POLITECNICO DI TORINO

Department of Mechanical and Aerospace Engineering

Master's degree thesis

Design and development of the optical navigation system for Cubesat in support of the Martian rover mission

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A mio padre,
che tu possa essere sempre fiero di me.
A mia madre,
che mi ha sempre supportato.

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Abbreviation

ADC
: Attitude Determination and Control

AHP
: Analytical Hierarchy Process

ALTEC
: Aerospace Technology Engineering Company

AOCS
: Attitude and Orbit Control System

CDH
: Command and Data Handling

COTS
: Commercial Off-the-Shelf

DSN
: Deep Space Network

EIRP
: Equivalent Isotropic Radiated Power

EOL
: End Of Life

EOP
: Early Operation Phase

EPS
: Electric Power System

ESA
: European Space Agency

FEEP

Field Emission Electric Propulsion

FoM

Figure of Merit

FOV

Field Of View

G/T

Gain to noise Temperature

GNC

Guidance, Navigation and Control

GPS

Global Positioning System

GSD

Ground Separation Distance

HS

HyperSpectral

I/F

Intermediate Frequency

ILS

Instrument Landing System

IMU

Inertial Measurement Unit

IR

Infra-Red

IRES

Infra-Red Earth horizon Sensor

JPL

Jet Propulsion Laboratory

NavCam

Navigation Camera

NIR

Near Infra-Red

PCDU

Power Control and Distribution Unit

RANSAC

RANdom SAmple Consensus

RF

Radio Frequency

S/N

Signal to Noise

SINAV

Soluzioni Innovative per la Navigazione Autonoma Veloce

SoW

Statement of Work

STK

Systems Tool Kit

STM

Science Traceability Matrix

SURF

Speeded Up Robust Feature

TASI

Thales Alenia Space in Italy

TBC

To Be Confirme

TBD

To Be Define

TRL

Technology Readiness Level

TRN

Terrain Relative Navigation

TTM

Technological Traceability Matrix

UHF

Ultra high frequency

VIS

Visible Spectrum

Abstract

Exploration on the Red Planet has become increasingly frequent in recent years thanks to the increase in developed technologies. The objective of the mission under consideration is the use of the latest technologies on Small-sats in deep space, in particular in orbit around Mars. The following thesis will describe the project called SINAV (Innovative Solutions for Fast Autonomous Navigation), in collaboration with ALTEC (Aerospace Technology Engineering Company) and TASI (Thales Alenia Space in Italy). In particular, the part described in this thesis is focused on the implementation of an optical navigation algorithm, in order to determine the satellite position through images acquired in orbit. The algorithm is developed thanks to the use of the MATLAB programming and numerical calculation platform. The algorithm is based on identifying the landmarks from the image (acquired using a navigation camera) and then comparing this image with the database stored on board the satellite. Through this process, it is possible to derive the position of the satellite in the coordinates of longitude and latitude.

Chapter 1

Introduction

Mars has always been a source of interest because it is currently the only planet in the Solar System on which there is a strong possibility of finding evidence of past life. It is also a very good candidate for hosting human life.
The exploration of the Red Planet has become increasingly frequent in recent years thanks to the increase in technologies developed. The objective of the mission under consideration is to use the latest technologies on a Small-sat(s) in deep space environment, in particular in orbit around Mars.

For this project is considered the ESA (European Space Agency) mission Mars Sample Return, which has the purpose to bring back to Earth some samples of Mars Soil to study the under-surface terrain compositions for the first time. Therefore, it will be allowed to have a deeper understanding of Mars' chemical and geological composition. During the planetary exploration mission, a rover will be used which will have to guarantee high autonomy considering that direct human intervention is not possible; due to the large distance, the ground stations on Earth cannot control the motion of the rover and the satellite. Therefore, it is necessary to guarantee an autonomous navigation system and also the automatic processing of data acquired from different platforms on the ground, in orbit, and in flight.
The main purpose of this scenario is to demonstrate how, by processing the images taken from the satellite, it is possible to determine inaccessible areas, dangerous or interesting before they are even visible from the rover itself, thus creating global and local maps.

The following thesis will describe the project called SINAV (Soluzioni Innovative per la Navigazione Autonoma Veloce), in collaboration with ALTEC (Aerospace Technology Engineering Company) and TASI (Thales Alenia Space in Italy). The workload has been divided among the team members to cover various aspects of the mission, in particular the part described in this thesis is focused on the implementation of optical navigation algorithm to determine the position of the satellite through images acquired in orbit. The algorithm is developed thanks to the use of the programming and numerical calculation platform MATLAB.

1.1 Introduction to the mission

Before entering into a deeper understanding and explanation of the mission, here the Mission Statement is reported in order to highlight the ultimate purpose the mission is to achieve:

"To develop a space mission to support the autonomous navigation of Martian rovers providing unprecedented, periodically updated, information from the orbit over the rover site. This support mission is based on interplanetary small-sat with innovative miniaturized technologies."

As it is reported in the previous lines, the Mission Statement is a synthetic summary of the mission's reason of existence, the SINAV Project has the ambition to support the improvements of the Martian rovers' ability and performance to autonomously explore the surface of the planet through a quicker coverage of the explored surface.
The intent of the present studied mission is to make the in-situ operations faster, more precise and more accurate thanks to an optimized planning of the rover paths obtained through local and regional maps (few square kilometers) highlighting obstacles and threads due to the terrain morphology and physical characteristics. The main goal can be achieved through small-sats with innovative technologies that are increasing their readiness level in these years, among other propulsion, navigation, optical and multispectral payloads, and communication. Moreover, the interplanetary missions impose a growing autonomy level of the systems.
The autonomy is indeed made necessary by the average distance between Earth and Mars, giving no room to the chance to have any sort of communication in real time. Therefore, it is impossible for the ground segment on Earth to transmit commands or information of any kind, as it is impracticable to receive any downlink communication, without a delay of at least 20 minutes.
Rovers themselves are limited in their movements of exploration on Mars' surface.
The present mission has been studied considering specific contour conditions, desired performance and constraints at mission and programmatic level (beyond that at

system level). For example, a mother-daughter architecture is considered both for the release in orbit of the Small-sat(s) and for the communication. The main performances to be achieved refer revisit time of the site of interest, coverage areas, number and quality of the data / maps. Moreover, limits on the operations, total cost, the definition of a launch windows have been included.

1.2 Mission Objectives

Mission objectives derives from the mission statement and they are listed in the table below:

ID	Type	Objective
OBJ1	Primary	To support Martian rovers to improve their autonomous navigation
OBJ2	Primary	To provide referenced-maps to Martian rovers
OBJ3	Primary	To validate new Small-sats technologies in deep space environment
OBJ4	Primary	To increase the number of access between rovers and the in orbit spacecraft/Earth through the data relay
OBJ5	Auxiliary	To provide possible paths planning to Martian rovers

Table 1.1: Mission objectives

The goal of the mission is to gather information about Mars' surface and, after that, to process the images acquired by the satellite(s) orbiting around the planet in order to provide maps and, if any, path planning, and move them to Earth and to the rover.
The obtained information would allow to identify and localize possible areas of interest, avoiding in the process dangerous or useless portions of the red planet, speeding up the exploration and optimizing paths and trajectories.

1.3 Mission Requirements

Mission/High level requirements have been derived in Table 1.2. They derive from objectives and programmatic constraints.
The different parts in which this table is divided, have a twofold origin, indeed they come from either the Statement of Work or the Mission Objectives.
During the early phases of the project, we need to put reasonable limits of acceptance

in order to consider this effort profitable and to ensure that the goals are achieved without risks or errors which could compromise the scientific truth and the objectives we need to satisfy. Guarantying these constraints are accomplished in the foreseen terms, the SINAV support mission is acceptable.
On the other hand, those parts of the table which strictly connected to the Mission Objectives, are there to remind the reasons why this mission is being developed and work as guidelines of the project.

	Mission Requirements	**Traceability**
MR01	The mission shall be accomplished by Small-sat(s)	OBJ01
MR02	The mission shall be provided raw Mars' map to performing navigation	OBJ02
MR03	The mission shall validate utility of Small-sat(s) technology in deep space environment	OBJ03
MR04	The mission shall provide data relay between the rovers and the mothercraft/Earth	OBJ4
MR05	The mission shall provide possible paths planning to Martian rovers	OBJ05
MR06	Mission duration shall be $\geq$ 2 years (extended mission duration shall be taken into account)	SoW
MR07	The Small-sat(s) shall be injected in a stable orbit near Mars by mothercraft	SoW
MR08	The total mass of Small-sat(s) shall be at least 250 kg	SoW
MR09	The mission shall guarantee a coverage of at least 95% of the Mars' surface where rovers operate	MR04
MR10	Mars shall be mapped in the visible spectrum to increase autonomous navigation of rovers' mission	MR02
MR11	Mars shall be mapped in the IR spectrum to increase autonomous navigation of Martian rovers	MR02
MR12	The launch date is schedule by 2030. Delays shall be taken into account	SoW
MR13	The mission shall end with de-orbiting maneuver to impact on Mars' surface	SoW
MR14	Low-cost technology (COTS with, at least, TRL 3 at 2022) shall be adopted in the mission	MR03
MR15	The mission shall cost less than 10M$	SoW
MR16	The mission shall guarantee a revisit time of TBD hours	SoW

Table 1.2: Mission requirements

1.4 STM and TTM

The Science Traceability Matrix (STM) and the Technological Traceability Matrix (TTM) are two important tools useful to define mission goals and requirements starting from the main needs. Both follow the same logic: from the goals/objective it is possible to decompose the problem increasing details in order to derive measurement, instrument and mission requirements. While the STM aims to choose the suitable payloads for the spacecraft and to understand the main mission drivers, the TTM considers technology need to improve mission autonomy.
The principal scientific need is to map Mars' surface in order to support the autonomous navigation of martian rovers. The technology's needs are to reduce the required propellant, in order to reach and maintain the desired orbit, and to determine the spacecraft position to develop a navigation system using landmarks. The navigation will be performed thanks to the use of the optical camera. Also to have a communication system is a need, so that two elements are able to communicate with each other or with Earth.
The detailed STM and TTM are shown in Table 1.3 and Table 1.4, respectively.

Science need /question	Science objective	Science requirements	Instrument /Technique	Measurements requirements	Instruments requirements	Mission requirements	Data products
How to mapping Mars surface?	To produce maps of strategic areas in rovers missions in every condition of light	Mars shall be mapped in the visible spectrum in strategic areas for rovers missions	Optical Imager	Spatial resolution $\leq$0,5m	Camera TBD FOV: 4-8 deg Pixel: 12 Mpixel	Orbit altitude: 50-100km (TBC)	High resolution Mars's surface map
	To characterize different terrain typology and their chemical composition	Mars shall be mapped in the spectral range of 0,4-4μm	Hyperspectral camera	Spectral range: $\leq$450-950nm Spectral resolution: $\leq$16nm	HS camera: HyperScout FOV: 31 deg Pixel: 12 Mpixel	Orbit altitude: 150km (TBC)	Chemical composition and map of high interest areas

Table 1.3: Science Traceability Matrix

Technology need /question	Technology objective	Technology requirements	Instrument /Technique	Measurements requirements	Instruments requirements	Mission requirements
How to minimize the required propellant for maintain Small-sat(s) in a stable orbit?	To provide ΔV needed for the operations	Part of the central volume shall be used to house the propulsion system	Electric/ Electro-magnetic Propulsion Thrusters	(-)	Average mass: 1-2 kg Average power: 100-1000 W	TBD
	To correct possible errors in the real orbit due to perturbation and external disturbances	The Small-sat(s) shall have (criogenic) tank to store the fuel	Cold-Gas Thrusters /Electric Propulsion	(-)	Average mass: 0,01-0,1 kg Average power: 1-10 W	TBD
How to define the Small-sat(s) position?	To produce global mapping	Mars shall be mapped to obtain raw images for navigation purpose	Optical Imager	Spatial resolution $\leq$1,5 m	Camera TBD FOV: 4-8 deg Pixel: 12 Mpixel	Orbit altitude $\leq$150 km (TBC)
	To design a navigation system using landmarks obtained from the optical camera images	The GNC system shall determine Small.sat(s) position through the use of reference points	Reaction Wheels	Pointing accuracy $\leq$1 deg	Lifetime at least 5 years Speed Range TBD [rpm] Speed control accuracy TBD [rpm]	TBD
How to communicate with the other element of the mission?	To develop an inter-satellite communication system	The ISL shall guarantee the communication between two element in Mars orbit and/or on ground	ISL system in UHF or S-band	The link margin shall be at least 6 dB for a slant range over to TBD km	EIRP > TBD [dBW] G/T > TBD [dBW]	TBD
	To develop an interplanetary communication system for Small-sat(s)	The interplanetary communication system shall guarantee the link between a Small-sat(s) in Mars orbit and DSN stations	Interplanetary Communication System	The link margin shall be at least 6 dB for a distance Mars-Earth	EIRP > TBD [dBW] G/T > TBD [dBW]	TBD

Table 1.4: Technology Traceability Matrix

1.5 Mission Design

1.5.1 Concept of operations

The Concept of Operations explain how is expected that the mission will work to satisfy mission requirements.
Starting from the end of the interplanetary transfer and the arrival at Mars, the mission has been divided in four main phases, which have been further decomposed into multiple mission scenarios, as reported in Table 1.5.

Mission Phases	**Mission Scenario**		**Duration**
EOP	Deployment	Release from the mother-craft	30 minutes
	Detumbling	Detumbling in a stable orbit	2 hours
	Appendix deployment	Subsystems' appendix deployment	2 hours
Commissioning	Spacecraft checkout	Advenced technology check-out	1 hour
		Payloads checkout	2 days
On-orbit operative phase	Maneuver 1 - Transfer to operative orbit 1		TBD
	Global observations and mapping		3 months
	Maneuver 2 - Transfer to operative orbit 2		TBD
	Detailed observation and mapping		1,5 years
EOL	Active disposal (extra mission)		2 months
	Passive disposal		1 months

Table 1.5: Concept of Operations

The SINAV Small-sats mission starts with the deployment of the small-sat(s)-based system from the mothercraft to a stable orbit and followed by the stabilisation of the spacecraft in the right attitude and appendix deployment occurs. After detumbling is executed, Commissioning phase starts and functional tests of subsystems and payloads are performed. The achievement of the desired instruments calibration leads to the transition to the On-orbit operative phase. In this phase the small-sat(s) stay in a stable orbit to mapping Mars for navigation purpose with an optical camera and to characterize different terrain typology and their chemical composition

with hyperspectral camera. This phase is required to collect numerous images of Mars' surface, that will be later processed by a dedicated component. After three months this process it should be completed and the small-sat(s) are able to navigate autonomously using optical camera. Subsequently the small-sat(s) enter in second maneuver phase for transfer to a lower orbit to perform optical remote sensing applications to provide possible paths planning to Martian rovers to increase their autonomous navigation. The end of this phase is expected after 1,5 years, when strategic areas map in rovers missions are produce. A series of lowering and raising of altitude can be envisaged to collect different data of Mars' surface for remote sensing applications.
At the end of the nominal mission, active disposal phase starts: small-sat(s) are still able to capture images and data of Mars' surface for remote sensing applications.
In the end, passive disposal phase provides a passivation of the small-sat(s) and a de-orbiting maneuver to impact on Mars' surface.
A graphical representation of the mission sequence according with the scenarios is reported in Figure 1.1.
For more details all mission phases are shown in Appendix A.

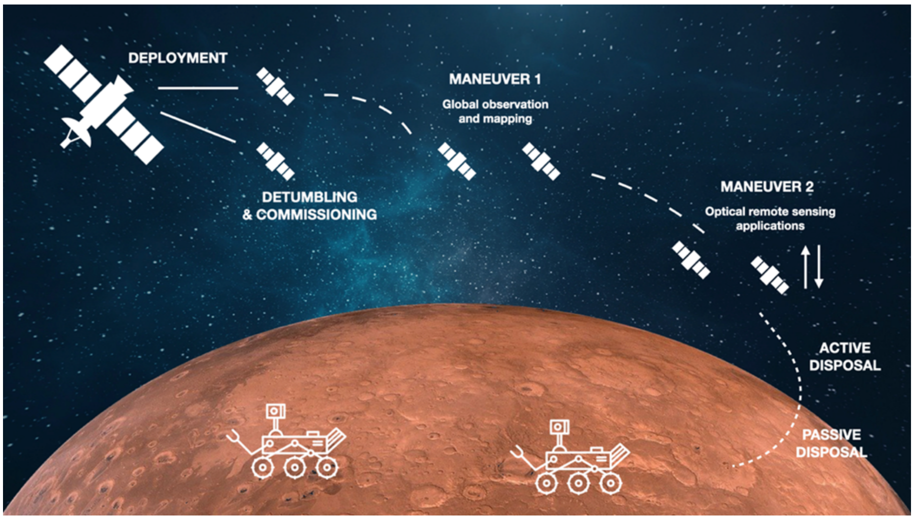


Figure 1.1: Design Reference Mission

1.5.2 Mission Architecture

Considering the description of the ConOps, seven mission architectures are proposed. The main mission element identified are:

- **Subject**: purpose of the mission, the same for all mission architectures.

- **Space segment**: identify the number of satellites capable of implementing the mission.
- **Payload**: instruments able to perform mission requirements, in this case are the same for all mission architectures.
- **Mission geometry**: orbits (and, in case, the constellation configuration) in which satellites will operate.
- **Operations**: define the number and types of the operations and the related efforts of facilities and human workload.
- **Communication**: define the communication architecture.
- **Ground segment**: includes all the infra-structure on Earth used to exchange date with the interplanetary elements.
- **Launch segment**: highlights the activity related to the launch and achievement of the orbit to start the mission.

While the last three elements remain the same for all the possible choices since derived from constraints that impose a communication network that includes the mothercraft in the loop, the ground station network of ALTEC and the mothercraft releases the Small-sat(s) after the achievement of its stable orbit. Subject is the areas of interest (where the rovers operate). Payload can include optic and hyperspectral elements that can be different in term of mass, volume and power but that meet the performance requirements on spatial and spectral resolutions. The architectures are substantially differentiated by two elements: number of satellites and orbit configuration. The method of release from the mothercraft is also considered. The differences between the seven proposed architectures are listed below.

Mission Architecture 1

The first mission architecture consists of a single Small-sat operating at an altitude of 150 km in a circular orbit performing global observation and mapping operations; after proper maneuvers to reach the altitude of 50-80 km, the Small-sat start remote sensing applications for maps definition. In this case the Small-sat has a mass of 150 kg, which allows to carry more propellant on-board. For this reason,it can be considered to perform more orbital maneuvers. Moreover, the volume and mass for payload is higher. More details are shown in Table 1.6.

Mission Architecture 2

The second mission architecture consists of two Small-sats operating in a circular orbit of 150 km. The deployment type split up the mission architecture in two solutions:

A. The two small-sats are released together by the mothercraft with a gap of time from each other and reach the altitude of 150 km in a circular orbit. In this phase the two small-sats produce global observation and mapping. In the second operational phase the two small-sats reach a lower altitude, one of them at 80 km in a circular orbit and the other one at 50 km in a circular orbit. (Table 1.7)

B. The two small-sats are released in a distributed way, giving them a phase shift of 180 deg in the operative orbit at 150 km. Once they have completed the first operative phase, both perform the Hohmann maneuver at the same time to reach the altitude of 80 km in a circular orbit in order to perform the second operational phase. In the circular orbit of 80 km the two small-sats keep the different phase of 180 deg. (Table 1.8)

Mission Architecture 3

The third mission architecture consists of three small-sats operating in the same circular orbit of 150 km of the previous mission architectures. Also in this case the deployment type provides two solutions:

A. The three Small-sats are released together by the mothercraft with a gap of time from each other and reach the altitude of 150 km in a circular orbit, where they produce global observation and mapping. In the second operational phase the three Small-sats reach a lower altitude, one of them at 50 km in a circular orbit and the other two at 80 km in a circular orbit with a phase shift of 180 deg from each other. (Table 1.9)

B. The three Small-sats are released in a distributed way, giving them a phase shift of 120 deg in the operative orbit at 150 km. Once they have completed the first operative phase, all the Small-sats perform the Hohmann maneuver at the same time to reach the altitude of 80 km in a circular orbit in order to perform the second operational phase. In the circular orbit of 80 km the three Small-sats keep the different phase of 120 deg. (Table 1.10)

Mission Architecture 4

The fourth mission architecture consists of four Small-sats operating in a circular orbit of 150 km, like all mission architectures described so far. The two solutions resulting by deployment type are:

A. The four Small-sats are released together by the mothercraft with a gap of time from each other and reach the altitude of 150 km in a circular orbit, where they produce global observation and mapping. After the Hohmann maneuver to reach a lower altitude in a circular orbit at 80 km, all Small-sats perform the second operative phase with a phase shift of 90 deg from each other. (Table 1.11)

B. The four Small-sats are released in a distributed way in order to have a different phase of 90 deg from each other at the altitude of 150 km, where all Small-sats perform the global observation and mapping. After the proper maneuver at the same time the four Small-sats reach the circular orbit at 80 Km with different phase of 90 deg to perform the second operational phase. (Table 1.12)

Mission element	Description			
Space segment configuration	Number of Sall-sats:	1	150 kg/ small-sat	Single deployment
Payload	Optical camera	1+	TBD	Optical imager shall be used to archive remote sensing applications
	Optical camera	1+	TBD	Optical imager shall be used to achieve global observation and mapping of Mars for navigation purpose
	Hyperspectral camera	1	TBD	Hyperspectral camera shall be used to achieve ground chemical composition of Mars with 20,1 m GSD at 150 km
Mission geometry	Transfer to operative orbit 1			The small-sat shall move in a circular orbit at 150 km after being released from the mothercraft (orbiting at 200 km)
	Global observation and mapping			The small-sat shall stay in a circular orbit at 150 km to produce raw global mapping for navigation purpose with optical camera
				In the same orbit at 150 km data of chemical composition of high interest area are provided by hyperspectral camera
	Transfer to operative orbit 2			The small-sat shall move from 150 km orbit to 50-80 km circular orbit
	Optical remote sensing applications			The small-sat shall stay in a circular orbit at 50-80 km to produce high resolution map of Mars' surface by optical camera in VIS and NIR range

Table 1.6: Mission Architecture 1

<table>
<tr><th>Mission element</th><th colspan="4">Description</th></tr>
<tr><td>Space segment configuration</td><td>Number of Sall-sats:</td><td>2</td><td>75 kg/ small-sat</td><td>Swarm deployment</td></tr>
<tr><td rowspan="3">Payload</td><td>Optical camera</td><td>1+</td><td>TBD</td><td>Optical imager shall be used to archive remote sensing applications</td></tr>
<tr><td>Optical camera</td><td>1+</td><td>TBD</td><td>Optical imager shall be used to achieve global observation and mapping of Mars for navigation purpose</td></tr>
<tr><td>Hyperspectral camera</td><td>1</td><td>TBD</td><td>Hyperspectral camera shall be used to achieve ground chemical composition of Mars with 20,1 m GSD at 150 km</td></tr>
<tr><td rowspan="5">Mission geometry</td><td colspan="3">Transfer to operative orbit 1</td><td>The small-sats shall release together (with a gap of TBD minutes) by the mothercraft (orbiting at 200 km) and reach the operative orbit at 150 km</td></tr>
<tr><td colspan="3" rowspan="2">Global observation and mapping</td><td>The small-sats shall stay in a circular orbit at 150 km to produce raw global mapping for navigation purpose with optical camera</td></tr>
<tr><td>In the same orbit at 150 km data of chemical composition of high interest area are provided by hyperspectral camera</td></tr>
<tr><td colspan="3">Transfer to operative orbit 2</td><td>The small-sats shall move in a lower orbit one by one</td></tr>
<tr><td colspan="3">Optical remote sensing applications</td><td>One small-sat shall stay in a circular orbit at 80 km. The second one shall stay in a circular orbit at 50 km. Both satellites produce high resolution map of Mars' surface by optical camera in VIS and NIR range.</td></tr>
</table>

Table 1.7: Mission Architecture 2A

<table>
<tr><th>Mission element</th><th colspan="4">Description</th></tr>
<tr><td>Space segment configuration</td><td>Number of Sall-sats:</td><td>2</td><td>100 kg/ small-sat</td><td>Distributed deployment</td></tr>
<tr><td rowspan="3">Payload</td><td>Optical camera</td><td>1</td><td>TBD</td><td>Optical imager shall be used to archive remote sensing applications</td></tr>
<tr><td>Optical camera</td><td>1</td><td>TBD</td><td>Optical imager shall be used to achieve global observation and mapping of Mars for navigation purpose</td></tr>
<tr><td>Hyperspectral camera</td><td>1</td><td>TBD</td><td>Hyperspectral camera shall be used to achieve ground chemical composition of Mars with 20,1 m GSD at 150 km</td></tr>
<tr><td rowspan="5">Mission geometry</td><td colspan="3">Transfer to operative orbit 1</td><td>The small-sats shall release by the mothercraft (orbiting at 200 km) at different times. After one reach 180 deg of the operative orbit (150 km), the other one will be released</td></tr>
<tr><td colspan="3" rowspan="2">Global observation and mapping</td><td>The small-sats shall stay in a circular orbit at 150 km with different phase of 180 deg to produce raw global mapping for navigation purpose with optical camera</td></tr>
<tr><td>In the same orbit at 150 km data of chemical composition of high interest area are provided by hyperspectral camera</td></tr>
<tr><td colspan="3">Transfer to operative orbit 2</td><td>The small-sats shall move in a lower orbit at the same time</td></tr>
<tr><td colspan="3">Optical remote sensing applications</td><td>Both small-sats shall stay in a circular orbit at 80 km with different phase of 180 deg. Both satellites produce high resolution map of Mars' surface by optical camera in VIS and NIR range</td></tr>
</table>

Table 1.8: Mission Architecture 2B

<table>
<tr><th>Mission element</th><th colspan="4">Description</th></tr>
<tr><td>Space segment configuration</td><td>Number of Sall-sats:</td><td>3</td><td>50 kg/ small-sat</td><td>Swarm deployment</td></tr>
<tr><td rowspan="3">Payload</td><td>Optical camera</td><td>1</td><td>TBD</td><td>Optical imager shall be used to archive remote sensing applications</td></tr>
<tr><td>Optical camera</td><td>1</td><td>TBD</td><td>Optical imager shall be used to achieve global observation and mapping of Mars for navigation purpose</td></tr>
<tr><td>Hyperspectral camera</td><td>1</td><td>TBD</td><td>Hyperspectral camera shall be used to achieve ground chemical composition of Mars with 20,1 m GSD at 150 km</td></tr>
<tr><td rowspan="5">Mission geometry</td><td colspan="3">Transfer to operative orbit 1</td><td>The small-sats shall release together (with a gap of TBD minutes) by the mothercraft (orbiting at 200 km) and reach the operative orbit at 150 km</td></tr>
<tr><td colspan="3" rowspan="2">Global observation and mapping</td><td>The small-sats shall stay in a circular orbit at 150 km to produce raw global mapping for navigation purpose with optical camera</td></tr>
<tr><td>In the same orbit at 150 km data of chemical composition of high interest area are provided by hyperspectral camera</td></tr>
<tr><td colspan="3">Transfer to operative orbit 2</td><td>The small-sats shall move in a lower orbit one by one</td></tr>
<tr><td colspan="3">Optical remote sensing applications</td><td>One small-sat shall stay in a circular orbit at 50 km. Two Small-sats shall stay in a circular orbit at 80 km with different phase of 180 deg. All satellites produce high resolution map of Mars' surface by optical camera in VIS and NIR range.</td></tr>
</table>

Table 1.9: Mission Architecture 3A

Mission element	Description			
Space segment configuration	Number of Sall-sats:	3	50 kg/ small-sat	Distributed deployment
Payload	Optical camera	1	TBD	Optical imager shall be used to archive remote sensing applications
	Optical camera	1	TBD	Optical imager shall be used to achieve global observation and mapping of Mars for navigation purpose
	Hyperspectral camera	1	TBD	Hyperspectral camera shall be used to achieve ground chemical composition of Mars with 20,1 m GSD at 150 km
Mission geometry	Transfer to operative orbit 1			The small-sats shall release by the mothercraft (orbiting at 200 km) at different times. After one reach 120 deg of the operative orbit (150 km), the other one will be released. The last one will be released when first small-sat reach 240 deg on his orbit
	Global observation and mapping			The small-sats shall stay in a circular orbit at 150 km with different phase of 120 deg to produce raw global mapping for navigation purpose with optical camera
				In the same orbit at 150 km data of chemical composition of high interest area are provided by hyperspectral camera
	Transfer to operative orbit 2			The small-sats shall move in a lower orbit at the same time
	Optical remote sensing applications			All small-sats shall stay in a circular orbit at 80 km with different phase of 120 deg. All satellites produce high resolution map of Mars' surface by optical camera in VIS and NIR range

Table 1.10: Mission Architecture 3B

Mission element	Description			
Space segment configuration	Number of Sall-sats:	4	50 kg/ small-sat	Swarm deployment
Payload	Optical camera	1	TBD	Optical imager shall be used to archive remote sensing applications
	Optical camera	1	TBD	Optical imager shall be used to achieve global observation and mapping of Mars for navigation purpose
	Hyperspectral camera	1	TBD	Hyperspectral camera shall be used to achieve ground chemical composition of Mars with 20,1 m GSD at 150 km
Mission geometry	Transfer to operative orbit 1			The small-sats shall release together (with a gap of TBD minutes) by the mothercraft (orbiting at 200 km) and reach the operative orbit at 150 km
	Global observation and mapping			The small-sats shall stay in a circular orbit at 150 km to produce raw global mapping for navigation purpose with optical camera
				In the same orbit at 150 km data of chemical composition of high interest area are provided by hyperspectral camera
	Transfer to operative orbit 2			The small-sats shall move in a lower orbit one by one
	Optical remote sensing applications			All small-sats shall stay in a circular orbit at 80 km with different phase of 90 deg to produce high resolution map of Mars' surface by optical camera in VIS and NIR range

Table 1.11: Mission Architecture 4A

<table>
<tr><th>Mission element</th><th colspan="4">Description</th></tr>
<tr><td>Space segment configuration</td><td>Number of Sallsats:</td><td>4</td><td>50 kg/ small-sat</td><td>Distributed deployment</td></tr>
<tr><td rowspan="3">Payload</td><td>Optical camera</td><td>1</td><td>TBD</td><td>Optical imager shall be used to archive remote sensing applications</td></tr>
<tr><td>Optical camera</td><td>1</td><td>TBD</td><td>Optical imager shall be used to achieve global observation and mapping of Mars for navigation purpose</td></tr>
<tr><td>Hyperspectral camera</td><td>1</td><td>TBD</td><td>Hyperspectral camera shall be used to achieve ground chemical composition of Mars with 20,1 m GSD at 150 km</td></tr>
<tr><td rowspan="5">Mission geometry</td><td colspan="3">Transfer to operative orbit 1</td><td>The small-sats shall release by the mothercraft (orbiting at 200 km) at different times. After one reach 90 deg of the operative orbit (150 km), the second one will be released. The third and the fourth will be released when first small-sat reach 180 deg and 270 deg</td></tr>
<tr><td colspan="3" rowspan="2">Global observation and mapping</td><td>The small-sats shall stay in a circular orbit at 150 km with different phase of 90 deg to produce raw global mapping for navigation purpose with optical camera</td></tr>
<tr><td>In the same orbit at 150 km data of chemical composition of high interest area are provided by hyperspectral camera</td></tr>
<tr><td colspan="3">Transfer to operative orbit 2</td><td>The small-sats shall move in a lower orbit at the same time</td></tr>
<tr><td colspan="3">Optical remote sensing applications</td><td>All small-sats shall stay in a circular orbit at 80 km with different phase of 90 deg. All satellites produce high resolution map of Mars' surface by optical camera in VIS and NIR range</td></tr>
</table>

Table 1.12: Mission Architecture 4B

1.5.3 Trade off mission architecture

Trade-off analysis ha been performed to identify the Mission Architecture baseline. The Figure of Merit (FoM) selected for this study are:

- **Coverage**: the amount of total area covered by small-sat(s) in relation to the timescales to cover it. Higher values are better.
  The ideal coverage of Mars' surface and the potential duration each architecture takes to cover at least 95% of the area of interest are:

  1. After 2 months and 24 days
  2. After 2 months and 4 days
  3. After 45 days
  4. After 40 days

- **Revisit time**: time between two passes of a satellite (one of the satellites of a constellation) over the area of interest (i.e rovers sites). Short re-visit time is better. In order to study the revisit time of the different architectures, has been placed a "point of interest" on Mars' surface with coordinates between 30°N and 30°S of latitude. The reports, generated by STK tool, gives the exact moment of the passage of the satellites over the target, since the satellites reach the altitude of 50 or 80 km.
  The access' number, along with the mean and the total duration of every mission architecture are shown in Appendix B.

- **Amount of information**: amount of valuable data collected by space segment. High quantity and quality of data is better. Thanks to the report generated by STK tool, the total images acquired in one hour were obtained for all the different architectures.
  In the first operation phase, global observation and Mars' surface mapping, the account was made in such a way as to have the minimum possible overlap between the images. It is obtained one image every 35 seconds.
  In the second operational phase, remote sensing application, it is necessary to have more images when the satellite passing over the point of interest; for the other areas it can be considered sufficient to have one photo every 30 seconds.
  An analysis of the weight in Mbyte of the images obtained per single orbit was made to generate a first data volume. The payload considered is:

  – VIS camera, used for navigation and the remote sensing;
  – HS camera, used for the chemical analysis of the Mars' surface.

More details are shown in Appendix C.

- **ΔV**: total variation of space segment velocity to maintain the desired mission geometry. Low ΔV is better because the mission is simpler and the quantity of propellant required is lower, higher volume for payload. The table containing the ΔV needed for each architecture is reported in Appendix D.

- **Cost**: amount of costs foreseen for the mission, taking on 10M€ for a mission with one satellite and 2,5M€ for each satellite in a mission composed by a satellites' constellation.

- **Operations**: includes all the activity required on ground (and onboard to perform the mission). Lower intervention from ground is better.

- **Technology**: parameter that considers complexity of the on-board technologies and its TRL.

Once established the FoM weight through Analytical Hierarchy Process (AHP), the relative score of each architecture has been calculated, as reported in Table 1.13.

FoM	**Weight[%]**	**1**	**2A**	**2B**	**3A**	**3B**	**4A**	**4B**
Coverage	0,18	0,006	0,024	0,028	0,024	0,033	0,025	0,038
Revisit time	0,25	0,018	0,023	0,028	0,037	0,038	0,049	0,057
Amount of information	0,18	0,013	0,016	0,023	0,026	0,028	0,037	0,037
ΔV	0,07	0,018	0,011	0,014	0,006	0,010	0,006	0,006
Cost	0,07	0,010	0,014	0,014	0,011	0,011	0,005	0,005
Operations	0,18	0,027	0,036	0,022	0,033	0,019	0,029	0,012
Technology	0,07	0,018	0,012	0,011	0,009	0,008	0,008	0,007
Trade-off		0,111	0,135	0,140	0,146	0,147	0,159	0,162

Table 1.13: Trade-off

For FoM such as coverage, revisit time and amount of information the score values increase with the number of satellites; on the other hand, the FoM like ΔV, cost and technology the score values decrease. The missions with the highest number of satellites have the possibility of collecting more information and having a greater number of passages on point of interest, but they require more complexity to handle

and communicate data.
Mission architectures with swarm or distributed deployment are also considered because some FoM are influenced by this choice.
Considering the final scores and the observation above, the mission architecture 4A and 4B can be chosen for the mission, but with further considerations, other parameters could be evaluated to analyze the mission architecture 3B, not far from the highest score obtained.

1.5.4 Communication Architecture

The communication architecture depends on the availability of the link with other elements of the mission architecture, such as motehrcraft, Deep Space Network (DSN) stations and the rover. The/each small-sat can communicate:

1. only with the mothercraft orbiting platform;
2. with the rover;
3. an interlink between small-sats should be introduced if a distributed solution is adopted.

Moreover, a direct link with the Deep Space Network (DSN) could be evaluated using technology based on JPL's IRES technology but the actual baseline for the mission considers a communication towards the Earth based on the mothercraft link, i.e. the main communication channel is with the mothercraft for reasons of vicinity so that a strong radio-frequency link is available using relative simple technology already available for small-sats, and because the mothercraft would be directly engaged in the small-sats mission. Communications with the DSN is now based on specific technology available for the direct communication lunar CubeSat-Earth. This link is generally closed thanks to the DSN performance so that the major issues are the DSN network availability and cost. The small-sat(s) communication with the rover on the surface depends on the orbit and the desired link availability. This link requires to be careful due to the low EIRP and S/N that both the small-sats and the rover have.
Moreover, the both the single small sat architecture and the constellation of small-sats would support the communication between Earth/motehrcraft and the rover through the data relay. That would increase the time of communication between mothercraft and rover improving the amount of data delivered and the commands sent to the rover.
Figure 1.2 summarizes the communication architecture.

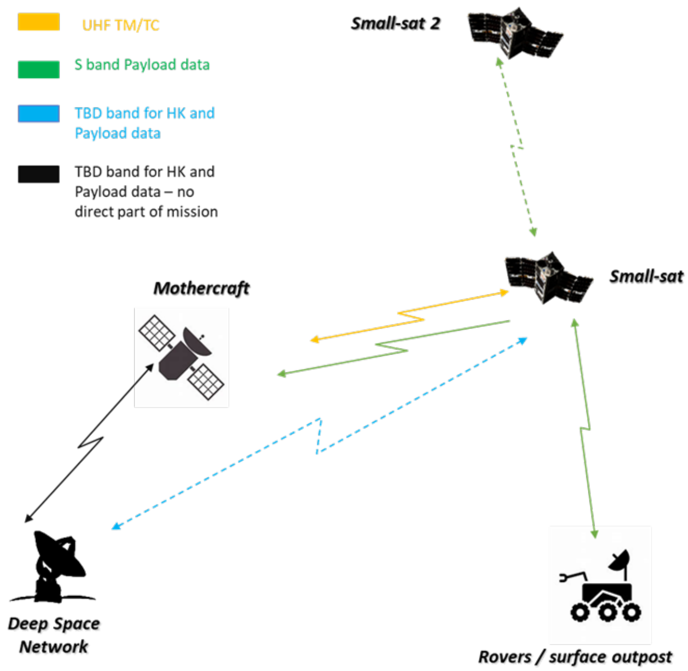


Figure 1.2: Communication Architecture

Chapter 2

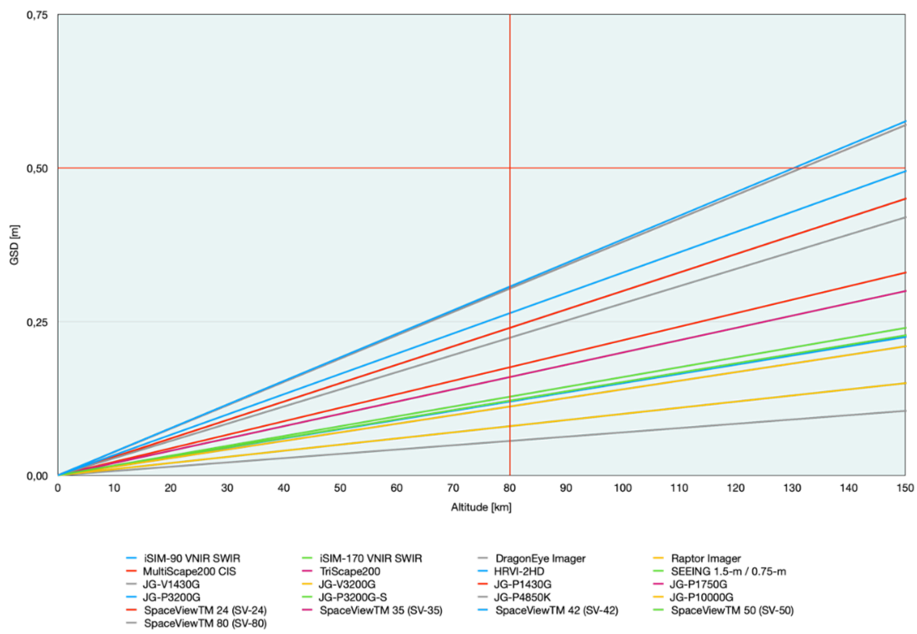
Payload Design

The optical payloads have a double scope within the mission because they serve both for mapping and for navigation. The market research led to the identification of some COTS products reported in Table 1.14. All the data in the table can be found in the product datasheets.

Referring to STM, Mars shall be mapped in the visible spectrum in strategic areas for rovers' missions with an optical imager that guarantees a spatial resolution at least of 0,5 m at 80 km of altitude, as specified in the various options of mission architectures. Some of the products available on the market do not meet the requirements of GSD, so they are excluded.
COTS payloads remaining has been analyzed to check the requirement of spatial resolution and has been compared Figure 2.1. In Figure 2.1: GSD for remote sensing applications, the GSD has been calculated according to the data identified on the available datasheets. These obtained values are considered ideal values but allows to provide a preliminary sizing.
All cameras can guarantee the requirement of GSD for remote sensing applications at altitude of 80 km. In the same way, the requirement of GSD is accomplished for navigation purposes, where the cameras guarantee at least 1,5 m of GSD at altitude of 150 km. The same analysis was carried out on the swath parameter.

COTS	Mass [kg]	W x L x H [mm]	GSD @500 km [m]	Swath @500 km [km]
iSIM-90 VNIR SWIR	<4	308x114x100	1,65	13
iSIM-170 VNIR SWIR	<8	593x276x308	0,8	13
Chameleon Imager	1,6	100x100x245	10	40
DragonEye Imager	18	320x x920	1,4	20
Raptor Imager	45	450x x 1200	0,7	11
MultiScape200 CIS	12,1	216x216x304	1,5	14
TriScape200	12,1	216x216x304	1,5	14x10,5
HRVI-2HD	19	520x780x335	1,92	15
Monitor Imager	3		6,5	13
JG-P4850K	600		<1	
JG-P10000G	<1100		<0,5	
SpaceViewTM 24 (SV-24)	10		0,9-1,1	
SpaceViewTM 35 (SV-35)	20-35		0,7-1,0	
SpaceViewTM 42 (SV-42)	25-40		0,5-0,75	
SpaceViewTM 50 (SV-50)	90-130		0,35-0,5	
SpaceViewTM 80 (SV-80)	150-225		0,22-0,35	

Table 2.1: Visual Cameras on the market



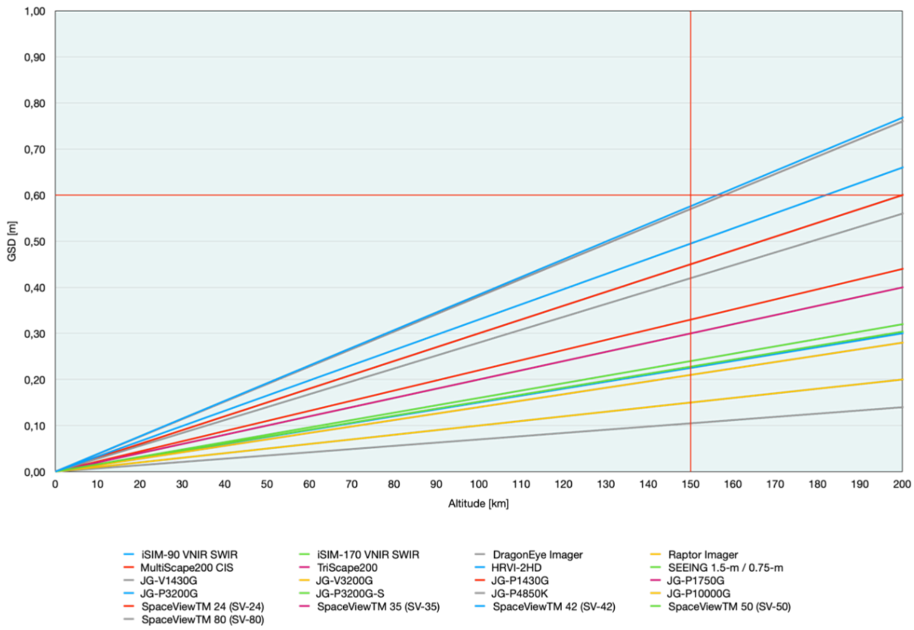


Figure 2.1: GSD for remote sensing applications and navigation purposes

In global observations and mapping phase it is possible to achieve a swath of less than 6,5 km, instead in remote sensing application phase it is possible to achieve a swath of less than 3,2 km. Considering that the total planned area to be covered is 20 km^2 wide, so a useful swath value could be around 4,47 km. This value is included in the range guaranteed by the optical cameras analyzed, as shown in Table 2.2.

	GSD @500 km [m]	**GSD @150 km [m]**	**GSD @80 km [m]**		**Swath @500 km [km]**	**Swath @150 km [km]**	**Swath @80 km [km]**
iSIM-90 VNIR SWIR	1,65	0,50	0,26		13,00	3,90	2,08
iSIM-170 VNIR SWIR	0,80	0,24	0,13		13,00	3,90	2,08
Chameleon Imager	10,00	3,00	1,60		40,00	12,00	6,40
DragonEye Imager	1,40	0,42	0,22		20,00	6,00	3,20
Raptor Imager	0,70	0,21	0,11		11,00	3,30	1,76
MultiScape200 CIS	1,50	0,45	0,24		14,00	4,20	2,24
TriScape200	1,50	0,45	0,24		14,00	4,20	2,24
HRVI-2HD	1,92	0,58	0,31		15,00	4,50	2,40

Table 2.2: GSD and Swath of cameras

Hyperspectral camera

Referring to Table 1.3 of STM, Mars shall be mapped in the spectral range to characterize different terrain typology and their chemical composition with a spectral range at least of 450-950 nm and a spectral resolution at least of 16 nm.
In Figure 2.2 and in Table 2.3 is possible see that all hyperspectral cameras analyzed guarantee, at altitude of 150 km, a GSD at least of 20 m. These obtained values are to be considered ideal values.

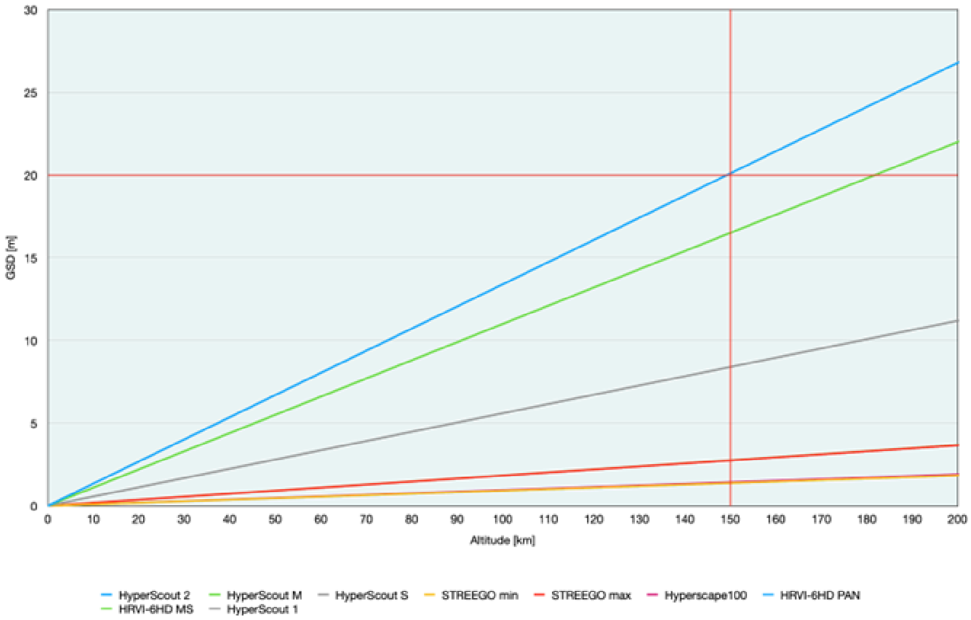


Figure 2.2: GSD Hyperspectral camera

COTS	Mass [kg]	W x L x H [mm]	GSD @600 km [m]	GSD @150 km [m]	Swath @500 km [km]
HyperScape100	1,1	98x98x176	5,70	1,43	19,4
HRVI-6HD PAN	10,45	540x320x170	5,52	1,38	36
HRVI-6HD MS	10,45	540x320x170	11,04	2,76	70
STREEGO min	20	600x700x850	5,50	1,38	11
STREEGO max	20	600x700x850	11,00	2,75	11
HyperScout 1			80,40	20,10	280
HyperScout 2			80,40	20,10	280
HyperScout M			66,00	16,50	225

Table 2.3: Hyperspectral camera

2.0.1 Optical payload requirements

For the operations related to the use of optical cameras a push-broom scanning technology has adopted, in order to decrease the technological and operations complexity and related costs.
Optical payload requirements have been derived in Table 2.4:

Instrument	Requirements	Min	Max
Vis camera	GSD @500 km	0,35 m	1,92 m
	Swath @500 km	11 km	20 km
	Resolution	4096x3072 pixel	
	Number of spectral bands	4	8
	Scanning technique	Push-broom	
Hyperspectral camera	GSD @600 km	5,50 m	80,4 m
	Swath @600 km	19,5 km	280 km
	Resolution	4096x3072 pixel	
	Number of spectral bands	32	150
	Scanning technique	Push-broom	

Table 2.4: Optical payload requirements

2.1 Navigation Camera

The primary objective of this work is to provide a Mars' surface map in order to determine the Small-sat(s)'s position, for this reason the choice of the camera is important.
The requirements are:

- GSD: at least 1,5 m
- Swath: less than 6,5 km

The Table 2.2 shows the values of these quantities for the selected cameras; the one that guarantees these requirements is *Chameleon Imager*, developed by Dragonfly Aerospace.
It is a compact CubeSat imager that takes advantage of the space-qualified electronics of the Gecko imager and combines this with high-performance optics to maximize imaging capability in small satellite. Nevertheless it was thought for 3U CubeSat, it is available for larger satellite too.
One of the biggest advantages is that the images are captured directly to the

integrated mass stored (128 Gigabytes); so, it means that there is no need of a additional payload storage capacity on the satellite. Also, data can be streamed directly to a transmitter or to an on-board computer as required.
In addition to these advantages, the camera was chosen for its coverage of a 144 km^2 wide area: this avoids having images that do not have enough landmarks for optical navigation purposes.

2.2 Platform Design

The platform design is carried out on the basis of a well-established process involving functional analysis, definition of functional architecture and derivation of the product tree. Payload deeply affects the spacecraft bus design. The management of images imposes capabilities in terms of quantity of data that should be handled and stored, computational power to execute image processing and stereoscopy algorithms, and data rate to transmit the image. Shooting images requires pointing accuracy to the target, pointing stability in order to avoid blurry pictures, and station-keeping capability to stay in selected hold points or virtual boxes. Moreover, payload mass, volume, and power consumption drive the subsystems sizing and the internal layout. Main high-level functions that the CubeSat shall provide are:

- To control the free-flying phases of the mission: control transition between orbits (transfer to operative orbit, orbit insertion, de-orbiting), maintain and control spacecraft attitude, maintain and control orbit (station keeping)
- To communicate with the orbiter: transmit payload data, transmit telemetry data, receive commands
- To ensure proper energetic autonomy for the mission: collect and convert electrical power, store electrical energy, distribute electrical power, control electrical power, and monitor and protect the system
- To handle on-board data: generate and distribute commands, collect-analyze-store data for system and payload monitoring and control, execute automated procedures, generate and manage automated procedure (when applicable)
- To survive in martian environment: protect from radiation, monitor and control thermal environment (heat collection and transport, heat rejection)
- To ensure structural integrity for the entire mission life cycle

The components of each subsystem are shown in detail in the Table 2.5.

Subsystem	Components
Structure	Frames and Brackets
Attitude and Orbit Control System (AOCS)	ADC Processor
	3 Reaction Wheels
	2 Star Trackers
	1 Inertial Measurement Unit (IMU), including accelerometers and gyro
	NavCam
Command and Data Handling (C&DH)	C&DH Processor
	Data Storage Module
	Clock
Electric Power System (EPS)	Power Control and Distribution Unit (PCDU)
	Deployable Solar Panels
	Body Mounted Solar Panel
	Battery Pack(s)
Communication System	S-band (Antenna + Transceiver)
	UHF System (Antenna + Transceiver)
Thermal Control System	Heaters
	Passive components
Navigation System	NavCam - Visual based + Landmarking algorithms
	(optional RF/ILS with the mothercraft)
Propulsion System	Cold Gas thruster vs Electric propulsion (i.e. Resistojet or FEEP)

Table 2.5: List of components

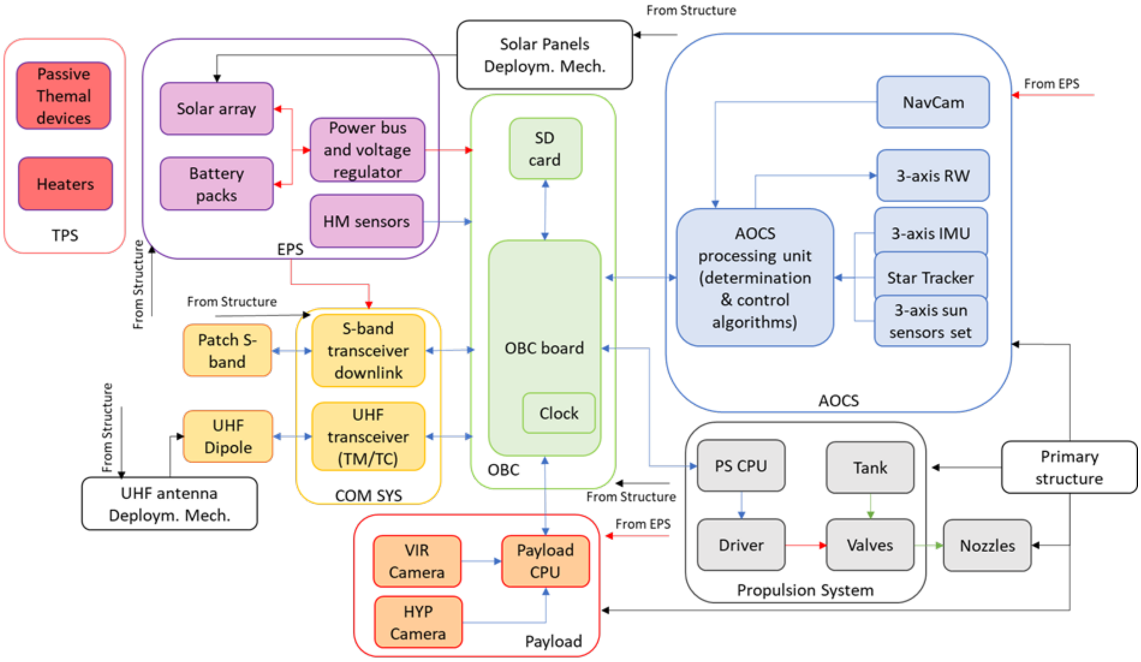


Figure 2.3: Satellite block diagram

The high-level architecture diagram of the spacecraft is shown in Figure 2.3. It can be considered as independent from the form factor, i.e. it holds both 12U platforms and higher solutions.

Chapter 3

Autonomous Navigation

The Guidance, Navigation & Control (GNC) subsystem includes both the components used for position determination and the components used by the Attitude Determination and Control System (ADCS).
In Earth orbit, onboard position determination can be provided by a Global Positioning System (GPS) receiver, but in deep space navigational aids do not currently exist. For this reason, a different technique must be utilized.
A new era of low-cost small satellites for space exploration will require autonomous deep-space navigation. This will decrease the reliance on ground-based tracking and provide a substantial reduction in operational costs because of crowded communication networks.
When applied to a spacecraft, a system is considered autonomous when navigation is performed onboard the spacecraft in real time and without ground support.
Autonomous navigation for deep space satellites is a technique that has been used on satellite missions in the past, including Deep Space 1, STARDUST, and Deep Impact. Additionally satellites such as Voyager 1 and 2 have demonstrated optical techniques for navigation.
Deep Space 1 was the first spacecraft launched under the new millennium program to develop and certify new high-risk technologies for use in future low-cost science missions. Among the many technologies was the first onboard autonomous navigation system (AutoNav). The task for this system was to:

1. perform interplanetary cruise orbit determination using images of distant asteroids;

2. control and maintain the orbit of the spacecraft using the ion propulsion system and conventional thrusters;

3. perform approach orbit determination and control using images of the science

targets;

4. perform late knowledge updates of target position during close, fast flybys to facilitate a high degree of quality data return from 2 targets: asteroid Braille and comet Borrelly.

Deep Impact, the eighth mission in NASA's Discovery Program, had the most challenging use of AutoNav to date. The goal of the mission was to perform a high speed impact of a comet with one spacecraft while observing the event with another.Deep Impact used standard ground radiometric and optical navigation techniques for the cruise and approach phases of the mission. AutoNav was used only in the hours prior to the impact event.
STARDUST was the fourth mission in NASA's Discovery Program. The development of AutoNav for STARDUST closely matched that of Deep Space 1; algorithmically, the code was nearly identical to the final Deep Space 1 version, with the primary difference being that STARDUST used a unique camera/scan mirror combination for imaging.
Voyager 1 and *Voyager 2* were the first missions that required optical navigation to meet mission objectives for deep space navigation. Voyager used radiometric data types to determine spacecraft range and velocity relative to Earth, but optical measurements of planetary bodies were used to obtain position relative to the planetary body.
Typically, autonomous navigation systems have no way to autonomously determine time, position, and velocity without prior information typically provided by ground-based systems. This strategy mostly relies on two types of measurements: radiometric and optical.

Radiometric Measurements

Radiometric tracking provides spacecraft position and velocity estimates along the line connecting a given ground station and the spacecraft, i.e. the line of sight. This type of measurements is performed by a network of facilities distributed around the globe and provided with parabolic high-gain antennas, with dishes up to 70 m in diameter. NASA's infrastructure for deep-space radiometric tracking is called the *Deep Space Network* (DSN).
Ranging is the process of estimating the spacecraft's line-of-sight distance. It includes various techniques, all based on the same key concept: measuring the signal's time of flight, i.e. the time it takes for the signal to travel from the ground station to the spacecraft and vice versa. Since it is known that uplink and downlink carriers

travel at the speed of light (in vacuum), time observations can be used to recover the spacecraft distance. The most commonly used ranging technique for deep space navigation is called Two-Way Ranging, which measures the round-trip time of flight of the signal. This method has the advantage of being independent of the spacecraft's clock error.
Doppler measurements, on the other hand, are used to estimate the spacecraft line-of-sight velocity. This is done by comparing transmitted and received frequencies of the signal.

Optical Measurements

Optical measurements serve to recover body-relative navigation parameters and are expressed as angular measurements or pixel coordinates within the onboard camera's field of view (FoV). Such measurements include the target body's centroid, usually employed during the far approach, and landmarks on the body surface, observable at closer distances and hence higher image resolution.
Centroiding, i.e. the process of determining the target body's centroid, is usually performed algorithmically, for example by using a brightness moment algorithm or Normalized-Cross-Correlation. Landmark tracking, on the other hand, consists in detecting the image patch related to an interest point (i.e. a landmark) on the body surface, and tracking such a point over a series of sampled images. To date, this process requires experienced human operators in order to select the best landmark candidates and precisely detect the image-to-image displacement of the related patches.
At the same time, the selection and tracking of landmarks is carried out by the optical navigation team, where operators, backed by radiometric tracking data, process and analyze images, detect optical measurements, and reject outliers through an iterative process. In the current human-intensive process, different teams of experts must carefully coordinate and continuously iterate as the estimated parameters are strongly coupled. This process drives the complexity of the operations for this kind of missions, imposes limitations on what can be achieved given the coupling and time-delayed information, and overall mission cost.

3.1 Landmark Navigation

Figure 3.1 shows the methods for navigating in deep space.
The method used in this thesis is Terrain Relative Navigation (TRN), an optical

navigation that use landmarks tracking.

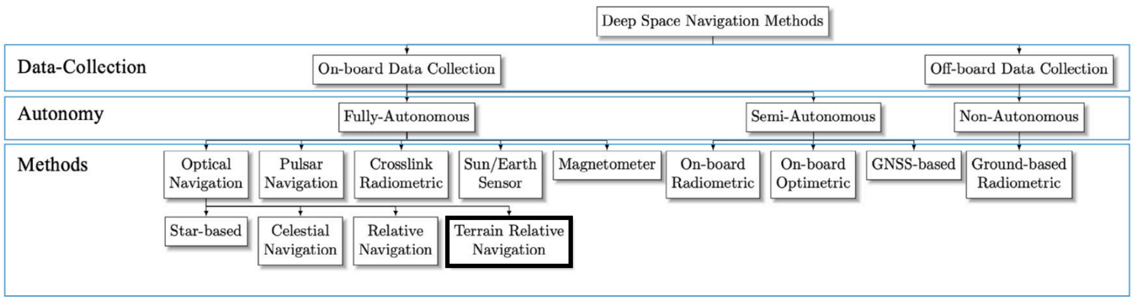


Figure 3.1: Deep space navigation methods

Landmark tracking is an approach to navigation using surface features of the celestial body the satellite is orbiting. This process uses an onboard camera to take surface images which are then processed onboard the satellite and compared to an onboard map to determine the positions of the landmarks. This data is then processed in the orbit determination algorithm with other sensor data to process and orbit determination solution. Landmark tracking requires two main things to work correctly, a complete onboard database is required to do the landmark tracking orbit determination, and the satellite must be close enough to detect the landmarks needed to search in the database. It is composed of three major activities:

1. Obtain a map: images of the target body are acquired to determine its coarse shape and construct digital elevation maps around surface landmarks.

2. Define the landmarks points: it is supposed that the onboard shape model includes estimated body-fixed Cartesian coordinates of points on the surface of the planet referred to as landmarks. For example, the landmarks could be the center points of prominent craters or boulders on Mars' surface.

3. Determine position: once the map has been combined, the simulated landmarks' appearance is predicted and correlated with actual images to determine the spacecraft's position through matching. Then the onboard software autonomously performs natural landmarks/feature identification and tracking. Next, the line-of-sight vector from the Small-sat to the center of each landmark can be constructed from the image coordinates in the navigation camera focal plane. After image processing is complete, a landmark tracking based planet navigation algorithm is required.

Landmarks can be geometric shapes and they may include additional information; its are carefully chosen to be easy to identify. Before a satellite can use landmarks for navigation, the characteristics of the landmarks must be known and stored in the Small-sat's memory. The general procedure for performing landmark-based positioning is shown in Figure 3.2, while an example of TRN is shown in Figure 3.3.

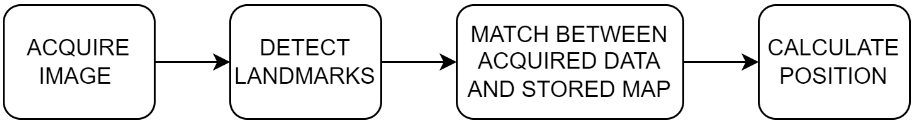


Figure 3.2: General procedure for landmark-based positioning

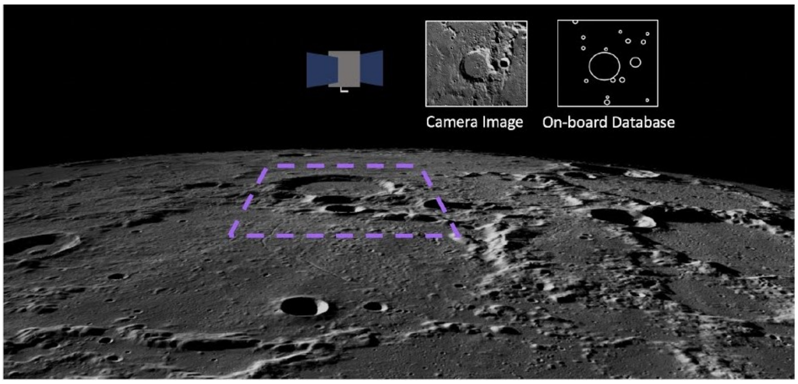


Figure 3.3: Terrain Relative Navigation example

3.2 Critical Technology

The autonomy of the mission is a crucial point for interplanetary missions. The satellite shall decide on the mission operations plan, on the activation of onboard hardware modules and software tasks, and on the management of off-nominal conditions. The selection of the possible strategy for autonomy implementation depends on the resources available onboard the small-sats. The autonomous decision-making process can follow "traditional approaches" based on deterministic algorithms or "new approaches" based on artificial intelligence algorithms.

A feature-based image-matching algorithm finds the natural landmarks and gives feedback to an onboard control system for autonomous navigation. It's clear that if one of the parameters is severely compromised, then the algorithm did not generate a good quality solution. The main sources of error are:

- Camera resolution: since the algorithm is based on feature correspondence, the camera resolution affects the accuracy in computing each correspondence constraints.

- Camera memory: the camera must have a good storage capacity in order to save the reference terrain map a priori.
- Field of view: in order to compute an accurate solution, a sufficiently rich geometry should be available.
- Structure of observed terrain: as any other algorithm for terrain navigation, the algorithm requires terrain variability.

3.3 Algorithm development

The basis of optical navigation is to process images and convert them into an observation data point that can be input into an orbit determination filter. Most algorithms will be explained in a scenario of two images where the first image is analyzed first. In addition to landmark navigation, other ways to perform image processing are:

- **Visual Odometry** is the process of determining the location and orientation of a camera by analyzing a sequence of images.
- **Deep learning** uses neural networks to learn useful representations of features directly from data.

3.3.1 Image Processing

The images are obtained from an onboard camera whose various physical parameters are determined by a combination of science and navigation requirements.
Image processing is considered one of the key technologies for autonomous optical navigation to extract high-precision navigation observables from a raw image. Thanks to MatLab image processing toolbox is possible to do:

- Transformations of spatial images
- Morphological operations
- Linear filtering and filter design
- Transform
- Image analysis and enhancement
- Image registration
- Blur

- Region of interest operation

The definitions that apply to algorithms for performing image matching are keypoints, descriptors, matching and outlier rejection. A keypoint is the position of a feature of interest in an image. A descriptor is a mathematical way of describing what it looks like. It is necessary to have keypoint location and description, which make a feature, to employ a matching algorithm. Matching techniques use the location of features and a vector map of their shape and size information to index each set in two images to find matches. Most techniques still do not use color, as standard image processing works in grayscale.
Even with a good set of descriptors, mistakes can be made and outlier rejection techniques are needed to make sure the set of matches average out to the same rotation and translation for an image. If all the matches give different results, it is necessary to throw out outliers to get a usable result. Feature detectors only find a keypoint's position, while a descriptor generator considers its shape.

SURF (*Speeded Up Robust Features*) is both a keypoint detectors and a descriptor generators. The main interest of the SURF approach lies in its fast computation of operators using box filters, thus enabling real-time applications such as tracking and object recognition.
Outliers may be roughly classified in three classes:

1. Outliers due to incorrect feature matching between frames
2. Outliers caused by the terrain shape
3. Outliers due to terrain mismatch.

As outlier rejection is used RANSAC (*RANdom SAmple Consensus*): it is capable of smoothing data that contain a significant percentage of gross errors. This paradigm is particularly applicable to scene analysis because local feature detectors, which often make mistakes, are the source of the data provided to the interpretation algorithms. The RANSAC procedure randomly select a minimum number of points required to fit a line of data and tries to fit the model and reject outliers, repeats this until inliers are maximized. The number of iterations is chosen high enough to ensure that the probability (usually set to 0.99) of at least one of the sets of random samples does not include an outlier.

3.3.2 Code steps explanation

The logical flow of the code is described in the following points:

- Collect material to create a database
- Divide the images into different sub-images
- Create a map of Mars' surface
- Select a random image from the sub-images folder
- Landmarks detection through the SURF feature
- Image matching with database
- Coordinate extraction in pixel
- Show the location on the map
- Convert to longitude and latitude coordinates
- Crater detection

They can be grouped into three macro steps:

- Step 1: find the position of the selected random image relative to the database image
- Step 2: extract satellite coordinates in terms of longitude and latitude
- Step 3: detection of the characteristics of the terrain, i.e. of the craters

Three simulations will be presented showing different areas of the map in terms of the number of landmarks; this choice was made in such a way as to be able to carry out a robustness analysis of the code for every single simulation.

Chapter 4

Simulation and analysis

This chapter will describe the results obtained for the three simulations carried out. The selected map is the part of interest for this work of the Mars' surface, that is the band between -30° and 30° of latitude.

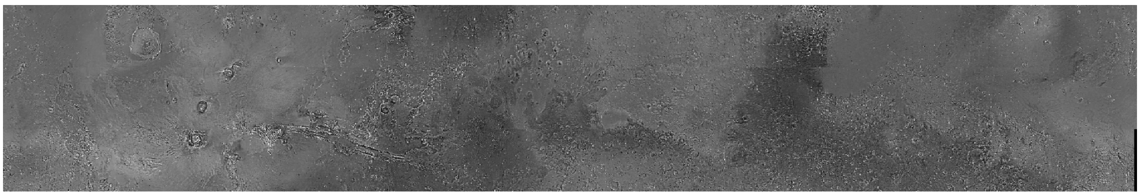


Figure 4.1: Map of the Mars's surface

The MatLab function used to display the image data set is *montage*: this function displays multiple image frames as rectangular montage, as shown in Figure 4.1. Before proceeding with the various simulations, it is necessary to create an index for searching the images and detecting the SURF characteristics. Thanks to the MatLab function *indexImages* it is possible:

- Selecting feature point locations using the detector method
- Extracting SURF features from the selected feature point locations
- The function detectSURFFeatures is used to detect key points for feature extraction.

4.1 Simulation 1

The random image selected in the first simulation is shown in Figure 4.2.

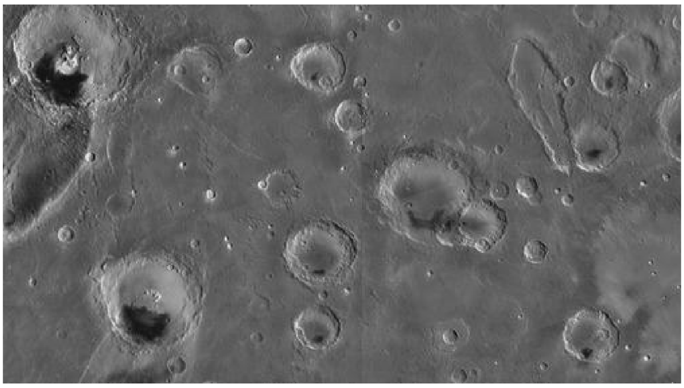


Figure 4.2: Random image selected

In this case, the selected image has a discrete number of features to be able to execute the code correctly.

Step 1

According to the logical flow of the algorithm, the first step is to compare the features of the selected image with those of the image stored in the database. A match between the two images is obtained through an iterative loop.
The final result is shown in Figure 4.3.

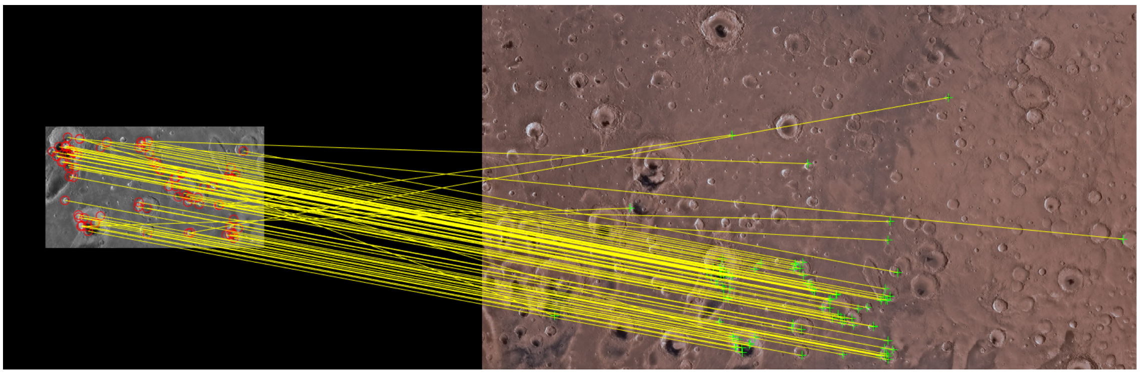


Figure 4.3: Matching

The corresponding points are connected by a line, but it is possible that one point is erroneously connected to another by similarity. For this reason it is necessary to eliminate the incorrect points and select only the inlier points.
The MatLab function that executes this process is *estimateGeometricTransform2D*.

The function excludes outliers using the M-estimator sample consensus (MSAC) algorithm. The MSAC algorithm is a variant of the random sample consensus (RANSAC) algorithm. Results may not be identical between runs due to the randomized nature of the MSAC algorithm.

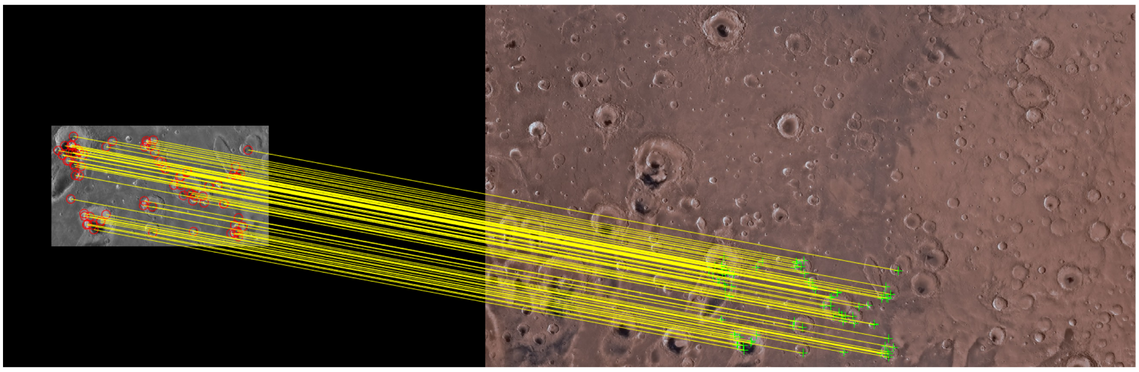


Figure 4.4: Matching without wrong features

The next step is to show the position of the selected image relative to the database image by displaying its edges, as shown in Figure 4.5.

Figure 4.5: Random image location

Step 2

The ultimate goal of the algorithm is to obtain the satellite coordinates in terms of longitude and latitude. Before that, it is necessary to identify the position of the selected image on Mars' surface map so that the coordinates in terms of pixels can be obtained in the first instance. Figure 4.5 becomes the new reference point for matching the features with the map of Mars' surface (Figure 4.1).

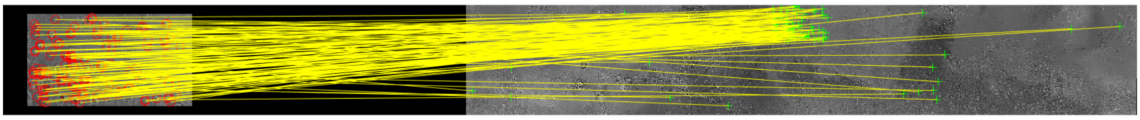


Figure 4.6: Matching with map of Mars' surface

As before, the incorrect pair points are eliminated by the function *estimateGeometricTransform2D*.

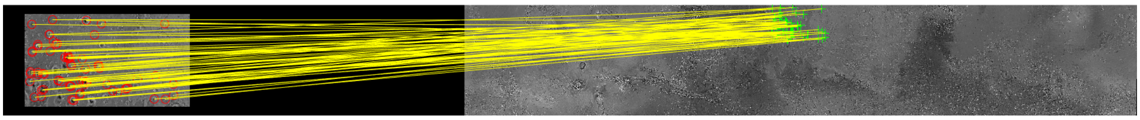


Figure 4.7: Matching with map of Mars' surface without wrong features

For better visualization of the results, 70 key points have been selected.

By building the edges of the image, they show its position on the map and also identify the position of the satellite in terms of pixels.

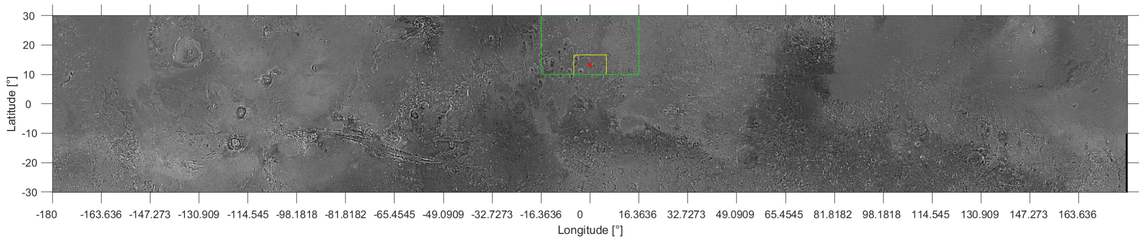


Figure 4.8: Satellite location on the Mars' surface map

The red mark indicates the position of the small-sat in terms of longitude and latitude coordinate, after converting them from pixel coordinates.

$$longitude = 0{,}02 \quad deg \qquad\qquad latitude = 13{,}33 \quad deg$$

Note that the longitude value in this simulation is a coincidence because it is a random selection.

To identify a satellite it is necessary to have, in addition to longitude and latitude, also a third coordinate, i.e. the altitude. The image database was created at an altitude of 150 km while the selected images are acquired at a lower altitude. To obtain the current satellite altitude value, the following data are taken into consideration:

- reference altitude;
- pixel dimensions of the reference image;
- pixel dimensions of the database image;
- scale factor between the two images.

The value obtained is $altitude$ = 83,53 km. The satellite position in its three coordinates is shown in Figure 4.9.

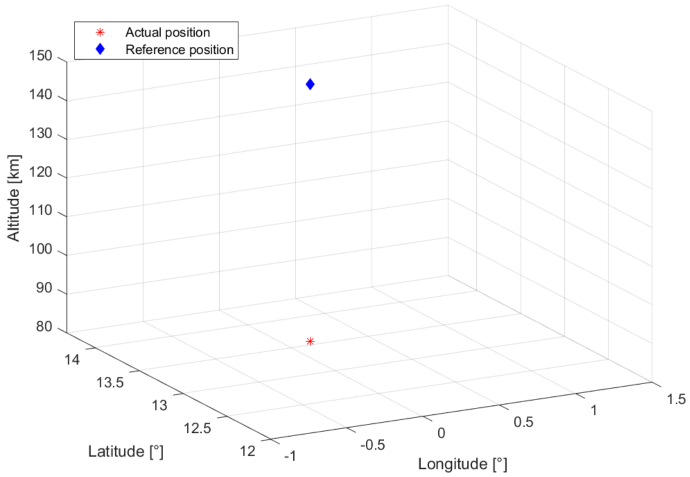


Figure 4.9: Satellite position in 3D

Step 3

The last step of the algorithm is to be able to identify the craters.
Craters can be classified into two principal categories: the main crater and secondary crater. Secondary craters are small ones that are formed by the ejecta falling down the surface. Craters are features commonly used as research landmarks.
The proposed topography-based Craters Detection Algorithm is primarily based on actual image analysis. The algorithm flowchart can be reduces to the diagram show in Figure 4.10.
The *drawline* function defines the crater range. Images were categorised into two components, light and dark patches. For crater detection, use *imfindcircles* with the Hough transform and *viscircles* function.

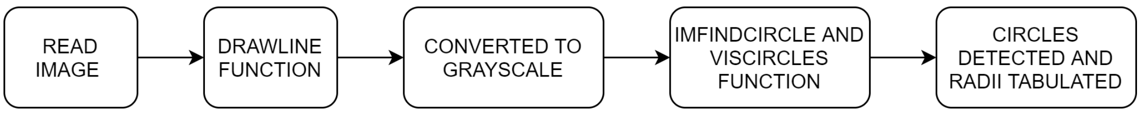


Figure 4.10: Crater detection flowchart

Crater detection with matlab is performed both on the selected image and on the image stored in the database.

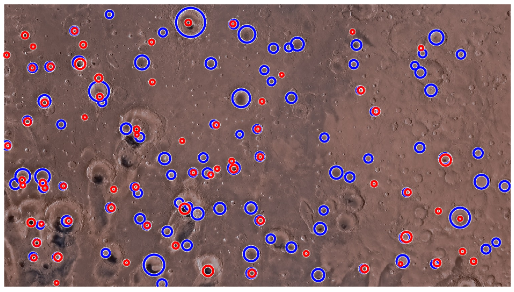


Figure 4.11: Crater detection database image

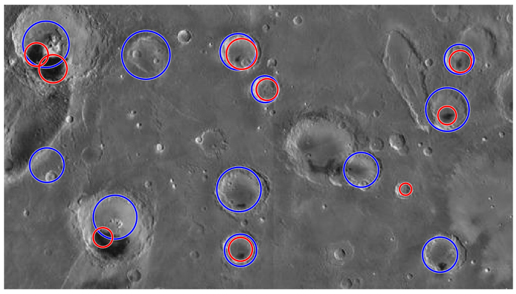


Figure 4.12: Crater detection random image

4.2 Simulation 2

The random image selected in the second simulation in shown in Figure 4.13. Unlike the previous simulation, this is a case where there are more features.

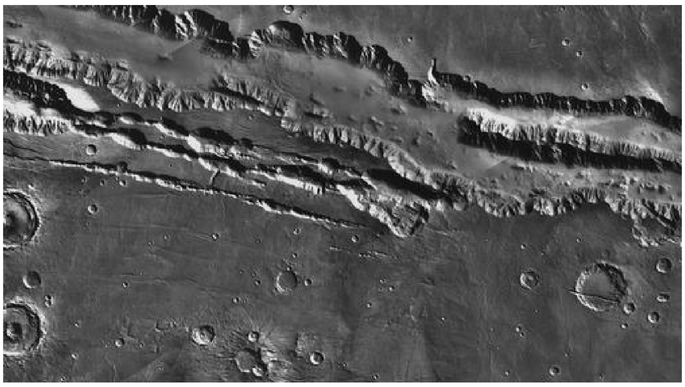


Figure 4.13: Random image selected

Step 1

The same logic of the first simulation is followed.
Figure 4.14 shows the match of the selected image with the database image obtained through the iterative loop.

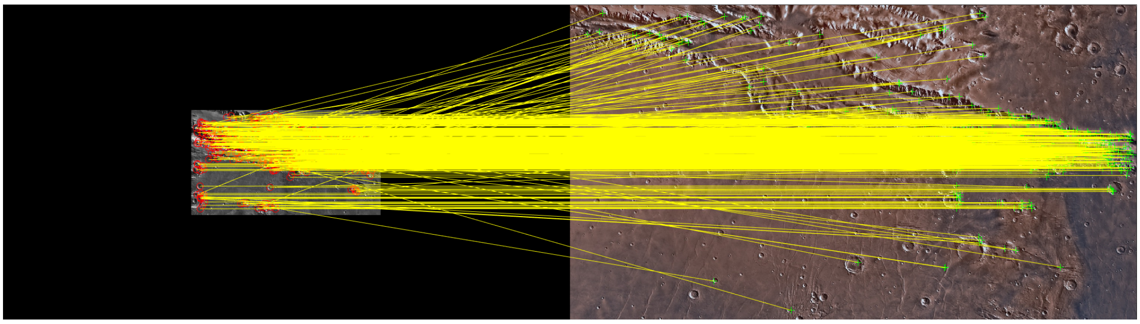


Figure 4.14: Matching image selected with database image

Similarly, only inlier points are selected thanks to the function *estimateGeometricTransform2D*.

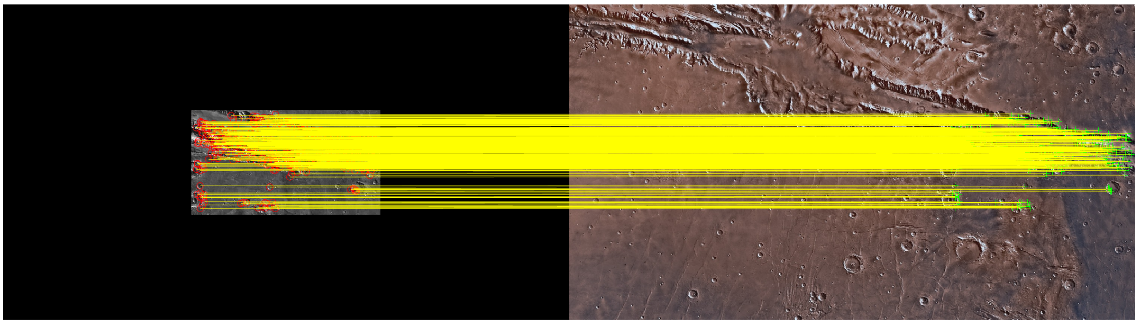


Figure 4.15: Matching images without wrong features

The edges of the image are reported on the database image and then become the new reference to be compared with the map of the Mars' surface.

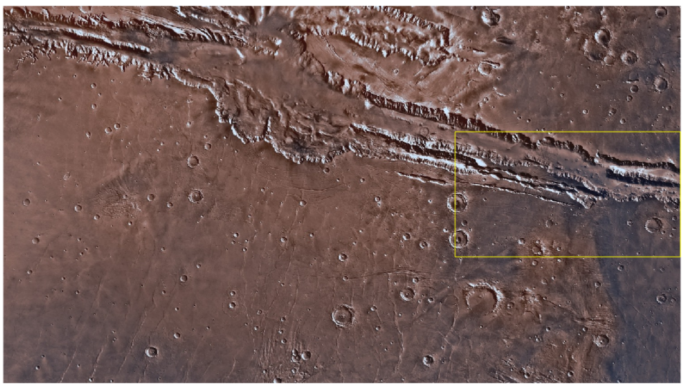


Figure 4.16: Random image location on database image

Step 2

The *estimateGeometricTransform2D* function is used again and only 70 points are selected in order to make the visibility of the figure clearer.

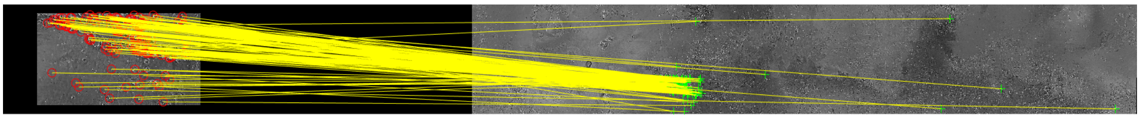


Figure 4.17: Matching database image with map of Mars' surface

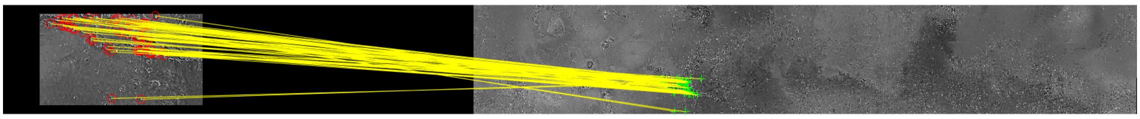


Figure 4.18: Matching database image with map of Mars' surface without wrong features

The position on the map of Mars' surface is shown in Figure 4.19 and is shown also the satellite position with the red mark.

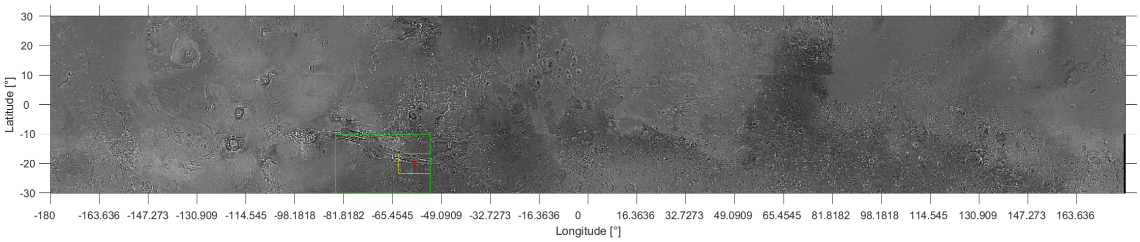


Figure 4.19: Satellite location on the map

The resulting longitude and latitude values, after converting from pixels, are:

$$longitude = -58{,}11 \quad deg \qquad\qquad latitude = -19{,}94 \quad deg$$

The altitude value of the satellite is the same of the first simulation because the dimensions of the selected image are equal.
The satellite position in the 3D plane is shown in Figure 4.20.

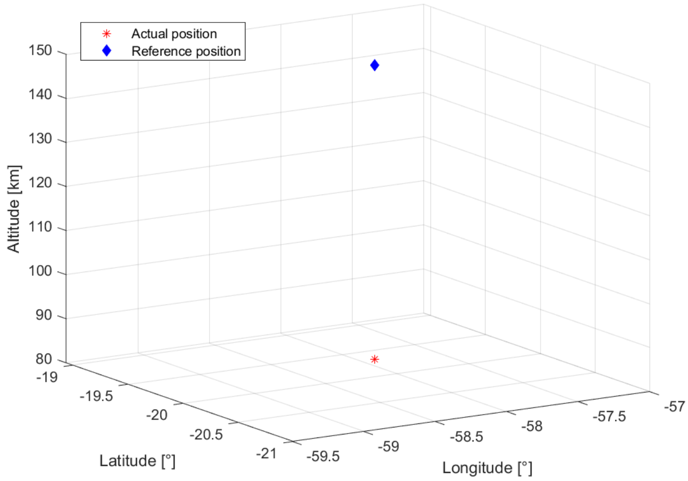


Figure 4.20: Satellite position in 3D

Step3

The crater detection for this simulation is shown below.

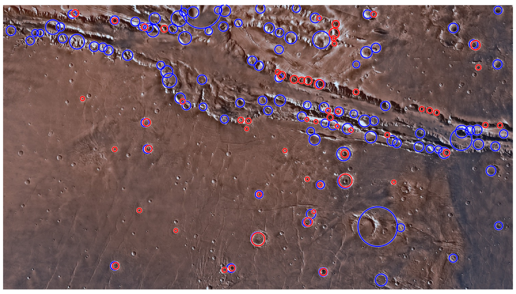


Figure 4.21: Crater detection database image

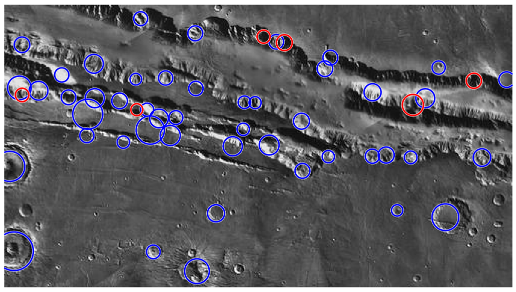


Figure 4.22: Crater detection random image

Given the rich morphology present in the image, the algorithm not only identifies the craters but also hills and mountains (wrongly). This indicates that the method is not entirely efficient.

4.3 Simulation 3

The random image selected in the third simulation in shown in Figure 4.23.

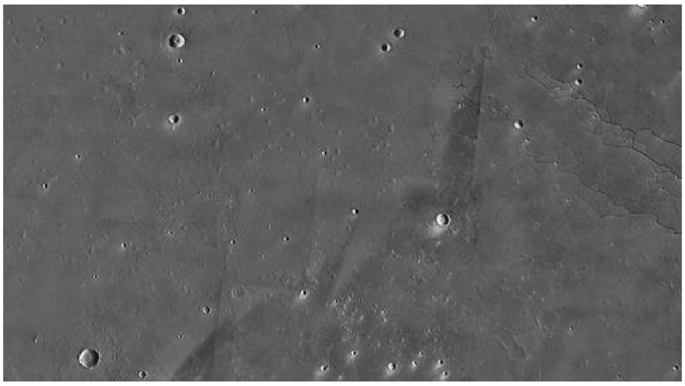


Figure 4.23: Random image selected

In this case, there are few features to test the execution of the code even in the condition where it is difficult to find a match between the selected image and the image database.

Step1

Figure 4.24 shows the matching obtained through the iterative loop, while Figure 4.25 shows the selection of the correct pairs of points with the *estimateGeometricTransform2D* function.

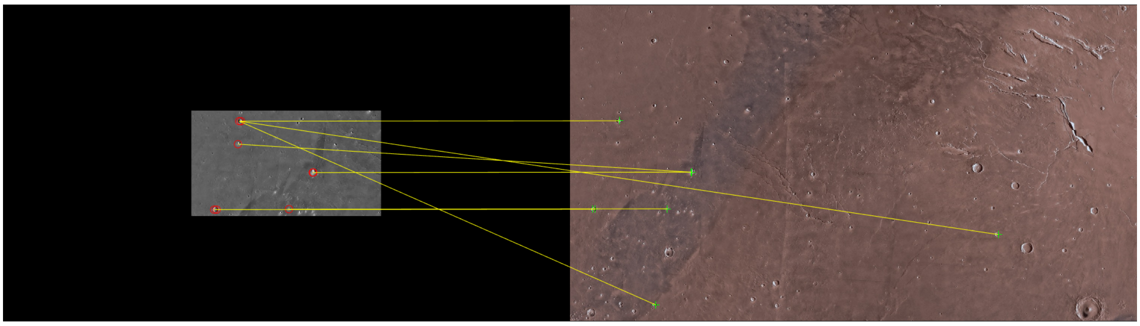


Figure 4.24: Matching image selected with database image

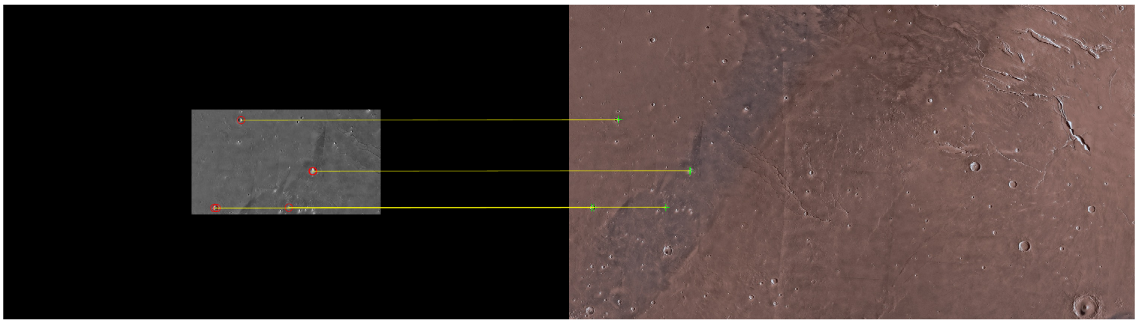


Figure 4.25: Matching images without wrong features

The identified features are at the limit of the minimum value required by the code to be able to be executed. The *estimateGeometricTransform2D* function requires a minimum number of matched pairs of points to estimate a transformation. For this work, the minimum number has been set at 3 pairs of points to increase the accuracy, but in the most extreme cases it can be decreased to a value of 2 pairs of points.

The visualization of the image selected position relative to that of the database is shown in Figure 4.26.

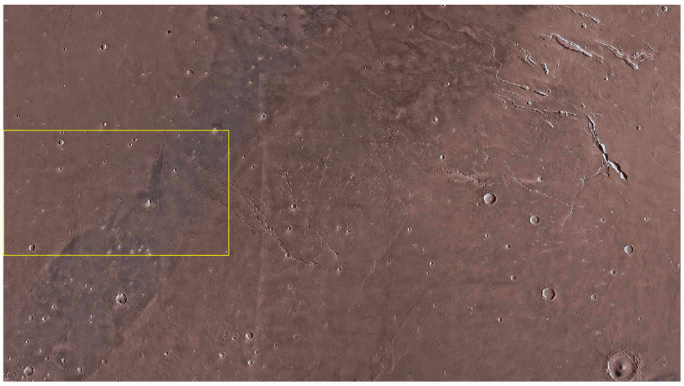


Figure 4.26: Random image location on database image

Step 2

The next step is to identify the position on the map of Mars' surface through the same logical process presented in the previous simulations.

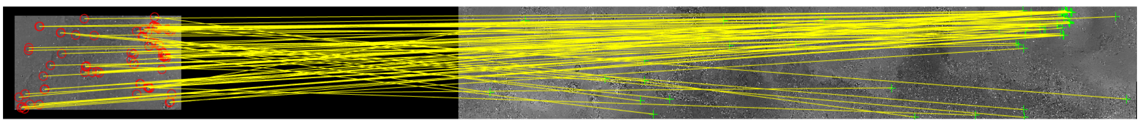


Figure 4.27: Matching database image with map of Mars' surface

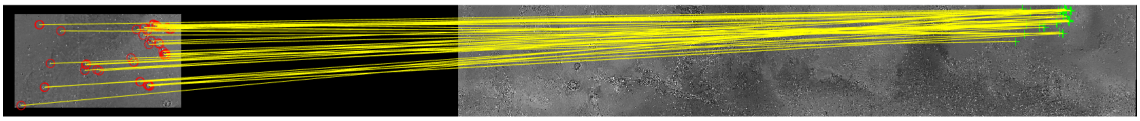


Figure 4.28: Matching database image with map of Mars' surface without wrong features

The final result of the location on the map of the satellite and its coordinates are shown below (Figure 4.29).

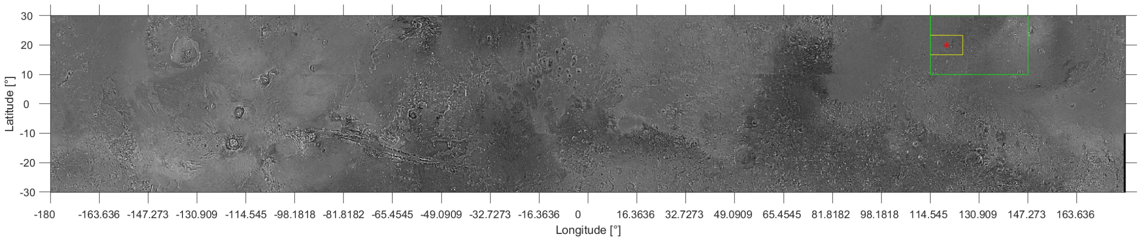


Figure 4.29: Satellite position on the map

$$longitude = 119{,}92 \quad deg \qquad\qquad latitude = 20{,}01 \quad deg$$

Also in this simulation, the value of the satellite altitude is the same obtained previously.

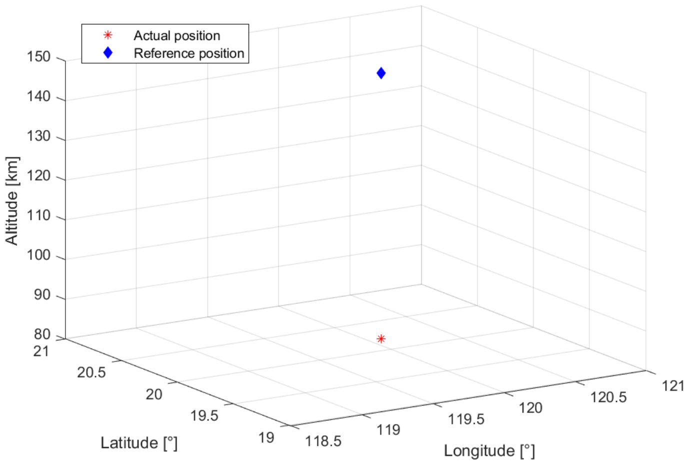


Figure 4.30: Satellite position in 3D

Step 3

In contrast to the second simulation, the landforms in the selected image are almost non-existent. In fact, the figures obtained from the crater detection, as expected, show a poor presence of craters.

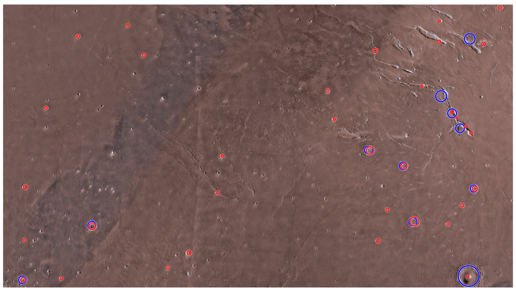


Figure 4.31: Crater detection database image

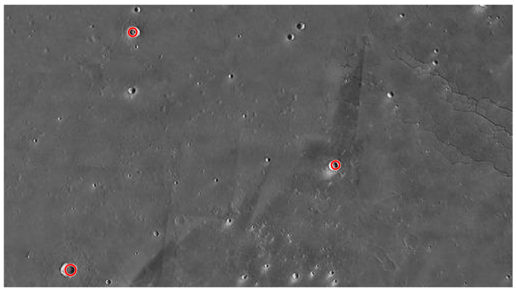


Figure 4.32: Crater detection random image

4.4 Code robustness analysis

Regarding to the three simulations described, an analysis is made to test the limits of the code in the various conditions presented.
The robustness analysis includes:

- alter the illumination of the reference image by increasing or decreasing it;
- alter the size of the reference image relative to the original image;
- rotate the reference image;
- select a part of the reference image to reproduce a malfunction of the camera.

4.4.1 Simulation 1

Brightness analysis

Following the analysis steps, in the first simulation the brightness of the selected image is altered to the point where the code is no longer able to recognize the features.
The original image is brightened starting from 20% and then the altered image is matched to the database image. This way the limits of the code are tested.

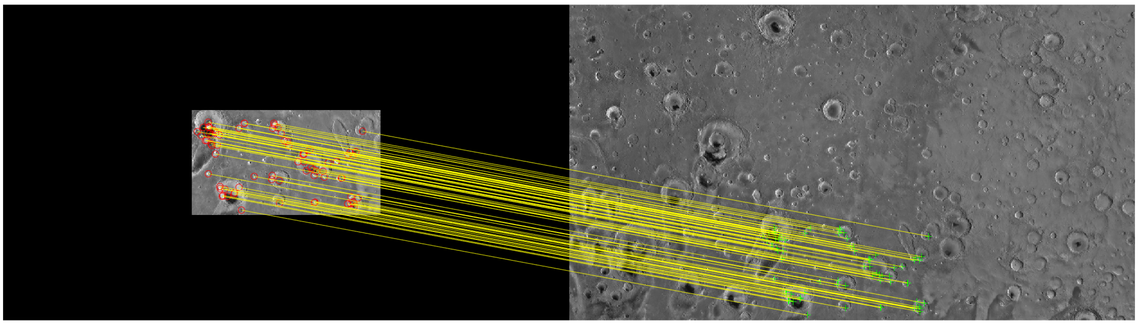


Figure 4.33: 20% brighter image

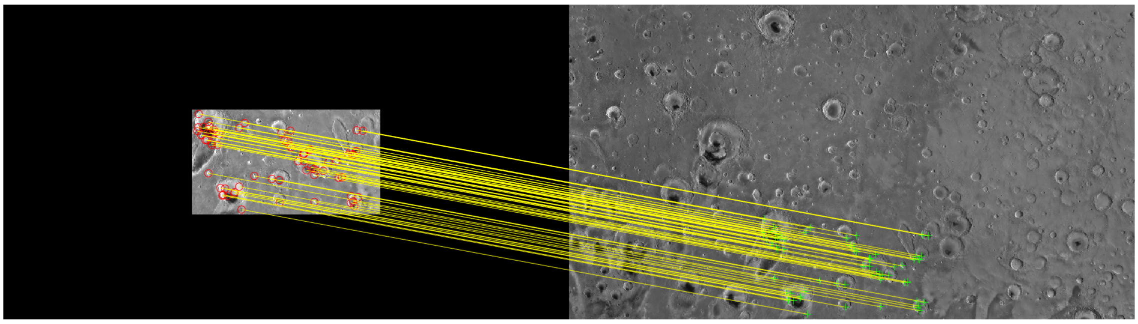


Figure 4.34: 30% brighter image

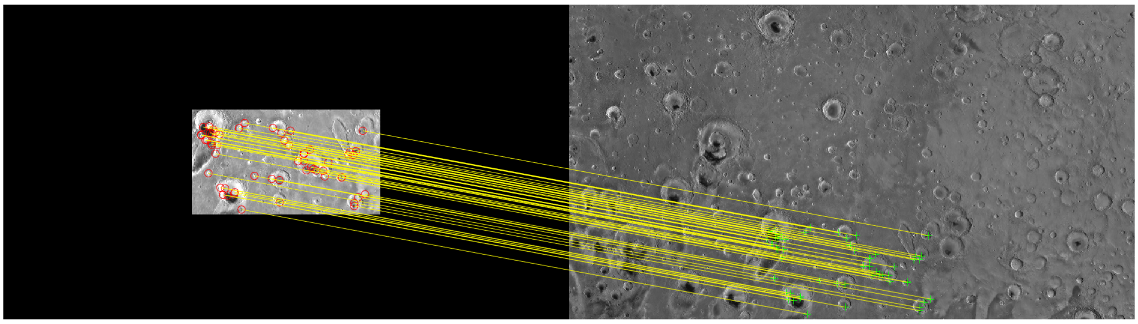


Figure 4.35: 40% brighter image

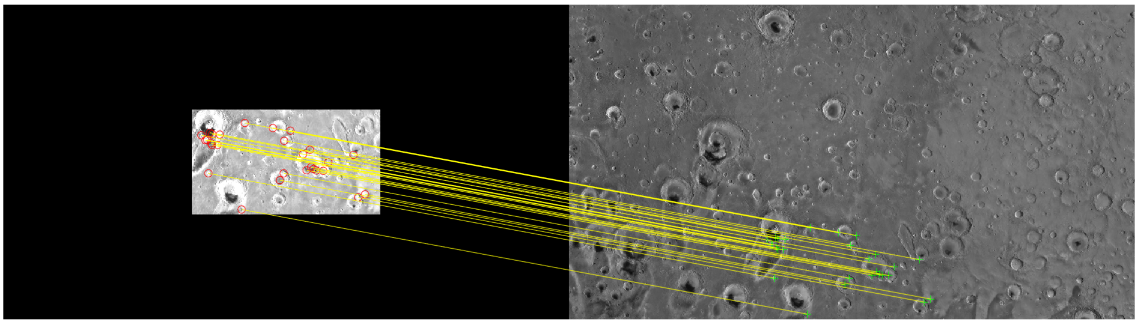


Figure 4.36: 50% brighter image

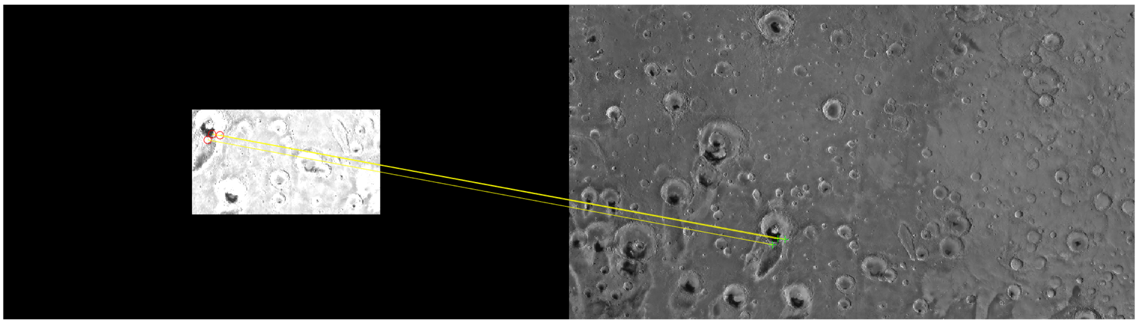


Figure 4.37: 60% brighter image

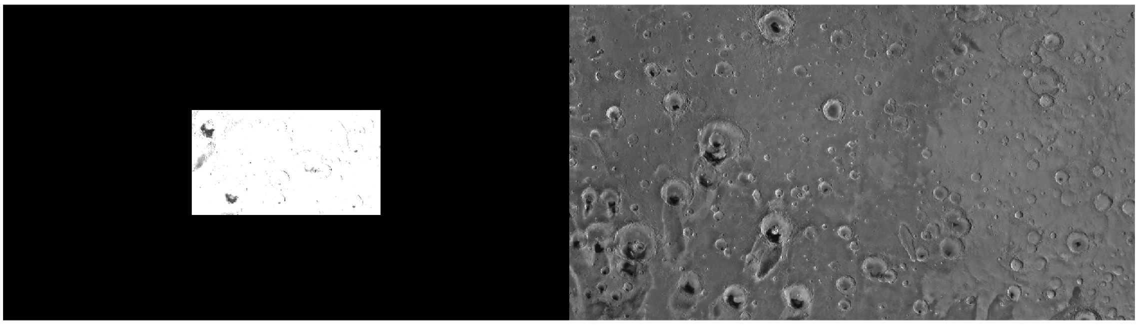


Figure 4.38: 70% brighter image

The code still works fine up to 50% more brightness. In the case of 60% more brightness, the number of pairs of points is at the limit of those required, it identifies the margin to which the code can reach. In fact, when the brightness is increased by 70% the code fails.

Otherwise, the brightness of the image is reduced, making it darker. Likewise, it starts with 20% less brightness than the original image.

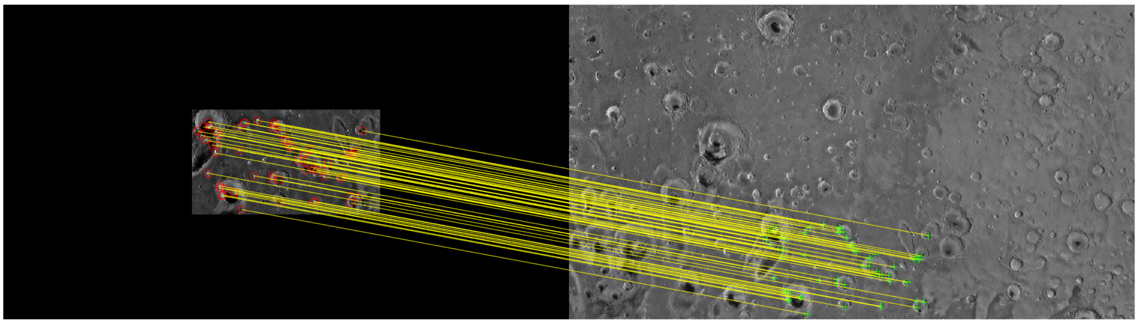


Figure 4.39: 20% darker image

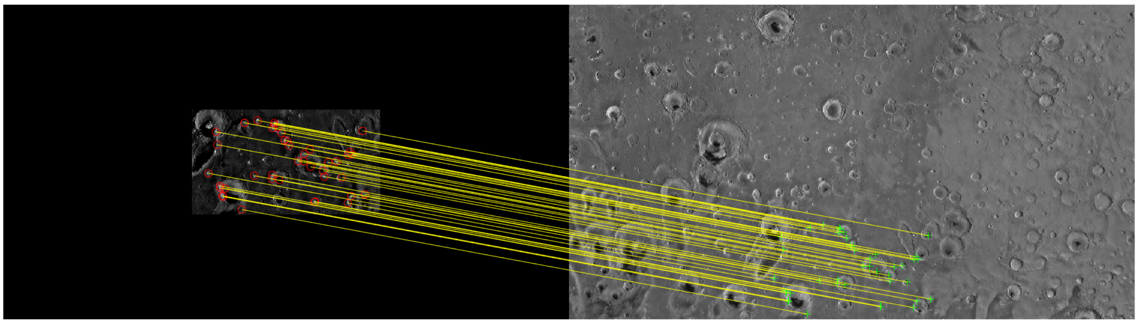


Figure 4.40: 30% darker image

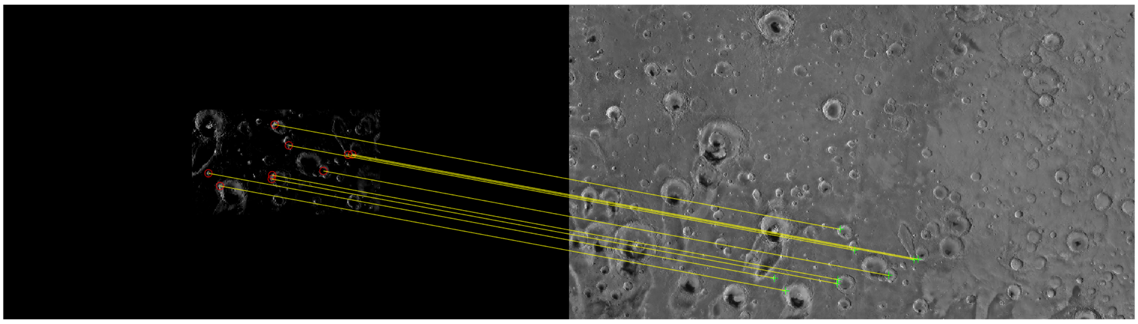


Figure 4.41: 40% darker image

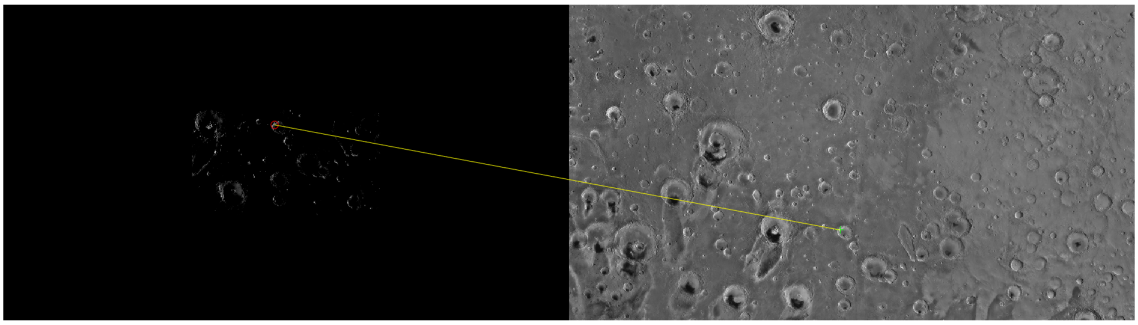


Figure 4.42: 50% darker image

The code continues to work up to 40% less brightness. But in the 50% case the features identified are below the limit of required points, even though the code appears to recognize the match.

Resize analysis

The second step of the analysis is to alter the size of the original image by increasing the scale factor between it and the database image. The image size is increased by a certain number from the original and then matched to the database image.

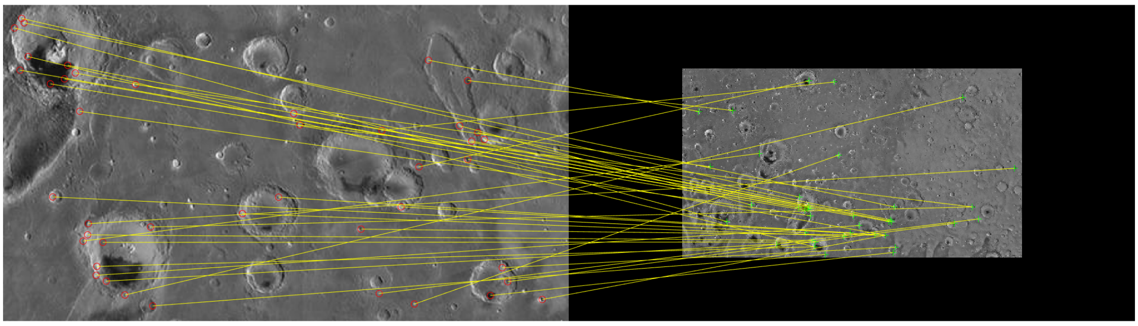


Figure 4.43: Image resized 5 times from the original

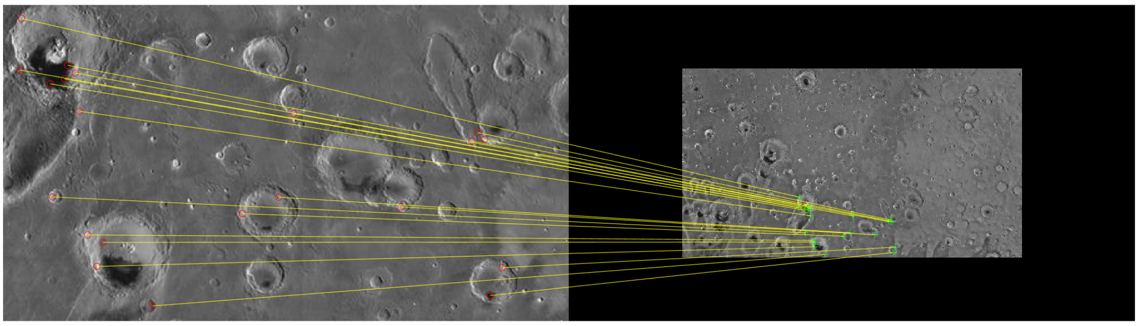


Figure 4.44: Image resized 5 times from the original with only inlier points

Figure 4.43 shows how it is possible to obtain more wrong pairs of points than in the original case, given the similarity of the terrain morphology between the two images. This happens because the resolution of the image is decreased as its size increases. However, the strongest features continue to be recognized and therefore to make the code work (Figure 4.44).
The size of the original image is increased even more to reach the limiting case.

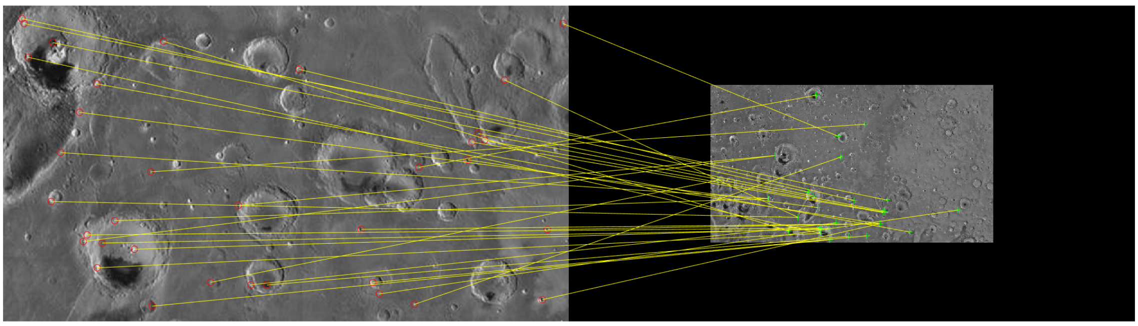


Figure 4.45: Image resized 6 times from the original

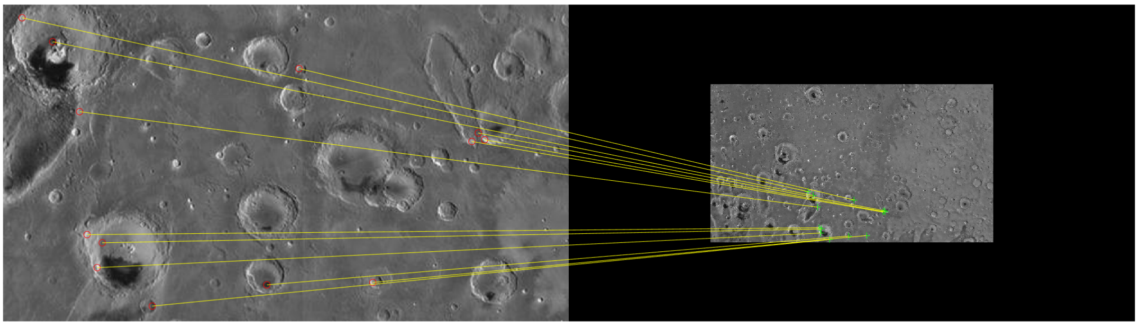


Figure 4.46: Image resized 6 times from the original with only inlier points

The number of correct pairs of points has decreased (Figure 4.46) compared to the previous case , just as the wrong pairs of points have increased (Figure 4.45). At this point, the size of the image is increased even more. Figure 4.48 shows how the limit case is reached since the only pairs of points recognized are the wrong ones.

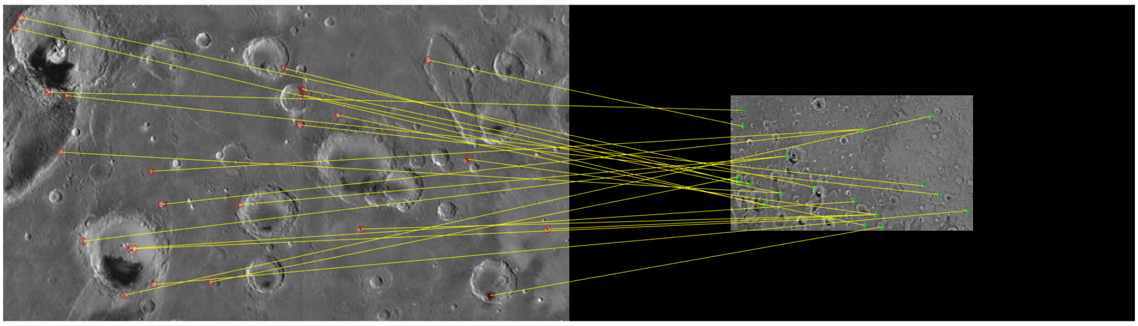


Figure 4.47: Image resized 7 times from the original

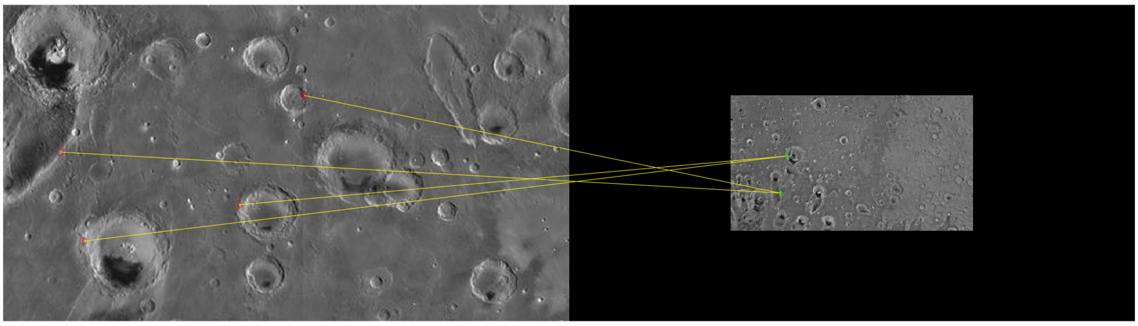


Figure 4.48: Image resized 7 times from the original with only inlier points

Rotate analysis

The next step is to rotate the original image to understand if the code can find the match between the two images. Image rotation is implemented randomly in the code and each time it runs, an angle between 0 and 360 degrees relative to the horizontal axis of the image is obtained. Two examples are shown below.

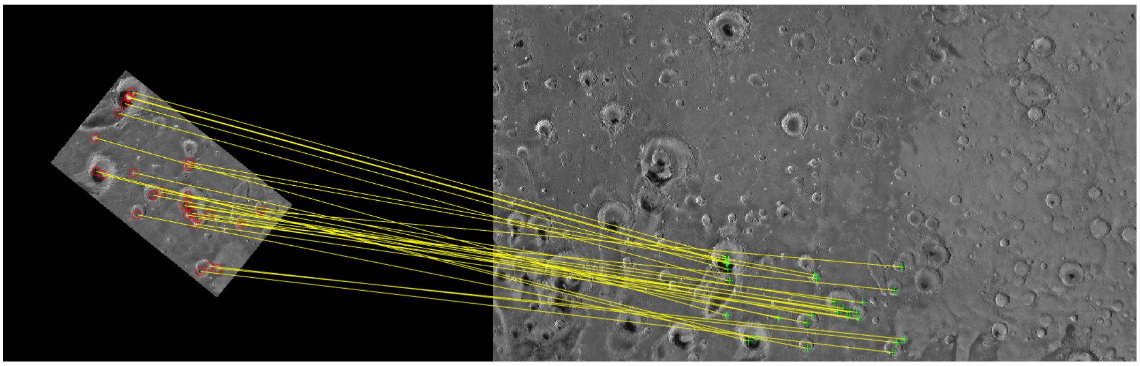


Figure 4.49: Example 1: rotated image

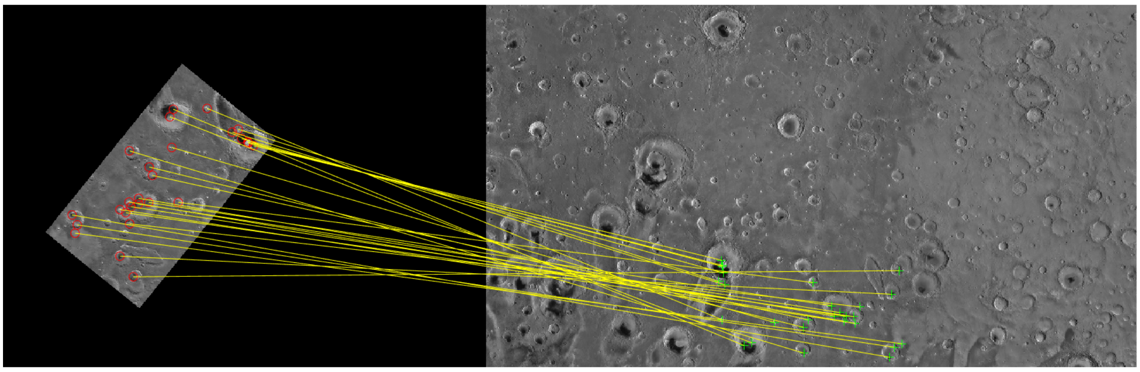


Figure 4.50: Example 2: rotated image

Both examples do not present problems or limits in the execution of the code, therefore the subsequent steps of the program are guaranteed. In conclusion, whatever the angle of the captured image, the final objective of this work is reached.

Damaged image analysis

The camera used for navigation purposes may malfunction and acquire a damaged image. To reproduce a similar situation it was decided to select only a part of the original image assuming that the remaining part is obscured or blurred. The selected part of the image is then compared with the database images to find the right match and compare this result with the one obtained from the original simulation.

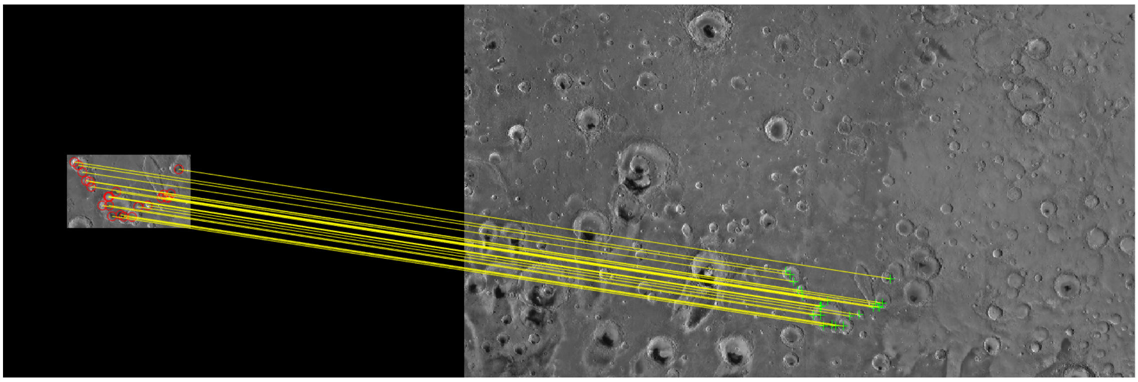


Figure 4.51: Match between part of original image and database image

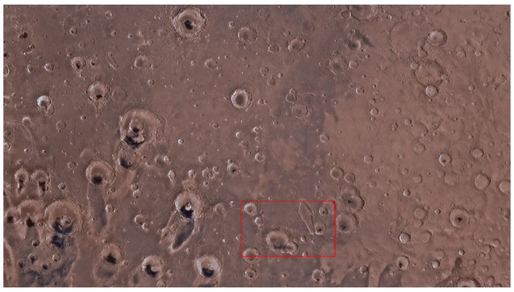


Figure 4.52: Part of original image position

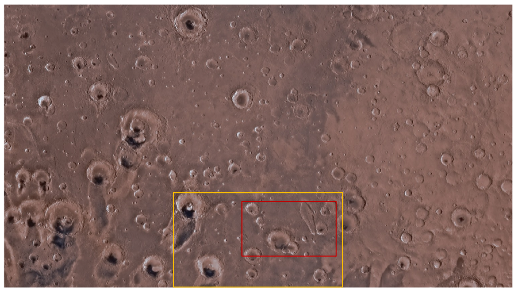


Figure 4.53: Part of original image position and original image position in comparison

In this case there are no limitations in the procedure of the following steps, since the code recognizes the features and is able to perform the matching.

4.4.2 Simulation 2

Brightness analysis

The second simulation has the original image with rich morphology so the brightness alteration is expected to reach high values. Always start from 20% more brightness than the original image.

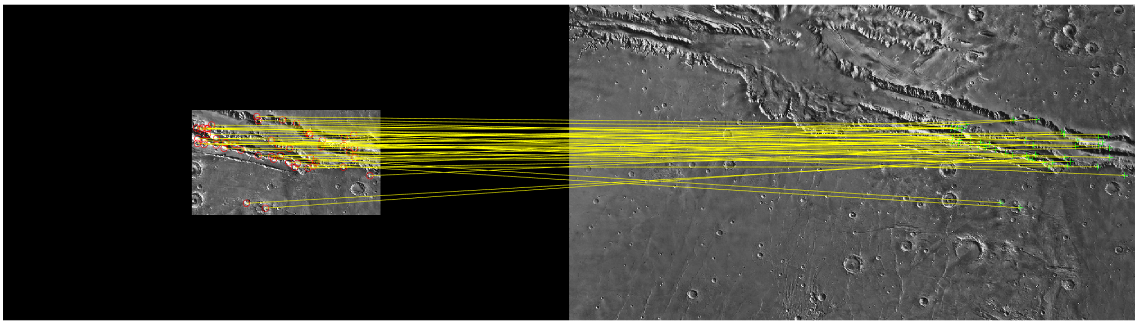


Figure 4.54: 20% brighter image

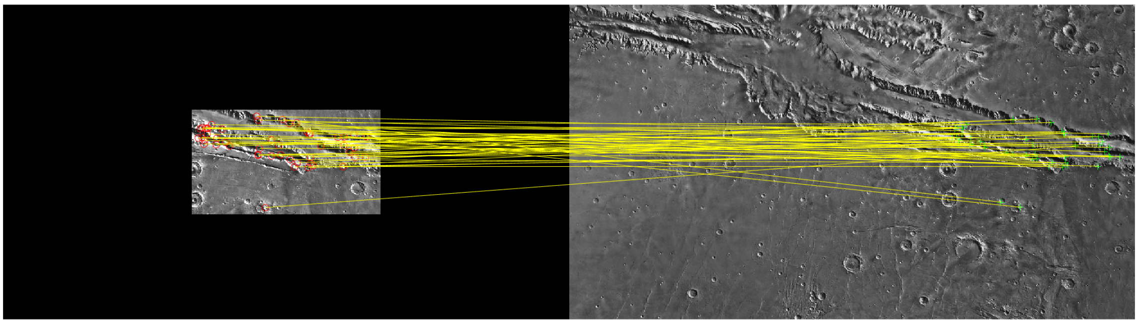


Figure 4.55: 30% brighter image

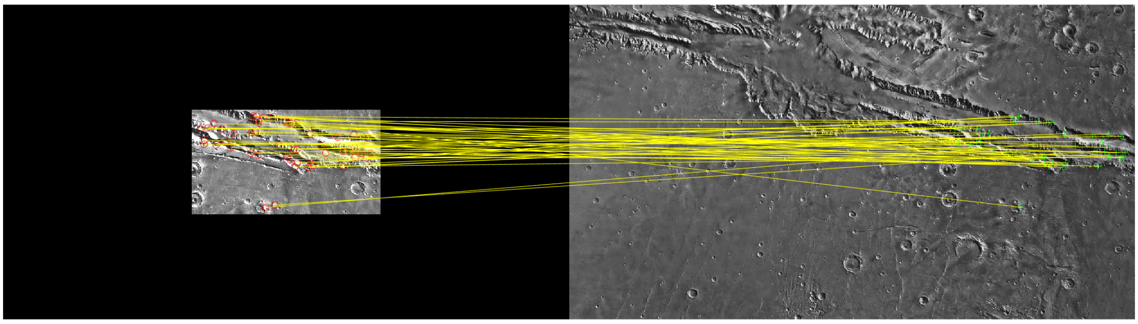


Figure 4.56: 40% brighter image

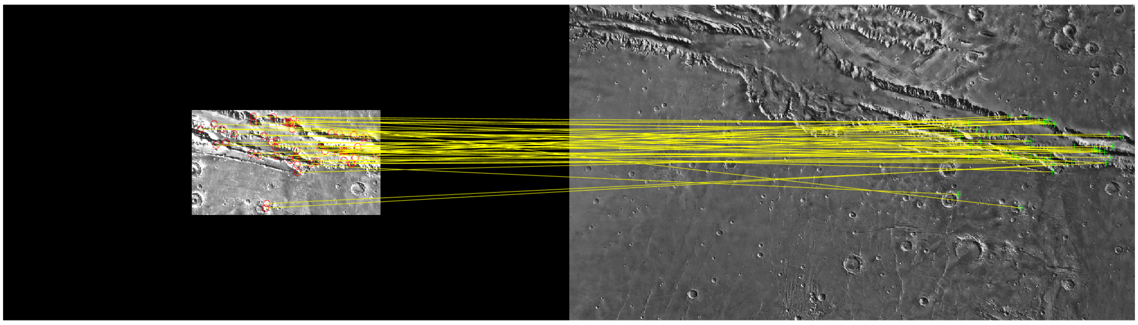


Figure 4.57: 50% brighter image

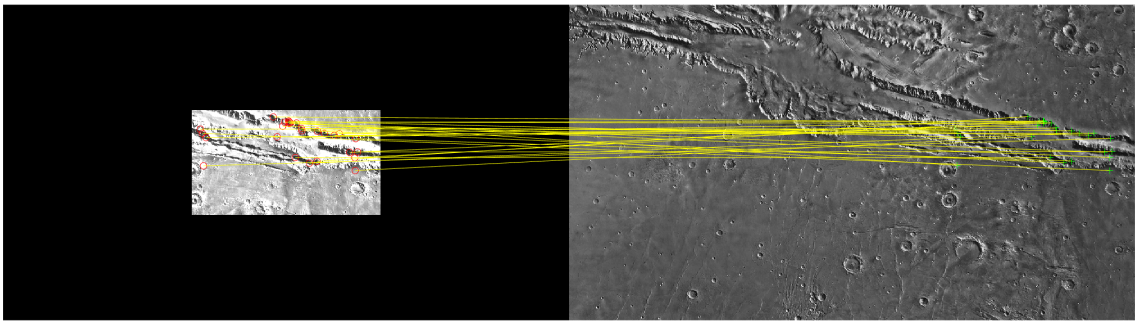


Figure 4.58: 60% brighter image

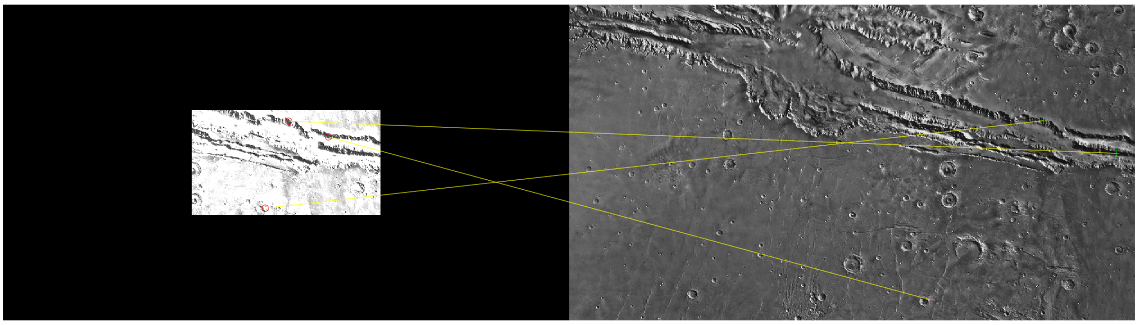


Figure 4.59: 70% brighter image

With up to 60% more brightness, the code can match the two images well. In the case of 70% more brightness, it is no longer possible to match, giving only incorrect pairs of points due to the high contrast. There is a clear distinction between Figure 4.58 and Figure 4.59 and not gradual as in the case of the first simulation.

Always altering the brightness of the original image, it is reduced starting from 20% up to the maximum limit that can be obtained.

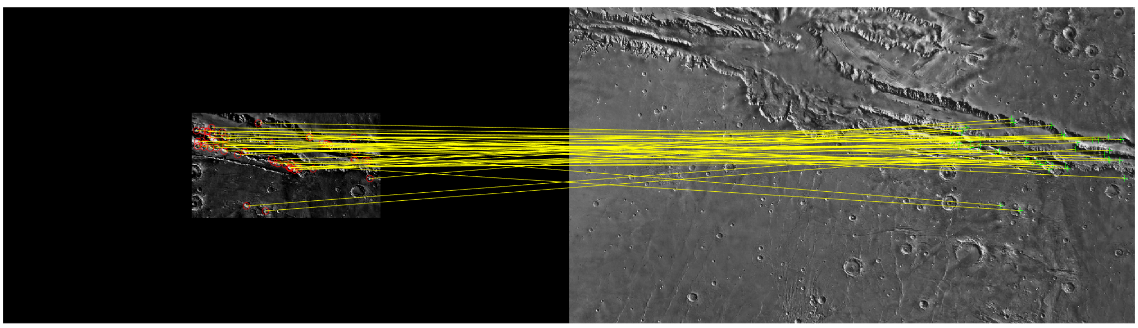


Figure 4.60: 20% darker image

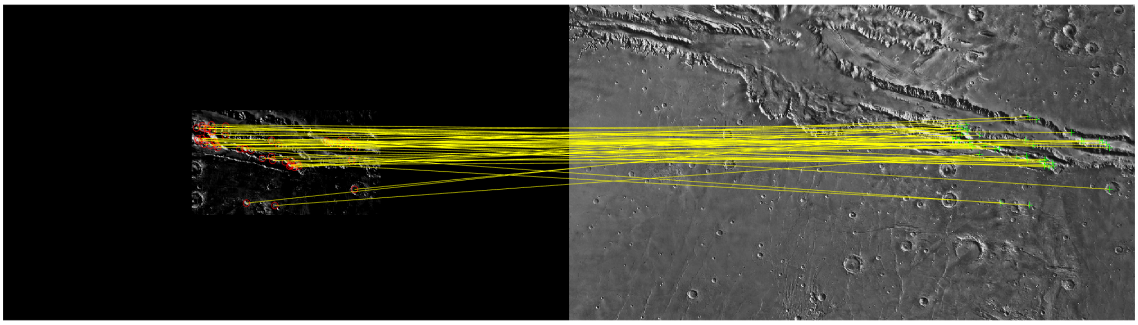


Figure 4.61: 30% darker image

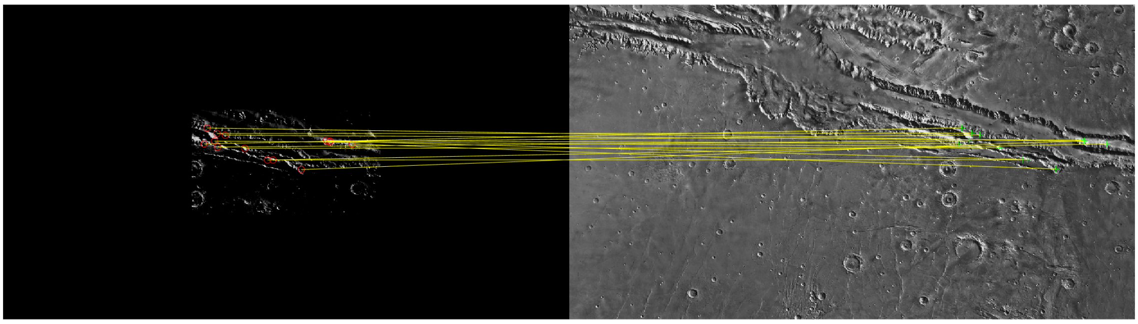


Figure 4.62: 40% darker image

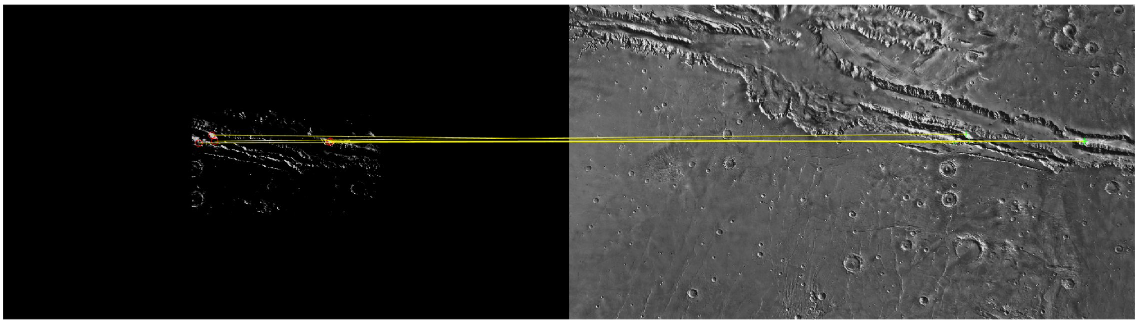


Figure 4.63: 50% darker image

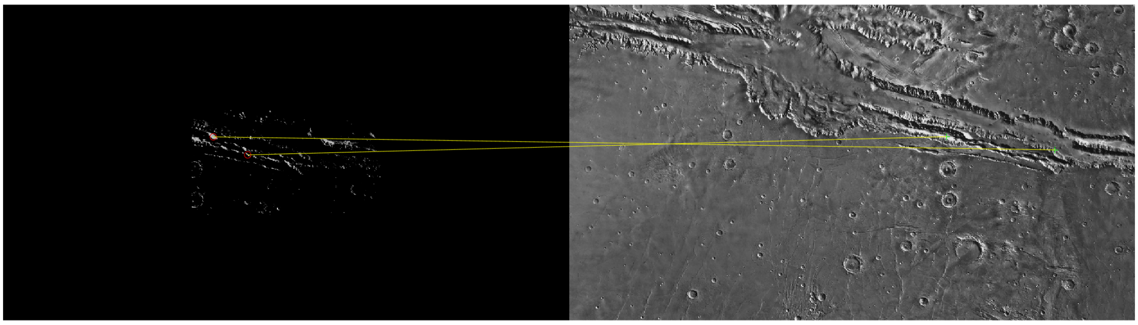


Figure 4.64: 60% darker image

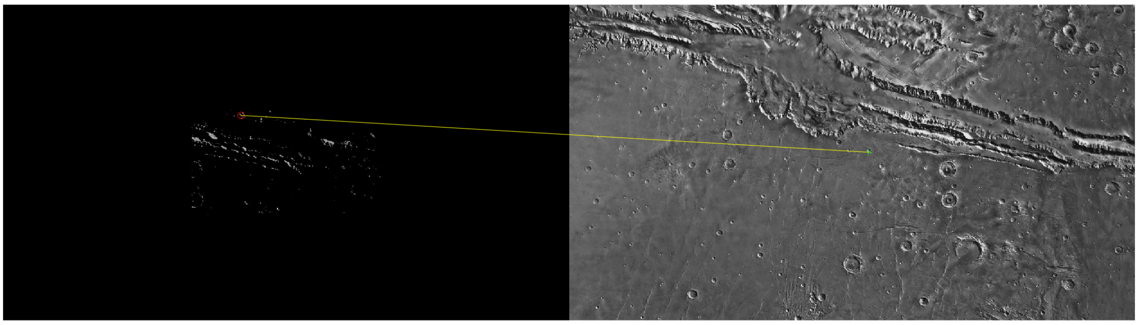


Figure 4.65: 70% darker image

Image matching works normally up to 40% less brightness. Even for 50% and 60%, the match is performed but the number of features present is close to the limit of required features. For 70% less brightness the image is almost totally blacked out and mismatched.

Resize analysis

Resizing the original image is the second step of this analysis which is performed for each simulation. The matching between the resized image and the database image is performed and subsequently select only the inlier points.

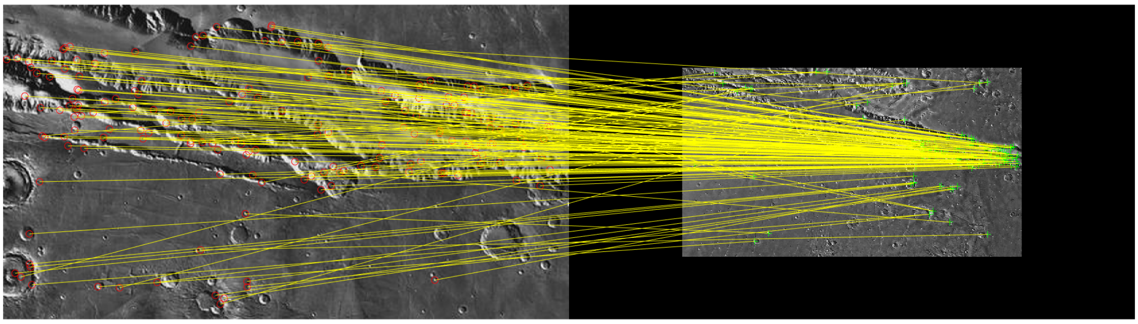


Figure 4.66: Image resized 5 times from the original

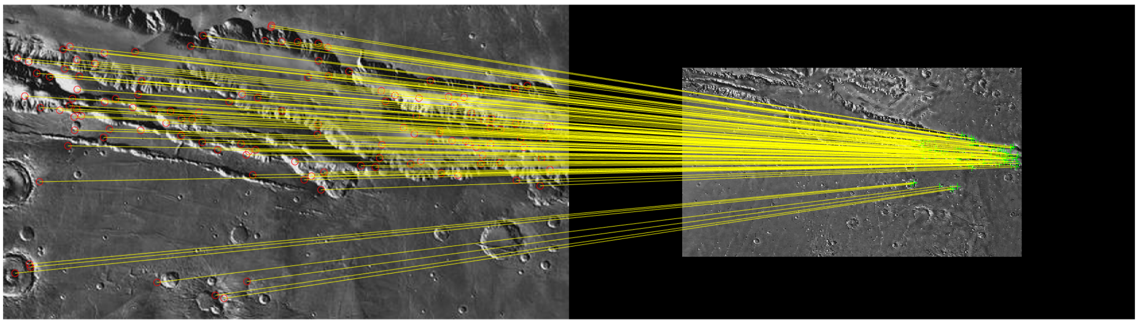


Figure 4.67: Image resized 5 times from the original with only inlier points

Again, increasing the size also increases the number of incorrect pair points. In Figure 4.69 the right features identified are less than in the previous case while the wrong features are more or less of the same quantity (Figure 4.68).

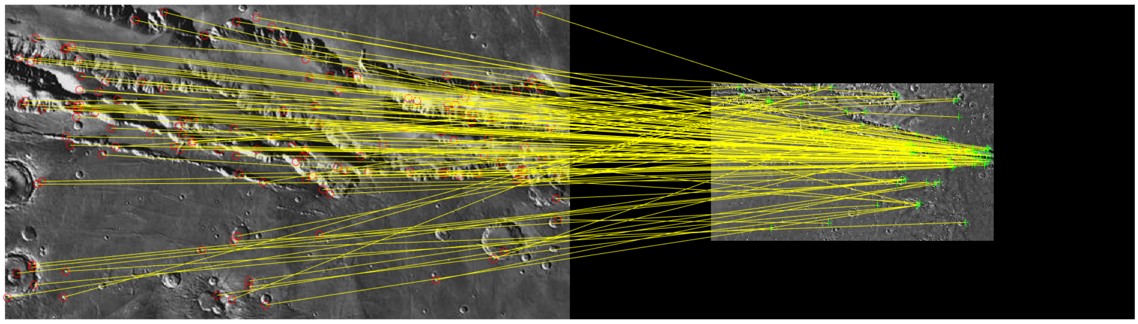


Figure 4.68: Image resized 6 times from the original

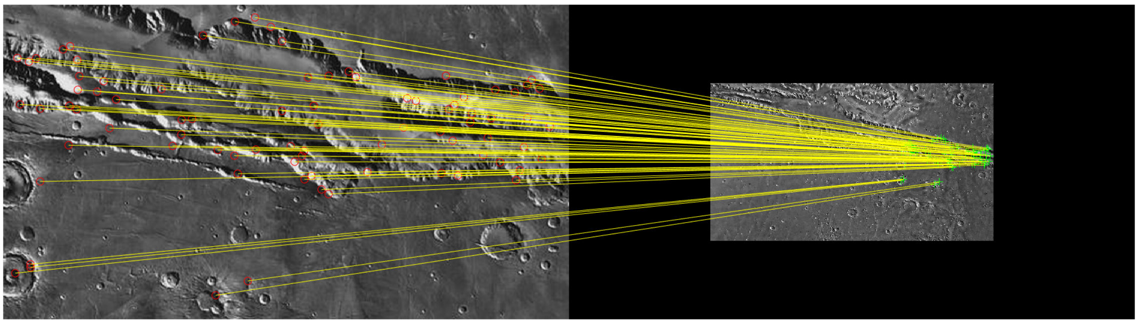


Figure 4.69: Image resized 6 times from the original with only inlier points

The image size keeps increasing as shown below and fewer and fewer correct features identified.

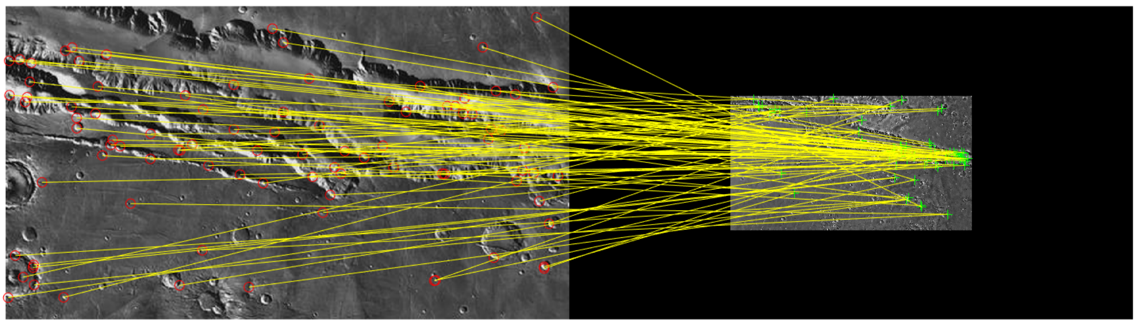


Figure 4.70: Image resized 7 times from the original

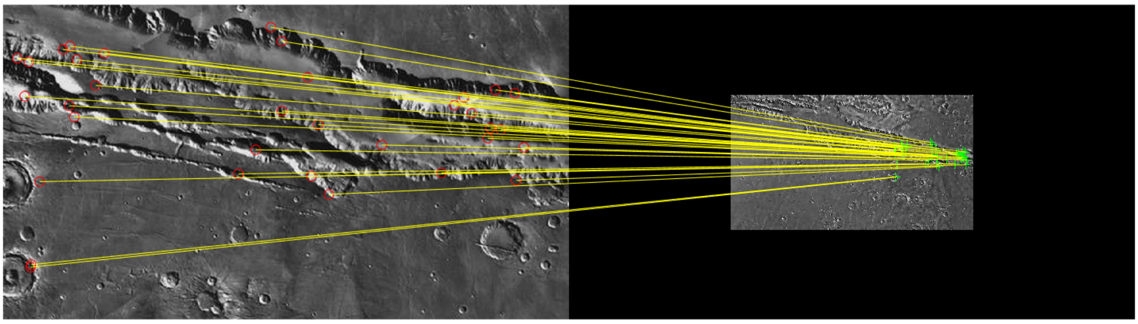


Figure 4.71: Image resized 7 times from the original with only inlier points

The limit is encountered when the image increases by 8 times compared to the original one. The number of pairs of points is somewhat moderate but they are all incorrect and therefore the code does not work correctly. The match is not guaranteed.

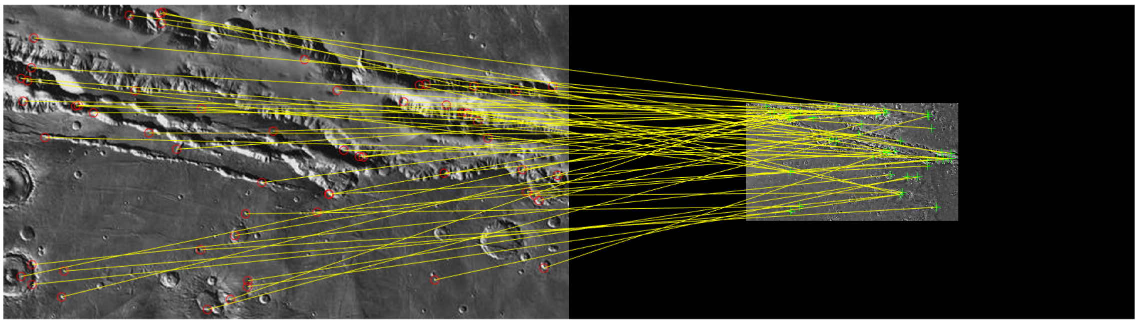


Figure 4.72: Image resized 8 times from the original

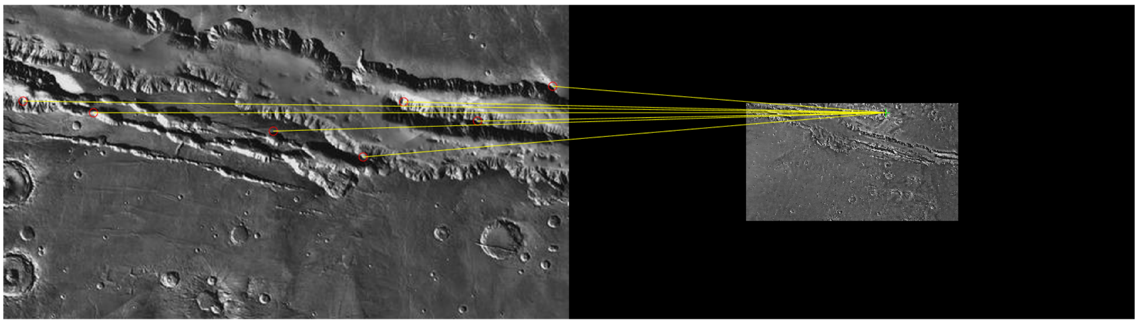


Figure 4.73: Image resized 8 times from the original with only inlier points

Rotate analysis

Rotating the original image randomly, has already been shown not to be a significant alteration for the purposes of the robustness analysis. In this simulation are shown three examples. All three examples show the expected results.

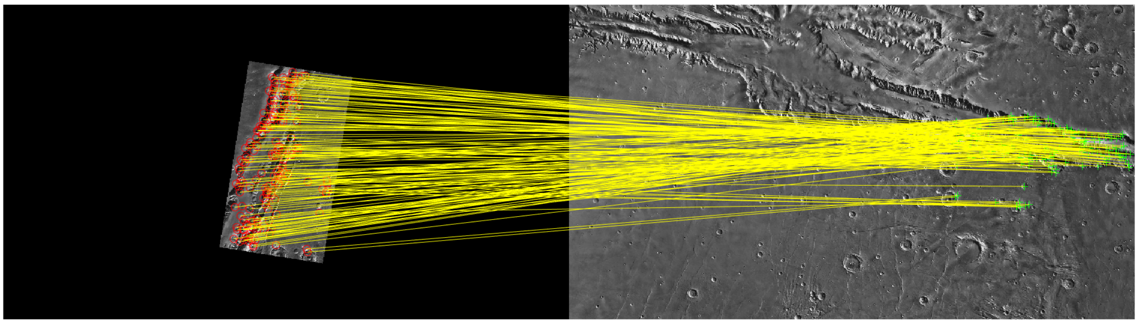


Figure 4.74: Example 1: rotated image

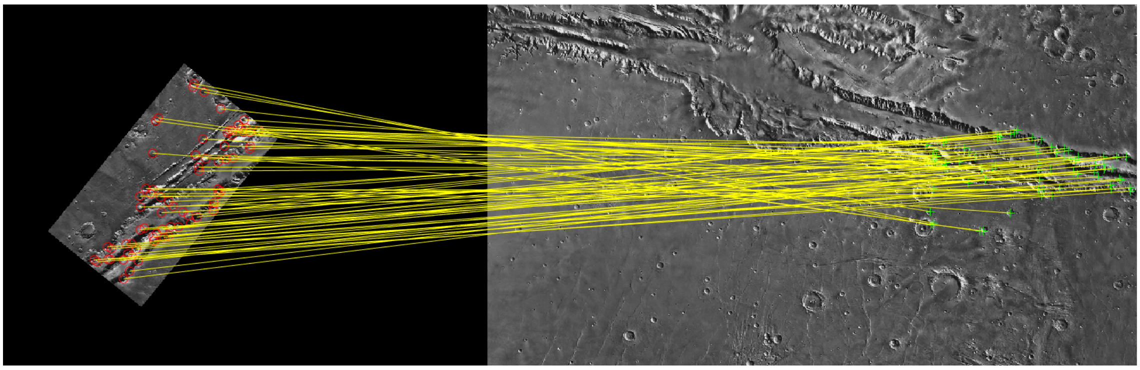


Figure 4.75: Example 2: rotated image

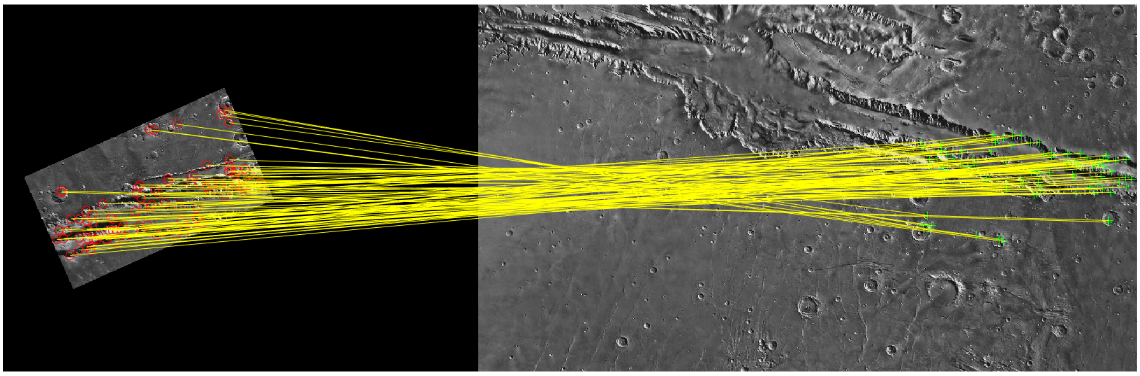


Figure 4.76: Example 3: rotated image

Damaged image analysis

The last analysis to be carried out is to simulate the camera malfunction. In the same way, a part of the original image is extracted and the code is executed.

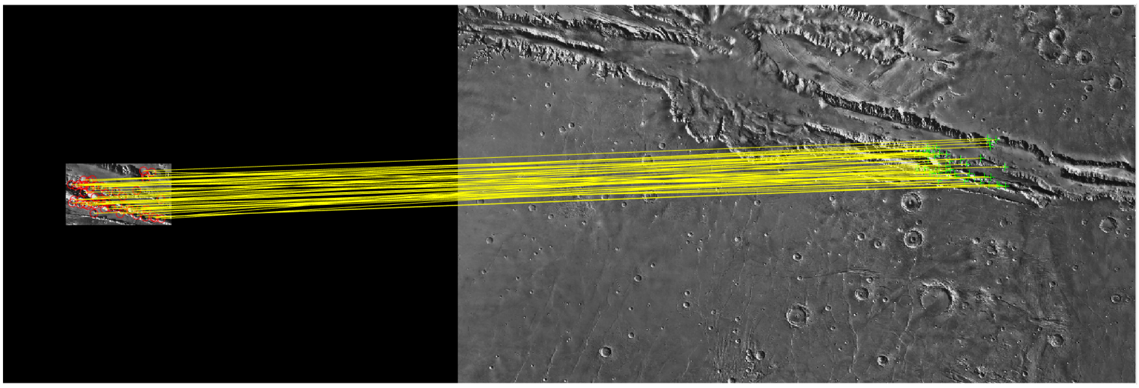


Figure 4.77: Match between part of original image and database image

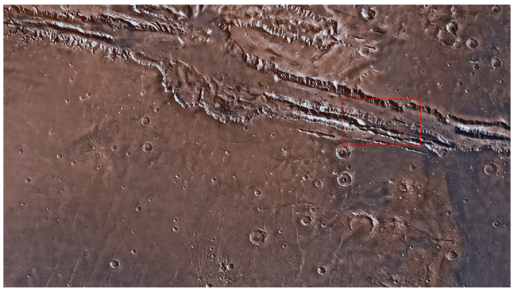


Figure 4.78: Part of original image position

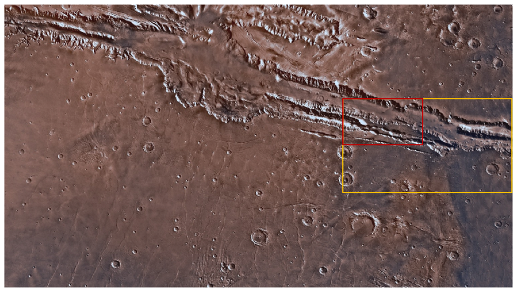


Figure 4.79: Part of original image position and original image position in comparison

4.4.3 Simulation 3

Brightness analysis

The third simulation presents an original image that is morphologically poor. The features are few and bordering on the minimum requirement. The brightness alteration analysis is performed as in the previous simulations.

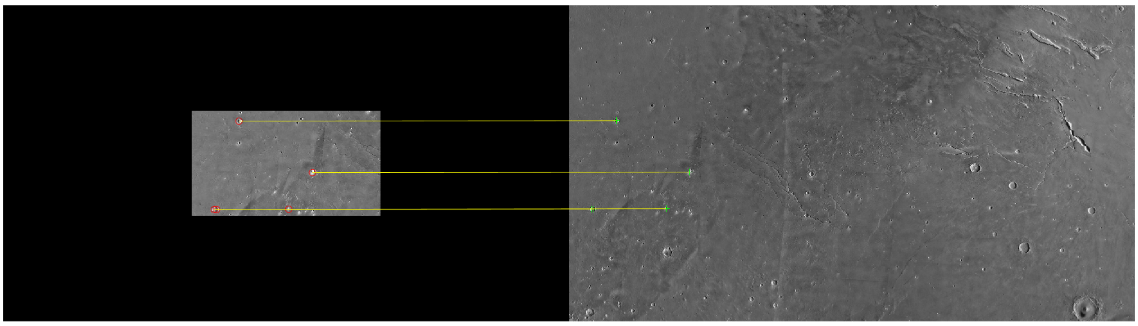


Figure 4.80: 20% brighter image

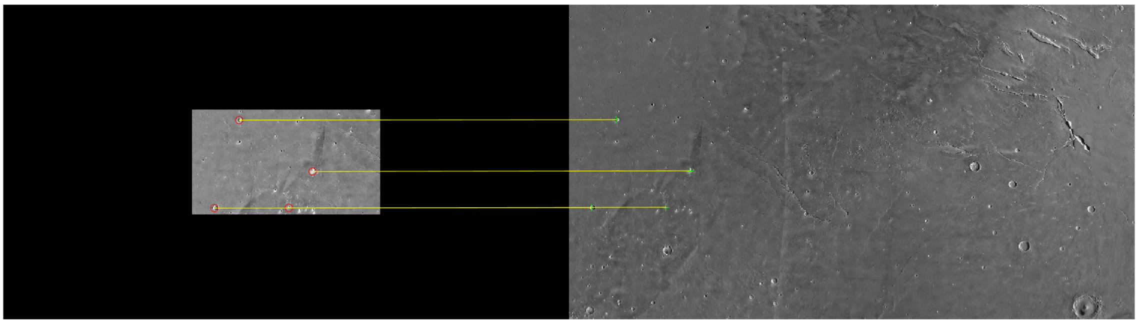


Figure 4.81: 30% brighter image

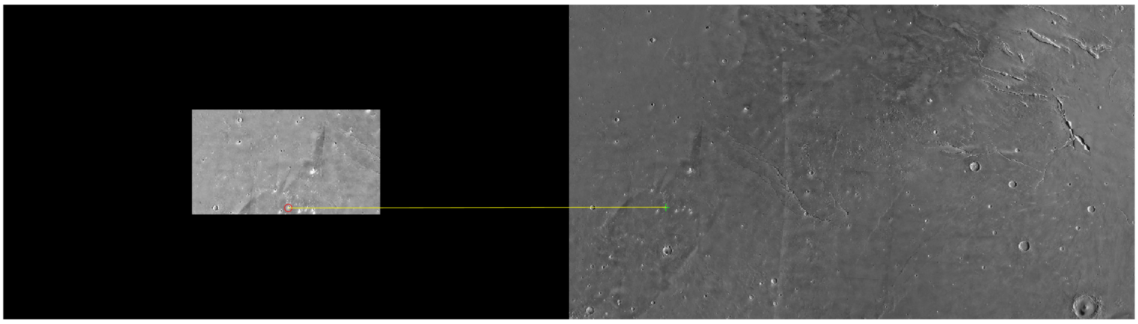


Figure 4.82: 40% brighter image

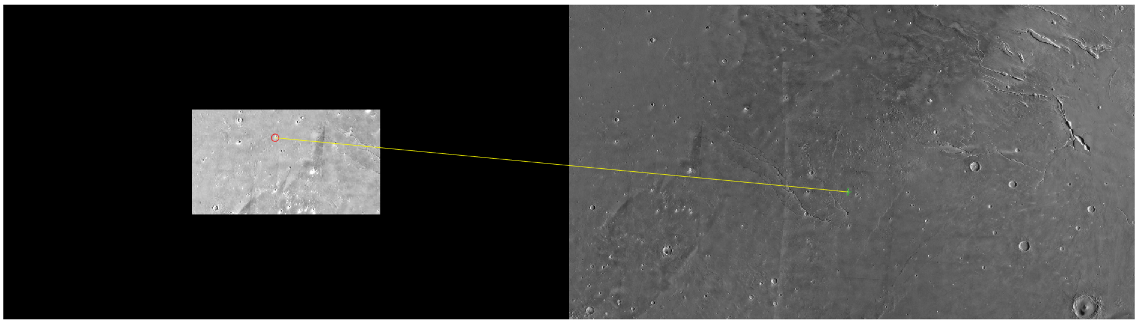


Figure 4.83: 50% brighter image

The alterations shown in Figure 4.80 and Figure 4.81 still cause the code to execute correctly. Figure 4.82, with 40% more brightness, already imposes the limitation of the analysis as it presents only one correct feature. In Figure 4.83, on the contrary, the identified feature is incorrect.
Instead, reducing the brightness of the original image causes the few features that make the matching work disappear.

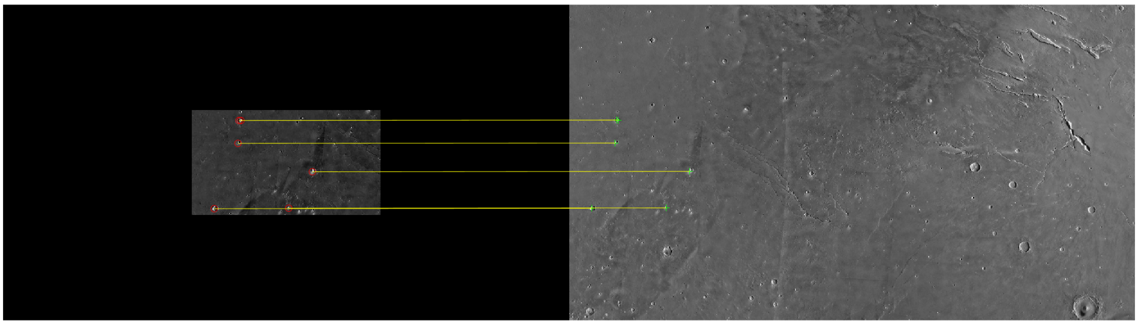


Figure 4.84: 20% darker image

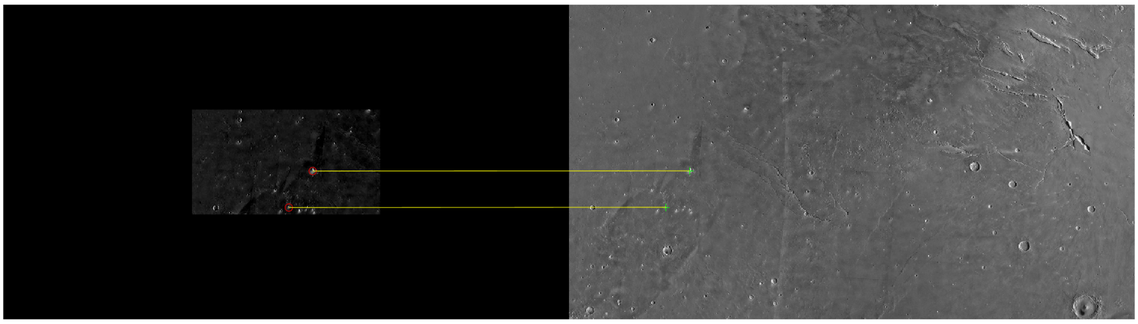


Figure 4.85: 30% darker image

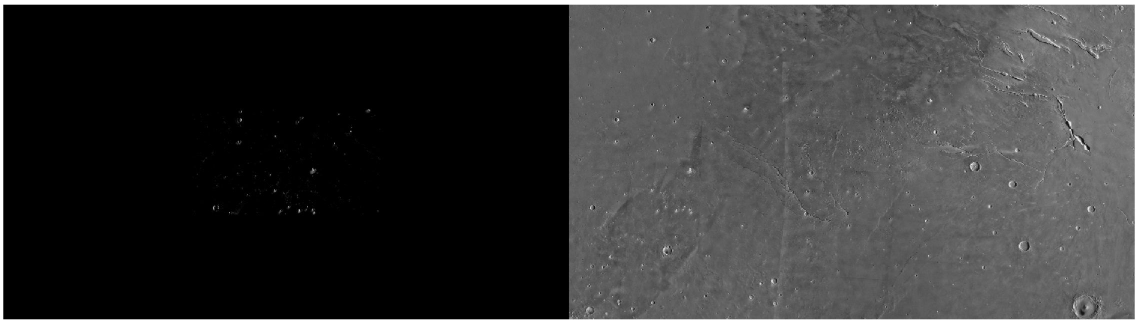


Figure 4.86: 40% darker image

By gradually decreasing the brightness, the features tend to decrease and then disappear (Figure 4.86) due to the few reference points present in the image.

Resize analysis

Due to the type of image, resizing the image also lowers the performance compared to the previous two simulations. While in simulations 1 and 2 the resizing started from 5 times compared to the original image, in this case increasing the dimensions by 4 times causes the minimum limit of features required by the code to be reached.

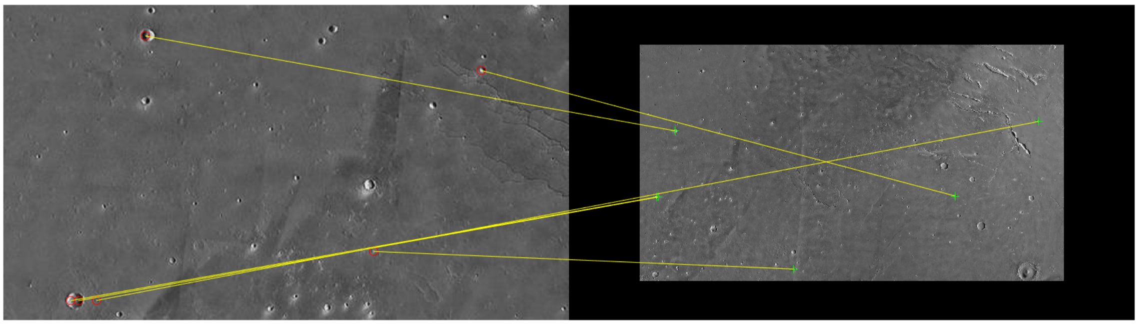


Figure 4.87: Image resized 4 times from the original

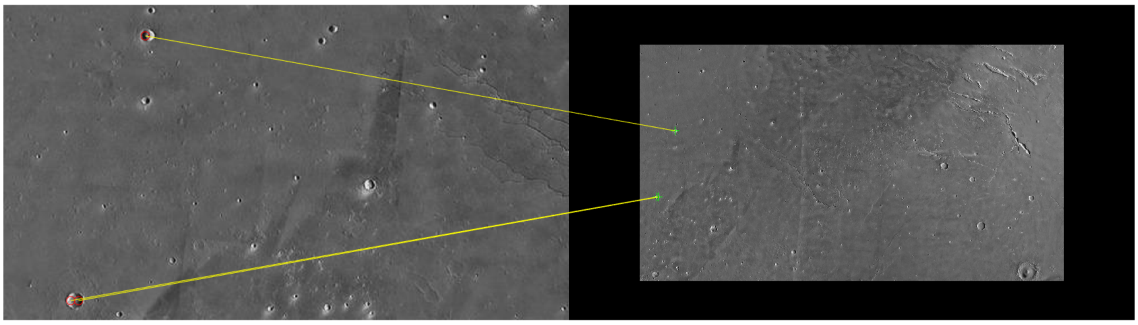


Figure 4.88: Image resized 4 times from the original with only inlier points

Rotate analysis

The rotation analysis is at the limits of execution due to the few features present in the image. Although it might seem like a problem, the solution would be to lower the value to 2 pairs of points. For this simulation are shown two examples.

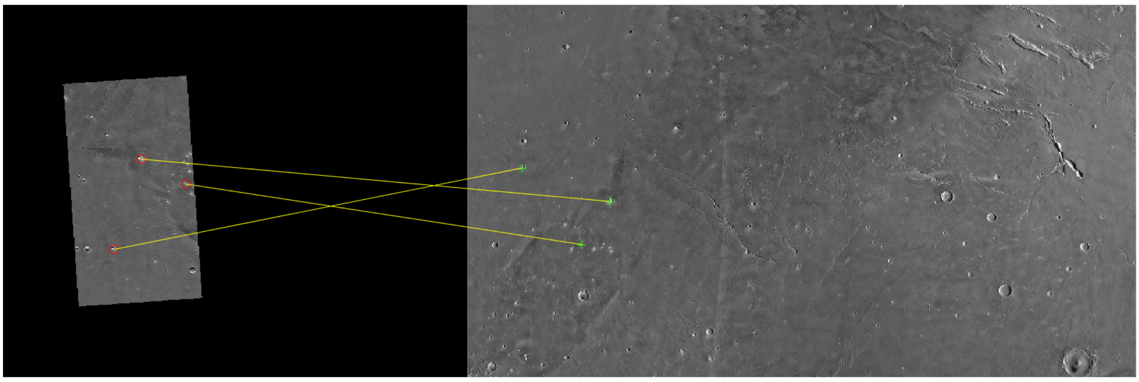


Figure 4.89: Example 1: rotated image

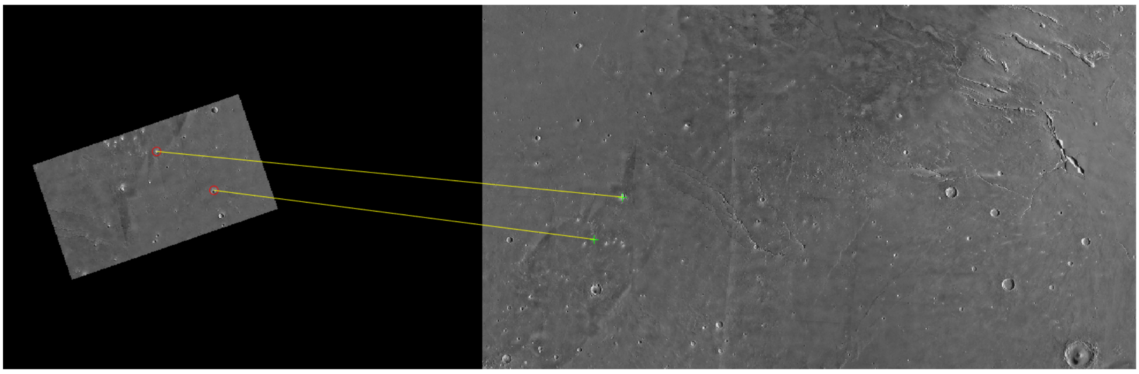


Figure 4.90: Example 2: rotated image

Damaged image analysis

The highest risk is found in this last analysis. Selecting a part of the original image further reduces the chance of matching the database image. The features found are at the limit of the requirements, even if the code manages to execute (Figure 4.91).

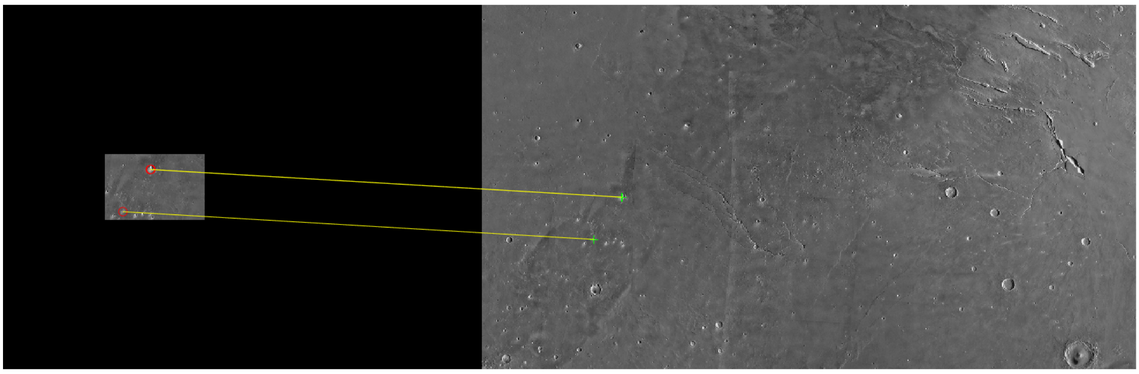


Figure 4.91: Match between part of original image and database image

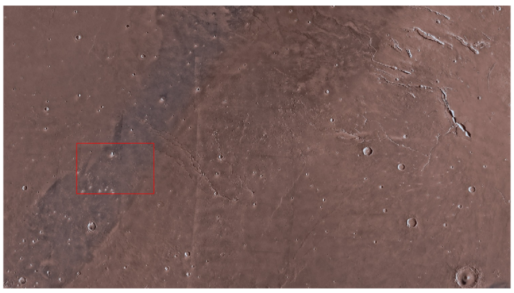


Figure 4.92: Part of original image position

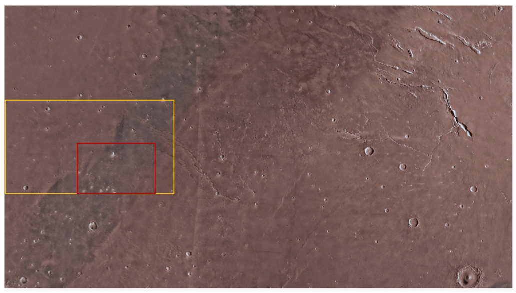


Figure 4.93: Part of original image position and original image position in comparison

Chapter 5

Conclusion

In the course of this work, the problem of determining the satellite position in a deep space mission was studied and analyzed. The goal of processing images of the Mars' surface in order to provide maps and eventual path planning to martian rover, has been achieved.
The algorithm implemented for autonomous navigation was designed for the generic position of the satellite at that specific time. To analyze more situations for the different areas of the red planet, the algorithm chooses a random image in order to simulate the image acquired by the satellite's onboard camera.
The solution obtained at the end of this work, chapter 4, show how it is possible to obtain the satellite position for each random simulation in its three spatial coordinates (longitude, latitude, altitude).
To add robustness to current autonomous system, its limit is tested by altering and "dirtying" the basic image of code execution, in fact a margin of error is obtained for every case described. It follows that the algorithm can work correctly until the image is completely corrupted if it has a rich morphology; the algorithm has more limits in its execution given an image with poor morphology.
An important aspect is that the code processes the features for every image of which the database is composed, taking a certain amount of time, every time it is executed. In the real case this situation does not occur since the characteristics of the database remain stored after being identified for the first time, and then saved.
Thus this work manages to allow a mission to be fully autonomous without having direct communications to the ground. A spacecraft would be able to obtain position and altitude, and carry out onboard navigation .

5.1 Future developments

As a future work you might think about using a different image processing method like:

- Visual Odometry to obtain the position of the moving satellite at any time;
- Deep Learning to get a classification of features and maintain a steady satellite self-localization.

Another aspect that could be developed as a future work is the craters detection through Convolutional Neural Networks (Deep Learning).
Crater detection algorithms are traditionally used to automate the process of crater counting for cataloguing means. In particular, Convolutional Neural Networks learn how to extract image features on their own. This method has already been used on the Moon, it is not difficult to think of being able to implement it on Mars as well.

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Appendix A

Mission phases

Characteristics	**Deployment**	**Detumbling**	**Appendix deployment**
Initial condition	Mothercraft has reached a stable orbit	Small-sat(s) are separated from the mothercraft	Small-sat(s) have been stabilised in the right attitude
Final condition	Small-sat(s) are separated from the mothercraft	Small-sat(s) have been stabilised in the right attitude	Complete deployment of solar arrays and antennas
Environment	Mars space environment	Mars space environment	Mars space environment
Top Level Objectives	To separate Small-sat(s) from the mothercraft	To prevent tumbling or spinnig of the Small-sat(s) To manage the three-axis set-up of the Small-sat(s) To ensure the right attitude of the Small-sat(s)	To ensure the right deployment of subsystems' appendix
Required I/F with other system	Mechanical, electrical and data I/F with mothercraft	Link with mothercraft for communication to/from Earth	Link with mothercraft for communication to/from Earth
General description	In this phase the Small-sat(s) is released from the mothercraft after preliminary check	This phase provides the stabilization process of the Small-sat(s)'s angular velocity after orbital insertion	This phase allows deployment of subsystems' appendix
Duration	30 minutes	2 hours	2 hours
Constraints	The constraints are defined in terms of: - Link with mothercraft for both communications to/from Earth - On orbit perturbations - Environmental conditions - Deployers	The constraints are defined in terms of: - Link with mothercraft for both communications to/from Earth - On orbit perturbations - Environmental conditions	The constraints are defined in terms of: - Link with mothercraft for both communications to/from Earth - Environmental conditions - Appendix deployment system
Potential Off-Nominal Events	Failure/impossibility to communicate with the Earth Failure of the deployer	Failure/impossibility to communicate with the Earth the correct attitude Failure of the AOCS system	Failure/impossibility to communicate with the Earth the correct deployment of appendix Failure of appendix deployment system

Table A.1: Early Operation Phase

Characteristics	**Advanced Technologies checkout**	**Payload checkout**
Initial condition	Complete deployment of solar arrays and antennas	The correct functioning of the primary systems has been checked
Final condition	The correct functioning of the primary systems has been checked	The correct functioning of the payloads has been checked
Environment	Mars space environment	Mars space environment
Top Level Objectives	To ensure the proper functioning of the subsystems	To ensure the proper functioning of the payloads To ensure the proper calibration of the payloads
Required I/F with other systems	Link with mothercraft for communication to/from Earth	Link with mothercraft for communication to/from Earth
General description	This phase provides functional tests of subsystems in order to verify that they working correctly	This phase provides functional tests of payloads in order to verify that they working correctly
Duration	1 hour	2 days
Constraints	The constraints are defined in terms of: - Link with mothercraft for both communications to/from Earth in order to communicate the status of all the primary systems - On orbit perturbations - Environmental conditions	The constraints are defined in terms of: - Link with mothercraft for both communications to/from Earth in order to communicate the status of all the payloads - On orbit perturbations - Environmental conditions
Potential Off-Nominal Events	Failure/impossibility to communicate with the Earth the correct functioning or failure of one/more than one subsystem Failure of one/more than one primary system Failure while booting up the functional test	Failure/impossibility to communicate with the Earth the correct functioning or failure of one/more than one payload Failure of one/more than one payload Failure while booting up the functional test

Table A.2: Spacecraft checkout

Characteristics	Maneuver 1 - Transfer to operative orbit 1	Global observation and mapping	Maneuver 2 - Transfer to operative orbit 2	Detailed observation and mapping
Initial condition	The correct functioning of the payloads has been checked	Small-sat(s) reached the desired orbit	All surfaces of interest have been mapped	All surfaces of interest have been mapped
Final condition	Small-sat(s) reached the desired orbit	All surfaces of interest have been mapped	Small-sat(s) reached the desired orbit	Small-sat(s) reached the desired orbit
Environment	Mars space environment	Mars space environment in a circulat orbit at the altitude of 150 km	Mars space environment	Mars space environment
Top Level Objectives	To complete the transfer to a stable orbit which is used to accomplish the primary objectives mission	To complete surface mapping for navigation pourpose To characterize different terrain typology and their chemical composition	To complete the transfer to a stable orbit which is used to accomplish the secondary objectives mission	To complete the transfer to a stable orbit which is used to accomplish the secondary objectives mission
Required I/F with other systems	Link with mothercraft for communication to/from Earth	Link with mothercraft for communication to/from Earth	Link with mothercraft for communication to/from Earth	Link with mothercraft for communication to/from Earth
General description	The Small-sat(s) reach the operative orbit for navigation pourpose and definition of surface's chemical composition	This phase allows to collect data about the planet, its environment and to map its surface thanks to the optical payload in various frequences of light. Small-sat(s) maintain a stable orbit with maneuvers of station-keeping	The Small-sat(s) reach the operative orbit for remote sensing applications	The Small-sat(s) reach the operative orbit for remote sensing applications

Characteristics	Maneuver 1 - Transfer to operative orbit 1	Global observation and mapping	Maneuver 2 - Transfer to operative orbit 2	Detailed observation and mapping
Duration	TBD days	3 months	TBD days	TBD days
Constraints	The constraints are defined in terms of: - Link with mothercraft for both communications to/from Earth - On orbit perturbations - Environmental conditions - Attitude control - Proper functioning of the propulsion system	The constraints are defined in terms of: - Link with mothercraft for both communications to/from Earth - On orbit perturbations - Environmental conditions - Attitude control	The constraints are defined in terms of: - Link with mothercraft for both communications to/from Earth - On orbit perturbations - Environmental conditions - Attitude control - Proper functioning of the propulsion system	The constraints are defined in terms of: - Link with mothercraft for both communications to/from Earth - On orbit perturbations - Environmental conditions - Attitude control - Proper functioning of the propulsion system
Potential Off-Nominal Events	Failure of propulsion system Failure of AOCS system and impossibility to correctly point the thrusters	Failure of the visual camera used for navigation Failure of the hyperspectral camera used for study chemical composition of Mars' surface Failure of propulsion system for station-keeping pourpose	Failure of propulsion system Failure of AOCS system and impossibility to correctly point the thrusters	Failure of propulsion system Failure of AOCS system and impossibility to correctly point the thrusters

Table A.3: On-Orbit Phase

Characteristics	Active Disposal (extra mission)	Passive Disposal
Initial condition	Remote sensing applications has been completed	Start of space segment passivation
Final condition	Start of space segment passivation	Impact on Mars' surface
Environment	Mars space environment	Mars space environment, Mars surface
Top Level Objectives	To produce maps of strategic areas in rovers missions for paths planning definition	To perform a de-orbiting maneuver to impact on Mars' surface To passivate the Small-sat(s)
Required I/F with other systems	Link with mothercraft for communication to/from Earth	Link with mothercraft for communication to/from Earth
General description	Mission is complete, but Small-sat(s) reduces its altitude up to 20 km (TBC) while still capturing images	Small-sat(s) ends his life in a de-orbiting maneuver to impact on Mars' surface
Duration	2 months (TBC)	1 month (TBC)
Constraints	The constraints are defined in terms of: - Link with mothercraft for both communications to/from Earth - Position of martian rovers	The constraints are defined in terms of: - Link with mothercraft for both communications to/from Earth - Position of martian rovers
Potential Off-Nominal Events	Failure of one/more than one subsystems Failure/impossibility to communicate with the Earth Failure of the visual camera used for remote sensing applications	Failure of one/more than one subsystems Failure/impossibility to communicate with the Earth

Table A.4: End of Mission

Appendix B

Preliminary revisit time analysis

Revisit time	**1**	**2A**		**2B**	
Satellite	1	1	2	1	2
Access	3488	4082	3491	4083	4072
Mean duration [s]	321,58	390,02	319,88	390,02	389,95
Total access duration [s]	1121663,64	1592044,09	1116701,18	1592044,09	1587890,42
Mission duration [s]	57024000				
Revisit time [%]	1,97	2,79	1,96	2,79	2,78
	1,97	4,75		5,58	

Revisit time	**3A**			**3B**		
Satellite	1	2	3	1	2	3
Access	3488	4110	3626	3810	4110	4103
Mean duration [s]	321,58	406,31	328,69	389,92	406,31	400,27
Total access duration [s]	1121664,19	1669926,01	1191823,15	1592047,33	1669926,01	1642329,44
Mission duration [s]	57024000					
Revisit time [%]	1,97	2,93	2,09	2,79	2,93	2,88
	6,99			8,60		

Revisit time	**4A**				**4B**			
Satellite	1	2	3	4	1	2	3	4
Access	4083	4113	4072	4118	4083	4113	4072	4118
Mean duration [s]	389,92	405,66	389,95	407,42	389,92	405,66	389,95	407,42
Total access duration [s]	1592047,33	1668501,29	1587890,5	1677771,69	1592047,33	1668501,29	1587890,5	1677771,69
Mission duration [s]	57024000							
Revisit time [%]	2,79	2,93	2,78	2,94	2,79	2,93	2,78	2,94
	11,44				11,44			

Table B.1: Preliminary revisit time analysis

Appendix C

Preliminary Data Volume

Amount of information	**1**	**2A**	**2B**	**3A**	**3B**	**4A**	**4B**
Global observation and mapping [image/hour]	100	200	200	300	300	400	400
Remote sensing applications on target* [image/hour]	71	171	201	251	310	412	412
Remote sensing applications in other areas [image/hour]	118	115	114	112	110	107	107

*Number of images on target refers to the percentage obtained in the analysis of the revisit time

Table C.1: Amount of information analysis

Payload	Pixels	Total pixels	N° bands	N° bit	Single image Data Volume [bit]	Single image Data Volume [MByte]	N° acquisition per hour		Observation Period [h]	Data Volume per orbit [MByte]	Data Volume per orbit [Mbit]
VIS camera [navigation]	4096*3072	12582912	3	8	301989888	37,75	100*	1image/35 sec	1,78	6719,28	53754,20
HS camera	2048*1944	3981312	13	8	414056448	51,76	100*	1 image/35 sec	1,78	9212,76	73702,05
VIS camera [remote sensing]	4096*3072	12582912	3	8	301989888	37,75	519*	1 image/sec on target 1 image/30 sec	1,73	33893,46	271147,66

*Image in one hour

Table C.2: Preliminary Data Volume

Appendix D

Preliminary ΔV analysis

Architecture		Deployment phase from 200 km to 150 km	Global observations and mapping phase from 150 km to 80 km or 50 km		Remote sensing applications phase to 80 km or 50 km		ΔV satellite [m/s]	ΔV architecture [m/s]
1	ΔV [m/s]	-12,10	satellite 1	-29,51	satellite 1	-17,45	59,07	59,07
	Description	Hohmann Transfer	Orbit circularization and Hohmann Transfer		The satellite enters into the last orbit at 80 km			
2A	ΔV [m/s]	-24,21	satellite 1	-29,51	satellite 1	-17,45	71,17	157,59
			satellite 2	-37,09	satellite 2	-25,12	86,42	
	Description	Hohmann Transfer	Orbit circularization then: satellite1) Hogmann Transfer from 150 km to 80 km satellite2) Hohmann Transfer from 150 km to 50 km		Satellite 1 enters into the last orbit at 80 km Satellite 2 enters into the last orbit at 50 km			
2B	ΔV [m/s]	-24,21	satellite 1 satellite 2	-59,02	satellite 1 satellite 2	-34,91	118,14	118,14
	Description	Hohmann transfer	Orbit circularization and Hohmann Transfer		The satellites enter into the last orbit at 80 km			
3A	ΔV [m/s]	-36,31	satellite 1 satellite 2	-59,02	satellite 1 satellite 2	-39,91	130,24	228,76
			satellite 3	-37,09	satellite 3	-25,12	98,52	
	Description	Hohmann Transfer	Orbit circularization then: satellite1+2) Hohmann transfer from 150 km to 80 km satellite3) Hohmann Transfer from 150 km to 50 km		Satellite 1+2 enters into the last orbit at 80 km Satellite 3 enters into the last orbit at 50 km			

Architecture		Deployment phase from 200 km to 150 km	Global observations and mapping phase from 150 km to 80 km or 50 km		Remote sensing applications phase to 80 km or 50 km		ΔV satellite [m/s]	ΔV architecture [m/s]
3B	ΔV [m/s]	-36,31	satellite 1 satellite 2 satellite 3	-88,54	satellite 1 satellite 2 satellite 3	-52,35	177,20	177,20
	Description	Hohmann transfer	Orbit circularization and Hohmann Transfer		The satellites enter into the last orbit at 80 km			
4A	ΔV [m/s]	-48,41	satellite 1 satellite 2 satellite 3 satellite 4	-118,05	satellite 1 satellite 2 satellite 3 satellite 4	-69,80	236,26	236,26
	Description	Hohmann transfer	Orbit circularization and Hohmann Transfer		The satellites enter into the last orbit at 80 km			
4B	ΔV [m/s]	-48,41	satellite 1 satellite 2 satellite 3 satellite 4	-118,05	satellite 1 satellite 2 satellite 3 satellite 4	-69,80	236,26	236,26
	Description	Hohmann transfer	Orbit circularization and Hohmann Transfer		The satellites enter into the last orbit at 80 km			

Table D.1: Preliminary ΔV analysis