = T_{obs_{az}} N_{el} = 146673 \text{ s} \quad (4.69)$$

²the satellite viewing angle directly downward, in this case, towards the Didymos asteroid

From this, the expected data rates (in Msps) and volume (in Gbit) for a target area that includes Didymos A and B was computed:

$$Data\ Rate = \frac{(\Delta_{Target} + N_{peak})N_{pfs}PRF_{eff_{az}}}{1024} = \frac{3480}{1024} \approx 3.40\ ksp/s \quad (4.70)$$

$$Data\ Volume\ (Gbit) = Data\ Rate\ (Gsp/s) \times T_{obs} \times 32 = \frac{3.40 \times 146673 \times 32}{1024 \times 1024} \approx 15.2\ Gbit \quad (4.71)$$

The peak power is the double of the intended peak transmission power P_{TX} (50% power efficiency), i.e. $P_{peak} = 8\ W$, and the average power consumption is given by:

$$P_{Tx_{avg}} = P_{TX} \left(D + \frac{1-D}{5} \right) = 1.9072\ W \quad (4.72)$$

$$D = \tau \times PRF_{eff} \times N_{coh} = 3.2\% \quad (4.73)$$

The average power consumption over the entire mission can also be computed as:

$$P_{Tx_{avg,mission}} = P_{Tx_{avg}} \frac{T_{obs}}{T_m} = 0.058\ W \quad (4.74)$$

The $N_{coh} = 300$ averages considered, result in a burst minimum time of $\Delta_{t_{Burst}} = 18\ ms$, which can be accommodated in a 50 ms ISL time-slot.

For this solution, the minimum azimuth pulse repetition frequency is $PRF_{az} \approx 0.95\ pps$ and the main spacecraft is expected to ride very close to the maximum elevation orbital velocity $v_{SAT_{el}} = 0.1978\ mm/s$ (with the applied safety margins).

4.9.1 Link Budget

A link budget for the BSAR approach for Didymos observation is presented and discussed in this section. The fulfillment of this table was based on trade-offs amongst the requirements determined to be most influential whilst designing a deep-space remote sensing SAR system. However, not all systems are the same and specially no space-mission plan remains unaltered for much time. Hence, they were kept as generic as possible.

The link budget is expressed in terms of the noise equivalent sigma-zero, which itself is a function of the roughness and dielectric permittivity of the soil. [Table 4.2](#) gives a numerical meaning to the of the version radar equation (first discussed in [section 2.1](#)) for this experiment, presented from [Equation 4.75](#) to [Equation 4.80](#).

$$SNR = \frac{P_{TX} G_{TX} G_{RX} T A G \sigma_0}{L_{fs} L_{PLD} N_s R_T^2 R_R^2 L_{TX} L_{RX} L_r} \quad (4.75)$$

$$SNR_{img} = SNR \times G_{r_{proc}} \times G_{az_{proc}} \times G_{el_{proc}} \times G_{I_{avg,az}} \times G_{I_{avg,el}} \quad (4.76)$$

$$G_{r_{proc}} = \frac{a_{wr}\tau B}{L_r} \approx 0.75\tau B \quad (4.77)$$

$$G_{az_{proc}} \approx N_{az} = \frac{\lambda PRF_{az}}{\delta_{az} w_{ss}} \quad (4.78)$$

$$G_{el_{proc}} \approx N_{el} = \frac{2\vartheta_{ap_{el}}}{\omega_{el}(P_{orb_S} \pm P_{orb_{SAT}})} \quad (4.79)$$

$$NESZ = \frac{\sigma_0}{SNR_{img}} \quad (4.80)$$

Tx Power (P_{TX})	36.0 dBm
Tx Antenna Gain (G_{TX})	13.9 dB
Tx Antenna Losses (L_{TX})	(-) 2 dB
Free Space Path Loss (L_{fs})	(-) 239.7 dB
Asteroid Path Loss (L_{PLD})	(-) 44.2 dB
Pixel Area Gain (TAG)	24.2 dB
Rx Antenna Gain (G_{RX})	13.9 dB
Rx Antenna Losses (L_{RX})	(-) 2 dB
System Losses (L_r)	(-) 5 dB
Noise Power (N_S)	(-) -96.2 dBm
Coherent Sums Gain ($N_{coh,dB}$)	24.8 dB
Range Compression Gain ($G_{r_{proc},dB}$)	37.8 dB
Azimuth Compression Gain ($G_{az_{proc},dB}$)	30.9 dB
Elevation Compression Gain ($G_{el_{proc},dB}$)	20.7 dB
Image Azimuth Averaging Gain ($G_{Iavg,az}$)	6 dB
Image Elevation Averaging Gain ($G_{Iavg,el}$)	0 dB
Surface Noise-Equivalent Sigma-Zero ($NESZ$)	-59.9 dB m^2/m^2
4.5m Buried Target Noise-Equivalent Sigma-Zero ($NESZ$)	-20.2 dB m^2/m^2

Table 4.2: Link Budget for the tomographic bistatic synthetic aperture radar

As it is readily possible to conclude, the presented BSAR is capable of characterizing the subsurface of an asteroid (besides mapping it like in conventional synthetic aperture radar applications) up to 4.5 meters for targets with a distributed reflectivity of $\sigma_0 = -20.2 \text{ dBm}^2/m^2$ and at the surface for targets with a distributed reflectivity of $\sigma_0 = -59.9 \text{ dBm}^2/m^2$. This is within the expected for Earth-based rock and soil terrain [117]. The performance at several penetration distances is shown in Table 4.3.

An extended discussion is sequentially presented on how the proposed system could be changed in the scope of strict mission requirements affecting one of the chosen parameters.

Penetration Distance (m)	0	1	2	3	4	5	6	7	8	9	10
NESZ (dB m^2/m^2)	-59.9	-51.0	-42.2	-33.4	-24.6	-15.8	-6.9	1.9	10.7	19.5	28.4

Table 4.3: Signal-to-noise ratio performance (Noise-equivalent sigma zero) for vertical penetration distances up to 10 m at $f = 2.65$ GHz.

4.9.2 Increased Detection and Penetration

The capability to detect buried scatterers is naturally one of the goals of this mission, as is being able to adequately map the surface. Increasing the transmitted power would be an obvious solution. However, in a low-powered platform such as a deep-space satellite (specially CubeSats), this is usually a precious resource. An analysis is therefore presented on how altering other key parameters affects this objective. Again, state-of-the-art microwave elements are neglected, although they could positively impact the antenna gains, the system losses and the noise power.

4.9.2.1 Altering Frequency

Frequency is a crucial parameter, that influences the type of surface and subsurface that is possible to detect. Thence, one of the design constraints was to select a central frequency above 2 GHz.

Working at lower frequencies however, would indeed improve the signal to noise ratio. At $f_c = 2.3$ GHz, for example, for a penetration distance of 5 m $NESZ = -21.5$ dB m^2/m^2 and at the surface, $NESZ = -59.9$ dB m^2/m^2 . To obtain the same resolution, however, the angular azimuth aperture and elevation aperture have to be wider in a way that, respectively, $2\vartheta_{ap_{az}} = 13.0^\circ$ and $2\vartheta_{ap_{el}} = 6.3^\circ$. The apertures are also chosen so that the ambiguity requirements are respected in both dimensions ($PRF_{az_{min}} = 0.979$ pps and the velocity in elevation is at its maximum at $v_{SAT_{el}} = 0.1978$ mm/s). In this case, the mission duration would increase to 64 days, 1 hours and 12 minutes (roughly 10 weeks) and the total data to 20.72 Gbit. The experience has to be working for almost 25 min for every (apparent) Didymos orbit. In this case, for several penetration distances, the signal-to-noise performance is shown in Table 4.4.

Penetration Distance (m)	0	1	2	3	4	5	6	7	8	9	10
NESZ (dB m^2/m^2)	-59.9	-52.2	-44.5	-36.9	-29.2	-21.5	-13.9	-6.2	1.4	9.1	16.8

Table 4.4: Signal-to-noise ratio performance (Noise-equivalent sigma zero) for vertical penetration distances up to 10 m at $f = 2.3$ GHz

For higher frequencies, (e.g. for $f_c = 2.85$ GHz) a smaller aperture is needed to achieve a metric resolution ($2\vartheta_{ap_{az}} = 10.2^\circ$ and $2\vartheta_{ap_{el}} = 5.1^\circ$). However, the signal-to-noise is reduced, for a penetration distance of 5m, $NESZ = -12.5$ dB m^2/m^2 and at the surface, $NESZ = -59.9$ dB m^2/m^2 . The ambiguity requirements are respected in both dimensions ($PRF_{az_{min}} = 0.950$ pps and

the velocity in elevation is at its maximum at $v_{SAT_{el}} = 0.1972$ mm/s). In this case, the mission duration would decrease to 51 days, 19 hours and 19 minutes (roughly 8 weeks) and the total data to 13.1 Gbit. The experience has to be working for 23 min for every (apparent) Didymos orbit. To obtain the same SNR at 4.5 m of penetration distance as the selected frequency ($f_c = 2.1$ GHz for which $NESZ = -20.2$ dB m^2/m^2), the elevation aperture must be increased to $2\vartheta_{ap_{el}} = 8.40^\circ$, resulting in also a slower orbital elevation velocity $v_{SAT_{el}} = 0.1196$ mm/s to respect ambiguity constraints. The azimuth aperture cannot be increased without increasing the number of ISL time-slots occupied, since that would increase the minimum PRF_{az} . In fact, increasing the ISL needed time-slots per second, however, could dictate the in-feasibility of the solution, since numerous other experiments/operations will most likely require the otherwise monopolized ISL bandwidth by this experiment. Therefore, the mission duration must be approximately of 21 weeks.

An explicit trade-off can be noticed in this examples. That is mission duration versus signal-to-noise ratio at the receiver. A lower frequency could be an option if the mission time is extended beyond 8 weeks. The central frequency of $f_c = 2.65$ GHz was determined as an optimal trade-off between this two, providing mission completion within 8 weeks and a capability of imaging 4.5 m buried targets with distributed target reflectivity of less than $\sigma_0 = -20$ dB m^2/m^2 . Furthermore, this frequency is within the operational range of the Arecibo Observatory and is capable of supporting the scanning the asteroid at higher resolution and versatility [1].

4.9.2.2 Increasing Bandwidth and Pulse Duration

Increasing the transmitted pulse bandwidth would increase the range compression gain ideally so would increasing the pulse duration or the number of combined narrow-bandwidth pulses. However, in this work, the time-bandwidth product was considered to be constrained at an upper limit of 2000 to guarantee the coherence for the entire pulse duration. In the case where a phase-coded waveform is used, it could be beneficial to use the length of a maximum length sequence (MLS), i.e. $2^k - 1$, where k is an integer. This factor is passive of a more adequate selection for a radar system with more detailed specifications. It will, in this analysis, remain as is. In this case, the bandwidth effects only the resolution and the consumed ISL resources.

4.9.2.3 Increasing the Azimuthal Effective Pulse Repetition Frequency

An increase in pulse repetition frequency increases the azimuth compression gain. A similar effect would have a decrease in the apparent angular velocity between the satellites and Didymos B ω_{SS} . However, this increase in PRF_{az} is restrained by the appearance of azimuth ambiguities and by the ISL resources consumed. A decrease in velocity would, as previously mentioned in [section 4.5](#), increase the mission duration time. For it to be noticed, in terms of SNR, the mission duration time would increase beyond the limit specified in the beginning of the chapter. Increasing the PRF would create a necessity to transmit more than one wide-bandwidth pulse per second. That would translate, if a burst occurs at a given central frequency per time-slot, into at least the double of the utilized ISL resources. A solution would be to increase the time-slot time. It was not

considered relevant to detail this case as it was believed to be too demanding in terms of system constraints.

4.9.2.4 Working at Non-nominal Distances

The nominal distance was defined to be 10 km as it is the distance at which most operations are expected to occur. It can however, be beneficial to decrease this distance. It influences the path loss in free-space (Equation 4.48), as well as the azimuth compression gain. This is due to an increase in the apparent angular azimuthal velocity w_{SS} . The elevation aperture could be reduced to $2\vartheta_{ap_{el}} = 5.4^\circ$ at $R = 9$ km and to $2\vartheta_{ap_{el}} = 5.34^\circ$ at $R = 8.5$ km, resulting in approximately the same mission time for the same resolution. The pulse duration can be decreased to be less than the difference between round-trip time and the separation between the transmitter and receiver, so that the technique to accumulate pulses in a burst is applied (subsection 4.7.2). Even in this case, an increase of signal-to-noise ratio of almost 3dB is possible ($NESZ = -22.6$ dB m^2/m^2 at 4.5 meters depth). Naturally, increasing the distance results in an SNR reduction. For an orbit with radius $R = 11.5$ km, at 4.5 meters of penetration, $NESZ = -16.4$ dB m^2/m^2 . The angular aperture in elevation must increase to $2\vartheta_{ap_{el}} = 5.58^\circ$ for the same resolution. Mission completion is obtained after the 9 week mark by one day. If the distance is larger, the ambiguity constraints get looser. However, for distances closer than roughly $R = 8.1$ km, w_{SS} must be decreased so that the azimuthal ambiguity constraint is respected.

In general, the system has the versatility to work at different distances, even within the mission time determined as maximum. It must nevertheless be adapted and/or corrections must applied to the the acquired data.

4.9.3 Obtaining a Finer Resolution

The three-dimensional resolution over the target area is stringently defined by science requirements. Howbeit a metric resolution was determined to be sufficient to obtain relevant information from NEA's [1], the mission impact of an acquisition with coarser and finer resolutions is hereby presented.

The voxel size in the developed solution is driven by the elevation resolution. This is the worst-case resolution in the several dimensions and the finer it is, the longer is the mission time. The range resolution can be set accordingly, since it can be increased to approximately $\delta_r = 0.89$ m without any additional time-slot occupied in the ISL and with a decrease in SNR of around half-decibel. It can be reduced to $\delta_r \approx 0.825$ m without any SNR reduction, by using an additional time-slot and to $\delta_r \approx 0.711$ m with the SNR loss and the additional time-slot. Therefore, if the elevation resolution is increased, the overall three-dimensional resolution can be finer. Figure 4.13 represents the evolution of mission duration for a specified resolution.

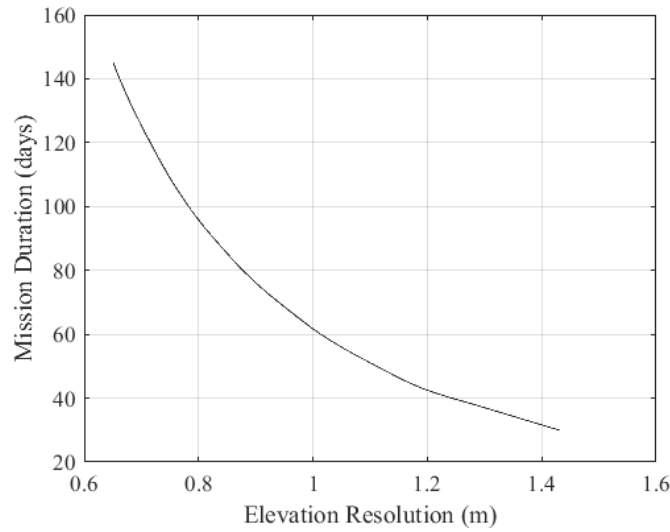


Figure 4.13: Elevation resolution (the limiting one) as a function of mission duration (days).

4.10 Key Solution Parameters Summarized

A summarized version of the main parameters selected for a tomographic bistatic synthetic aperture radar configuration for the investigation of Didymos surface and subsurface is shown in this section. It might prove useful for a brief overview of the developed solution without thoroughly reviewing the design choices or for comparison with other missions/solutions.

Design Parameters		Dependent Parameters	
Distance (nominal)	10 km	Burst Transmit Time	18 ms
Frequency (nominal)	2650 MHz	Resolution	≈ 1 m (3D)
Bandwidth Pulse (Sweep)	50 MHz (200 MHz)	Range Comp. Gain	37.8 dB
Pulse Duration (Total)	40 μ sec (160 μ sec)	Azimuth Comp. Gain	30.9 dB
Receiver Sample Rate	60 Msps	Elevation Comp. Gain	20.7 dB
Tx power	4 W	At the surface	NESZ = -59.9 dB m^2/m^2
Pulse repetition	1 s (0.25) s	4.5 m Pen. Dist	NESZ = -20.2 dB m^2/m^2
Data Generated	15.2 Gbit	Mission Duration	8 weeks
Azimuth Aperture	11.0°	Power max/mean acq/mean	8 W/ 1.80 W/ 0.058 W
Elevation Aperture	5.47°	Occupied Time-Slots	4
No. of Coherent Sums	300	Power-on Time	21 min every 11.3 hours

Table 4.5: Key parameters for Didymos tomographic bistatic synthetic aperture radar experiment

Chapter 5

Experimental Bistatic Tomographic Synthetic Aperture Radar

To simulate the geometry conditions of the proposed solution and the man-made interference free environment that is space, we developed a testbed in the University of Porto's anechoic chamber. An object of similar electrical permittivity at the wavelengths explored in this test and the proposed configuration in [chapter 4](#) was chosen. Moreover, to mimic Didymos B's orbital movement around the main Didymos body, the object was placed in a rotating platform, at a certain radius from its rotation axis. Then, wavelengths that allowed enough resolution and at the same time extend comparisons to the asteroid scenario were chosen. Two sensors were used, being moved slightly upwards for each azimuth complete rotation, to integrate pulses in elevation.

5.1 The asteroid model

Asteroids can present different morphologies, depending on their formation scenario. In this study, we assume that the asteroid Didymos is a rubble-pile. To study the feasibility of the configuration, an object closer to a layered-pile was chosen. In this way, the authors believe that the morphology could be more clearly investigated at microwave frequencies up to 30 GHz and inside the available controlled environment (the University of Porto's anechoic chamber). This layered-pile model has been simplified by considering only two main regions, with distinct electromagnetic properties: an outer shell, representing a first layer of rock and an inner region, representing a void inside the asteroid.

We studied the possibility of placing several objects to mimic this behavior. Interestingly enough, an object with fitting characteristics was available in the University of Porto. This object was nothing more than a human-like hollow doll that has a long history of experiments for the study of sound conducted by professor Diamantino Freitas (from University of Porto) and his students. A picture of this unexpected but effective asteroid model is shown in [Figure 5.1](#).

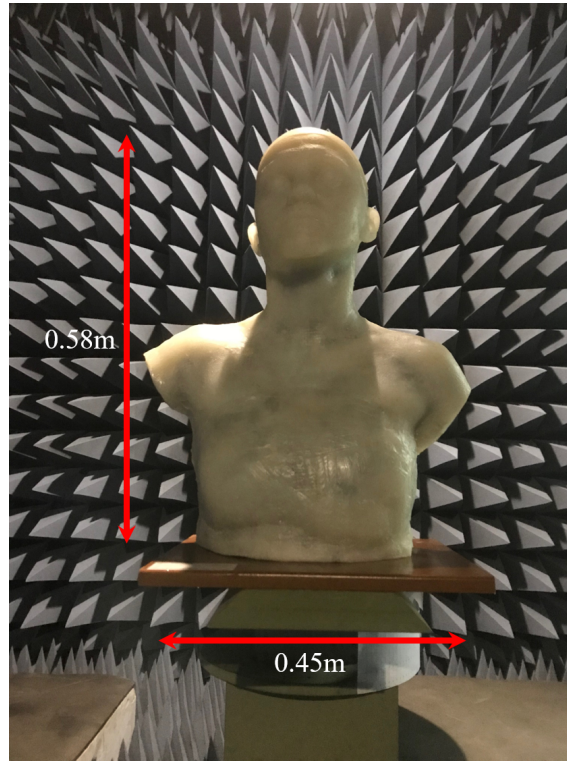


Figure 5.1: Doll front view.

5.1.1 Geometrical Aspects

The asteroid's dimensions are clearly too large for a study in a controlled environment such as the available anechoic chamber. Being so, the microwave analogy was used to reduce the dimensions of the object [118]. Microwave analogue measurements exploit the scale invariance of the Maxwell equations to rescale both the dimensions of the target and the wavelength by the same factor, keeping the dielectric properties constant. Considering the Didymos B whose largest dimension is expected to be about 163 m and analyzed at $f = 2.65$ GHz, the largest dimension of the analogue would still exceed 14 m at $f = 30$ GHz. As this dimensions are still too large for the developed setup, we chose to work with a smaller target in this study. The working frequency was chosen to be 17.5 GHz and the scale model can be included in a rectangular case of $0.58m \times 0.45m \times 0.2m$. The actual shape of Didymos B has a different shape than our scale model (let's say with a very high probability), although it was not possible to estimate accurately yet. Nevertheless a comparison between the size of the dimensions of a case enclosing the body enables the determination of a scale factor equal to about 123 (in terms of wavelengths) between our experiment and the real target. Indeed, even smaller scaled models have been proven to be useful to understand what kind of information can be retrieved [119]. Furthermore, the penetration determined for possible rocky and soil materials is below 10m, for which the scale-factor is roughly 86. A comparison between the layered structure and corresponding dimensions of the doll and the wavelength is shown in Figure 5.2.

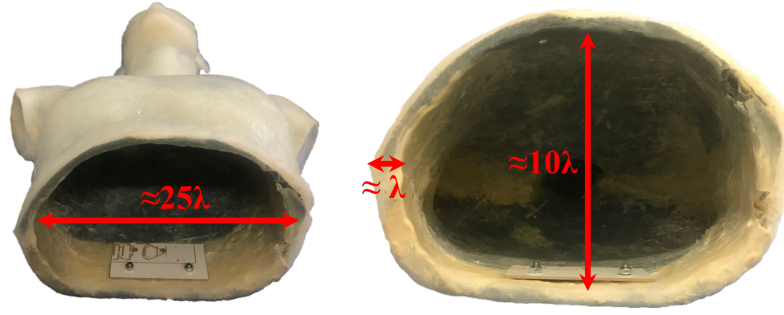


Figure 5.2: A comparison between the doll dimensions and the wavelength (at a frequency of 17.5 GHz).

5.1.2 Electromagnetic Aspects

In our model, we consider similarities with an asteroid with roughly 40% porosity, as in [1]. In this conditions, it was also considered to have a bulk real relative electrical permittivity in the range of $\epsilon_r = 4$ to $\epsilon_r = 5$ and a loss tangent of about $\tan \delta = 0.008$. The material of which each layer is made was chosen to keep the same permittivity values as the ones expected in the asteroid surface and subsurface (in the presence of a void). It was also of great importance to choose materials with a known permittivity value. Indeed, to simulate the void, the air inside the hollow doll was sufficient. For the outer rocky layer, there was the need for a material with permittivity close to the expected for the S-type asteroid's bulk composition. The doll's outer layer is composed by silicone rubber layer applied over a fiberglass structure. The respective permittivities are expected to be range approximately between $\epsilon_r = 3.1$ and $\epsilon_r = 4.6$ for the silicone rubber layer [120] for frequencies from $f = 9.6$ GHz to 26 GHz. For the fiberglass layer, the relative electrical permittivity can be from $\epsilon_r = 3.7$ to $\epsilon_r = 6.3$ for $f = 30$ GHz, which are similar to the values at $f = 10$ GHz [121].

5.2 System Characterization

Before showcasing the setup, a brief overview of the system is presented.

5.2.1 Anechoic Chamber and Associated Instrumentation

University of Porto's anechoic chamber is roughly $5 \text{ m} \times 3 \text{ m} \times 2.5 \text{ m}$. It has a rotor already mounted for measuring antennae radiation patterns. Below the camera, cabling is connecting a calibrated network analyzer to the two sensors. By measuring the S parameters, in particular $S_{2,1}$ the sensor in port 2 was acting as a receiver and the other, in port 1 as a transmitter. As an additional remark we provide the network analyzer calibration unit used, which is the 85052D Agilent 3.5 mm Economy Calibration Kit, compatible with the used Agilent's E8363A Precision Network Analyzer (PNA) that operates from 45 MHz to 40 GHz.

The rotor's movement has slight deviations from the ideal one. It typically accumulates a few degrees of error after an aperture of 120° in the azimuth direction. Therefore, at each elevation position, this was corrected by adjusting the rotor starting point and using a ruled visual guide with a precision of 0.125 cm. The deviations at each azimuth aperture were also noted with the same precision and so that this imperfection could be corrected through signal processing.

5.2.2 Antennas

The antennas used for the measurements were A-INFOMW Standard 15 dB Gain Horn Antennae, displayed in Figure 5.3. Their working frequencies are 15.0 – 22.0 GHz. They were mounted on a stepped structure so that they could be easily moved throughout the elevation aperture. The antennas were kept aligned with their vertical polarization throughout the entire experiment. For a rigorous description of the scenario, we provide the actual measured antenna gains as well as radiation patterns at the explored polarization. The transmitter antenna gain was determined to be 16.92 dB and for the receiver antenna, this value was of 16.88 dB at a frequency of 17.5 GHz (central frequency of the final presented results).

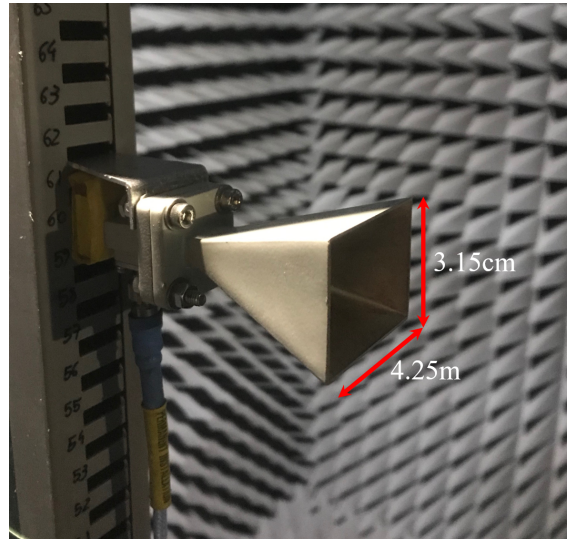


Figure 5.3: Horn antenna used for the measurements.

5.2.3 Pulse Compression

Each frequency tone generated by the PNA (acting as a stepped-frequency synthesizer) is highly stable and uniformly spaced across a wide fractional bandwidth. The total effective bandwidth B_{eff} of the stepped-frequency waveform is:

$$B_{eff} = N_p \Delta_f \quad (5.1)$$

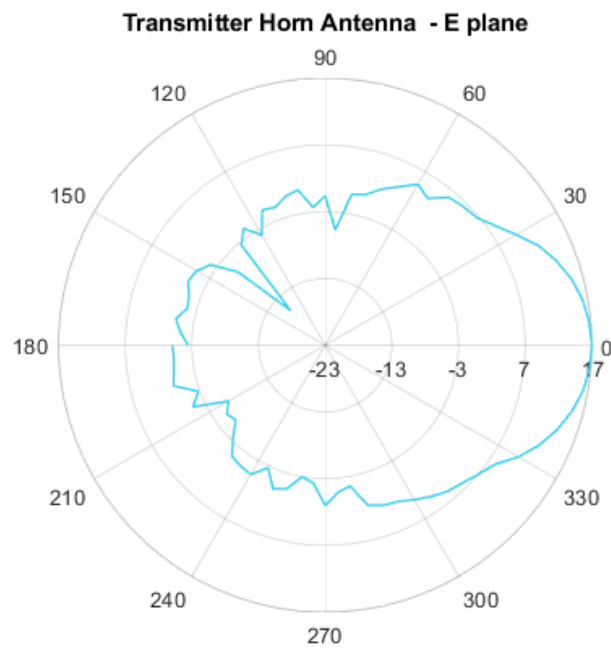


Figure 5.4: Transmitter horn antenna radiation pattern in the vertical polarization and gain $G_T = 16.92$ dB for the frequency of 17.5 GHz.

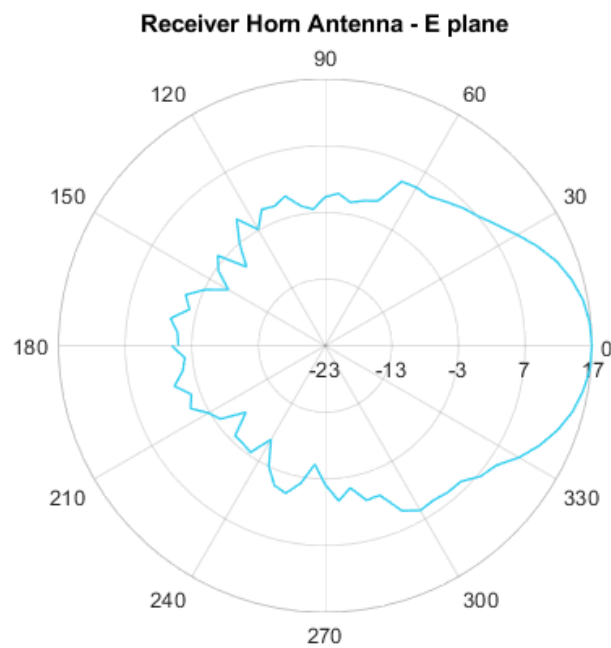


Figure 5.5: Receiver horn antenna radiation pattern in the vertical polarization and gain $G_R = 16.88$ dB for the frequency of 17.5 GHz.

The range resolution is not the conventional value of $c\tau/2$, but a synthetic range resolution is obtained from coherently processing a series of N_p returns, as [122]:

$$\delta_r = \frac{c}{2B_{eff}} = \frac{c}{2N_p\Delta_f} \quad (5.2)$$

The frequency spacing Δ_f was chosen to set the maximum unambiguous range R_{max} accordingly, since:

$$R_{max} = \frac{c}{2\Delta_f} \quad (5.3)$$

To avoid range ambiguities within the target area, R_{max} was chosen to be 6 m so that it was higher than the anechoic chamber size in the target's direction (that is 5 m). Thus, the frequency spacing chosen was $\Delta_f = 25$ MHz. In our study, we selected a 5 GHz bandwidth, corresponding to $N_p = 201$. Even though it is a stepped-frequency waveform, the PNA emits pulses rather than a continuous wave with an intermediate-frequency bandwidth of $IFBW = 35$ kHz and takes a sweep time $T_{sweep} = 119.0$ ms to cover the entire bandwidth. The PNA also provides high precision analog to digital conversion for sampling the received frequency signal.

5.2.4 Aperture Parameters

Unlike in the asteroid case, we chose an aperture of $2\vartheta_{ap_{az}} = 120^\circ$. This was due to the difficulty in precisely rotating small angles using the available rotor and thus in accumulating large quantities of azimuth samples with small apertures. As we opted for a wide-aperture, the PRF constraints are looser. In this case, azimuth ambiguities can be tolerated, as long as they do not overlap with the target area (doll dimensions). Hence, an angular step of $\Delta\vartheta = 1^\circ$ was used. To accumulate enough pulses in azimuth to establish an equivalence with the Didymos situation.

The elevation aperture was limited by the size of the anechoic chamber itself. The position of one sensor is aligned with the rotor, located below the doll's height and directly aligned with the center of rotation. In this way, it was reasonably above the pyramidal foams that cover the camera. The other sensor's vertical path (and consequently aperture) is limited by the foams in the roof of the anechoic chamber. Thus, the elevation aperture was limited to about $L_{el} = 1.425$ m. As a note, this aperture was performed in a rectilinear trajectory, due to the complexity of doing so in an orbital-like movement using the actual setup.

5.2.5 Theoretical Resolution

The resolutions associated to this solution are directly dependent on the used wavelength and the distances between the target, the radar and scene center. The distance between the radar and the scene's center of rotation is $r_0 = 4.22$ m and the target is located at $r_p = 0.59$ m from the same point. Being the center frequency 17.5 GHz, and the bandwidth of 5 GHz, the range resolution is:

$$\delta_r \approx \frac{c}{2B_{eff}} \approx 3 \text{ cm} \quad (5.4)$$

According to the resolution for an "orbital" ISAR aperture formation (Equation 4.34), after 120° of aperture, the azimuth resolution yields:

$$\delta_{cr} \lesssim \frac{\lambda(r_0 - r_p)}{4r_0 \sin \vartheta_{ap}} \approx 0.43 \text{ cm} \quad (5.5)$$

The elevation aperture is formed by the movement of only the receiver for a total of about 1.425m, hence, the resolution in this dimension is as deduced in subsection 2.2.1:

$$\delta_{el} \approx \frac{\lambda}{L_{el}}(r_0 - r_p) \approx 4.36 \text{ cm} \quad (5.6)$$

The worst resolution drives the resulting image resolution. Therefore, for this scenario, the 3D theoretical resolution is equivalent to the limiting elevation resolution, which is about 4.36 cm.

5.3 Setup

A picture of this setup is presented in Figure 5.6. This object is then assumed to be totally in free space, as it is placed on a wooden structure and as the anechoicity provided by the absorbing materials reduces efficiently the effect of scatterers in the surroundings. A two sensors configuration connected to a VNA form a discrete stepped-frequency radar. The sensors are placed at a certain distance and fixed in the same elevation position in a plastic stick, which also allows to assume free space conditions at the utilized frequencies. The platform rotates from -60° to 60° , forming an inverse synthetic aperture. For each rotation, the position of sensor 1 is altered to about 2.5 cm higher, completing a total of $L_{el} = 1.425$ m of elevation aperture.

The data is acquired using a MATLAB[®] program that commands the PNA. The data is averaged 20 times and then collected for further processing using the detailed SAR algorithms. A preprocessing procedure is also applied to remove drift errors and correct calibration drifts.

A summarized version of the utilized parameters can be found in Table 5.1.

5.4 Matched Filter Algorithm

The mathematical ideal method for image formation is matched filtering (MF). It is essentially a maximum likelihood estimator for the reflectivity of points in a scene. The matched filter algorithm for 3D SAR scenarios is essentially an integral over the volume of a target area. It can be simply described (for a monostatic radar) by:

$$s_f(t, \chi, \zeta) = \iiint_V S_R(f_r, \chi, \zeta) \cdot \exp \left[\frac{j4\pi(r_r - r_{r,ref})}{\lambda} \right] \exp \left[\frac{j4\pi(r_{az} - r_{az,ref})}{\lambda} \right] \exp \left[\frac{j4\pi(r_{el} - r_{el,ref})}{\lambda} \right] \quad (5.7)$$

Where S_R is the raw data in the range frequency domain, s_f is the focused data in time, t is the range time, f_r is the range frequency, χ is the azimuth time and ζ is the elevation time. The

Radio	Frequency	17.5 GHz
	Signal Modulation	Stepped-Frequency
	Effective Bandwidth	5 GHz
	Sweep Time	190.0 ms
	Frequency Step	25 MHz
	IFBW	35 kHz
	Power Tx	1 mW
Geometry	Distance (rotor)	4.22 m
	Elevation Initial Offset	2.20°
	Nadir Angle	0°
Signal Processing/Geometry	Azimuth Aperture	120°
	Azimuth Angular Step	1°
	Elevation Aperture	1.425 m
	Elevation Step	2.5 cm
	N coherent sums	20

Table 5.1: Radar parameters for the tomographic bistatic synthetic aperture radar.

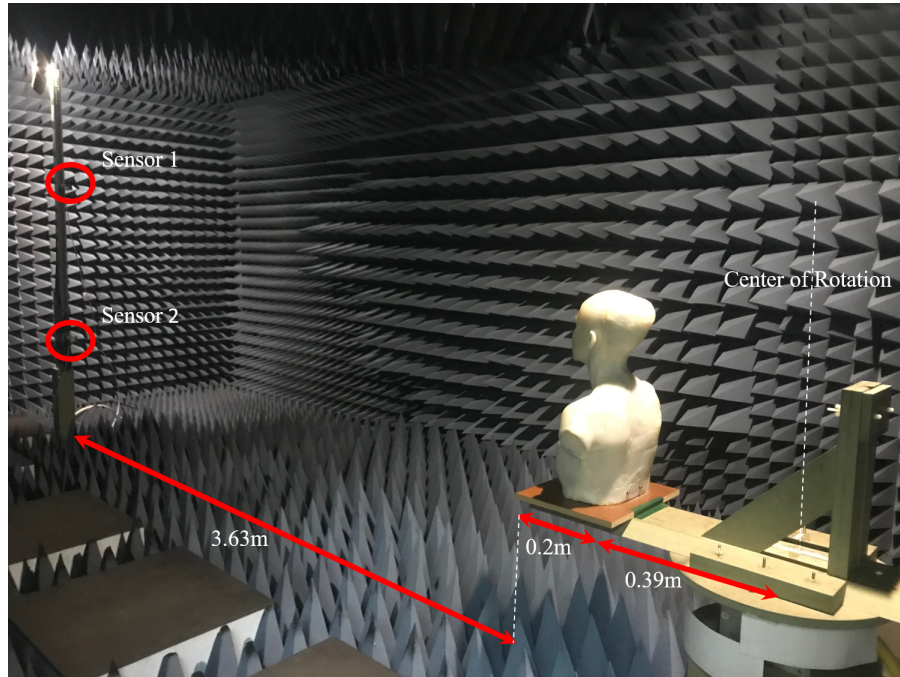


Figure 5.6: View of the complete test scenario with visual distance indicators.

reference ranges in range, azimuth and elevation, respectively, $r_{r,ref}$, $r_{az,ref}$ and $r_{el,ref}$, define the target area.

5.5 Tomographic Bistatic Range-Doppler Algorithm (TB-RDA)

Among the several SAR algorithms, the range-Doppler algorithm (RDA) is one of the more versatile and computationally efficient [44]. It can, thereby, be applied independently of the modulation used for range compression and in stricter geometry constraints (e.g. higher squint angles). In the developed algorithm, we treat each dimension of the 3D SAR image as approximately independent of each other. In this way, the processing can be done with several 1D steps. This causes additional distortions, but significantly decreases the computation time required to obtain the output volume. The first step for image processing using this algorithm is the range compression. A wide-band technique such as matched-filter or stretch processing is used to achieve higher range resolution than the intrinsic limit given by the transmitted pulse length. Following this procedure, an elevation discrete Fourier transform (or fast Fourier transform (FFT), in a digital processor) is performed, thus, moving from the range-elevation to the range-Doppler (RD) domain. This enables the use of frequency domain techniques for both range cell migration correction and for azimuth and elevation compressions. A scheme of the most relevant operations that characterize the RDA is represented in Figure 5.7

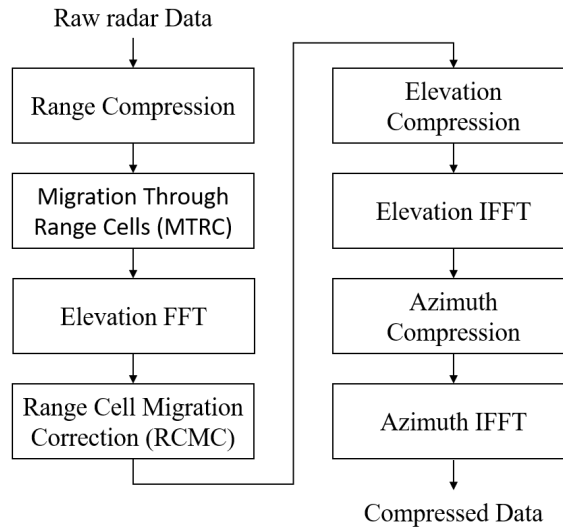


Figure 5.7: Tomographic Bistatic Range Doppler Algorithm (TB-RDA) main operations.

5.5.1 Range Compression

Range compression is the standard radar operation. It increases range resolution and maximizes the signal to noise ratio using the principle of the matched filter. The most common approach is to correlate a copy of the transmitted signal with the received from the antennas. A correlation can also be translated into a frequency domain multiplication, which can improve significantly the performance of this operation, making use of the efficient FFT algorithm (complexity of $O(N \log N)$) [123]. For this type of pulse compression, the matched filter operation can then be digitally applied

(usually in the form of an inverse discrete Fourier transform, IFFT) to form high-resolution time domain profiles from the sampled frequency domain data. It is implemented, in a one-dimensional way, for each azimuth and elevation positions, as follows [124]:

$$D_{range,cmp} = \frac{1}{N} D_{raw}(k) W_n^{-(j-1)(k-1)} \quad (5.8)$$

$$W_n = e^{(-2\pi i)/n} \quad (5.9)$$

Where W_n is one of n roots of unity and N is the number of samples. The output image at this stage is still unfocused. It contains reflected energy from the same scattering object at different distances in range.

5.5.2 Migration Through Range Cells Caused by the Target's Azimuthal Motion

There is a distortion associated with the rotation in the azimuthal plane, if [125]:

$$D_r \leq \frac{4\delta_{az}^2}{\lambda} \quad (5.10)$$

$$D_a \leq \frac{4\delta_{az}\delta_r}{\lambda} \quad (5.11)$$

$$(5.12)$$

Being D_r and D_a are the range and azimuth target dimensions. An additional step between the range compression and the elevation compression can be adopted in this case. Assuming that the rotation rate is uniform during the coherent processing interval (CPI), the slant range rotation can be compensated without the use of computationally costly optimization techniques [126]. If the variation in the target aspect angle $\Delta\theta$ is small, it can be shown that the migration in slant range of the scatterer $\Delta Y(\chi)$ in azimuth time χ is:

$$\Delta Y(\chi) = X\Delta\theta(\chi) \quad (5.13)$$

The azimuth position can be expressed as:

$$X = i\delta_{az} = i \frac{\lambda}{2M\delta\theta} \quad (5.14)$$

Where i is the azimuth cell X number and M is the total azimuth accumulated samples. The aspect angle change can be expressed as a function of the number of the observation j :

$$\Delta\theta(\chi) = j\delta\theta \quad (5.15)$$

Thus, the migration in slant-range is, thus:

$$\Delta Y(\chi) = ij \frac{\lambda}{2M} \quad (5.16)$$

This operation corresponds to an interpolation.

5.5.3 Range Cell Migration Correction Caused by Elevation Motion

A fully focused image can be obtained if the reflections from each target are associated with the same range bin throughout the whole elevation synthetic aperture. Due to the movement of the imaging platform, there is a range-dependent dispersion along the elevation direction. If the platform movement is regular, a target's reflected energy distribution across the elevation synthetic aperture will be approximately parabolic. Range cell migration (RCM) exists when, anywhere inside the period of data collection, the following condition is not respected.

$$\frac{(v_p)^2 t_{el}^2}{8R_0} < \delta_r \quad (5.17)$$

This essentially means that the platform's velocity, v_p , and the total illumination time, t_{el} , that together define the length of the synthetic aperture impose an important constraint in the radar's design. This equation derives from the imaged swath definition, i.e. from the relation between the minimum and maximum unambiguous range of each individual scattering object. In other words, their difference cannot be higher than the range resolution itself. Finer range resolutions than possible respecting this constraint are imposed for the radar's intended application (since Equation 5.17 results in $6 \text{ cm} > \delta_r$). Therefore, the SAR processor must be able to correct RCM. This effect is corrected, as aforementioned, in the range-Doppler domain. The relation between elevation time, t_ζ , to frequency, f_ζ can be mapped as a constant, Equation 5.18 and Equation 5.19.

$$f_\zeta \approx -K_{el} t_\zeta \quad (5.18)$$

$$K_{el} \approx \frac{v_p^2}{\lambda R_0} \quad (5.19)$$

Therefore, the signal in this domain, can be represented by the envelope of the radar data, m_r , the antenna's beam pattern envelope in the Doppler spectrum, M_{el} , centered around the Doppler centroid, $f_{\zeta c}$, and the elevation phase function, θ_{rd} , as follows.

$$S_{r,d}(\tau, f_\zeta) \approx m_r \left(\tau - \frac{2R_{rd} f_\zeta}{c} \right) M_{el}(f_\zeta - f_{\zeta c}) e^{-j\theta_{rd}} \quad (5.20)$$

The elevation phase function in the RD domain can be further approximated. In the case of a transmitted frequency modulated waveform, where K_r and K_{el} represent, respectively, the constants associated with the range and elevation chirp effects, it is approximately equivalent to

$$\theta_{rd} \approx \frac{\pi f_\zeta^2}{K_{el}} \quad (5.21)$$

Transversally to any pulse compression or modulation, the slant range, in this domain, $R_{rd}(f_\zeta)$, represents the cell migration [44] and is given by

$$R_{rd} \approx R_0 + \frac{\lambda^2 R_0}{8v_p^2} f_\zeta^2 \quad (5.22)$$

The elevation frequency, f_ζ , is centered in zero at the closest point that the radar is from a target and defined within the interval of a pulse repetition frequency (with a natural step of $1/t_{el}$). The cell migration correction operation fundamentally translates into mapping the original slant-range vector and its associated energy distribution into the correct range vector, R_{rd} . This can be performed via a one-dimensional interpolation. Apart from processors that implement short-interpolation to avoid time-consuming operations, the assumed approximations lead to a final output image of reasonably high precision level in comparison with other common algorithms [55]. Figure 5.8 refers to the effect of range migration in targets located within the synthetic aperture in "elevation" time and frequency and, therefore, to the practicality of the RDA approach.

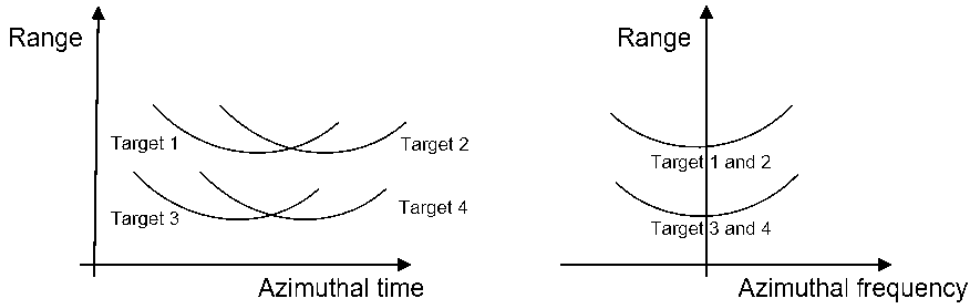


Figure 5.8: Range Migration in the range-"elevation" time domain (left) and in the range-Doppler domain (right).

As is it promptly noticeable, families of scattering targets at the same range are mapped, approximately, within the same curve in the frequency domain, parallel to the azimuthal frequency axis. We assume that the targets lie within a well-defined curve in the range-Doppler domain, or, in other words, circumstances of moderate range migration are presumed. Usually, frequency and phase corrections need to be applied if this effect is excessive [127]. The range migration is corrected taking advantage of the relationship between range and Doppler frequency. It is also assumed, in the derivation, that the radar moves regularly [44]. This is only possible until some extent due to slight velocity variations and flight path's minor deviations from a rectilinear trajectory. These differences need to be measured, recorded and compensated to deliver a correct result. Respectively, velocity variations and deviations from the intended path can be compensated, by an interpolation of the raw data and a phase correction with respect to the nominal course.

5.5.4 Elevation Compression

Once each scattering object is aligned in the same range bin throughout the synthetic aperture in elevation, it is necessary to match its position in elevation. In fact, this procedure is responsible for increasing the elevation resolution. An elevation reference function Equation 5.23 is calculated for each range bin and over the total integration time, t_{el} .

$$s_e(t) = A_e(t) e^{\frac{j2\pi}{\lambda} [r_{TX}(t) + r_{RX}(t)]} \quad (5.23)$$

This function compensates the phase distortion created by the platform's movement. As a bistatic SAR, the distance from the transmitter and receiver to the target, respectively, $r_{TX}(t)$ and $r_{RX}(t)$, are considered. It is essentially the complex conjugated and time-reversed version of the expected phase shift received from each point in the 2D slice in elevation and range, $r_{TX}(t) + r_{RX}(t)$ and, naturally, also dependent on the wavelength, λ . Additionally, an amplitude shaping function A_e is added to account for the non-omnidirectional antennae's radiation patterns. In noisy or non-clutter free environments, the decrease of gain in the edges of the antenna's beam-width, if integrated, can contribute to the overall loss of image signal-to-noise ratio, especially at larger distanced scenes. For efficiency purposes, as aforementioned, the correlation of the reference function with the range compressed and RCMC corrected data is done in the frequency domain. An elevation IFFT is performed before azimuth compression.

5.5.5 Azimuth Compression

Similarly to the elevation aperture, the azimuth compression can be performed in a 1D step by correlation with a reference function. It is calculated for each range bin and over the total integration time, t_a .

$$s_a(t) = A_a(t) e^{\frac{j4\pi}{\lambda} r(t)} \quad (5.24)$$

Where $r(t)$ is the equivalent monostatic radar distance to the target, since there is no movement from the sensor arrangement in this direction. This function compensates the phase distortion created by the target's movement. Therefore, it is given by (Equation 4.32):

$$r(t) = \sqrt{r_0^2 + r_p^2 - 2r_0r_p \cos \vartheta} \quad (5.25)$$

As in the elevation case, an amplitude shaping function A_e is added to account for the non-omnidirectional antennae's radiation patterns. An azimuth IFFT is then performed, to obtain the processed 3D image in the time domain in all dimensions.

5.5.6 Polar Coding to Cartesian Coordinates

The data at this point is processed, however it is coded in polar coordinates. Therefore, it has to be transformed into cartesian so it can be plotted using the used 3D viewing function. This corresponds also to an interpolation in all dimensions (a 2D interpolation for the range and azimuth

directions and a 1D interpolation for the elevation aperture) to map the data into a cartesian grid, derived from the previous polar grid (using MATLAB[®]'s function *meshgrid*).

5.6 Results

The raw radar data was processed using two algorithms. A Tomographic Bistatic range-Doppler algorithm (TB-RDA) and a Matched Filter (MF) algorithm. The latter is a brute forcing approach whose output is by definition a finer image since it makes use of no approximations for reducing computational times. However, providing a coarser resolution, the range-Doppler algorithm is a fast processing technique whose computational demands can possibly be burdened by computers on-board the satellite.

A 3D image was created using MATLAB[®] built-in functions and some adaptation to the *image* function to be able to accommodate 3D data [128]. To better visualize the data, a norm (i.e. an exponent, higher than one) can be applied to the final data, so that the differences between strong and weak scatterers increase. It resolves the spatial ambiguity by scaling the received signal intensity in different opacities for the red color. For the generation of the final output image, an additional processing step was needed for the correct its visualization. Since range and elevation resolution was coarser than the cross-range resolution, the aspect ratio of the illuminated area was incorrect, without any correction. This factor affects the perception of the volume itself and must, therefore, be corrected. This can be done with an equalization of the image axis. Distinct perspectives of the 3D target area are shown in Figure 5.9 to Figure 5.15.

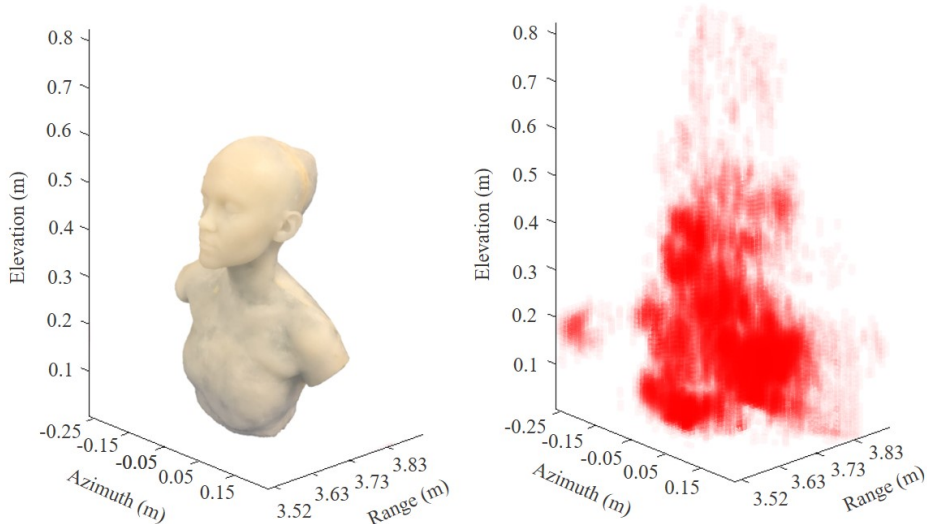


Figure 5.9: Data processed with MF algorithm, observed from front-left side. Norm = 1.8 applied.

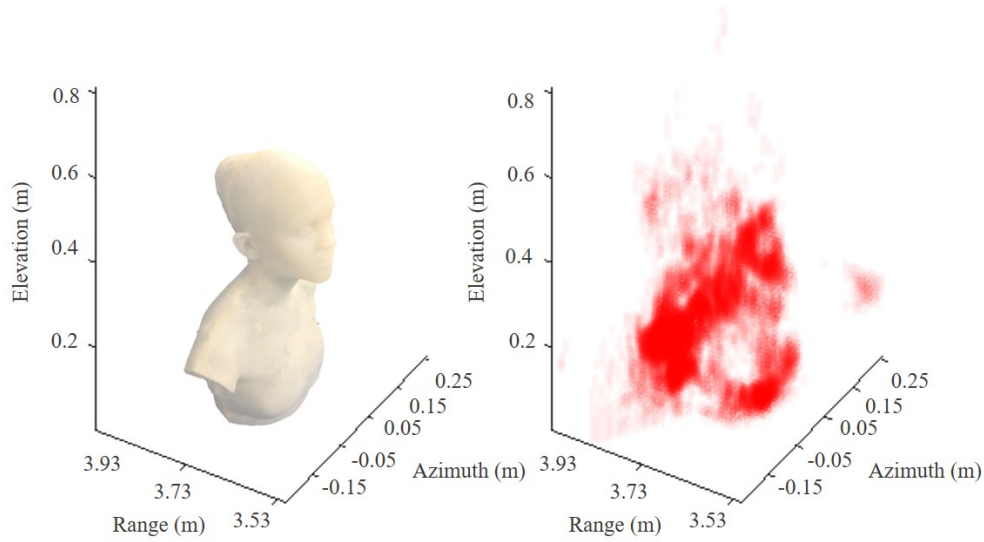


Figure 5.10: Data processed with MF algorithm, observed from front-right side. Norm = 2.0 applied.

Two distinct images are shown in [Figure 5.9](#) and [Figure 5.10](#), with an approximate true representation of the doll at its side to provide orientation based on a ground truth. Both are represented in a three-dimensional case and thus an indication of the dimensions determined. The same procedure is done for the subsequent images.

[Figure 5.11](#) to [Figure 5.13](#) enable an easier visualization and comparison between the ground truth and the measurements. This procedure was only applied to the images where a trustworthy perspective of the real target was attainable.

From [Figure 5.14](#) and [Figure 5.15](#), the measurements processed with the TB-RDA are shown in similar perspectives as the initial MF processed images so that it is possible to strike a comparison.

5.7 Results Analysis

The results obtained after processing the radar echoes showed indeed that it is possible to understand human-like features in the measurements. The doll is located at roughly $R = 3.63$ m from the radar in every measurement and its dimensions of $0.58\text{ m} \times 0.45\text{ m} \times 0.20\text{ m}$ in (elevation, azimuth and range) are readily noticeable in every orientation observed. Some noise can be seen on the top of some images. This could be avoided if a higher norm was applied, but to visually guide the reader and showcase lower reflective areas of the doll, some images were shown with lower

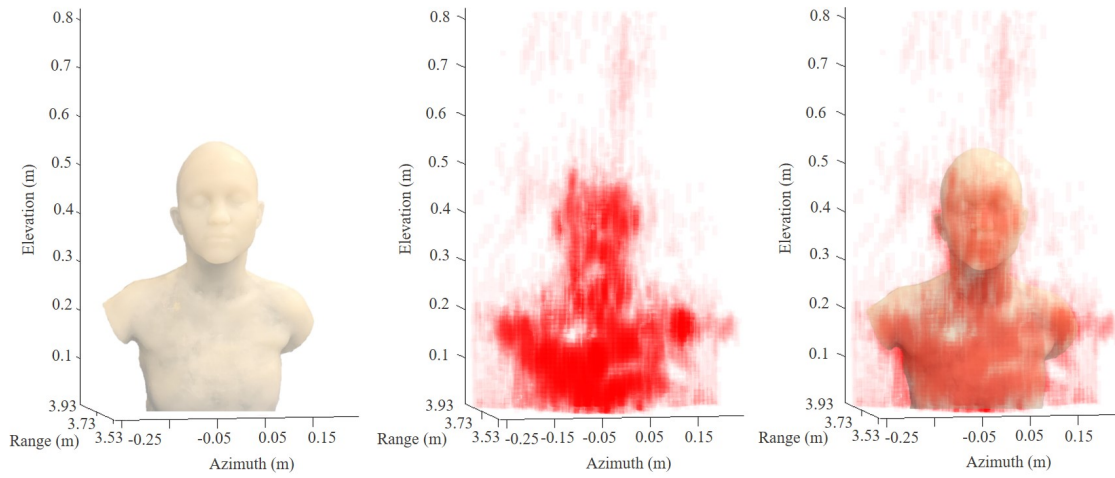


Figure 5.11: Data processed with MF algorithm, front view. Norm= 1.8 applied.

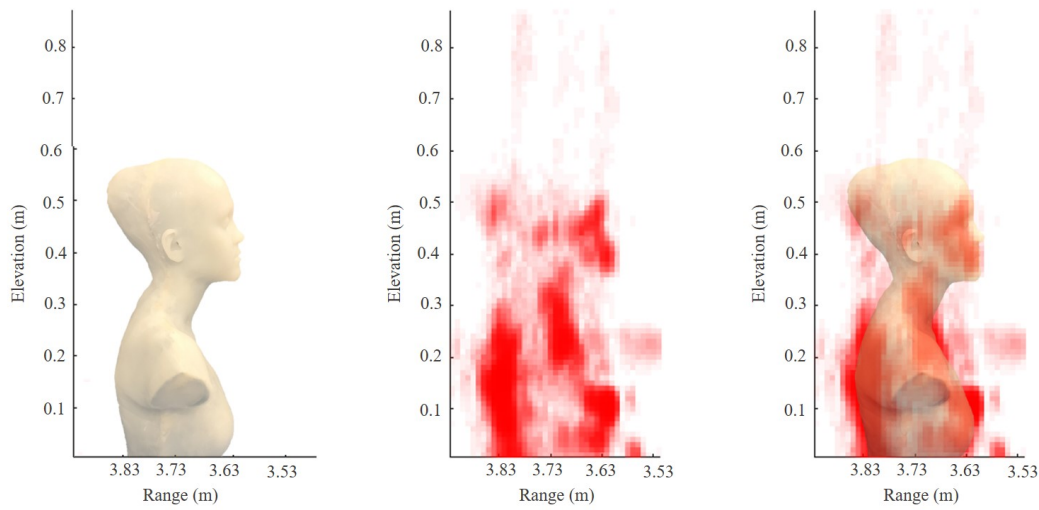


Figure 5.12: Data processed with MF algorithm, right-side view. Norm= 1.8 applied.

norms. It can also be observed that the RD image has less SNR, since for approximately the same level of distortions, the RD image has to have a higher norm applied. No correction was applied to residual errors. These can happen due to imperfections in the chamber anechoic chamber or due to the metallic part of the rotor, that can scatter signal power received.

Results from the range-Doppler Bistatic tomoSAR algorithm indicate that a fast processing beget more distortions in the image (the applied norm, i.e. exponent, has to be higher), however, it can be useful as a quick quality indicator of the data gathered from the asteroid. The data rates

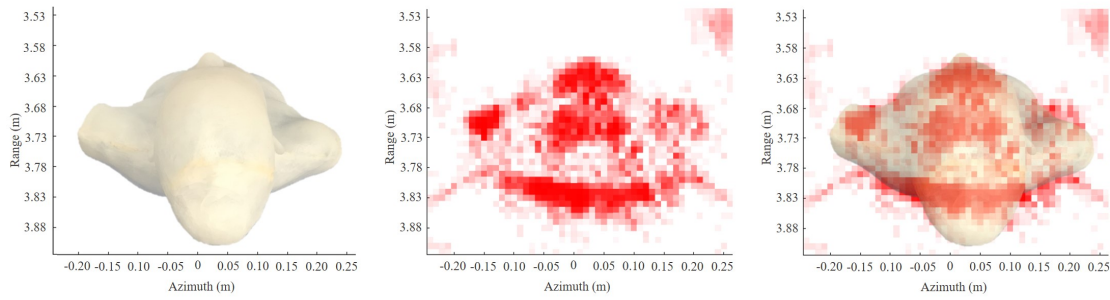


Figure 5.13: Data processed with MF algorithm, top view, Norm=1.8 applied.

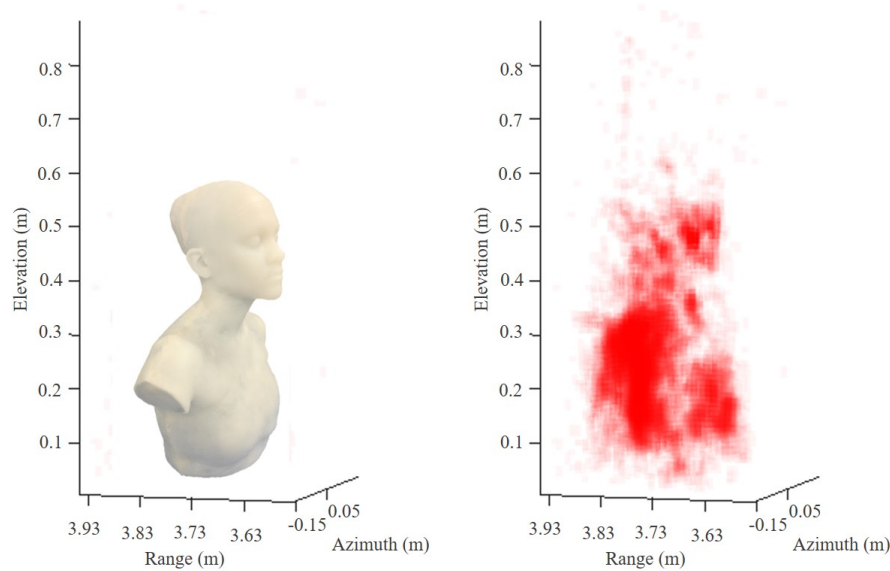


Figure 5.14: Data processed with TB-RDA algorithm, front-right side view. Norm= 2.6 applied.

are so low that it is possible to transmit the data to Earth during the acquisition time. With the computational power on Earth, the MF algorithm can be comfortably used for high-resolution imagery. Even so, both the MF and the RDA algorithm seem to permit the identification of layers within the doll itself (within the limits of the almost 4.5 cm of resolution). This is clearly visible in, for example, [Figure 5.10](#), [Figure 5.12](#), [Figure 5.13](#), and [Figure 5.14](#). Different parts of the doll are clearly stronger scatterers than others, namely those that are oriented towards the radar, as expected. Layers in the range direction are ultimately better imaged than those on the sides of the

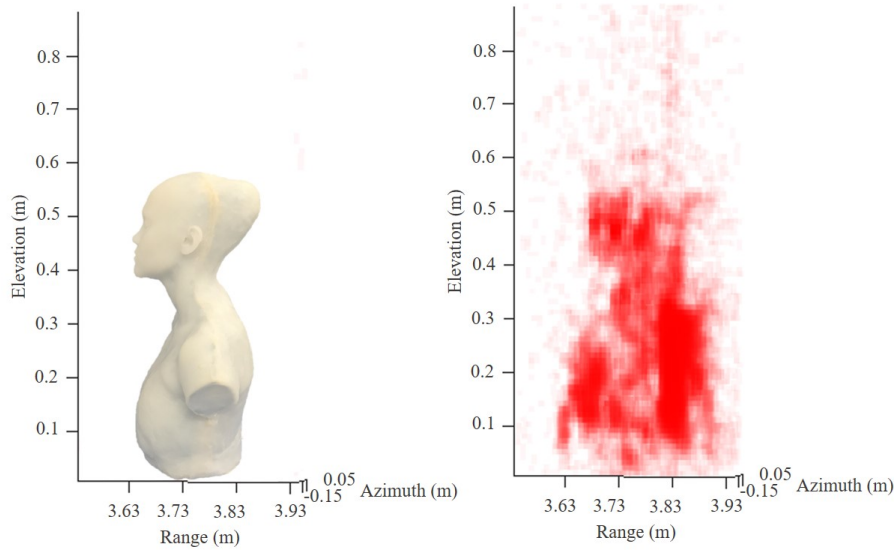


Figure 5.15: Data processed with TB-RDA algorithm, left-side view. Norm= 2.4 applied.

doll. This was also an expected behavior due to the inherent radar's working principle.

Furthermore, it was possible to image the scenario, even with a reasonably wide-bandwidth and wide-aperture.

5.7.1 Resolution

Due to the complexity associated with assembling the target area to be an accurate representation of the asteroid scenario, the system was not evaluated with a point target or corner reflector. The resolution, however, could be inferred from visible features from the target object. The doll's eye cavities are readily identifiable in [Figure 5.9](#), [Figure 5.10](#) and [Figure 5.14](#). The eye cavity is approximately 4.5 cm wide, corresponding necessarily to more than the 3D resolution. The 3D representation method visually merges different features depending on the viewer's point of view. Therefore, in other perspectives, the visibility is reduced. The obtained resolution is, thus, as expected, close to the one determined theoretically.

Chapter 6

Conclusions and Further Work

6.1 Summary

Rapidly changing space paradigm regarding multiple spacecraft arrangements is motivating entities previously involved in monostatic synthetic aperture radar (SAR) system research, development and production to expand their work and consider bistatic scenarios. The objectives of this thesis have been to investigate and test a waveform and optimal configuration for characterizing the surface and subsurface of a near-Earth object (NEO). Additionally, to design an algorithm that resolved the three-dimensional nature of the signal. The following is a summary of the work and contributions contained in the thesis.

The theory of SAR and bistatic SAR imaging has been reviewed, such that bistatic SAR processing has been presented in terms of matched filtering. Radar geometries designed for asteroid missions and NEO were analyzed and its advantages/difficulties were highlighted. The geometrical dependence of the bistatic resolution measurement has also been discussed in detail. The ambiguity requirement for a deep-space SAR system with an orbital trajectory and for an inverse synthetic aperture radar (ISAR) target with the same behavior was thoroughly analyzed and its increase in resolution was derived.

The study of asteroid propagation properties, supported by other authors, allowed to determine the baseline for a tomographic radar mission. In this work, we first started by analyzing an extension of a state-of-the-art deep-space remote sensing solution with a lander and an orbiter, proven already useful for mapping a comet. A first direct measurement of the interior of an asteroid is proposed. From typical deep-space missions constraints, we developed an in-situ scenario that exploits reasonable signal-to-noise ratio along with an increased versatility, a higher frequency and an increased exploration of backscattering properties than available asteroid remote sensing SAR solutions. The frequency was selected to be in the S-band. The configuration was characterized by a low-power and low-propulsion requirement on one of the satellites (expectable to be a Cube-Sat) and an elevation aperture formed by another satellite. The average power during acquisition phases $P_{avg} = 1.91$ W and an average power below 0.06 W throughout its entire mission duration. They move in the same azimuthal plane. The integration with a possible inter-satellite link (ISL)

is discussed. Time requirements, such as resulting signal-to-noise ratio and mission duration was derived for several cases. For an 8-week mission, the three-dimensional resolution obtained is roughly 1 m and the satellite arrangement is capable of detecting targets with a distributed target reflectivity of $\sigma_0 = -20.2 \text{ dB } m^2/m^2$ at 4.5 m of depth and $\sigma_0 = -59.9 \text{ dB } m^2/m^2$ at the surface. It was determined that the ISL can be serving other experiments and foremost that the clock stability requirement is within normal parameters for an affordable space system, namely enabling the use of an oven-controlled crystal oscillator (OCXO).

The following experiment was presented to verify the feasibility of the proposed geometry for the acquisition of 3D SAR data. Frequencies in the K_u band ($f_c = 17.5 \text{ GHz}$) allowed to scale the asteroid model to an acceptable size for a small scale model, using the microwave analogy. Asteroid properties and namely Didymos were studied to design a scaled model with relatable size-to-frequency and electrical properties. From the model, layers could be visible identified, such as the void in-between the layers. This was the intended objective, since it is crucial for the configuration to be able to recognize voids inside an asteroid.

A new 3D tomographic bistatic range-Doppler algorithm (TB-RDA) has been derived using one dimensional processing steps for investigation the three-dimensional point target spectrum. It applies to azimuth-invariant cases where the transmitter and receiver are operating in the same orbital tracks with the same angular velocity. It is applied also to the case where the aperture in elevation is ensured by one of the sensors. The algorithm was applied successfully to the data acquired from the asteroid experimental campaign. The resolution was indeed coarser than using the matched-filter (MF) approach, however it could be useful for on-board processing of partial data. Nevertheless, the mission duration vs data rates, in the order of *ksp/s*, allow the data relay to Earth, where it can be processed without computational burden constraints.

6.2 Original Contributions of this Thesis

This dissertation makes a number of significant contributions to near-Earth asteroids remote sensing technology and for tomographic bistatic SAR image formation. Also, within the development of tomographic bistatic SAR algorithms to accommodate a space-based bistatic SAR geometry for imaging small proto-planetary bodies. The following is a list of the major contributions of this thesis:

1. A competitive study for surface and subsurface measurements of a near-Earth asteroid, Didymos, in the scope of ESA's Hera mission, that considers a valid ISL protocol and an acceptable noise performance, is presented on [chapter 4](#). This solution brings a novel SAR configuration that contributes to the development of deep-space remote sensing.
2. In [section 5.5](#) is described the TB-RDA developed, which is able to image wide-bandwidth, wide-aperture azimuth-invariant cases. This method is applied successfully to focus real bistatic data.

3. Derivation of ambiguities for circular orbital SAR and ISAR for the elevation and azimuth apertures within the scope of the developed mission in [subsection 4.4.2](#). This contributes to the development of SAR, providing mathematical formulation for the utilized configuration.
4. This thesis is also beneficial for the author's research group and for the Department of Electrical Engineering from University of Porto, specially the within the Telecommunications, Electronics and Computers branch.

6.3 Future Work

Some topics are hereby detailed as future work, since they can be important complements to the subject studied in this thesis.

- The first item would be naturally to consider more accurate mission constraints that will come as part of the development of the next phases of the Hera mission. Also, the mission orbital characteristics might change, specially regarding the second body, the after DART impact.
- Conducting similar tests inside a larger anechoic chamber would allow tests to analyze larger asteroid models.
- In this work, no emphasis was given to polarimetry. However, it would indeed be interesting to analyze the Didymos asteroid under several polarizations.
- Testing a true rubble-piled model could also be enlightening in terms of scattering properties expected from Didymos.
- Regarding the focusing techniques, errors in the estimated orbital path may lead to phase errors in the processed image, degrading image quality. Autofocus is a technique that could help to estimate this errors and correct them accordingly. It could relax the accuracy needed for navigation and thus improve the overall complexity.
- The accuracy of registration of the image to the ground has not been studied in detail. This registration is dependent on the geometry of the platforms and thus must be determined for an ultimate solution.
- Better resolution imagery could be obtained if the working frequency is higher (and the bandwidth, if the range resolution is the limiting one).

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