POLITECNICO DI TORINO

Master's degree course in Aerospace Engineering

Master's Degree Thesis

Mission Analysis for CubeSat Rendezvous and Docking operations

Supervisors:
Prof.ssa Sabrina Corpino
Ing. Giorgio Ammirante

Candidate:
Domenico Parrinello

Academic year 2022-2023

Politecnica
di Torino

ABSTRACT

Since the first launch in 2003, CubeSats raised in importance on the low-cost mission's panorama. Widely used to date, not only by universities but also by agencies, due to their versatility and ever-increasing deployment possibilities. This is the context of the ESA Space Riders mission.
Space Rider is the first European reusable transportation system, an uncrewed robotic laboratory. After launch on Vega-C, it will stay in low orbit for about two months. Experiments inside its cargo bay will allow benefice research in various scientific fields as well as the possibility to demonstrate and validate technologies for different applications, such as robotics, Earth observation, telecommunication, and Surveillance. At the end of its mission, Space Rider will return to Earth with its payloads and land on a runway to be unloaded and refurbished for another flight. At the end of its mission, Space Rider will, then, re-enter the Earth's atmosphere and land, returning its valuable payload to eager engineers and scientists at the landing site. After minimal refurbishment it will be ready for its next mission with new payloads and a new mission.
SROC (Space Rider Observer Cube) is a 12U mission developed by the Polytechnic of Turin in collaboration with ESA (European Space Agency), Tyvak International and the University of Padua. SROC is expected to be launched as a Space Rider payload at its maiden flight on-board the Vega-C, SROC will serve as an in-orbit demonstrator for rendezvous and docking operating for periods longer than two months in low Earth orbit. At the end of its mission, SROC could be retrieved on-board the Space Rider cargo bay, hence return on Earth.

This thesis describes the SROC mission design and analysis in terms of orbit, trajectories, and manoeuvres as they have been developed during Phase B1. The document is intended to support the mission planning prior to launch providing information on mission elements such as the mission geometry, the ground segment, and operations, and complementing the design of the space segment (payload and spacecraft) and the communication architecture. The relationships between mission phases and trajectory segment and manoeuvres are also illustrated. Two mission scenarios are analysed: the *Observe & Retrieve* mission and the *Observe* mission. For both scenarios, nominal and off-nominal conditions are considered. The document also lists those requirements that are applicable to the mission design and analysis, including ConOps, Observations, Orbit & Trajectory, and Proximity Operations requirements. Useful information is provided as well for the verification of such high-level requirements. The structure of the document mimics the top-down approach followed to perform the mission design and the mission analysis, starting with the CubeSat deployment from Space Rider MPCB (Multi-Purpose CubeSat Dispenser) up to SROC docking (or disposal) for which a dedicated illumination analysis was performed. In conclusion, Delta-V budgets calculated for all possible SR operative orbits are presented, together with a brief description of the selected SROC mission design baseline.

TABLE OF CONTENTS

1 INTRODUCTION 17
1.1 CubeSats Mission Overview 17
1.2 Rendezvous, Proximity Operations and Docking 17
2 Mission Overview 20
2.1 Space Rider mission overview 20
2.2 SROC mission overview 21
3 Mission Analysis 27
3.1 Mission requirements 27
3.1.1 ConOps requirements 27
3.1.2 Launch Vehicle and Site requirements 30
3.1.3 Observations requirements 31
3.1.4 Orbit & Trajectory requirements 31
3.1.5 Proximity Operations requirements 33
3.2 Proximity operations 35
3.3 Assumptions 37
3.4 Optimization analyses 38
3.4.1 STK/MATLAB Interface 39
3.4.2 File JSON and MATLAB 39
3.4.3 Programme and file structure 42
3.5 Mission Segments 44
3.5.1 Deployment analysis 45
3.5.2 Commissioning analysis 49
3.5.3 Hold Point 1 51
3.5.4 Rendezvous 53
3.5.5 Hold Point 2 58
3.5.6 SR Observation Phase 59
3.5.7 Hold Point 3 67
3.5.8 Final Approach 69
3.5.9 Decommissioning 70
3.6 Delta-V Budgets 72
3.7 Ground stations visibility analysis 78
3.8 Illumination analysis 84
3.9 Space Rider Coverage analysis 96
4 Off-Nominal Manoeuvres Analysis 99
4.1 Rendezvous Option 1 100
4.1.1 Off-nominal manoeuvre entering Hold Point 1 100
4.1.2 Off-Nominal manoeuvre entering the In-Plane Approach Rendezvous (IPA) 102
4.1.3 Off-Nominal manoeuvre entering the Out-of-Plane (OPA) 109
4.1.4 Off-Nominal manoeuvre entering the Space Rider Inspection – WSE Inspection 118
4.1.5 Off-Nominal manoeuvre Closing 125
4.1.6 Off-Nominal manoeuvre for insertion in the Hold Point 3 135
4.2 Rendezvous Option 2 145
4.2.1 Off-Nominal manoeuvre entering the In-Plane Approach Rendezvous (IPA) 145

4.2.2 Off-Nominal manoeuvre for the Hold Point 2 Insertion trajectory 150
4.2.3 Off-Nominal manoeuvre entering the Hold Point 2 159
4.2.4 Off-Nominal manoeuvre entering the Out-of-Plane (OPA) 168
4.2.5 Off-Nominal manoeuvre Closing 178
4.2.6 Off-Nominal manoeuvre entering the Hold Point 3 187
5 Baseline scenario at SRR 197
6 AKNOWLEDGEMENTS 199
7 Bibliography 201

LIST OF FIGURES

Figure 1: SR-AOM Module 20
Figure 2: SR-RM Module 21
Figure 3: SROC Axonometric cutaway 22
Figure 4: SROC Design Reference Mission 24
Figure 5: LVLH and RIC frames comparison 35
Figure 6: Example of JSON for STK scenario inputs - 1 40
Figure 7: Example of JSON for STK scenario inputs - 2 41
Figure 8: MATLAB Main script - Detail 42
Figure 9: Relative view of 8 satellites propagation deployment from SR with different directions 45
Figure 10: Space Rider's reference orbits (scenarios 1, 2, 3, 4, 5 respectively) 46
Figure 11: SROC Deployment Direction 49
Figure 12: SROC Deployment overview 49
Figure 13: SROC first orbits after Deployment 50
Figure 14: Commissioning Relative Distance with time 51
Figure 15: Different Commissioning Trajectories Comparison 53
Figure 16: SROC Relative Distance without the OPA - Option 1 54
Figure 17: In-plane Rendezvous - Final Relative Orbits 55
Figure 18: From in-plane IPA to OPA - InTrack Target View 55
Figure 19: SROC Relative Distance without the HP#2 Insertion - Option 2 56
Figure 20: From in-plane IPA to HP#2 Insertion - InTrack Target View 57
Figure 21: HP#2 Insertion trajectory 59
Figure 22: Safety Ellipse Plane with Polar Angle 60
Figure 23: InTrack-CrossTrack view of the Safety Ellipse 60
Figure 24: Primary Centred (left) and Offset (right) Safety Ellipse 61
Figure 25: Safety Ellipse Offset Scheme 62
Figure 26: WSE relative distance components and range module 65
Figure 27: WSE in a prospective view 66
Figure 28: WSE Radial-CrossTrack View 66
Figure 29: HP#3 Insertion trajectory 67
Figure 30: Final Approach scenarios 69
Figure 31: De-orbit analysis for the Quasi-Equatorial orbit 70
Figure 32: SROC-SR relative distance 71
Figure 33: SROC-SR relative distance: re-approach details 71
Figure 34: SROC ground track with Ground Stations locations 82
Figure 35: GS take over with Additional Antenna 83
Figure 36: β-angle annual evolution for the Baseline scenario 84
Figure 37: Baseline SR Radial axis angle-to-Sun Vector 85
Figure 38: Baseline SR Radial axis angle-to-Sun Vector good illumination window (Detail) 85
Figure 39: Baseline SR Intrack axis-to-Sun Vector angle 86
Figure 40: Baseline SR Intrack axis-to-Sun Vector angle good illumination window (Detail) 86
Figure 41: SSO MM SR Radial axis-to-Sun Vector angle 87
Figure 42: SSO MM SR Radial axis-to-Sun Vector angle good illumination window (Detail) 87
Figure 43: SSO MM SR Intrack axis-to-Sun Vector angle 88
Figure 44: SSO MM SR Intrack axis-to-Sun Vector angle good illumination window (Detail) 88
Figure 45: SSO DD SR Radial axis-to-Sun Vector angle 89
Figure 46: SSO DD SR Intrack axis-to-Sun Vector angle 89
Figure 47: Intermediate MM SR Radial axis-to-Sun Vector angle 90
Figure 48: Intermediate MM SR Radial axis-to-Sun Vector angle good illumination window (Detail) 90
Figure 49: Intermediate MM SR Intrack axis-to-Sun Vector angle 91

Figure 50: Intermediate MM SR Intrack axis-to-Sun Vector angle good illumination window (Detail) 91
Figure 51: Intermediate DD SR Radial axis-to-Sun Vector angle 92
Figure 52: 37 Intermediate DD SR Radial axis-to-Sun Vector angle good illumination window (Detail) 92
Figure 53: Intermediate DD SR Intrack axis-to-Sun Vector angle 93
Figure 54: Intermediate DD SR Intrack axis-to-Sun Vector angle good illumination window (Detail) 93
Figure 55: Good illumination and GS visibility window 94
Figure 56: Good illumination and GS visibility window – Detail on the GS visibility 95
Figure 57: Good illumination and GS visibility window – Detail on the GS visibility - additional GS95
Figure 58: Mesh of the Space Rider model 96
Figure 59: SR Coverage and Cumulative Coverage over one Observation cycle 97
Figure 60: VNC Frame for SROC Manoeuvres 99
Figure 61: HP#1 Nominal Trajectory 100
Figure 62: HP#1 Off-Nominal Direction and Magnitude - maximum SMA 102
Figure 63: HP#1 Off-Nominal Direction and Magnitude - minimum SMA 102
Figure 64: IPA Nominal Trajectory 103
Figure 65: Scatter plot Direction errors – IPA Opt 1 104
Figure 66: IPA Off-Nominal Magnitude - minimum distance for no OPA 105
Figure 67: IPA Off-Nominal Magnitude – minimum distance during IPA 106
Figure 68: Scatter plot Magnitude errors – IPA Opt 1 107
Figure 69: IPA Off-Nominal Direction and Magnitude – minimum distance during IPA 108
Figure 70: IPA Off-Nominal Direction and Magnitude – minimum distance for no OPA 108
Figure 71: OPA Nominal Trajectory 110
Figure 72: OPA Nominal Trajectory - Out-Of-Plane View 110
Figure 73: OPA Off-Nominal Direction - minimum distance 111
Figure 74: OPA Off-Nominal Direction – worst Final Position 112
Figure 75: Scatter plot Direction errors – OPA Opt 1 113
Figure 76: OPA Off-Nominal Magnitude – minimum distance 114
Figure 77: OPA Off-Nominal Magnitude – worst Final Position 115
Figure 78: Scatter plot Magnitude errors – OPA Opt 1 116
Figure 79: OPA Off-Nominal Direction and Magnitude – minimum distance 117
Figure 80: OPA Off-Nominal Direction and Magnitude – minimum distance 118
Figure 81: Inspection 1 Nominal Trajectory 119
Figure 82: WSE Off-Nominal Direction – minimum distance 120
Figure 83: Scatter plot Direction errors – WSE Opt 1 121
Figure 84: Inspection Off-Nominal Magnitude - 50% of manoeuvre magnitude 122
Figure 85: Inspection Off-Nominal Magnitude - 150% of manoeuvre magnitude 122
Figure 86: Inspection Off-Nominal Magnitude – minimum distance 123
Figure 87: Scatter plot Magnitude errors – WSE Opt 1 124
Figure 88: Inspection Off-Nominal Direction and Magnitude - minimum distance 125
Figure 89: Closing Nominal Trajectory 126
Figure 90: Closing Nominal Trajectory – Out-of-Plane View 126
Figure 91: Closing Off-Nominal Magnitude – minimum distance 128
Figure 92: Closing Off-Nominal Magnitude – worst Final Position 129
Figure 93: Scatter plot Direction errors – Closing Opt 1 130
Figure 94: Closing Off-Nominal Magnitude – minimum distance 131
Figure 95: Closing Off-Nominal Magnitude – worst Final Position 132
Figure 96: Scatter plot Magnitude errors – Closing Opt 1 133
Figure 97: Closing Off-Nominal Direction and Magnitude - minimum distance 134
Figure 98: Closing Off-Nominal Direction and Magnitude – worst Final Position 135
Figure 99: HP#3 Nominal Trajectory 136

Figure 100: HP#3 Off-Nominal Direction - minimum distance 137
Figure 101: HP#3 Off-Nominal Direction - worst Final Position 138
Figure 102: Scatter plot Direction errors – HP#3 Opt 1 139
Figure 103: HP#3 Off-Nominal Magnitude - minimum distance 140
Figure 104: HP#3 Off-Nominal Magnitude - worst Final Position 141
Figure 105: Scatter plot Magnitude errors – HP#3 Opt 1 142
Figure 106: HP#3 Off-Nominal Direction and Magnitude - minimum distance 143
Figure 107: HP#3 Insertion Off-Nominal Direction and Magnitude – worst Final Position 144
Figure 108: IPA Nominal Trajectory 145
Figure 109: IPA Nominal Trajectory – Out-of-Plane View 146
Figure 110: Scatter plot Direction errors – IPA Opt 2 147
Figure 111: IPA Off-Nominal Magnitude – minimum distance during IPA 148
Figure 112: Scatter plot Magnitude errors – IPA Opt 2 149
Figure 113: IPA Off-Nominal Direction and Magnitude – minimum distance during IPA 150
Figure 114: HP#2 Insertion Nominal Trajectory 151
Figure 115: HP#2 Insertion Nominal Trajectory – Out-of-Plane View 152
Figure 116: HP#2 Insertion Off-Nominal Magnitude – minimum distance 153
Figure 117: Scatter plot Direction errors – HP#2 Insertion Opt 2 154
Figure 118: HP#2 Insertion Off-Nominal Magnitude – minimum distance 155
Figure 119: HP#2 Insertion Off-Nominal Magnitude – worst Final Position 156
Figure 120: Scatter plot Magnitude errors – HP#2 Insertion Opt 2 157
Figure 121: HP#2 Insertion Off-Nominal Direction and Magnitude - minimum distance 158
Figure 122: HP#2 Insertion Off-Nominal Direction and Magnitude – worst Final Position 159
Figure 123: HP#2 Nominal Trajectory 160
Figure 124: HP#2 Off-Nominal Direction - minimum distance 161
Figure 125: HP#2 Off-Nominal Direction - worst Final Position 162
Figure 126: Scatter plot Direction errors – HP#2 Opt 2 163
Figure 127: HP#2 Off-Nominal Magnitude - minimum distance 164
Figure 128: HP#2 Off-Nominal Magnitude - worst Final Position 165
Figure 129: Scatter plot Magnitude errors – HP#2 Opt 2 166
Figure 130: HP#2 Off-Nominal Direction and Magnitude - minimum distance 167
Figure 131: HP#2 Off-Nominal Direction and Magnitude –worst Final Position 168
Figure 132: OPA Nominal Trajectory 169
Figure 133: OPA Nominal Trajectory - Out-Of-Plane View 170
Figure 134: OPA Off-Nominal Direction - minimum distance 171
Figure 135: OPA Off-Nominal Direction – worst Final Position 172
Figure 136: Scatter plot Direction errors – OPA Opt 2 173
Figure 137: OPA Off-Nominal Magnitude – minimum distance 174
Figure 138: OPA Off-Nominal Magnitude – worst Final Position 175
Figure 139: Scatter plot Magnitude errors – OPA Opt 2 176
Figure 140: OPA Off-Nominal Direction and Magnitude – minimum distance 177
Figure 141: OPA Off-Nominal Direction and Magnitude – worst Final Position 178
Figure 142: Closing Nominal Trajectory 179
Figure 143: Closing Nominal Trajectory – Out-of-Plane View 179
Figure 144: Closing Off-Nominal Magnitude – minimum distance 180
Figure 145: Closing Off-Nominal Magnitude – worst Final Position 181
Figure 146: Scatter plot Direction errors – Closing Opt 2 182
Figure 147: Closing Off-Nominal Magnitude – minimum distance 183
Figure 148: Closing Off-Nominal Magnitude – worst Final Position 184
Figure 149: Scatter plot Magnitude errors – Closing Opt 2 185
Figure 150: Closing Off-Nominal Direction and Magnitude - minimum distance 186
Figure 151: Closing Off-Nominal Direction and Magnitude – worst Final Position 187
Figure 152: HP#3 Nominal Trajectory 188

Figure 153: HP#3 Off-Nominal Direction - minimum distance 189
Figure 154: HP#3 Off-Nominal Direction - worst Final Position 190
Figure 155: Scatter plot Direction errors – HP#3 Opt 2 191
Figure 156: HP#3 Off-Nominal Magnitude - minimum distance 192
Figure 157: HP#3 Off-Nominal Magnitude - worst Final Position 193
Figure 158: Scatter plot Magnitude errors – HP#3 Opt 2 194
Figure 159: HP#3 Off-Nominal Direction and Magnitude - minimum distance 195
Figure 160: HP#3 Off-Nominal Direction and Magnitude - worst Final Position 196

LIST OF TABLES

Table 1: Summary of relevant-to-SROC missions 18
Table 2: ConOps "Observe & Retrieve" scenario 24
Table 3: ConOps "Observe" scenario 24
Table 4: SROC mission architecture 25
Table 5: Space Rider baseline orbit 37
Table 6: Space Rider orbits 37
Table 7: Deployment Design of Experiment and selected strategy (in green) 48
Table 8: WSE DoE summary table 63
Table 9: Effective WSE percentage 64
Table 10: Delta-V budget for baseline scenario 72
Table 11: Delta-V Budget – Observe and Retrieve - Option 1 - Intrack Docking 73
Table 12: Delta-V Budget – Observe and Retrieve - Option 1 - Radial Docking 73
Table 13: Delta- V Budget – Observe & Retrieve - Option 1 - Fly Around Radial Docking 74
Table 14: Delta- V Budget – Observe and Retrieve - Option 2 - Radial Docking 74
Table 15: Delta-V Budget – Observe and Retrieve - Option 2 - Fly Around Radial Docking 75
Table 16: Delta-V Budget - Observe - Option 1 75
Table 17: Delta-V Budget - Observe - Option 2 76
Table 18: Delta-V and Mission Durations comparison 77
Table 19: Visibility analysis for the Baseline scenario: Quasi-equatorial orbit 78
Table 20: Visibility analysis for the Intermediate orbit (37 deg Dawn-Dus) 78
Table 21: Visibility analysis for the Intermediate orbit (37 deg Midday-Midnight) 79
Table 22: Visibility analysis for the SSO Dawn-Dusk 79
Table 23: Visibility analysis for the SSO Midday-Midnight 80
Table 24: Ground Stations Information and frequencies 81
Table 25: Hold Point 1 Nominal Manoeuvre Values 100
Table 26: HP#1 Off-Nominal Manoeuvre Values 101
Table 27: In-Plane Approach Nominal Manoeuvre Values 103
Table 28: IPA Off-Nominal Manoeuvres Values Comparison 106
Table 29: IPA Off-Nominal Manoeuvres Values Comparison 109
Table 30: OPA Nominal Manoeuvre Values 109
Table 31: OPA Off-Nominal 1 Manoeuvre Values Comparison 111
Table 32: OPA Off-Nominal 2 Manoeuvre Values Comparison 112
Table 33: OPA Off-Nominal 1 Manoeuvre Values Comparison 114
Table 34: OPA Off-Nominal 2 Manoeuvre Values Comparison 115
Table 35: OPA Off-Nominal 1 Manoeuvre Values Comparison 117
Table 36: OPA Off-Nominal 2 Manoeuvre Values Comparison 118
Table 37: WSE Insertion Nominal Manoeuvre Values 119
Table 38: WSE Insertion Off-Nominal Manoeuvre Values Comparison 120
Table 39: WSE Insertion Off-Nominal Manoeuvre Values Comparison 122
Table 40: WSE Insertion Off-Nominal Manoeuvre Values Comparison 123
Table 41: WSE Insertion Off-Nominal Manoeuvre Values Comparison 125
Table 42: Closing Nominal Manoeuvre Values 125
Table 43: Closing Off-Nominal Manoeuvre Values Comparison 128

Table 44: Closing Off-Nominal Manoeuvre Values Comparison 129
Table 45: Closing Off-Nominal 1 Manoeuvre Values Comparison 131
Table 46: Closing Off-Nominal 2 Manoeuvre Values Comparison 132
Table 47: Closing Off-Nominal 1 Manoeuvre Values Comparison 134
Table 48: Closing Off-Nominal 2 Manoeuvre Values Comparison 135
Table 49: HP#3 Nominal Manoeuvre Values 136
Table 50: HP#3 Off-Nominal 1 Manoeuvre Values Comparison 137
Table 51: HP#3 Off-Nominal 2 Manoeuvre Values Comparison 138
Table 52: HP#3 Off-Nominal 1 Manoeuvre Values Comparison 140
Table 53: HP3 Off-Nominal 2 Manoeuvre Values Comparison 141
Table 54: HP#3 Off-Nominal 1 Manoeuvre Values Comparison 143
Table 55: HP#3 Off-Nominal 2 Manoeuvre Values Comparison 144
Table 56: In-Plane Approach Nominal Manouvre Values 145
Table 57: IPA Off-Nominal 1 Manoeuvres Values Comparison 148
Table 58: IPA Off-Nominal Manoeuvres Values Comparison 150
Table 59: HP#2 Insertion Nominal Manoeuvre Values 151
Table 60: HP#2 Insertion Off-Nominal Manoeuvre Values Comparison 153
Table 61: HP#2 Insertion Off-Nominal Manoeuvre Values Comparison 155
Table 62: HP#2 Insertion Off-Nominal Manoeuvre Values Comparison 156
Table 63: HP#2 Insertion Off-Nominal Manoeuvre Values Comparison 158
Table 64: HP#2 Insertion Off-Nominal Manoeuvre Values Comparison 159
Table 65: HP#2 Nominal Manoeuvre Values 160
Table 66: HP#2 Off-Nominal Manoeuvre Values Comparison 161
Table 67: HP#2 Off-Nominal Manoeuvre Values Comparison 162
Table 68: HP#2 Off-Nominal Manoeuvre Values Comparison 164
Table 69: HP#2 Off-Nominal Manoeuvre Values Comparison 165
Table 70: HP#2 Off-Nominal Manoeuvre Values Comparison 167
Table 71: HP#2 Off-Nominal Manoeuvre Values Comparison 168
Table 72: OPA Nominal Manoeuvre Values 169
Table 73: OPA Off-Nominal Manoeuvre Values Comparison 171
Table 74: OPA Off-Nominal Manoeuvre Values Comparison 172
Table 75: OPA Off-Nominal Manoeuvre Values Comparison 174
Table 76: OPA Off-Nominal Manoeuvre Values Comparison 175
Table 77: OPA Off-Nominal Manoeuvre Values Comparison 177
Table 78: OPA Off-Nominal Manoeuvre Values Comparison 178
Table 79: Closing Nominal Manoeuvre Values 178
Table 80: Closing Off-Nominal Manoeuvre Values Comparison 180
Table 81: Closing Off-Nominal Manoeuvre Values Comparison 181
Table 82: Closing Off-Nominal Manoeuvre Values Comparison 183
Table 83: Closing Off-Nominal Manoeuvre Values Comparison 184
Table 84: Closing Off-Nominal Manoeuvre Values Comparison 186
Table 85: Closing Off-Nominal Manoeuvre Values Comparison 187
Table 86: HP#3 Nominal Manoeuvre Values 188
Table 87: HP#3 Off-Nominal Manoeuvre Values Comparison 189
Table 88: HP#3 Off-Nominal Manoeuvre Values Comparison 190
Table 89: HP#3 Off-Nominal Manoeuvre Values Comparison 192
Table 90: HP3 Off-Nominal Manoeuvre Values Comparison 193
Table 91: HP#3 Off-Nominal Manoeuvre Values Comparison 195
Table 92: HP#3 Off-Nominal Manoeuvre Values Comparison 196

DEFINITIONS AND ABBREVIATIONS

Definitions

DOCKS	Interface between the SROC spacecraft and the MPCD. DOCKS is devoted to assuring safe docking and mating between the spacecraft and the retrieval system. The DOCKS is constituted by two main elements: DOCKS-A is attached and interfaced with the Spacecraft and DOCKS-B is attached and interfaced with the MPCD.
MPCD	System devoted to the deployment and the retrieval of the SROC spacecraft. The MPCD is the interface of the SROC Space System towards the Space Rider vehicle. It hosts (in its pusher plate) the DOCKS-B element to support the SROC docking.
Platform	Part of the SROC space system that includes all subsystems needed for operating the spacecraft, excluding the payload and the interface for docking to the MPCD.
Spacecraft	Part of the SROC space system that is deployed from Space Rider, i.e. the assembly of platform, payload and interface to the MPCD (DOCKS-A).
SROC Ground System	Ground system constituted by the SROC Mission Control Centre (MCC) and the ground stations. The system is devoted to support SROC-SS operations from launch up to disposal.
SROC Space System	Space system constituted by the SROC spacecraft and the MPCD system. The SROC Space System is installed in the Space Rider Cargo Bay for launch and re-entry phases. During the orbital phase, the Spacecraft is deployed from Space Rider, while the MPCD stays into the Space Rider Cargo Bay for the whole mission duration. The Spacecraft and the MPCD are interfaced by the DOCKS.

Abbreviations

CPVP	Commissioning and Performance Verification Phase
DRP	Docking and Retrieval Phase
EMP	End of Mission Phase
ESA	European Space Agency
FF	Free Flight
IPLP	Integration and Pre-Launch Phase
ISS	International Space Station
KOS	Keep Out Sphere
KOZ	Keep Out Zone
LEO	Low Earth Orbit
LEO/FF	Low Earth Orbit / Free Flight (environment, SROC free flight in orbit)
LEO/SR	Low Earth Orbit / Space Rider (environment, SROC in orbit inside SR)
LEOP	Launch and Early Operations Phase
MCC	Mission Control Centre
MPCB	Multi Purpose Cargo Bay
MPCD	Multi Purpose CubeSat Dispenser
NIR	Near Infra Red (wavelength)
POLITO	Politecnico di Torino
POP	Proximity Operations Phase
ProxOps	Proximity Operations
Qx	Quarter x (of a year)
SR	Space Rider
SR-IOCC	Space Rider In Orbit Control Centre
SR- PLCC	Space Rider Payload Control Centre
SROC	Space Rider Observer Cube

SROC-GS	SROC Ground System
SROC-SS	SROC Space System
SSO	Sun Synchronous Orbit
TBC	To Be Confirmed
TBD	To Be Defined
TIR	Thermal Infra-Red (wavelength)
UHF	Ultra High Frequency
UNIPD	Università di Padova
VIS	Visual (wavelength)
VLEO	Very Low Earth Orbit
WSE	Walking Safety Ellipse

Context, objectives, and research project outline

The Thesis was carried out in the framework of the Space Rider Observer Cube (SROC) mission, funded by European Space Agency (ESA) and by the Italian Space Agency (ASI). The mission consists of a 12U CubeSat, deployed from Space Rider cargo bay, the new ESA's reusable space transport system, with the purpose of formation flight and imaging of the mothercraft vehicle from its vicinity with a visual camera. SROC will serve as an in-orbit technological demonstrator for Rendezvous and Docking operations with Space Rider.
The present document has the objective to illustrate all the work done during the Phase B1 of the SROC project for the Work Package 210 (WP-210) i.e Mission Analysis & Concept of Operations, up to the System Requirements Review (SRR). In particular, the objective of this study is the definition and consolidation of the SROC mission, mission requirements in line with the SROC Mission Requirements Document [7] (Phase B1). The study includes an update and review of the Phase 0/A scenarios, to follow the latest issues of Space Rider user manual and a harmonisation of the SROC deployment in light of the new SR date of launch.
The study includes a refinement and consolidation of the mission requirements, the associated system concept (space segment, ground segment and operations). In addition, an off-nominal manoeuvres study it has been conducted to investigate all the possible cases of erroneous manoeuvre and a visibility analysis both from SROC-to-ground and SROC-to-SR, so as to verify the communication and observation capability respectively.

On the Introduction Chapter, an overview on the state of art is given regarding the major topics covered: a brief introduction of the CubeSat world opens this Chapter, then, a review on the proximity operations literature.

The *second* Chapter begins with the overall description of the and Space Riders, paying attention on the physical interfaces in the cargo bay, and SROC missions, particularly focusing on the ConOps.

The *Third* Chapter aims to report the design process, in term of main analyses description and results of the optimization processes for Mission Analysis & Concept of Operations the pursued under the SROC Phase B1 and the results of the Baseline scenario optimization divided in term of mission segments (i.e. trajectory fractions separated by manoeuvres), and the relevant SROC mission requirements are presented, as well as the assumptions and the main orbital mechanics theory and reference frame used.

The *Fourth* Chapter deals with the Off-Nominal scenarios, defined as scenarios in which the last manoeuvre is not properly executed. The Chapter, after a more precise definition of Off-Nominal scenarios, presents all the possible cases considered and the main results in terms of DeltaV, relative distance and peculiar safety considerations.
The analyses take into account each mission segment and eventually the different mission concept presented in the previous chapters.

The *last* Chapter summarised the chosen Baseline scenario, with its main features and safety considerations.

1 INTRODUCTION

1.1 CubeSats Mission Overview

A CubeSat is a miniaturized spacecraft belonging to the class of nanosatellites, initially developed to support educational and affordable mission for university students. The idea came from the collaboration between Professor Jordi Puig-Suari, of California Polytechnic State University at San Luis Obispo, and Professor Bob Twiggs, of Stanford University, since then the development of these mission followed the "CubeSat Standard" know as *CubeSat Design Specification (CDS) [17]*, which defines the external dimensions of the satellite within several cubic U units of $10\ cm\ x\ 10\ cm\ x\ 11.5\ cm$ and an approximate weight of $1.33\ kg$ for each unit.
Nowadays for the low cost and versatility that distinguishes these missions, CubeSats are largely employed by private agencies and not only by university for educational purposes. CubeSats are indeed modular and mostly constituted by COTS components, which guarantee faster and relatively economic development while reducing the risk of mission failure. CubeSats are usually launched as secondary payloads onboard a launch vehicle and put into orbit by specific deployers or deployed on the ISS.

By 2028 over 4100 CubeSats are expected to be launched [16], this rise in investment is justified in addition to the various benefits listed above, by the possibility to execute in-orbit demonstrations of technological components and flight procedures (rendezvous and docking, formation flight), to make scientific investigations in the field of:

- Earth observation
- Space weather
- Amateur radio
- Biological research
- Climate change

To mention a non-exhaustive list. From 2018 with the MarCO mission, CubeSat were progressively used for deep space exploration missions, with particular interest in Moon and Mars missions.

1.2 Rendezvous, Proximity Operations and Docking

Rendezvous and Proximity Operations (RPO) is typically associated with the ability or operation of two (or more) independent space objects that purposefully manoeuvre to within close "proximity" of each other, via various rendezvous techniques. RPO is critical for any "servicing" missions, which may include inspection, repair, refuel, upgrade or assembly activities. RPO-associated research does not only include orbital dynamics techniques, but also a wide and robust variety of related research fields such as processing and data fusion, sensors, and hardware for contact and dock.

The rendezvous and docking/berthing operations consists of a series of orbital manoeuvres and controlled trajectories, which successively bring two spacecrafts to a desired relative distance (Rendezvous) eventually followed by a further soft approach ending in controlled physical contact (Docking or Berthing). A classic way to approach is to bring the active vehicle (usually called Chaser) into the vicinity of, and eventually into contact with, the passive vehicle (called Target). The last part of the approach trajectory has to put the Chaser inside the narrow boundaries of position, velocities, and attitude and angular rates required for the mating process. The two primary mating strategy are:

- *Docking*: The Chaser makes contact, and it is captured by the docking interface of the Target vehicle. The docking sequence is controlled by the guidance, navigation and control (GNC) system of the Chaser that controls the vehicle state parameters.
- *Berthing*: The Chaser GNS system delivers the vehicle to a meeting point with nominally zero relative velocities and angular rates. The main difference lies in the way contact is carried out through a manipulator, located either on the Chaser or the Target, that grasps

the other vehicle, transfer it to the final position and inserts it into the interfaces of the relevant target berthing port.

To prove the complexity of the RPO and of the all the systems conditions required for its accomplishment few examples are given below. These represents the conditions and constraints which must be fulfilled to result in a nominal and successful Rendezvous and Docking operation:

1. Launch and phasing trajectory strategy
2. Operations in the vicinity of the target station
3. On-board system requirements and constraints
4. Synchronization with Sun illumination conditions and crew work cycle
5. Communication link constraints
6. Effects on system and operations

In the following Chapters, only the points investigated within the scope of this Thesis will be further described.

The analysis of the state-of-the-art covers an overview of past missions that can be of interest for the SROC mission. For each mission, only the characteristics and/or applications relevant to the SROC mission have been reported. Critical areas, disciplines and technologies have been identified by studying these missions, from literature publicly available, and based on the experience of the design team [3][4][10].

Table 1: Summary of relevant-to-SROC missions

Mission Name	Comments
CAN X 4-5 (University of Toronto, Launched in 2014)	A dual nanosatellite mission to demonstrate **satellite formation flying with low deltaV** requirements exploiting differential drag (deltaV 14 m/s with maximum thrust of 5mN).
AeroCube-4 (The Aerospace Corporation, Launched in 2012)	A 1U CubeSat able to estimate its **position with 20m accuracy using GPS**. Tested **formation flying by changing drag pole by external wings.**
CubeSat Proximity Operations Demonstration (CPOD) (Tyvak Nano-Satellite Systems, Inc., on-hold)	First CubeSat **formation, docking and undocking demonstration mission**. Navigation with proximity camera.
UIUC-JPL formation flying mission (Concept study, JPL)	4 CubeSats exploiting multiple J2 invariant orbits. **Thrusters** and relative **position sensors** are the major **bottlenecks technology.**
SNAP-1 (University of Surrey, launched in 2000)	A CubeSat demonstrator for remote inspection exploiting **GPS navigation and optical camera**.
PICS 1 & **2** (Brigham Young University, to be launched in 2019)	A technology demonstration mission of a spacecraft capable of performing **inspection, maintenance, and assembly on another spacecraft. Passive fly-away trajectory for safe inspection**.
Autonomous Assembly of a Reconfigurable Space Telescope (**AAReST**) (Caltech and University of Surrey, to be launched in 2020)	**Autonomous assembly of small independent spacecraft**, each with its own mirror, while in orbit to form a space telescope. The AAReST Rendezvous & Docking (RV&D) system uses the SSC Electro-Magnetic (EM) Kelvin Clamp Docking mechanism. It is composed by 3 “probe and drogue” (60º cone and 45º cup) type mechanical docking ports, arranged to form an extended area docking surface. Small COTS lidar systems for relative navigation are used; technology based on Microsoft KINECTTM and Softkinetic DS325.

RACE (ESA Phase A/B study, Prime: GomSpace, 2019)	Two CubeSats for testing **formation, docking and undocking**.
Multipurpose CubeSat at the ISS (**CubISSat**) (ESA Phase A/B study, Tyvak International, PoliTO, OHB Bremen, 2016)	A CubeSat for proximity operations in the vicinity of the International Space Station for inspection of blind spots and external configuration of the station. **Trajectory** analysis and **safety** aspects, support to EVA, **detection** of MMODs impacts and leakages.
Iperdrone (ASI mission. Prime: CIRA, with Tyvak International and Kaiser Italia. To be launched 2021 - TBC)	Operational mission at the International Space Station for **proximity operations**, risk reduction of **navigation**, inspection and safety.
Prototype Research Instruments and Space Mission technology Advancement (**PRISMA**) (OHB Sweden, DLR, CNES, DTU, launched 2010)	The main objective of PRISMA is to carry out flight demonstrations using experimental manoeuvres requiring new **GN&C** (Guidance, Navigation & Control) and **sensor technologies** for future rendezvous and formation flying missions. The system is constituted by two spacecraft (Main/Mango and Target/Tango). They were launched together as one unit and then separated to start the demonstration. Albeit the objective of the mission is relevant to SROC, Mango and Tango are larger than the spacecraft target size of the SROC mission (Mango is 145 kg and Tango 50 kg). The difference in size implies most technologies cannot be applied directly to SROC. However, some results of the PRISMA mission can be useful for SROC, 29/10/2020 SROC Mission Assessment Page 17 of 99 considering the technological development and miniaturisation occurred in the last five years.
Seeker & **Kenobi** (NASA, launched 2019)	The mission aimed at demonstrating advanced **autonomous inspection capability** at **low cost** (1.8MUSD budget) and **fast delivery** (14-month schedule from sketch to operations). Seeker is a 3U CubeSat that operated for 40 minutes around Cygnus on September 2019, taking **visual images** of the vehicle and performing a set of manoeuvres (including detumbling and **target tracking**, station-keeping, translations) and communication tests with its paired CubeSat Kenobi, which provided the interface to the mothership.

2 MISSION OVERVIEW

2.1 Space Rider mission overview

Space Rider (Space Reusable Integrated Demonstrator for Europe Return) is an uncrewed orbital lifting body spaceplane.
designed to orbit in Low Earth Orbit (LEO) for few months, with accurate pointing capabilities (Nadir and Zenith). SR cargo bay has a load capacity of 800 kg useful to enable access to and return from LEO orbits for a wide variety of applications such as:

- Smaller satellites or space experiment with the possibility to return to Earth.
- Micro-gravity experimentation.
- In-orbit Demonstration & Validation of technologies for exploration, orbital infrastructure servicing, Earth observation, Earth science, Telecoms, etc…
- In-orbit Applications for Earth monitoring, satellites inspections
- Educational missions
- European pathfinder for commercial services in access and return from Space.

To sum up, the SR without being limited to the above-mentioned applications, is an affordable, independent, reusable end-to-end space transportation system and it is composed by two modules: The SR-AOM is a modified version of the Vega-C upper stage, able to supply power, perform manoeuvres and provide attitude control in orbit to the whole SR systems up to the separation of the two modules prior to the return to Earth.

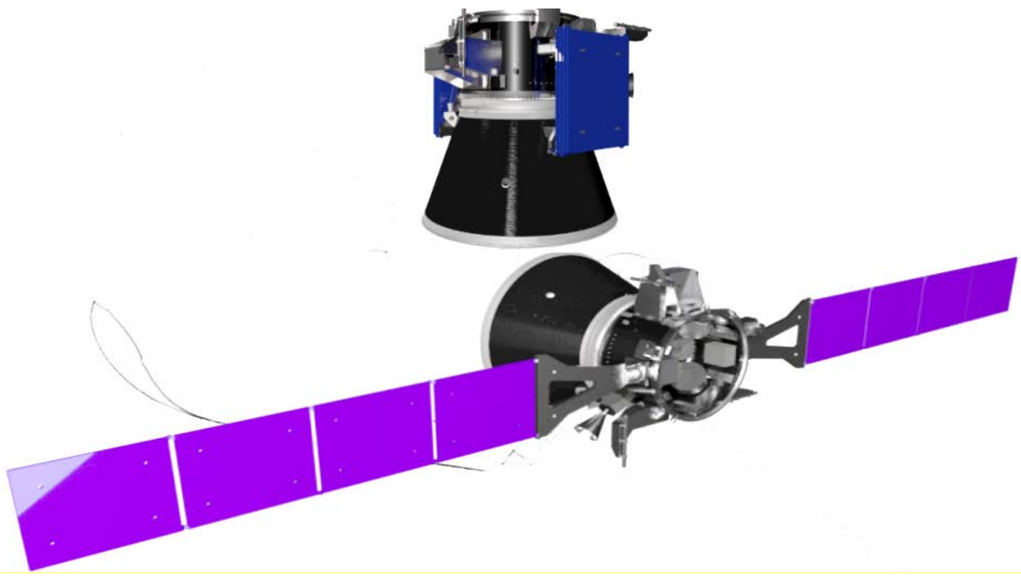


Figure 1: SR-AOM Module

The SR-RM (Re-entry Module) is a modified version of the IXV (Intermediate eXperimental Vehicle) demonstrator, integrating a Multi-Purpose Cargo Bay (MPCB) for payloads integration, able to perform ground landing and to re-fly after limited refurbishment.

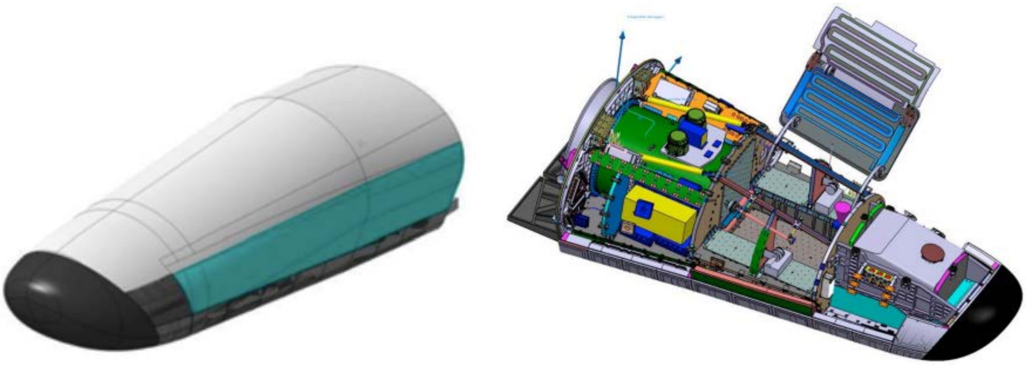


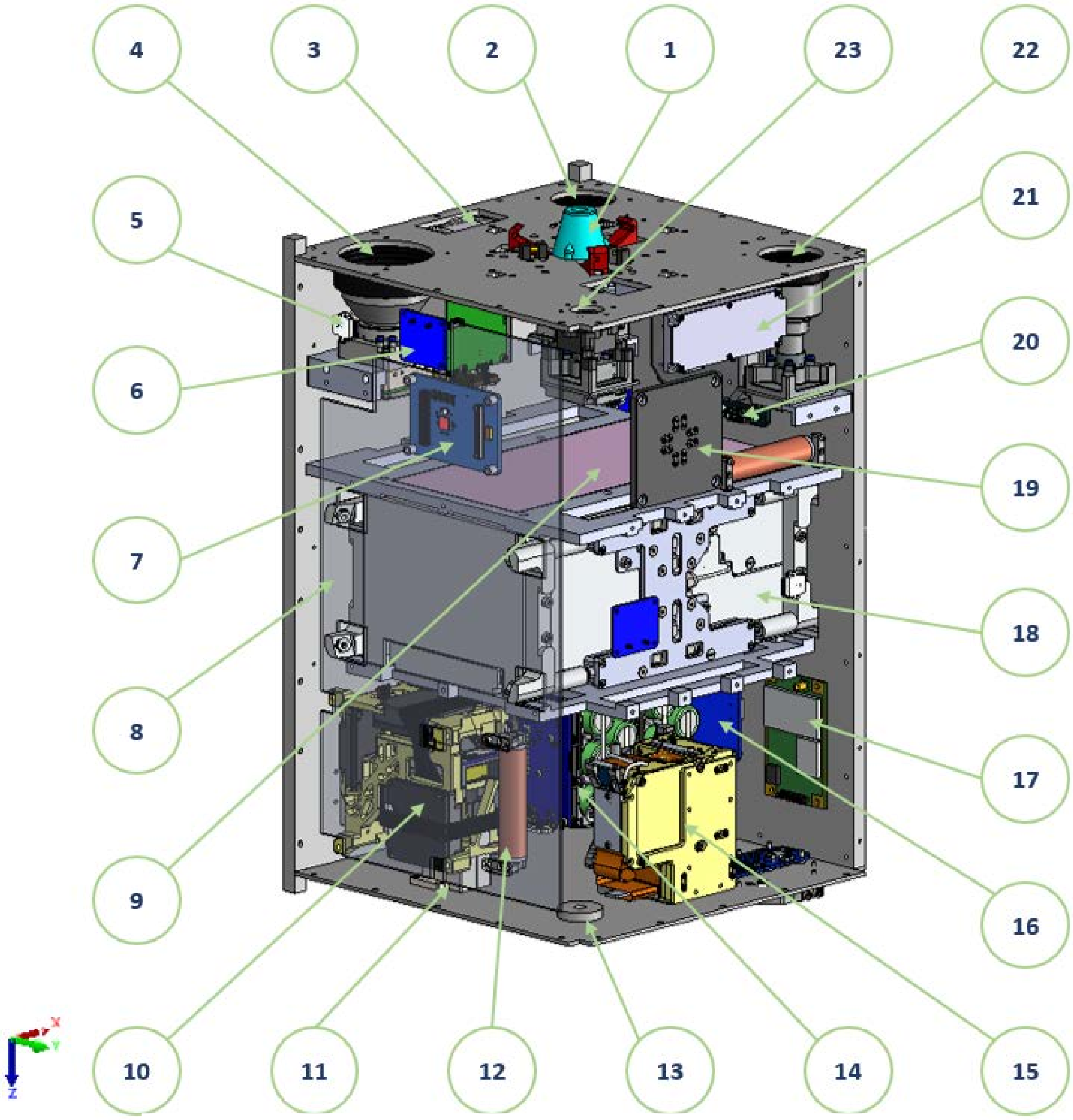
Figure 2: SR-RM Module

The Space Rider is launched from Europe's Spaceport in Kourou, French Guiana, will stay in orbit for to 2 months or more, and will re-enter Earth for the recovery of the user's payloads. After the flight, the SR will be refurbished for the next mission.

2.2 SROC mission overview

The **Space Rider Observer Cube (SROC)** mission aims at demonstrating the critical capabilities and technologies required for successfully executing a **rendezvous and docking** mission in a **safety-sensitive context**. The SROC multipurpose space system is constituted by a **nanosatellite** and a **deployment&retrieval system**. The system will perform a mission featuring **Proximity Operations** in the vicinity of the **Space Rider (SR)** vehicle before **docking** and **re-entering Earth** with the mothership.
The SROC project aims at developing and testing in space novel **key technologies** in the area of proximity operations and optical navigation, such as: Propulsion systems (cold gas), Guidance Navigation and Control (hardware and software), Electro-optical systems (visual camera), Mechanisms (docking, deployment and retrieval), and at improving Autonomous Operations.

All these technologies are of interest for a broad set of mission goals involving proximity operations. This in-orbit demonstration has the potential of opening a wide spectrum of novel applications for nanosatellites in the area of **inspection missions**. Furthermore, the development of the advanced technologies needed for the SROC mission will have a positive impact also for pursuing other mission objectives, especially in the domains of **in-orbit servicing**, space **exploration** and **debris mitigation**.
The SROC mission has been thought as an add-on to complement the Space Rider project. From the SROC side, the mission will demonstrate enabling technologies in the proximity operations domain, which can also be transferred to other targets. From the Space Rider side, there is the opportunity to demonstrate the capability to deploy & retrieve payloads, thus expanding the range of possible applications of the vehicle.



1. DOCKS-A
2. NFOV CAMERA
3. LIDAR
4. IR CAMERA
5. SUN SENSOR (x6)
6. SENSOR MODULE (x6)
7. HOUSEKEEPING
8. BACKPLANE
9. PIB
10. IRM
11. STAR TRACKER (x2)
12. TORQUE ROD (x3)
13. HDRM HOUSING (x2)
14. BATTERY MODULE (x2)
15. REACTION WHEEL
16. MPPT (x2)
17. GPS RADIO
18. PERSEUS
19. PATCH ANTENNA S-BAND
20. LCM
21. S BAND ANTENNA
22. PAYLOAD
23. WFOV CAMERA

Figure 3: SROC Axonometric cutaway

The SROC mission will advance current CubeSat technology and capabilities with respect to:

- **formation flight, in terms of:**

- *Proximity Navigation*
- *Guidance and Control*
- *Communications*
- *Autonomous operations*

- **deployment, docking and retrieval of CubeSats:**
  - *Guidance, navigation and control algorithms for close approach up to docking*
  - *Deployment and retrieval mechanisms*
  - *Docking systems*
- **space targets observation:**
  - *Imaging*

Due to the novelty and perceived complexity of the mission objectives, the SROC programme might require multiple sequential missions at incremental level of complexity. Two mission concepts are considered at the moment:

- In the ***baseline*** case, the **Observe & Retrieve** mission is implemented. The spacecraft is deployed from Space Rider, observes the vehicle from close distance, and eventually approaches Space Rider, performs docking and is retrieved and stowed into its cargo bay for re-entry Earth. A further option would be performing multiple deployment/retrieval within the same mission in a sort of ***enhanced*** scenario called **Observe & Reuse**[1] mission, which is however excluded for the first mission of the SROC system. This case is the most technologically demanding, as it involves the development and implementation of a Deployment and Retrieval Mechanism (DARM), which has the function of safe deployment, retrieval and stowage, and development of GNC algorithms for safe close proximity operations. It also is the most demanding with respect to safety, as SROC docks and physically interfaces again with Space Rider. In case of off-nominal performance of SROC, the approach and retrieval phase shall not be performed, and the mission shall revert back to the 'Observe' scenario.
- In the ***reduced*** (or ***demo***) case, i.e. the **Observe** mission, a simplified ConOps is taken into consideration, in which the spacecraft is deployed from Space Rider but it is disposed into space after the inspection of the rider, i.e. SROC is not retrieved in the SR cargo bay at the end of its mission, but rather it shall perform a disposal in an (un)controlled re-entry manoeuvre, in compliance with the ESA's space debris mitigation guidelines. The reduced scenario represents either an option for the first mission in a cost- and/or time-constrained framework, although with reduction of mission objectives, or it can be seen as the off-nominal scenario of the baseline case should any failure occur that prevents docking of SROC to SR.

In the current baseline, the 12U SROC CubeSat will be launched with Vega C inside the Space Rider vehicle and deployed from the Multi-Purpose CubeSat Dispenser (MPCD) once in orbit. Target launch is the Space Rider Maiden Flight, currently planned Q4 2024. Once deployed and commissioned, SROC will execute a performance verification at a safe relative distance, then it will fly in formation with Space Rider taking observation of the vehicle from close distance in a passively safe trajectory. At a certain point in time, SROC will rendezvous and dock with its Multi-Purpose CubeSat Dispenser hosted in the Space Rider Multi-Purpose Cargo Bay (MPCB). The docking and mating of SROC to the MPCD is made possible by the DOCKS interface that is developed *ad-hoc* for this mission. Figure 4 illustrates the design reference mission, in which the Observe & Retrieve scenario is assumed as baseline, and the Observe scenario is considered as off-nominal mission in case the retrieval is not possible. Table 2 and Table 3 describe the mission phases and subphases for both scenarios. The mission duration is less than 30 days from deployment from the Rider to

[1] The Observe and Reuse mission has been conceived during the Phase 0/A, but not further analysed at Phase B stage.

completion of retrieval in the cargo bay. In case of an independent disposal in orbit (i.e. no retrieval) is necessary, the SROC spacecraft will lower its orbit and disintegrate in Earth upper atmosphere in less than 1.5 years.

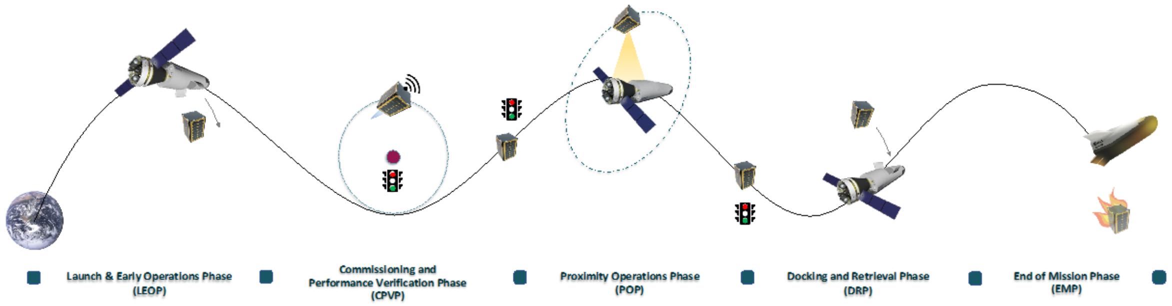


Figure 4: SROC Design Reference Mission

Table 2: ConOps "Observe & Retrieve" scenario

SROC Observe and Retrieve Scenario	
Mission phase	**Mission subphases**
Integration & Pre-Launch Phase (IPLP)	Integration phase Pre-Launch phase
Launch & Early Operations Phase (LEOP)	Launch phase Deployment phase
Commissioning and Performance Verification Phase (CPVP)	Commissioning phase Verification phase
Proximity Operations Phase (POP)	Rendezvous phase SR Observation phase
Docking & Retrieval Phase (DRP)	Closing phase Final Approach phase Mating phase Retrieval phase
End of Mission Phase (EMP)	Re-entry phase Post-landing phase Post-flight phase

Table 3: ConOps "Observe" scenario

SROC Observe Scenario	
Mission phase	**Mission subphases**
Integration & Pre-Launch Phase (IPLP)	Integration phase Pre-Launch phase
Launch & Early Operations Phase (LEOP)	Launch phase Deployment phase
Commissioning and Performance Verification Phase (CPVP)	Commissioning phase Verification phase
Proximity Operations Phase (POP)	Rendezvous phase SR Observation phase
End of Mission Phase (EMP)	Disposal phase Re-entry phase

The mission architecture is summarized in Table 4, where the baseline mission is presented together with some options still under investigation.

Table 4: SROC mission architecture

Mission element	Description of baseline	Options / Comments
Subject	Space Rider observations	Visual observations are considered for the baseline design with the objective of achieving 1 cm spatial resolution
	Close Proximity Operations demonstration	Experiments: 1) execution of manoeuvre(s) for acquisition of hold points, for insertion into rendezvous trajectories with respect to Space Rider, for insertion into observation trajectories, 2) determination of relative distance from Space Rider with different sensors and techniques, 3) acquisition of Space Rider imagery
	Docking & Retrieval capability demonstration (only "observe and retrieve scenario")	Single deployment and retrieval of SROC (no reuse within the same mission)
Payload	Visual camera	The baseline solution for the payload is a visual camera based on Tyvak detector (the same used for the navigation cameras) with *ad-hoc* optics
Space Segment	1 CubeSat (SROC)	12U form factor, based on Tyvak Phoenix platform, with body mounted solar arrays and cold gas propulsion system
	1 Multi-Purpose CubeSat Dispenser (MPCD)	MPCD design is compliant with the Observe & Retrieve scenario Standard Tyvak 12U CubeSat deployer is an option only for the Observe mission scenario
	1 Docking System (DOCKS)	DOCKS is the interface between SROC and the MPCD. It includes the sensors suite for supporting the navigation function for relative distance < 1m and the mechanisms needed to guarantee soft and hard docking of SROC to SR
Orbit & Constellation	LEO circular @400 km	Quasi-equatorial orbit (i=5deg) assumed as baseline. Other orbits considered: i=37deg Midday-Midnight, i=37deg Dawn-Dusk, SSO Midday-Midnight, SSO Dawn-Dusk (only for the Observe scenario)
	Formation flying with respect to SR	Rendezvous trajectory: passively safe in-plane + out-of-plane segments SR observation: Walking Safety Ellipse with relative inclination change and variable geometry Docking: along the in-track axis (baseline). Radial docking considered as option
	Disposal orbit	

	Re-entry (uncontrolled) orbit	Manoeuvre(s) to avoid space debris impact, up to passivation of the satellite (only for the Observe scenario, or off-nominal Observe & Retrieve Scenario) Natural decay within 1.5 years

Communication Architecture	Store & Forward architecture	Direct link to Earth for communication purposes Crosslink between SROC spacecraft and MPCD is an option considered for supporting navigation function (not baselined)
Ground Segment	Ground station network MCC	Network of UHF and S-band ground stations. Compatibility with Estrack network is guaranteed SROC MCC in Torino. The SROC MCC shall be in contact with the SR MCC for specific mission phases and/or needs
Operations	Mission Planning Spacecraft Control Flight dynamics	Drivers for Ops design: safety, reliability & autonomy Compliance with ESA standards Coordination with SR operations
Launch Segment	CSG spaceport + Vega C + Space Rider	Launch assumed Q4 2024 (baseline, target: SR maiden flight). Other late launch dates are considered

3 MISSION ANALYSIS

In this section the analysis of orbit geometry and trajectories for the SROC mission is described. Assumptions about Space Rider orbits and system configuration have been made in order to develop formation and rendezvous strategies.

3.1 Mission requirements

The mission requirements applicable to this study are presented here according to the following format:

Requirement ID	**Requirement Title**
Requirement text	

The full SROC requirements specification developed during Phase B1 is included in the "*D111 – System Technical Specifications*" [13], where further details (e.g. Rationale/Traceability) are given for each requirement.

3.1.1 ConOps requirements

SROC-MIS-001	**CubeSat in SR mission**
The mission shall employ a CubeSat as a SR Deployable Payload (D-PL (KZ)) that can separate from Space Rider MPCB into its own free-flying mission with operations within the Space Rider Keep Out Zone	

SROC-MIS-002	**Mission Scenarios**
The mission shall be compatible with the mission scenarios defined as: • "Observe and Retrieve" (baseline scenario) • "Observe" (reduced scenario) *Note: the "Observe and Reuse" mission (enhanced scenario, considered in Phase 0/A) will be considered as a future development, but it is excluded as possible scenario for the first flight and it has not been studied in Phase B1*	

SROC-MIS-003	**Launch date**
SROC mission shall be compatible with the Space Rider's launch date on Q4 2024 (TBC). *Note: Compliance with other late launch dates shall also be guaranteed*	

SROC-MIS-004	**MMOD damage**
The mission shall identify MMOD damage larger than 15 (TBC) mm on the Space Rider surface	

SROC-MIS-005	**Lifetime**
The SROC system, subsystems and equipment shall be compatible with a time on-orbit of at least 2 months nominally	

SROC-MIS-006	Mission phases
The following mission phases shall be defined, listed chronologically: • Integration and Pre-Launch Phase (IPLP) • Launch and Early Operations Phase (LEOP) • Commissioning and Performance Verification Phase (CPVP) • Proximity Operations Phase (POP) • Docking and Retrieval Phase (DRP) - only for the "Observe and Retrieve Scenario" • End of Mission Phase (EMP)	

SROC-MIS-007	LEOP functions
During the LEOP, the SROC spacecraft: • shall be deployed from SR through the Multi Purpose CubeSat Dispenser (MPCD) • shall be activated autonomously via kill switch(es) *Note: MPCD can be replaced by a standard 12U deployer only for the Observe scenario*	

SROC-MIS-008	LEOP subphases
The LEOP shall be divided into the following sub-phases to support SROC release in space: • Launch • Deployment	

SROC-MIS-009	CPVP functions 1
During the CPVP, calibration and performance verification of all subsystems shall be performed	

SROC-MIS-010	CPVP functions 2
During the CPVP, compliance to performance specifications needed for safe proximity operations shall be demonstrated. *Note: are excluded functions that cannot be tested with the target at a certain distance (e.g. close proximity sensors performance) and/or around a virtual point instead of at the actual target (e.g. docking)*	

SROC-MIS-011	CPVP subphases
The CPVP shall be divided into the following sub-phases to support SROC verification: • Commissioning • Verification	

SROC-MIS-012	Commissioning duration
The Commissioning phase shall take no longer than 7 (TBC) days. *Note: target duration is 5 days*	

SROC-MIS-013	POP functions
During the POP, SROC shall perform on-orbit observations of Space Rider taken in its vicinity	

SROC-MIS-014	POP subphases
The POP shall be divided into the following sub-phases to support autonomous safe proximity operations: • Rendezvous • Observation	

SROC-MIS-015	DRP functions
During the DRP, the mission shall demonstrate in orbit CubeSat docking and retrieval capabilities	

SROC-MIS-016	DRP subphases
The DRP shall be divided into the following sub-phases to support safe docking and retrieval operations of SROC into SR MPCB: • Closing • Final Approach • Mating • Retrieval	

SROC-MIS-017	EMP functions
The EMP shall consist of: • Moving SROC into a disposal orbit which does not interfere with Space Rider (for "Observe Scenario"); or • Retrieval and storage of SROC in the MPCD for Earth return within the Space Rider MPCB (for "Observe & Retrieve Scenario")	

SROC-MIS-018	EMP subphases
The EMP shall be divided into the following sub-phases according to the applicable mission scenario: -Observe and Retrieve scenario: • Re-entry • Post-landing • Post-flight -Observe scenario: • Disposal • Re-entry	

SROC-MIS-019	Scenario switch
In case of off-nominal performance during the "Observe & Retrieve Scenario", the mission shall be able to revert back to the "Observe Scenario" and SROC shall be decommissioned accordingly.	

SROC-MIS-020	Hold points
The SROC approach trajectory towards SR shall include predefined hold-points where SROC can receive “go/no-go” commands from the SROC and SR mission control centres.	

SROC-MIS-021	Collision Avoidance Manoeuvre (CAM)
SROC shall be able to perform CAMs, commanded by the SROC MCC, in case of high-risk conjunction events with spacecraft or space debris.	

SROC-MIS-022	CAM capability
SROC shall have a Collision Avoidance Manoeuvre (CAM) capability that places it in a trajectory that does not cross a predefined Keep Out Zone (KOZ) around Space Rider for at least 24 (TBC) hours.	

SROC-MIS-023	ESTRACK compatibility
All aspects of the SROC mission shall be compatible with the network of ESA ground stations.	

SROC-MIS-024	G2S Docking link
During the final approach, mating and retrieval phases, a continuous bi-directional ground-to-space link between the SROC MCC and SROC shall be established to monitor and command SROC.	

SROC-MIS-025	Time-to-dock
Time-to-dock (i.e. the duration of the manoeuvres from the last hold point to the mating point) shall be less than 500 (TBC) s.	

SROC-MIS-026	Space Debris Mitigation Policy
All aspects of the SROC mission shall be compliant with the Space Debris Mitigation for Agency Projects [4].	

3.1.2 Launch Vehicle and Site requirements

SROC-MIS-030	Launch vehicle
SROC shall be compatible with a launch within the MPCB of Space Rider.	

SROC-MIS-031	Vega-C launcher
The mission shall be compatible with launch by Vega-C.	

SROC-MIS-032	Launch site
SROC shall be compatible with a launch campaign from Centre Spatial Guyanais (CSG) in Kourou.	

SROC-MIS-033	Landing site ground facilities
In the Observe and Retrieve scenario SROC shall be compatible with the Landing Site Ground facilities during retrieval and post-flight operations	

3.1.3 Observations requirements

SROC-MIS-040	SR observation phase coverage
The mission should achieve at least 90% (TBC) of Space Rider coverage mapping except for areas which might be permanently in shadow during the observation.	

SROC-MIS-044	Observation distance
The observation and imagery of Space Rider shall be taken from a relative distance between SROC and Space Rider > 200 (TBC) m, i.e. from outside the KOZ.	

SROC-MIS-045	SR Single Inspection duration
Each observation cycle of Space Rider shall have a duration of at least 4 (TBC) hours.	

SROC-MIS-046	Observation cycles
SROC shall perform at least 1 (TBC) observation cycle of Space Rider.	

SROC-MIS-047	Relative velocity
The transversal component of the relative velocity between SROC spacecraft and Space Rider surface shall be less than 1.5 (TBC) m/s during the observation of Space Rider. *Note: considering an imaging system exposure time of 0.01 s.*	

3.1.4 Orbit & Trajectory requirements

SROC-MIS-050	Operational orbit
SROC shall be compatible with an operational orbit in LEO (nominal 400 km circular) and inclination between 5-55 degrees, or SSO.	

SROC-MIS-051	HP#1 trajectory
SROC shall be able to acquire a trajectory around a virtual point (HP#1) with null mean motion in the positive InTrack direction at a defined relative distance from Space Rider. *Note: the relative distance between HP#1 and SR along the positive InTrack axis depends on the duration of the Commissioning phase. The range is approximately 330 – 1400 km.*	

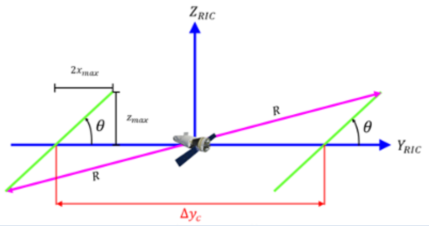
SROC-MIS-052	HP#1 maintenance
SROC shall be able to maintain the HP#1 trajectory for at least 3 (TBC) hours without manoeuvring. *Note: the HP#1 is useful to perform manoeuvres for demonstrating the required capabilities for proximity operations (e.g. orbit determination and control, attitude determination and control) and to decide whether to start the rendezvous or not.*	

SROC-MIS-053	HP#2 trajectory
SROC shall be able to acquire a hold point (HP#2) at 2 - 5 (TBC) km from Space Rider along the positive InTrack axis. *Note: the HP#2 is useful to set up the navigation sensor suite for proximity operations and lock the target. The set up and locking can be also done during the rendezvous, i.e. without the need of HP#2, but having a steady point in space is preferred from a GNC perspective.*	

SROC-MIS-054	HP#2 maintenance
SROC shall maintain the trajectory in the HP#2 with null relative motion wrt SR for at least 3 (TBC) hours.	

SROC-MIS-055	Approach Corridor
The final approach trajectory shall be executed in the Space Rider Approach Corridor defined as a 10˚ (TBC) cone centred to the docking port axis (the MPCD pusher plate +Z axis in the Space Rider MPCB) within the KOZ.	

SROC-MIS-056	WSE Geometry
SROC shall perform the observation of SR remaining within a passive safe and out of plane Walking Safety Ellipse (WSE) trajectory, whose geometry is defined by the following parameters:	



SROC-MIS-057	SROC KOZ
SROC trajectories shall not cross the Space Rider KOZ defined as 200 (TBC) m radius sphere centred at the Space Rider vehicle center of mass. *Note: SROC is allowed to enter the KOZ during mission-specific phases (deployment, final approach, and docking) agreed with Space Rider.*	

SROC-MIS-058	HP#3 trajectory
SROC shall be able to acquire one of the following holding trajectories (HP#3) to reach the Radial or InTrack axis depending on the selected docking option: • InTrack docking: Holding consists of a trajectory with null relative motion wrt Space Rider < 150 (TBC) m along the positive InTrack axis • Radial docking: Holding consists of a passive-safe out-of-plane closing trajectory until reaching the radial axis/approach corridor. This trajectory maintains SROC < 150 (TBC) m mean distance from Space Rider.	

SROC-MIS-059	HP#3 maintainance
SROC shall maintain the holding trajectory HP#3 for at least 3 (TBC) hours.	

SROC-MIS-060	Maximum DeltaV
The ΔV for all SROC manoeuvres shall be less than 20 (TBC) m/s including margins.	

3.1.5 Proximity Operations requirements

SROC-MIS-100	FAP conditions - orbit
The SROC conditions in the Final Approach Point (FAP) wrt Space Rider shall be: • relative position components RIC [100, 0, 0] ± 5 m (TBC) • relative velocity components less than -0.2 m/s ± 0.04 m/s along Radial and 0.05 m/s ± 0.01 m/s along In-Track and Cross-Track *Note: only applicable when the final approach is performed along the Radial axis.*	

SROC-MIS-101	HP#3 conditions - orbit
The SROC conditions in HP#3 wrt Space Rider shall be: • relative position components RIC [0, 100, 0] ± 5 m (TBC) • relative velocity components less than -0.2 m/s ± 0.04 m/s along In-track and 0.05 m/s ± 0.01 m/s along Radial and Cross-Track *Note: only applicable when the final approach is performed along the In-Track axis.*	

SROC-MIS-102	FAP conditions – Relative attitude/angular velocity
The SROC conditions in the Final Approach Point (FAP) wrt Space Rider shall be: • relative attitude less than 1 deg, single axis, 2σ • relative angular velocity less 0.1 deg/s *Note: only applicable when the final approach is performed along the Radial axis.*	

SROC-MIS-103	HP#3 conditions – Relative attitude/angular velocity
The SROC conditions in HP#3 wrt Space Rider shall be: • relative attitude less than 1 deg , single axis, 2σ • relative angular velocity less 0.1 deg/s *Note: only applicable when the final approach is performed along the In-Track axis.*	

SROC-MIS-104	Final approach velocity profile
The velocity profile for the final approach manoeuvre shall include an acceleration up to max velocity, velocity maintenance and exponential deceleration. *Note: applicable for both Straight Line manoeuvre and Fly Around manoeuvre.*	

SROC-MIS-105	Final approach max velocity
SROC maximum approach velocity along the docking axis shall be: • less than 0.2 (TBC) m/s for the Straight-line manoeuvre • less than 0.4 (TBC) m/s for the Fly Around manoeuvre	

SROC-MIS-106	Mating conditions (Radial docking)
The SROC conditions in the mating point wrt Space Rider shall be: • relative velocity component less than -0.01 m/s along Radial axis • In-track and Cross-track misalignment less than 7.5 mm (2σ) *Note: only applicable when the final approach is performed along the Radial axis.*	

SROC-MIS-107	Mating conditions (In-Track docking)
The SROC conditions in the mating point wrt Space Rider shall be: • relative velocity component less than -0.01 m/s along In-track axis • Radial and Cross-track misalignment less than 7.5 mm (2σ) *Note: only applicable when the final approach is performed along the In-track axis.*	

SROC-MIS-108	Mating conditions – attitude/angular velocity
The SROC conditions in the mating point wrt Space Rider shall be: • relative attitude less than 1 deg along any axis • relative angular velocity be less 0.1 deg/s along any axis	

SROC-MIS-109	APE – target pointing
APE shall be in the range ± 0.1 deg (TBC) during the WSE and the final approach	

SROC-MIS-110	RPE – target pointing
RPE shall be in the range ± 0.004 deg in 100 msec (TBC) (single axis, 2σ) during the WSE and the final approach	

SROC-MIS-111	Illumination conditions
The angle between the Sun Vector and the docking axis shall be less than 60 (TBC) deg for the final approach and docking	

3.2 Proximity operations

Spacecraft proximity operations is the tracking or maintenance of a desired relative separation, orientation, or position between or among spacecraft. In this situation, there is not just one orbit (or location on the orbit) to be controlled, but there are many, and the typical approach consists in controlling the orbit of one of the spacecrafts (the leader) and regulating the others (the followers) relatively to it. The leader is also called target or chief while the followers are also called chasers or deputies, depending usually on the application.

While the leader's orbit is handled with an absolute reference frame, for the followers a relative frame is considered: this is a local orbital reference frame in which the motion is described relatively to a particular point in orbit or to another spacecraft; in this way the local orbital frame for both the leader and the follower can be defined, but the trajectories of the chaser are defined relatively to the target. For our application, two different frames are proposed: 1) the local-vertical/local-horizontal (LVLH) frame; 2) the Hill's frame [10].

The LVLH frame has its origin in the centre of mass of the leader spacecraft, the first axis is in the direction of the orbital velocity vector (V), the second axis is in the opposite direction of the angular momentum vector (H) of the orbit and the third one completes the triad. In rendezvous literature, these coordinates are also called Vbar, Hbar and Rbar respectively (the last one refers to the radial direction in case of a circular orbit). The Hill's frame also has its origin in the centre of the spacecraft mass, the first axis is the radial outwards direction (Radial), the second axis is the direction of the orbital velocity vector (InTrack) and the third one completing the triad is the orbital angular momentum direction (CrossTrack).

It is preferable to operate the second reference frame proposed, also called RIC frame (Radial-InTrack-CrossTrack), as it is the one used in the relative equations of motion, described below, and the most widely used in relative proximity operations literature. Both the frames are compared and shown in Figure 5, together with the absolute position, velocity, and angular momentum vectors ($\vec{r}, \vec{v}$ and $\vec{h} = \vec{r} \times \vec{v}$ respectively), assuming a circular orbit for the leader spacecraft. The motion of a spacecraft relative to another spacecraft is described by a system of non-linear differential equations; fortunately, under certain conditions, it is possible to linearize these equations and solve them easily. In fact, assuming that the orbit of the leader is circular, and the orbit of the follower is just slightly elliptic or inclined with respect to it, the motion of the two spacecraft looks very similar, and the system of equations can be simplified, obtaining the Hill-Clohessy-Wiltshire (HCW) equations.

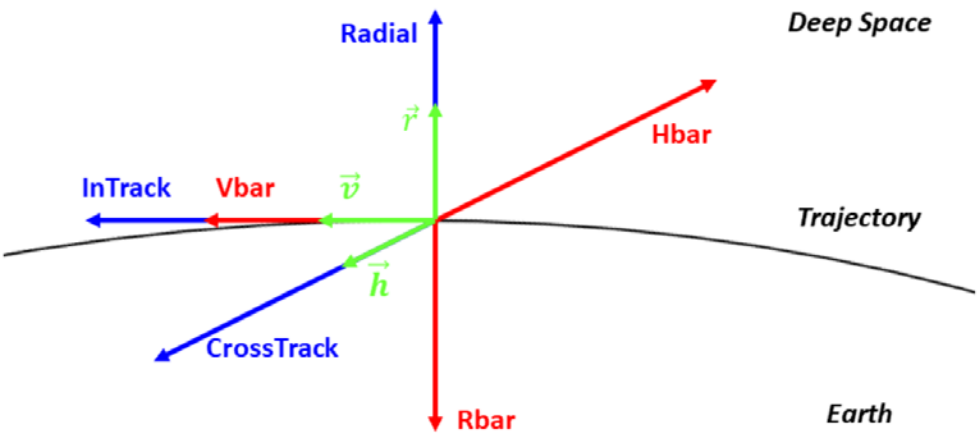


Figure 5: LVLH and RIC frames comparison

Not considering perturbations or other forces, HCW equations are homogeneous and assume the following form:

$$\ddot{x} + 2n\dot{z} = 0$$
$$\ddot{y} + n^2 y = 0$$
$$\ddot{z} - 2n\dot{x} - 3n^2 z = 0$$

where $n = 2\pi/T$ is the mean motion and T is the orbital period.
A first important observation is that the equations of motion in the orbital plane (x, y) are uncoupled from the equation of motion in the normal direction (y). Given an initial state, the solutions of these equations are:

$$x(t) = -[6nz(0) + 3\dot{x}(0)]t + \left[x(0) - \frac{2\dot{z}(0)}{n}\right] + \left[6z(0) + \frac{4\dot{x}(0)}{n}\right]\sin(nt) + \frac{2\dot{z}(0)}{n}\cos(nt)$$
$$y(t) = \frac{\dot{y}(0)}{n}\sin(nt) + y(0)\cos(nt)$$
$$z(t) = \left[4z(0) + \frac{2\dot{x}(0)}{n}\right] - \left[3z(0) + \frac{2x(0)}{n}\right]\sin(nt) + \frac{z(0)}{n}\sin(nt)$$

$$\dot{x}(t) = -[6nz(0) + 3\dot{x}(0)] + [6z(o)n + 4\dot{x}(0)]\cos(nt) - 2\dot{z}(0)\sin(nt)$$
$$\dot{y}(t) = \dot{y}(0)\cos(nt) - y(0)n\sin(nt)$$
$$\dot{z}(t) = \dot{z}(0) cosu(nt) + [3nz(0) + 2\dot{x}(0)]\sin(nt)$$

Analysing these solutions, the variation of the different components leads to the following effects:

- A displacement of the initial position in the direction of motion x results in a stationary condition: the position is different, but the relative velocity does not change.
- A displacement of the initial position in the y direction results in a harmonic oscillation along this direction with period T.
- A displacement of the initial position in the radial direction z results in a periodic oscillatory motion along both radial and along-track directions, this drift produces an elliptical relative trajectory with period T.
- A variation of the initial velocity in the along-track direction produces a periodic oscillatory motion in the radial direction and a drift along the x direction; changing the along-track velocity means changing the semimajor axis and so breaking the main requirement to keep a formation, that is why after one orbit the follower will be drifted.
- A variation of the initial velocity in the y direction has a similar effect of the variation of initial position in this direction.
- A variation of the initial velocity in the radial direction results in a periodic elliptical relative motion on the orbital plane with period T. Depending on the variation and the starting position, the semimajor axis of the ellipse will grow or become smaller, but its period will not change.

The most important condition to keep a formation is that all the spacecraft shall have the same orbital period so that, after completion of one orbit they are back in the same relative position. According to the third Kepler's law, it is known that same orbital period means same semimajor axis, which also means same specific energy.

3.3 Assumptions

The Space Rider Baseline scenario has been considered, adopting as the initial date of the SROC mission 1st Mar 2024 00:00:00.000 UTG. Other assumptions are listed below:

- SR Orbit parameters according to the user guide [2]:

Table 5: Space Rider baseline orbit

Quasi Equatorial -Baseline	
Apoapsis Altitude	400 km
Eccentricity	0.0
Inclination	5 deg
RAAN	0 deg
AOP	0 deg
True Anomaly	0 deg

Table 6: Space Rider orbits

Sun Synchronous – midday/midnight		Sun Synchronous – dawn/dusk	
Apoapsis Altitude	400 km	Apoapsis Altitude	400 km
Eccentricity	0.0	Eccentricity	0.0
Inclination	97.03 deg	Inclination	97.03 deg
RAAN	339.23 deg	RAAN	249.23 deg
AOP	0 deg	AOP	0 deg
True Anomaly	0 deg	True Anomaly	0 deg
Intermediate orbit – midday/midnight		**Intermediate orbit – dawn/dusk**	
Apoapsis Altitude	400 km	Apoapsis Altitude	400 km
Eccentricity	0.0	Eccentricity	0.0
Inclination	37 deg	Inclination	37 deg
RAAN	339.23 deg	RAAN	249.23 deg
AOP	0 deg	AOP	0 deg
True Anomaly	0 deg	True Anomaly	0 deg

- SR Dry Mass: 4165 kg
- SR attitude is fixed with TPS towards nadir direction, except for the SROC deployment.
- SR motion is controlled (i.e. not perturbed except for gravitational J2 effects)
- SROC parameters:
  - Dry Mass: 24 kg
  - Drag Coefficient: 2.2
  - Drag Area: 0.06 m^2
  - SRP Coefficient: 1.3
  - SRP Area: 0.06 m^2
- Deployment conditions has been assumed after a deployment analysis considering the combination of different ΔV, based on existing technology, and different deployment angles with respect to negative Radial direction (anticlockwise wrt nadir vector). An accurate description and the analysis results are presented below (Paragraph 3.5.1).
- Holding points are considered for go/no go commands and for possible rehearsal operations in order to increase mission safety.
- SROC orbit propagators and environmental models:
  - Integrator: RungeKutta89
  - Gravitational perturbation: JGM-2 at order J4

- Drag Model (MSISE 1990 Atmospheric Density Model)
- SRP: spherical model
- Third bodies: Sun and Moon

Two different synchronised propagators have been used for the follower and the leader: while the first one uses perturbations, the second does not, assuming that SR, being the leader, is always in the correct orbit. The SRP and the third body perturbations influence the trajectories of SROC varying its orbital parameters, but they are much less effective than the atmospheric drag, which slow down the CubeSat. This effect is significant in hold points because varying the semimajor axis, the proximity operations condition is not satisfied. Finally, for the relative motion phases, such as Hold Points, Rendezvous and SR observation, the RIC reference frame will be used, described in section (8.2). While the LVLH system will be used for the docking phase, in accordance with the main reference adopted, and for the deployment analysis.

3.4 Optimization analyses

In this Paragraph, an overview on the simulation software STK, the MATLAB scripts and a brief description on their interfaces (i.e. STK-MATLAB interface) are reported, for a better comprehension of the technical tools used.

In the field of engineering and mission analysis, the ability to model and evaluate complex systems is of utmost importance. Engineers, mission analysts, operators, and decision-makers from various global organizations rely on powerful software tools to simulate and analyse the performance of critical assets such as aircraft, satellites, optical payloads, and ground stations. One such tool that has gained significant recognition is Systems Tool Kit® (STK). With its 2D and 3D modelling capabilities, STK provides a comprehensive environment for studying system behaviour in both real-time and simulated scenarios.
STK, based on a time-dynamic, physics-based geometry engine, offers engineers the means to answer fundamental questions that are crucial to solving dynamic analysis problems. These questions revolve around the precise location and orientation of assets, the visibility and detection capabilities of these assets, and the quality of relationships among various system components. By addressing these queries, STK assists engineers in gaining valuable insights into system behaviour and performance.
To enhance the computational capabilities of STK and leverage the flexibility of MATLAB, the STK/MATLAB Interface acts as a communication bridge between the two software platforms. This interface empowers users to evaluate mission parameters and geometric conditions by seamlessly integrating the visualization capabilities and the aerospace-specific mathematical models and attributes of STK with MATLAB's versatile workspace. By employing the STK/MATLAB Interface, it was possible to assess critical factors such as relative distances, inter-visibility between objects, and Delta-V evaluations.

One of the key advantages of utilizing the STK/MATLAB Interface is the ability to perform multi-parameter optimizations to automate the process of optimizing multiple parameters simultaneously. This enabled to search for optimal solutions that satisfy the specific mission effectiveness criteria and geometric conditions defined within the STK environment, in accordance with requirements for both the nominal scenario and off-nominal analyses. In addition to the optimization capabilities, the STK/MATLAB Interface enabled MATLAB data visualization within the STK environment. Indeed, it was possible to utilise STK's 2D and 3D visualization capabilities to obtain an intuitive understanding of geo-referenced or geometric SROC data. For instance, position and attitude information or camera FOV can be overlaid on STK's immersive visualizations. This integration allowed to assess the impact of the different solutions within the context of the same mission segment and make informed decisions based on the visualized effects and quantitative results.

In addition, the integration of STK with MATLAB provides a range of benefits and applications, for instance the ability to automate and perform fully customised multi-parameter optimizations. The automated search for optimal solutions can drastically save time and effort while ensuring fulfilment of mission requirements. Additionally, the visualization of MATLAB data within the STK environment enhances the understanding of complex data and facilitates the interpretation of results.
More in detail on the case presented, the overall files structure was depicted to facilitate the logical process behind the analyses.

3.4.1 STK/MATLAB Interface

The STK/MATLAB interface is based on Object Oriented Programming (OOP). Each STK feature is linked to a corresponding MATLAB object, according to the AGI "STK Programming Help" website for the right syntax. The purpose of the optimization analyses was to determine the best combination of value (in terms of mission segments duration, relative velocity, and position) that minimise SROC Delta-V.
To connect the MATLAB with STK, it is necessary to open the right STK scenario and follow the sequence given here:

- Connection with the simulation software
- Retrieve the scenario, with all the feature and settings
- Get the STK objects (i.e. SROC is modelled as a "Satellite" object)
- Execute the desired commands

A major hint concerns the units of measure, they must be in agreement between the values used in the MATLAB scripts and the default units in STK.
Hereafter, the simplified file structure is summarised. Similarly, an equivalent file structure exists to perform analyses of the off-nominal scenarios. For the sake of brevity, it is chosen to omit the further explanation of these files as they follow the same structure and logic set out below.
In addition, during the course of the thesis, it became necessary to upgrade to STK 12, therefore starting from the same files it was necessary to make changes that includes adaptation to the new syntax, which, although to a less extent, differed from the previous one.

3.4.2 File JSON and MATLAB

To efficiently manage multiple scenarios with their respective characteristics and prevent the loss of crucial information in the event of a System Tool Kit (STK) crash, the utilization of JSON files has been employed. Moreover, it is feasible to save the settings of the nominal mission, conduct various off-nominal analyses, and subsequently restore these values with a straightforward MATLAB Run operation.
The JSON files were loaded into MATLAB as structs, and accordingly, each attribute was referred to as a *field* by analogy. Since MATLAB structures are accessed through fields, these fields serve as actual variables. The convenience of JSON files stems from their human-readable format, enabling the seamless management of various variable types (integers, floating-point numbers, characters, strings, booleans, vectors, matrices, and even structs) within a given scenario. These files consist of a field, representing the attribute name, and its corresponding value.

The functionality of this type of file is diverse. Some of them were used to configure analysis settings, acting as a graphical interface between the user and MATLAB. This approach eliminates the need to manually scroll through lines of code or navigate between different scripts to modify various settings.
In addition to the JSON files for analysis settings, they were also employed to store parameters for different scenarios. Each scenario had its own JSON file, containing, for example, the orbital parameters of the spacecraft, the properties of the two spacecraft, the mission segment durations, and the geometrical parameters of the WSE.
The JSON files for analyses settings (located in MATLAB script/Settings) will be discussed in detail in subsequent sections, providing insights into the functions that reference them. Regarding the JSON files for scenarios, an exemplary file is presented. The JSON file is divided into two parts: the first half pertains to information defined as Initial Conditions (Figure 6):

```
{
"flag_save":true,
"flag_activeInitialChanging":false,
"AnalysisStartTime":"1 Mar 2022 11:00:00",
"AnalysisStopTime":"1 May 2022 11:00:00",
"SpaceRider_ApoAltitude":400,
"SpaceRider_Ecc":0,
"SpaceRider_INC":97.034,
"SpaceRider_RAAN":339.232,
"SpaceRider_AOP":0,
"SpaceRider_TA":0,
"SpaceRider_DryMass":4165,
"SpaceRider_Cd":2.2,
"SpaceRider_DragArea":2.13,
"SpaceRider_Cr":1.6,
"SpaceRider_SRPArea":2.13,
"SpaceRider_FuelMass":0,
"SpaceRider_FuelMassMax":0,
"SROC_DryMass":24,
"SROC_Cd":2.2,
"SROC_DragArea":0.06,
"SROC_Cr":1.3,
"SROC_SRPArea":0.06,
"SROC_FuelMass":0,
"SROC_FuelMassMax":0,
"SROC_preDeployDuration_sec":0,
"SROC_EOP_IOCP_day":5,
```

Figure 6: Example of JSON for STK scenario inputs - 1

while the second half contains information regarding the various mission segments (Figure 7).

```
"FarRendezvous_strategy":true,
"FarRendezvous_inTrack_Km":70,
"FarRendezvous_duration_day":4.125,
"CloseRendezvous_duration_hr":[19,2.625,20.5,2.625,20.5,2.62505],
"SE_num_inspection":6,
"SE_x_max_m":[250,250,250,250,250,250],
"SE_z_max_m":[250,-250,250,-250,250,-250],
"SE_Insertion_csi_deg":[300,180,0,180,0,180],
"SE_y_c_m":[-169.352,157.88,-182.223,182.751,-188.418,209.964],
"SE_y1_c_m_s":[-0.0045,-0.0285,-0.0075,-0.0285,-0.0075,-0.03157],
"SE_Inspection_duration_hr":8,
"SE_RangeMax_m":750,
"FreeFly_duration_hr":[3,24,3,24,3,24],
"Docking_FlyAround_target_m":[50,0,0],
"Docking_FlyAround_duration_hr":16.5,
"Docking_CloseApproach_target_m":[30,0,0],
"Docking_CloseApproach_duration_min":1.5,
"Docking_Mating_target_RangeRate_cm_s":5
}
```


Figure 7: Example of JSON for STK scenario inputs - 2

In the first half, it is possible to find the mission starts and end dates, Space Rider's orbital parameters, the physical characteristics of both Space Rider and SROC, the Pre-employment and EOP durations, and several flag variables were found. These flag variables were used to activate specific parts of the script or execute particular actions. In this case:

- **flag_save**: This flag allowed the scenario to be saved at the end of an analysis, as not every scenario needed to be saved after analysis.
- **flag_activeInitialChanging**: Defining the initial parameters required time. Therefore, this variable was set to true only when there was a need to modify the parameters. Otherwise (in the false case), the function responsible for this part was skipped.

In the second half, the specific details of the scenario were presented. The following details are discussed in depth:

- **FarRendezvous_strategy**: This flag variable was set to true ONLY for scenarios implementing the Far Range Rendezvous in the orbital plane. All scenarios included this flag, even if it wasn't necessary. However, this approach allowed for a generalized writing of both scripts and JSON files.
- **FarRendezvous_inTrack_Km** and **FarRendezvous_duration_day**: These variables represented the duration of the propagative segment of the FRR (to which the time to reach the nodal line must be added) and the InTrack Target, as described in [6].
- **SE_num_inspection**: As the name suggests, it defined the number of inspection cycles (CRR + Insertion + Inspection). This number facilitated correct iteration over the vectors containing the subsequent information.
- **CloseRendezvous_duration_hr**: This represented the duration in hours of the segment that positioned SROC at the initial position of the WSE. The first segment would actually be a CRR, while the others corresponded to the durations of the Approach, which functioned as CRRs in practice. This variable was a vector, where each element corresponded to a cycle of observation indicated by the **SE_num_inspection** variable.
- **SE_******: These variables contained the design parameters of the WSE, including **x_max**, **z_max**, **χ**, **y_c**, and **y_c^'**. The meaning of each parameter is described in the Paragraph 3.5.4. Notably, **x_max**, **z_max**, **inspection_duration**, and **RangeMax** were defined by the user, based on the SROC payload and other inputs. On the other hand, **χ**, **y_c**, and **y_c^'** were obtained through optimizations. In a previous version, these results had to be

manually entered, but now, if a flag is active, the results are automatically inserted into the JSON file.

- **FreeFly_duration_hr**: This variable contained the durations of the various Free Flights. It is worth noting that in principle it is possible to perform multiple inspection cycles and in this case, it could be feasible to choose different duration for each of them. However, this is a design choice subject to change over time.

As observed, the attribute names in the JSON file also include measurement units. This approach eliminates any ambiguity regarding the magnitude of the number to be inserted.
STK operates with precise units of measurement, employing seconds [sec] for time and kilometres [km] for distances. Therefore, careful attention must be given to accurate conversions. For practical purposes, it is convenient to work with hours and days for time calculations, while meters are used for the WSE measurements. However, all these quantities are converted within the scripts before being passed to STK.
To load and save JSON files in MATLAB, functions were created. These functions take the file name as input and, in the case of loading, return a struct as the output.
As it can be ascertained, some of the attribute names above described do not match the respective mission segment names. This is due to the amount of work required to update files and scripts. Latency times as opposed to tight deadlines imposed that these changes be left to later developments. Although, it is important to reiterate that the nomenclature is transitory, but the purpose of the segments remains the same.

3.4.3 Programme and file structure

Following the workflow, the description of the MATLAB file's structure is presented below. As it is not possible to explain in detail all the function, and commands a useful outline is summarised to highlights the flow of work adopted for all the analyses executed.
Each analysis starts by setting the *Initial Conditions*, the *Optimization Conditions*, and *Results* to-be-saved in the congruous JSON files.
Once the input parameters have been set, the *Main script* in MATLAB is executed. This file is divided into segments, the first one *Initialization* consents to declare the global variables, to upload the settings from the JSON files above presented, and to establish the connection between the STK scenario and the MATLAB scripts.

```
%% Connect to STK and retrieve scenario and spacecrafts

% Get reference to running STK instance
uiApplication = actxGetRunningServer('STK11.Application');
% Get our IAgStkObjectRoot interface
root = uiApplication.Personality2;

% Get the scenario
scenario = root.CurrentScenario;
% Check if it is the correct scenario!
if ~contains(fileName_scenario, convertCharsToStrings(scenario.InstanceName))
    error("Scenario: <strong>%s</strong> ||| JSON settings: <strong>%s</strong>\nThey do NOT MATCH -> CHECK IT!!!\n", ...
        convertCharsToStrings(scenario.InstanceName), fileName_scenario)
end

% Get the spacecraft
SROC = scenario.Children.Item('SROC');
SpaceRider = scenario.Children.Item("SpaceRider");

driver = SROC.Propagator;
driver.Options.SmartRunMode = 1; % Run Only Changed Segments
```

Figure 8: MATLAB Main script - Detail

Additionally, a check condition verifies the connection between the correct STK scenario and JSON files. This condition is mandatory in order to retrieve the right data from the STK Objects, namely Astrogator, Space Rider, and SROC.
Secondly, the *Set Initial Condition* segment allows updating of any changes made to the general settings, eventually modifying the propagator and spacecraft leader parameters. Specifically, this block of code is executed only if the user changes the scenario settings, who modifies in the following order: starting and ending date, orbital parameters, and the spacecraft mass. Moreover, to complete the process the propagation of the Space Rider's orbit is updated, and to avoid useless action the SROC one is not updated since it will be optimised in the following code sections.
Nevertheless, the Initialization part is always executed because it uploads the current general attributes and scenario settings from a past analysis. Subsequently, an equal number of code sections as the mission segments are recalled by the Main script. Only if the user wants to optimise a specific mission segment for the current analysis, the corresponding JSON file will be set with a true flag, and the congruent MATLAB function will be recalled by the Main script performing the analysis with the chosen optimization parameters (i.e. orbit duration, and relative distance), otherwise the STK scenario will not be modified.
Finally, a set of *Utility Scripts* serve as complementary functions allowing the analysis of specific mission segments easing the process of computation, choosing the best solution, and saving results. At the end of each optimization cycle, all the outputs are stored into the scenario folder *Results* as *struct* variable in *.mat* format. Then, at the end of the analysis a user defined function is able to search the best solution that minimise the overall *Delta-V.*

3.5 Mission Segments

According to the user guide [2], the SR could operate in circular orbits at 400 km of altitude with different inclinations. For all this possible SR scenarios, different strategies and SROC mission phases duration can be adopted.
The SROC mission phases are reported in Table 2 and Table 3 while SROC mission segments are referred to the trajectory design reported in this document and listed hereafter:

- Deployment: SROC is deployed from the MPCD system inside the SR cargo bay
- Commissioning: the duration may vary, between the best case of 5 days and the worst of 10 days
- Hold Point 1 (HP#1): the first hold point is needed to stop the drift away motion after Commissioning and, as part of the Verification phase, to test the capability of SROC of performing (entering and maintaining the trajectory) a complex manoeuvre. Specifically, an elliptic trajectory around a virtual point with null relative mean motion with respect to SR.
- Rendezvous: the goal is to reduce the distance between SROC and SR, after the free drift during the Commissioning phase, and to achieve the relative position to start the observation phase or to enter the Hold Point phase. These two different strategies are developed to accomplish the task and they will be explained in detail later [8.4.4]
- Hold Point 2 (HP#2): otherwise from HP#1, the second hold point is needed to maintain a constant relative position with respect to SR, to facilitate the Navigation sensors switch and the SR locking operations. This phase is characterized by the execution of a finite manoeuvre.
- SR Observation: this phase is divided into different scenarios that could be repeated several times, according to the number of desired observations. This phase is composed by:
    - WSE insertion: SROC performs a manoeuvre to enter the WSE which, thanks to the contribution of the atmospheric drag, will advance along the positive InTrack direction allowing the observation of SR in total passive safety.
    - SR observation: SROC passively maintains its motion in the WSE to observe SR, guaranteeing the payload operating range.
    - Free Flight: after the observation period, SROC continues its motion without manoeuvring to allow the downlink with ground stations up to a maximum distance of 5 km in the positive Intrack direction to avoid the payload unlocking of SR.
    - Approach: SROC manoeuvres to approach again SR and to start another observation cycle. In case of multiple Observation phases, this scenario is not performed for the last observation cycle, where instead a Hold Point insertion manoeuvre is executed.
- Hold Point 3 (HP#3): the third hold point is needed to stop the relative motion after the last approach segment and prepare for docking. Depending on the Docking strategies, the HP#3 could be a Hold Point in case of docking along the intrack axis, this phase will be characterized by the execution of a finite manoeuvre, or a holding phase characterised by a passively safe trajectory around SR in case of docking along the radial axis.
- Docking & Retrieval Phase (DMP): the last phase is composed by two different segments to perform the mating with Space Rider:
    - Final Approach: Final approach consists of a straight-line trajectory along the Radial or In-track axis to reach the mating conditions. Relative velocity gradually decreases according to a defined profile. Decision points can be set as needed. Collision Avoidance Manoeuvres can be executed up to 2 (TBC) m from the docking port in nominal conditions of velocity, and up to 15 (TBC) m in off-nominal conditions.
    - Mating: SROC SROC is captured through the docking mechanism (DOCKS) and a rigid connection is established. After that, it is checked to decide if the retrieval can start.

3.5.1 Deployment analysis

To better choose the right direction for the deployment, a preparatory analysis has been conducted. A new scenario has been created with a leader spacecraft and its RIC reference frame; eight CubeSats have been added to the scenario with null starting position and velocity relatively to the leader. At the same time for each spacecraft an impulse of 1 m/s has been created with different deployment directions in the SR orbital plane:

- spacecraft *One (red)* deployed along Intrack → (1, 0, 0) m/s;
- spacecraft *Two (orange)* deployed with an angle 45 deg from positive Intrack → (0.71, 0, 0.71) m/s;
- spacecraft *Three (yellow)* deployed along negative Radial → (0, 0, 1) m/s;
- spacecraft *Four (green)* deployed with an angle 135 deg from positive Intrack → (-0.71, 0, 0.71) m/s;
- spacecraft *Five (cyan)* deployed along negative Intrack → (-1, 0, 0) m/s;
- spacecraft *Six (indigo)* deployed with an angle 225 deg from positive Intrack → (-0.71, 0, -0.71) m/s;
- spacecraft *Seven (magenta)* deployed along Radial → (0, 0, -1) m/s;
- spacecraft *Eight (fuchsia)* deployed with an angle 315 deg from positive Intrack → (0.71, 0, -0.71) m/s

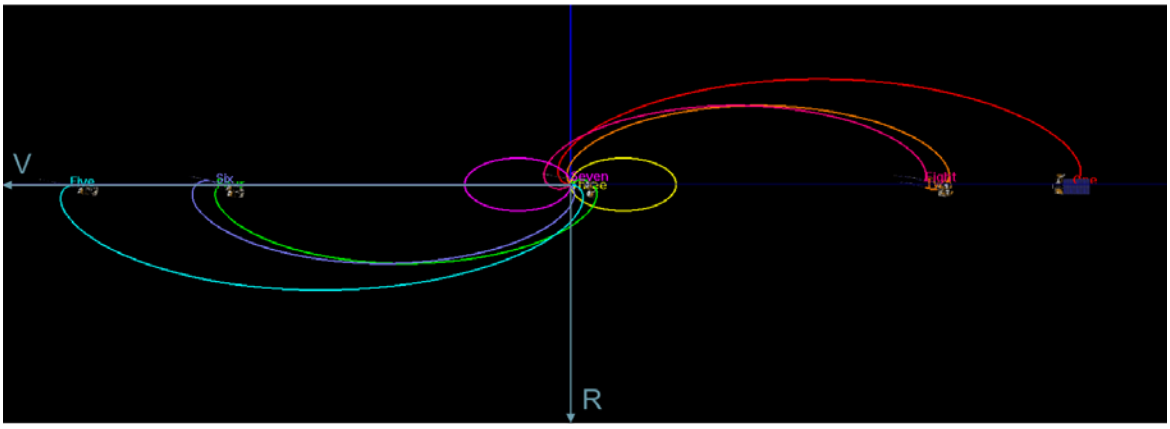


Figure 9: Relative view of 8 satellites propagation deployment from SR with different directions

It can be observed from Figure 9 that, after the propagation of one orbit, the CubeSats with positive Intrack component of the deployment velocity find themselves in a negative Intrack position and vice versa; this is because a positive component increases the velocity relative to the Earth and results in a more energetic orbit, which means that the orbital period increases, while a negative component decreases it. When the main spacecraft has completed one orbit, the CubeSats with a longer period still have to complete their orbit while the ones with a shorter period already completed it. The CubeSats with a pure radial deployment velocity change their orbit without varying the orbital period, so, after one orbit, they reach the same position. Observing the evolution in time of the displacements along the Intrack and negative Radial, it can be observed that every CubeSat has a symmetric behaviour with respect to the CubeSat with an opposite deployment velocity.

According to the user guide, SR shall operate in circular orbits at 400km of altitude with an inclination that can vary from quasi-equatorial to Sun-Synchronous orbits; therefore, the following different scenarios have been simulated: the chosen starting time for each scenario is the UTC Gregorian time 1st of March 2024 00:00:00:

- Scenario 5: quasi-equatorial orbit with inclination of 5.00 deg and RAAN of 0 deg
- Scenario 1: sun synchronous midday/midnight orbit with inclination of 97.03 deg and RAAN of 94.79 deg
- Scenario 2: sun synchronous down/dusk orbit with inclination of 97.03 deg and RAAN of 4.79 deg
- Scenario 4: intermediate midday/midnight orbit with inclination of 37.00 deg and RAAN of 94.79 deg
- Scenario 3: intermediate down/dusk orbit with inclination of 37.00 deg and RAAN of 4.79 deg

The five mission scenarios are depicted in Figure 10.

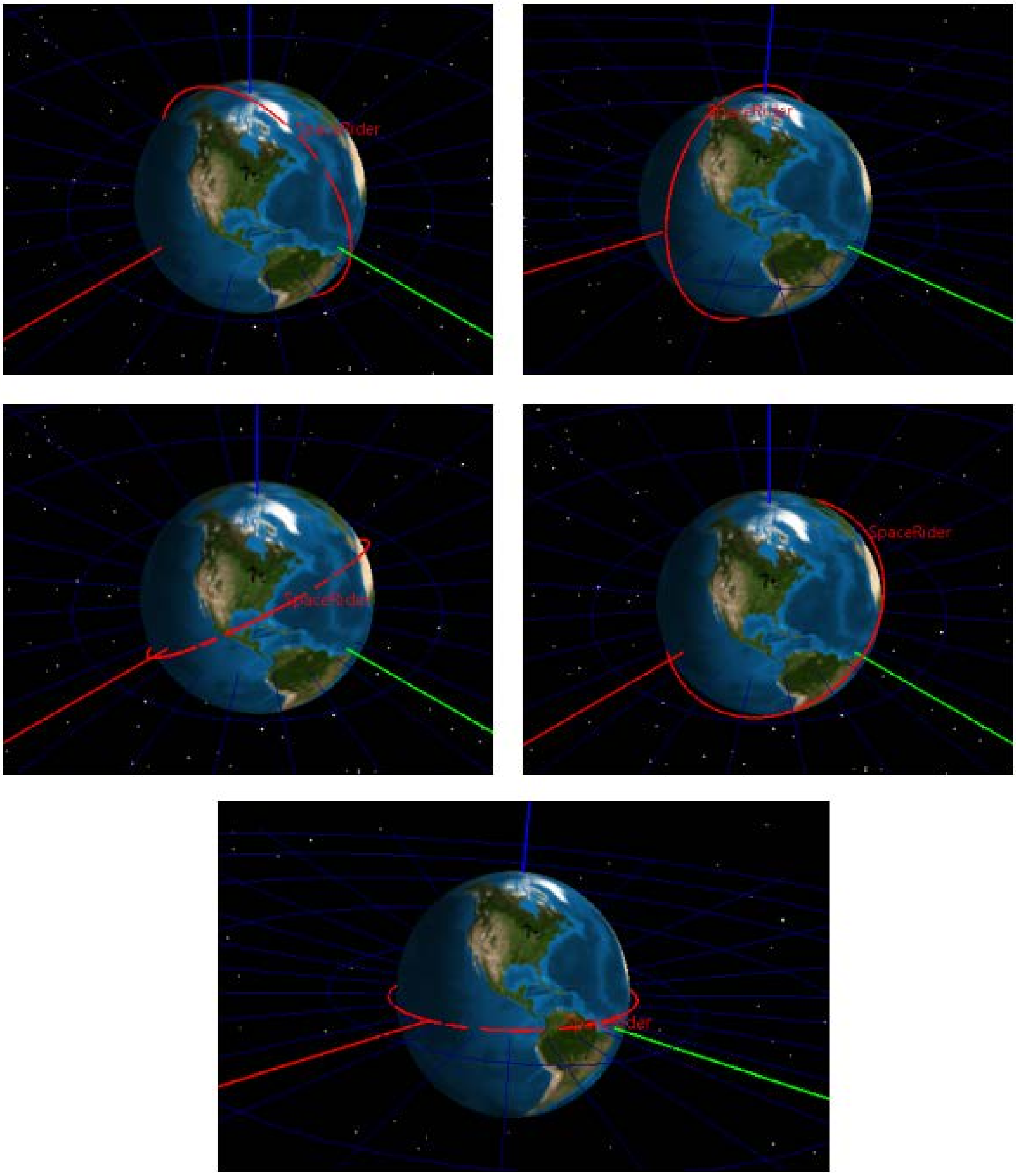


Figure 10: Space Rider’s reference orbits (scenarios 1, 2, 3, 4, 5 respectively)

From the preparatory analysis reported on the "Assessment of the SROC mission and preliminary functional specification" [6], it can be seen that, regardless the specific scenario:

- the distance of SROC from SR always increases with time for deployment with negative component of velocity along Intrack (deployment angles from 90 to 270 deg wrt positive Intrack)
- if a positive component exists, the SROC-SR relative distance first increases then decreases. The SROC orbit becomes higher, then the effect of the perturbations makes it to decay, so the orbit is lowered. After a certain time from deployment there is a (local) maximum distance and then the spacecraft returns near SR. Then, the distance just increases because the orbit keeps being lowered by drag
- the maximum relative distance (around 3500 km) is achieved when deploying in the negative Intrack direction, the shortest is instead in the range 800-900 km for deployment in the ±Radial direction, for deployment velocity of 1 m/s
- the maximum relative distance is achieved when deploying in the -Intrack direction, the shortest is instead reached for deployment in the +Intrack direction, for deployment velocity of 0.2 m/s. The values of maximum and minimum distance vary depending on the scenarios (max: 1300-1500 km, min: 250-400 km)
- when deploying along ±Radial direction, the deployment velocity has negligible effect over the relative distance
- the influence of the RAAN is negligible
- when deploying along ±Radial direction, it can also be noticed that the relative distance increases very slowly, as it is caused only by perturbations. In particular, in the first orbits the relative distance is very small. For this reason, a pure radial deployment is not recommended, to avoid possible collision between SROC and SR
- Another interesting result of deployment in 45 deg and 315 deg (±45 deg wrt +Intrack) is the different relative distance achieved after 10 days in the scenarios depending on the deployment velocity: for SSO (scenario 1) the difference is maximum (around 300 km), while it shrinks as the inclination decreases (less than 200 km for intermediate orbits, around 50 km for the quasi-equatorial orbit). This is ascribable to the effect of perturbations due to the combination of solar pressure and gravitation.

From this analysis it can be noticed that, when considering a certain deployment impulse in the orbital plane, the higher the Intrack component, the higher is the drift after one orbit, but, if the impulse is purely radial, there is the risk of an impact of SROC on SR after one orbit. Therefore, the best choice is to deploy SROC with a velocity with a small Intrack component, in order to have a small drift and a certain margin of safety.
The refined deployment analysis has been conducted only for the baseline scenario (quasi-equatorial orbit), considering a combination of different deployment velocities and different deployment angles. In the following table the Deployment Design of Experiment (DoE) is summarised:

Table 7: Deployment Design of Experiment and selected strategy (in green)

α [°]	V [m/s]	Intrack [km] 1 Orbit	5 Days	10 Days
5	0.45	0.69	273	999
	0.5	0.77	280	1012
	0.55	0.84	285	1022
	0.9	1.3	324	1100
	1	1.5	336	1125
	1.1	1.6	348	1152
10	0.45	1.3	324	1101
	0.5	1.5	336	1124
	0.55	1.6	348	1147
	0.9	2.6	426	1302
	1	2.9	450	1349
	1.1	3.2	472	1392
15	0.45	2	374	1200
	0.5	2.2	390	1233
	0.55	2.4	408	1266
	0.9	3.9	526	1500
	1	4.3	560	1567
	1.1	4.8	594	1633

The study aims at understanding the variation of the relative distance of SROC from Space Rider after a certain period of time considering the effect of the deployment angle (in the orbital plane, and with respect to the Intrack direction) and the deployment velocity. Ten days of free drift is considered in the simulation, to take into account the commissioning of the satellite after deployment as a worst-case scenario.
From the results presented on the Table 7 it can be noticed that the final relative distance depends only on the Intrack velocity components regardless of the overall velocity magnitude and the deployment angle.
To choose the best deployment strategy, two main factors was taken into account:

- Higher safety: lower deployment angle means lower Intrack velocity component that in turn leads to closer distance to SR after one orbit. The worst condition is a pure Radial deployment, since in this case the positions of the two spacecraft would coincide after one orbit.
- Relative distance: it has been considered not only the relative distance after one orbit but, also the final distance at the end of the Commissioning phase. Higher final distance leads to either an higher ΔV or longer Rendezvous phase.

3.5.2 Commissioning analysis

After the deployment design process, i.e. for the baseline (shown in Figure 11 and Figure 12), the deployment angle has been assumed to be 10 deg with respect to -Radial (anticlockwise wrt nadir vector) with velocity of 0.5 m/s (imposed by current deployment technology), and components -0.087 m/s along Intrack, 0 m/s in Crosstrack and -0.492 m/s along Radial.

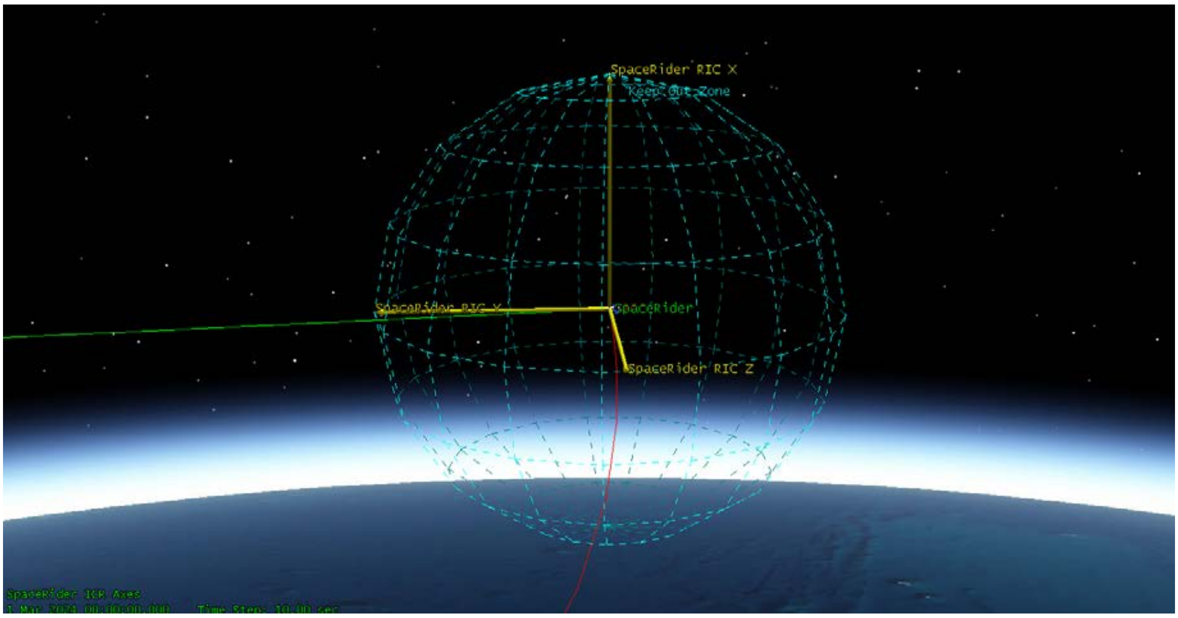


Figure 11: SROC Deployment Direction

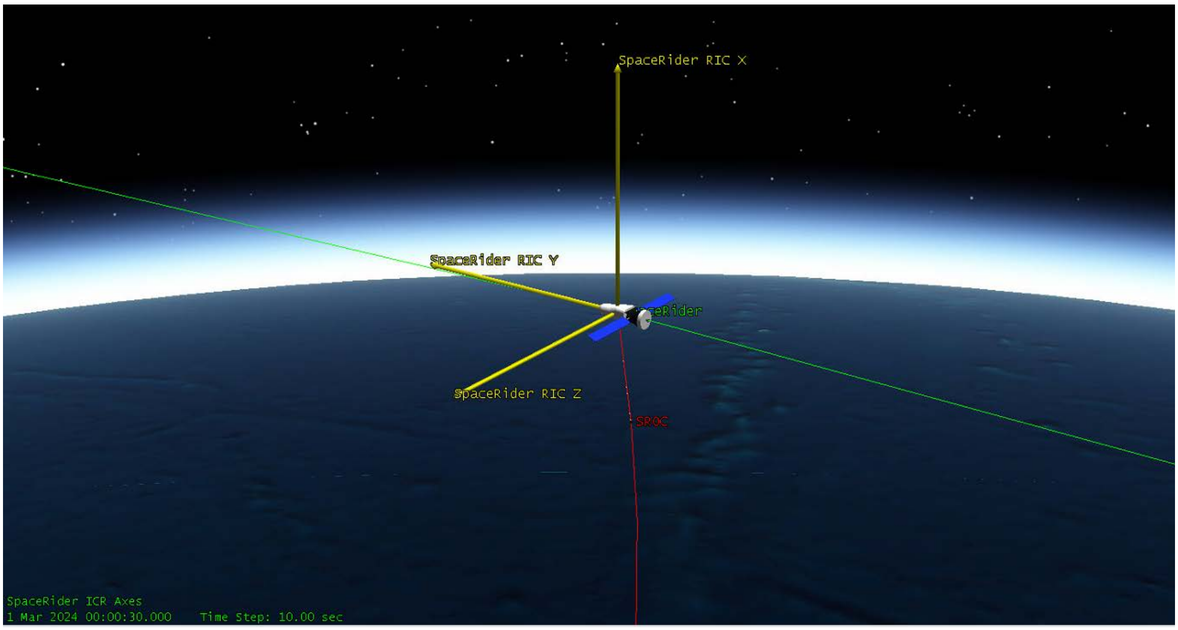


Figure 12: SROC Deployment overview

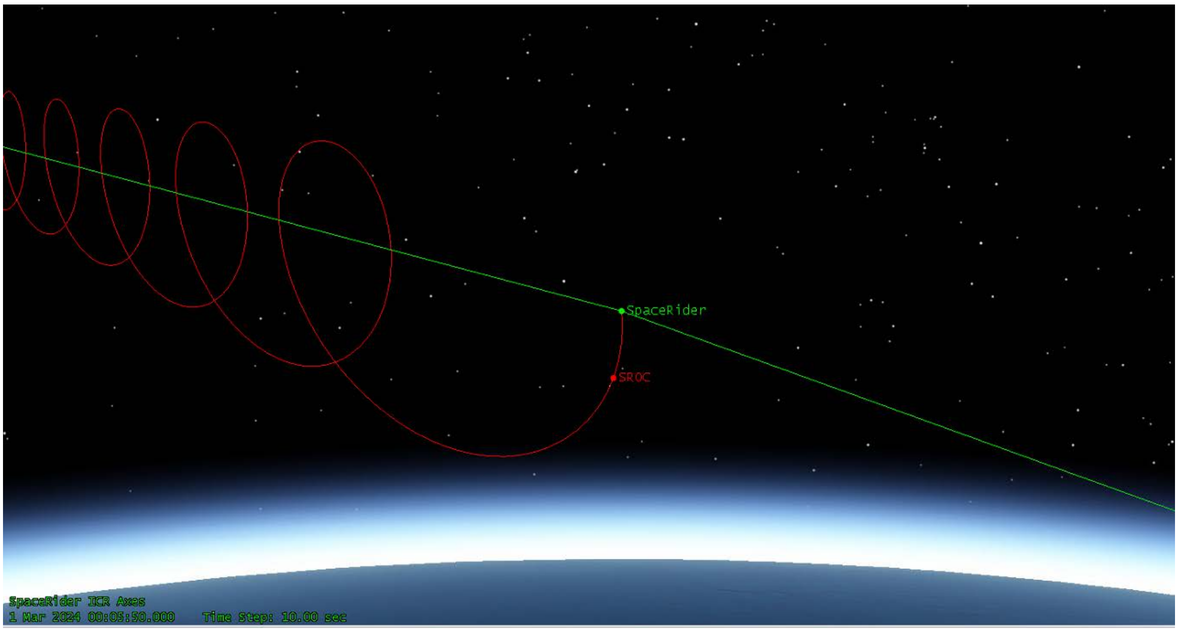


Figure 13: SROC first orbits after Deployment

The Intrack negative component results in a decrease of the SROC orbit SMA to increase safety in case of failure. Moreover, the SROC ballistic coefficient is always lower than the SR one, guaranteeing, in case of no manoeuvre, a relative advance of SROC along the Intrack direction, caused by the atmospheric drag that decrease its orbit altitude. From the optimization analysis, it has been assessed the velocity magnitude (constrained by the deployment mechanism) and the deployment angle (constrained by SR interface).

The analysis of the Commissioning makes use of the RIC reference frame as defined in Section 8.2. As mentioned before, the Commissioning durations may vary. For our purposes, the best and worst cases are considered for all the SR scenarios. During the Commissioning phase, SROC drifts away from Space Rider along the positive InTrack, also increasing the relative distance along negative Radial, according to the ballistic coefficients of both target and chaser spacecraft and to the deployment direction. The relative position of SROC after this phase depends on the duration of the free drift and the deployment velocity and direction. Figure 13 shows the relative distance between the two spacecraft in the best scenario of 5 days for Commissioning phase (left graph) and in the worst scenario of 10 days (right graph) for all possible Space Rider orbits. These durations are increased by an amount of time that takes into account the propagation to the ascending or descending node of the orbit, where the next and first manoeuvre can be executed.

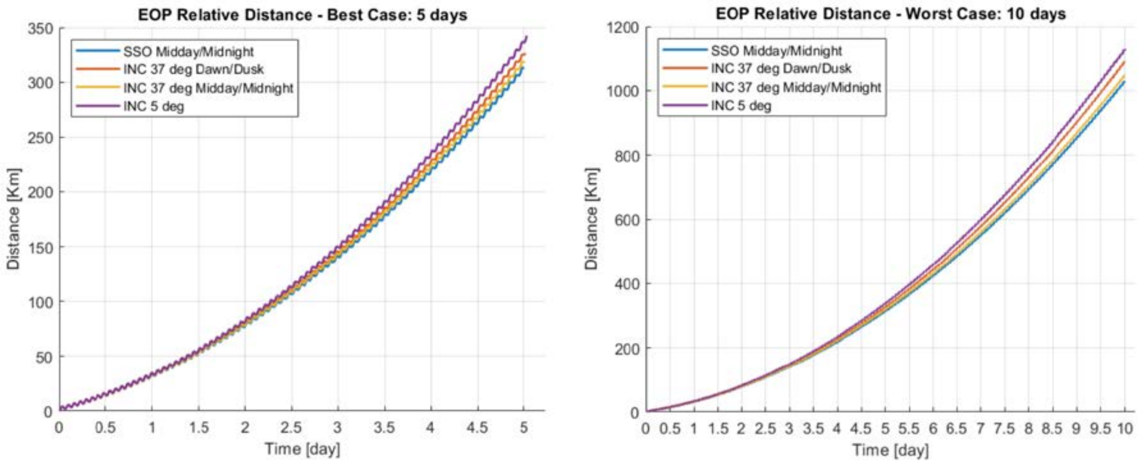
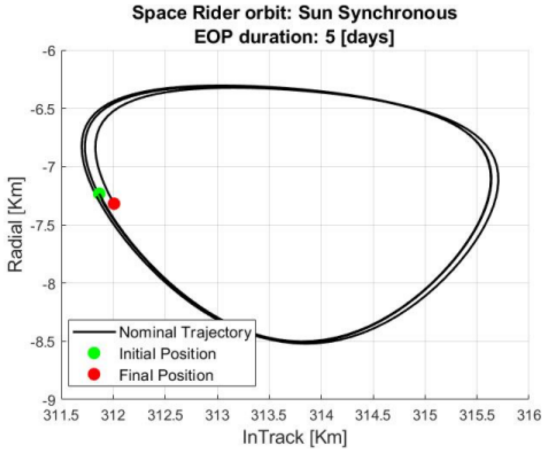


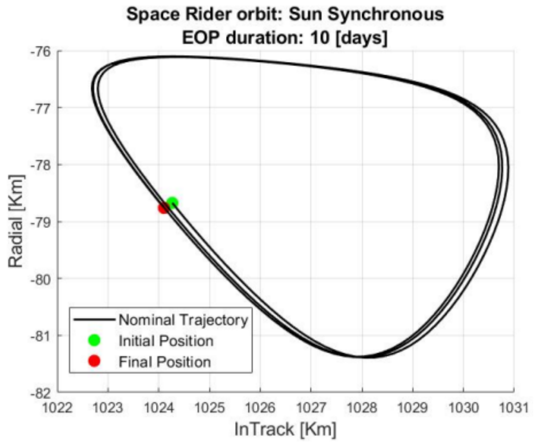
Figure 14: Commissioning Relative Distance with time

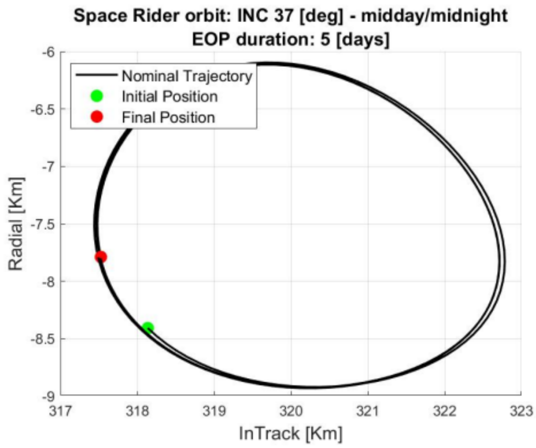
3.5.3 Hold Point 1

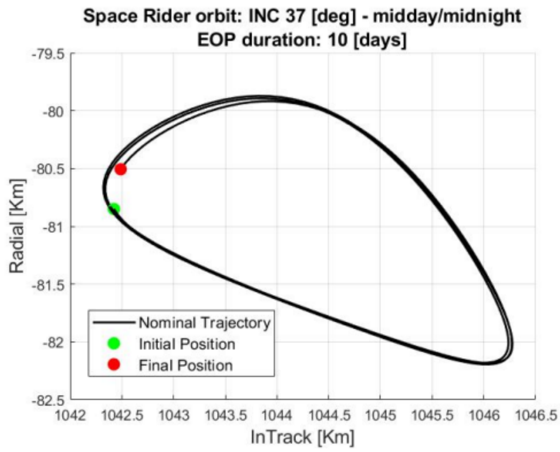
According to the "*Mission Concept of Operations Document SROC*" [9], a *Hold Point* is a mission time-flexible element (trajectory) to synchronise the mission timeline with external event and in which the chaser spacecraft can stay at nominally zero ΔV costs. It consists in a quasi-elliptical orbit around a virtual point with null mean motion with respect to SR; to reach the same orbital period of SR, SROC executes a manoeuvre which makes its semimajor axis increase of the same quantity it was decreased with the deployment. The hold point insertion manoeuvre should target the mean Space Rider SMA. It is important to notice that increasing the separation time, not only a drift on the InTrack, but also a drift on the negative Radial direction appears; that is why, even if the proximity operations condition is fulfilled, the Radial displacement does not result in a stationary point, but in a quasi-elliptical motion around the stationary point. In its trajectory SROC shall maintain a maximum distance of 6 km w.r.t the above-mentioned virtual point. Each HP should be propagated for a duration of at least **4.5 hours** (approximately 3 orbits at this altitude) to simulate the waiting time before starting the SR approach. After about 3 orbits, the perturbations would start to advance the chaser spacecraft again. For the SROC mission, one Hold Point is considered in the current baseline concept of operations.

The following graphs (Figure 15) show the different Hold Point 1 shapes (on the Radial-InTrack plane) for both the best and worst SROC Commissioning duration of the Space Rider considered orbits. The diversity of the trajectories is due to the duration of the E Commissioning OP phase. SROC manoeuvres to match its mean SMA with that of Space Rider and stop drift away motion, but the greater the difference in altitude between the two spacecraft (i.e. the smaller the average position along the Radial direction), the greater the eccentricity of the SROC orbit during the Hold Point. In fact, the Hold Points of the scenarios with 5 days of Commissioning have more elliptical shapes than those with a duration of 10 days, whose shape is strongly influenced by the different average altitude.


Space Rider orbit: Sun Synchronous
EOP duration: 5 [days]
Radial [Km]
InTrack [Km]
Nominal Trajectory
Initial Position
Final Position


Space Rider orbit: Sun Synchronous
EOP duration: 10 [days]
Radial [Km]
InTrack [Km]
Nominal Trajectory
Initial Position
Final Position


Space Rider orbit: INC 37 [deg] - midday/midnight
EOP duration: 5 [days]
Radial [Km]
InTrack [Km]
Nominal Trajectory
Initial Position
Final Position


Space Rider orbit: INC 37 [deg] - midday/midnight
EOP duration: 10 [days]
Radial [Km]
InTrack [Km]
Nominal Trajectory
Initial Position
Final Position

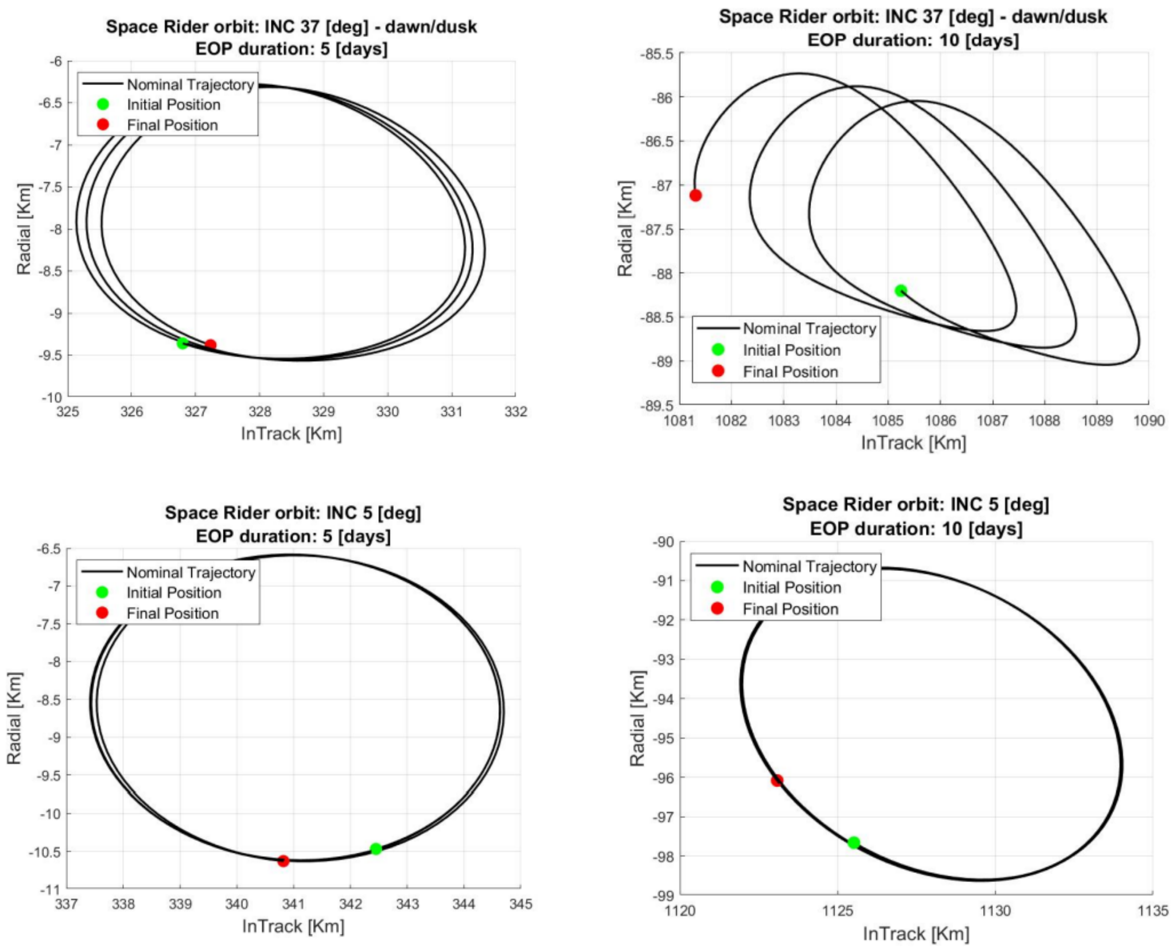


Figure 15: Different Commissioning Trajectories Comparison

3.5.4 Rendezvous

After the first hold point, SROC stops its drift away motion wrt Space Rider, but its position is far away from it and it needs to rendezvous with SR. Before describing the strategies developed for achieving this, the definitions adopted for In-Plane approach and Out-of-Plane approach rendezvous are given:

- In-Plane Approach Rendezvous (IPA): the objective is the reduction of the relative distance, acquiring the target orbit, reducing the approach velocity, and synchronising the mission timeline. At the end of this phase, the chaser inserts into a passive safety trajectory to continue the Rendezvous phase.
- Out-of-Plane Approach Rendezvous (OPA): the objective is to reach a precise relative position close to the target. The differences with respect to the IPA are related to the conditions of the motion at the end of the propagation, in terms of position (closer to the target) and final velocity. To ensure the necessary safety during the OPA rendezvous phase (i.e. no risk of collision with the target), this type of approach is performed out-of-plane

The two rendezvous strategies are:

Option 1) The first one consists of an In-Plane Approach contained into the SR orbital plane ended at a defined position along the Intrack axis followed by an Out-of-Plane Approach until the Observation Phase initial point.

Option 2) The second Rendezvous approach is divided into two non-consecutive segments: an In-Plane Approach to a closer distance with respect to the *Option 1*, then Rendezvous is interrupted by HP#2 and resumed with an Out-of-Plane approach until the Observation Phase starting point.

In-Plane Approach Rendezvous: Option 1

Considering these two definitions, a Rendezvous phase is need in order to reduce the large distance accumulated distance during the Commissioning phase. The first strategy starts with an **In-Plane** trajectory envisages the SROC approach to SR in two steps: 1) SROC performs an in-plane manoeuvre to exit the HOP#1 and initiate the approach in the orbital plane of SR until a defined relative distance along InTrack direction is reached, called "InTrack Target". The manoeuvre should be performed at a high distance from SR, so the SROC average forward velocity decreases over time due to the effect of the atmospheric drag. A high value for the "InTrack Target" implies a high ΔV cost for the next manoeuvre, while a low value implies a high increase in the propagation time. Therefore, an iteration analysis to find the optimal value was performed. If at the end of this rendezvous SROC will not execute any manoeuvres, the in-plane approach is conceived so that the chaser continues its approach in the SR plane, up to a minimum allowed distance along InTrack of 1 km within an additional 24 hours propagation in case the OPA is not executed, according to the passive safety condition mentioned above.

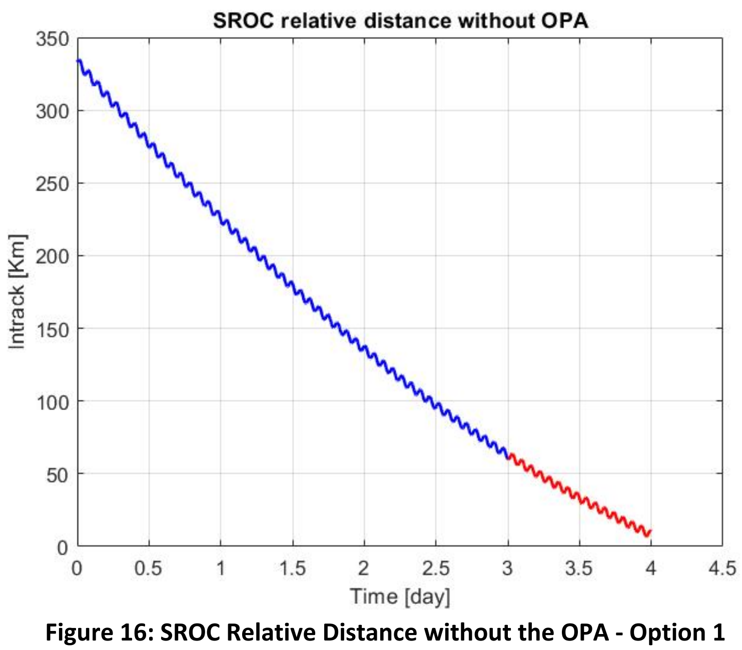


Figure 16: SROC Relative Distance without the OPA - Option 1

After reaching the InTrack target, SROC starts a OPA, exiting the orbital plane of Space Rider to arrive to the initial relative position for SR observations. The out-of-plane rendezvous guarantees a high reduction in the probability of collision (i.e. increasing the mission safety), which is why the *Option 1* strategy has been designed in two steps. Moreover, a Out-of-Plane rendezvous is performed every time SROC approaches again SR to execute another observation cycle, after the Free Flight scenario in case of multiple Observation phases are needed.
Figure 16 shows the relative distance between SROC and SR if the manoeuvre to initialize the OPA is not executed. For this Rendezvous option the "InTrack Target" is **60 km** (blue line in the graph

above) reached within **3 days** from the IPA start; SROC propagates to a minimum distance of around 7 km within 1 day after the IPA end. The real minimum distance reached depend on the IPA optimization (duration and InTrack target).

Figure 17 shows the last orbits of an In-Plane Rendezvous (red) until the propagation to a node, i.e. zero relative CrossTrack component and the insertion on a OPA (green) to approach SR. The out-of-plane component of the OPA is not so appreciable in the image because it strongly depends on the final position to be reached, that, as will be described in the next section, should be a few hundreds of meters compared to the tens of kilometres along the InTrack.

Figure 18 shows a more distant perspective of the passage from IPA to OPA, where is also reported the distance in which this passage must take place, the InTrack Target, whose value is a few tens of kilometres, depending on the scenario.

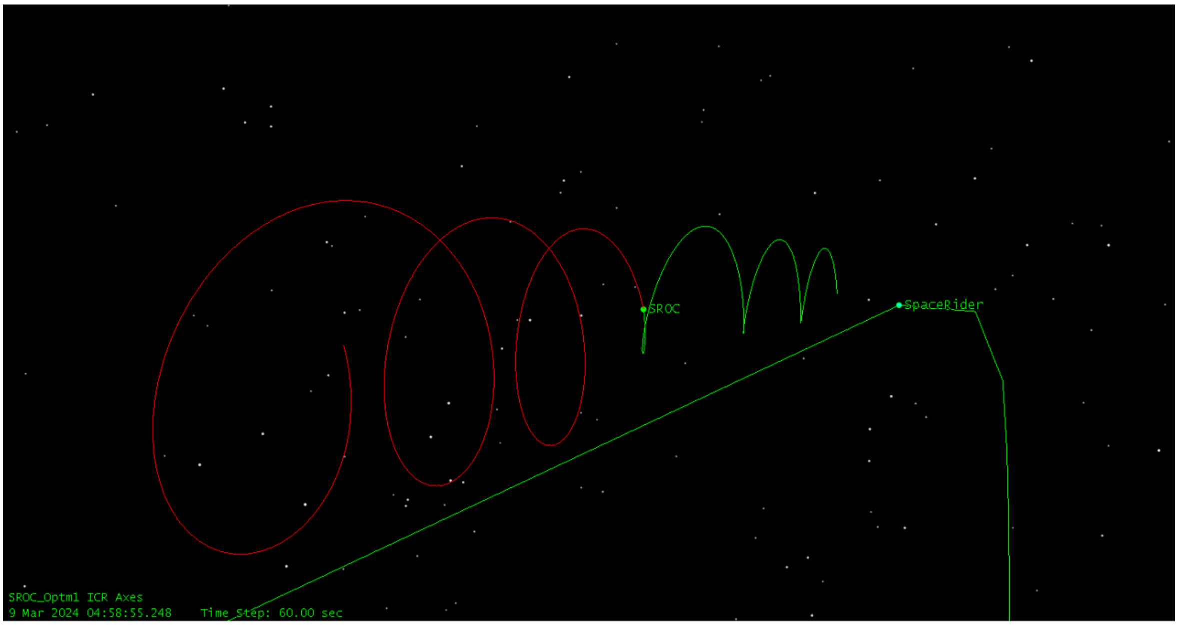


Figure 17: In-plane Rendezvous - Final Relative Orbits

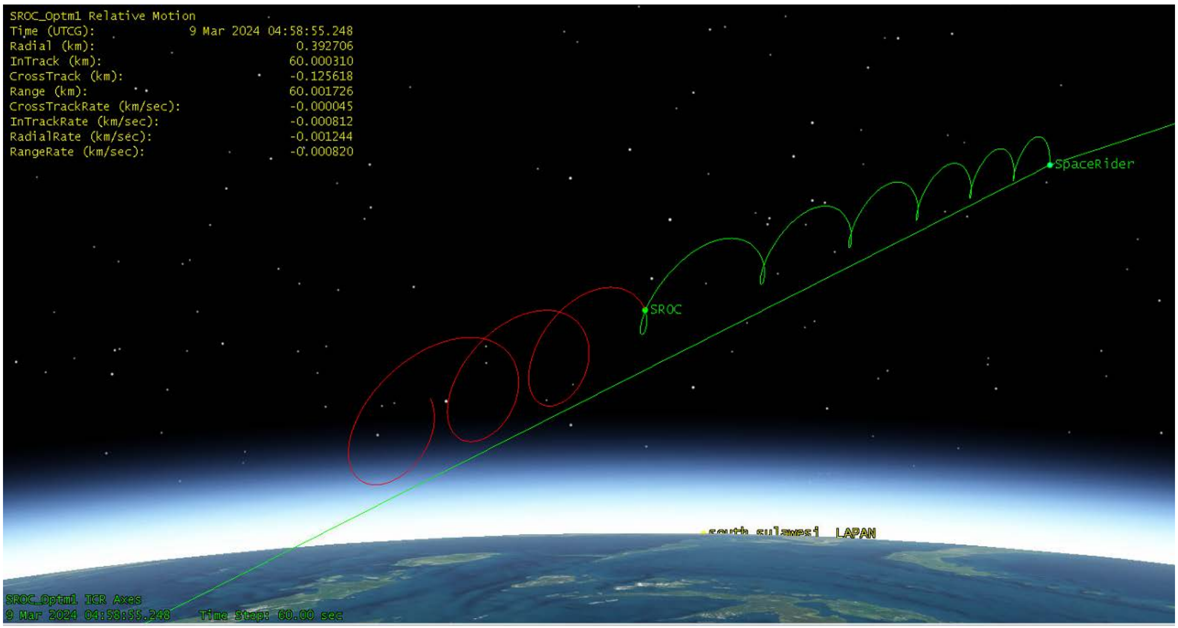


Figure 18: From in-plane IPA to OPA - InTrack Target View

In-Plane Approach Rendezvous: Option 2

The second strategy has the HP#2 as segment of discontinuity inside the Rendezvous phase. The first portion of this approach could be equally executed with an In-Plane or an Out-of-Plane approach while for safety considerations, the remaining distance until the Observation phase starting point will be covered with an Out-of-Plane approach.
Differently from the Option 1, in this case SROC reaches an "Intrack Target" value of **5 km**, reached after **5.7 days** from the IPA start, at that point it will perform an insertion manoeuvre into the HP#2. Due to the presents of this discontinuity element the optimization process took into account only the IPA duration while the "Intrack Target" was chosen in order to ensure the passive safe condition within 24 hours after the IPA end, in case the HP#2 Insertion manoeuvre is not performed.

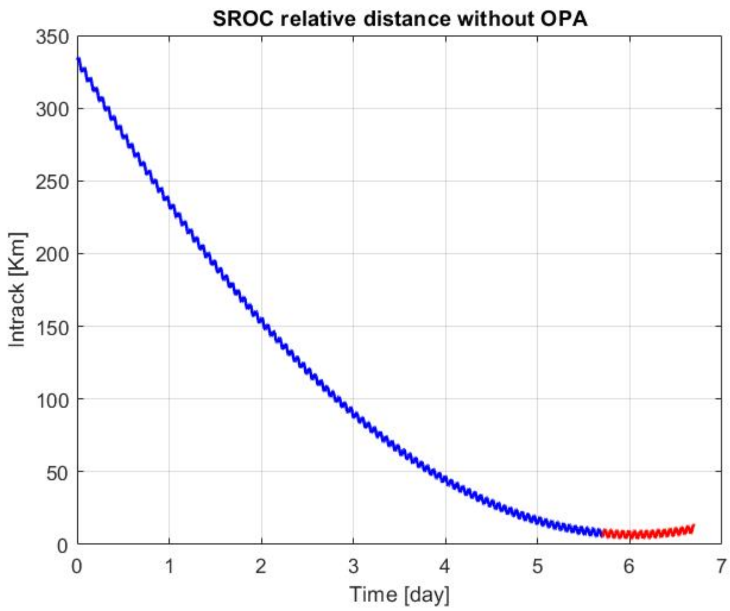


Figure 19: SROC Relative Distance without the HP#2 Insertion - Option 2

Figure 19 shows the relative distance between SROC and SR if the manoeuvre to initialize the HP#2 Insertion is not executed. For the Option 2 the "InTrack Target" is 5 km (blue line in the graph above); SROC propagates to a minimum distance of around 4 km within 1 day after the IPA end, then due to the differential drag effect it drifts away from Space Rider. The real minimum distance reached depend on the IPA optimization (duration and InTrack target). At the end the HP#2, SROC will resume its motion with an Out-of-Plane approach to complete the Rendezvous Phase and correctly insert into the Observation phase trajectory.

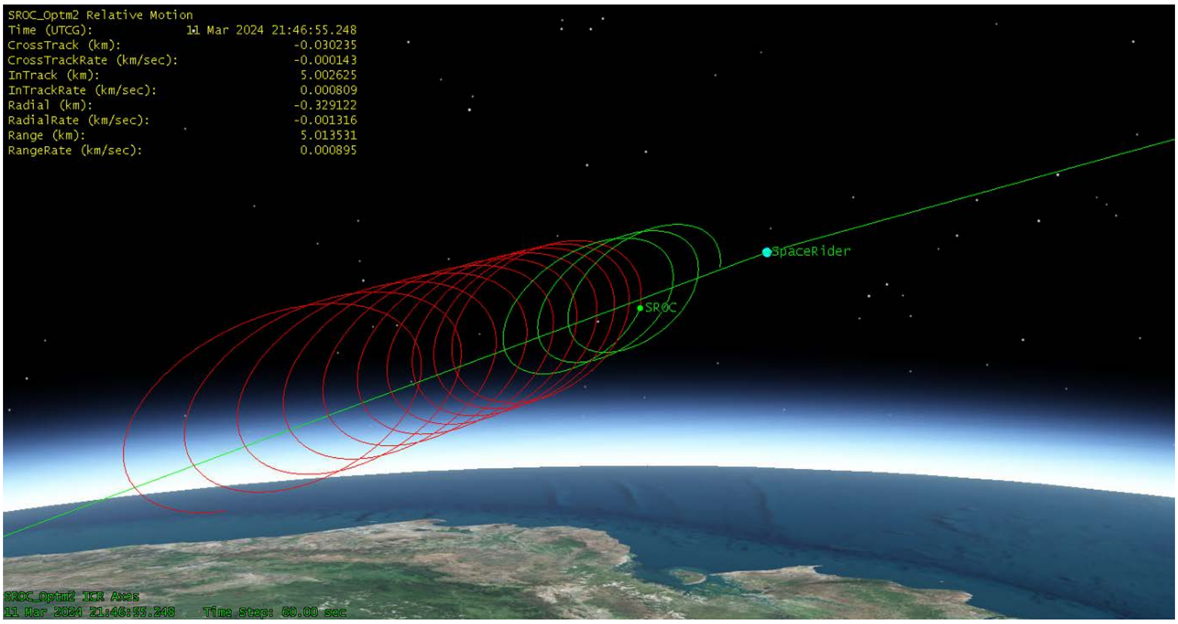


Figure 20: From in-plane IPA to HP#2 Insertion - InTrack Target View

Figure 20 shows the last orbits of an In-Plane Rendezvous (red) concluded with the propagation to a node, i.e. zero relative CrossTrack component, and the insertion on a HP#2 Insertion (green). The same considerations about the out-of-plane nature of the HP#2 Insertion apply for this case. Despite this, it can be noted the densification of the last orbits of the IPA, caused by the advance towards SR slowed by the atmospheric drag. Furthermore, is reported the distance in which this passage must take place as well as the relative position and velocity components.

In this way, for the *Option 1* the navigation sensors switch from far range to the close-range ones will be executed on the go during the OPA, without carrying out any further manoeuvre (unless needed for safety or correction of the trajectory), while for the *Option 2* the navigation sensors switch will be performed during the HP#2, then continuing to follow the Rendezvous trajectory with a OPA.

During the last portion of the Rendezvous, the close-range navigation sensors allow a more precise determination of the relative position between the two spacecraft, therefore SROC can perform corrective manoeuvres if it is needed, and it reaches the desired final position in the vicinity of Space Rider. The SR observation cannot take place without reaching the relative initial position, which is evaluated by solving the same equations, regardless of the SROC starting position. Both strategies have been designed to ensure the highest level of mission safety; the major differences between them lie in the duration and cost of approaching SR and in some accuracy aspect.
With the same relative position at the start of the inspection phase to be reached, the IPA ΔV cost for the Option 2 depends solely on the propagation duration. Concerning the Option 1, the ΔV cost depends on the duration, on the InTrack target value and on the next manoeuvres (i.e. OPA+WSE). In fact, as mentioned previously, a low InTrack target means a lower average velocity along the InTrack direction, so the cost of the next OPA will be higher to recover the velocity lost due to atmospheric drag. A high InTrack target also entails a higher cost due to the greater distance from the target. For this reason, to compare the two strategies it is necessary to consider the cost of the IPA together with the cost of the first insertion into the observation phase.
Another difference between these strategies concerns the accuracy on the final position achieved. The duration of the rendezvous may vary from 3 to 10 days (best and worst case), during which

SROC will accumulate all the environment perturbations. Therefore, the chaser propagates for hundreds of kilometres along the relative InTrack direction before starting the Space Rider observation. The Option 1 strategy envisages three manoeuvres, starting from HP#1, then continuing with the second one performed at the "InTrack Target" distance, and finally reaching a precise position near SR, where performing the observation. The Option 2 strategy, on the other hand, envisages to approach SR with four nominal manoeuvres, with an additional manoeuvre needed to enter the HP#2 after which, SROC will propagate for a few hours; therefore, the effects of the perturbations are reduced, with consequent greater accuracy on the final position reached. Any other manoeuvre to correct its trajectory is additional and involves cost increases.
Considering the mission safety point of view, the Option 1 ensures a higher safety during the approach and a reduced trajectory complexity, but in this case no holding phase is present, and both the sensors switch, and the eventual go/no-go command will be executed while approaching to SR. Besides for the Option 2 by accepting a higher trajectory complexity and risk, the HP#2 offers easier navigation sensors switch and the possibility to wait a go/no-go command before approaching SR at a closer distance.

Out-of-Plane Approach Rendezvous

To start the observation phase, SROC must achieve a precise relative position near Space Rider determined by the Safety Ellipse equations of motion that will be described in the next section. According to the strategies considered for the Rendezvous phase, a OPA is needed to exit the SR orbital plane and reach the desired position (Option 1) or to resume the approach trajectory after the HP#2 (Option 2). In case multiple Observation cycles are requested, this kind of trajectory is also needed to re-approach SR after a completed inspection, thus starting another cycle of observation (i.e. with the Approach segment). The ΔV cost and manoeuvre direction of the Out-of-Plane Rendezvous depends on three variables:

1) the initial position, which varies according to the mission profile as above described
2) the propagation duration, that varies from **9.55 hours** to **4.55 hours**, for the Option 1 or 2 respectively
3) the final position to be reached.

The first two variables are part of an optimization process to minimize the manoeuvre ΔV cost in accordance with acceptable times. The third, on the other hand, is a function of the SR observation strategy adopted, (i.e. the Walking Safety Ellipse with in and out-of-plane fly around components) its geometry and size which were determined using the Design of Experiment described in the 8.4.6 section.

3.5.5 Hold Point 2

The Hold Point 2 will be present only if the Option 2 is chosen, this holding segment is executed along the Intrack axis at a relative distance of **2 km** from SR. Differently from the HP#1, this phase is characterised by a null relative motion with respect to SR with a zero Crosstrack and Radial components. SROC shall be able to maintain the trajectory in the HP#2 with a determined precision offset of 20 (TBC) m, i.e. how much the position can vary along the three axis to still be regarded as maintaining the hold point. To reach that precise point an insertion manoeuvre is needed at the end of the IPA. Figure 21 shows the insertion trajectory in green, the holding point out-of-plane coordinates have been chosen so as to allow the holding of a fixed point in the relative framework with a contained ΔV value, otherwise the manoeuvre cost required to maintain a fixed relative point with nonzero crosstrack or radial components will rise significantly, while the Intrack component derives from GNC considerations, so as to simplify the SR locking and navigation sensors switch.

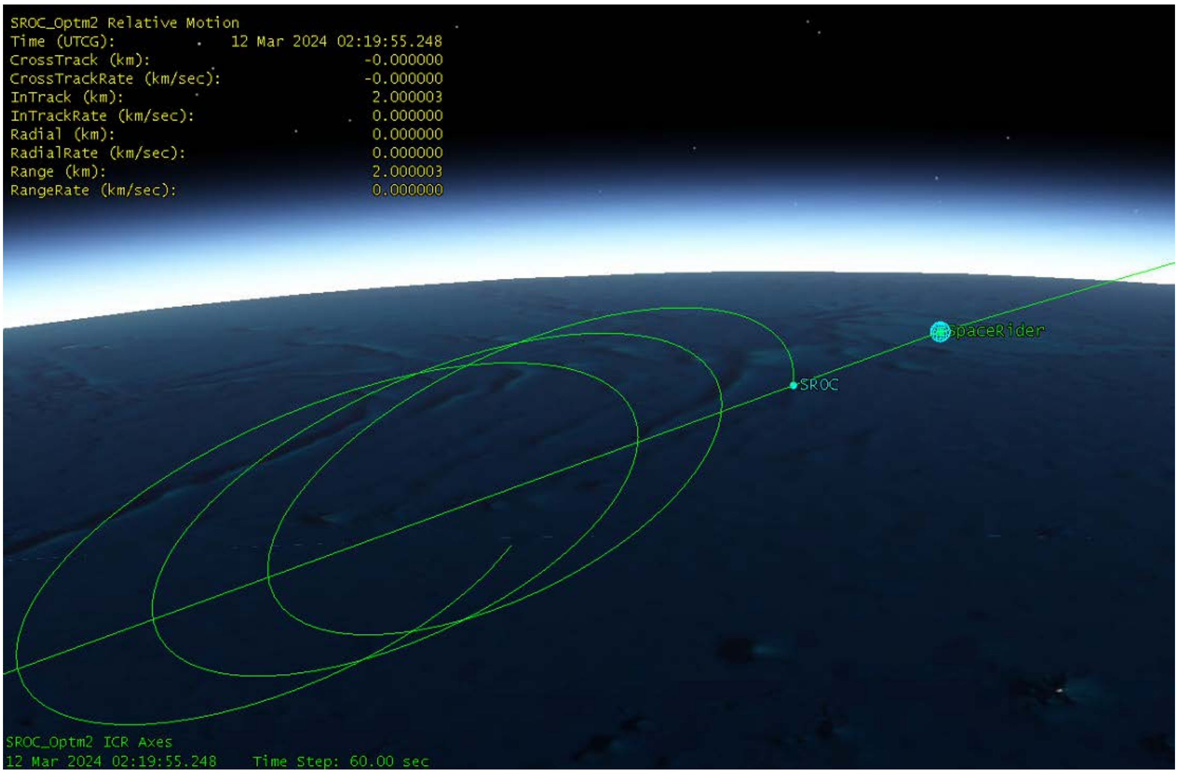


Figure 21: HP#2 Insertion trajectory

The HP#2 should last **4.5 hours** at least and its presence of enables several advantages to the mission scenario: easier sensors switching from the far range navigation to close range navigation ones, easier SR locking, presence of safe segment during which SROC will wait for a go/no-go command. Conversely, the HP#2 imposes some disadvantages: firstly, to maintain the exact position a series of continuous trajectory corrections are needed, thus the manoeuvre was modelled as a finite manoeuvre into the STK environment. Then, to resume the motion from a situation of null relative velocity along the Intrack axis a high without entering the KOZ, high out-of-plane ΔVcomponents are required so the associated manoeuvres are the most ΔV consuming of the entire scenario. Moreover, the higher is the relative distance from SR the more difficult is to maintain the same SMA of the leader with a contained overall ΔV cost.

3.5.6 SR Observation Phase

This is the most crucial phase of this mission, during the Observation Phase SROC shall observe SR from a relatively small distance flying in a passively safe trajectory named Walking Safety Ellipse (WSE) from now on. The WSE geometry is determined by the insertion point and velocity, the correct WSE insertion point strictly depends on the OPA, while a manoeuvre to set the correct insertion velocity will be executed in correspondence of WSE starting point.

Safety Ellipse Theory

A "safety ellipse" is an out-of-plane elliptical periodic relative trajectory around the target spacecraft such that the chaser never crosses the primary spacecraft velocity vector. In a Safety Ellipse (SE) trajectory, drift of the two spacecraft will not result in a collision, so the trajectory is considered passively safe. [8] The equation of motion that describes the chaser trajectory around the target in a safety ellipse are derived from geometric consideration concerning the position of the chaser on the ellipse as shown in the figure below.

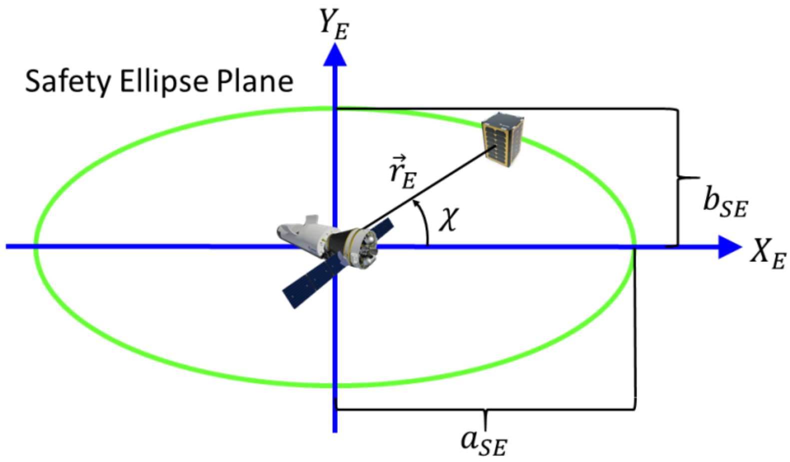


Figure 22: Safety Ellipse Plane with Polar Angle

Figure 22 shows the safety ellipse plane with the X_E axis lying in the $Y_{RIC}Z_{RIC}$ plane and the Y_E axis perpendicular to it, aligned with the X_{RIC} direction. The figure also introduces a polar angle, χ, in this plane, referenced to the X_E axis. This angle specifies the location of the inspector spacecraft on the SE at any time. Noting the semi-axis lengths of the safety ellipse, a_{SE} and b_{SE}, it is possible to express the position vector as a function of the polar angle χ:

$$\begin{bmatrix} a_{SE}\cos(\chi) \\ b_{SE}\sin(\chi) \\ 0 \end{bmatrix}$$

The position vector is expressed in the ellipse reference frame. To transform it into the RIC reference system, it is necessary to consider the quantities shown in Figure 23.

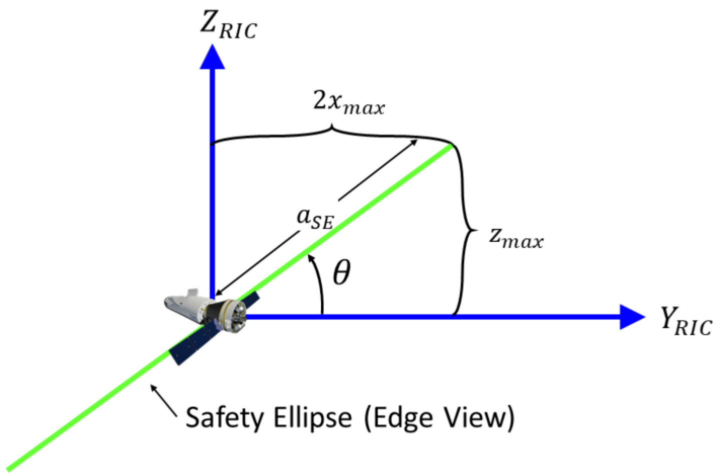


Figure 23: InTrack-CrossTrack view of the Safety Ellipse

The angle θ reprensents the inclination between the ellipse plane and the orbital plane$X_{RIC}Y_{RIC}$ of the spacecraft. Furthermore, it is possible to demonstrate the relationship between the ellipse axes lengths with the maximum displacement along the respective coordinates in the RIC system x_{max}, and z_{max} . Finally, the SE described so far is centred in the primary spacecraft, but the relative trajectory will move along the velocity direction, Y_{RIC} , due to the environment perturbations, especially the atmospheric drag. Therefore, it is necessary to consider an initial offset of the safety ellipse, X_E, and its forward velocity in the positive InTrack direction (SROC decays faster than SR), $\dot{y}_c$, as shown in Figure 24.

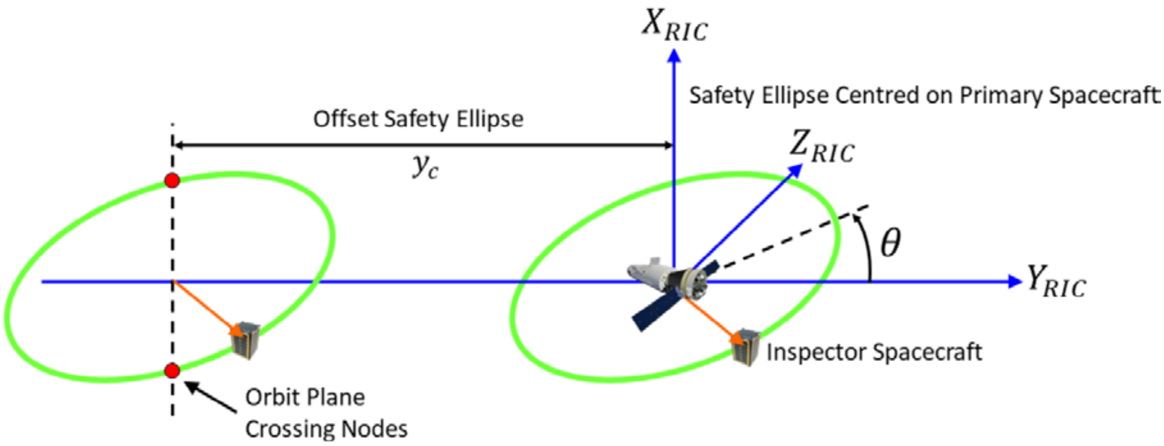


Figure 24: Primary Centred (left) and Offset (right) Safety Ellipse

The equations describing the SROC motion within a Walking Safety Ellipse ("Walking" is due to relative advancement) are functions of time expressed through the polar angle χ, and they are shown below, where n represents the mean motion of the primary spacecraft:

$$x(\chi) = x_{max}\sin(\chi) - \frac{2\dot{y}_c}{3n}$$
$$y(\chi) = 2x_{max}\cos(\chi) + \frac{\dot{y}_c(\chi - \pi/2)}{n} + y_c$$
$$z(\chi) = z_{max}\cos(\chi)$$
$$\dot{x}(\chi) = x_{max}\,\mathrm{n}\cos(\chi)$$
$$\dot{y}(\chi) = -2x_{max}\,n\,\sin(\chi) - \dot{y}_c$$
$$\dot{z}(\chi) = -z_{max}n\sin(\chi)$$

The position and the velocity, that describe the SROC motion in the safety ellipse, depend on five design parameters:

- x_{max}: the maximum displacement along the radial direction (Radial)
- z_{max}: the maximum displacement along the out-of-plane direction (CrossTrack)
- χ: the polar angle that defines the position of the spacecraft in SE (zero starting from the InTrack-CrossTrack plane and positive counter-clockwise)
- y_c: the initial position offset of the Safety Ellipse
- $\dot{y}_c$: the initial velocity along the Y_{RIC} direction

As described above, x_{max} and z_{max} are the maximum displacements along the Radial and CrossTrack directions and when SROC is on the maximum position along one of these directions, the other component is zero. For this reason, they represent the minimum distance in module between SROC and Space Rider in the Safety Ellipse plane and their values depend on the minimum operative range for the SROC inspector payload.

The polar angle χ is defined by an optimization analysis, hence is a design parameter for the insertion on a WSE, but it is not determined by other SROC requirements. The last two parameters in turn depend on the SROC payload performance and on the ballistic coefficient difference between Space Rider and SROC, that affects the amount of relative perturbations accumulated by SROC. In fact, y_c and $\dot{y}_c$ are a function of:

- R (Range): the maximum distance allowed between SROC and SR during an inspection imposed by the SROC payload constrains
- $T_{Inspection}$: the inspection duration around Space Rider and within the range imposed by the SROC payload. It depends on the payload power constrains and on the data budget of the spacecraft.

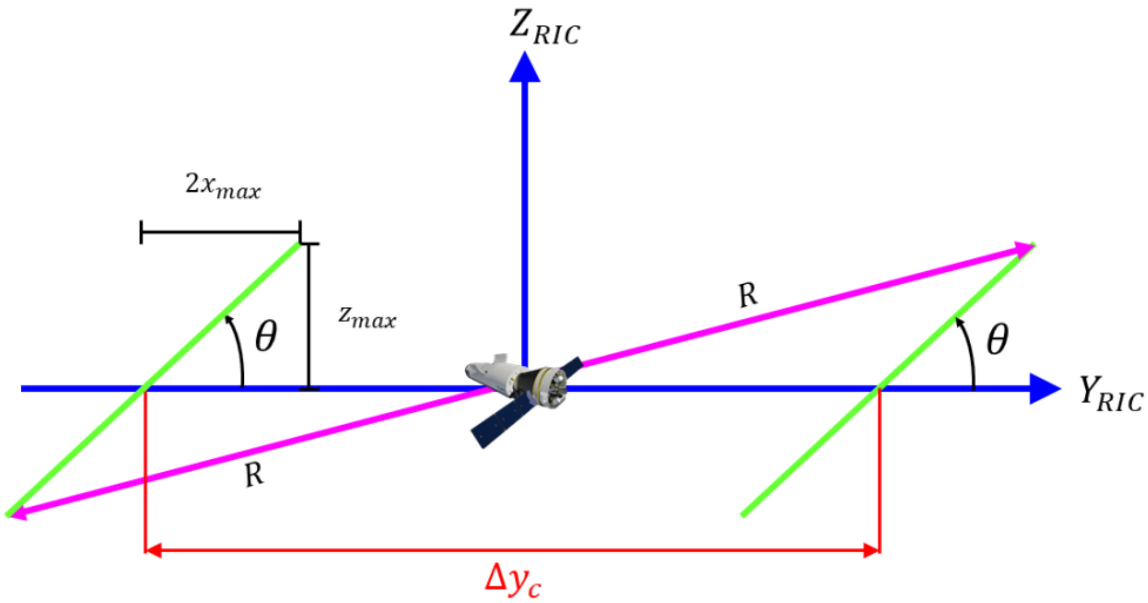


Figure 25: Safety Ellipse Offset Scheme

Figure 25 shows the relationship between the payload maximum range R, the SE geometry (x_{max} and y_{max}) and the InTrack range in which the WSE should operate. The green lines represent the first and last functional orbits (safety ellipses in edge view) for the inspection phase, tilted by a θ angle with respect to the orbital plane of SR. The vector R therefore indicates the positions furthest away from SR which must fall within the operating range of the SROC payload.
The Δy_c value came from the Design of Experiment (DoE) presented hereafter. It represents the Intrack displacement of the SE centre covered during an observation cycle. This value cannot be neither too high, due to the requirement imposed by the payload (i.e. maximum range R), nor too low, due to the uneven atmospheric drag effect on the two spacecraft.

Due to the complex nature of perturbations and relative motion, at present, y_c and $\dot{y}_c$are evaluated through an iterative process that aims to bring the WSE within the desired InTrack interval, starting from a particular initial position. The iterative process ends when the SEs with the most negative and most positive y_c are inside the range, i.e. $-y_{c\ lim} < y_c < +y_{c\ lim}$, where $y_{c\ lim} = \pm\frac{\Delta y_c}{2}$.

All the above demonstration is an approximation for the design of a WSE useful for the SR observation. Further studies and improvements shall be implemented to increase accuracy, especially due for the natural forward movement of the WSE. In fact, since the advancement of the WSE depends on the perturbative accelerations it undergoes, in the next phase of the SROC project,

y_c and $\dot{y}_c$ should be determined by deriving those accelerations and analytically evaluating the initial position and velocity of the WSE.

WSE geometry selection

In order to understand which parameters of the WSE can be varied, in what range and combination and their influence on the trajectory geometry and, thus on the Observation performance, a Design of Experiment (DoE) was conducted. In the following Table 8 and Table 9 there is summary of all the simulations carried out with the main results in terms of ΔV, the primary selection factor, and with the effective WSE percentage, defined as the time percentage of the WSE in which SROC is under the maximum allowed range R.

			WSE geometric parameters [m]									
Δyc [m]	Max Range [m]	Duration [hr]	75-75	75-100	75-150	100-75	100-100	100-150	150-75	150-100	150-150	
200	150	2	2.23	1.30	0.95	0.86	0.87	0.83	0.70	0.78	0.70	DeltaV [m/s]
		4	2.23	1.04	0.74	0.44	0.48	0.49	0.39	0.35	0.54	
		6	-	-	-	-	-	-	-	-	-	
	200	2	2.23	1.30	0.95	0.88	0.84	0.85	0.67	0.78	0.73	
		4	2.23	1.04	0.74	0.44	0.48	0.49	0.39	0.35	0.54	
		6	-	-	-	-	-	-	-	-	-	
	300	2	2.23	1.30	0.95	0.88	0.84	0.85	0.67	0.78	0.73	
		4	2.23	1.04	0.74	0.44	0.48	0.49	0.39	0.35	0.54	
		6	-	-	-	-	-	-	-	-	-	
400	150	2	2.23	1.30	0.95	0.91	0.83	0.85	0.68	0.72	0.75	
		4	2.23	1.08	0.75	0.49	0.43	0.54	0.37	0.37	0.51	
		6	2.23	1.46	0.74	0.40	0.58	0.44	0.52	0.47	0.52	
	200	2	2.23	1.30	0.95	0.91	0.83	0.85	0.68	0.72	0.75	
		4	2.23	1.08	0.75	0.49	0.43	0.54	0.37	0.37	0.51	
		6	2.23	1.46	0.74	0.40	0.58	0.44	0.52	0.47	0.52	
	300	2	2.23	1.30	0.95	0.91	0.83	0.85	0.68	0.72	0.75	
		4	2.23	1.08	0.75	0.49	0.43	0.54	0.37	0.37	0.51	
		6	2.23	1.46	0.74	0.40	0.58	0.44	0.52	0.47	0.52	

Table 8: WSE DoE summary table

The WSE geometry selection was prompted by the ΔV minimization criteria ensuring that the Observations requirements [3.1.3] were met. In particular, the compliance to the SROC coverage requirements was preliminarily verified by evaluating the results of a coverage analysis submitted after [3.10], in addition to the value of Valid Range percentage.

			WSE geometric parameters [m]									
Δyc [m]	Max Range [m]	Duration [hr]	75-75	75-100	75-150	100-75	100-100	100-150	150-75	150-100	150-150	Percentage of Valid Range [%]
200	150	2	77.2	75.6	53.1	50.3	44.2	39.7	3.1	2.8	2.8	
		4	68.3	60.6	46.4	44.4	39.2	36.1	2.8	2.8	1.9	
		6	-	-	-	-	-	-	-	-	-	
	200	2	100	100	80.3	79.2	70.8	57.5	38.6	36.9	33.9	
		4	96.7	91.9	77.5	82.2	66.1	57.5	32.5	32.5	28.6	
		6	-	-	-	-	-	-	-	-	-	
	300	2	100	100	100	100	100	100	83.9	82.2	69.7	
		4	100	100	100	100	100	100	79.4	79.2	71.1	
		6	-	-	-	-	-	-	-	-	-	
400	150	2	68.1	66.9	53.3	46.4	44.7	36.7	12.2	9.7	8.3	
		4	63.1	62.2	42.8	56.1	38.9	38.9	5.6	5.6	2.8	
		6	62.2	53.9	45.3	44.4	38.9	38.9	5.6	11.1	6.9	
	200	2	75.8	82.8	77.8	70.0	64.7	58.1	44.4	45.6	34.4	
		4	73.9	75.6	71.1	73.6	67.8	66.4	36.1	32.2	30.6	
		6	88.9	89.4	74.7	69.7	63.3	58.6	34.2	37.5	35.8	
	300	2	100	100	100	100	100	92.2	80.0	77.2	66.7	
		4	100	100	100	100	92.5	95.8	76.1	74.7	69.4	
		6	96.9	95.6	95.8	95.0	92.5	96.7	74.2	79.2	64.2	

Table 9: Effective WSE percentage

According to the SROC payload and subsystems requirements, the design parameters so far adopted for the baseline WSE analysis are:

- $x_{max} = +150\ [m]$
- $z_{max} = +150\ [m]$
- $T_{Inpsection} = 6\ [hr]$
- $R = 200\ [m]$
- $\Delta y_c = 400$ [m]

The plus or minus sign on the z_{max} involves the alternate inclination of the safety ellipses with respect to the orbital plane of SR, i.e. the θ angle is positive if z_{max} is positive and vice versa. This could allow for better coverage of the Space Rider surface, in case of multiple Observation phases. The following Figure 26 shows an example of the relative distance components and module during a WSE for the Space Rider Quasi-Equatorial Orbit scenario. In the left figure the Radial and CrossTrack components are periodic and do not undergo high perturbations during the observation period. Instead, the InTrack component evolves over time and determines if the observation occurs within the operating range of the SROC payload.
The different orbits of Space Rider and the different strategies adopted for SROC do not significantly affect the cost of insertion in the WSE or the relative distance between the two spacecraft.

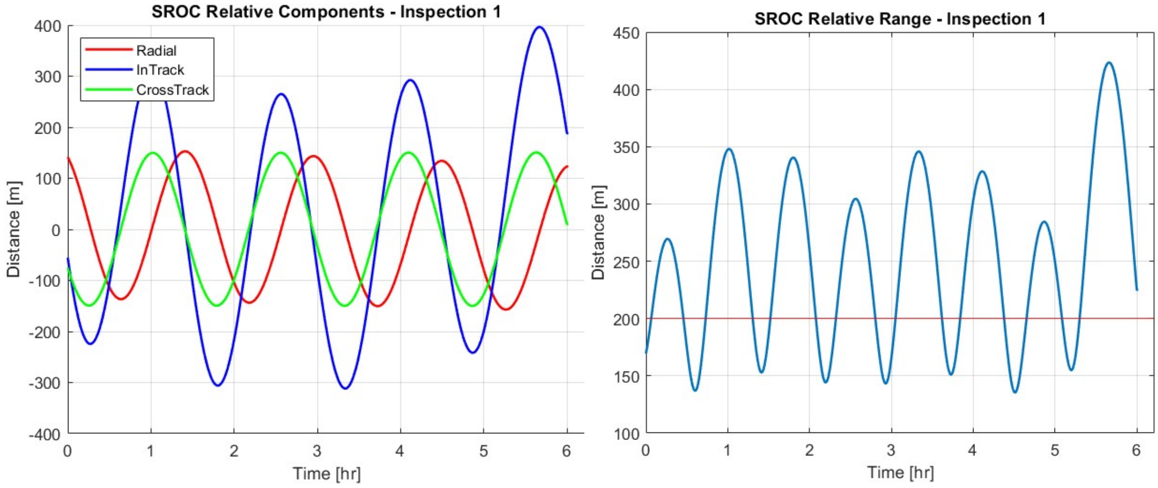


Figure 26: WSE relative distance components and range module

In the right graph is reported the relative range during the WSE (in blue), the red horizontal line represents both the maximum payload range (R = 200 m) and the KOZ border (a sphere of radius 200 m), therefore only the 35% of the entire Inspection could be effectively used to observe SR. This parameter could influence the number of Observation cycles to be performed.

SE Insertion

At the end of the Out-of-Plane Rendezvous, SROC should be in the inspection start relative position [$x(\chi), y(\chi)$ and $z(\chi)$], but it would not yet be on a safety ellipse. In fact, if no manoeuvre is executed, SROC would continue its out-of-plane motion towards the negative InTrack direction. This motion would be slowed down more and more by the atmospheric drag until it reversed its direction, getting closer to SR and then overcoming it in the positive InTrack direction. This would happen in high safety condition, as the motion is out of the plane and crosses the orbital plane of SR only in the nodes. The probability of collision with SR is therefore reduced to the sole situation in which the passage from the nodes coincides with the position of SR. To start the inspection, it is therefore necessary to perform an insertion manoeuvre, to change the relative velocity components of the SROC according to WSE equations [$\dot{x}(\chi), \dot{y}(\chi)$ and $\dot{z}(\chi)$]. The ΔV cost of this manoeuvre, such as for the OPA, also depends on the polar angle of insertion χ in the SE. For this reason, a ΔV optimization study was carried out by varying also the χ angle.

SR Observation

After SROC performs the insertion in the WSE, the cost of maintaining the relative orbit in terms of ΔV is zero. In fact, SROC will continue to propagate the passive safety ellipses which, due to orbital decay, will advance over time, performing a Space Rider inspection starting from a SE centred on the negative InTrack direction that moves forward in the positive InTrack direction, as shown in Figure 27 and Figure 28. In this phase, SROC stays in the vicinity of Space Rider for at least 6 hours (approximately 4 orbits), during which the images of the vehicle are taken, with the purpose of covering as much Space Rider surface as possible. The inspection partial percentage of SR during a single observation (about 4 orbits on a WSE) determines the number of observation cycles required, i.e. how many times this phase (composed by the Approach, the SR Observation and the Free Flight) shall be repeated to reach a cumulative 90% of the surface coverage.

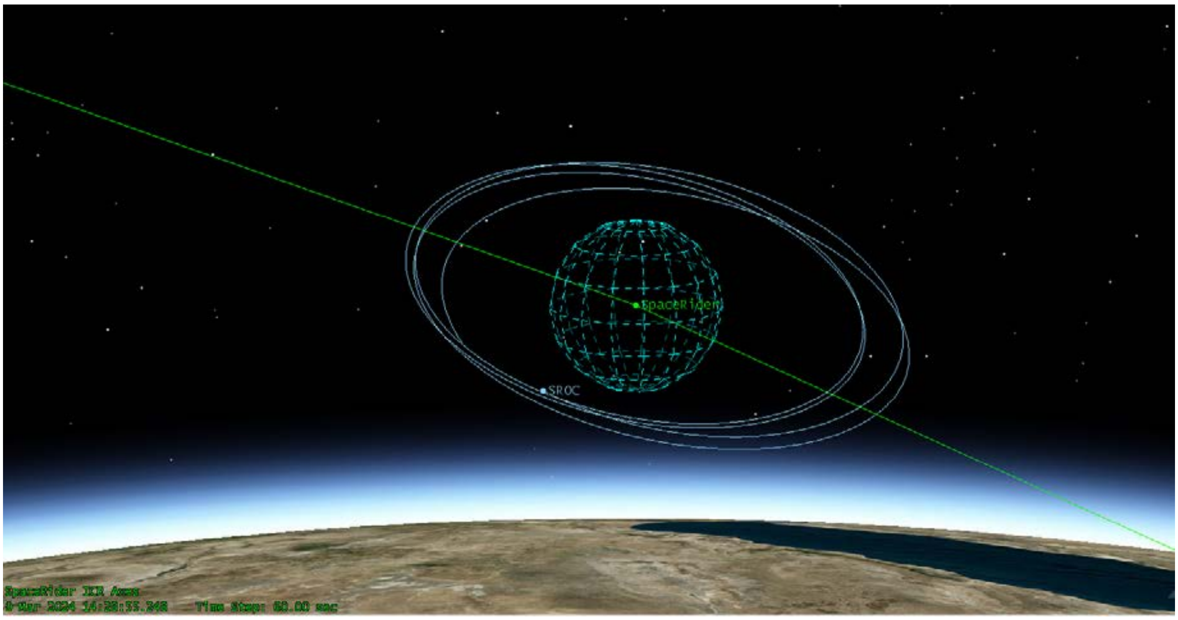


Figure 27: WSE in a prospective view

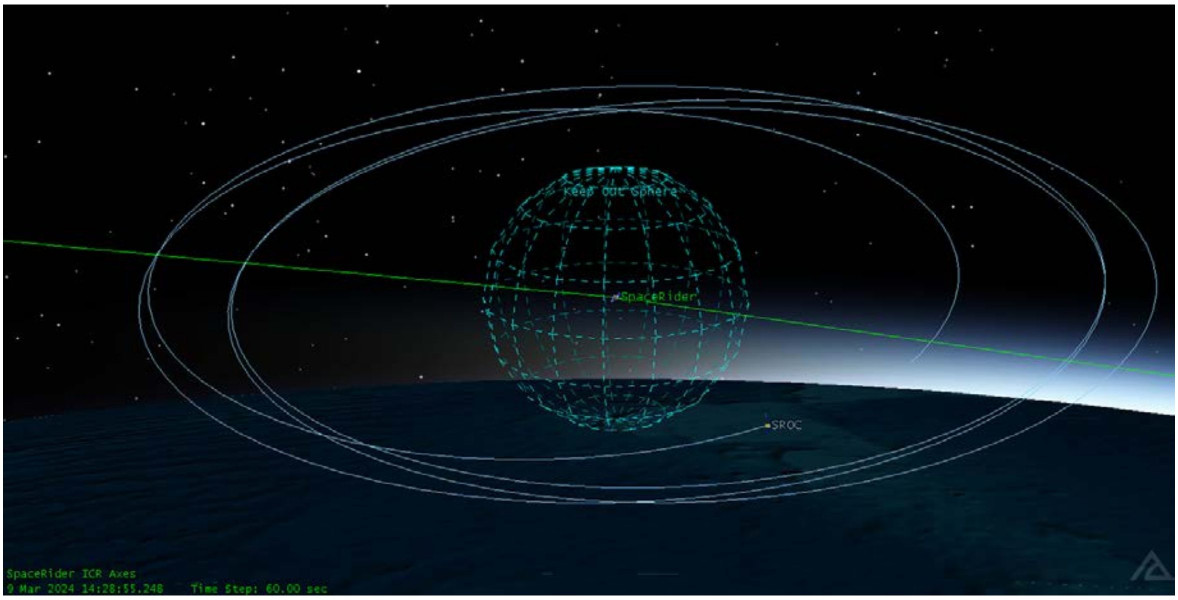


Figure 28: WSE Radial-CrossTrack View

The same WSE geometry is adopted regardless of the scenario.

SROC Free Flight

The WSE plane is inclined to the orbital plane of SR, so the distance between the two spacecraft varies on a single orbit over time. A single observation phase ends when the maximum distance for the observation payload to be operative is no longer guaranteed. Once this condition is reached, SROC could get closer to SR as it continues to propagate the SE. From that moment, SROC starts the Free Flight phase.

During the Free Flight, SROC does not perform any orbital manoeuvres, maintaining the relative elliptical and periodic orbits outside the Space Rider plane. It moves away from SR reaching a maximum InTrack distance of **5 km**, in this way SROC can maintain the SR locking and, therefore,

avoid to repeat this task (with an additional Hold Point if needed). The larger is the distance reached, the higher is the ΔV cost of the next manoeuvre to re-approach SR.
The Free Flight scenario is used as time-flexible element (similar to the Hold Point concept). During the Free Flight, SROC sends payload data to Ground and receives go/no go commands to start another Observation Cycle, performs health checks and any other operations if needed. The duration of the Free Flight scenario depends on several factors: amount of data to be downlinked, Ground Stations coverage, status of the system in general (e.g. battery state of charge), and operations needs.

This segment marks the end of the *Observe* scenario, thus the End of Mission Phase start, from the *Observe & Retrieve* scenario, for which begin the Docking and Retrieval Phase at this point.

3.5.7 Hold Point 3

Completed the Observation Phase if the *Observe & Retrieve* scenario is performed, SROC will start the Closing segment approaching to SR after the end of the Free Flight in order to execute the Retrieval into the SR cargo bay. To accomplish at this mission phase an additional holding segment is conceived as a waiting point for go/no-go command as well as both good illumination condition and appropriate ground station visibility. Two different scenarios were considered for the HP#3 in line with the Docking strategies.

Intrack Approach

For a Retrieval strategy along the Intrack axis a hold point along the same axis (similar to HP#2) is required. The holding point will be located between 100 and 150 m and will last for at least **4.5 hours**. During this Hold Point SROC will wait for good illumination conditions and ground stations visibility. Similarly, to the HP#2, to maintain a fixed relative position a finite manoeuvre is necessary, but thanks to the smaller relative distance the required ΔV is lower than the HP#2 one.

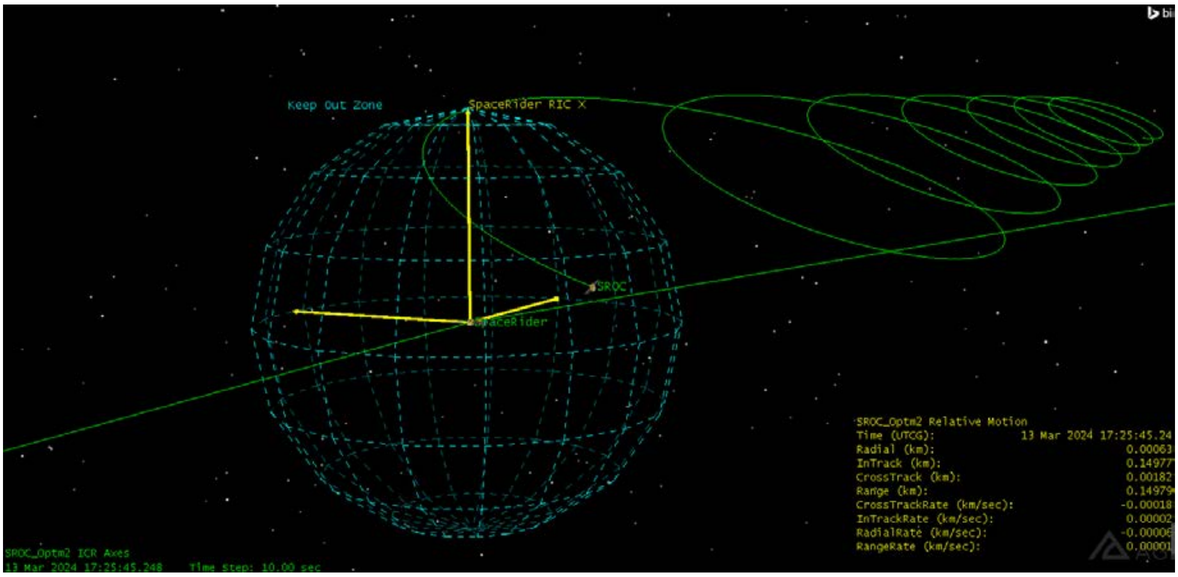


Figure 29: HP#3 Insertion trajectory

Figure 29 shows the HP#3 insertion manoeuvre, starting from the Free Flight final position until the fixed relative position of the HP#3, SROC will perform an out-of-plane trajectory.

Regarding the differences associated with this mission segment, since the starting distance (i.e. Free Flight end) and the final position (i.e. HP#3 coordinates) are the same for both the Option 1 and the Option 2, the only difference lies on the HP#3 Insertion duration, that in turn influences the required ΔV. Both values came from an optimization process designed to reduce the required ΔV while assuring that the Insertion manoeuvre does not lead SROC through negative Intrack positions or intersect the KOZ, so for the HP#3 Insertion lasts for 7.3 hr or 10.6 hr for the Option 1 or 2 respectively.

Radial Approach

For a Retrieval strategy along the Radial axis, since a holding is not possible due to high ΔV cost required, two different approaches were considered. The first one is conceived with an HP#3 along the Intrack axis as for the previous strategy, SROC from this position will execute a manoeuvre to perform a Fly Around manoeuvre until reaching the Final Approach Point (FAP) along the Radial axis at a relative distance of approximately 100 m. The FAP is a way point along the trajectory final approach and mating. It is not a hold point that can be maintained.
The second approach is composed by an Out-of-Plane Closing from the Free Flight end to a closer distance, where SROC will manoeuvre to enter into a passively safe trajectory, until reaching the FAP point to start the Final Approach mission segment. This last trajectory is similar to the WSE one but with a smaller geometry, so as to start the Final Approach at a distance of approximately 100 m.
The objective of this phase is to reach the Radial axis with a relatively small velocity with respect to SR and, in particular, with relatively close to zero Radial and Intrack components. Moreover, this second segment will fulfil the role of an holding point, indeed good illumination condition and ground stations visibility, as well as go/no-go command will be waited during this phase.

3.5.8 Final Approach

The analyses for Final Approach design aim at assessing the performance requirements for three different scenarios:

- Straight-line manoeuvre along Radial axis: the starting point is the HP#3 that lies on -Radial. SROC moves along Radial up to the mating on Space Rider (SR).
- Straight-line manoeuvre along InTrack axis: the starting point is the HP#3 that lies on +InTrack. SROC moves along -InTrack up to the mating on SR.
- Fly-Around manoeuvre from InTrack to axis Radial axis + Straight-line manoeuvre along Radial axis: the starting point is the HP#3 that lies on +InTrack. SROC performs a fly-around manoeuvre up to FAP (Final Approach Point) where start to manoeuvre along Radial up to the mating on SR.

Figure 30 also reports the approach cone defined according to safety constraint. Further details on this analysis can be found on Support Analysis document [15].

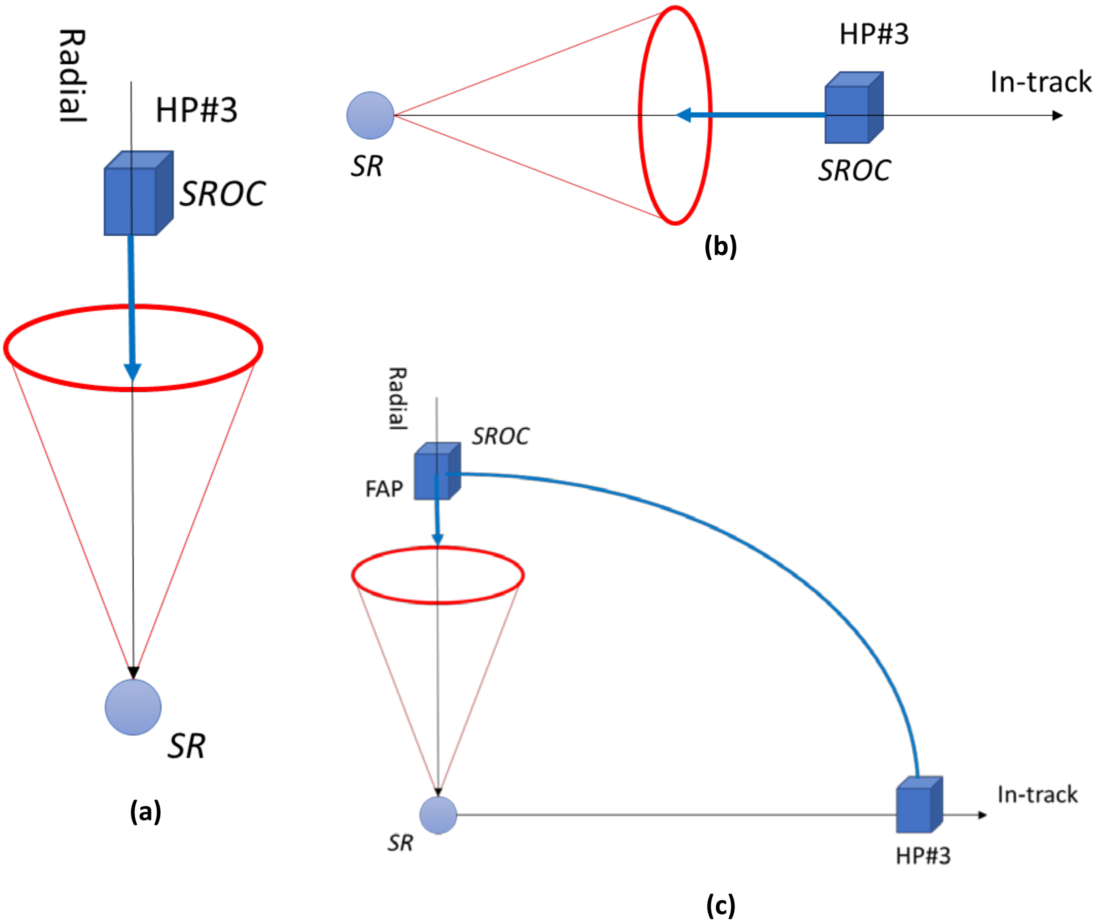


Figure 30: Final Approach scenarios

3.5.9 Decommissioning

In case the retrieval of SROC does not occur, either as a consequence of a failure or because the reduced mission is chosen, SROC shall be decommissioned and disposed. The atmospheric re-entry (natural orbit decay) has been simulated from the baseline SR's orbits until SROC reaches the altitude of 100 km. The duration of this simulation is 402 days for the quasi-equatorial orbit. The analysis of this phase revealed that the stability of the orbit drastically decays under 300 km of altitude, as illustrated in Figure 31. A 12U CubeSat with mass of 21 kg and random attitude (uncontrolled tumbling satellite) has been considered for the analysis. The average cross section area is 0.0796 m2. The simulation started on March 20th, 2024.

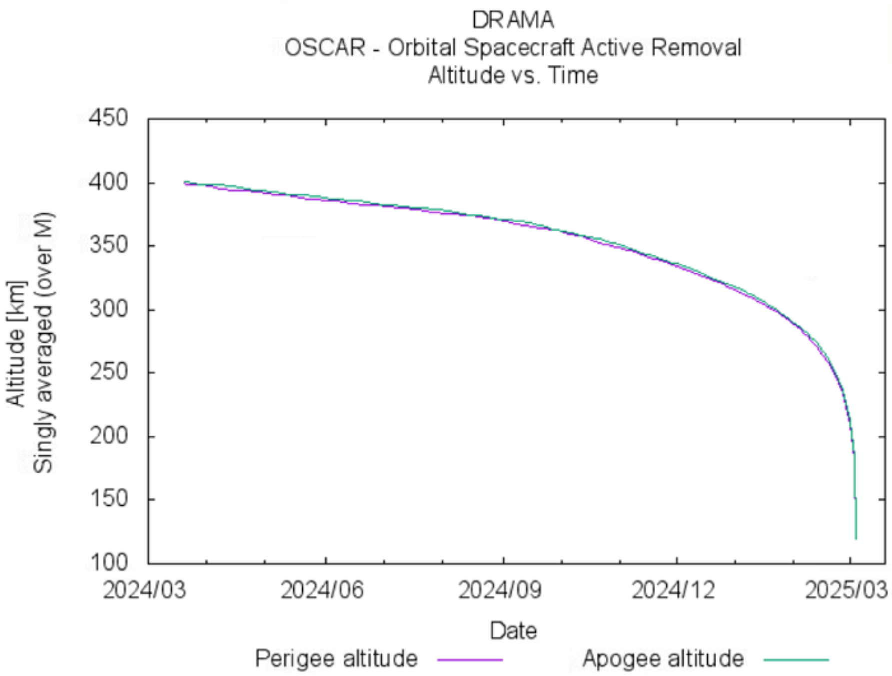


Figure 31: De-orbit analysis for the Quasi-Equatorial orbit

In the Figure 32 is presented the relative distance throughout the entire mission and disposal phase of the two spacecraft in case that no disposal manoeuvre is performed. It is important to notice that the SR mission is expected to last until May 1, 2024, thus only the first approach should be considered. Figure 33 shows a detail on the minimum relative distance associated at each SROC re-approach, the closest of which occurs on 14 Jun 2024, and it is characterised by a 13 km displacement along negative Radial direction, due to the effect of atmospheric drag.

For safety considerations, since numerous uncertainties could impact the effective values of this analysis varying the actual re-approach distances a disposal manoeuvre could be conceived so as to reduce or nullify the relative velocity and, in this way, postpone the first re-approach date, while waiting the SR mission end.

For the sake of completeness, another disposal strategy was taken into account: an altitude reduction manoeuvre was considered to lower the SROC lifetime and prevent any future re-approach with Space Rider. In order to effectively reduce the collision risk, thus increasing the relative distance at the first re-approach both an apogee altitude reduction and a circularization manoeuvre would be required. Considering the maximum ΔV set at 20 m/s, this second strategy is not feasible.

For the first strategy, instead, the required ΔV would be up to 5 m/s delaying the re-approach of about 5-10 days depending both on the mission scenario and on the disposal manoeuvre date of execution. More specifically, SROC starts the Disposal Phase after the Free Flight segment and the later the disposal manoeuvre is executed the higher would be, since the relative velocity will increase due to the atmospheric drag effect.
Additional information regarding the ΔV cost will be discussed in the 3.6 Section.

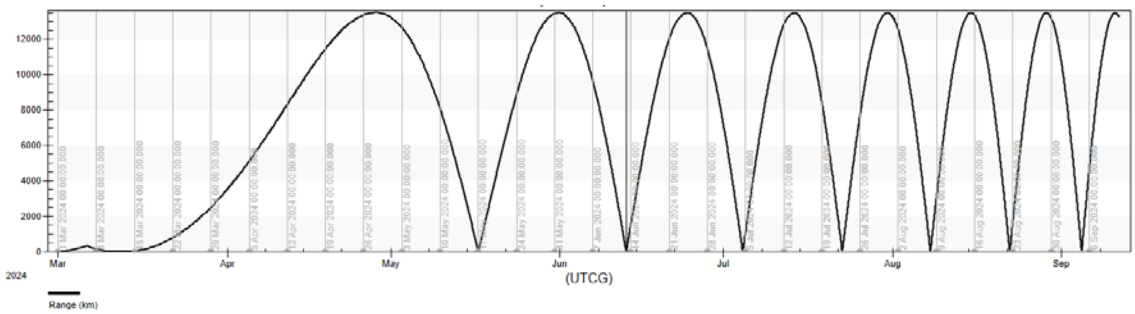


Figure 32: SROC-SR relative distance

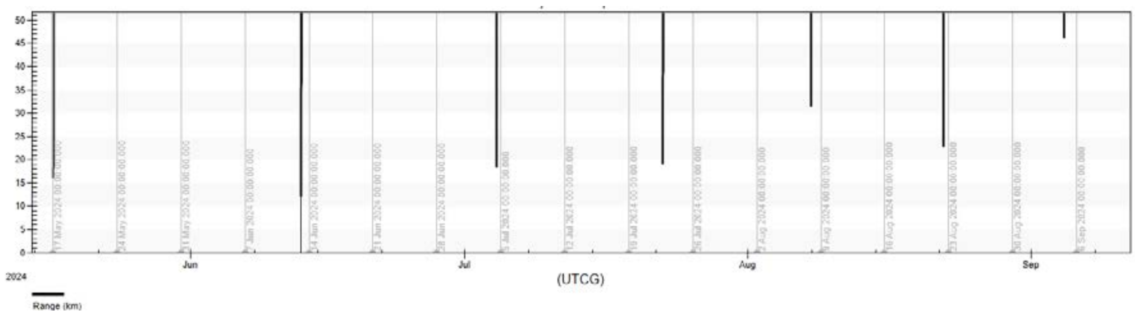


Figure 33: SROC-SR relative distance: re-approach details

3.6 Delta-V Budgets

The manoeuvres executed by SROC during the mission were calculated considering all the above-mentioned scenario (wrt the SROC Rendezvous and Docking strategies). The Delta-V budget for the baseline SROC mission is shown in Table 10, while for all other analyses options a detailed Delta-V budget is presented in the following tables, from Table 11 to Table 18.

Table 10: Delta-V budget for baseline scenario

BASELINE: Observe and Retrieve – Option 2 – InTrack docking			
Manoeuvre	**ΔV [m/s]**	**Margin**	**ΔV [m/s]**
Hold Point 1 insertion	0.44	5%	0.46
Virtual CAM + HP#1_bis	1.04	100%	2.08
Virtual WSE + HP#1_ter	0.50	100%	1.00
IPA	0.42	5%	0.44
Hold Point 2 insertion	0.39	5%	0.41
Hold Point 2 maintenance	1.46	5%	1.53
OPA	0.15	5%	0.16
WSE Insertion	0.06	5%	0.06
Closing	0.11	5%	0.12
Hold Point 3 maintenance	0.30	5%	0.32
Docking	0.90	5%	0.95
D CAM	0.10	100%	0.20
SR CAM	0.60	5%	0.63
Delta-V TOT [m/s]	**6.47**	**Delta-V TOT with Margin**	**8.36**

The table reports the cost of only one observation cycle and only one CAM w.r.t. SR, which additional value of 0.6 m/s for Collision Avoidance Manoeuvres is included in the Delta-V budget. A margin of 5% has been considered for each calculated manoeuvre and the Space Rider CAMs (SR CAM), while a margin of 100% has been considered for the Debris CAMs (D CAM).
The CAM SR refers to all the possible manoeuvres executed to avoid a collision with Space Rider, while D CAM refers to all the possible manoeuvres executed to avoid a collision with space debris. As reported in the tables, a Delta-V is allocated within the “D CAM” and “SR CAM” items to take into account the avoidance manoeuvres required to prevent possible collisions with either Space Rider or space debris during the mission. For the D CAMs the analysis was conducted with DRAMA’s Ares tool. Moreover, the details of the operations during the verification phase are still to be analysed in detail. However, the current plan is to perform (at least):

- the insertion manoeuvre into a hold point (HP#1)
- one manoeuvre to simulate the "virtual" CAM (that in turn requires another manoeuvre of insertion into a hold point, namely the HP#1_bis)
- one manoeuvre to simulate the insertion into a "virtual" WSE trajectory (and the subsequent manoeuvre of insertion into another hold point, namely the HP#1_ter)

The fact that the last verification manoeuvres require some iteration on simulations also explains the large margin (100%) adopted for the Delta-V.

Table 11: Delta-V Budget – Observe and Retrieve - Option 1 - Intrack Docking

Observe and Retrieve – Option 1 – Intrack docking			
Manoeuvre	**ΔV [m/s]**	**Margin**	**ΔV [m/s]**
Hold Point 1 insertion	0.44	5%	0.46
Virtual CAM + HP#1_bis	1.04	100%	2.08
Virtual WSE + HP#1_ter	0.50	100%	1.00
IPA	0.45	5%	0.47
OPA	0.58	5%	0.61
WSE Insertion	0.58	5%	0.61
Closing	0.15	5%	0.16
Hold Point 3 maintenance	0.42	5%	0.44
Docking	0.90	5%	0.95
D CAM	0.10	100%	0.20
SR CAM	0.60	5%	0.63
Delta-V TOT [m/s]	**5.76**	**Delta-V TOT with Margin**	**7.61**

Table 12: Delta-V Budget – Observe and Retrieve - Option 1 - Radial Docking

Observe and Retrieve – Option 1 – Radial docking			
Manoeuvre	**ΔV [m/s]**	**Margin**	**ΔV [m/s]**
Hold Point 1 insertion	0.44	5%	0.46
Virtual CAM + HP#1_bis	1.04	100%	2.08
Virtual WSE + HP#1_ter	0.50	100%	1.00
IPA	0.45	5%	0.47
OPA	0.58	5%	0.61
WSE Insertion	0.58	5%	0.61
Closing	0.10	5%	0.11
Hold Point 3 maintenance	0.24	5%	0.25
Docking	1.00	5%	1.05
D CAM	0.10	100%	0.20
SR CAM	0.60	5%	0.63
Delta-V TOT [m/s]	**5.63**	**Delta-V TOT with Margin**	**7.47**

Table 13: Delta- V Budget – Observe & Retrieve - Option 1 - Fly Around Radial Docking

Observe and Retrieve – Option 1 – Fly around Radial docking			
Manoeuvre	**ΔV [m/s]**	**Margin**	**ΔV [m/s]**
Hold Point 1 insertion	0.44	5%	0.46
Virtual CAM + HP#1_bis	1.04	100%	2.08
Virtual WSE + HP#1_ter	0.50	100%	1.00
IPA	0.45	5%	0.47
OPA	0.58	5%	0.61
WSE Insertion	0.58	5%	0.61
Closing	0.15	5%	0.16
Hold Point 3 maintenance	0.42	5%	0.44
Docking	3.00	5%	3.15
D CAM	0.10	100%	0.20
SR CAM	0.60	5%	0.63
Delta-V TOT [m/s]	**7.86**	**Delta-V TOT with Margin**	**9.81**

Table 14: Delta- V Budget – Observe and Retrieve - Option 2 - Radial Docking

Observe and Retrieve – Option 2 – Radial docking			
Manoeuvre	**ΔV [m/s]**	**Margin**	**ΔV [m/s]**
Hold Point 1 insertion	0.44	5%	0.46
Virtual CAM + HP#1_bis	1.04	100%	2.08
Virtual WSE + HP#1_ter	0.50	100%	1.00
IPA	0.42	5%	0.44
Hold Point 2 insertion	0.39	5%	0.41
Hold Point 2 maintenance	1.46	5%	1.53
OPA	0.15	5%	0.16
WSE Insertion	0.06	5%	0.06
Closing	0.21	5%	0.22
Hold Point 3 maintenance	0.09	5%	0.09
Docking	1.00	5%	1.05
D CAM	0.10	100%	0.20
SR CAM	0.60	5%	0.63
Delta-V TOT [m/s]	**6.46**	**Delta-V TOT with Margin**	**8.34**

Table 15: Delta-V Budget – Observe and Retrieve - Option 2 - Fly Around Radial Docking

Observe and Retrieve – Option 2 – Fly around Radial docking			
Manoeuvre	**ΔV [m/s]**	**Margin**	**ΔV [m/s]**
Hold Point 1 insertion	0.44	5%	0.46
Virtual CAM + HP#1_bis	1.04	100%	2.08
Virtual WSE + HP#1_ter	0.50	100%	1.00
IPA	0.42	5%	0.44
Hold Point 2 insertion	0.39	5%	0.41
Hold Point 2 maintenance	1.46	5%	1.53
OPA	0.15	5%	0.16
WSE Insertion	0.06	5%	0.06
Closing	0.11	5%	0.12
Hold Point 3 maintenance	0.30	5%	0.32
Docking	3.00	5%	3.15
D CAM	0.10	100%	0.20
SR CAM	0.60	5%	0.63
Delta-V TOT [m/s]	**8.57**	**Delta-V TOT with Margin**	**10.56**

Table 16: Delta-V Budget - Observe - Option 1

Observe – Option 1			
Manoeuvre	**ΔV [m/s]**	**Margin**	**ΔV [m/s]**
Hold Point 1 insertion	0.44	5%	0.46
Virtual CAM + HP#1_bis	1.04	100%	2.08
Virtual WSE + HP#1_ter	0.50	100%	1.00
IPA	0.45	5%	0.47
OPA	0.58	5%	0.61
WSE Insertion	0.58	5%	0.61
D CAM	0.10	100%	0.20
SR CAM	0.60	5%	0.63
Delta-V TOT [m/s]	**4.29**	**Delta-V TOT with Margin**	**6.06**

Table 17: Delta-V Budget - Observe - Option 2

Observe – Option 2			
Manoeuvre	**ΔV [m/s]**	**Margin**	**ΔV [m/s]**
Hold Point 1 insertion	0.44	5%	0.46
Virtual CAM + HP#1_bis	1.04	100%	2.08
Virtual WSE + HP#1_ter	0.50	100%	1.00
IPA	0.42	5%	0.44
Hold Point 2 insertion	0.39	5%	0.41
Hold Point 2 maintenance	1.46	5%	1.53
OPA	0.15	5%	0.16
WSE Insertion	0.06	5%	0.06
D CAM	0.10	100%	0.20
SR CAM	0.60	5%	0.63
Delta-V TOT [m/s]	**5.16**	**Delta-V TOT with Margin**	**6.98**

For scenarios with the Hold Point 2 (*Option 2*), the overall cost of the manoeuvres is higher due higher number of manoeuvres required. The ΔV of the first insertion in the WSE to start the observation phase depends on the Rendezvous strategy adopted. The relative trajectory does not require maintenance and the Delta-V depends on the distance reached during the Free Flight. The total Delta-V cost for the observation phase in a Quasi Equatorial orbit varies from 0.79 m/s to 1.22 m/s (including margin). The Delta-V required for the Docking and Mating phase is approximately 1 m/s , while only for the Fly-around Radial Docking the Delta-V needed is 3 m/s. Further details on the docking analysis, (i.e. how the thrust is used in this phase and how to navigate to the docking port) are reported in the "*D122 – SROC System Design Justification File + Annex*". [15]
For the Observe&Retrieve scenario the ΔV was computed considering the worst case, for which SROC performs the docking approach but at certain point it receives a *no-go* command, and it is forced to executed a CAM and switch back to the Observe scenario where a Disposal manoeuvre could expected.
The tables showing the Delta-V budget do not report the value needed for an hypothetical disposal manoeuvre, as this manoeuvre is not strictly needed for the accomplishment of the mission in compliance with all requirements. However, it is not excluded that a disposal manoeuvre can be added in the future iterations of the design, so it would be better to still consider it as a possibility and to design the system accordingly. This manoeuvre has been simulated and it costs 5 m/s +5% margin (minimum value, if executed at the end of the free flight of the last observation phase).
If implemented, the disposal manoeuvre would postpone the first close approach of SROC to Space Rider by 15 days (currently the first close approach, i.e. 15 km along radial) occurs at T0+2.5 months (T0 is the deployment date of SROC from SR), that is when SR would have already completed its mission and be back on ground. That is why we did not consider the disposal manoeuvre in the baseline Delta-V budget.

Table 18: Delta-V and Mission Durations comparison

	Quasi-Equatorial (5 deg) – Baseline			
	Option 1 – Intrack HP3	Option 1 – Radial HP3	Option 2 – Intrack HP3	Option 2 – Radial HP3
DeltaV [m/s]	4.53	4.39	5.28	5.23
Duration [day]	10.94	11.18	19.79	13.91
	Intermediate (37 deg) – Dawn/Dusk			
	Option 1 – Intrack HP3	Option 1 – Radial HP3	Option 2 – Intrack HP3	Option 2 – Radial HP3
DeltaV [m/s]	4.85	5.02	5.24	5.98
Duration [day]	10.99	11.23	13.91	13.91
	Intermediate (37 deg) – Midday/Midnight			
	Option 1 – Intrack HP3	Option 1 – Radial HP3	Option 2 – Intrack HP3	Option 2 – Radial HP3
DeltaV [m/s]	4.44	6.84	5.24	7.13
Duration [day]	10.99	11.18	13.91	13.91
	SSO – Dawn/Dusk			
	Option 1 – Intrack HP3	Option 1 – Radial HP3	Option 2 – Intrack HP3	Option 2 – Radial HP3
DeltaV [m/s]	5.21	5.03	9.8	9.82
Duration [day]	11.02	11.25	13.92	13.92
	SSO – Midday/Midnight			
	Option 1 – Intrack HP3	Option 1 – Radial HP3	Option 2 – Intrack HP3	Option 2 – Radial HP3
DeltaV [m/s]	4.90	5.63	7.37	7.22
Duration [day]	11.01	11.23	13.92	13.92

Table 18 summarizes the ΔV cost with margins of the manoeuvres carried out by SROC (including the CAMs) and the durations of the mission with respect to the analysed Space Rider orbits and different SROC strategies. Considering the target scenario in which the duration of the Commissioning is 5 days, the total Delta-V vary from 4.39 m/s (Quasi-Equatorial Orbit and Option 1 Rendezvous strategy with Radial Docking) to 9.82 m/s (SSO Dawn/Dusk Orbit and Option 2 Rendezvous strategy with Radial Docking). Considering only the Quasi-Equatorial orbit and from a ΔV cost perspective, the Option 1 Rendezvous strategy and Radial Docking strategy is the best scenario.

The requirement regarding the Delta-V has been finally set to **20 m/s**. A margin has been adopted for the following reasons:

- launch date is still uncertain, now set in March 2024. If the launch date is postponed, the atmosphere conditions might vary to a great extent due to changing solar cycle.
- the baseline mission concept (Observe & Retrieve mission) has been considered for the Delta-V calculation.

3.7 Ground stations visibility analysis

The analysis of visibility of the ground stations has been carried out considering the following assumptions:

- Stations in the simulation: all ESTRACK stations, a set of commercial stations including some run by Tyvak, and the PoliTo CubeSat Control Centre (C3).
- Only access with duration longer than 3 minutes have been reported, considering a margin on the time needed for tracking the signal and establish a stable link with SROC.
- Minimum elevation angle of 10 degrees has been considered.
- AzEl Mask has been considered for each ground station taking into account the natural morphology and horizon obstacles.
- The simulation starts on March 2024 (Launch date is set to 01.03.2024) and ends on May 1, 2024.

Table 19 to Table 24 report the number of accesses for each station during the mission (two months) and per day, with average duration of the single pass, for the different scenarios. The analysis is fundamental for the SROC mission, especially to identify the proper operations strategy in relation with the need for “go” commands from ground before execution of critical manoeuvres.

Table 19: Visibility analysis for the Baseline scenario: Quasi-equatorial orbit

Location	Average Duration[min]	Access [#/mission]	Access [#/day]
Kourou	4.745	609	10
Malindi_Station_STDN_KENS	4.633	859	14
south_sulawesi__LAPAN	4.748	736	12
SriLanka_LeafSpace	4.627	504	9

For each visible Ground Station of the Quasi-Equatorial orbit additional useful information are the maximum access duration and the number of accesses above 5 minutes:

- Kourou Station: the maximum access duration is 5.28 minutes and 324 out of 609 access are above 5 minutes
- Malindi Station: the maximum access duration is 5.28 minutes and 457 out of 859 access are above 5 minutes
- South Sulawesi Station: the maximum access duration is 5.28 minutes and 416 out of 736 access are above 5 minutes
- Sri Lanka Station: the maximum access duration is 5.18 minutes and 204 out of 504 access are above 5 minutes

Table 20: Visibility analysis for the Intermediate orbit (37 deg Dawn-Dus)

Location	Average Duration[min]	Access [#/mission]	Access [#/day]
Turin	3.09	52	1
AbuDhabi_Tyvak	4.58	190	4
Cebreros_DSA_2	4.48	174	3
Dongara_Station_AUWA01_STDN_USPS	4.34	302	5
DSS_26_Goldstone_STDN_D26D	4.95	244	4
ESRIN	4.20	148	2
Kourou_Station	4.56	133	2
Malargue_DSA_3	4.92	244	4

Malindi_Station_STDN_KENS	4.56	133	2
Masuda_USB_F2	4.62	299	5
New_Norcia_DSA_1	4.68	289	5
Orbcomm_Hartebeesthoek_A	4.54	206	4
Petaluma_Tyvak	4.81	207	4
RiodeJaneiro_Telespazio	4.57	179	2
SanDiego_Tyvak	4.82	216	4
Santa_Maria_Station	4.90	224	4
Santiago_Leolut	4.90	270	5
South_Point_Station_USHI01_STDN_USHS	4.53	164	3
south_sulawesi__LAPAN	4.55	133	2
SriLanka_LeafSpace	4.54	138	2
Usuda	4.9	242	4
Villafranca_VIL-4	4.64	293	5

Table 21: Visibility analysis for the Intermediate orbit (37 deg Midday-Midnight)

Location	Average Duration[min]	Access [#/mission]	Access [#/day]
Turin	3.09	52	1
AbuDhabi_Tyvak	4.55	192	4
Cebreros_DSA_2	4.46	176	3
Dongara_Station_AUWA01_STDN_USPS	4.35	302	5
DSS_26_Goldstone_STDN_D26D	4.95	247	4
ESRIN	4.21	147	2
Kourou_Station	4.58	132	2
Malargue_DSA_3	4.93	239	4
Malindi_Station_STDN_KENS	4.58	131	2
Masuda_USB_F2	4.61	296	5
New_Norcia_DSA_1	4.7	290	5
Orbcomm_Hartebeesthoek_A	4.53	207	3
Petaluma_Tyvak	4.79	213	3
RiodeJaneiro_Telespazio	4.55	182	3
SanDiego_Tyvak	4.81	220	4
Santa_Maria_Station	4.89	225	3
Santiago_Leolut	4.91	266	4
South_Point_Station_USHI01_STDN_USHS	4.58	159	2
south_sulawesi__LAPAN	4.57	132	2
SriLanka_LeafSpace	4.6	131	2
Usuda	4.9	238	4
Villafranca_VIL-4	4.64	294	5

Table 22: Visibility analysis for the SSO Dawn-Dusk

Location	Average Duration[min]	Access [#/mission]	Access [#/day]
Turin	4.42	183	2
AbuDhabi_Tyvak	4.39	89	2
Awaruna_LeafSpace	4.41	125	2

Bardufoss_Tyvak	4.45	268	5
Cebreros_DSA_2	4.41	112	2
Dongara_Station_AUWA01_STDN_USPS	4.39	95	2
DSS_26_Goldstone_STDN_D26D	4.38	104	2
Esrange_Station_ESTC_STDN_KU2S	4.45	249	4
Esrange_Station_SSC-CNES	4.45	249	4
ESRIN	4.42	113	2
Kerguelen_Island_STDN_KGLQ	4.42	133	2
Kourou_Station	4.34	82	2
Malargue_DSA_3	4.38	104	2
Malindi_Station_STDN_KENS	4.35	81	2
Masuda_USB_F2	4.38	97	2
New_Norcia_DSA_1	4.40	97	2
Orbcomm_Hartebeesthoek_A	4.37	92	2
Petaluma_Tyvak	4.41	107	2
Peterborough_Tyvak	4.45	142	2
Poker_Flat_Station_PF1_STDN_DX2S	4.48	214	3
Redu_Station	4.44	133	3
RiodeJaneiro_Telespazio	4.41	88	2
SanDiego_Tyvak	4.38	107	2
Santa_Maria_Station	4.4	106	2
Santiago_Leolut	4.40	99	2
Shetland_Islands_LeafSpace	4.46	180	3
South_Point_Station_USHI01_STDN_USHS	4.38	84	2
south_sulawesi__LAPAN	4.36	81	2
SriLanka_LeafSpace	4.35	82	2
Svalbard_STDN_S22S	4.68	511	9
TrollSat_Ground_Station	4.42	328	6
Usuda	4.38	104	2
Villafranca_VIL-4	4.39	95	2

Table 23: Visibility analysis for the SSO Midday-Midnight

Location	Average Duration[min]	Access [#/mission]	Access [#/day]
Turin	4.43	182	2
AbuDhabi_Tyvak	4.39	90	2
Awaruna_LeafSpace	4.41	125	2
Bardufoss_Tyvak	4.44	269	5
Cebreros_DSA_2	4.38	114	2
Dongara_Station_AUWA01_STDN_USPS	4.38	96	2
DSS_26_Goldstone_STDN_D26D	4.39	102	2
Esrange_Station_ESTC_STDN_KU2S	4.47	247	4
Esrange_Station_SSC-CNES	4.47	247	4
ESRIN	4.42	113	2
Kerguelen_Island_STDN_KGLQ	4.43	132	2
Kourou_Station	4.38	81	2
Malargue_DSA_3	4.37	106	2
Malindi_Station_STDN_KENS	4.36	81	2

Masuda_USB_F2	4.39	97	2
New_Norcia_DSA_1	4.37	99	2
Orbcomm_Hartebeesthoek_A	4.35	93	2
Petaluma_Tyvak	4.40	109	2
Peterborough_Tyvak	4.45	142	3
Poker_Flat_Station_PF1_STDN_DX2S	4.44	219	3
Redu_Station	4.43	135	2
RiodeJaneiro_Telespazio	4.36	91	2
SanDiego_Tyvak	4.4	104	2
Santa_Maria_Station	4.39	105	2
Santiago_Leolut	4.36	103	2
Shetland_Islands_LeafSpace	4.44	183	3
South_Point_Station_USHI01_STDN_USHS	4.38	84	2
south_sulawesi__LAPAN	4.35	82	2
SriLanka_LeafSpace	4.30	85	2
Svalbard_STDN_S22S	4.68	513	9
TrollSat_Ground_Station	4.43	325	6
Usuda	4.38	102	2
Villafranca_VIL-4	4.36	98	2

Table 24: Ground Stations Information and frequencies

Location	ESTRACK	Owner	Frequency
Turin	No	Polito	S, UHF
AbuDhabi_Tyvak	No	Tyvak	S
Awaruna_LeafSpace	No	Leafspace	S, UHF
Bardufoss_Tyvak	No	Tyvak	UHF
Cebreros_DSA_2	Yes	ESA	Ka, K, X
Dongara_Station_AUWA01_STDN_USPS	No	Universal Space Network	S, Ku, X, Ku
DSS_26_Goldstone_STDN_D26D	No	NASA	
Esrange_Station_ESTC_STDN_KU2S	No	SSC	S, X (UHF downlink)
Esrange_Station_SSC-CNES	No	SSC	S, X, (UHF downlink)
ESRIN	No	ESA	
Kerguelen_Island_STDN_KGLQ			
Kourou_Station	Yes	ESA	
Malargue_DSA_3	Yes	ESA	Ka, K, X
Malindi_Station_STDN_KENS	Yes	ESA	X
Masuda_USB_F2			
New_Norcia_DSA_1	Yes	ESA	S, X
Orbcomm_Hartebeesthoek_A	No	Sansa (South African Space Agency)	L, S, C, Ext C, X, Ku, DBS and Ka
Petaluma_Tyvak	No	Tyvak	S
Peterborough_Tyvak	No	Tyvak	S
Poker_Flat_Station_PF1_STDN_DX2S	No	NASA	S, C
Redu_Station	Yes	ESA	L, S X Ku Ka

RiodeJaneiro_Telespazio	No	Telespazio	L, S, C, Ku e Ka
SanDiego_Tyvak	No	Tyvak	UHF
Santa_Maria_Station	Yes	ESA/Leafspace	S, X
Santiago_Leolut	No	SSC	S, C, Ka
Shetland_Islands_LeafSpace	No	Leafspace	S, X, UHF
South_Point_Station_USHI01_STDN_USHS	No	SSC	S, X, Ku
south_sulawesi__LAPAN	No	Lapan	S
SriLanka_LeafSpace	No	Leafspace	S, X
Svalbard_STDN_S22S	No	Norwegian Space Agency	C, L, S, X and K
TrollSat_Ground_Station	No	Kongsberg Satellite Services	S, X, C (uplink)
Usuda	No	JAXA	S, X
Villafranca_VIL-4	No	ESA	S, C
SMILE Lab	Yes	ESA	S, UHF

In case a quasi-equatorial orbit is chosen for the SR maiden flight, only four stations will be available for communication with SROC. It might be the case to consider other commercial stations, or the possibility to build ad-hoc stations. The latter option is feasible and affordable, but it adds complexity to the mission implementation (especially for the integration in the ESA SROC mission control system). All other scenarios offer a wide range of options for the ground control network, including institutional and commercial stations already available in the organizations involved in the SROC mission.

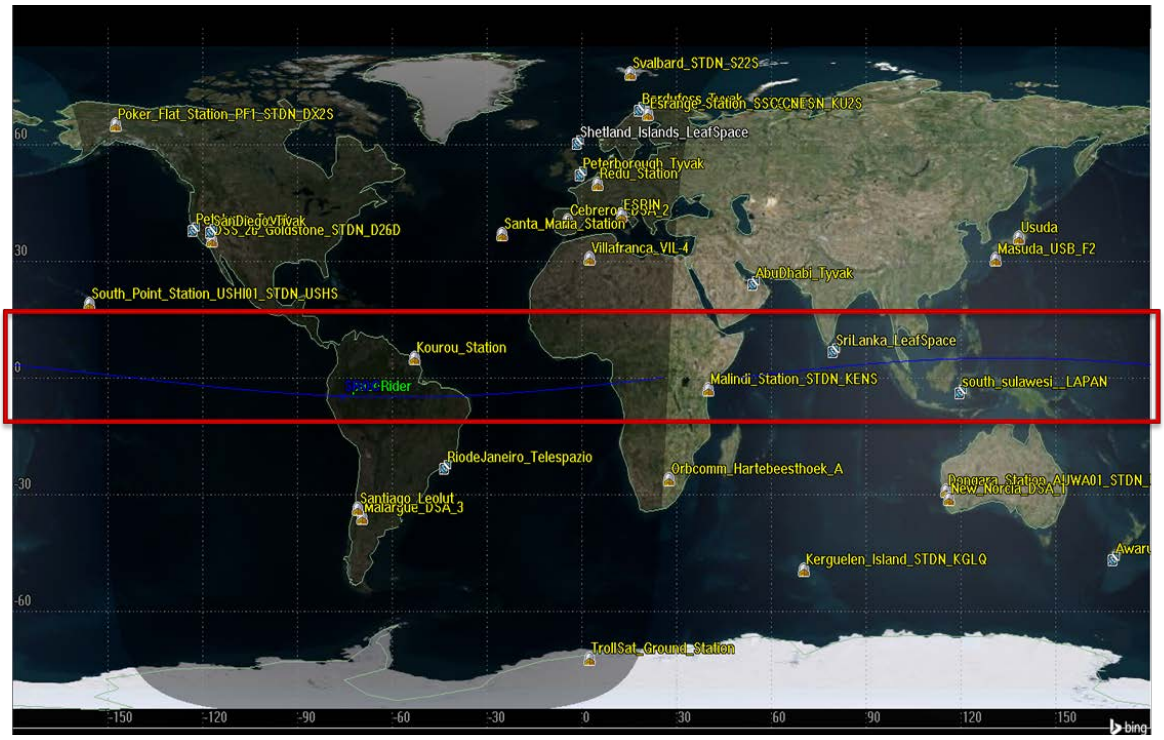


Figure 34: SROC ground track with Ground Stations locations

In the Figure 34 is shown the SROC ground track with all the considered Ground Stations, for the Quasi-Equatorial Orbit SROC will not have Ground Stations take over, so in order to guarantee a sufficient continuous visibility and communication from ground an additional GS could be added between the Malindi Station and the Sri Lanka Station (i.e. between 60° and 65° of longitude and with 2° of latitude) so as to ensure at least a 15 minutes uninterrupted communication window. This case is reported in the Figure 35.

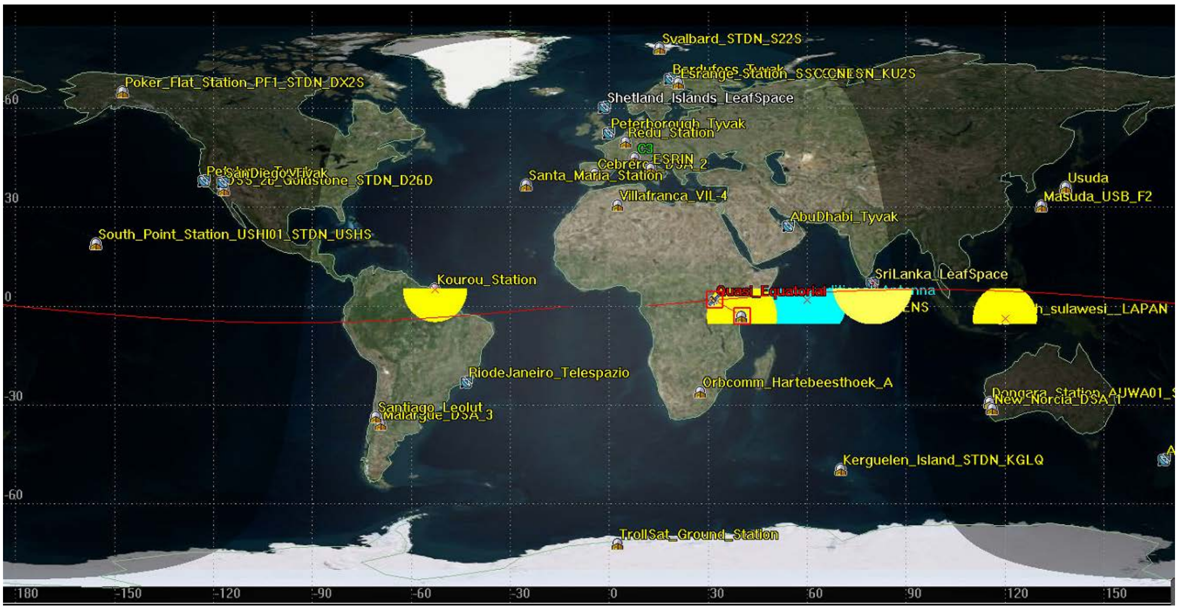


Figure 35: GS take over with Additional Antenna

3.8 Illumination analysis

The main objective of the illumination analysis is to identify the illumination conditions suitable for performing the docking of SROC to SR. Unfortunately, not all the illuminated part of an orbit is suitable for visual monitoring of the OPA rendezvous and approach operations, as shadowing may make monitoring impossible. There could be two unsuitable cases for the docking:

- The Sun vector is orthogonal with respect to the approach axis: the structural features with extensions along the approach line project long shadows, resulting in little or no illumination of surfaces in the capture interface plane
- The Sun vector is parallel with respect to the approach axis: at close distances, SROC casts shadow on the docking port of SR.

The best illumination conditions for executing the docking operations occur when the interface plane for capture is illuminated, shadows of structural features are not too long and shadow casting from one vehicle on the other is limited to a minimum. In order to find this condition, it is first necessary to know the β-angle, i.e. the angle between the Sun vector and the orbital plane.
The trend of the β-angle has been computed for the Baseline scenario and an evaluation of the elevation Sun angle to start the approach has also been done.
This analysis has been performed for the scenarios described in section 8.4.2 under the assumptions reported in section 8.3. As result of this analysis, the evolution of the β-angle over 1 year is reported in Figure 36.

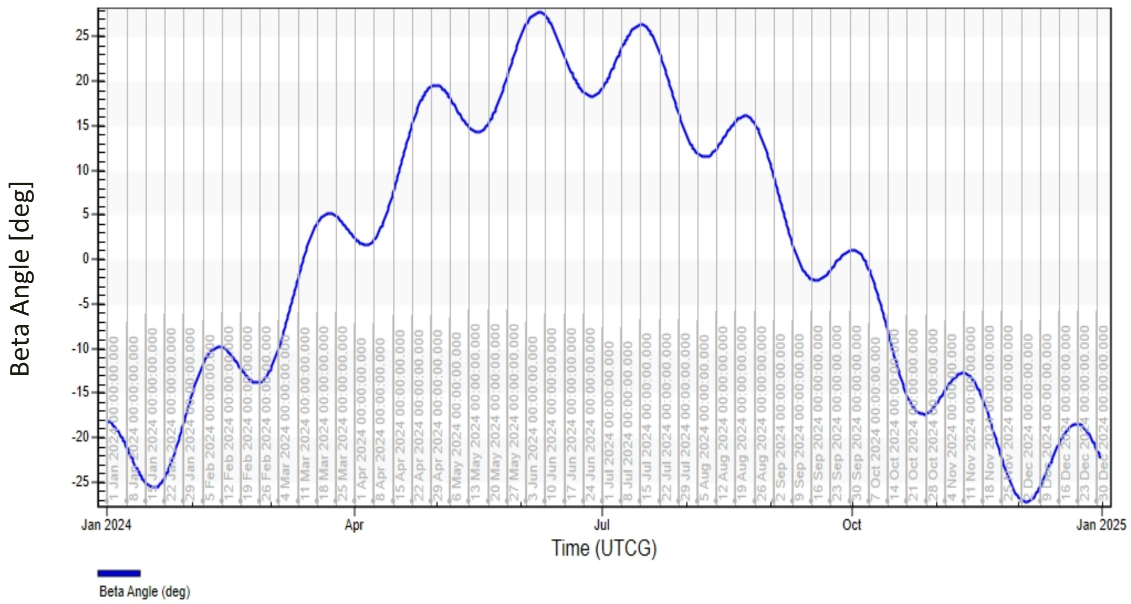


Figure 36: β-angle annual evolution for the Baseline scenario

As it can be seen from above, for the Quasi-Equatorial orbits, the trend of the β-angle is little variable throughout the duration of the mission. The β-angle will increase during the SR mission, even though the angle will remain relatively low, thus the same considerations below reported are in case of a small SR launch delay. This angle offers a best estimate for the illumination condition during a Docking approach into the SR orbital plane.
A more precise illumination analysis has been carried out considering all the SR orbits and the specific Docking axis-to-Sun Vector angle for both Intrack and Radial approaches. Moreover, 60 degrees was set as the threshold maximum angle required to start the docking manoeuvres the results are reported on the following figures, from Figure 37 to Figure 54.

QUASI-EQUATORIAL ORBIT

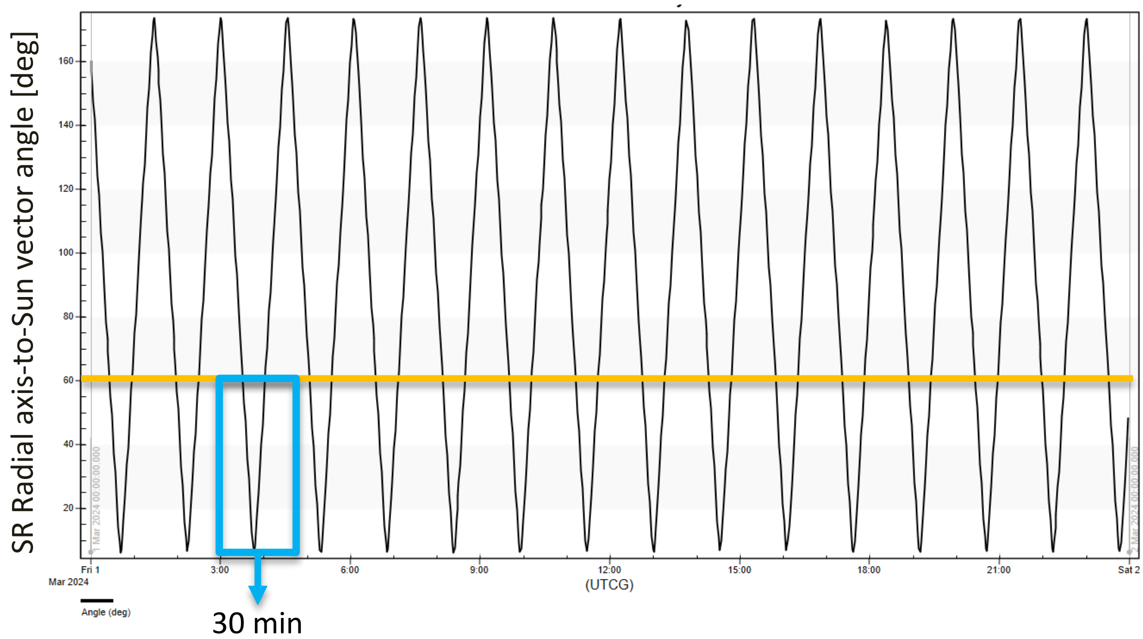


Figure 37: Baseline SR Radial axis angle-to-Sun Vector

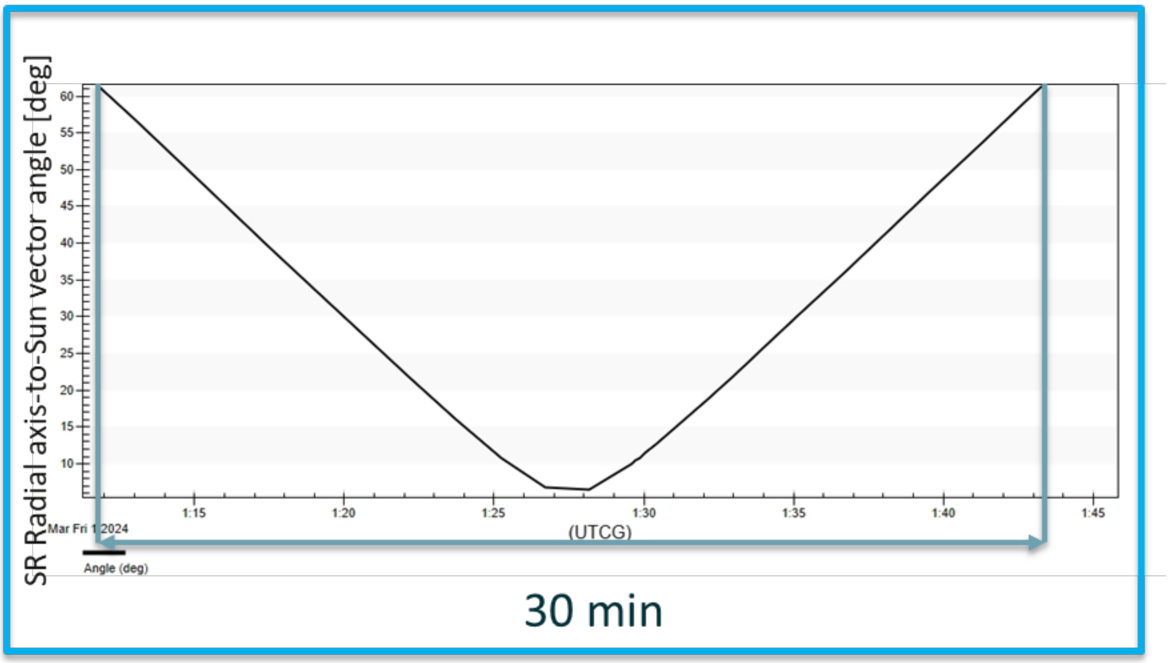


Figure 38: Baseline SR Radial axis angle-to-Sun Vector good illumination window (Detail)

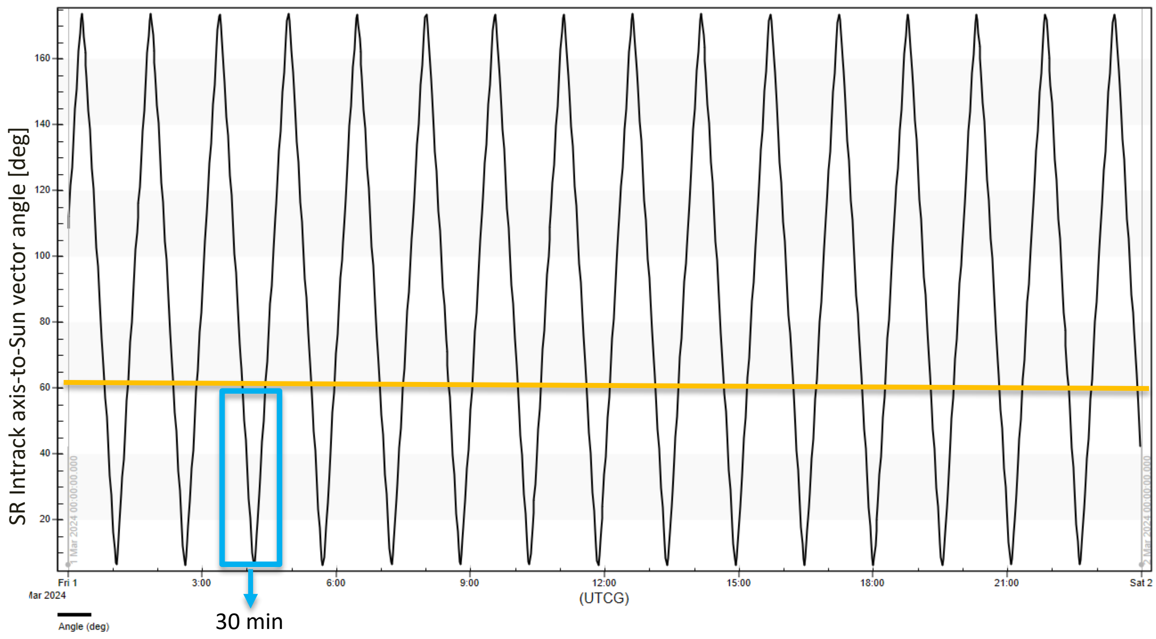


Figure 39: Baseline SR Intrack axis-to-Sun Vector angle

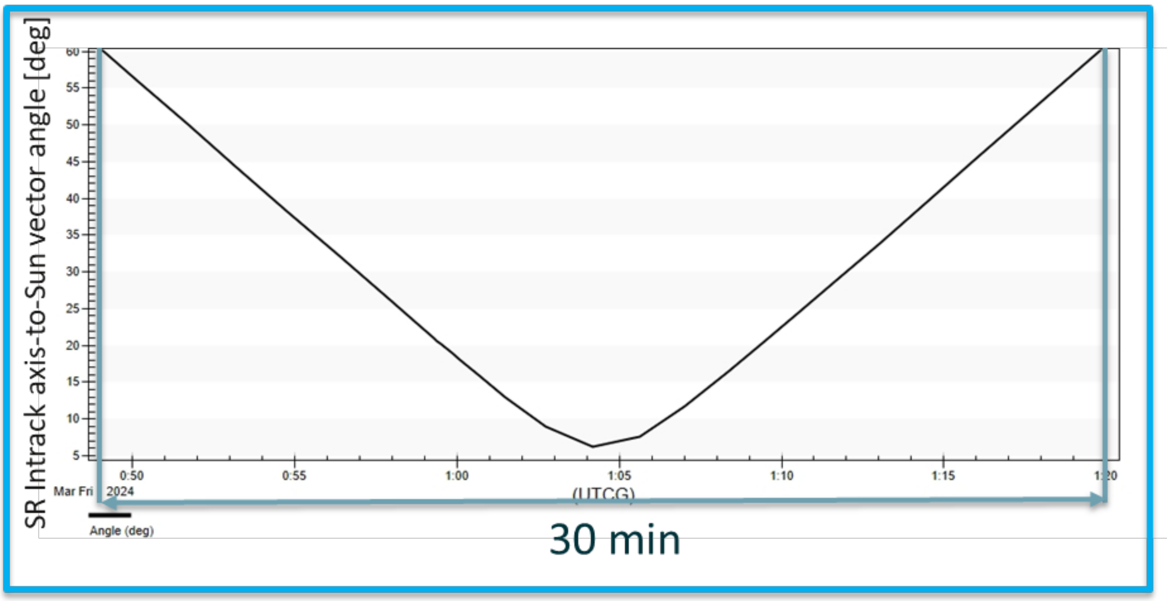


Figure 40: Baseline SR Intrack axis-to-Sun Vector angle good illumination window (Detail)

SSO MIDDAY-MIDNIGHT ORBIT

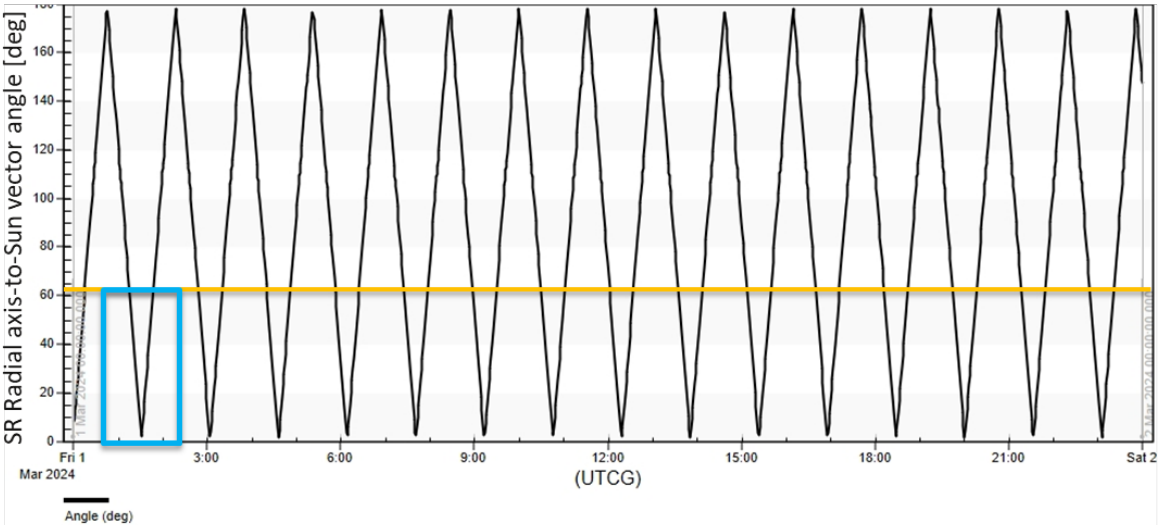


Figure 41: SSO MM SR Radial axis-to-Sun Vector angle

<u>15.5</u>

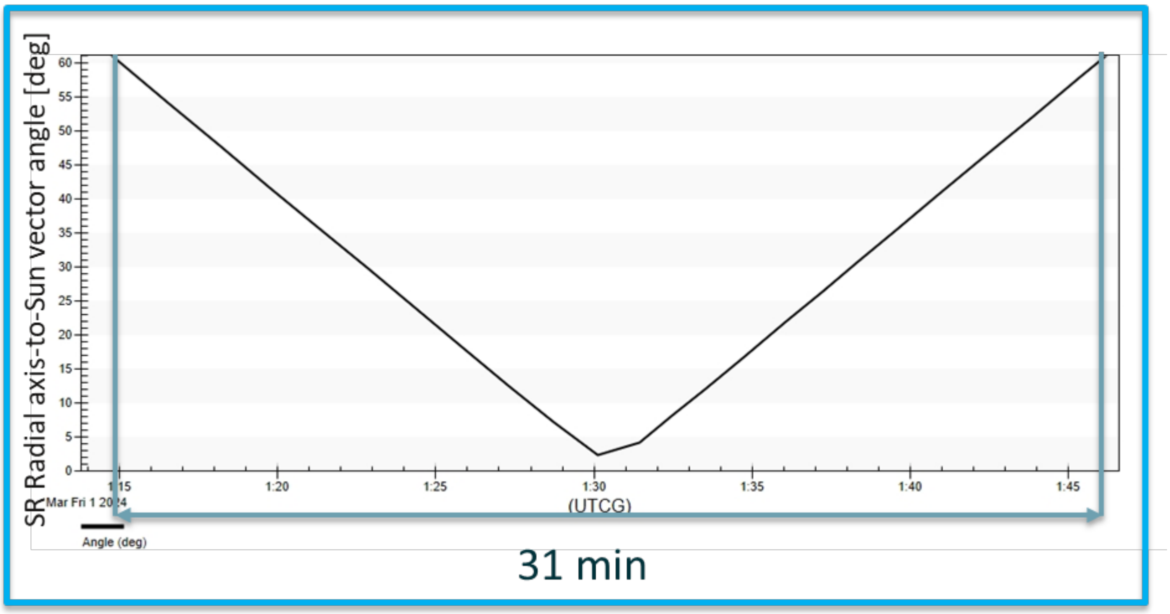


Figure 42: SSO MM SR Radial axis-to-Sun Vector angle good illumination window (Detail)

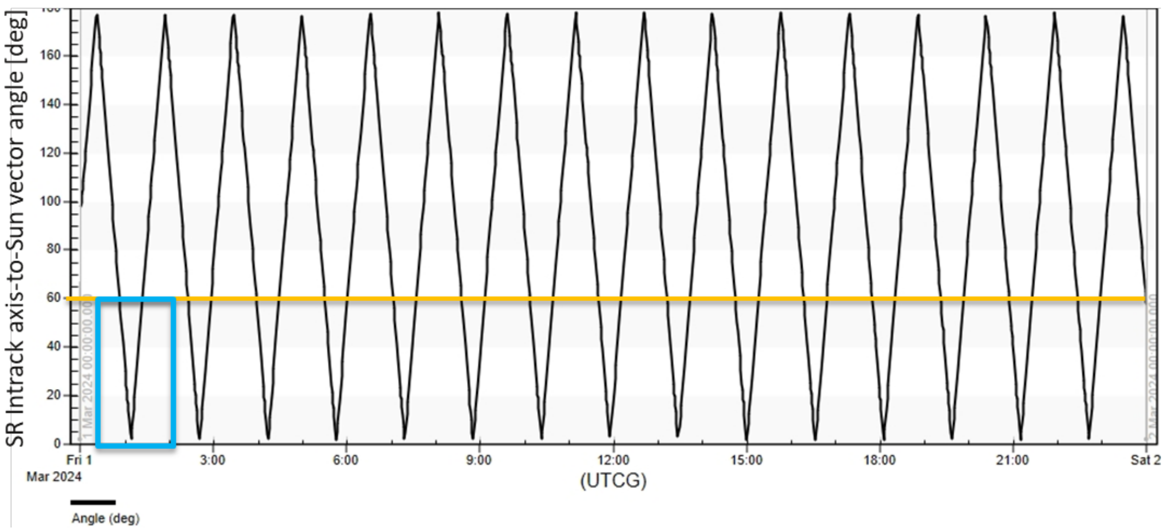


Figure 43: SSO MM SR Intrack axis-to-Sun Vector angle

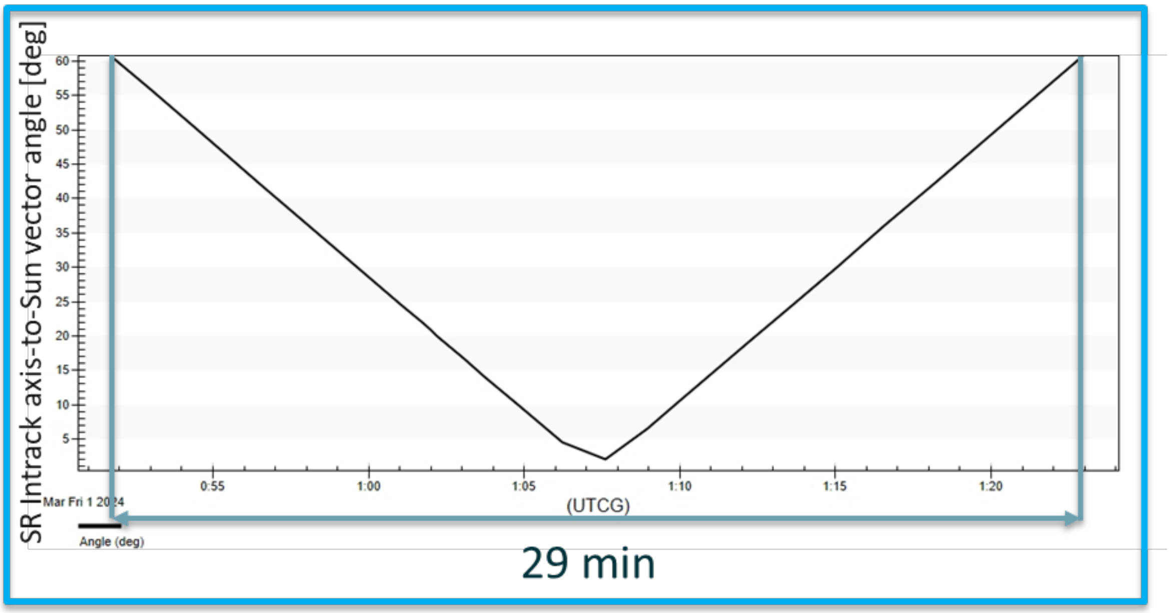


Figure 44: SSO MM SR Intrack axis-to-Sun Vector angle good illumination window (Detail)

SSO DAWN-DUSK ORBIT

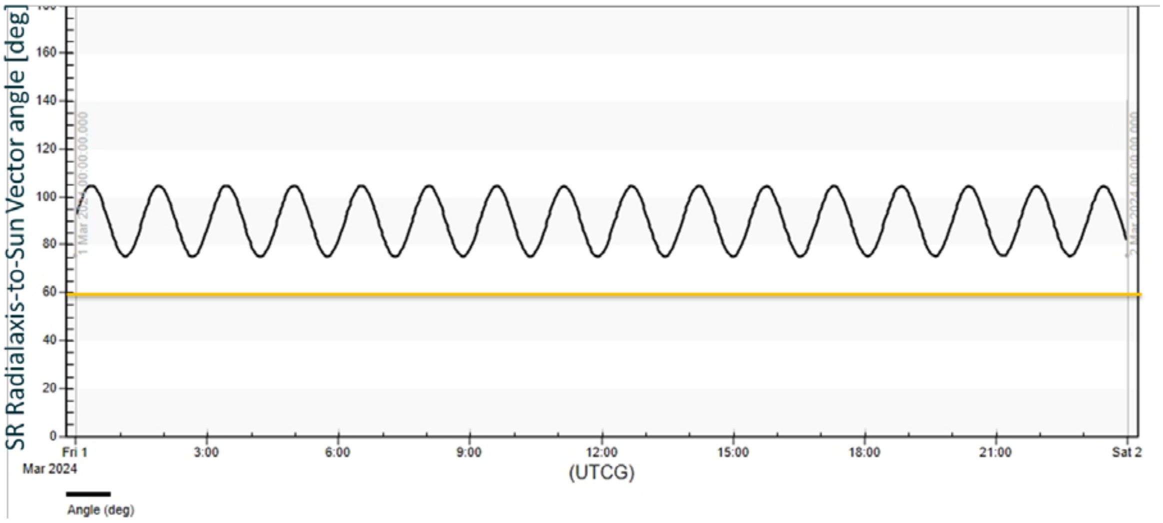


Figure 45: SSO DD SR Radial axis-to-Sun Vector angle

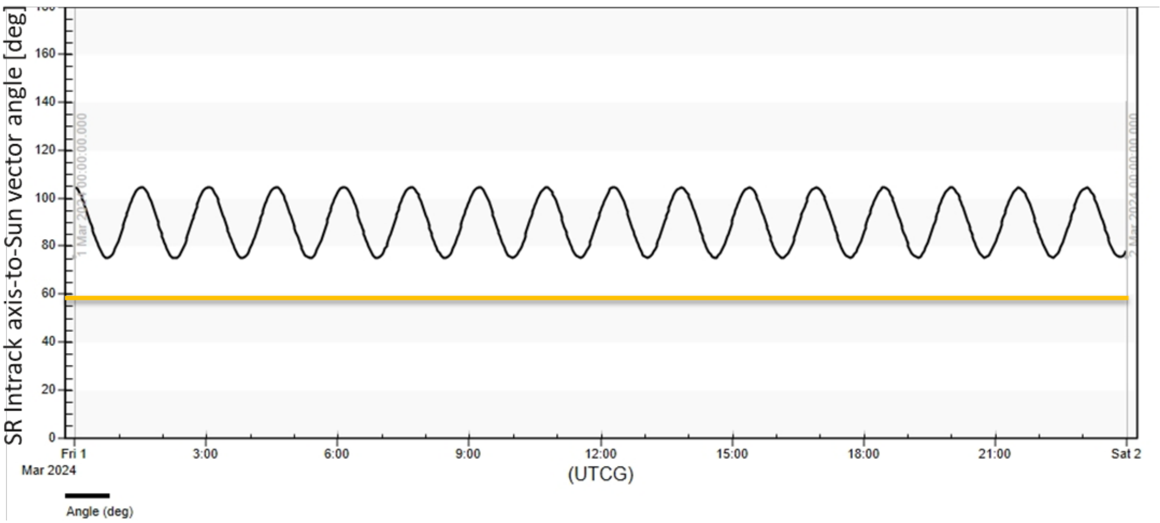


Figure 46: SSO DD SR Intrack axis-to-Sun Vector angle

INTERMEDIATE MIDDAY-MIDNIGHT ORBIT

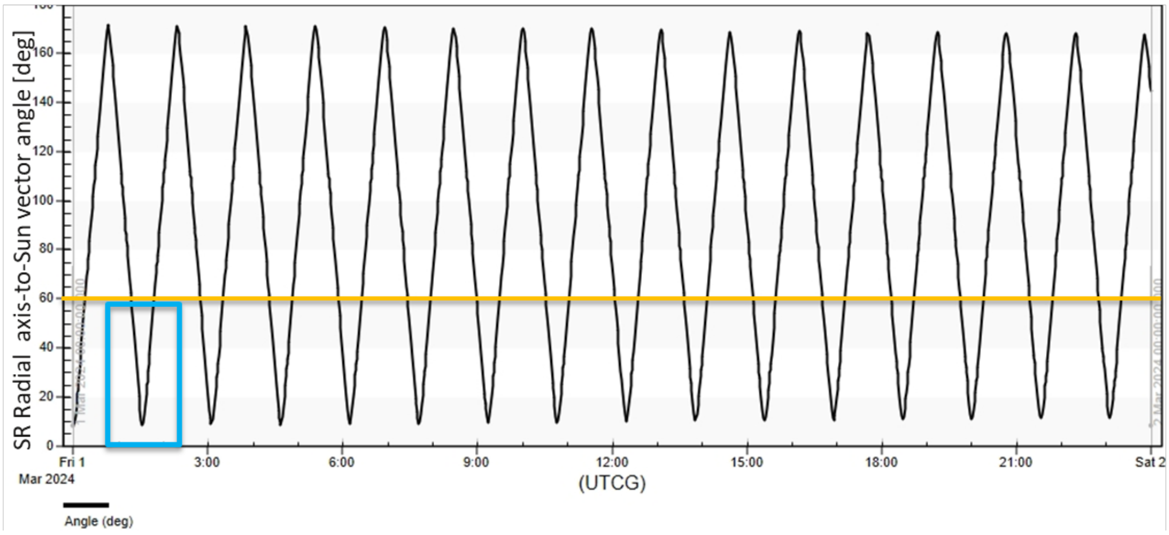


Figure 47: Intermediate MM SR Radial axis-to-Sun Vector angle

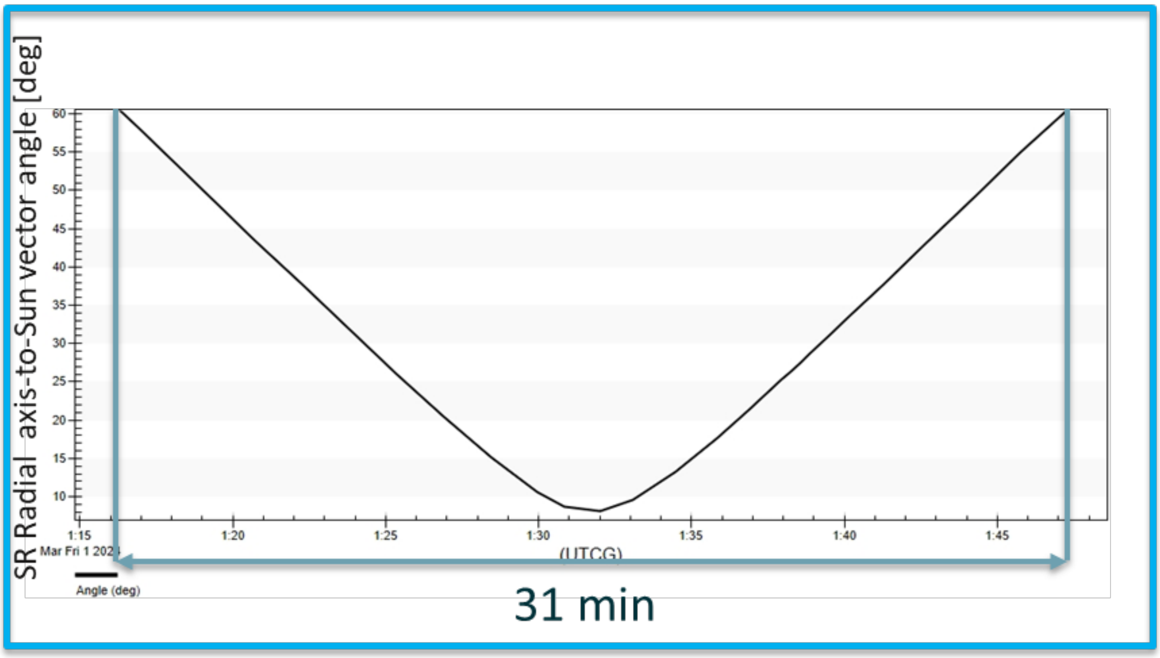


Figure 48: Intermediate MM SR Radial axis-to-Sun Vector angle good illumination window (Detail)

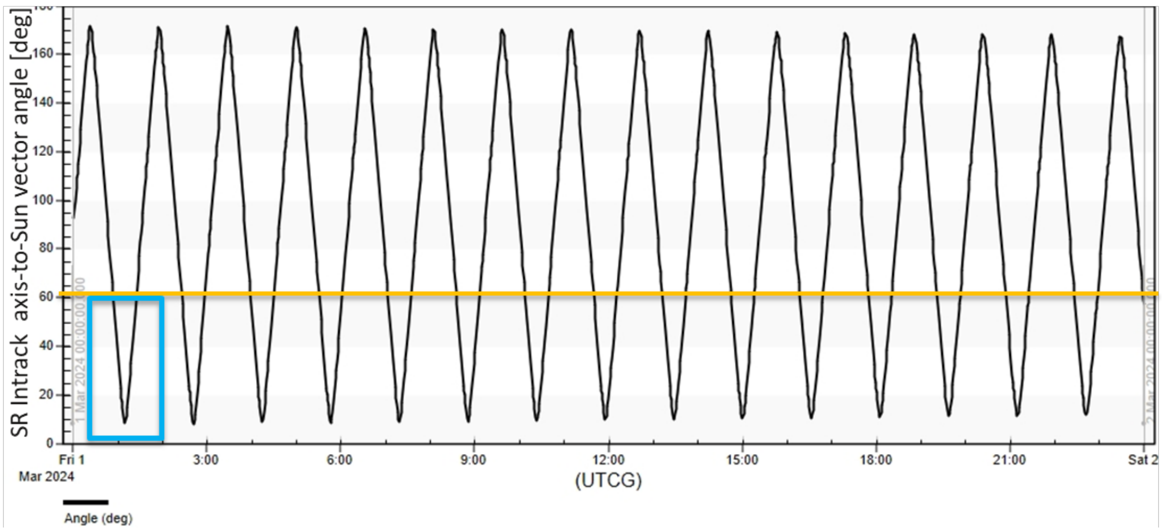


Figure 49: Intermediate MM SR Intrack axis-to-Sun Vector angle

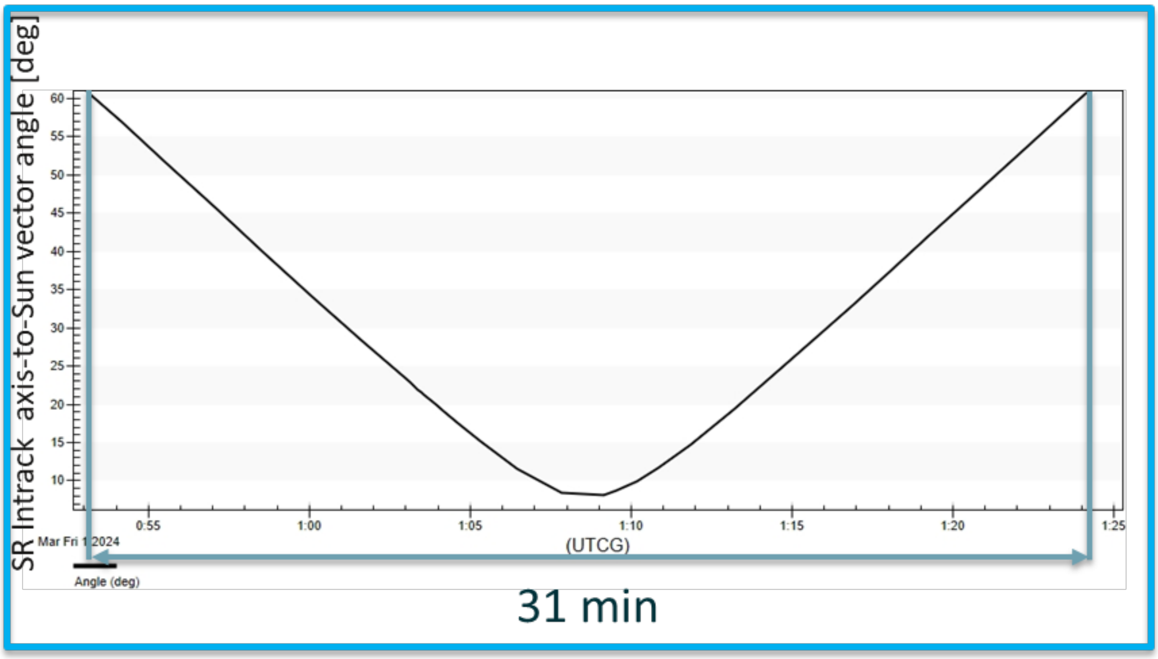


Figure 50: Intermediate MM SR Intrack axis-to-Sun Vector angle good illumination window (Detail)

INTERMEDIATE DAWN-DUSK ORBIT

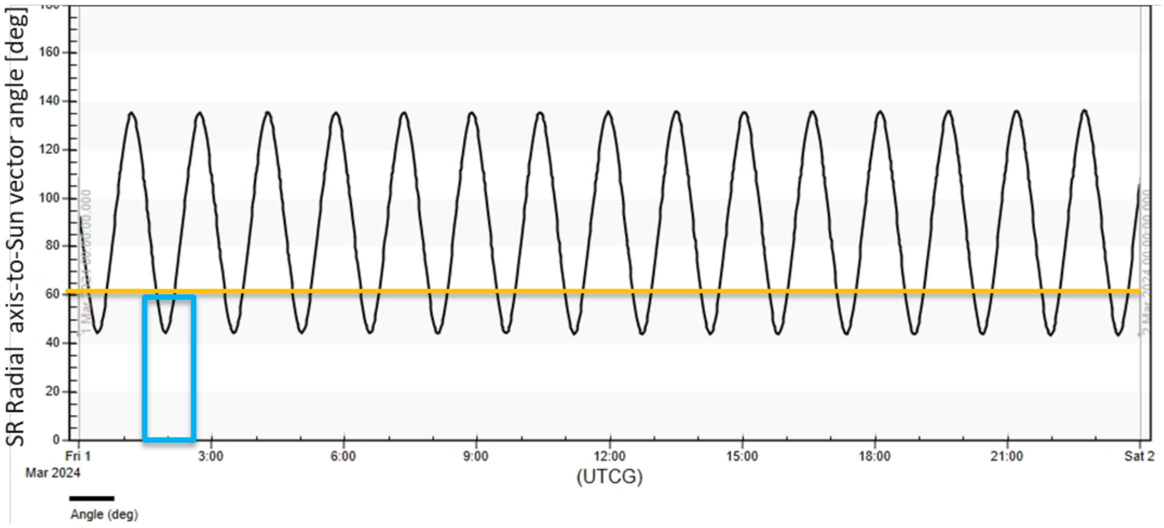


Figure 51: Intermediate DD SR Radial axis-to-Sun Vector angle

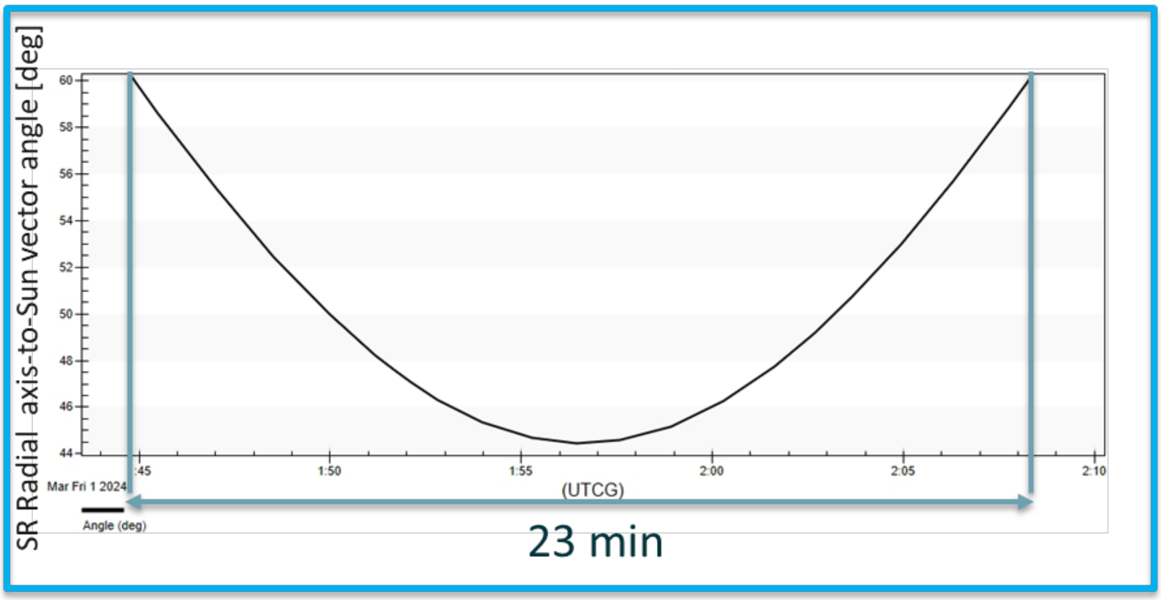


Figure 52: 37 Intermediate DD SR Radial axis-to-Sun Vector angle good illumination window (Detail)

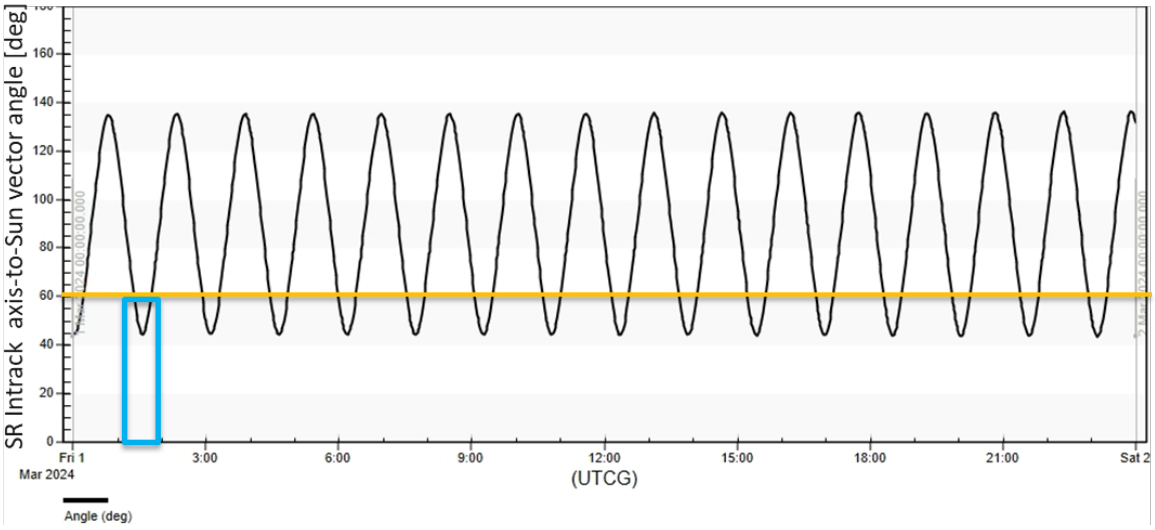


Figure 53: Intermediate DD SR Intrack axis-to-Sun Vector angle

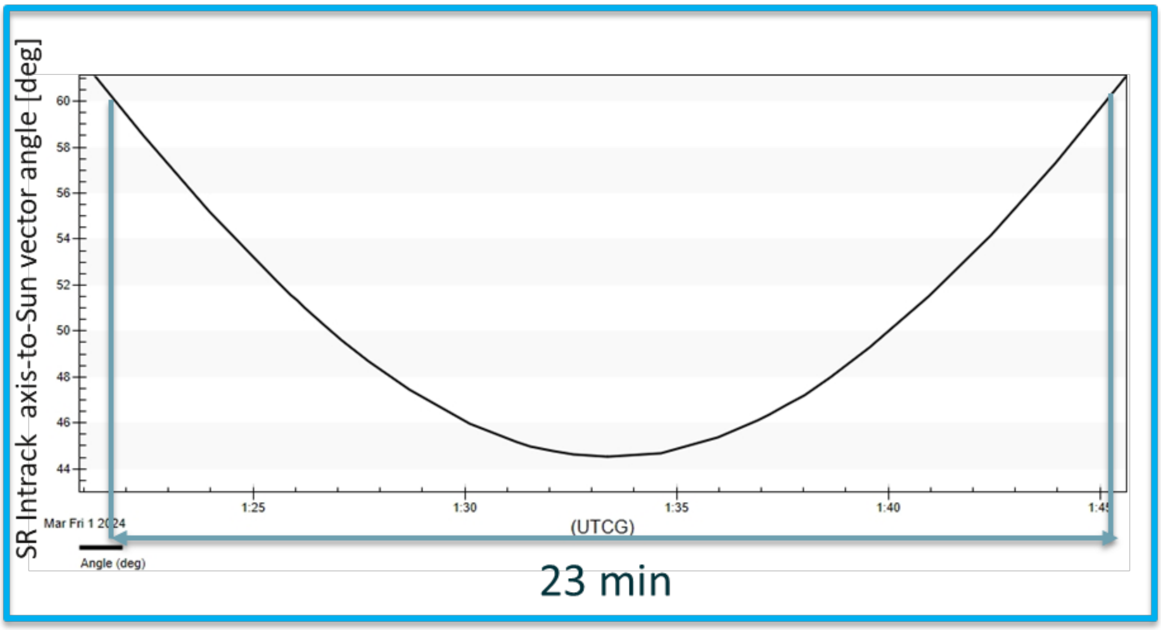


Figure 54: Intermediate DD SR Intrack axis-to-Sun Vector angle good illumination window (Detail)

Regardless of the chosen docking axis an SR Orbit about a 30 minutes of good illumination window will be ensured, except for the Sun Synchronous Orbit Dawn-Dusk and for both Radial and Intrack Docking axis, in this case the illumination threshold is never reached.
Considering the good illumination window and the Ground Station visibility, SROC should start the Final Approach Phase with the appropriate synchronization.
To complete the Docking SROC requires both a good illumination and ground stations visibility window. In the following Figure 55 it is presented the results for the combined analysis:

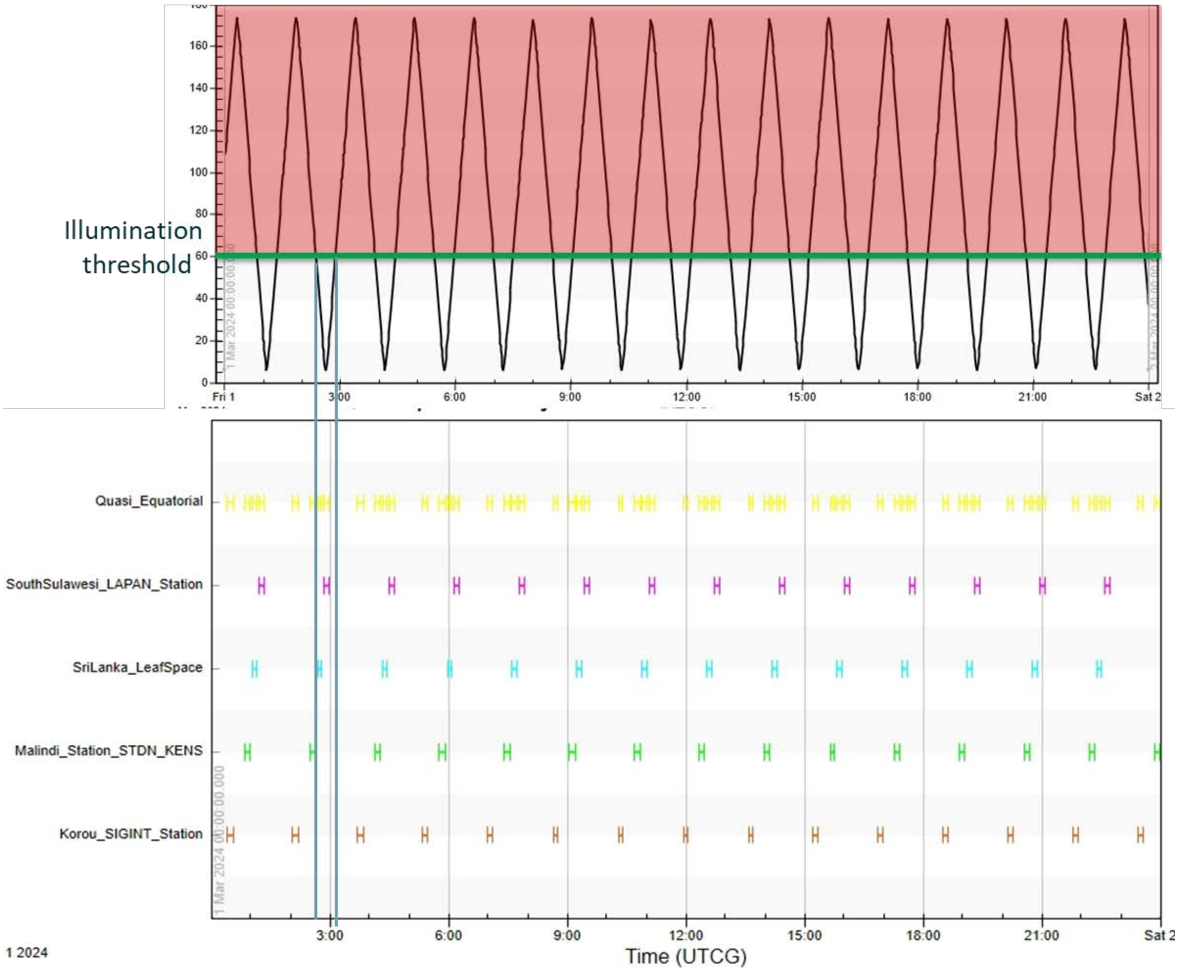


Figure 55: Good illumination and GS visibility window

For the Baseline scenario, considering the set of GS presented in Section 8.8, it is presented the simultaneous availability of good illumination conditions and GS visibility. In this case no continuous communication window is present during the good illumination window.

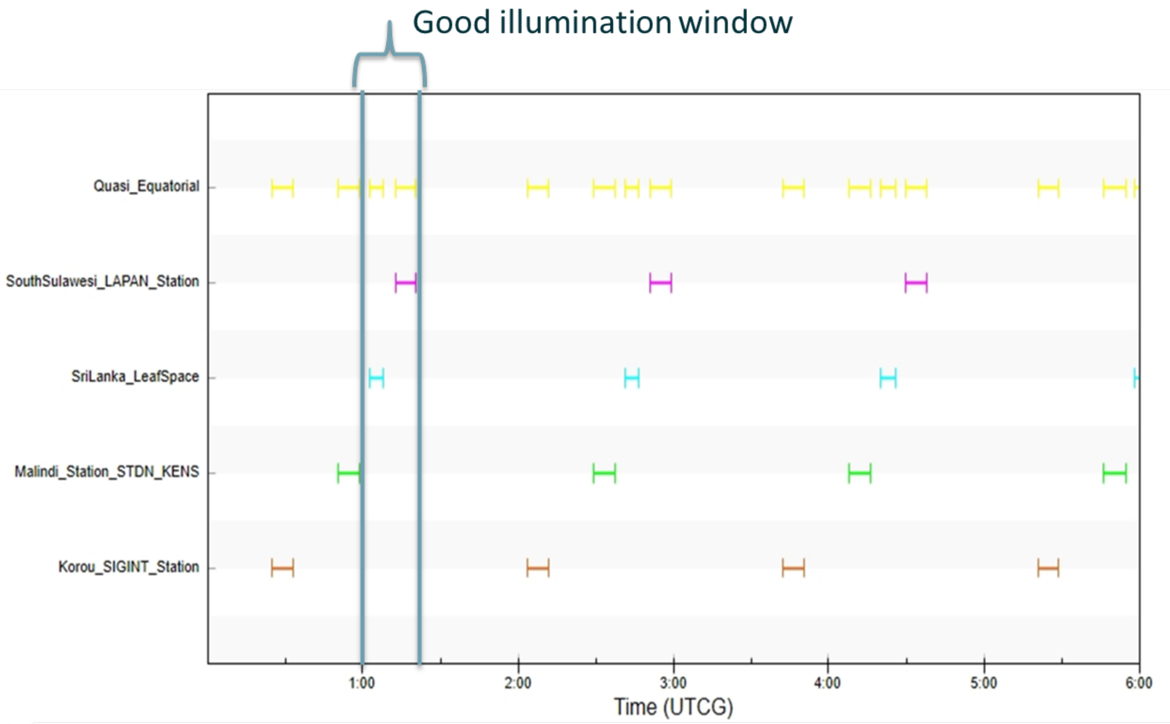


Figure 56: Good illumination and GS visibility window – Detail on the GS visibility

In order to guarantee a minimum 15 minutes of continuous GS visibility, an additional GS was considered. The additional GS is situated in Singapore (Lat: 1.35° N; Long: 103.82° E) with a GS takeover between Sri Lanka/Singapore/South Sulawesi Ground Stations.

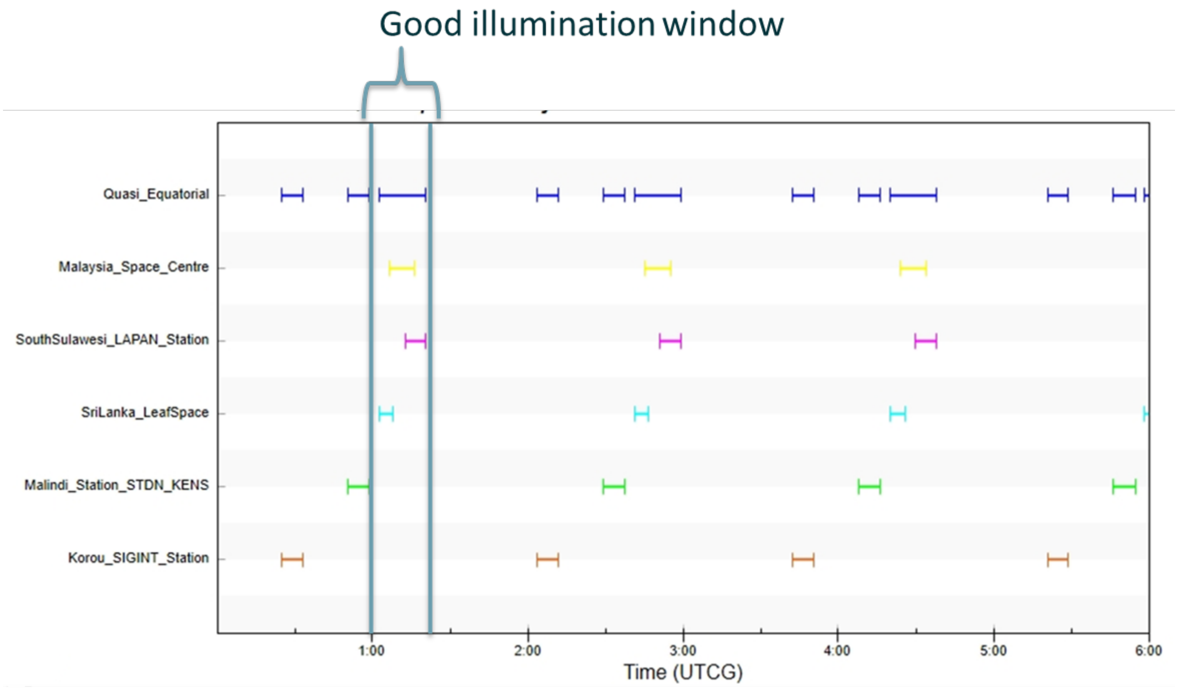


Figure 57: Good illumination and GS visibility window – Detail on the GS visibility - additional GS

3.9 *Space Rider Coverage analysis*

A preliminary coverage analysis was conducted to evaluate the effectiveness of the chosen WSE geometry, to complete the DoE above presented [3.6.6]. As reported in the appropriate Coverage Requirement [SROC-MIS-040], SROC shall cover at least 90% of the SR surface during the Observation Phase.
This analysis was executed within the STK environment employing the 'Coverage Definition' feature. To accomplish this analysis, it is necessary to define a sensor associated to the SROC spacecraft with an appropriate optic geometry and subsequently the lens aperture.

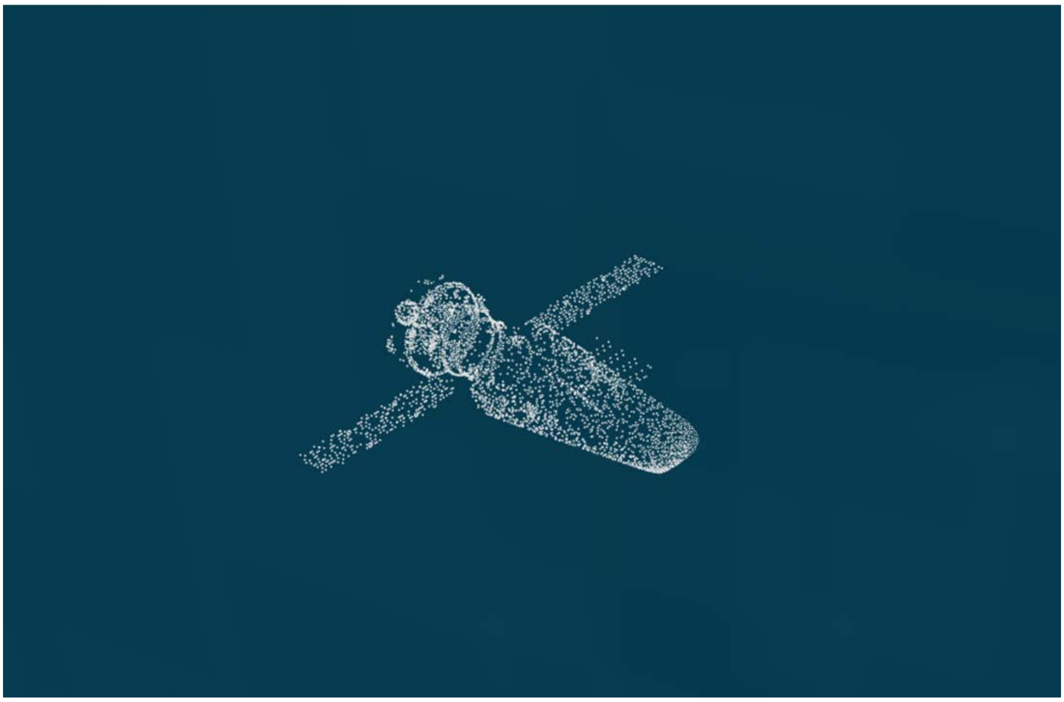


Figure 58: Mesh of the Space Rider model

All the considered assumptions are listed below:

1) The SR Coverage analysis was carried out taking into account the chosen WSE geometry (i.e. 150-150 m).
2) Space Rider attitude is considered fixed, so the spacecraft is oriented toward positive Intrack.
3) Only a single Observation cycle was considered, thus the coverage requirement shall be pursued within this mission segment.
4) The SROC surface was modelled with a set of 4926 not-homogeneous mesh points, in particular a finest mesh was used for the SR-AOM Module in order to better describe the complex series of surfaces, while a less dense mesh was used for the SR-SM and the Solar Panels due to the simple surface geometry, with low or no surfaces curvature.
5) SR ephemerides were used to simulate the rotation of the model in the relative reference system by entering the necessary parameters in the STK rotation file.
6) The visual camera was modelled with a simple conic optic sensor with a 2.5 deg cone half angle.
7) A target pointing attitude is assumed during the entire Observation, thus SROC payload is continuously directed toward Space Rider.
8) No resolution constraints were imposed, since the analysis aims to evaluate the spacecraft potential capability to accomplish the mission objectives, regardless of the specific payload

chosen. That in turn means that “Visibility” (i.e. SR is fully or partially inside the SR sensor FOV) is the only investigated parameter. Concurrently, a payload evaluation was carried out within the same Work Package, but the results are omitted as they are beyond the scope of the present thesis.

The analysis results are given in the following graph:

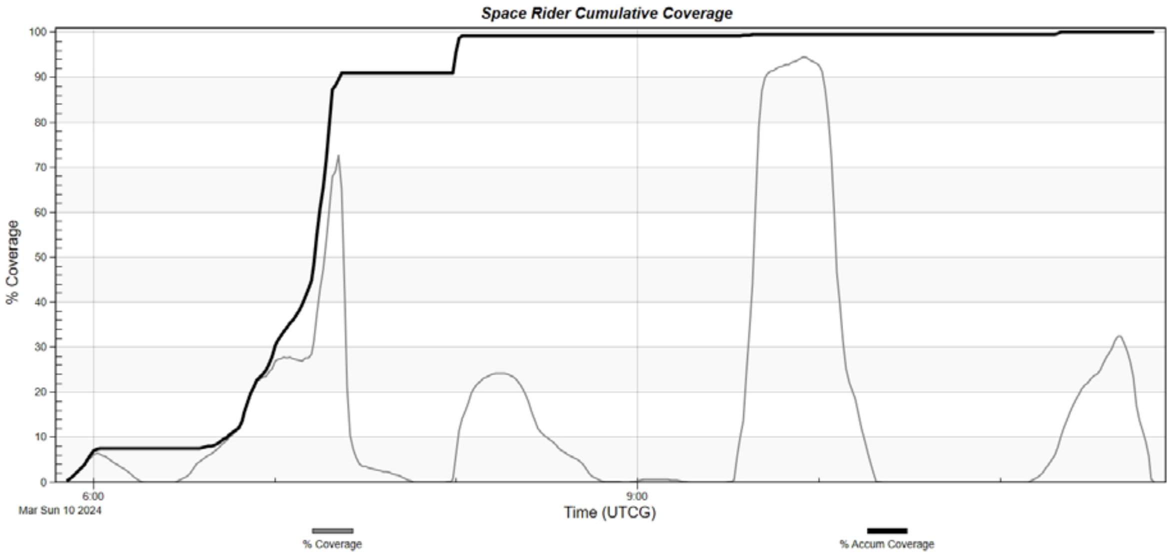


Figure 59: SR Coverage and Cumulative Coverage over one Observation cycle

In grey is reported the actual coverage taken step-by-step every 60 seconds, while in black is reported the cumulative coverage. As it can be seen, the minimum required coverage is reached after ~90 minutes, this means that even one full orbit is sufficient to cover the 90% of the SR surface, moreover within the Baseline Observation cycle of 4.5 hours the entire SR surface is covered.
Looking at the actual coverage it is possible to notice a great variability on this parameter, that reaches a maximum value of approximatively 92% after 4 hours, when SROC is almost at the farthest point from SR thus the FOV is maximised, whereas the minimum instantaneous value is almost zero and it is justified considering the coverage overlap.
For the same reason, the first orbit is sufficient to reach the imposed requirement since none of the mesh points are covered yet, then almost 3.5 orbits are needed to complete the coverage, as long as the SR surface is partially covered, and those points does not enter into the “actual” coverage value.

4 OFF-NOMINAL MANOEUVRES ANALYSIS

An analysis of the off-nominal manoeuvres is carried out, in order to evaluate the limits in which the safety of Space Rider is guaranteed despite the SROC trajectory deviations due to thrust errors. For this purpose, the values of the nominal manoeuvres parameters of the scenario were considered and starting from these values errors were added in terms of direction and magnitude of the manoeuvre performed. The analysed scenarios are both the Space Rider Quasi-Equatorial orbit in which SROC performs the in-plane strategy after 5 days of Commissioning (baseline scenario) up to a higher distance and then starts a OPA until the WSE insertion or the Option 2 scenario where a Hold Point 2 is situated after the IPA at a closer distance from SR.

The nominal manoeuvres are expressed in a frame centred in the SROC centre of mass with the x-direction aligned with the SROC velocity direction, the y-direction aligned with the orbit normal direction (the orbit angular momentum direction) and the z-axes completes the triad (i.e. in a circular orbit the z-axes is along the radial direction). This is the RIC frame (Radial, Intrack, Crosstrack), see Figure 60. So, the ΔV vector that define a manoeuvre in this reference frame is expressed by three polar coordinates: elevation angle, azimuth angle and magnitude. The Elevation angle is the angle between the x-axis (velocity direction) and the projection of the ΔV vector in the x-z plane, positive towards z. The Azimuth angle is the angle between the x-axis and the vector projection in the x-y plane, positive towards y.

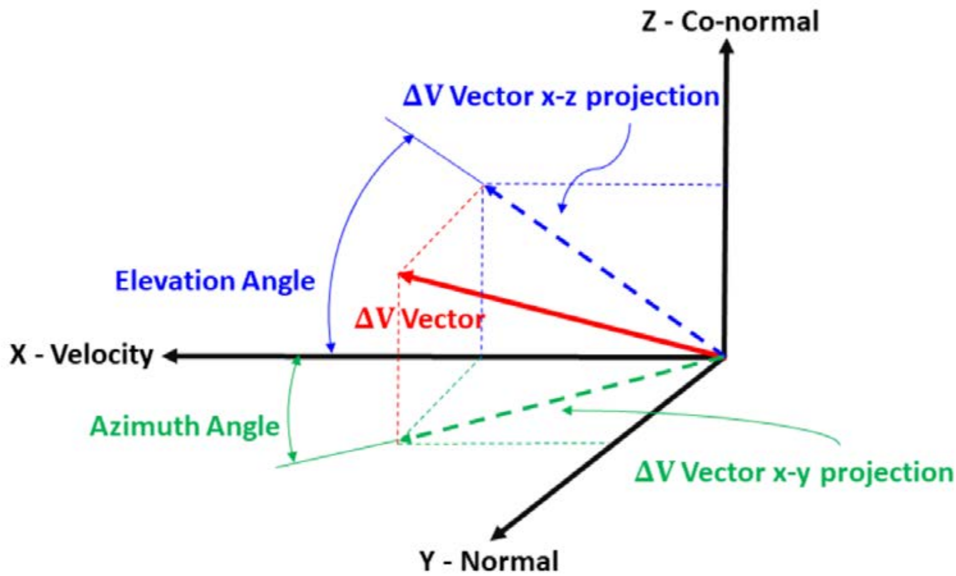


Figure 60: VNC Frame for SROC Manoeuvres

The results of the off-nominal manoeuvres are parsed without considering any corrective actions, that is SROC continues to propagate its trajectory for 24 additional hours from the manoeuvre execution. This choice has two reasons: 1) to evaluate the severity of an incorrect manoeuvre without carrying out corrections; 2) to assess the severity without impacting on the operations planning.

A sensibility analysis was conducted to assess the influence of the single direction or magnitude errors on the minimum relative range for each off-nominal case considered the results are presented in a 2D scatter plot for the directions errors and 1D magnitude errors. Similar results for the mixed direction-magnitude errors are not graphically representable.

4.1 *Rendezvous Option 1*

4.1.1 Off-nominal manoeuvre entering Hold Point 1

The entry manoeuvre in the HP#1 is performed at the beginning of the Verification Phase. This manoeuvre increases the mean SMA of SROC to reach the same value of SR in order to stop the drift away motion and synchronize the mission’s timelines. Hereafter (Table 25) are reported the manoeuvre values for the nominal mission and some other parameters useful to compare the off-nominal scenarios to the nominal one:

Table 25: Hold Point 1 Nominal Manoeuvre Values

Elevation [deg]	Azimuth [deg]	Magnitude [m/s]
0	0	0.44
mean SMA [km]	6778.08	
min Range [km]	331.76	
max Range [km]	335.13	
next Manoeuvre [m/s]	0.44	

Figure 61 shows the nominal relative trajectory during the HP#1. The manoeuvre to enter HP#1 is along the velocity direction to change the mean SMA, but the trajectory that follows is outside the orbital plane of SR. This is due to the perturbations suffered during the Commissioning phase which have not yet been corrected.

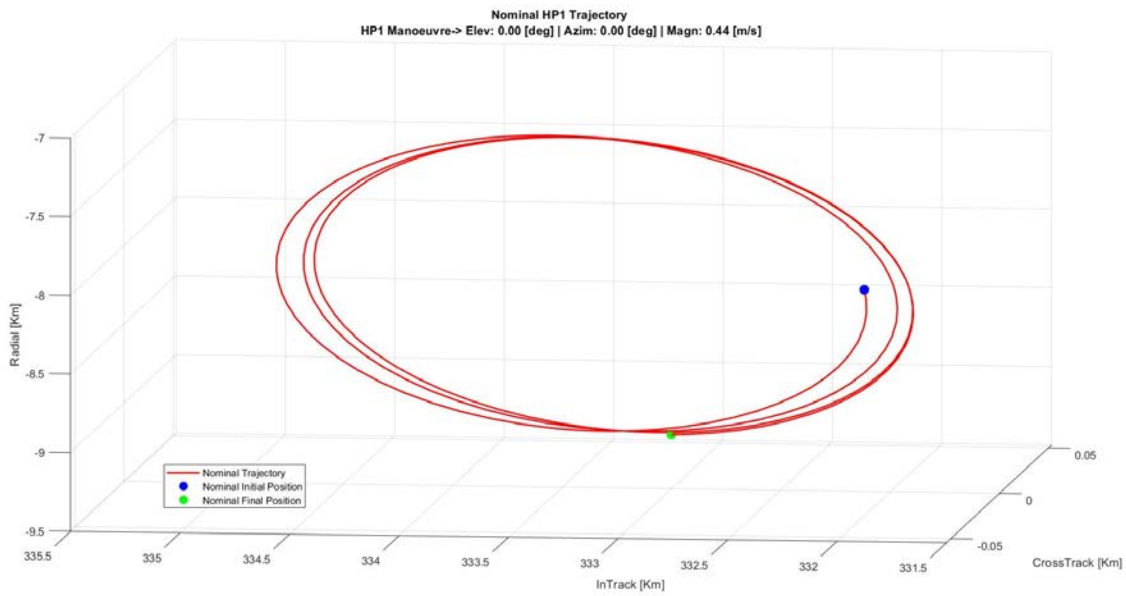


Figure 61: HP#1 Nominal Trajectory

The off-nominal analysis was performed by varying the angles of ± 5 [*deg*] from the nominal value, with a step of 0.5 [*deg*]; while the magnitude was varied by ± 100% from the nominal value, with a 5% step. Comparisons with the nominal mission profile are made in terms of mean SMA achieved and of minimum and maximum relative distance reached during the Hold Point propagation. The minimum and maximum distance, in the worst cases, represents the end position of the Hold Point, therefore it will affect the cost of the next manoeuvre to be carried out.
Since the relative distance does not differ significantly for any of the Off-Nominal case, the resuming scatter plots are not reported for this manoeuvre.

Direction errors

Mistaking only the manoeuvre direction does not change the mission profile. The worst case occurs when the off-nominal thrust direction has an elevation angle of 5 deg and an azimuth angle of -5 deg (the magnitude is the nominal one). In this case the reached mean SMA is 6778.84 km and differs from the nominal value by 0.76 km.

Magnitude errors

If the direction is nominal, by varying the manoeuvre magnitude the mission profile will deviate more from the baseline. The worst situations occur when 100% more than the nominal manoeuvre is performed and when it is not performed at all. If the magnitude increases of 100% (0.87 [m/s]), the SROC mean SMA will raise up to 6778.85 km (0.77 km greater than the nominal). In this scenario SROC will be in a higher orbit, so it will start relative motion toward SR. During the Hold Point phase, the minimum relative range between the two spacecraft decreases to 309.9 km. If the manoeuvre is not executed (i.e. the magnitude is decreased of 100%), the situation is similar but opposite to that just described. SROC will continue its drift away motion, decreasing its mean SMA to 6777.31 km and reaching a maximum distance of 355.09 km. These two off-nominal scenarios as resumed in the following table (Table 26).

Table 26: HP#1 Off-Nominal Manoeuvre Values

	Nominal	Off-Nominal 1	Off-Nominal 2
Elevation [deg]	0	0	0
Azimuth [deg]	0	0	0
Magnitude [m/s]	0.44	0.88	0.0
mean SMA [km]	6778.08	6778.85	6777.31
min Range [km]	331.75	309.9	331.92
max Range [km]	335.13	333.27	355.09
next Manoeuvre [m/s]	0.44	0.45	0.45

Direction and magnitude errors

If at the same time the manoeuvre is performed with errors in both direction and magnitude, the resulting trajectory would not differ much from the cases just presented. In fact, the effect of a wrong direction up to 5 degrees is weak when compared to the errors on magnitude. Figure 62 and Figure 63 show two off-nominal trajectories in which SROC reaches the minimum (below) and maximum (above) values of the mean SMA.

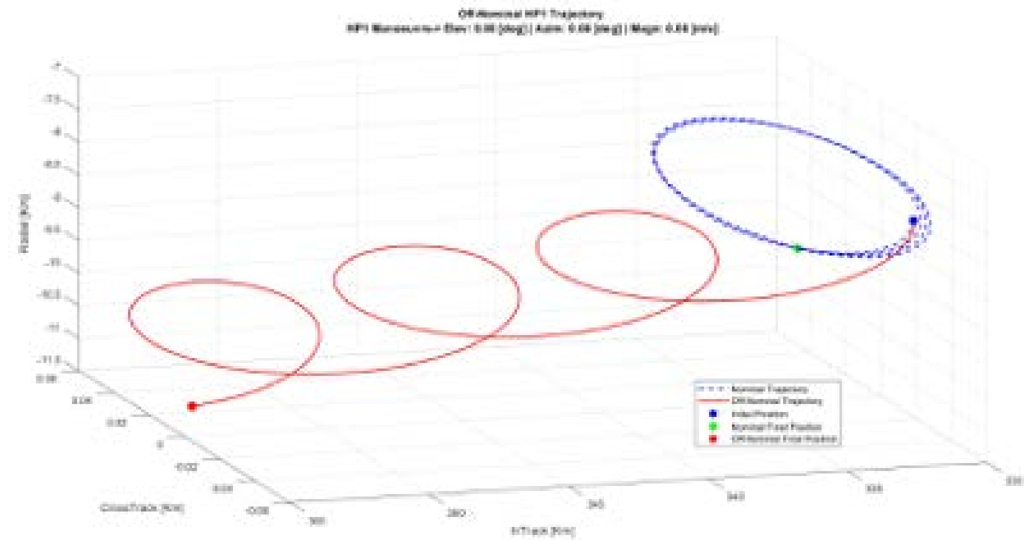


Figure 62: HP#1 Off-Nominal Direction and Magnitude - maximum SMA

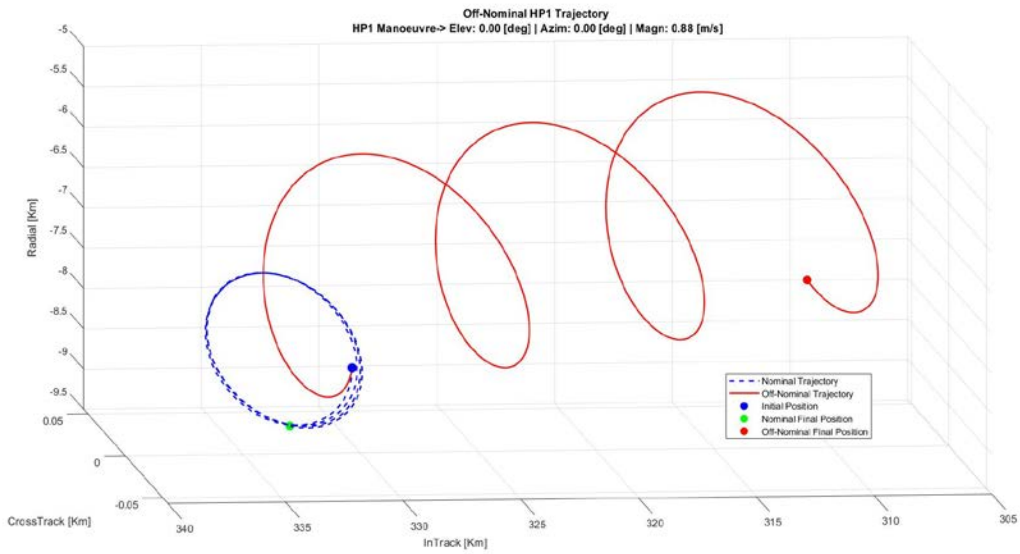


Figure 63: HP#1 Off-Nominal Direction and Magnitude - minimum SMA

A failure on the manoeuvre to enter the Hold Point 1 does not involve any risk towards Space Rider, but only an increase in the cost of the Delta-V for SROC and a new optimized trajectory for the subsequent In-Plane Approach Rendezvous.

4.1.2 Off-Nominal manoeuvre entering the In-Plane Approach Rendezvous (IPA)

To approach Space Rider and start the inspection phase, SROC performs an in-plane manoeuvre to execute the In-Plane Approach Rendezvous. After the in-plane trajectory toward SR and reaching the InTrack Target (60 km in the nominal scenario), SROC performs an out of plane manoeuvre to get close to SR with a the Out-of-Plane Approach Rendezvous (OPA). The IPA is considered valid if the minimum reached distance along the InTrack direction is greater than 1 Km in case the OPA manoeuvre is not performed.

The *IPA validity* idea derives from safety considerations, and it was introduced to understand the range of acceptable thrust level (in other words to "determine the manoeuvre") that can be applied

for the insertion in the IPA segment. If the IPA manoeuvre, in case no OPA is executed as planned at the end of the "nominal" IPA segment (i.e. at 60km from SR), leads SROC to arrive at a distance shorter than 1km from SR in 24 hours after the missed OPA manoeuvre, then the IPA manoeuvre is not acceptable, that is it is considered non valid. This 'IPA validity' ensures that even in the off-nominal case (no OPA executed) a distance from SR of less than 1 km is never reached in the following 24 hours. So, the IPA validity check can be seen as an additional precaution for the off-nominal case in which no OPA manoeuvre is performed and SROC propagates (free flight) for 24 hours.
This definition is fundamental for the conclusions made after the analysis. Hereafter (Table 27) are reported the ΔV vector for the nominal scenario and some other parameters useful to compare the off-nominal scenarios to the nominal one:

Table 27: In-Plane Approach Nominal Manoeuvre Values

Elevation [deg]	Azimuth [deg]	Magnitude [m/s]
0	0	0.45
min Range [km]	60.98	
max Range [km]	334.83	
next Manoeuvre [m/s]	0.58	
IPA Duration [day]	3	

It must be noticed that the minimum range for the nominal mission profile is the InTrack target. Furthermore the "next Manoeuvre ΔV" includes the entry manoeuvre in the OPA trajectory. It depends on the execution of the IPA. Figure 64 shows the nominal relative trajectory during the In-Plane Rendezvous. As SROC approaches the final position of the IPA, the relative orbits become closer and closer. In fact, due to the atmospheric drag, the SROC velocity is reduced, up to zero before reaching SR, if the OPA is not performed.

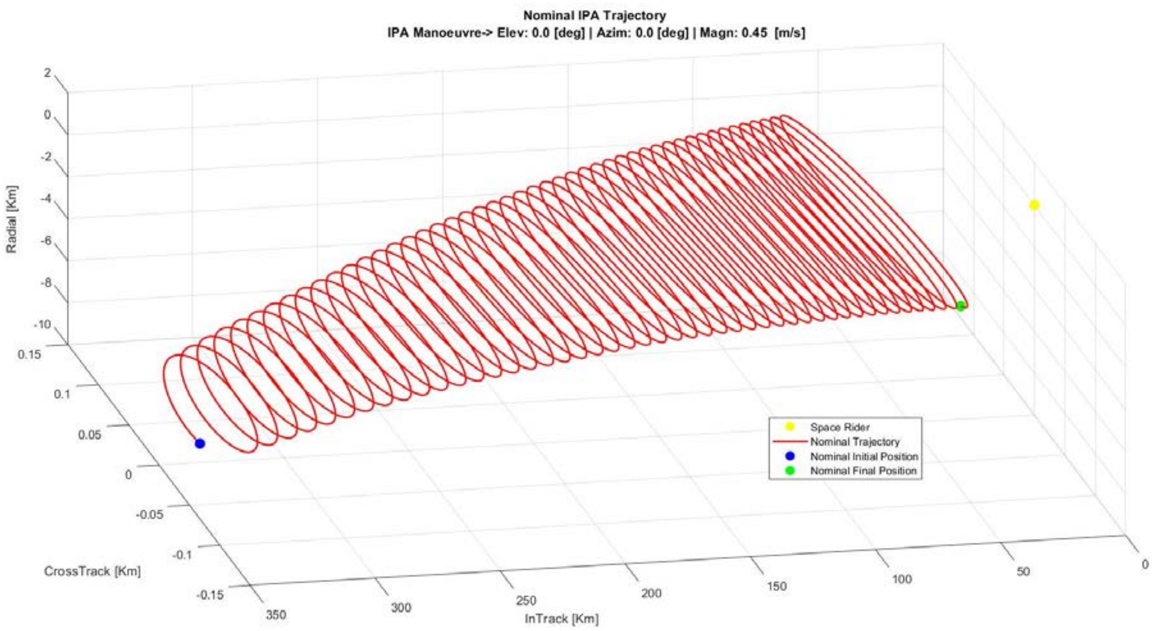


Figure 64: IPA Nominal Trajectory

The off-nominal analysis was performed by varying the angles of ± 5 $[deg]$ from the nominal value, with a step of 0.5 $[deg]$, the magnitude of ± 100% from the nominal value, with a 5% step, and the combinations of the two errors were also considered. Since the IPA is a trajectory towards the target spacecraft into its orbital plane (although the perturbations naturally cause the SROC orbit to tilt), performing an off-nominal manoeuvre could increase the risk of collision with the target itself. Therefore, the objective of the analysis is to determine the maximum permissible errors so that the IPA is still considered valid, even if no longer optimized. Furthermore, for an off-nominal IPA it is necessary to evaluate the minimum distance reached with respect to SR and the time needed to reach this position.

Direction errors

As for the off-nominal HP#1, mistaking the thrust direction up to 5 degrees from the nominal values does not involve any greater risk to Space Rider. In fact, all the cases of off-nominal IPA analysed by varying the manoeuvre direction were valid and furthermore the minimum distance reached without the OPA is always higher than the nominal one. The correct manoeuvre is performed in the orbital plane of SR, therefore the manoeuvre magnitude to approach it is maximized along the velocity direction. If the manoeuvre is performed with the same magnitude but outside the SROC orbital plane, there is a dispersion of ΔV as there would be a greater out of SR plane trajectory. From this point of view, an off-nominal manoeuvre with a wrong direction is safer for SR.

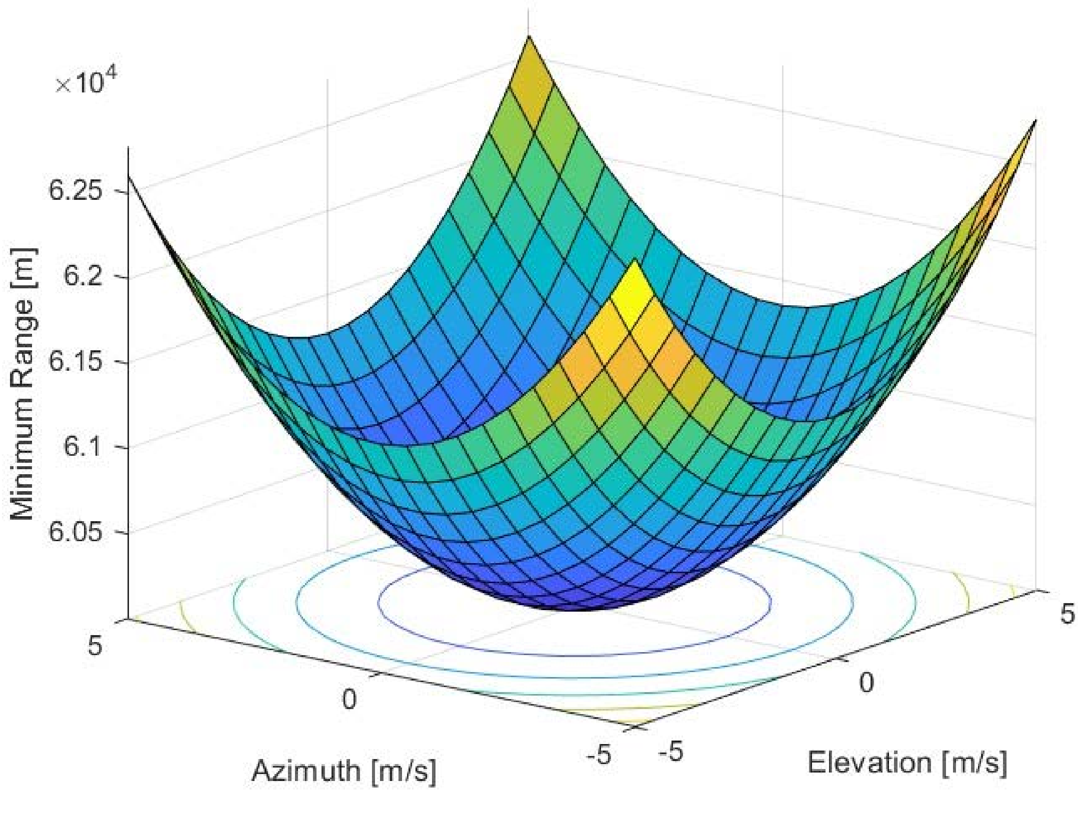


Figure 65: Scatter plot Direction errors – IPA Opt 1

Magnitude errors

As regard mistaking the thrust magnitude, two different aspects are considered: the minimum reached distance during the IPA and the minimum reached distance if the OPA manoeuvre is not executed with the respective time duration. If the magnitude is less than nominal, SROC reaches a greater relative distance, a greater InTrack Target (considering the same propagate duration) before running the OPA. This does not involve any additional risk for Space Rider, but simply an increase in ΔV cost for SROC. For this reason, it is necessary to carefully parse the manoeuvres with a greater magnitude. The first non-valid IPA occurs for a 105% of magnitude. In this case the minimum distance if the OPA is not executed (remembering the definition for valid IPA) is 267.1 m. This off-nominal scenario involves a higher risk of collision with Space Rider only if the Out-of-Plane Rendezvous is not performed. In fact, the minimum distance reached during the In-Plane Rendezvous is 42.31 km, so if SROC performs a new re-defined OPA manoeuvre the mission can continue without other risks. The following Figure 66 shows the off-nominal trajectory with highlighting the positions in which the distance has a minimum value during the IPA and in case of no OPA.

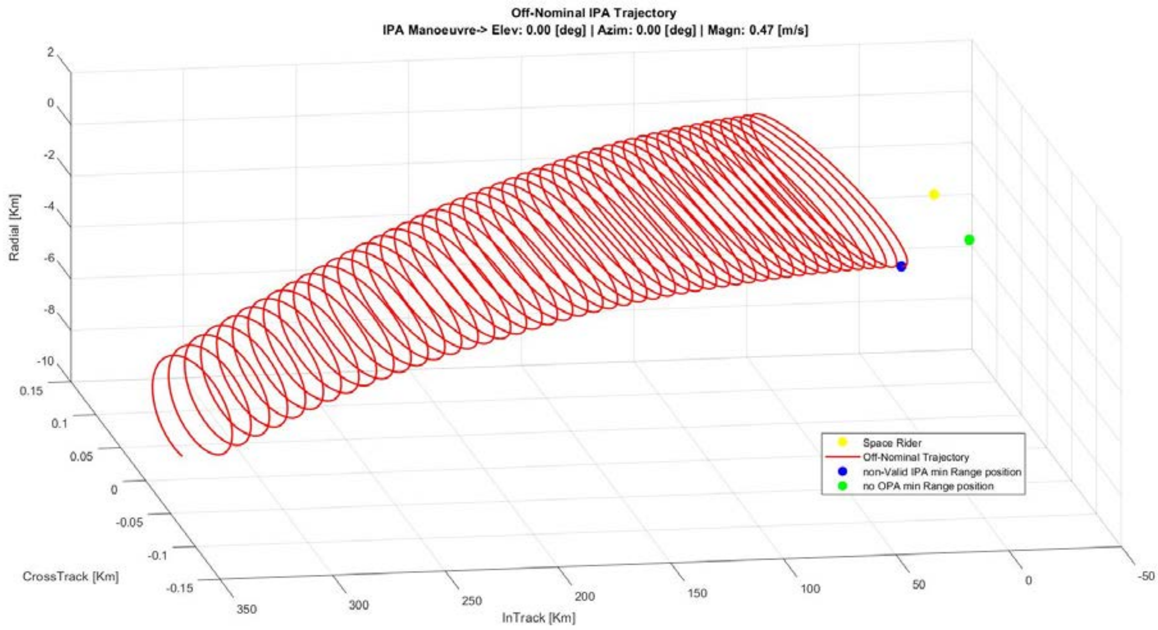


Figure 66: IPA Off-Nominal Magnitude - minimum distance for no OPA

By further increasing the magnitude of the manoeuvre, the trajectory of the IPA would be ever closer to SR, up to overcoming it towards the negative InTrack direction. The minimum distance between the two spacecraft occurs for a manoeuvre performed with 150% of the nominal value (0.67 [m/s]). In this scenario the minimum distance with no OPA is 149.8 m, starting in the negative InTrack direction. Figure 67 shows that trajectory and Table 28 resumes the two described off-nominal scenarios.

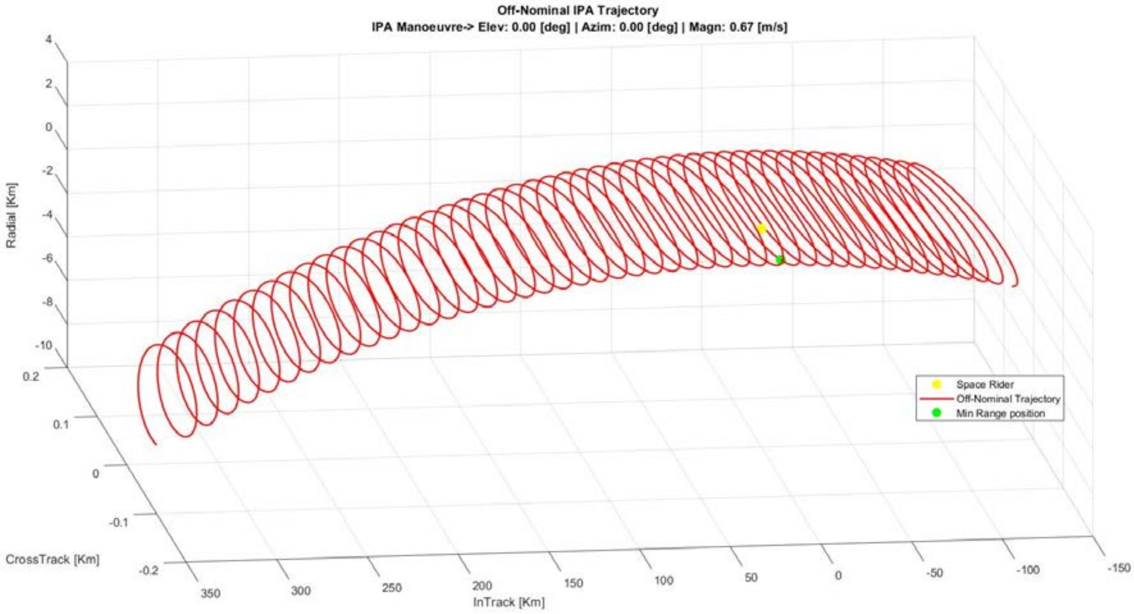


Figure 67: IPA Off-Nominal Magnitude – minimum distance during IPA

Table 28: IPA Off-Nominal Manoeuvres Values Comparison

	Nominal	Off-Nominal 1	Off-Nominal 2
Elevation [deg]	0.0	0.0	0.0
Azimuth [deg]	0.0	0.0	0.0
Magnitude [m/s]	0.45	0.47	0.67
IPA min Range [m] (module and RIC frame components)	$60.98 \cdot 10^3$ [392.7 $60.0 \cdot 10^3$ -125.61]	$42.31 \cdot 10^3$ [555.4 $42.3 \cdot 10^3$ -125.8]	149.8 [4.65 -135.3 -64.1]
Time to the min Range [day]	3	3	2.1 [-69.7 -257.4 14.6]
No OPA min Range [m] (module and RIC frame components)	14.55 [919.2 $14.51 \cdot 10^3$ 272.6]	267.1	/
Time to the min Range no OPA [day]	4	3.71	/

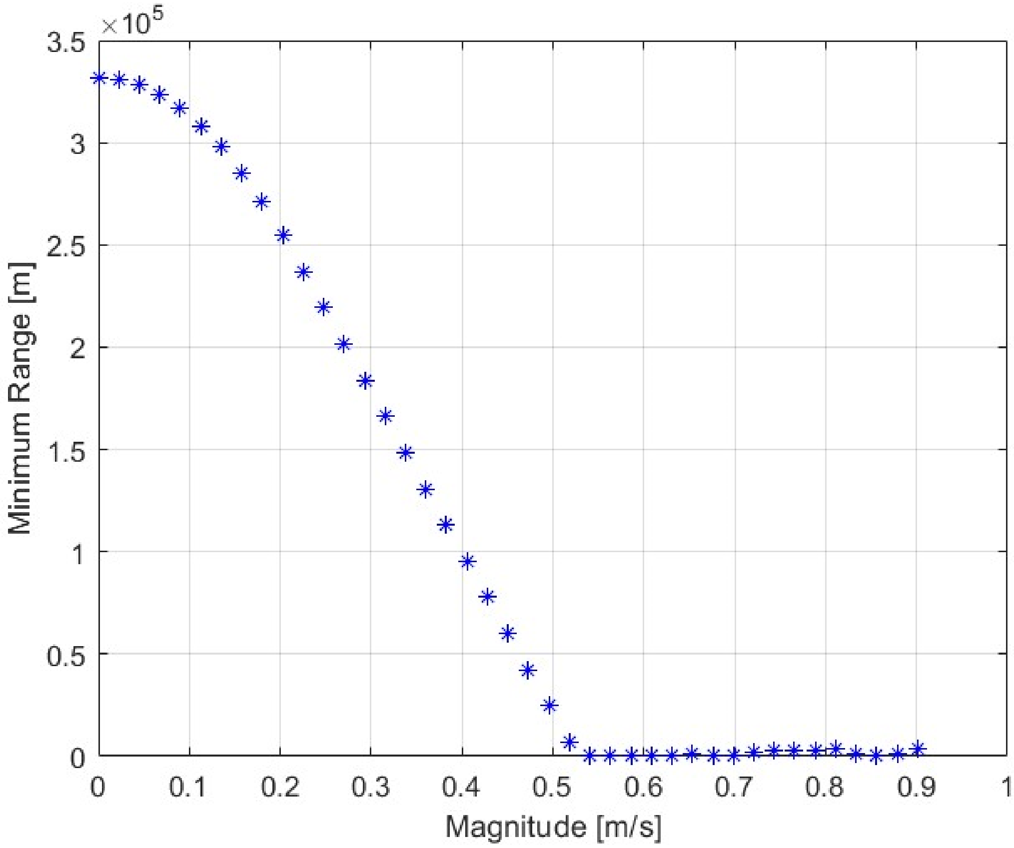


Figure 68: Scatter plot Magnitude errors – IPA Opt 1

Direction and magnitude errors

Direction errors involve no additional risk but combined with magnitude errors they become critical for the mission safety. The minimum distance during the IPA drops to 29.88 m and is reached with errors of -4.5 deg on the elevation, -3.0 deg on the azimuth and a magnitude 190% the nominal. This distance is well below the 200-meter radius of the KOZ so far considered. The relative trajectory of this scenario is shown in Figure 69.

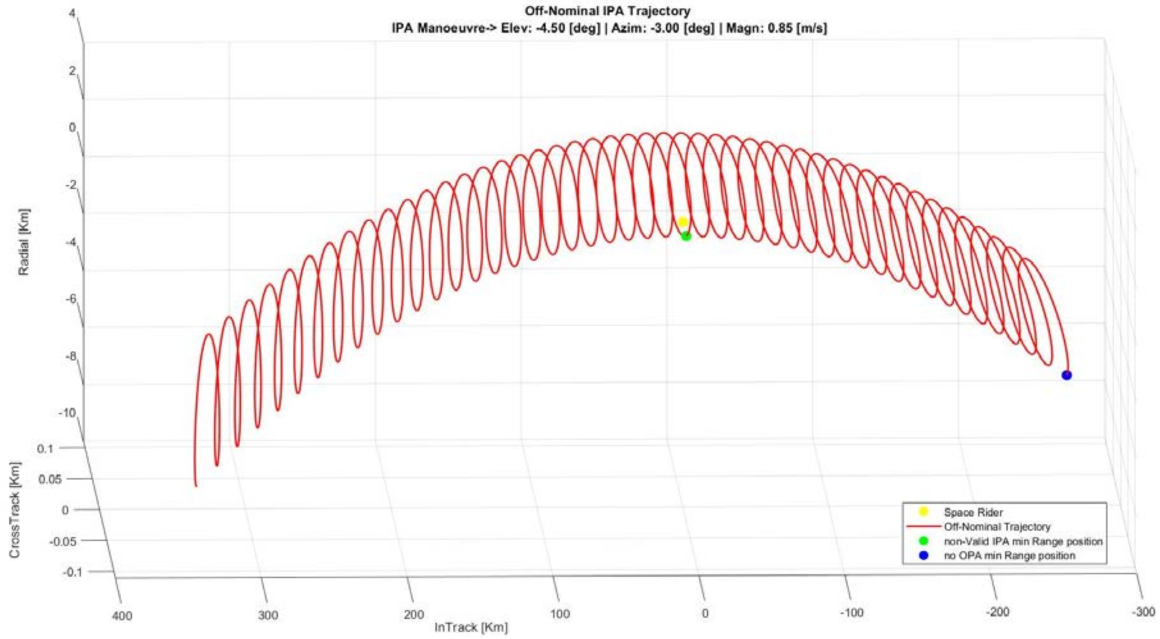


Figure 69: IPA Off-Nominal Direction and Magnitude – minimum distance during IPA

If the OPA is not performed, the minimum distance reached is 10.37 m with -4.5 deg of elevation, -5.0 of azimuth and a magnitude increased by 15% compared to the correct one. This off-nominal scenario is also to be avoided, because SROC shall not enter the KOZ. If the OPA entering manoeuvre is executed, the minimum distance reached during the In-Plane trajectory is up to 85.52 km, within 3.12 hours after the IPA end. Figure 70 shows the IPA relative trajectory and the minimum distance position if the OPA is not executed.

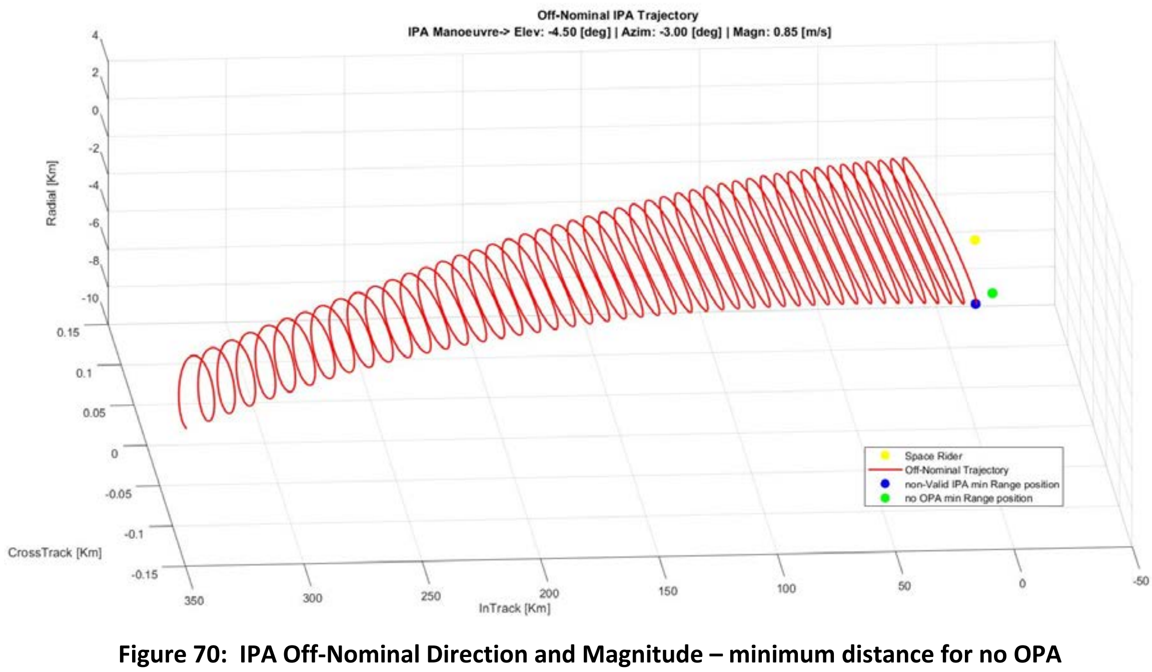


Figure 70: IPA Off-Nominal Direction and Magnitude – minimum distance for no OPA

Table 29 resumes the two off-nominal scenario that occur for a combination of direction and magnitude errors.

Table 29: IPA Off-Nominal Manoeuvres Values Comparison

	Nominal	Off-Nominal 1	Off-Nominal 2
Elevation [deg]	0.0	-4.5	-4.5
Azimuth [deg]	0.0	-3.0	-5.0
Magnitude [m/s]	0.45	0.855	0.518
IPA min Range [m] (module and RIC frame components)	60.98 [392.7 $60.0 \cdot 10^3$ -125.61]	29.88 [15.5 -10.6 -23.3]	$10.37 \cdot 10^3$ [662.3 $10.3 \cdot 10^3$ -93.508]
Time to the min Range [day]	3	2.59	3
No OPA min Range [m] (module and RIC frame components)	14.55 [919.2 $14.51 \cdot 10^3$ 272.6]	/	85.52 [24.872 -47.8 -66.4]
Time to the min Range no OPA [day]	4	/	3.13

4.1.3 Off-Nominal manoeuvre entering the Out-of-Plane (OPA)

The OPA allows to reach a precise position to start the Walking Safety Ellipse (WSE) and observe Space Rider. This manoeuvre, together with the insertion in the WSE trajectory, is the most critical for the mission, as it requires high precision to reach the position near Space Rider and guarantee the geometry of the WSE. The WSE is defined in such a way as to guarantee the operating range of the SROC payload and no risk of collision with Space Rider (the WSE is a passive safe trajectory). If the OPA does not lead to the desired position, it would be necessary to perform a new OPA to correct the error and then begin the inspection phase. Failing the insertion manoeuvre in the OPA leads to increased costs and delays for SROC, but could also increase the risk of collision with SR. For this reason, a Keep Out Zone (KOZ) with a radius of 200 meters has been considered. The off-nominal OPAs are therefore evaluated with respect to the minimum distance with the target spacecraft during the entire trajectory. Table 30 reports the nominal manoeuvre parameters for the OPA that comes before the Inspection cycle:

Table 30: OPA Nominal Manoeuvre Values

Elevation [deg]	Azimuth [deg]		Magnitude [m/s]
48.7	-14.7		0.58
CRR Final Position Radial – InTrack – CrossTrack – Range [m]			
-117.1	-100.3	-75.0	171.5
CRR min Range Radial – InTrack – CrossTrack – Range [m]			
-117.1	-100.3	-75.0	171.5
OPA Duration [hr]	9.5		
Next Manoeuvre ΔV [m/s]	0.58		

Figure 71 show two different views of the nominal OPA trajectory, while Figure 72 highlight the out-of-plane nature of the OPA trajectory.

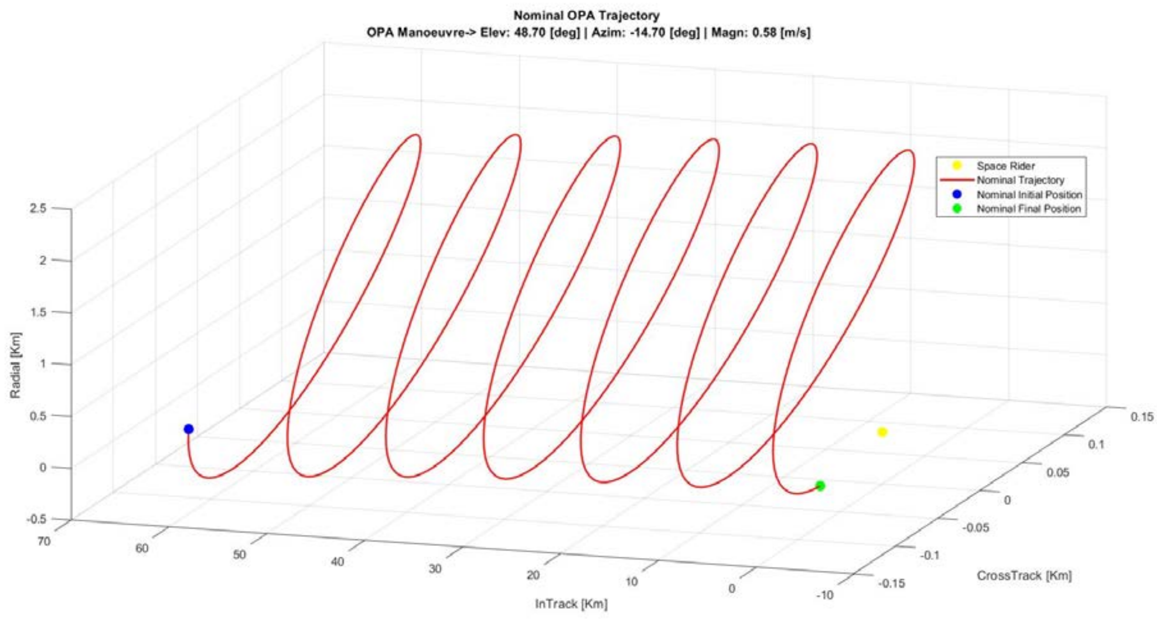


Figure 71: OPA Nominal Trajectory

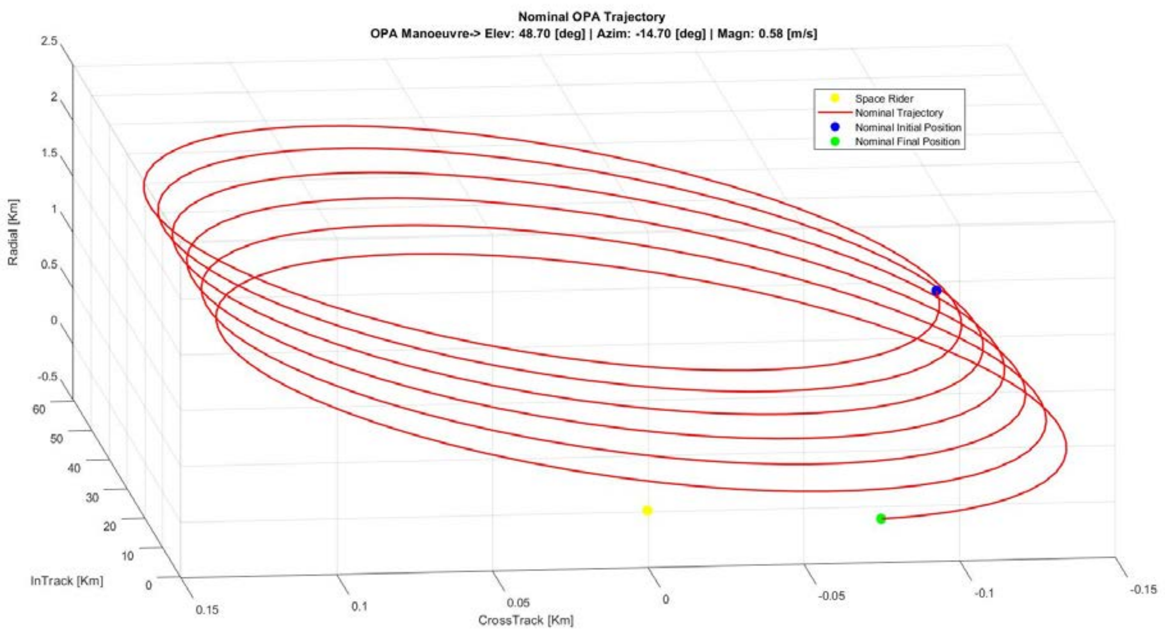


Figure 72: OPA Nominal Trajectory - Out-Of-Plane View

The off-nominal analysis was performed by varying the angles of ± 5 $[deg]$ from the nominal value, with a step of 0.5 $[deg]$, the magnitude of ± 100% from the nominal value, with a 5% step, and the combinations of the two errors were also considered.

Direction errors

Committing some errors on the manoeuvre direction could increase the risk of collision with SR, since the final position to be reached is close to the target spacecraft. However, some considerations must be added with respect to this statement: with the same manoeuvre magnitude, firing with a greater component outside the plane would reduce the effectiveness of the manoeuvre along the InTrack direction, therefore the final position of the OPA reached will be towards more positive InTrack. Conversely, if the direction is tilted to the orbital plane, the final position will be towards more negative direction. Therefore, it is not the final position that is less safe for SR, but the trajectory covered may be. Therefore, two cases of particular interest are reported below. The minimum distance during the OPA trajectory is for an off-nominal manoeuvre with -1 deg for the elevation angle and -5 deg for the azimuth with respect to the nominal values. In this scenario the minimum distance is less than the radius of the KOZ, so SROC would cross it. Despite this, the minimum distance is achieved with a high out of plane component compared to the other 2; in fact, the module of the minimum distance is 135.2 m and the CrossTrack component is -125.8 m. This is the worst off-nominal manoeuvre for the OPA mistaking only the direction with respect to Space Rider. The off-nominal trajectory is shown in Figure 73 and some values are resumed in Table 31.

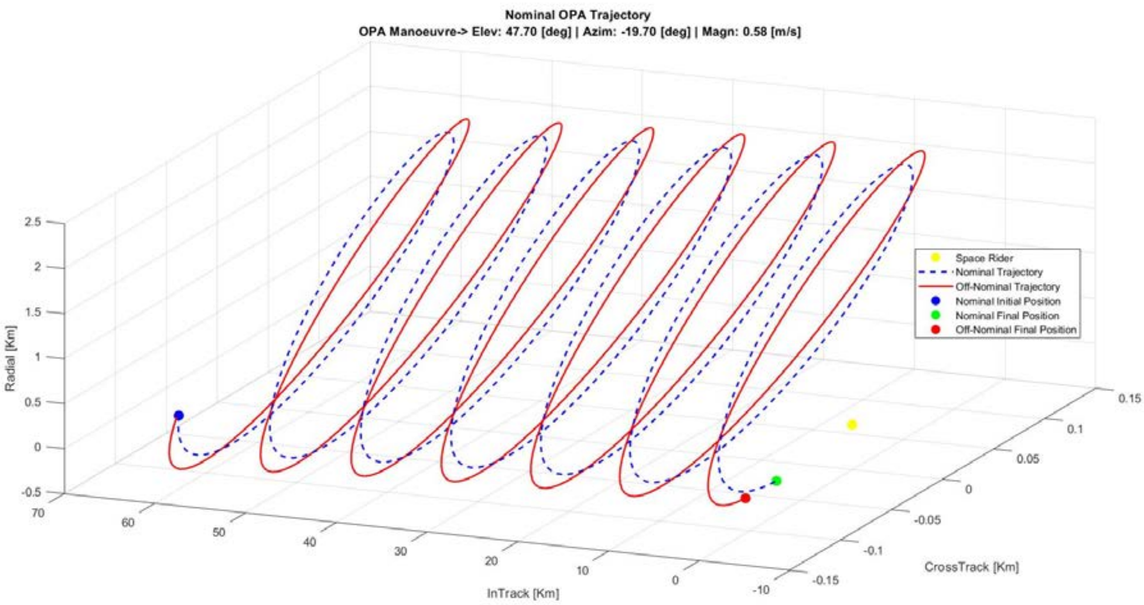


Figure 73: OPA Off-Nominal Direction - minimum distance

Table 31: OPA Off-Nominal 1 Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	48.7	47.7
Azimuth [deg]	-14.7	-19.7
Magnitude [m/s]	0.58	0.58
OPA min Range [m] (module and RIC frame components)	171.5 [-117.1 -100.3 -75.0]	135.2 [-48.6 -10.1 -125.8]
Time to the min Range [hr]	9.5	9.4

Another case of particular interest concerns the final position with the greater error than the nominal one. This occurs for an off-nominal manoeuvre mistaken by +5 degrees for the elevation angle and -5 degrees for the azimuth angle. The finale position reached is 4.58 km away (in module) from the desired position. The trajectory is shown in Figure 74 and some parameters are reported below (Table 32).

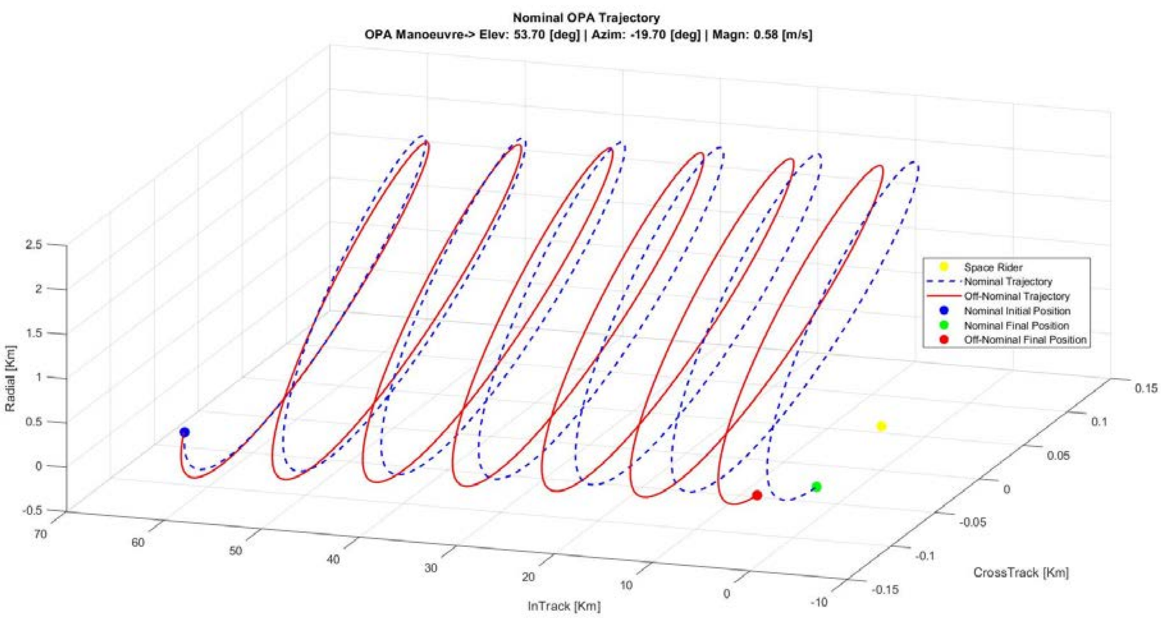


Figure 74: OPA Off-Nominal Direction – worst Final Position

Table 32: OPA Off-Nominal 2 Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	48.7	53.7
Azimuth [deg]	-14.7	-19.7
Magnitude [m/s]	0.58	0.58
OPA Final Position [m] (module and RIC frame components)	171.5 [-117.1 -100.3 -75.0]	$4.58 \cdot 10^3$ [-136.8 $4.57 \cdot 10^3$ -90.6]
Time to the min Range [hr]	9.5	9.5

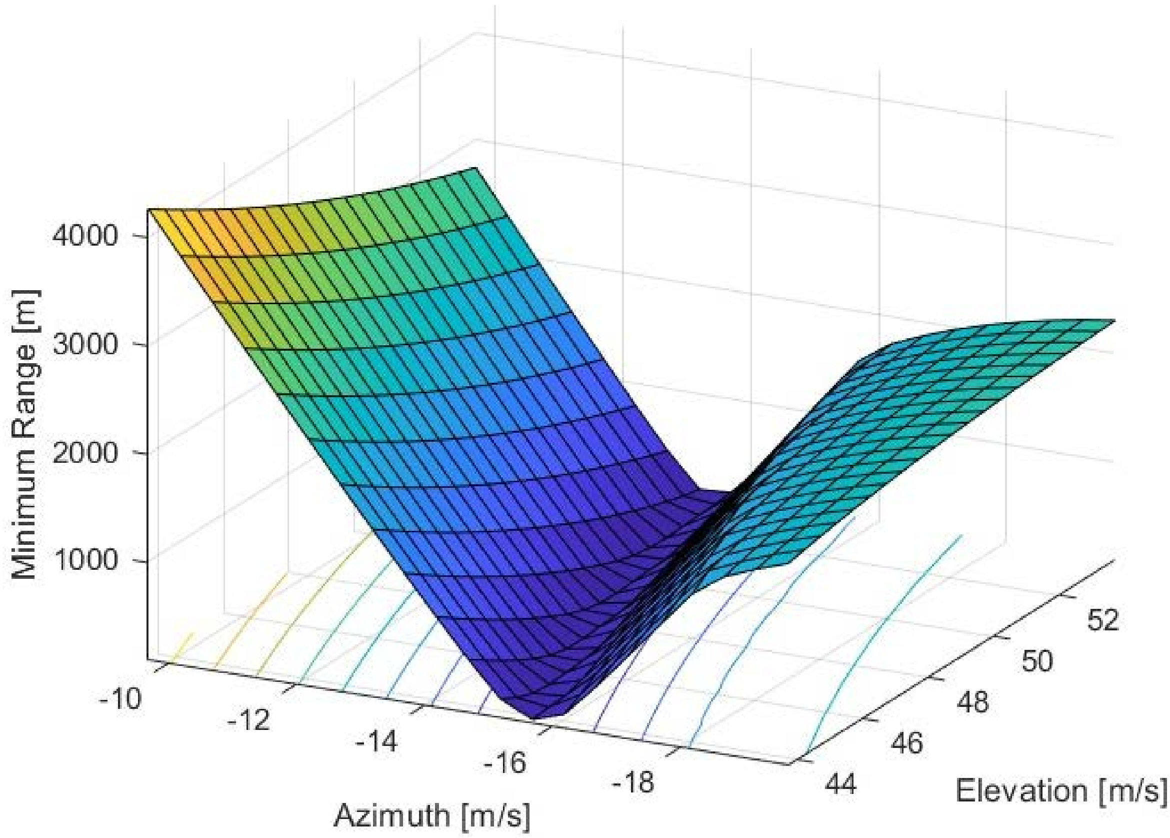


Figure 75: Scatter plot Direction errors – OPA Opt 1

Magnitude errors

A manoeuvre magnitude higher or lower than the nominal value involves a different final position at the end of the OPA, which, as for errors on the direction, will be respectively in the negative or positive part of the InTrack. Therefore, also in this case it is necessary to evaluate the error that involves the minimum distance between the two spacecraft and the error that involves the greatest difference between the final position reached and the desired one. The minimum distance during the OPA trajectory is achieved for an off-nominal manoeuvre more intense than 80%. The relative distance between the two spacecraft is 425.3 m, with a CrossTrack component of -153.6 m, so the chaser spacecraft will not cross the Space Rider KOZ. Furthermore, the final position in this scenario is in the negative InTrack direction, due to the greater manoeuvre magnitude. For this reason, if SROC did not perform any other manoeuvres, a second pass should be expected near SR, during the drift away motion which would be resumed after a short period. However, this second passage would not cause high collision risks, because in the meantime SROC would continue to lose altitude, increasing the relative distance along the Radial direction and, possibly, it would perform some correction manoeuvres. The off-nominal relative trajectory is shown in Figure 76 and Table 33 resumes the manoeuvre values and the relative final components.

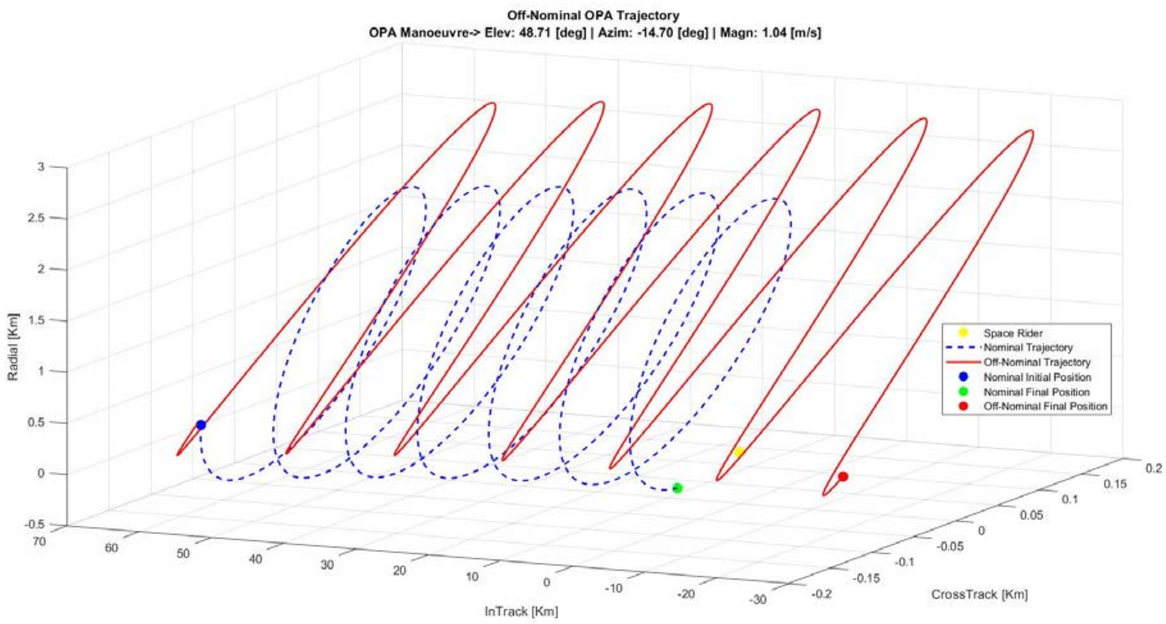


Figure 76: OPA Off-Nominal Magnitude – minimum distance

Table 33: OPA Off-Nominal 1 Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	48.7	48.7
Azimuth [deg]	-14.7	-14.7
Magnitude [m/s]	0.58	1.04
OPA min Range [m] (module and RIC frame components)	171.5 [-117.1 -100.3 -75.0]	425.2 [328.3 -222.3 -153.6]
Time to the min Range [hr]	9.5	6.3

The OPA final position with the greatest distance compared to the desired one is obtained when the insertion manoeuvre in the OPA is not performed at all (0% of the nominal value). This case is exactly what makes the In-Plane Rendezvous valid, therefore, from a safety point of view for Space Rider, this off-nominal manoeuvre does not cause any risk of collision. In fact, the minimum distance during the OPA would be 36.64 km, reaching a final position which differs from the nominal one of 36.54 km. The off-nominal trajectory is shown in Figure 77 and it can be noticed that it is the continuation of the previous IPA trajectory.

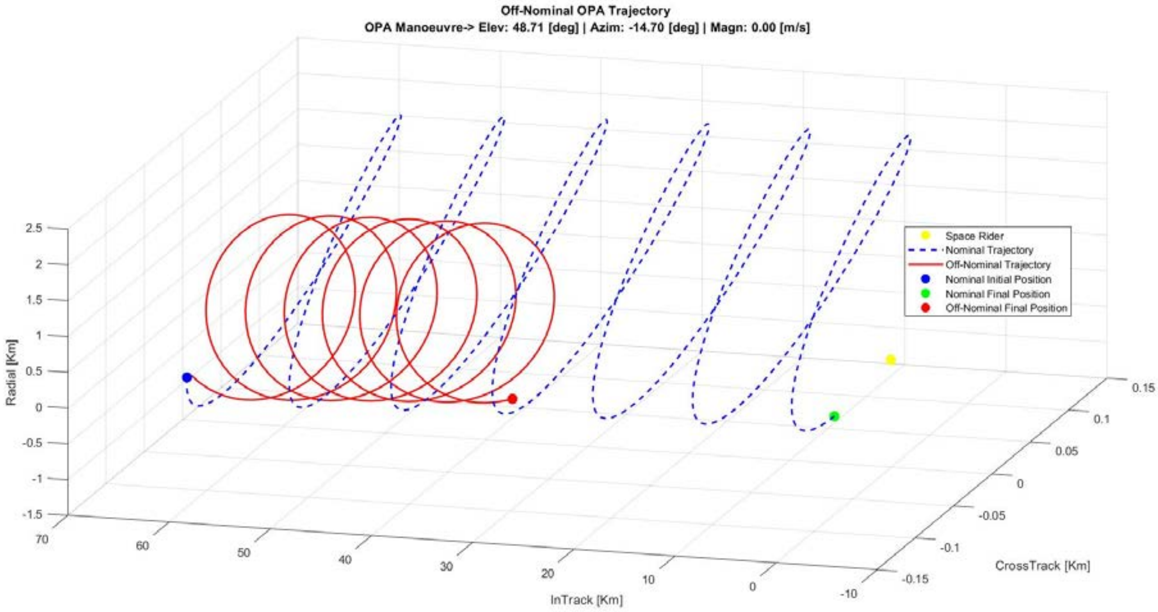


Figure 77: OPA Off-Nominal Magnitude – worst Final Position

Table 34: OPA Off-Nominal 2 Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	48.7	48.7
Azimuth [deg]	-14.7	-14.7
Magnitude [m/s]	0.58	0.0
OPA Final Position [m] (module and RIC frame components)	171.5 [-117.1 -100.3 -75.0]	$36.64 \cdot 10^3$ [-47.554 $36.64 \cdot 10^3$ -91.3]
Time to the min Range [hr]	9.5	9.3

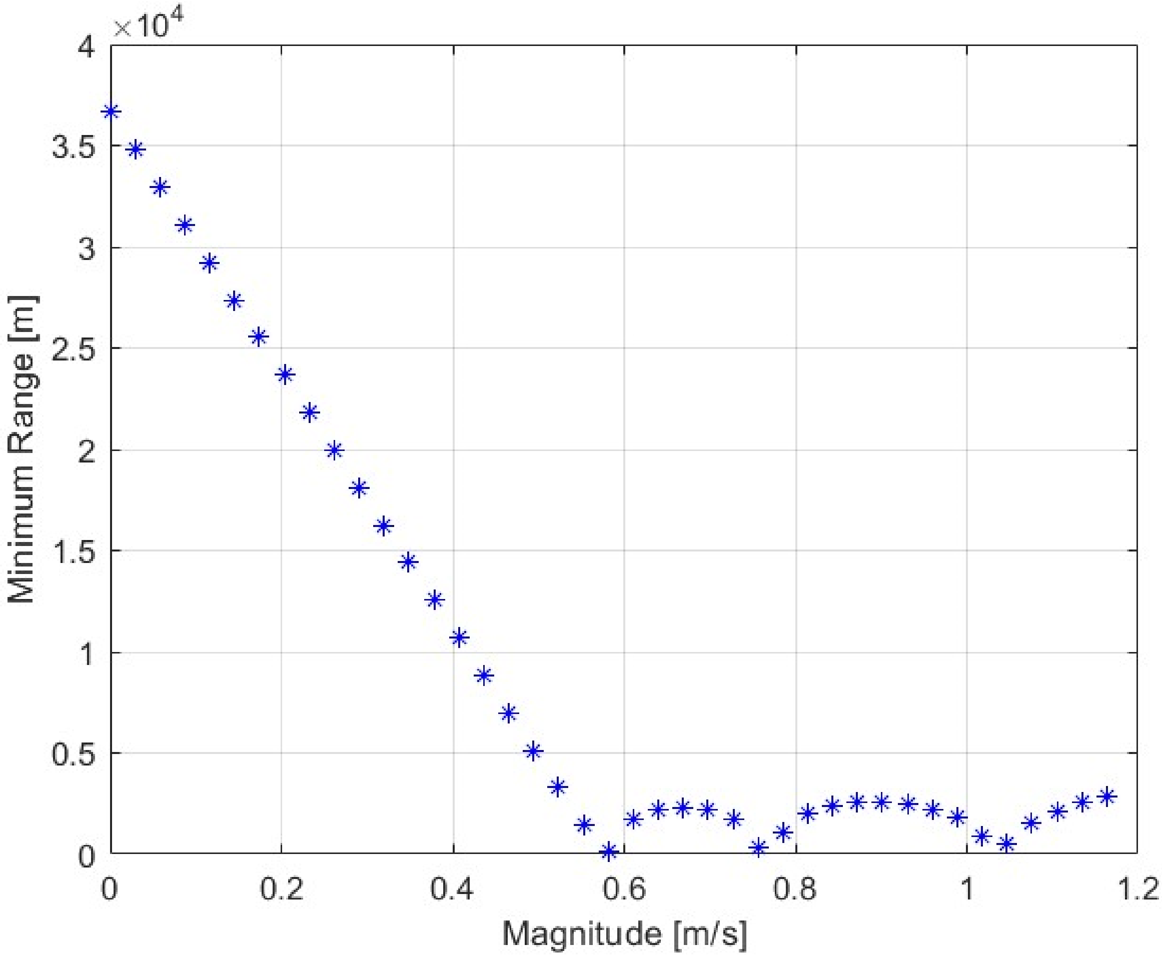


Figure 78: Scatter plot Magnitude errors – OPA Opt 1

Direction and magnitude errors

Combining errors in direction and magnitude of the thrust, the results are more critical. The minimum distance drops to 73 m with a CrossTrack component of 52 m for an off-nominal manoeuvre with an error of -4.0 deg for the elevation, +5.0 deg for the azimuth and a magnitude increased by 20%. The resulting trajectory and some parameters are shown in Figure 79 and in Table 35:

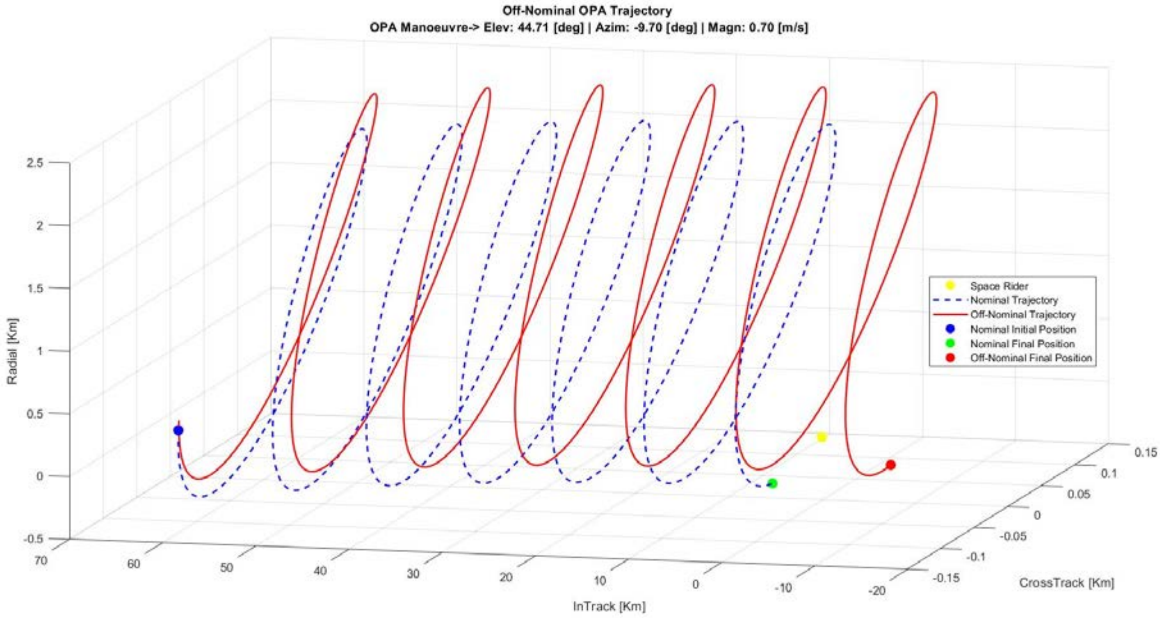


Figure 79: OPA Off-Nominal Direction and Magnitude – minimum distance

Table 35: OPA Off-Nominal 1 Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	48.7	44.7
Azimuth [deg]	-14.7	-9.7
Magnitude [m/s]	0.58	0.7
OPA min Range [m] (module and RIC frame components)	171.5 [-117.1 -100.3 -75.0]	73 [50.6 -8.5 -52]
Time to the min Range [hr]	9.5	7.99

The OPA final position with the greatest difference from the nominal one occurs with an elevation error of - 5.0 deg, an azimuth error of +5.0 deg and a double magnitude compared to the nominal one (+100%). In this event, the minimum range between the two spacecraft during the rendezvous is 3.23 Km. The relative trajectory is shown in Figure 80:

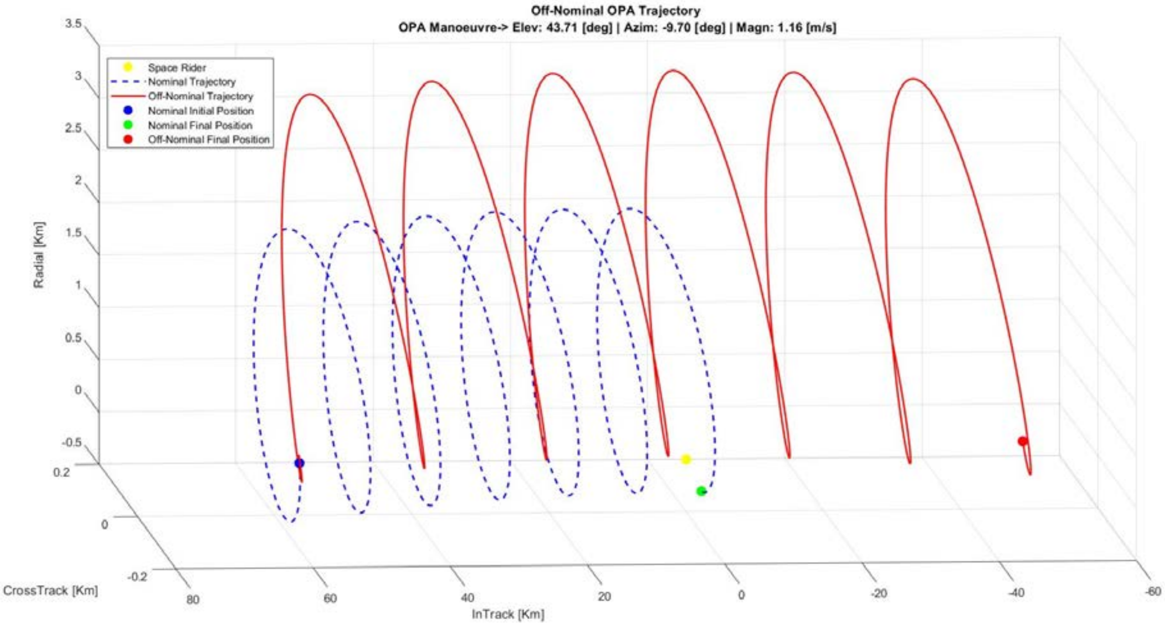


Figure 80: OPA Off-Nominal Direction and Magnitude – minimum distance

Table 36 resumes this off-nominal scenario.

Table 36: OPA Off-Nominal 2 Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	48.7	43.71
Azimuth [deg]	-14.7	-9.7
Magnitude [m/s]	0.58	1.16
OPA Final Position [m] (module and RIC frame components)	171.5 [-117.1 -100.3 -75.0]	$3.23 \cdot 10^3$ [$3.21 \cdot 10^3$ 390.6 135.5]
Time to the min Range [hr]	9.5	5.41

4.1.4 Off-Nominal manoeuvre entering the Space Rider Inspection – WSE Inspection

The insertion manoeuvre in the Walking Safety Ellipse (WSE) aims to change the SROC velocity components, in order to enter in the WSE trajectory and carry out the observation of the Space Rider. The position and velocity (in their components) are defined so as to always respect a minimum distance from Space Rider (for safety reasons) and a maximum distance imposed by the operating range of the SROC payload. Moreover, the initial position is deliberately a position outside the orbital plane of Space Rider, so as to increase the safety towards him during the approach motion. Mistaking this manoeuvre can only lead to a different inspection trajectory, with a different geometry with respect to the nominal and out of the SROC payload operational range. The WSE is defined so that the further back and further ahead single Safety Ellipses relative to SR (orbits of SROC) are within the required limits along the InTrack direction (the further ahead SE is also the last SE of the observation cycle).

The nominal Inspection trajectory that follows the SE Insertion manoeuvre is shown in Figure 81:

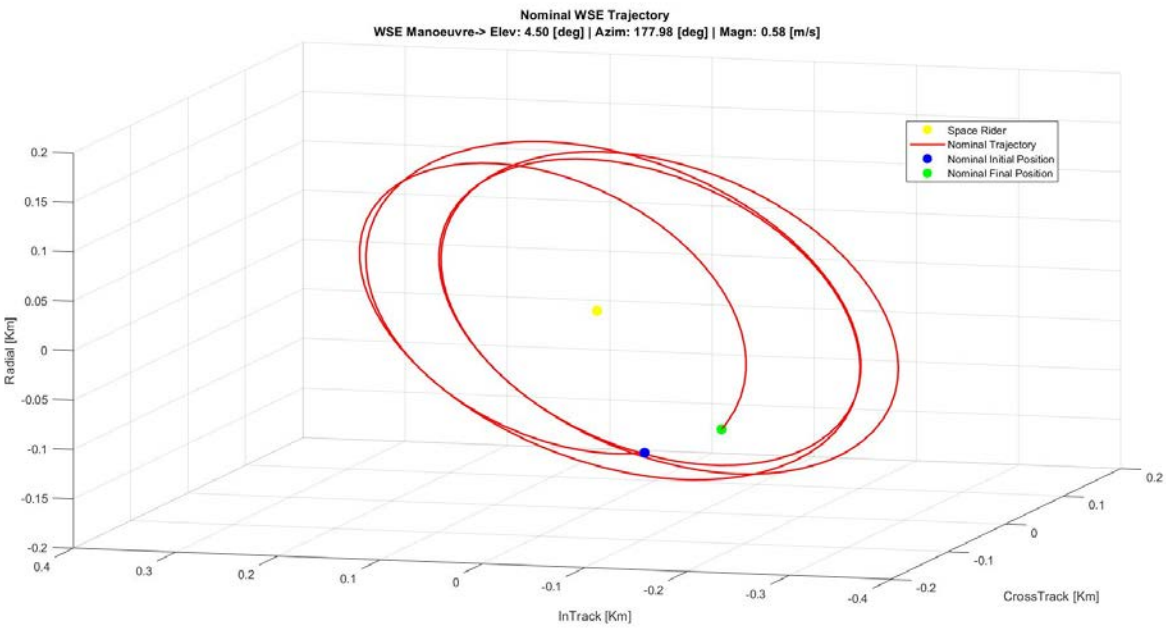


Figure 81: Inspection 1 Nominal Trajectory

The SR Keep Out Sphere must also be considered for the trajectory following the manoeuvre in question. The nominal manoeuvre parameters and other parameters of interest are reported below (see Table 37):

Table 37: WSE Insertion Nominal Manoeuvre Values

Elevation [deg]	Azimuth [deg]	Magnitude [m/s]
4.5	178	0.58
min Range [m]	137.5	
Time to the min Range [min]	5	

The off-nominal analysis was performed by varying the angles of ± 5 $[deg]$ from the nominal value, with a step of 0.5 $[deg]$, the magnitude of ± 100% from the nominal value, with a 5% step, and the combinations of the two errors were also considered.

Direction errors

Performing the insertion manoeuvre in the WSE with a direction different from the nominal one, involves a different geometry of the trajectory. Also, if the off-nominal manoeuvre increases the velocity component along the InTrack, the resulting inspection trajectory will be towards the negative direction of the InTrack, behind Space Rider; vice versa, if the InTrack component after the firing is less than the nominal one, the inspection will be translated ahead of Space Rider, in the positive InTrack direction. The off-nominal direction that involves the minimum distance with the target spacecraft occurs for an error of +5 degrees on the elevation angle and of +0 degrees on the azimuth angle. In this event, the minimum range between the two spacecraft is 83.9 m that is well below the KOZ radius. The trajectory that follows this manoeuvre is shown in Figure 82:

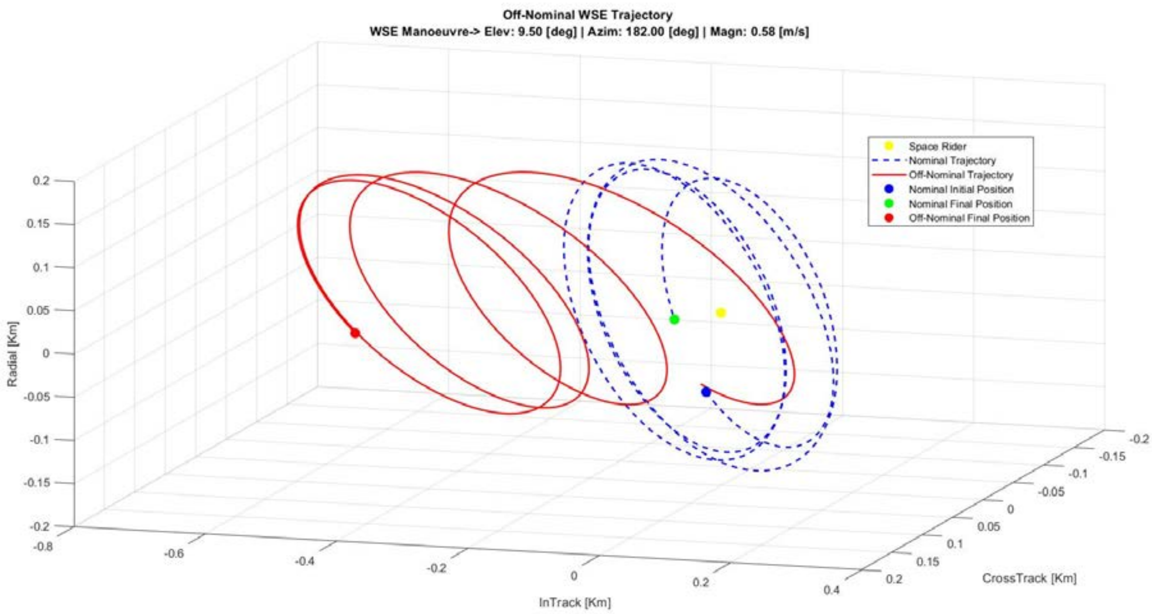


Figure 82: WSE Off-Nominal Direction – minimum distance

Table 38 compares the nominal with the off-nominal manoeuvre.

Table 38: WSE Insertion Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal
Elevation [deg]	4.5	9.5
Azimuth [deg]	178	178
Magnitude [m/s]	0.58	0.58
WSE min Range [m] (module and RIC frame components)	137.5 [-136.2 6.0 -17.9]	83.9 [-38.8 14.6 72.9]
Time to the min Range [min]	5	113

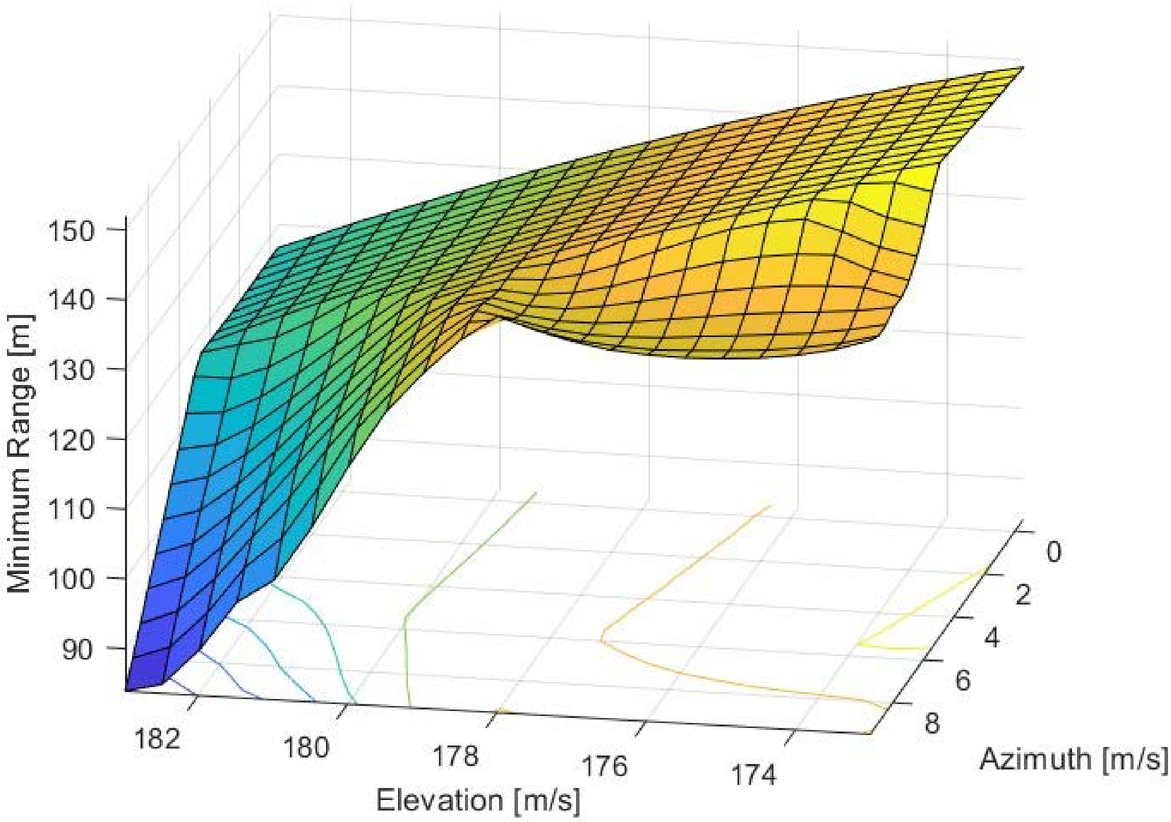


Figure 83: Scatter plot Direction errors – WSE Opt 1

Magnitude errors

The insertion manoeuvre in the WSE is to be carried out with high precision, both in terms of direction and magnitude. In fact, having a very specific direction to change the relative trajectory from the OPA to the inspection, making mistakes on the magnitude means upsetting the trajectory. As a demonstration of this, the trajectories in the case of a manoeuvre performed with 50% less and more magnitude are shown in Figure 84 and Figure 85:

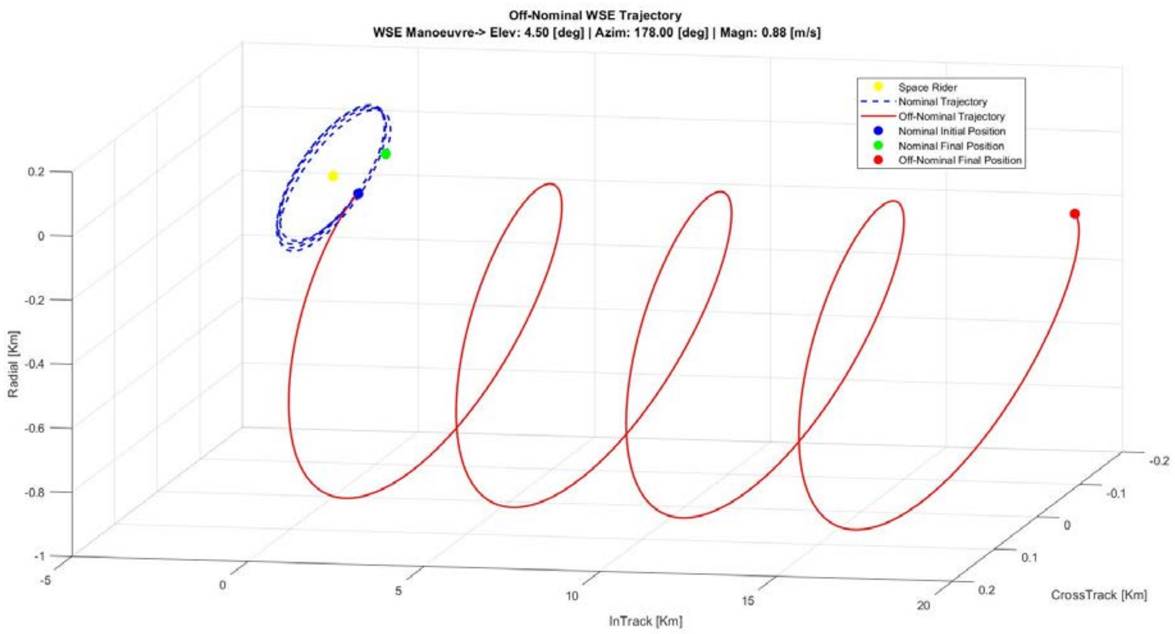


Figure 84: Inspection Off-Nominal Magnitude - 50% of manoeuvre magnitude

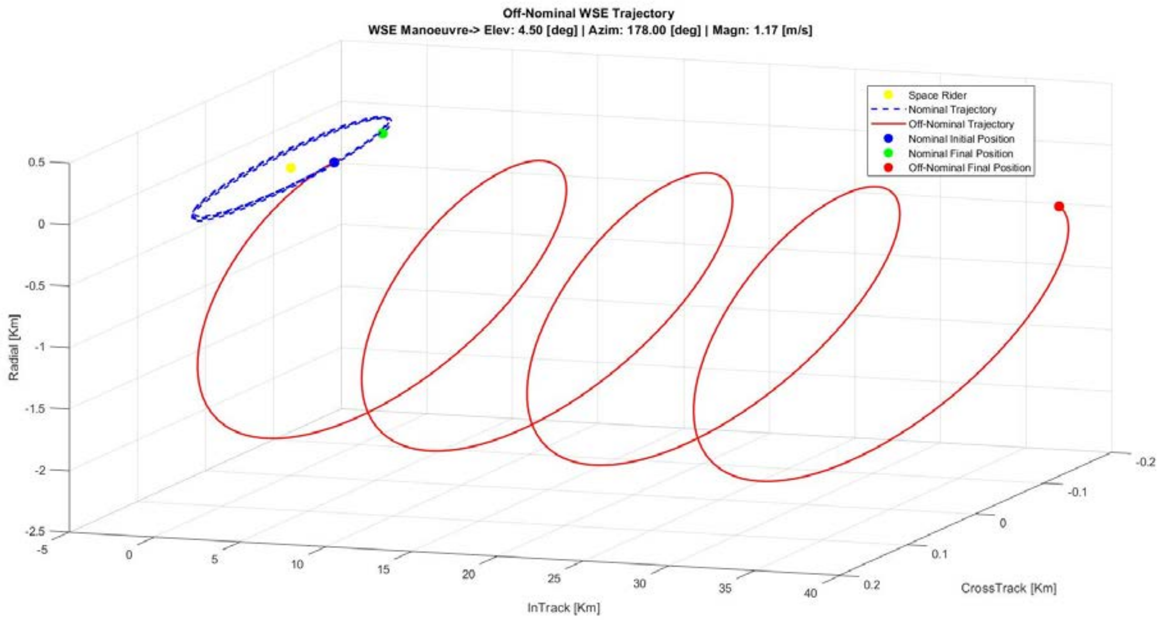


Figure 85: Inspection Off-Nominal Magnitude - 150% of manoeuvre magnitude

Table 39: WSE Insertion Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1	Off-Nominal 2
Elevation [deg]	4.5	4.5	4.5
Azimuth [deg]	178	178	178
Magnitude [m/s]	0.58	0.88	1.17
WSE min Range [m] (module and RIC frame components)	137.5 [-0.136.2 6.0 -17.9]	171.2 [-121.7 -101.1 -65.4]	171.5 [-117.1 -100.3 -75.0]

Time to the min Range [min]	5	2	1

The off-nominal magnitude that brings SROC to the minimum distance with respect to Space Rider has a value smaller than 30% of the nominal value, equal to 0.58 [m/s]. The minimum range is lower than the KOZ radius, in fact it is 129.9 m, and the inspection is out of the SROC payload range. Table 40 resumes the parameters described:

Table 40: WSE Insertion Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal
Elevation [deg]	4.5	4.5
Azimuth [deg]	178	178
Magnitude [m/s]	0.58	0.41
WSE min Range [m] (module and RIC frame components)	137.5 [-0.136.2 6.0 -17.9]	129.9 [-0.122.7 26.9 -33.2]
Time to the min Range [min]	5	4.6

The resulting trajectory is shown in Figure 86:

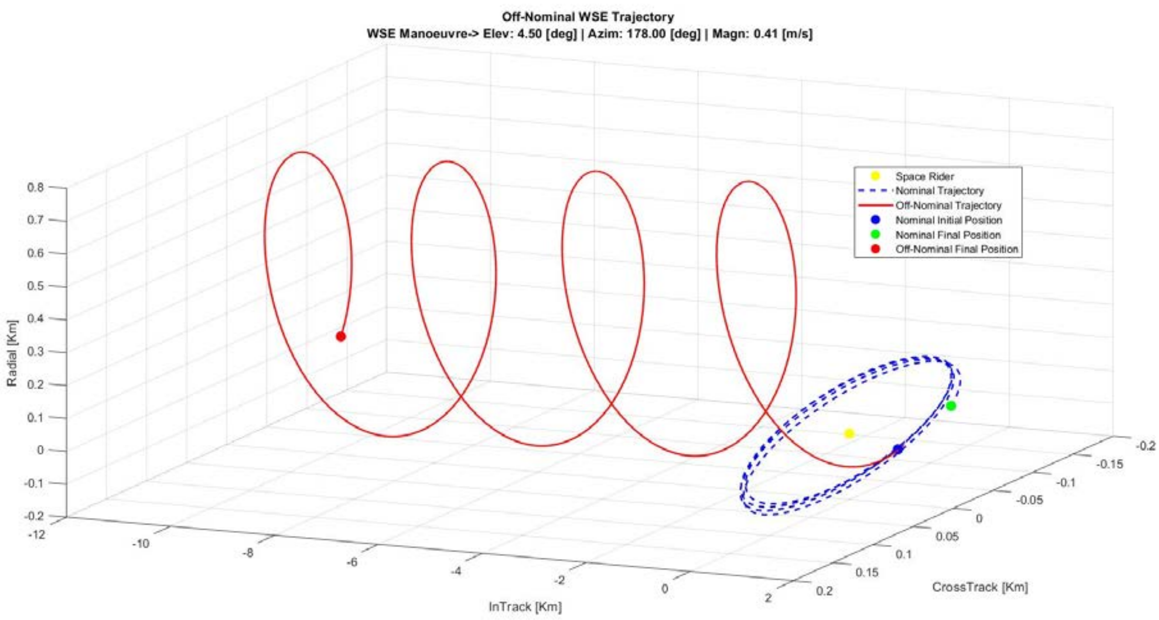


Figure 86: Inspection Off-Nominal Magnitude – minimum distance

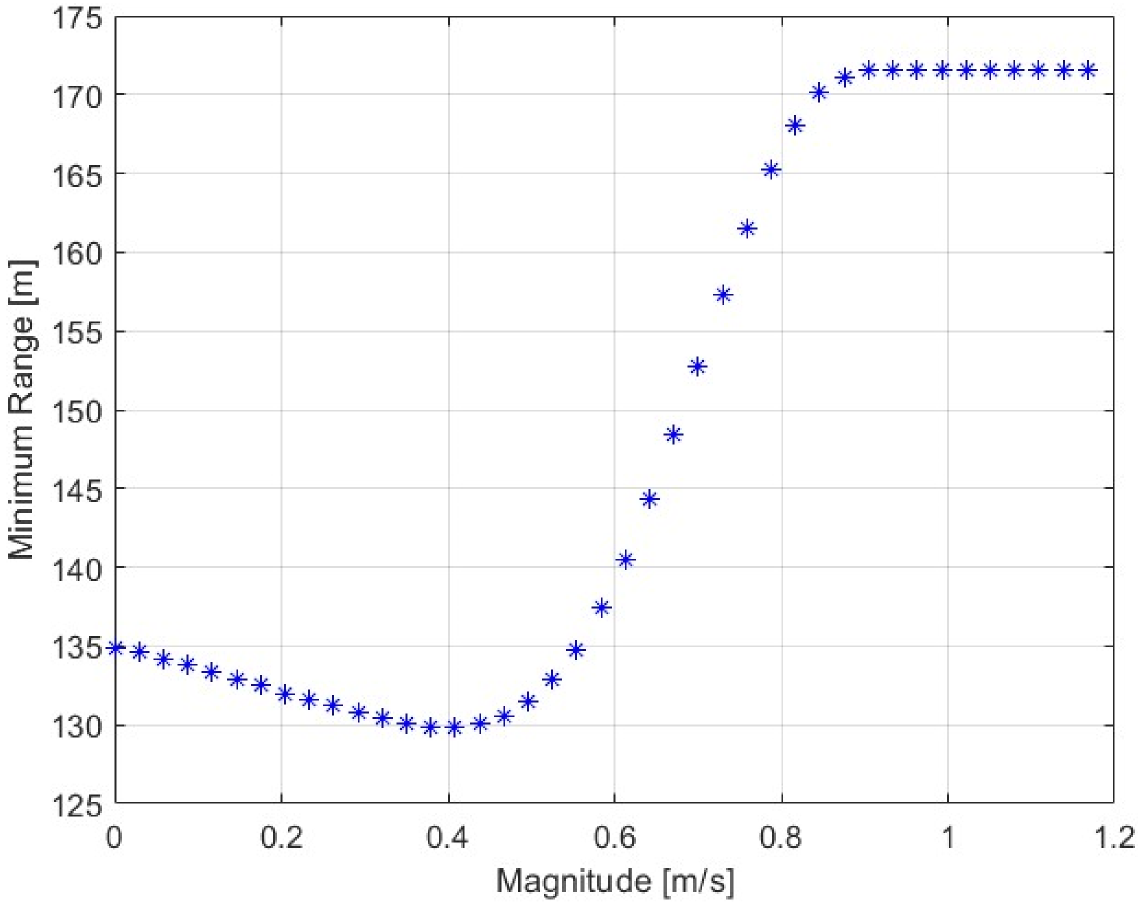


Figure 87: Scatter plot Magnitude errors – WSE Opt 1

Direction and magnitude errors

If two failures occur simultaneously causing both direction and magnitude errors, the Space Rider inspection could not be performed and the risk of collision between the two spacecraft would increase. In fact, the worst case in which there is the minimum distance between the two comes out for an elevation increased by +5 deg, the azimuth increased by +5 deg and the magnitude increased by 5% wrt to the nominal values. In this scenario, the minimum distance during the inspection trajectory is 51.31 m, with a very high risk of collision. The following table (Table 41) resumes the off-nominal values in which this event occurs, and the Figure 88 shows the relative trajectory.

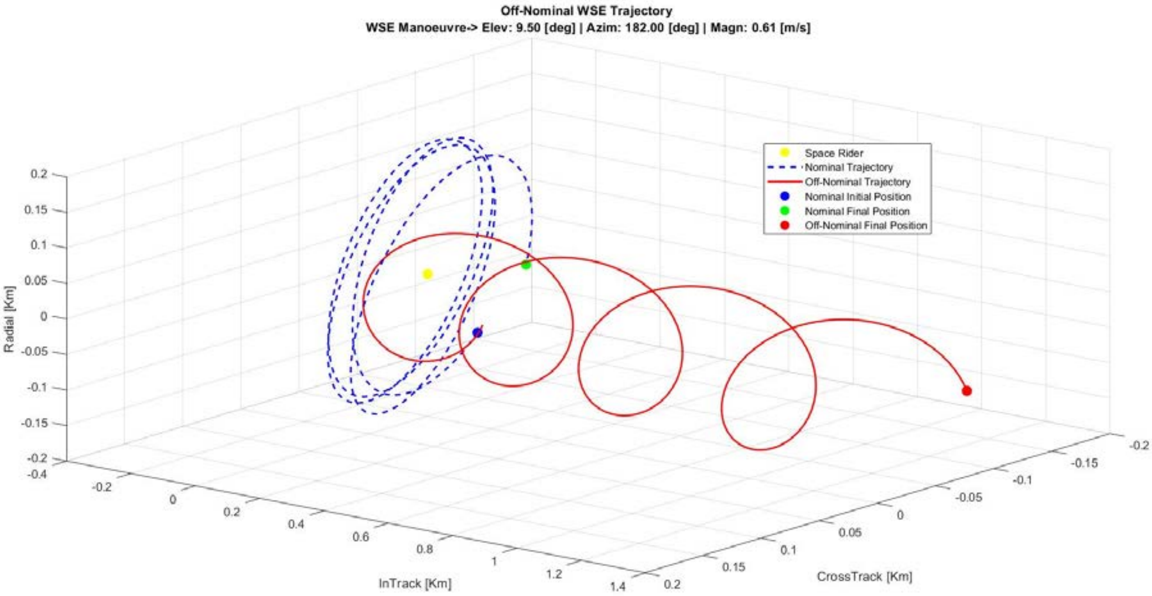


Figure 88: Inspection Off-Nominal Direction and Magnitude - minimum distance

Table 41: WSE Insertion Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal
Elevation [deg]	4.5	9.5
Azimuth [deg]	178	183
Magnitude [m/s]	0.58	0.61
WSE min Range [m] (module and RIC frame components)	137.5 [-0.136.2 6.0 -17.9]	51.31 [46.3 5.2 -22.0]
Time to the min Range [min]	5	59.7

Considering the physical dimensions of Space Rider, these analyses lead to the conclusion that a collision would not occur between the two even. Moreover, a CAMs could intervene before the collision by changing the trajectory of the SROC.

4.1.5 Off-Nominal manoeuvre Closing

To approach Space Rider after the inspection phase and start the docking phase, SROC performs an out-of-plane manoeuvre to execute the Hold Point 3. After the Free Flight phase SROC executes an out-of-plane trajectory toward SR and reaching the *InTrack Target* (150 m in the nominal scenario), SROC performs a holding phase finite manoeuvre close to SR to maintain this relative position during the HP#3. Hereafter (Table 42) are reported the ΔV vector for the nominal scenario and some other parameters useful to compare the off-nominal scenarios to the nominal one:

Table 42: Closing Nominal Manoeuvre Values

Elevation [deg]	Azimuth [deg]	Magnitude [m/s]
-10.1	-41.2	0.15
min Range [m]	150	
Time to the min Range [min]	7.3	
Next Manoeuvre ΔV [m/s]	0.42	

It must be noticed that the minimum range for the nominal mission profile is the InTrack target. Furthermore the "next Manoeuvre ΔV" includes the entry manoeuvre in the HP#3 trajectory and the finite manoeuvre needed to maitain this relative position. Both depend on the execution of the HP#3 Insertion. Figure 89 show two different views of the nominal Closing trajectory, while Figure 90 highlight the out-of-plane nature of the HP#3 Insertion trajectory.

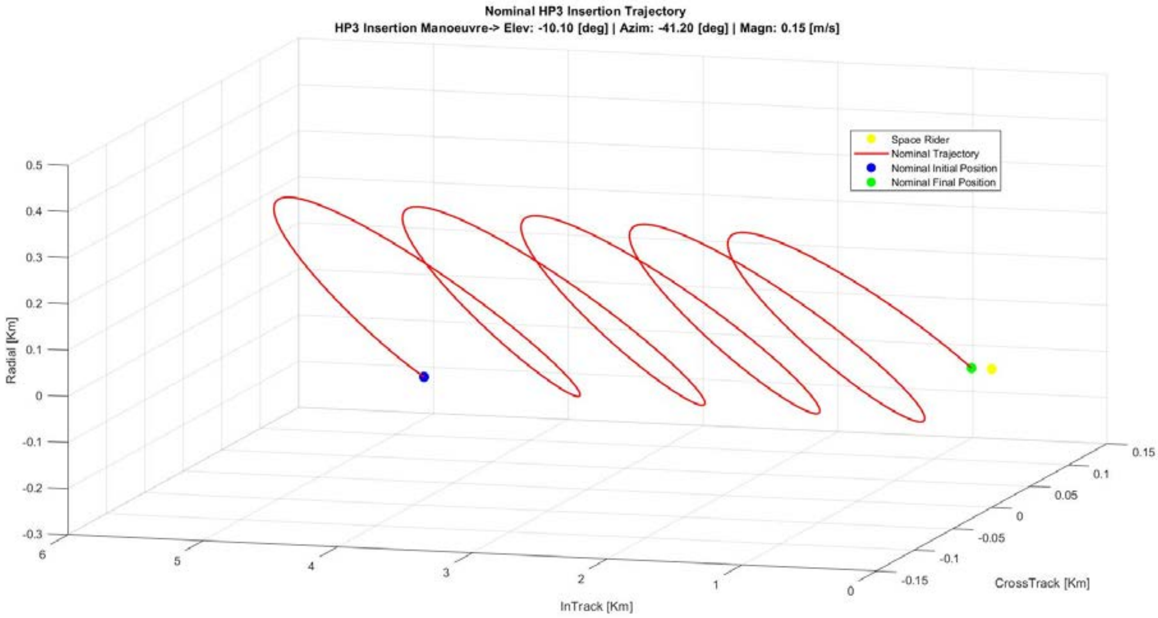


Figure 89: Closing Nominal Trajectory

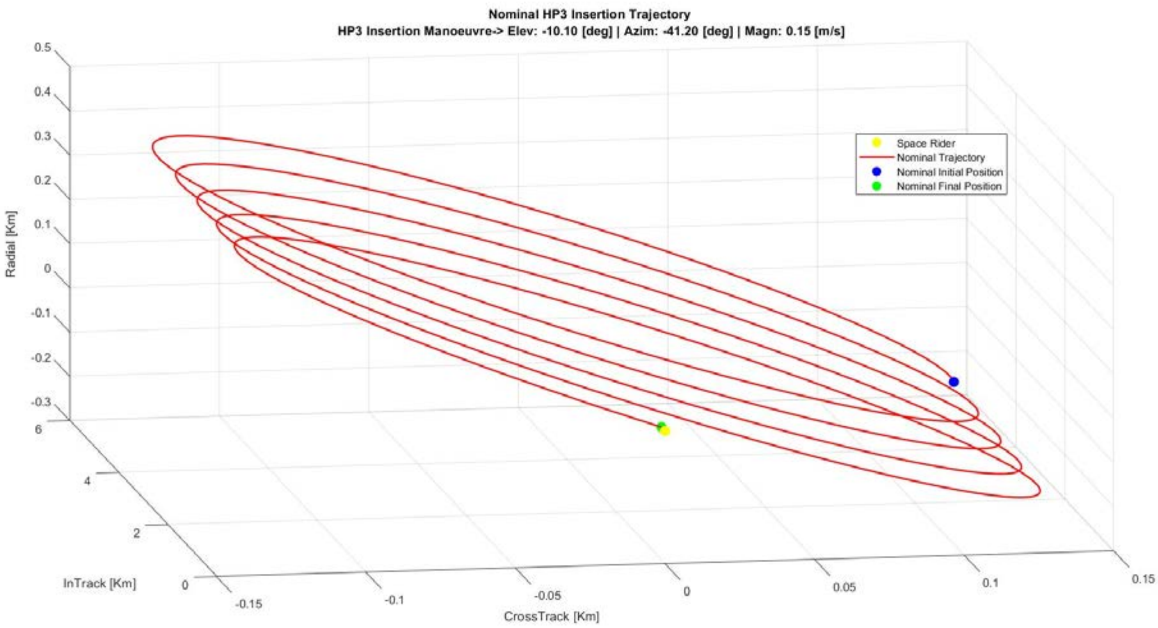


Figure 90: Closing Nominal Trajectory – Out-of-Plane View

The HP#3 allows to maintain a precise position with the respect to SRand wait the right moment to start the docking phase. This manoeuvre, together with the insertion in the WSE trajectory, is one of the most critical for the mission, as it requires high precision to reach the position near Space

Rider and guarantee a minimum safety distance. The HP#3 is defined in such a way as to simplify the docking operations reducing the ΔV required while lowering the risk of collision with Space Rider (the Closing is a passive safe trajectory). If the HP#3 Insertion does not lead to the desired position, it would be necessary to perform a new Closing to correct the error and then begin the holding phase. Failing the insertion manoeuvre in the HP#3 leads to increased costs and delays for SROC, but could also increase the risk of collision with SR. For this reason, a Keep Out Zone (KOZ) with a radius of 200 meters has been considered. The off-nominal Closings are therefore evaluated with respect to the minimum distance with the target spacecraft during the entire trajectory.
The off-nominal analysis was performed by varying the angles of ± 5 $[deg]$ from the nominal value, with a step of 0.5 $[deg]$, the magnitude of ± 100% from the nominal value, with a 5% step, and the combinations of the two errors were also considered. Since the Closing is a trajectory towards the target spacecraft out of its orbital plane, performing an off-nominal manoeuvre could increase the risk of collision with the target itself. Therefore, the objective of the analysis is to determine the maximum permissible errors so that the Closing is still considered valid, even if no longer optimized. Furthermore, for an off-nominal Closing it is necessary to evaluate the minimum distance reached with respect to SR.

Direction errors

Committing some errors on the manoeuvre direction could increase the risk of collision with SR, since the final position to be reached is close to the target spacecraft. However, similar considerations as reported for the OPA off-nominals must be taken into account: with the same manoeuvre magnitude, firing with a greater component outside the plane would reduce the effectiveness of the manoeuvre along the InTrack direction, therefore the final position of the Closing reached will be towards more positive InTrack. Conversely, if the direction is tilted to the orbital plane, the final position will be towards more negative direction. Therefore, it is not the final position that is less safe for SR, but the trajectory covered may be. Consequently, two cases of particular interest are reported below. The minimum distance during the Closing trajectory is for an off-nominal manoeuvre with -5 deg for the elevation angle and +3.5 deg for the azimuth with respect to the nominal values. The minimum distance is achieved at the end of this approaching phase and the module of the minimum distance is 89.0 m. This is the worst off-nominal manoeuvre for the Closing mistaking only the direction with respect to Space Rider. The off-nominal trajectory is shown in Figure 91 and some values are resumed in Table 43.

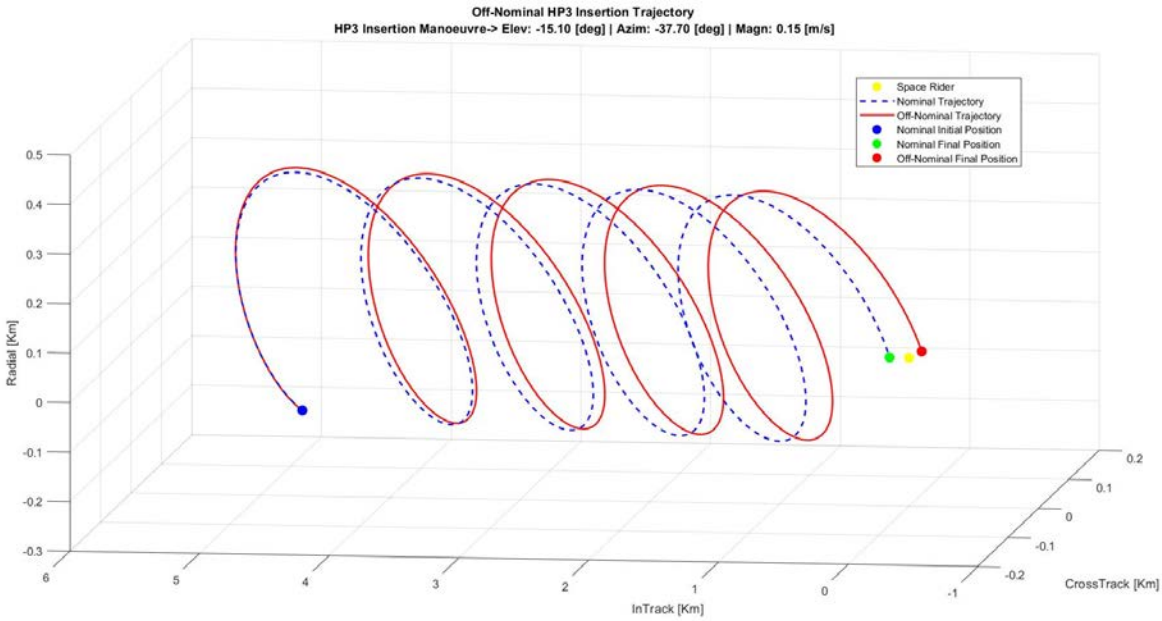


Figure 91: Closing Off-Nominal Magnitude – minimum distance

Table 43: Closing Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	-10.1	-15.1
Azimuth [deg]	-41.2	-37.7
Magnitude [m/s]	0.15	0.15
Closing min Range [m] (module and RIC frame components)	150 [0.35 149.96 -0.15]	89.0 [64.9 -14.8 -59.1]
Time to the min Range [hr]	7.3	7.3

Another case of particular interest concerns the final position with the greater error than the nominal one. This occurs for an off-nominal manoeuvre mistaken by -5 degrees for the elevation angle and -5 degrees for the azimuth angle. The final position reached is 1.2 km away (in module) from the desired position. The trajectory is shown in Figure 92 and some parameters are reported below (Table 44).

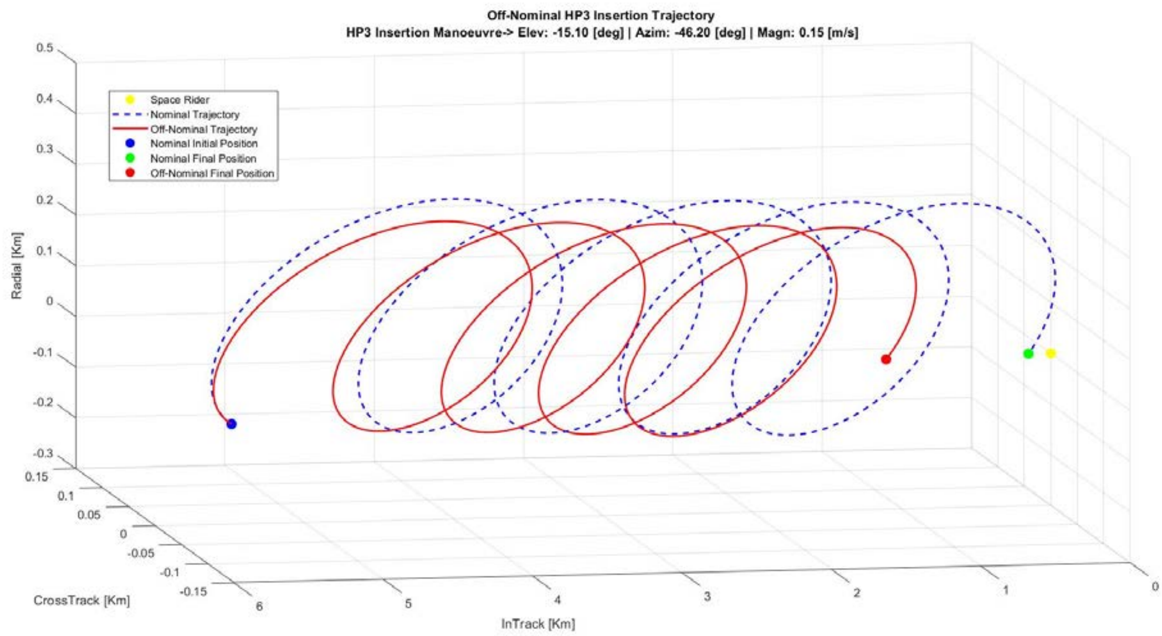


Figure 92: Closing Off-Nominal Magnitude – worst Final Position

Table 44: Closing Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	-10.1	-15.1
Azimuth [deg]	-41.2	-46.2
Magnitude [m/s]	0.15	0.15
Closingmin Range [m] (module and RIC frame components)	150 [0.35 149.96 -0.15]	$1.2 \cdot 10^3$ [52.2 $1.2 \cdot 10^3$ -62.7]
Time to the min Range [hr]	7.3	7.3

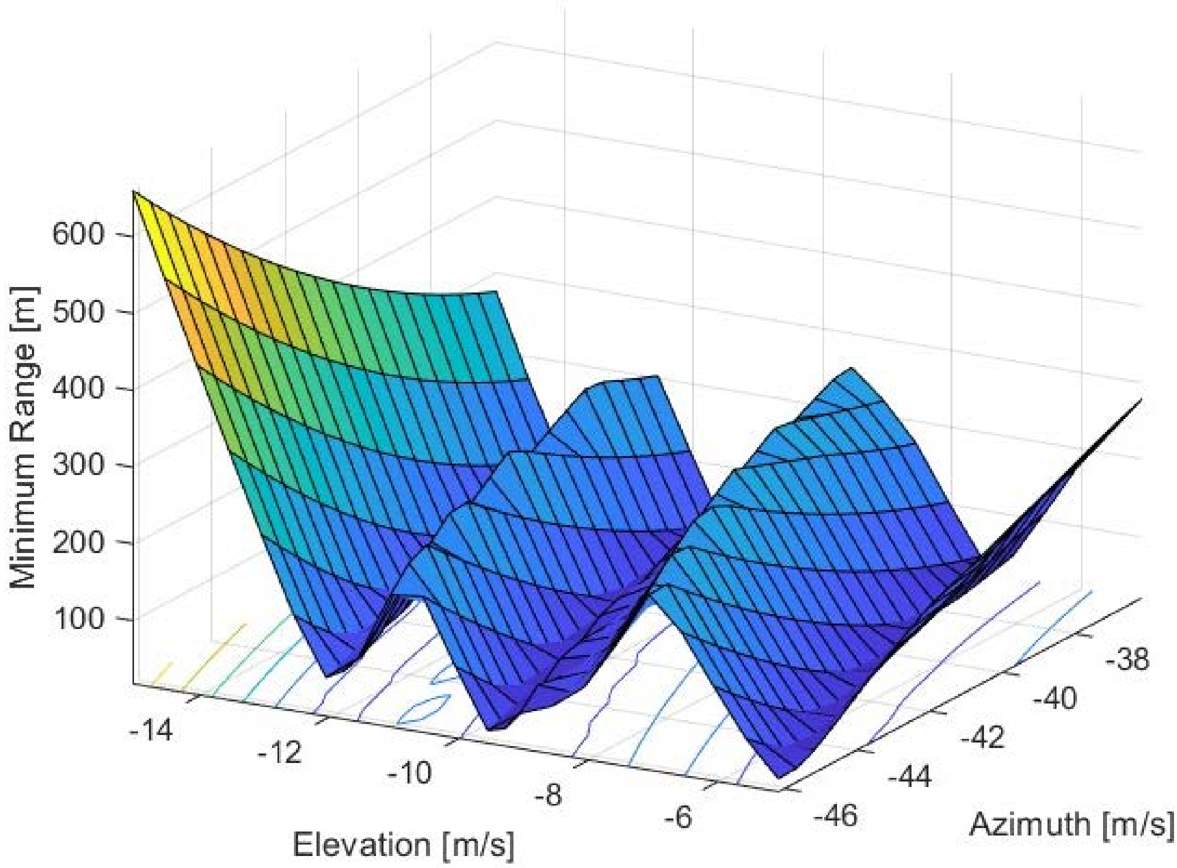


Figure 93: Scatter plot Direction errors – Closing Opt 1

Magnitude errors

A manoeuvre magnitude higher or lower than the nominal value involves a different final position at the end of the Closing, which, as for errors on the direction, will be respectively in the negative or positive part of the InTrack. Therefore, also in this case it is necessary to evaluate the error that involves the minimum distance between the two spacecraft and the error that involves the greatest difference between the final position reached and the desired one. The minimum distance during the Closing trajectory is achieved for an off-nominal manoeuvre more intense than 80%. The relative distance between the two spacecraft is 92.9 m. Furthermore, the final position in this scenario is in the negative InTrack direction, due to the greater manoeuvre magnitude. For this reason, if SROC did not perform any other manoeuvres, a second pass should be expected near SR, during the drift away motion which would be resumed after a short period. However, this second passage would not cause high collision risks, because in the meantime SROC would continue to lose altitude, increasing the relative distance along the Radial direction and, possibly, it would perform some correction manoeuvres. The off-nominal relative trajectory is shown in Figure 94 and Table 45 resumes the manoeuvre values and the relative final components.

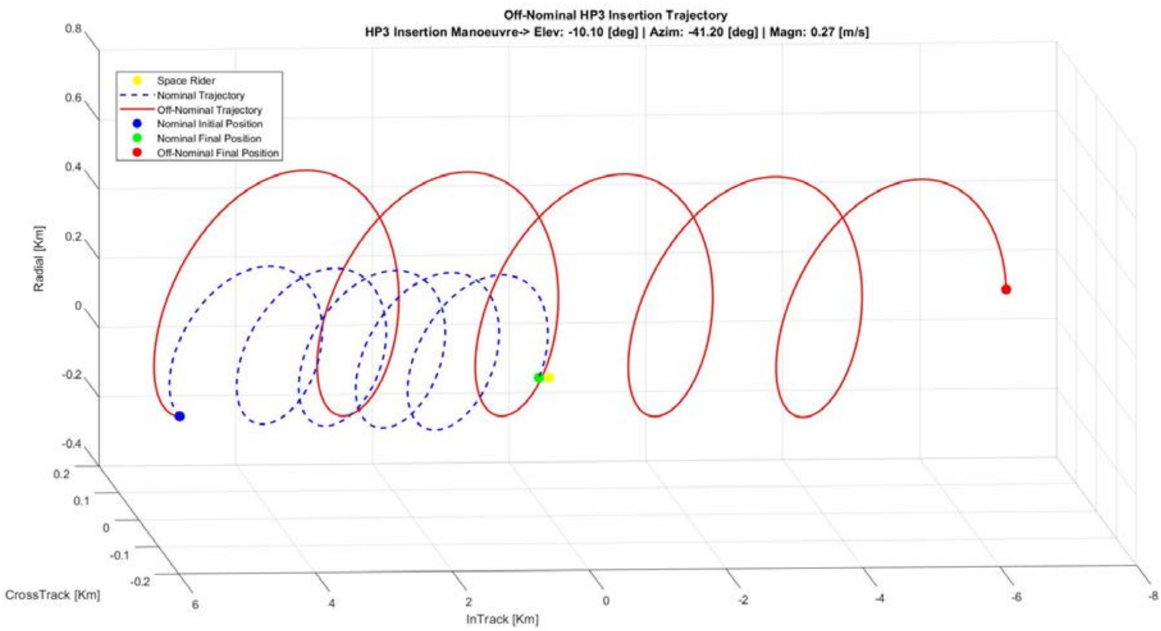


Figure 94: Closing Off-Nominal Magnitude – minimum distance

Table 45: Closing Off-Nominal 1 Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	-10.1	-10.1
Azimuth [deg]	-41.2	-41.2
Magnitude [m/s]	0.15	0.27
Closingmin Range [m] (module and RIC frame components)	150 [0.35 149.96 -0.15]	92.9 [-12.9 -79.1 46.9]
Time to the min Range [hr]	7.3	2.86

The Closing final position with the greatest distance compared to the desired one is obtained when the insertion manoeuvre in the HP#3 is not performed at all (0% of the nominal value), this off-nominal manoeuvre does not cause any risk of collision. In fact, the minimum distance during the HP#3 Insertion would be 5.0 km, reaching a final position which differs from the nominal one of 10.1 km along the Intrack direction. The off-nominal trajectory is shown in Figure 95 and it can be noticed that it is the continuation of the previous Free Flight trajectory.

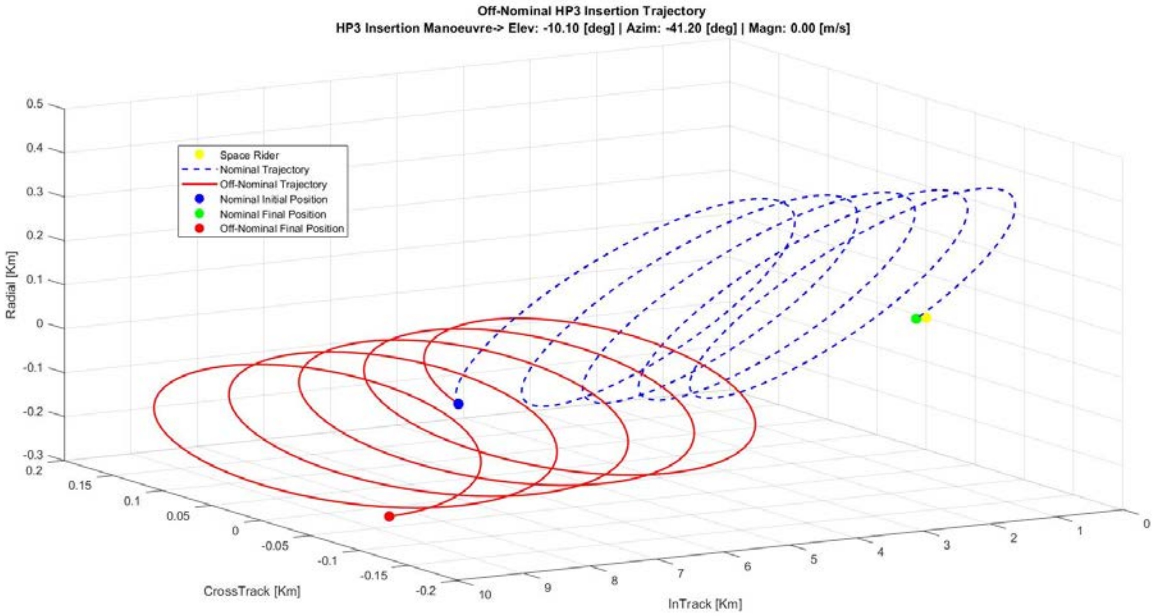


Figure 95: Closing Off-Nominal Magnitude – worst Final Position

Table 46: Closing Off-Nominal 2 Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	-10.1	-10.1
Azimuth [deg]	-41.2	-41.2
Magnitude [m/s]	0.15	0.0
Closingmin Range [m] (module and RIC frame components)	150 [0.35 149.96 -0.15]	$5.0 \cdot 10^3$ [-21.0 $4.9 \cdot 10^3$ -157.4]
Time to the min Range [hr]	7.3	0.85

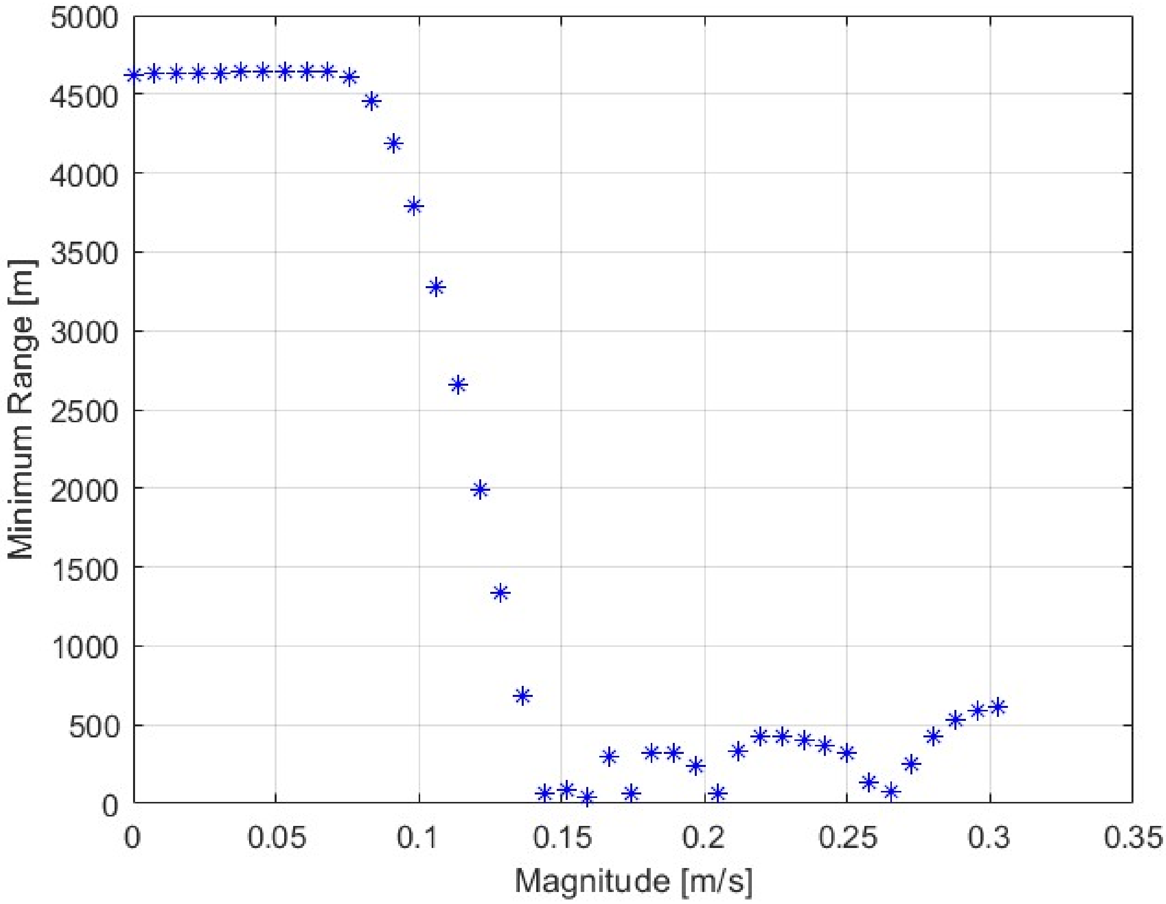


Figure 96: Scatter plot Magnitude errors – Closing Opt 1

Direction and magnitude errors

Combining errors in direction and magnitude of the thrust, the results are more critical. The minimum distance is 124.3 m with a CrossTrack component of 45 m for an off-nominal manoeuvre with an error of +0.5 deg for the elevation, +4.0 deg for the azimuth and a magnitude increased by 25%. The resulting trajectory and some parameters are shown in Figure 97 and in Table 47:

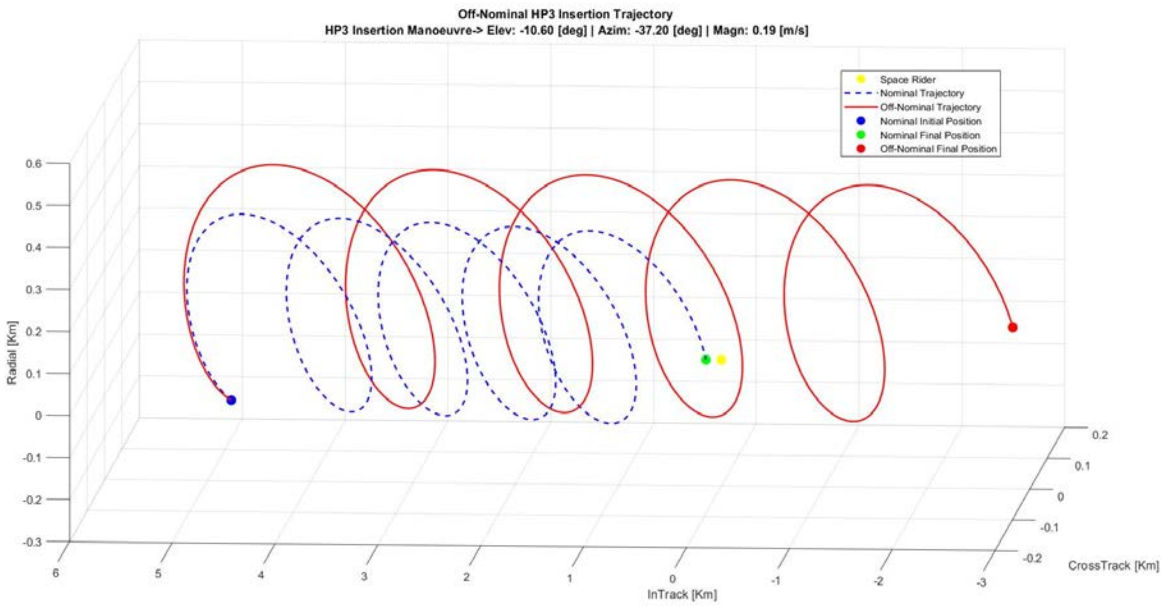


Figure 97: Closing Off-Nominal Direction and Magnitude - minimum distance

Table 47: Closing Off-Nominal 1 Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	-10.1	-10.6
Azimuth [deg]	-41.2	-37.2
Magnitude [m/s]	0.15	0.19
Closing min Range [m] (module and RIC frame components)	150 [0.35 149.96 -0.15]	124.3 [-5.4 -115.7 45]
Time to the min Range [hr]	7.3	4.3

The Closing final position with the greatest difference from the nominal one occurs with an elevation error of +5.0 deg, an azimuth error of +5.0 deg and a double magnitude compared to the nominal one (+100%). In this event, the final position is 10.54 km far away from the desired one along the Intrack axis and the minimum range between the two spacecraft during the rendezvous is 817.8 m. The relative trajectory is shown in Figure 98:

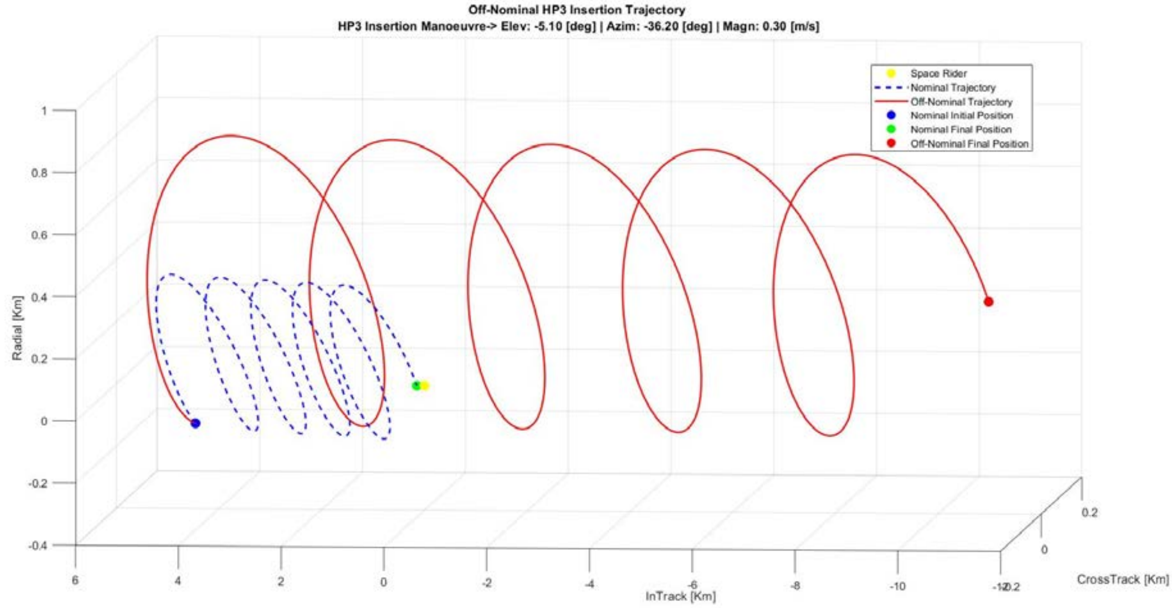


Figure 98: Closing Off-Nominal Direction and Magnitude – worst Final Position

Table 48 resumes this off-nominal scenario.

Table 48: Closing Off-Nominal 2 Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	-10.1	-5.1
Azimuth [deg]	-41.2	-36.2
Magnitude [m/s]	0.15	0.3
Closing min Range [m] (module and RIC frame components)	150 [0.35 149.96 -0.15]	817.8 [67.8 -807.2 112.5]
Time to the min Range [hr]	7.3	3.36

4.1.6 Off-Nominal manoeuvre for insertion in the Hold Point 3

The entry manoeuvre in the HP#3 is performed at the end of the HP#3 Insertion phase. This manoeuvre stops the relative motion along the Intrack axis at a desired value (*Intrack target*) of 150 m with respect to SR. Figure 99 shows the nominal relative trajectory during the HP#3. A relative motion is still present, but it is small compared to the examined distance.

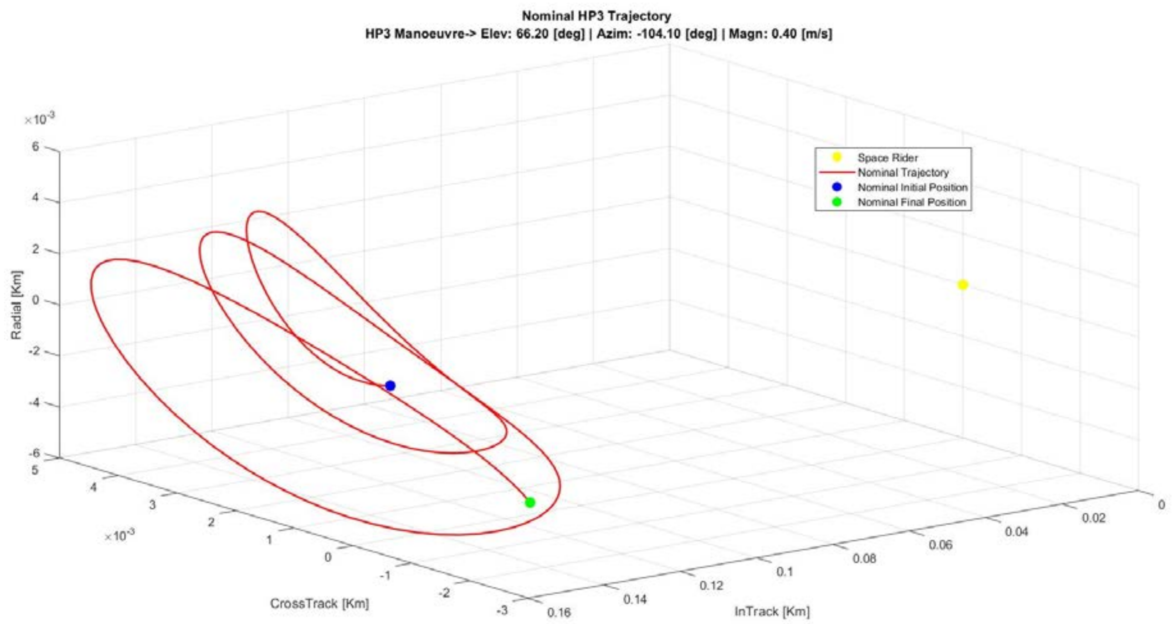


Figure 99: HP#3 Nominal Trajectory

Hereafter, (Table 49) are reported the manoeuvre values for the nominal mission and some other parameters useful to compare the off-nominal scenarios to the nominal one:

Table 49: HP#3 Nominal Manoeuvre Values

Elevation [deg]	Azimuth [deg]	Magnitude [m/s]
66.2	-104.1	0.42
min Range [m]	150	
Time to the min Range [hr]	0	

The off-nominal analysis was performed by varying the angles of ± 5 $[deg]$ from the nominal value, with a step of 0.5 $[deg]$, the magnitude of ± 100% from the nominal value, with a 5% step, and the combinations of the two errors were also considered.

Direction errors

Committing some errors on the manoeuvre direction could increase the risk of collision with SR, since the minimum distance to be reached could be close to the target spacecraft. Two cases of particular interest are reported below. The minimum distance during the HP#3 trajectory is for an off-nominal manoeuvre with +2 deg for the elevation angle and +2 deg for the azimuth with respect to the nominal values. In this scenario the minimum distance is 1.2 m and considering the SR size and geometry, this off-nominal scenario would lead to a collision after one orbit. This is the worst off-nominal manoeuvre for the HP#3 mistaking only the direction with respect to Space Rider. The off-nominal trajectory is shown in Figure 100 and some values are resumed in Table 50.

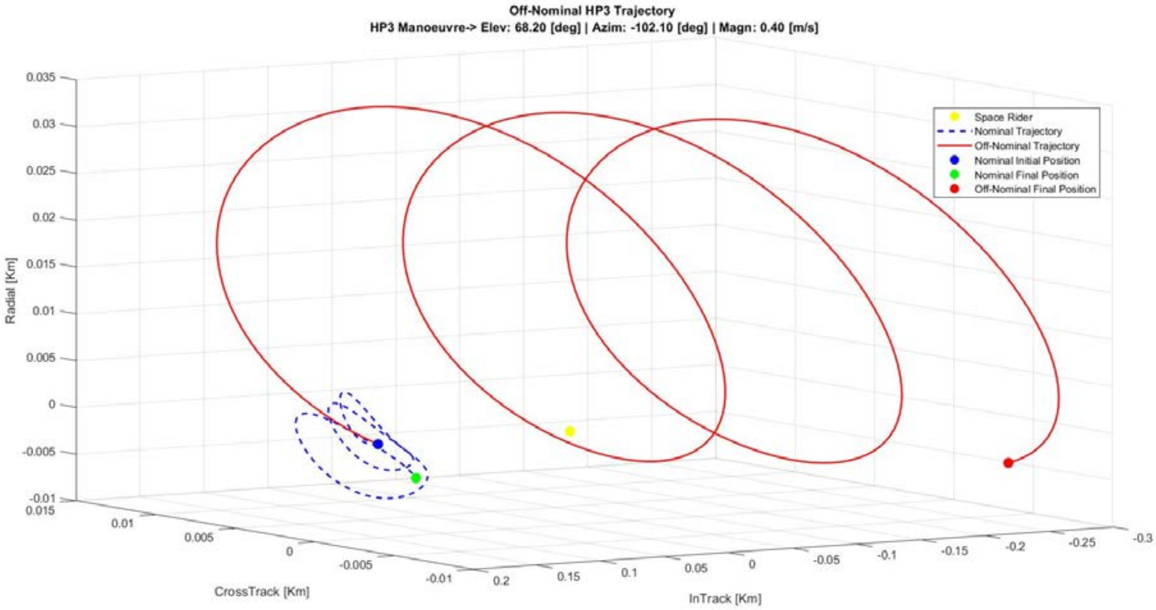


Figure 100: HP#3 Off-Nominal Direction - minimum distance

Table 50: HP#3 Off-Nominal 1 Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	66.2	68.2
Azimuth [deg]	-104.1	-102.1
Magnitude [m/s]	0.42	0.42
	150	1.2
HP#3 min Range [m] (module	[0	[-1.1
and RIC frame components)	150	0.4
	0]	0.3]
Time to the min Range [min]	0	1.57

Another case of particular interest concerns the final position with the greater error than the nominal one. This occurs for an off-nominal manoeuvre mistaken by -5 degrees for the elevation angle and +2 degrees for the azimuth angle. The minimum range is comparable to the nominal one and this scenario would not increase the collision risk. Nevertheless, this case would result to a higher ΔV and mission delay since a new approach will be required. The trajectory is shown in Figure 101 and some parameters are reported below (Table 51).

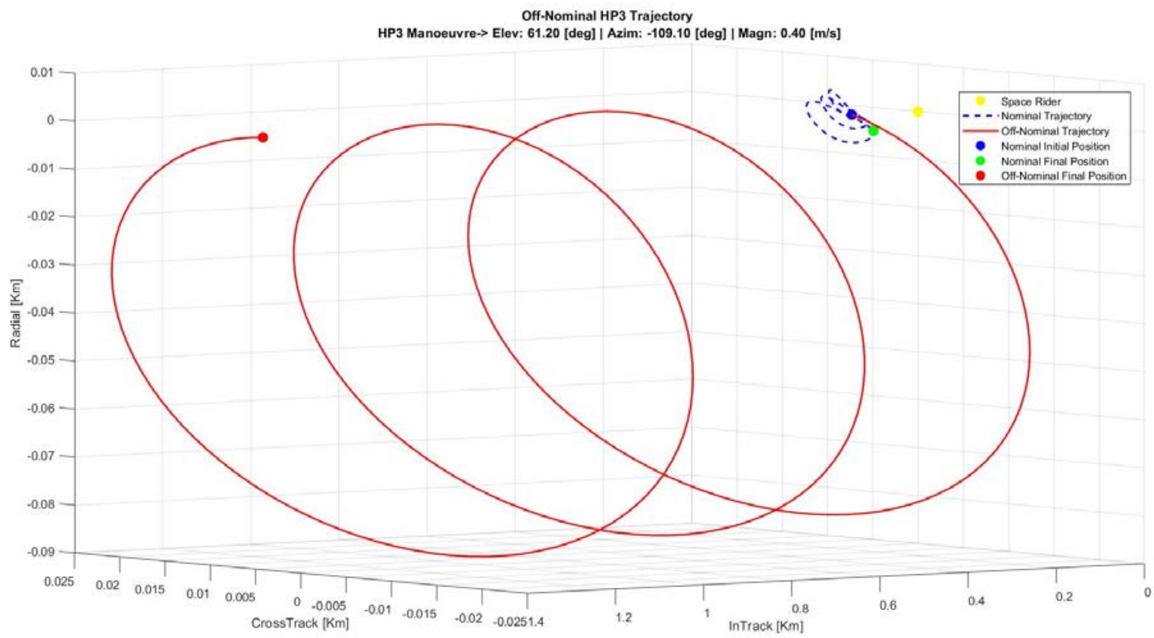


Figure 101: HP#3 Off-Nominal Direction - worst Final Position

Table 51: HP#3 Off-Nominal 2 Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	66.2	61.2
Azimuth [deg]	-104.1	-102.1
Magnitude [m/s]	0.42	0.42
HP#3 min Range [m] (module and RIC frame components)	150 [0 150 0]	145.2 [-8.9 144.6 -8.8]
Time to the min Range [min]	0	0.1

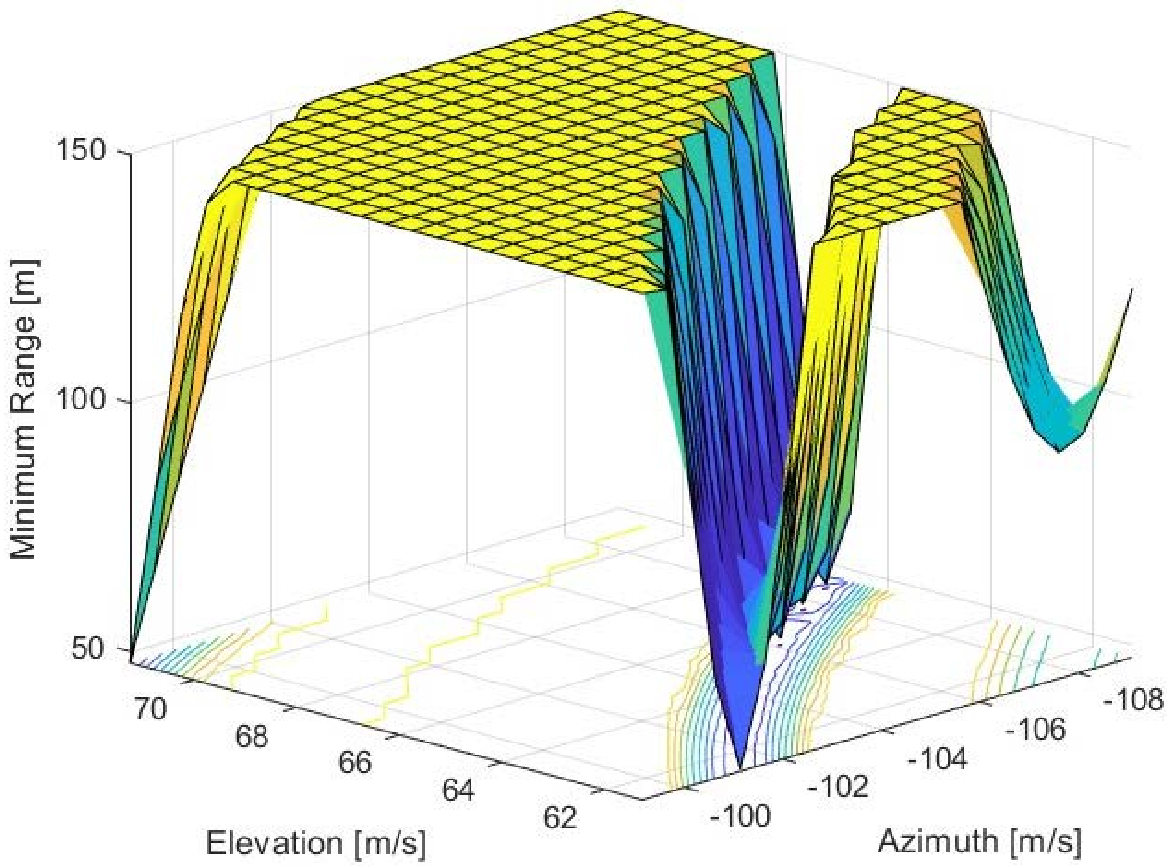


Figure 102: Scatter plot Direction errors – HP#3 Opt 1

Magnitude errors

A manoeuvre magnitude higher or lower than the nominal value involves a different final position at the end of the HP#3, which, as for errors on the direction, will be respectively in the positive or negative part of the InTrack. Therefore, also in this case it is necessary to evaluate the error that involves the minimum distance between the two spacecraft and the error that involves the greatest difference between the final position reached and the desired one. The minimum distance during the HP#3 trajectory is achieved for an off-nominal manoeuvre less intense than 20%. The minimum distance between the two spacecraft is 4.8 m and, even in this case, considering the SR size and geometry this off-nominal scenario would lead to a collision after one orbit. Furthermore, the finale position in this scenario is in the negative InTrack direction, due to the greater manoeuvre magnitude. For this reason, if SROC did not perform any other manoeuvres, a second pass should be expected near SR, during the drift away motion which would be resumed after a short period. However, this second passage would not cause high collision risks, because in the meantime SROC would continue to lose altitude, increasing the relative distance along the Radial direction and, possibly, it would perform some correction manoeuvres. The off-nominal relative trajectory is shown in Figure 103 and Table 52 resumes the manoeuvre values and the relative final components.

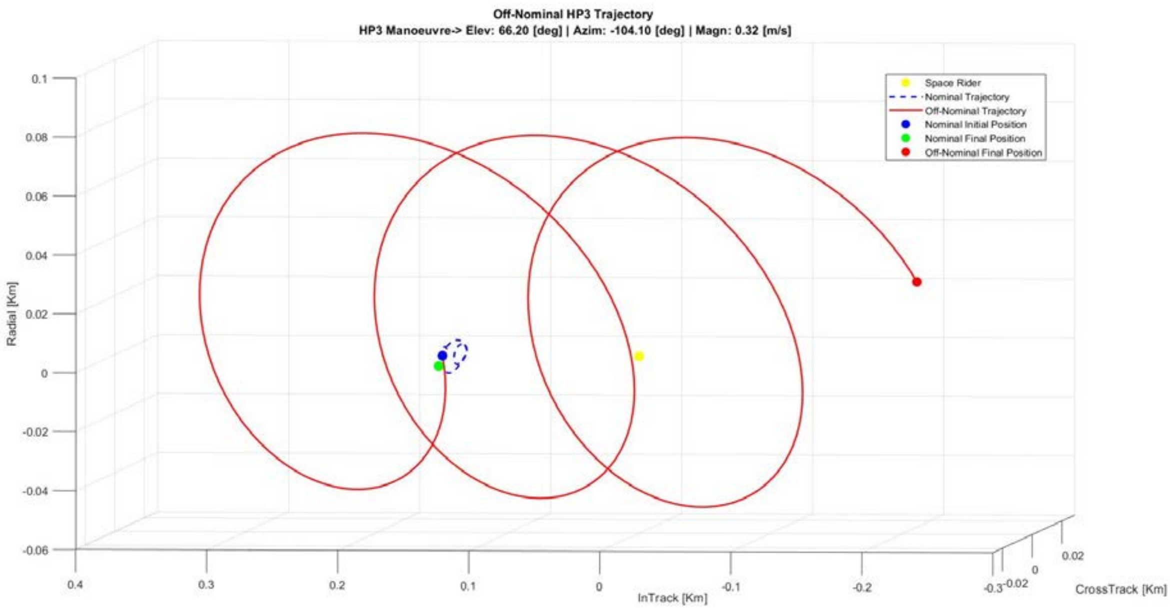


Figure 103: HP#3 Off-Nominal Magnitude - minimum distance

Table 52: HP#3 Off-Nominal 1 Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	66.2	66.2
Azimuth [deg]	-104.1	-104.1
Magnitude [m/s]	0.42	0.34
HP#3 min Range [m] (module and RIC frame components)	150 [0 150 0]	4.8 [-0.1 4.6 -1.1]
Time to the min Range [min]	0	1.54

The HP#3 final position with the greatest distance compared to the desired one is obtained when the manoeuvre is mistaken by +95%, this off-nominal manoeuvre does not lead to increased risk of collision. In fact, the minimum distance during the HP#3 would be 147 m, reaching a final position which differs from the nominal one of 1.88 km. The off-nominal trajectory is shown in Figure 104.

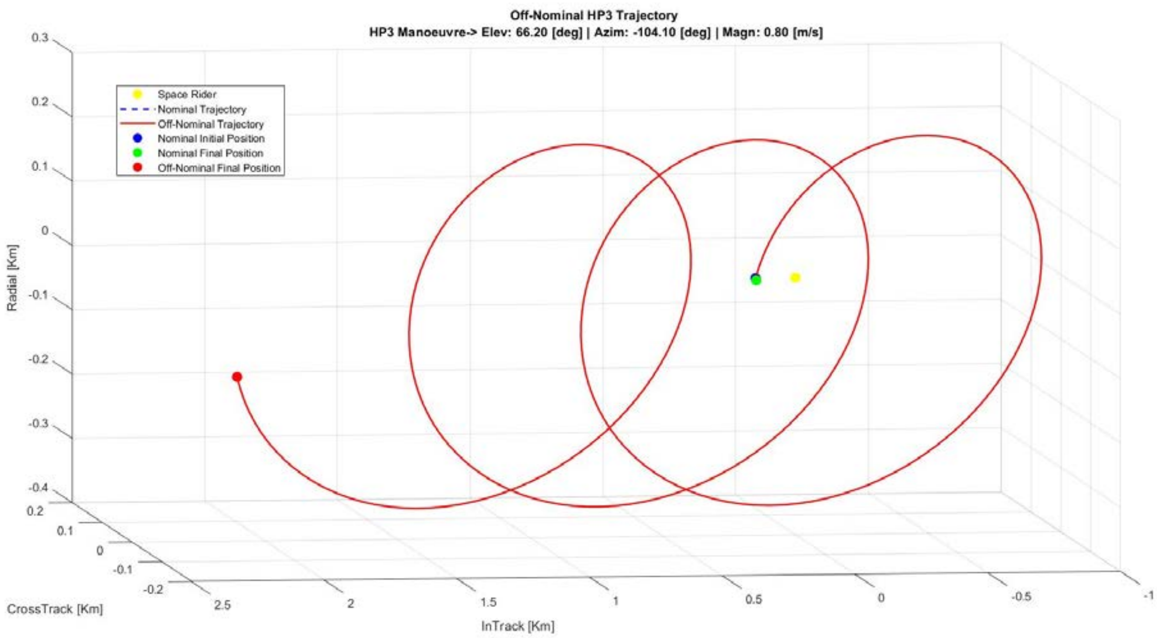


Figure 104: HP#3 Off-Nominal Magnitude - worst Final Position

Table 53: HP3 Off-Nominal 2 Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	66.2	66.2
Azimuth [deg]	-104.1	-104.1
Magnitude [m/s]	0.42	0.82
HP#3 min Range [m] (module and RIC frame components)	150 [0 150 0]	147 [50.6 136.2 -22.0]
Time to the min Range [min]	0	0

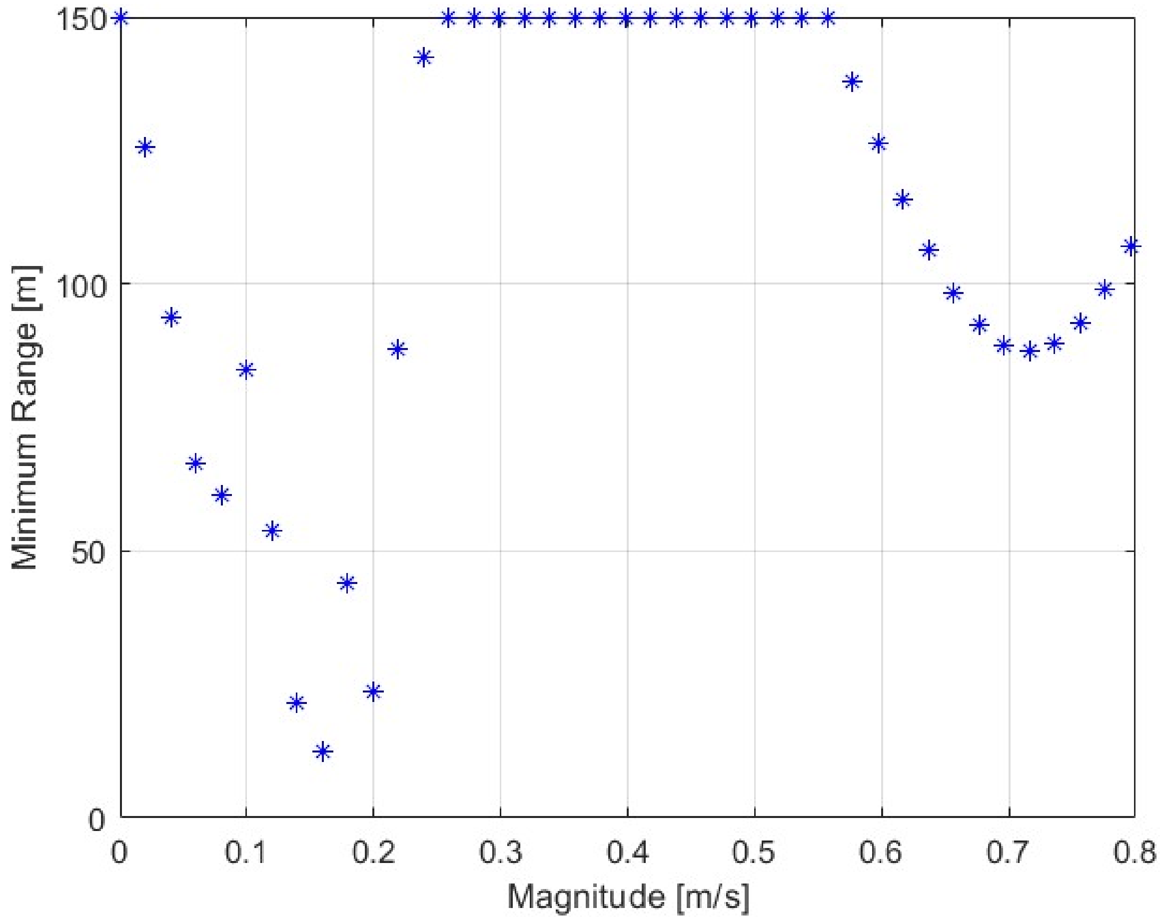


Figure 105: Scatter plot Magnitude errors – HP#3 Opt 1

Direction and magnitude errors

Combining errors in direction and magnitude of the thrust, the results are more critical. The minimum distance is 0.6 m for an off-nominal manoeuvre with an error of -4.0 deg for the elevation, -3.0 deg for the azimuth and a magnitude increased by 80%. The resulting trajectory and some parameters are shown in Figure 106 and in Table 54:

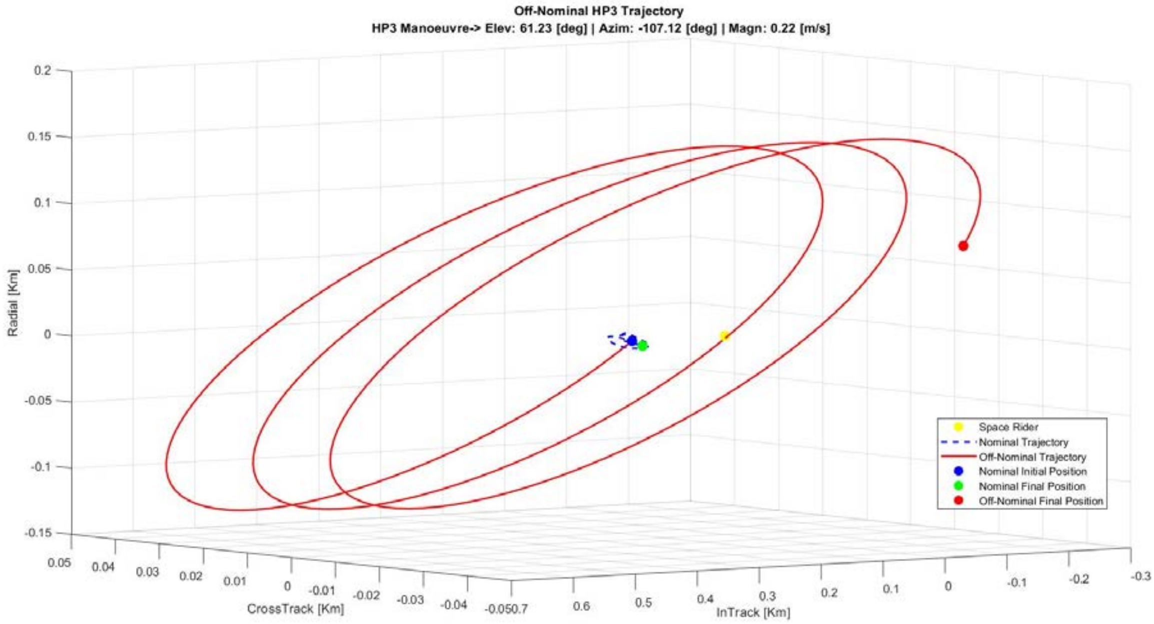


Figure 106: HP#3 Off-Nominal Direction and Magnitude - minimum distance

Table 54: HP#3 Off-Nominal 1 Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	66.2	61.2
Azimuth [deg]	-104.1	-107.1
Magnitude [m/s]	0.42	0.22
HP#3 min Range [m] (module and RIC frame components)	150 [0 150 0]	0.6 [-0.1 0.0 -0.6]
Time to the min Range [min]	0	92.3

The HP3 final position with the greatest difference from the nominal one occurs with an elevation error of - 5.0 deg, an azimuth error of +5.0 deg and a double magnitude compared to the nominal one (+100%). In this event, the minimum range between the two spacecraft during the rendezvous is 139.7 km. The relative trajectory is shown in Figure 107:

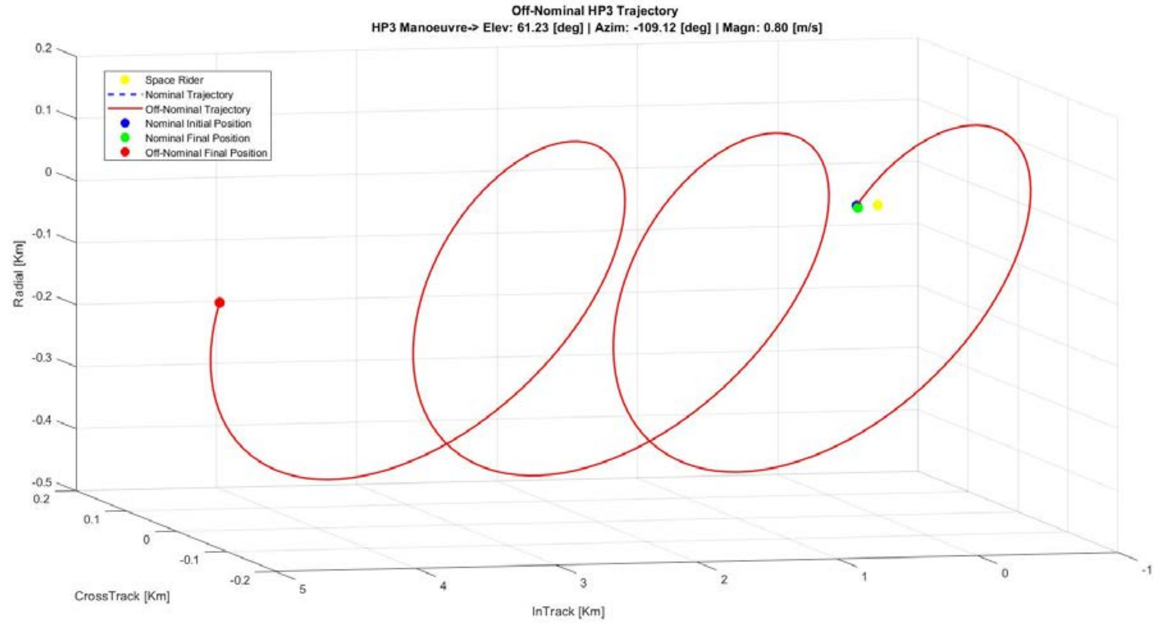


Figure 107: HP#3 Insertion Off-Nominal Direction and Magnitude – worst Final Position

Table 55 resumes this off-nominal scenario.

Table 55: HP#3 Off-Nominal 2 Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	66.2	61.2
Azimuth [deg]	-104.1	-109.1
Magnitude [m/s]	0.42	0.8
HP#3 min Range [m] (module and RIC frame components)	150 [0 150 0]	139.7 [65.4 115.7 -43.1]
Time to the min Range [min]	0	3.6

4.2 Rendezvous Option 2

4.2.1 Off-Nominal manoeuvre entering the In-Plane Approach Rendezvous (IPA)

To approach Space Rider and start the inspection phase, SROC performs an in-plane manoeuvre to execute the In-Plane Approach Rendezvous. After the in-plane trajectory toward SR and reaching the InTrack Target (5 km in the nominal scenario), SROC performs an out of plane manoeuvre to get close to SR with a the Out-of-Plane Approach Rendezvous (OPA). The IPA is considered valid if the minimum reached distance along the InTrack direction is greater than 1 Km in case the OPA manoeuvre is not performed. This definition is fundamental for the conclusions made after the analysis. Hereafter (Table 56) are reported the ΔV vector for the nominal scenario and some other parameters useful to compare the off-nominal scenarios to the nominal one:

Table 56: In-Plane Approach Nominal Manouvre Values

Elevation [deg]	Azimuth [deg]	Magnitude [m/s]
0.0	0.0	0.42
min Range [km]	4.92	
max Range [km]	334.75	
next Manoeuvre [m/s]	0.39	
IPA Duration [day]	5.7	

It must be noticed that the minimum range for the nominal mission profile is the InTrack target. Furthermore the "next Manoeuvre ΔV" includes the entry manoeuvre in the OPA trajectory. It depend on the execution of the IPA. Figure 108 shows the nominal relative trajectory during the In-Plane Rendezvous. As SROC approaches the final position of the IPA, the relative orbits become closer and closer. In fact, due to the atmospheric drag, the SROC velocity is reduced, up to zero before reaching SR, if the OPA is not performed.

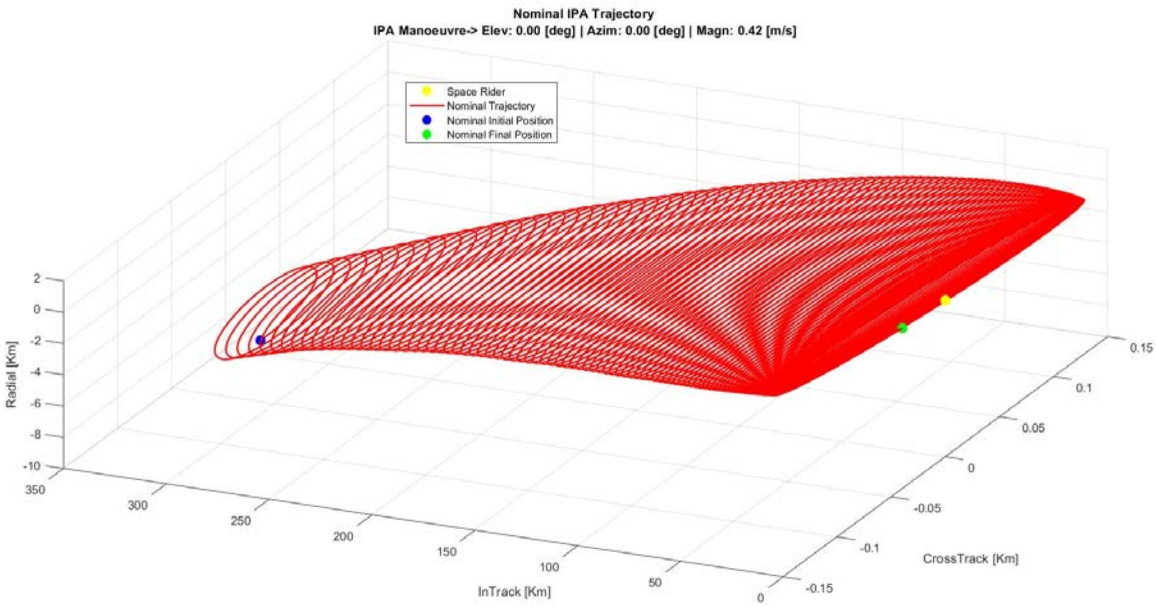


Figure 108: IPA Nominal Trajectory

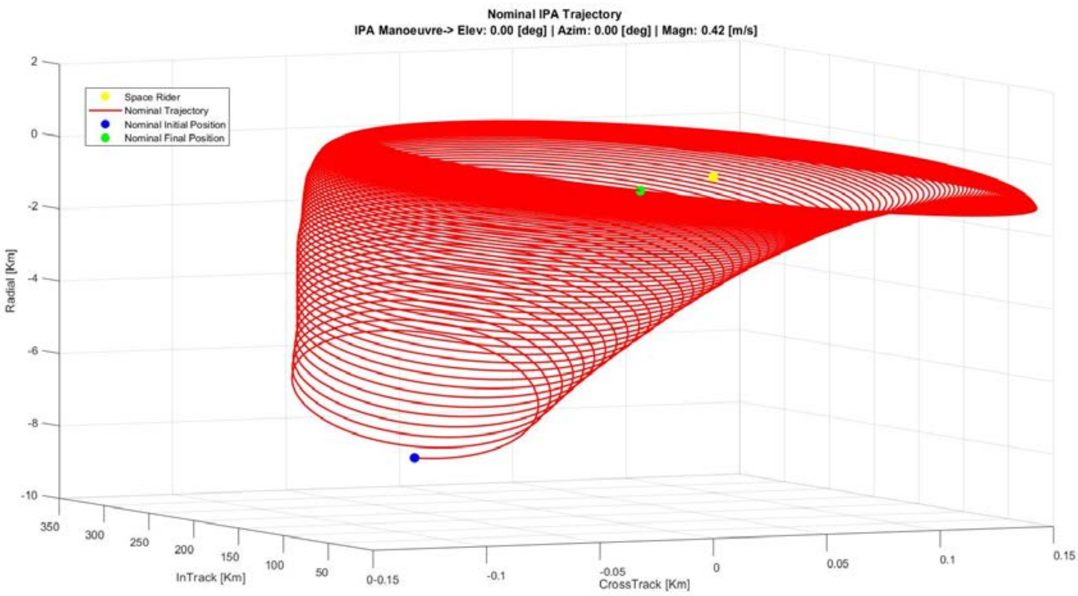


Figure 109: IPA Nominal Trajectory – Out-of-Plane View

The off-nominal analysis was performed by varying the angles of ± 5 $[deg]$ from the nominal value, with a step of 0.5 $[deg]$, the magnitude of ± 100% from the nominal value, with a 5% step, and the combinations of the two errors were also considered. Since the IPA is a trajectory towards the target spacecraft into its orbital plane (although the perturbations naturally cause the SROC orbit to tilt), performing an off-nominal manoeuvre could increase the risk of collision with the target itself. Therefore, the objective of the analysis is to determine the maximum permissible errors so that the IPA is still considered valid, even if no longer optimized. Furthermore, for an off-nominal IPA it is necessary to evaluate the minimum distance reached with respect to SR and the time needed to reach this position.

Direction errors

As for the off-nominal HP#1, mistaking the thrust direction up to 5 degrees from the nominal values does not involve any greater risk to Space Rider. In fact, all the cases of off-nominal IPA analysed by varying the manoeuvre direction were valid and furthermore the minimum distance reached without the OPA is always higher than the nominal one. The correct manoeuvre is performed in the orbital plane of SR, therefore the manoeuvre magnitude to approach it is maximized along the velocity direction. If the manoeuvre is performed with the same magnitude but outside the SROC orbital plane, there is a dispersion of ΔV as there would be a greater out of SR plane trajectory. From this point of view, an off-nominal manoeuvre with a wrong direction is safer for SR.

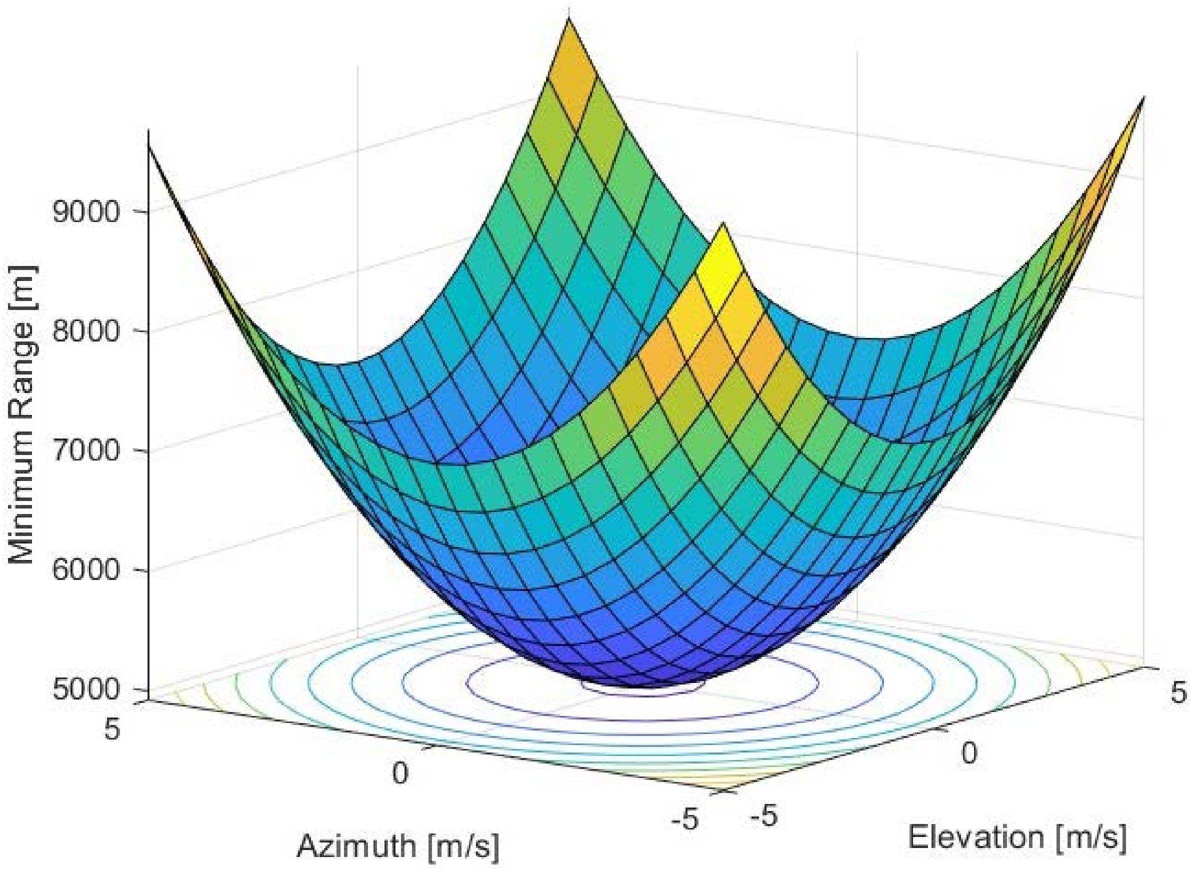


Figure 110: Scatter plot Direction errors – IPA Opt 2

Magnitude errors

As regard mistaking the thrust magnitude, two different aspects are considered: the minimum reached distance during the IPA and the minimum reached distance if the OPA manoeuvre is not executed with the respective time durations. If the magnitude is less than nominal, SROC reaches a greater relative distance, a greater InTrack Target (considering the same propagate duration) before running the OPA. This does not involve any additional risk for Space Rider, but simply an increase in ΔV cost for SROC. For this reason, it is necessary to carefully parse the manoeuvres with a greater magnitude. The first non-valid IPA occurs for a 105% of magnitude. In this case the minimum distance is 99.9 m. This off-nominal scenario involves a higher risk of collision with Space Rider and SROC will enter the KOZ. In fact, the minimum distance is reached during the In-Plane Rendezvous regardless of the OPA. The following Figure 111 shows the off-nominal trajectory with highlighting the positions in which the distance has a minimum value during the IPA and in case of no OPA.

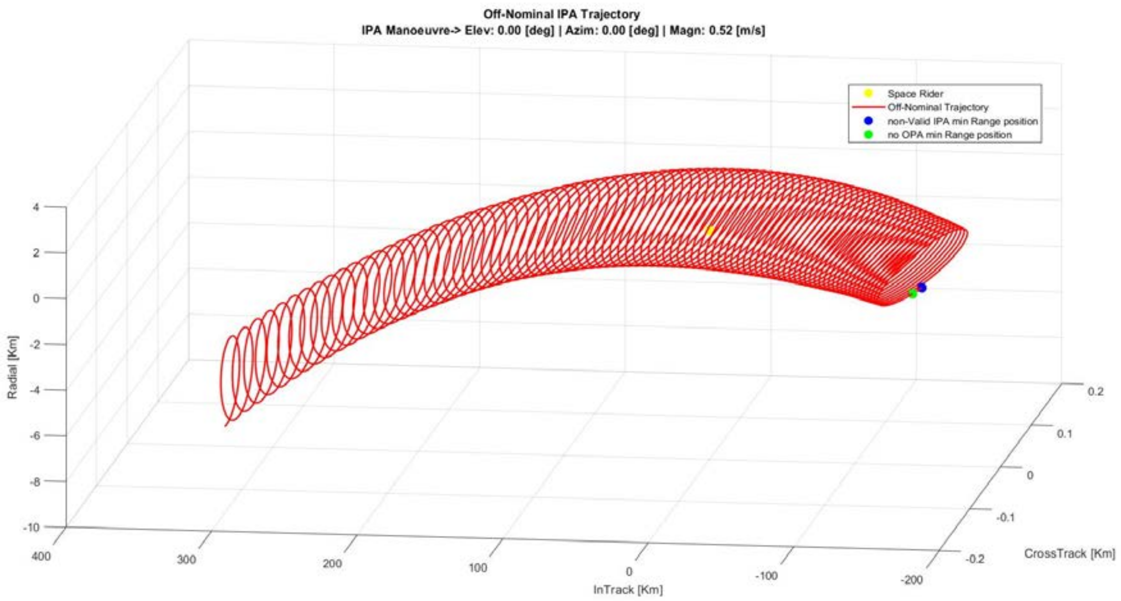


Figure 111: IPA Off-Nominal Magnitude – minimum distance during IPA

Table 57: IPA Off-Nominal 1 Manoeuvres Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	0.0	0.0
Azimuth [deg]	0.0	0.0
Magnitude [m/s]	0.42	0.52
IPA min Range [m] (module and RIC frame components)	$4.92 \cdot 10^3$ [55.4 $4.92 \cdot 10^3$ -67.6]	99.9 [-54.6 -37.5 -74.8]
Time to the min Range [day]	5.7	3.07
No OPA min Range [m] (module and RIC frame components)	$3.91 \cdot 10^3$ [32.4 $3.9 \cdot 10^3$ -57.5]	$147.33 \cdot 10^3$ [$-1.44 \cdot 10^3$ $-147.32 \cdot 10^3$ -64.9]
Time to the min Range no OPA [day]	5.83	6.6

With just a 5% error on the magnitude the trajectory of the IPA would be overcome SR towards the negative InTrack direction and reaching a very close distance, but it is important to notice that thanks to the long duration of this approach phase (5.7 days) it would be possible to detect and correct the trajectory in case any error occurs.

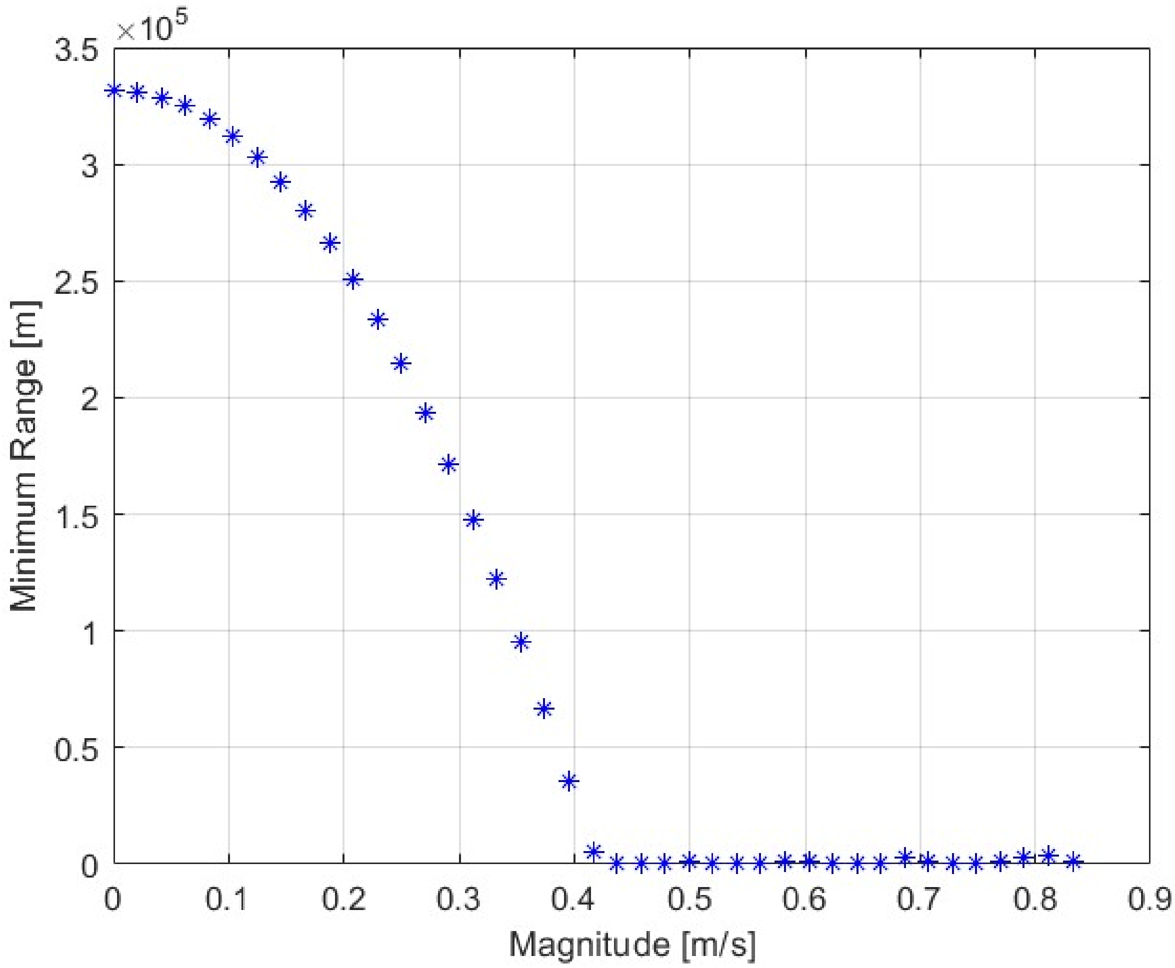


Figure 112: Scatter plot Magnitude errors – IPA Opt 2

Direction and magnitude errors

Direction errors involve no additional risk but combined with magnitude errors they become critical for the mission safety. The minimum distance during the IPA is 75.9 m and is reached with errors of -2.5 deg on the elevation, -5.0 deg on the azimuth and a magnitude 120% the nominal. This distance is below the 200-meter radius of the KOZ so far considered. The relative trajectory of this scenario is shown in Figure 113.

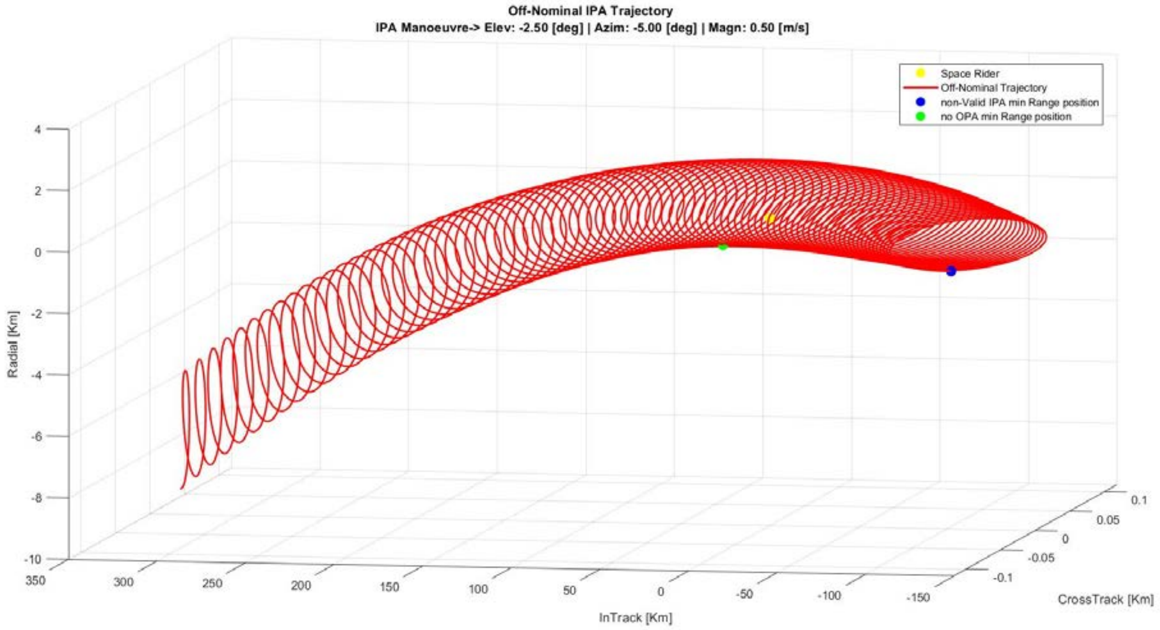


Figure 113: IPA Off-Nominal Direction and Magnitude – minimum distance during IPA

Table 58 resumes the two off-nominal scenario that occur for a combination of direction and magnitude errors.

Table 58: IPA Off-Nominal Manoeuvres Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	0.0	-2.5
Azimuth [deg]	0.0	5
Magnitude [m/s]	0.42	0.5
IPA min Range [m] (module and RIC frame components)	$4.92 \cdot 10^3$ [55.4 $4.92 \cdot 10^3$ -67.6]	75.9 [-21.5 26.9 -67.7]
Time to the min Range [day]	5.7	3.33
No OPA min Range [m] (module and RIC frame components)	$3.91 \cdot 10^3$ [32.4 $3.9 \cdot 10^3$ -57.5]	/
Time to the min Range no OPA [day]	5.83	/

If the OPA is not performed, the minimum distance reached is 3.91 km with the same off-nominal case presented for the direction only error, reported on the Figure 111 and Table 57.

4.2.2 Off-Nominal manoeuvre for the Hold Point 2 Insertion trajectory

To stop the Rendezvous Phase and ensuring the navigation sensors switch while waiting the go/no-go command, SROC performs an out-of-plane manoeuvre to execute the Hold Point 2. After the IPA, SROC executes an out-of-plane trajectory toward SR and reaching the *InTrack Target* (2 km in the nominal scenario), SROC performs a holding phase finite manoeuvre close to SR to maintain this relative position during the HP#2. Hereafter (Table 59) are reported the ΔV vector for the nominal scenario and some other parameters useful to compare the off-nominal scenarios to the nominal one:

Table 59: HP#2 Insertion Nominal Manoeuvre Values

Elevation [deg]	Azimuth [deg]	Magnitude [m/s]
38.9	-82.3	0.39
min Range [m]	$2 \cdot 10^3$	
Time to the min Range [min]	4.55	
Next Manoeuvre ΔV [m/s]	1.46	

It must be noticed that the minimum range for the nominal mission profile is the InTrack target. Furthermore the "next Manoeuvre ΔV" includes the entry manoeuvre in the HP#2 trajectory and the finite manoeuvre needed to maintain this relative position. Both depend on the execution of the HP#2 Insertion. Figure 114 shows two different views of the nominal HP#2 Insertion trajectory, while Figure 115 highlight the out-of-plane nature of the HP#2 Insertion trajectory.

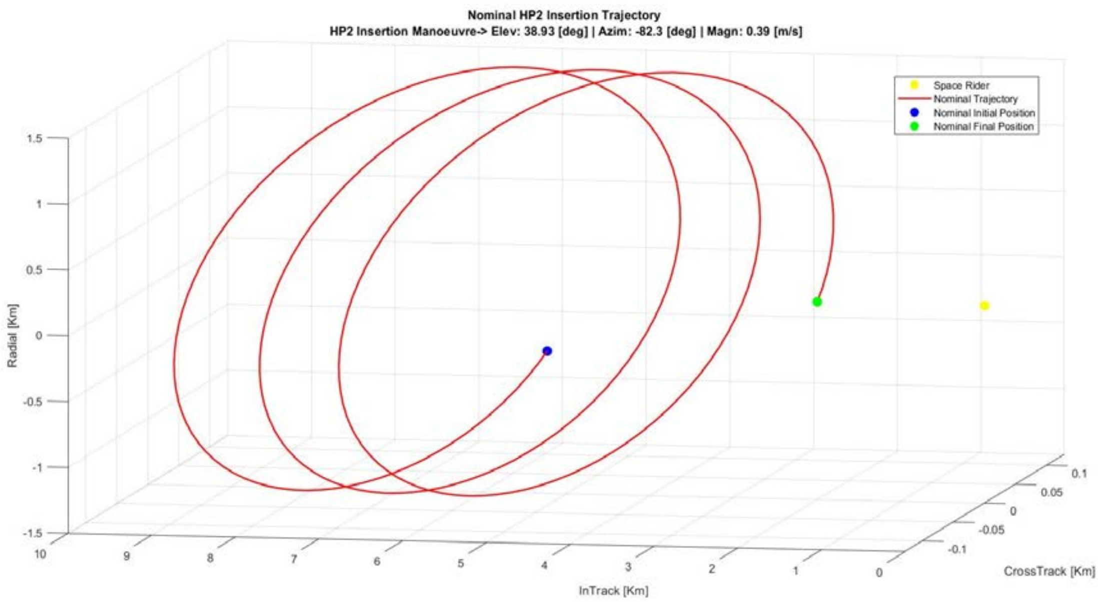


Figure 114: HP#2 Insertion Nominal Trajectory

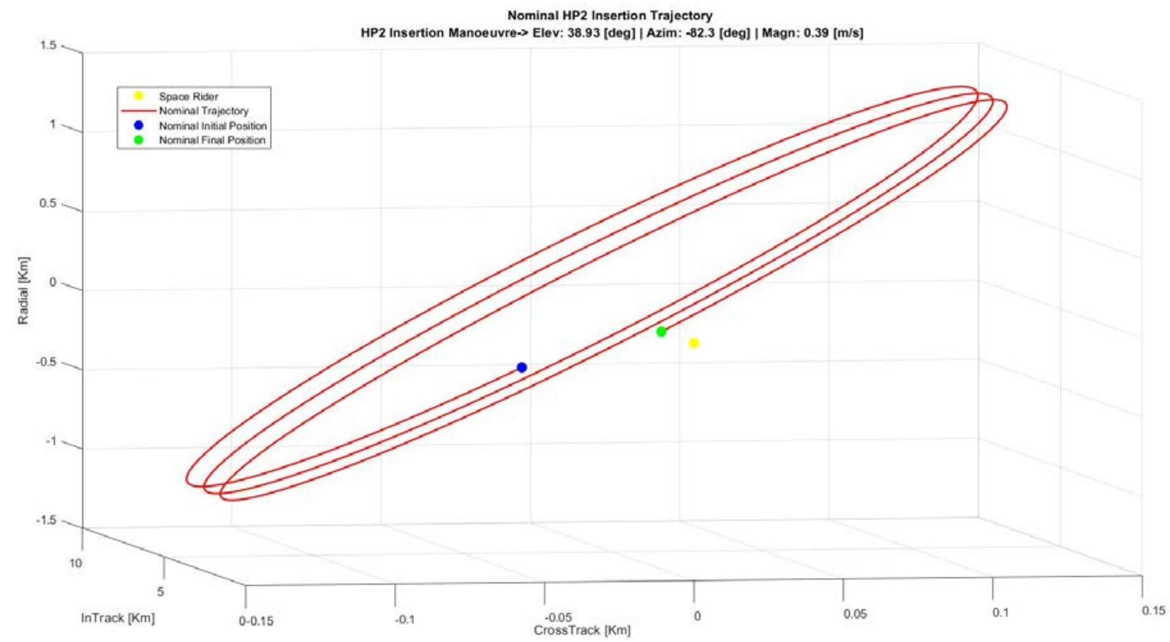


Figure 115: HP#2 Insertion Nominal Trajectory – Out-of-Plane View

The HP#2 allows to maintain a precise position with the respect to SR and wait the right moment to start the docking phase. This manoeuvre, together with the insertion in the WSE trajectory, is one of the most critical for the mission, as it requires high precision to reach the position near Space Rider and guarantee a minimum safety distance. The HP#2 is defined in such a way as to simplify the docking operations reducing the ΔV required while lowering the risk of collision with Space Rider (the HP#2 Insertion is a passive safe trajectory). If the HP#2 Insertion does not lead to the desired position, it would be necessary to perform a new HP#2 Insertion to correct the error and then begin the holding phase. Failing the insertion manoeuvre in the HP#2 leads to increased costs and delays for SROC, but could also increase the risk of collision with SR. For this reason, a Keep Out Zone (KOZ) with a radius of 200 meters has been considered. The off-nominal HP#2 Insertions are therefore evaluated with respect to the minimum distance with the target spacecraft during the entire trajectory.
The off-nominal analysis was performed by varying the angles of ± 5 $[deg]$ from the nominal value, with a step of 0.5 $[deg]$, the magnitude of ± 100% from the nominal value, with a 5% step, and the combinations of the two errors were also considered. Since the HP#3 Insertion is a trajectory towards the target spacecraft out of its orbital plane, performing an off-nominal manoeuvre could increase the risk of collision with the target itself. Therefore, the objective of the analysis is to determine the maximum permissible errors so that the HP#3 Insertion is still considered valid, even if no longer optimized. Furthermore, for an off-nominal HP#2 Insertion it is necessary to evaluate the minimum distance reached with respect to SR.

Direction errors

Committing some errors on the manoeuvre direction could increase the risk of collision with SR, since the final position to be reached is close to the target spacecraft. However, similar considerations as reported for the previous HP Insertion off-nominals must be taken into account. Two cases of particular interest are reported below. The minimum distance during the HP#2 Insertion trajectory is for an off-nominal manoeuvre with -5 deg for the elevation angle and +5 deg for the azimuth with respect to the nominal values. The minimum distance is achieved at the end of this insertion segment and the module of the minimum distance is 530 m. This is the worst off-nominal manoeuvre for the HP#2 Insertion mistaking only the direction with respect to Space Rider. The off-nominal trajectory is shown in Figure 116 and some values are resumed in Table 60.

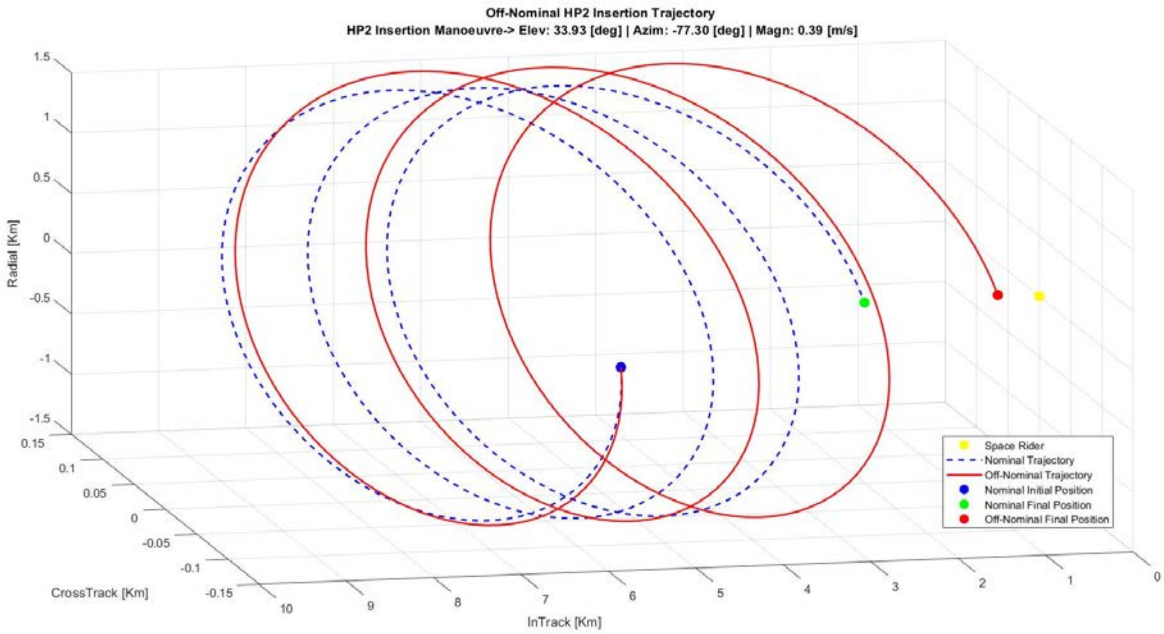


Figure 116: HP#2 Insertion Off-Nominal Magnitude – minimum distance

Table 60: HP#2 Insertion Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	38.9	33.9
Azimuth [deg]	-82.3	-77.3
Magnitude [m/s]	0.39	0.39
HP#3 Insertion min Range [m] (module and RIC frame components)	$2 \cdot 10^3$ [0.0 $2 \cdot 10^3$ 0.0]	529.9 [161.9 499.3 -73.1]
Time to the min Range [hr]	4.55	4.55

The same off-nominal is the same that would lead to the worst Final Position with 1.5 km along the Intrack axis, but SROC remains outside of the KOZ for the entire HP#2 off-nominal.

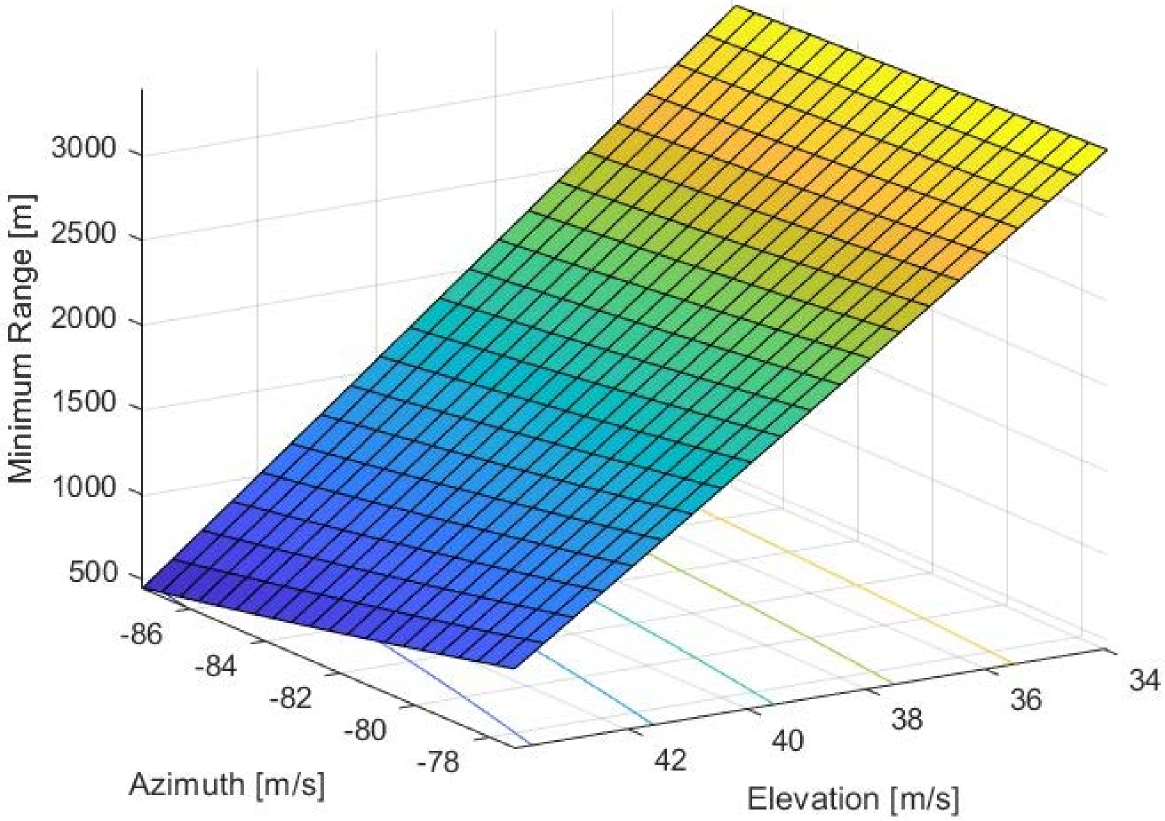


Figure 117: Scatter plot Direction errors – HP#2 Insertion Opt 2

Magnitude errors

A manoeuvre magnitude higher or lower than the nominal value involves a different final position at the end of the HP#2 Insertion, which, as for errors on the direction, will be respectively in the negative or positive part of the InTrack. Therefore, also in this case it is necessary to evaluate the error that involves the minimum distance between the two spacecraft and the error that involves the greatest difference between the final position reached and the desired one. The minimum distance during the HP#2 Insertion trajectory is achieved for an off-nominal manoeuvre more intense than 100%. The relative distance between the two spacecraft is 126.5 m. The off-nominal relative trajectory is shown in Figure 118 and Table 61 resumes the manoeuvre values and the relative final components.

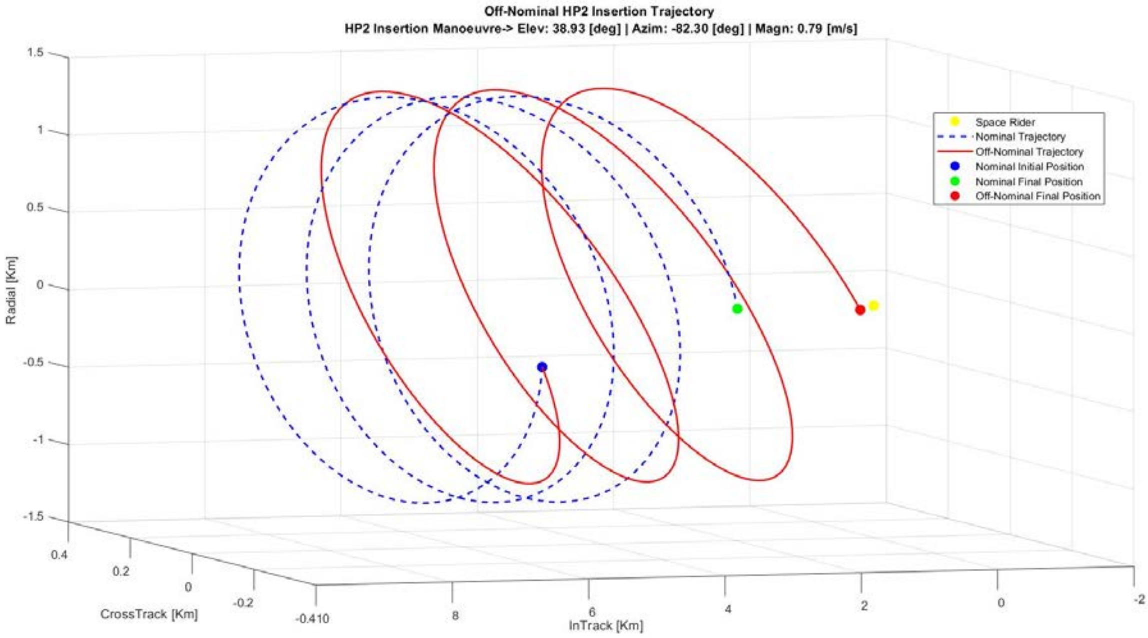


Figure 118: HP#2 Insertion Off-Nominal Magnitude – minimum distance

Table 61: HP#2 Insertion Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	38.9	38.9
Azimuth [deg]	-82.3	-82.3
Magnitude [m/s]	0.39	0.79
HP#3 Insertion min Range [m] (module and RIC frame components)	$2 \cdot 10^3$ [0.0 $2 \cdot 10^3$ 0.0]	126.5 [61.4 90.4 63.6]
Time to the min Range [hr]	4.55	4.55

The HP#2 Insertion final position with the greatest distance compared to the desired one is obtained when the insertion manoeuvre in the HP#2 is not performed at all (0% of the nominal value), this off-nominal manoeuvre does not cause any risk of collision. In fact, the minimum distance during the HP#2 Insertion would be 4.1 km, and this off-nominal represents the IPA nominal trajectory, so SROC will stop its motion within 4 km to SR and the resuming toward more positive Intrack values. The off-nominal trajectory is shown in Figure 119.

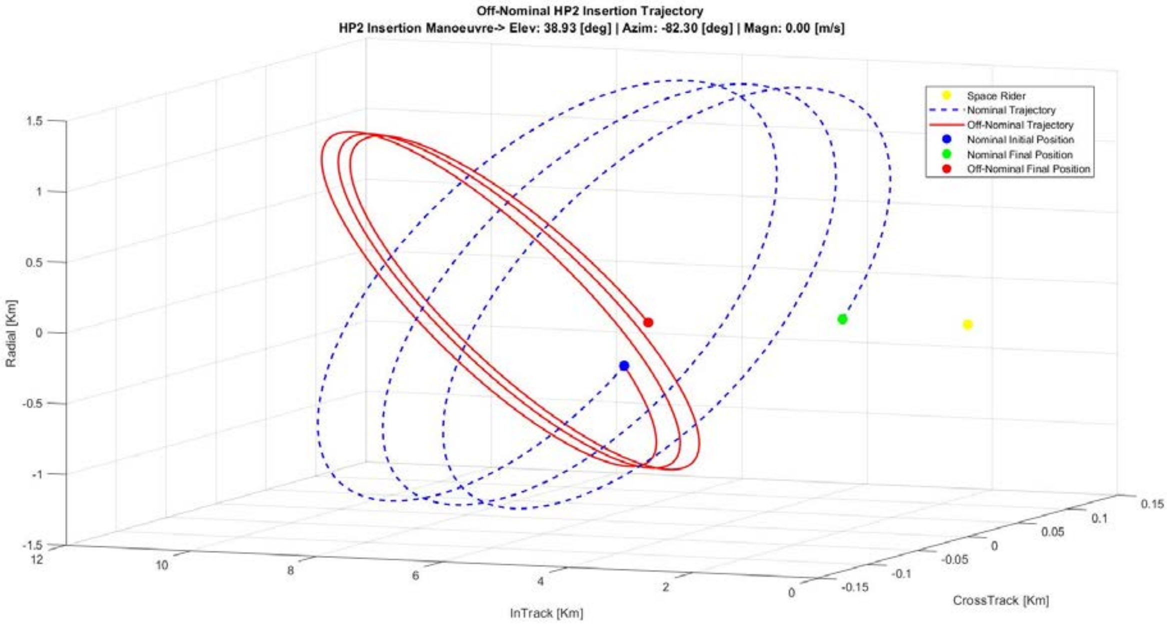


Figure 119: HP#2 Insertion Off-Nominal Magnitude – worst Final Position

Table 62: HP#2 Insertion Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	38.9	38.9
Azimuth [deg]	-82.3	-82.3
Magnitude [m/s]	0.39	0.0
HP#3 Insertion min Range [m] (module and RIC frame components)	$2 \cdot 10^3$ [0.0 $2 \cdot 10^3$ 0.0]	$4.09 \cdot 10^3$ [60.7 $4.09 \cdot 10^3$ -63.5]
Time to the min Range [hr]	4.55	4.55

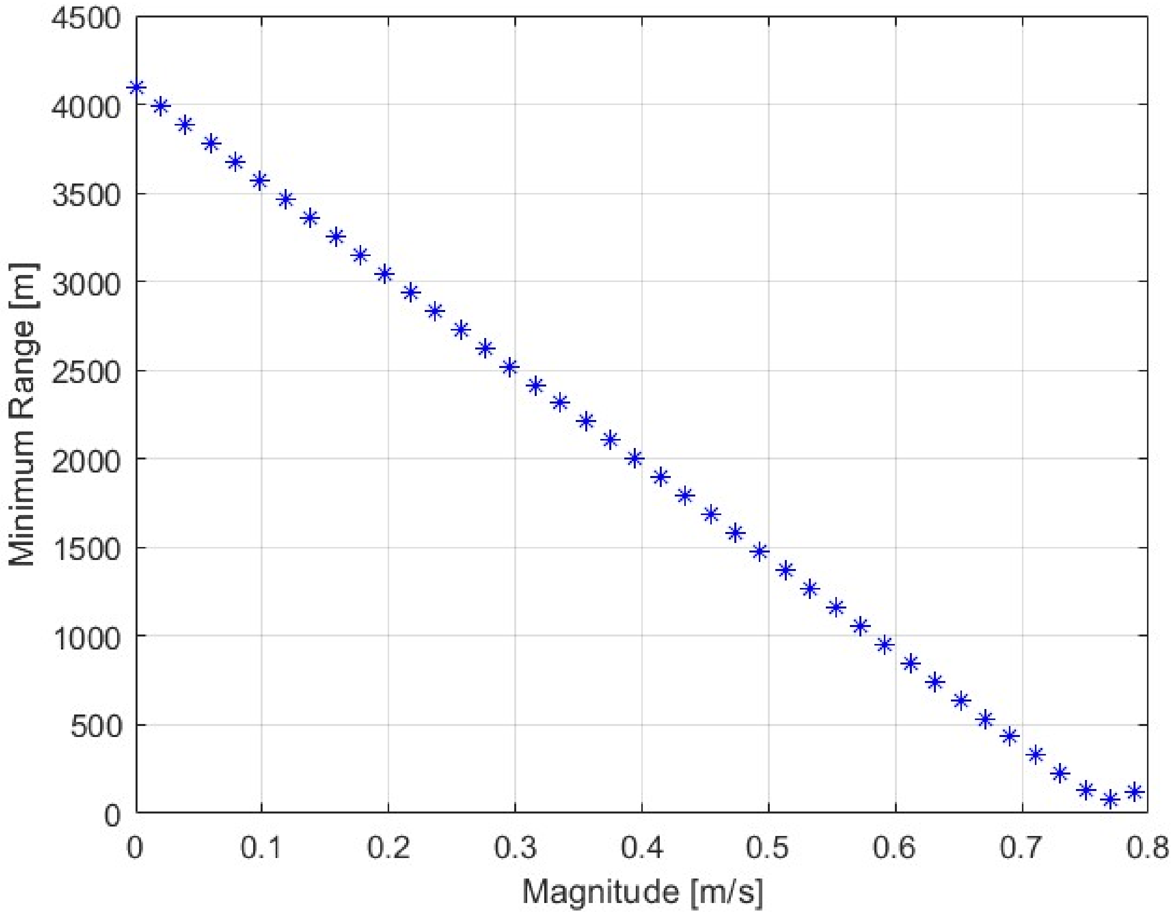


Figure 120: Scatter plot Magnitude errors – HP#2 Insertion Opt 2

Direction and magnitude errors

Combining errors in direction and magnitude of the thrust, the minimum distance is 12.9 m with a CrossTrack component of 11.8 m for an off-nominal manoeuvre with an error of -3.0 deg for the elevation, +5.0 deg for the azimuth and a magnitude increased by 20%. The resulting trajectory and some parameters are shown in Figure 121 and in Table 63:

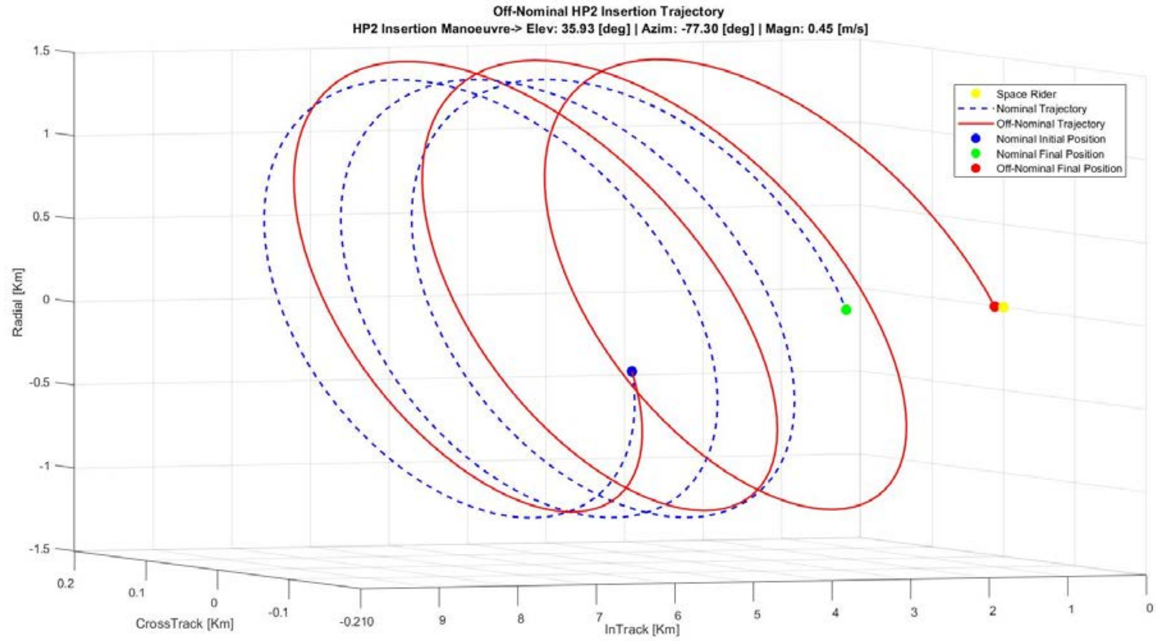


Figure 121: HP#2 Insertion Off-Nominal Direction and Magnitude - minimum distance

Table 63: HP#2 Insertion Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	38.9	35.9
Azimuth [deg]	-82.3	-77.3
Magnitude [m/s]	0.39	0.45
HP#3 Insertion min Range [m] (module and RIC frame components)	$2 \cdot 10^3$ [0.0 $2 \cdot 10^3$ 0.0]	12.9 [-1.4 4.8 -11.8]
Time to the min Range [hr]	4.55	4.55

The HP#2 Insertion final position with the greatest difference from the nominal one occurs if the following manoeuvre is not performed (-100%). In this event, the minimum range between the two spacecraft during the rendezvous is 4.09 km. The relative trajectory is shown in Figure 122:

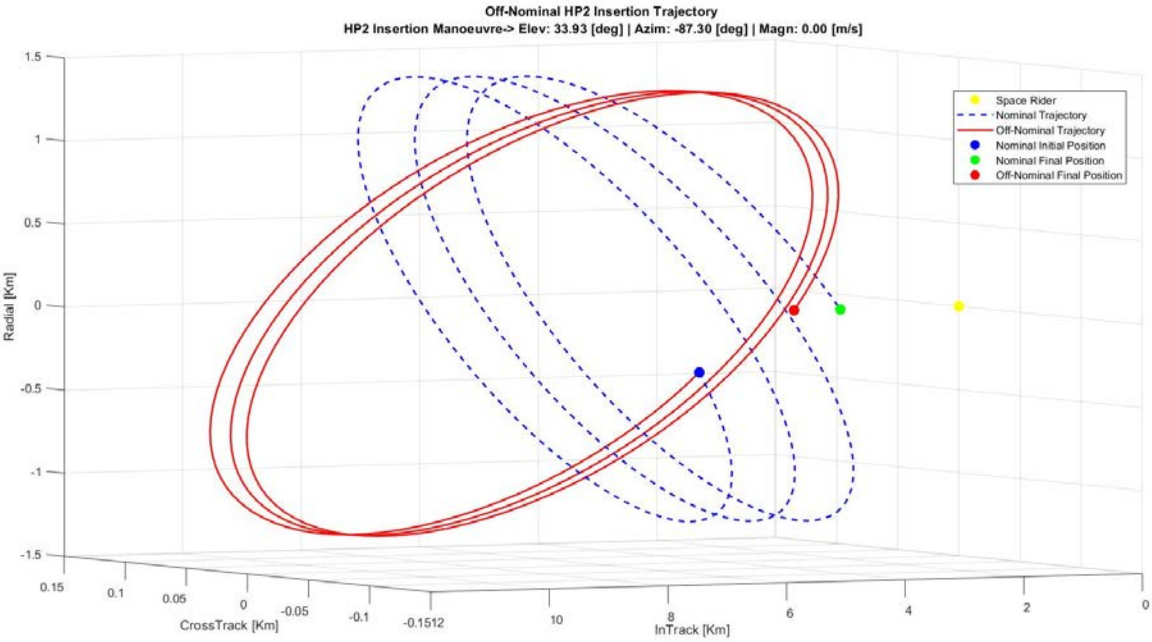


Figure 122: HP#2 Insertion Off-Nominal Direction and Magnitude – worst Final Position

Table 64 resumes this off-nominal scenario.

Table 64: HP#2 Insertion Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	38.9	33.9
Azimuth [deg]	-82.3	-87.3
Magnitude [m/s]	0.39	0.0
HP#3 Insertion min Range [m] (module and RIC frame components)	$2 \cdot 10^3$ [0.0 $2 \cdot 10^3$ 0.0]	$4.09 \cdot 10^3$ [60.7 $4.09 \cdot 10^3$ -63.5]
Time to the min Range [hr]	4.55	4.55

4.2.3 Off-Nominal manoeuvre entering the Hold Point 2

The entry manoeuvre in the HP#2 is performed at the end of the HP#2 Insertion phase. This manoeuvre stops the relative motion along the Intrack axis at a desired value (*Intrack target*) of 2 km with respect to SR. Figure 123 shows the nominal relative trajectory during the HP#2. A relative motion is still present, but it is small compared to the examined distance.

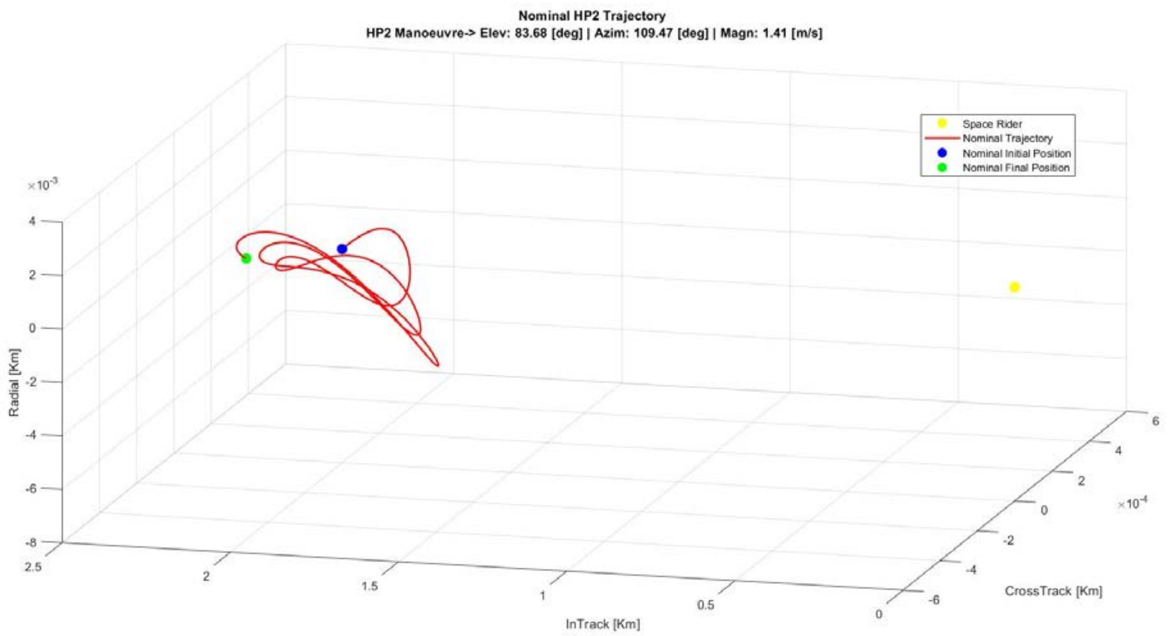


Figure 123: HP#2 Nominal Trajectory

Hereafter, (Table 65) are reported the manoeuvre values for the nominal mission and some other parameters useful to compare the off-nominal scenarios to the nominal one:

Table 65: HP#2 Nominal Manoeuvre Values

Elevation [deg]	Azimuth [deg]	Magnitude [m/s]
83.7	109.5	1.46
min Range [m]	$2 \cdot 10^3$	
Time to the min Range [hr]	4.5	

The off-nominal analysis was performed by varying the angles of ± 5 $[deg]$ from the nominal value, with a step of 0.5 $[deg]$, the magnitude of ± 100% from the nominal value, with a 5% step, and the combinations of the two errors were also considered.

Direction errors

Committing some errors on the manoeuvre direction could increase the risk of collision with SR, since the minimum distance to be reached could be close to the target spacecraft. Two cases of particular interest are reported below. The minimum distance during the HP#2 trajectory is for an off-nominal manoeuvre with +5 deg for the elevation angle and +0 deg for the azimuth with respect to the nominal values. In this scenario the minimum distance is 39 m and considering the SR size and geometry, this off-nominal scenario would not lead to a collision after one orbit. This is the worst off-nominal manoeuvre for the HP#2 mistaking only the direction with respect to Space Rider. The off-nominal trajectory is shown in Figure 124 and some values are resumed in Table 66.

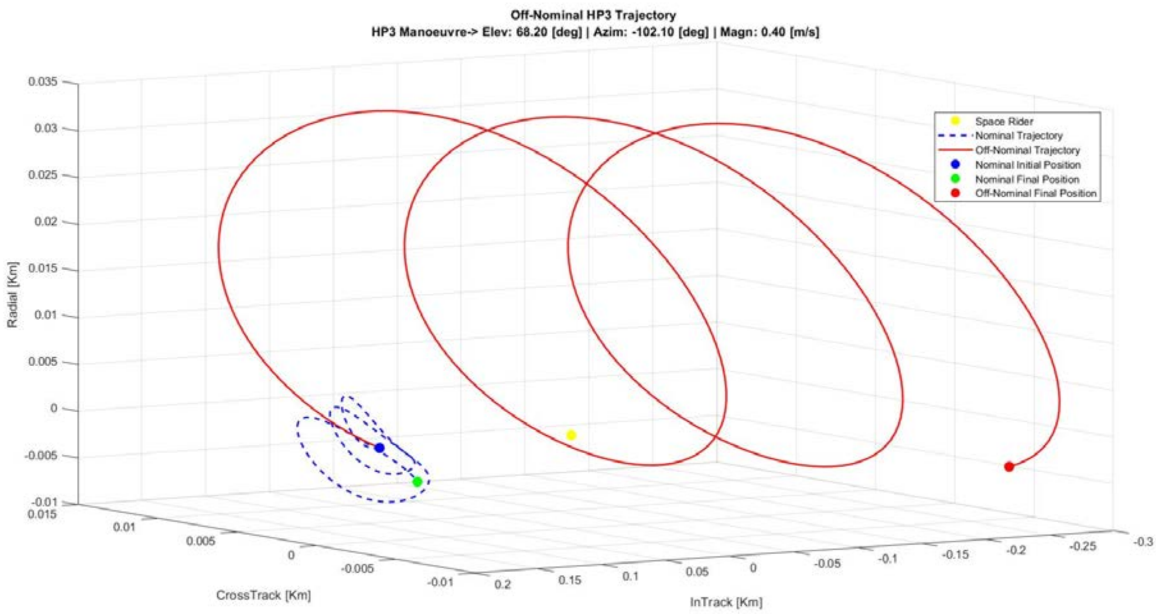


Figure 124: HP#2 Off-Nominal Direction - minimum distance

Table 66: HP#2 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	83.7	88.7
Azimuth [deg]	109.5	109.5
Magnitude [m/s]	1.46	1.46
HP#3 min Range [m] (module and RIC frame components)	$2 \cdot 10^3$ [0.0 $2 \cdot 10^3$ 0.0]	39.0 [5.1 1.6 38.6]
Time to the min Range [min]	4.5	4.50

Another case of particular interest concerns the final position with the greater error than the nominal one. This occurs for an off-nominal manoeuvre mistaken by +5 degrees for the elevation angle and +5 degrees for the azimuth angle. The minimum range is comparable to the nominal one and this scenario would not increase the collision risk. Nevertheless, this case would result to a higher ΔV and mission delay since a new approach will be required. The trajectory is shown in Figure 125 and some parameters are reported below (Table 67).

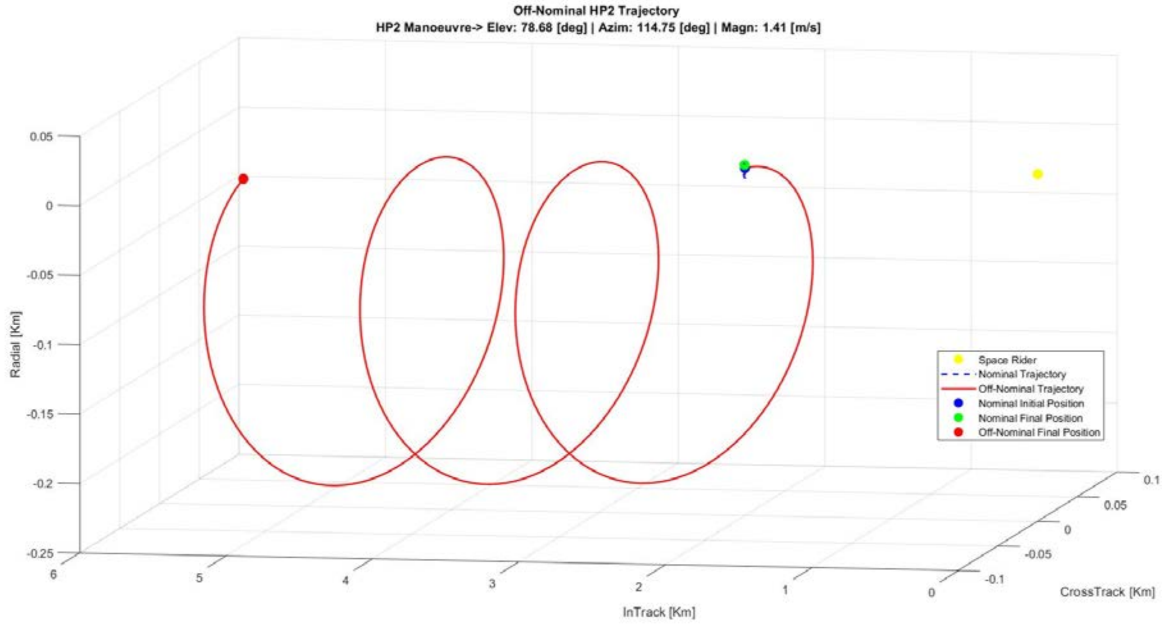


Figure 125: HP#2 Off-Nominal Direction - worst Final Position

Table 67: HP#2 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	83.7	78.7
Azimuth [deg]	109.5	114.7
Magnitude [m/s]	1.46	1.46
HP#3 min Range [m] (module and RIC frame components)	$2 \cdot 10^3$ [0.0 $2 \cdot 10^3$ 0.0]	$1.98 \cdot 10^3$ [-27.6 $1.98 \cdot 10^3$ 51.0]
Time to the min Range [min]	4.5	0.14

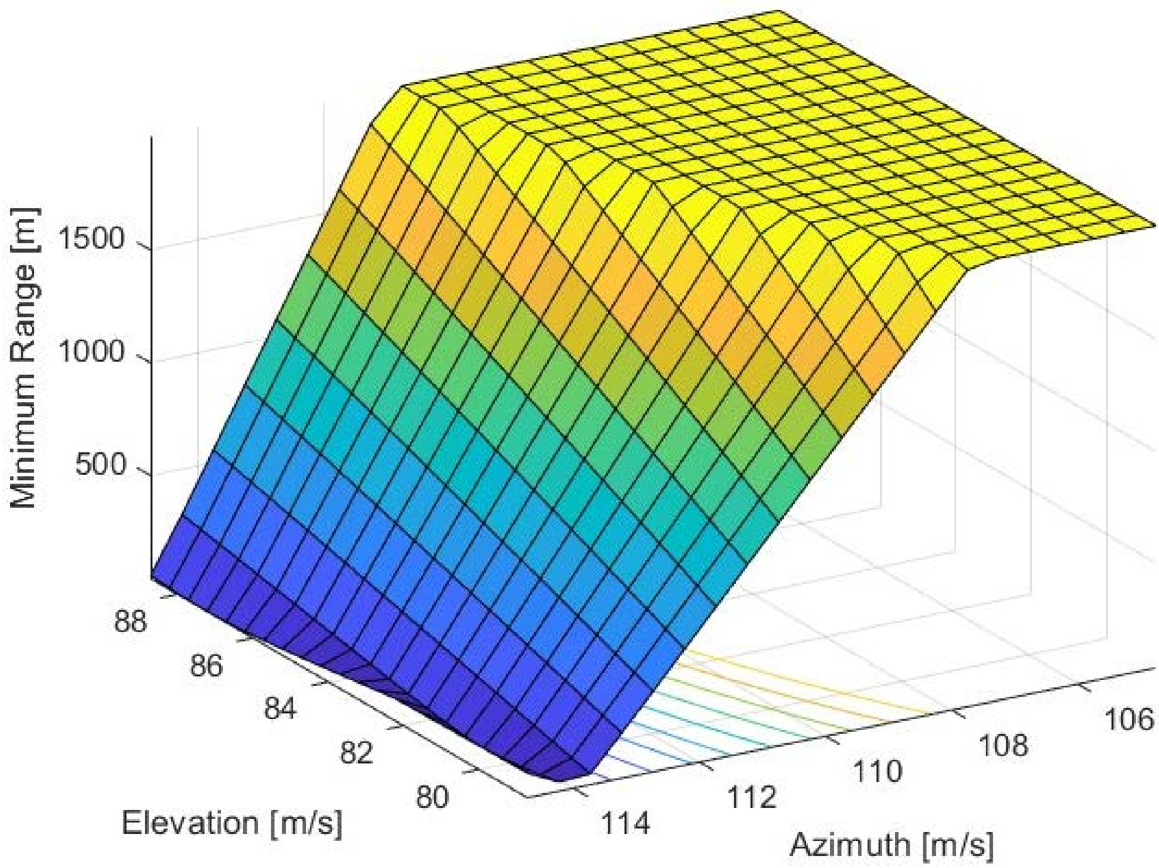


Figure 126: Scatter plot Direction errors – HP#2 Opt 2

Magnitude errors

A manoeuvre magnitude higher or lower than the nominal value involves a different final position at the end of the HP#2, which, as for errors on the direction, will be respectively in the positive or negative part of the InTrack. Therefore, also in this case it is necessary to evaluate the error that involves the minimum distance between the two spacecraft and the error that involves the greatest difference between the final position reached and the desired one. The minimum distance during the HP#2 trajectory is achieved for an off-nominal manoeuvre of +80%. The minimum distance between the two spacecraft is 21.8 m and, even in this case, considering the SR size and geometry this off-nominal scenario would not lead to a collision after one orbit. The off-nominal relative trajectory is shown in Figure 127 and Table 68 resumes the manoeuvre values and the relative final components.

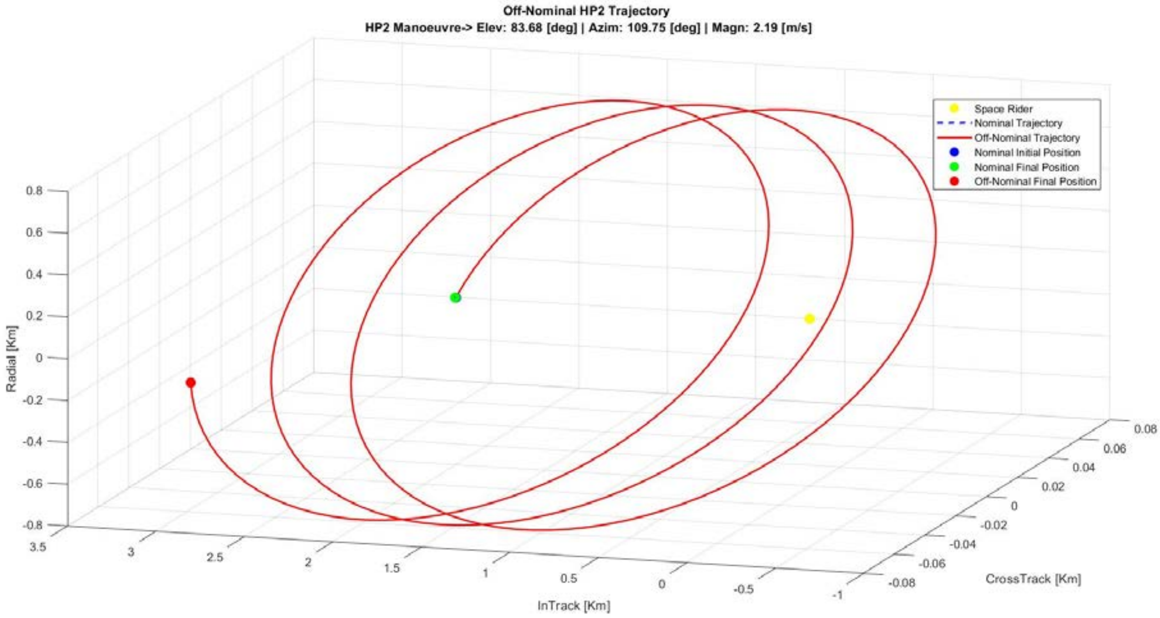


Figure 127: HP#2 Off-Nominal Magnitude - minimum distance

Table 68: HP#2 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	83.7	83.7
Azimuth [deg]	109.5	109.5
Magnitude [m/s]	1.46	2.63
HP#3 min Range [m] (module and RIC frame components)	$2 \cdot 10^3$ [0.0 $2 \cdot 10^3$ 0.0]	21.8 [0.0 -19.7 9.3]
Time to the min Range [min]	4.5	2.27

The HP#2 final position with the greatest distance compared to the desired one is obtained when the manoeuvre is mistaken by +100%, this off-nominal manoeuvre does not lead to increased risk of collision. In fact, the minimum distance during the HP#2 would be 745.2 m, reaching a final position which differs from the nominal one of about 1.5 km. The off-nominal trajectory is shown in Figure 128.

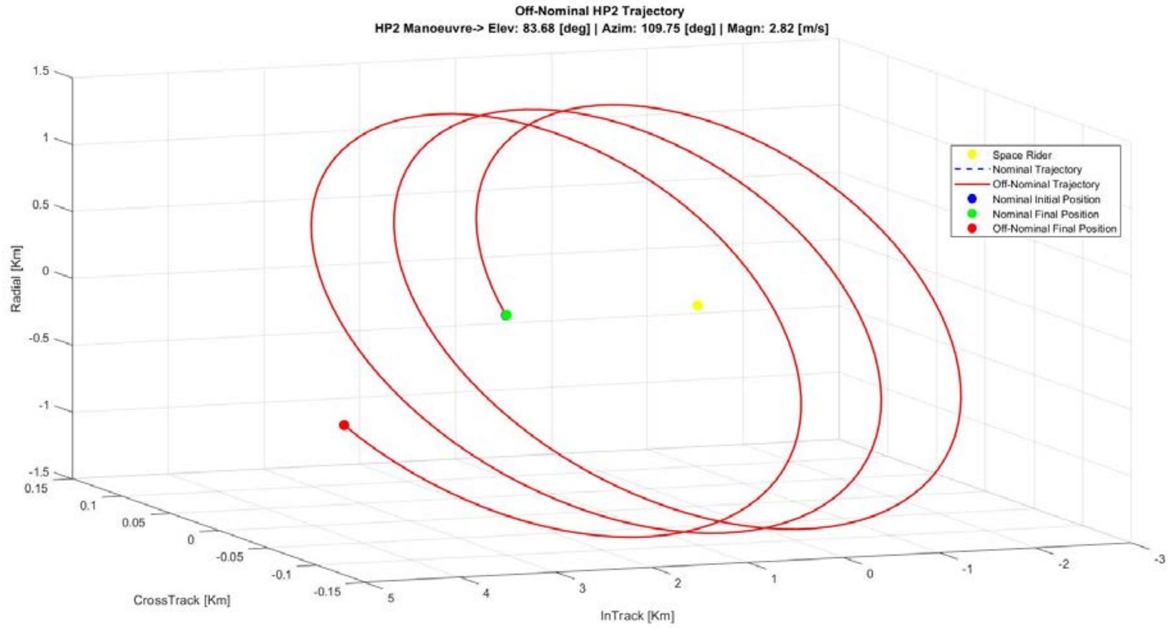


Figure 128: HP#2 Off-Nominal Magnitude - worst Final Position

Table 69: HP#2 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	83.7	83.7
Azimuth [deg]	109.5	109.5
Magnitude [m/s]	1.46	2.92
HP#3 min Range [m] (module and RIC frame components)	$2 \cdot 10^3$ [0.0 $2 \cdot 10^3$ 0.0]	745.2 [548.4 -512.8 71.3]
Time to the min Range [min]	4.5	3.7

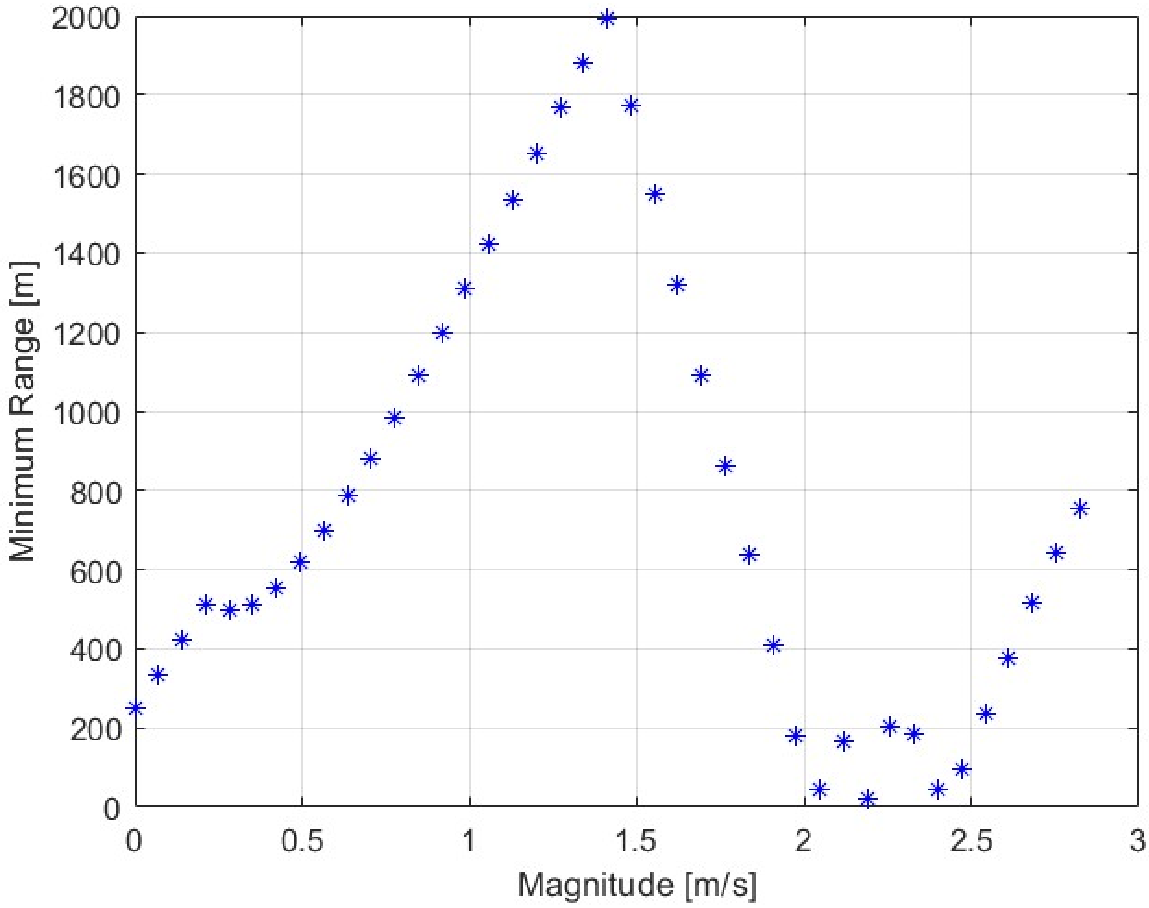


Figure 129: Scatter plot Magnitude errors – HP#2 Opt 2

Direction and magnitude errors

Combining errors in direction and magnitude of the thrust, the minimum distance is 0.4 m for an off-nominal manoeuvre with an error of +3.0 deg for the elevation, +5.0 deg for the azimuth and a magnitude increased by 40%. The resulting trajectory and some parameters are shown in Figure 130 and in Table 70:

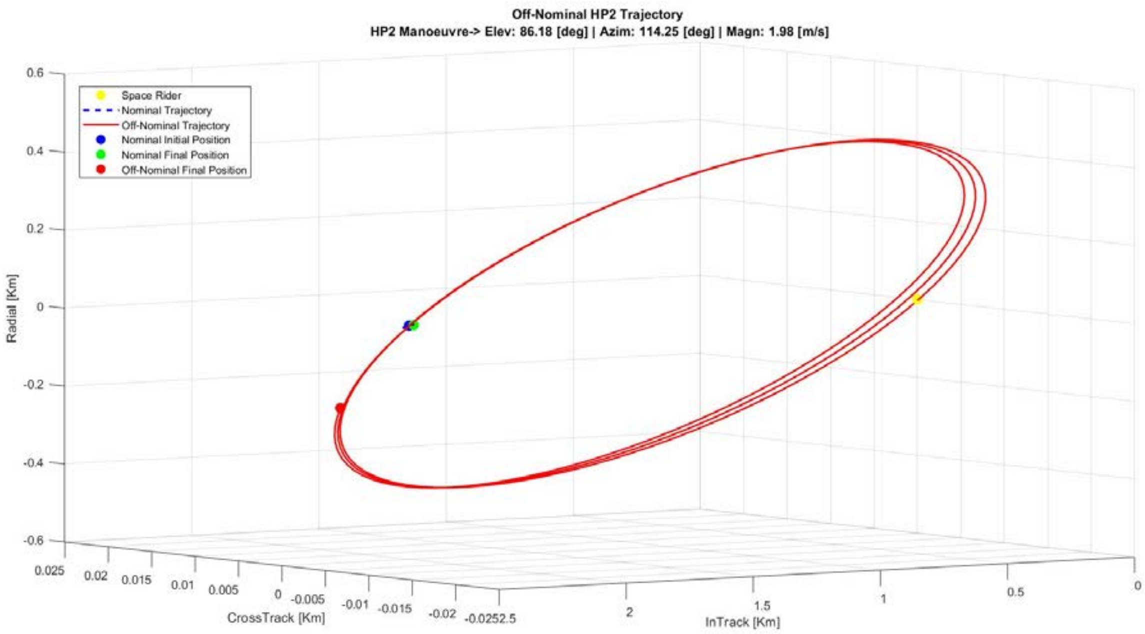


Figure 130: HP#2 Off-Nominal Direction and Magnitude - minimum distance

Table 70: HP#2 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	83.7	86.2
Azimuth [deg]	109.5	114.2
Magnitude [m/s]	1.46	1.98
HP#3 min Range [m] (module and RIC frame components)	$2 \cdot 10^3$ [0.0 $2 \cdot 10^3$ 0.0]	0.4 [-0.1 0.3 -0.1]
Time to the min Range [min]	4.5	46.1

The HP2 final position with the greatest difference from the nominal one occurs with an elevation error of - 5.0 deg, an azimuth error of +5.0 deg and a double magnitude compared to the nominal one (+100%). In this event, the minimum range between the two spacecraft during the rendezvous is 971.9 m. The relative trajectory is shown in Figure 131:

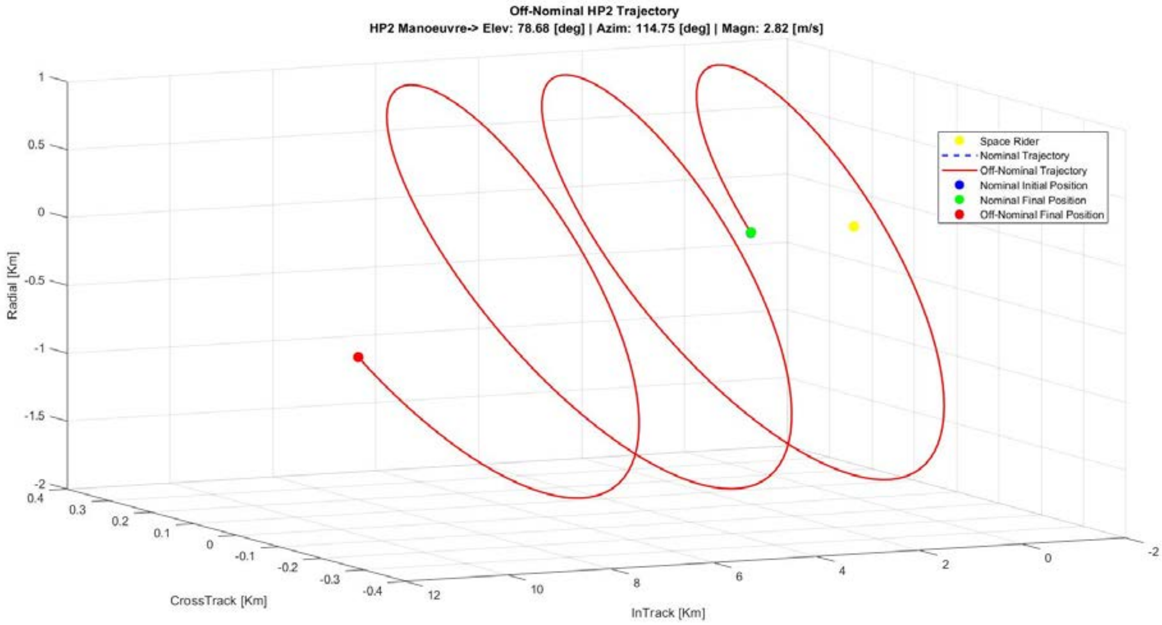


Figure 131: HP#2 Off-Nominal Direction and Magnitude –worst Final Position

Table 71 resumes this off-nominal scenario.

Table 71: HP#2 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	83.7	78.7
Azimuth [deg]	109.5	114.7
Magnitude [m/s]	1.46	2.82
HP#3 min Range [m] (module and RIC frame components)	$2 \cdot 10^3$ [0.0 $2 \cdot 10^3$ 0.0]	971.9 [917 -74.5 313.3]
Time to the min Range [min]	4.5	21.45

4.2.4 Off-Nominal manoeuvre entering the Out-of-Plane (OPA)

The OPA allows to reach a precise position to start the Walking Safety Ellipse (WSE) and observe Space Rider. This manoeuvre requires high precision to reach the position near Space Rider and guarantee the geometry of the WSE. The WSE is defined in such a way as to guarantee the operating range of the SROC payload and no risk of collision with Space Rider (the WSE is a passive safe trajectory). If the OPA does not lead to the desired position, it would be necessary to perform a new OPA to correct the error and then begin the inspection phase. Failing the insertion manoeuvre in the OPA leads to increased costs and delays for SROC, but could also increase the risk of collision with SR. For this reason, a Keep Out Zone (KOZ) with a radius of 200 meters has been considered. The off-nominal OPAs are therefore evaluated with respect to the minimum distance with the target spacecraft during the entire trajectory. Table 72 reports the nominal manoeuvre parameters for the OPA that comes before the Inspection cycle:

Table 72: OPA Nominal Manoeuvre Values

Elevation [deg]	Azimuth [deg]		Magnitude [m/s]
0.51	69.38		0.15
OPA Final Position			
Radial – InTrack – CrossTrack – Range [m]			
141.4	-55.5	-75.0	169.4
OPA min Range			
Radial – InTrack – CrossTrack – Range [m]			
150.9	9.4	-47.8	158.6
OPA Duration [hr]	4		
Next Manoeuvre ΔV [m/s]	0.06		

Figure 132 shows two different views of the nominal OPA trajectory, while Figure 133 highlight the out-of-plane nature of the OPA trajectory.

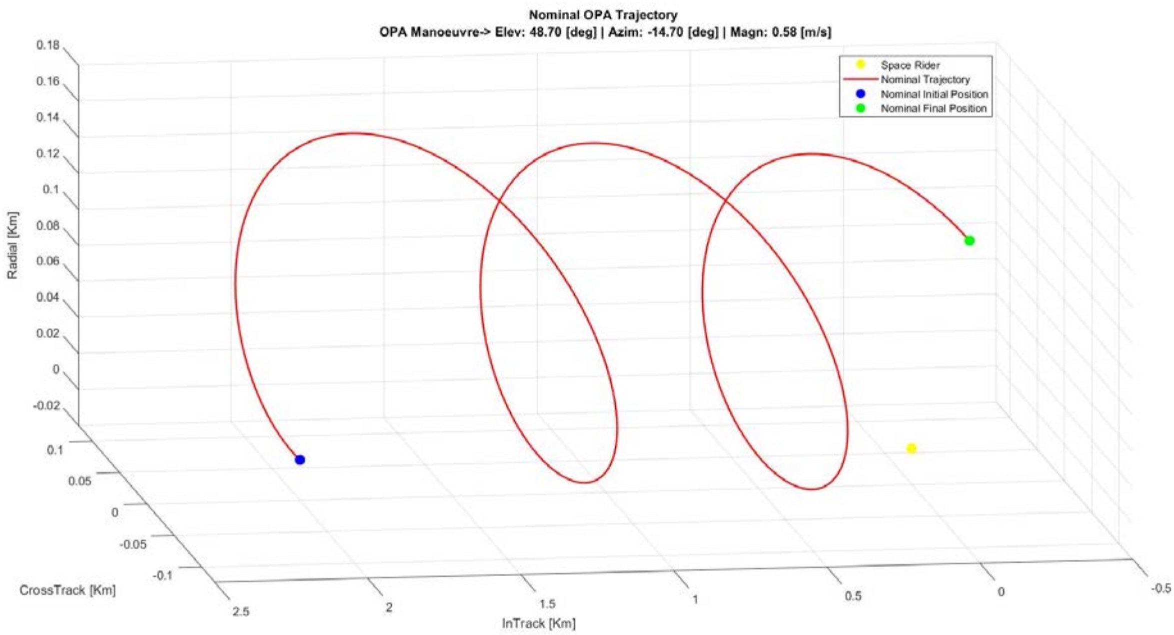


Figure 132: OPA Nominal Trajectory

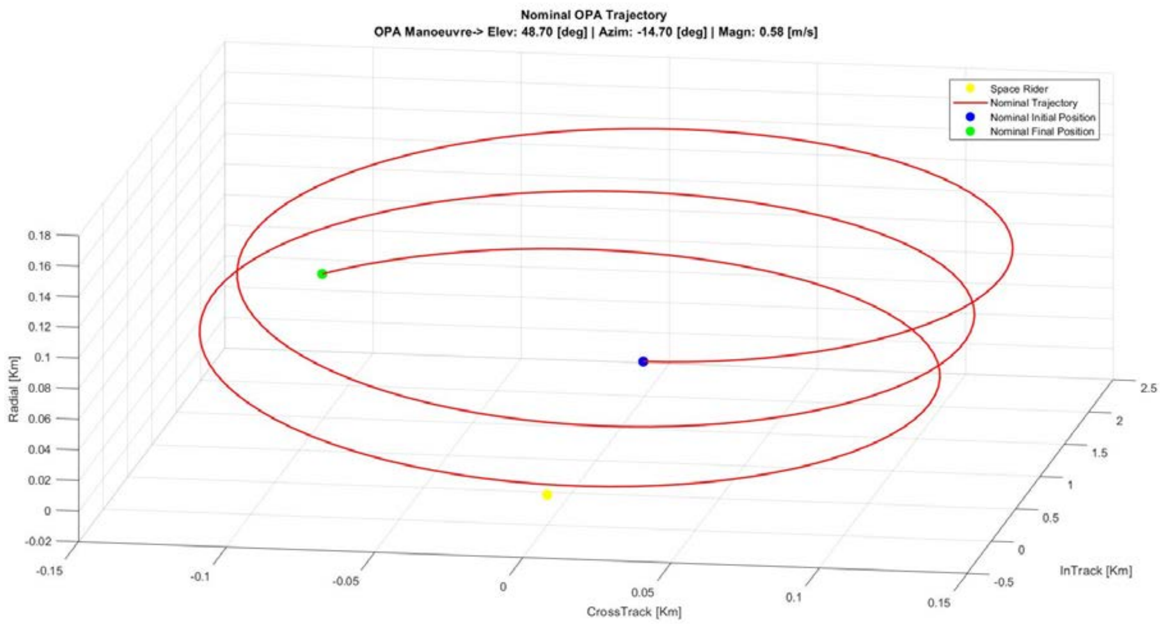


Figure 133: OPA Nominal Trajectory - Out-Of-Plane View

The off-nominal analysis was performed by varying the angles of ± 5 $[deg]$ from the nominal value, with a step of 0.5 $[deg]$, the magnitude of ± 100% from the nominal value, with a 5% step, and the combinations of the two errors were also considered.

Direction errors

Committing some errors on the manoeuvre direction could increase the risk of collision with SR, since the final position to be reached is close to the target spacecraft. However, some considerations must be added with respect to this statement: with the same manoeuvre magnitude, firing with a greater component outside the plane would reduce the effectiveness of the manoeuvre along the InTrack direction, therefore the final position of the OPA reached will be towards more positive InTrack. Conversely, if the direction is tilted to the orbital plane, the final position will be towards more negative direction. Therefore, it is not the final position that is less safe for SR, but the trajectory covered may be. Moreover, two cases of particular interest are reported below. The minimum distance during the OPA trajectory is for an off-nominal manoeuvre with -0.5 deg for the elevation angle and -5 deg for the azimuth with respect to the nominal values. In this scenario the minimum distance is less than the radius of the KOZ, so SROC would cross it. The module of the minimum distance is 32.3 m. This is the worst off-nominal manoeuvre for the OPA mistaking only the direction with respect to Space Rider. The off-nominal trajectory is shown in Figure 134 and some values are resumed in Table 73.

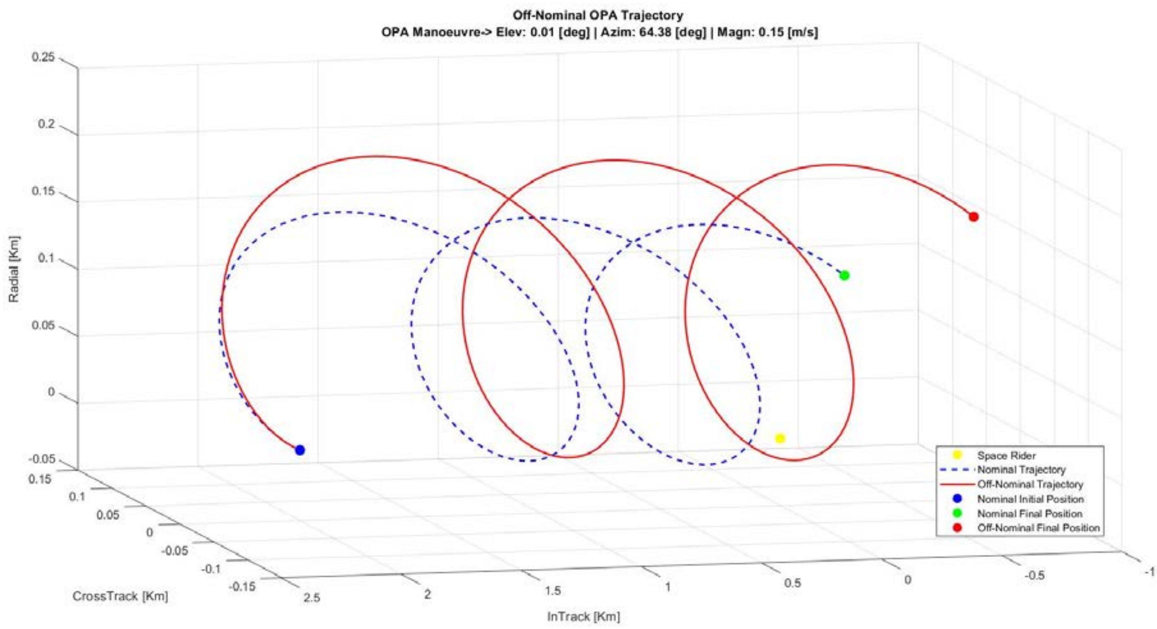


Figure 134: OPA Off-Nominal Direction - minimum distance

Table 73: OPA Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	0.51	0.0
Azimuth [deg]	69.38	64.38
Magnitude [m/s]	0.15	0.15
OPA min Range [m] (module and RIC frame components)	158.6 [150.9 9.4 -47.8]	32.3 [-11.2 25.1 -17.0]
Time to the min Range [hr]	4	3.04

Another case of particular interest concerns the final position with the greater error than the nominal one. This occurs for an off-nominal manoeuvre mistaken by +5 degrees for the elevation angle and -5 degrees for the azimuth angle. The minimum range reached is 40.6 m. The trajectory is shown in Figure 135 and some parameters are reported below (Table 74).

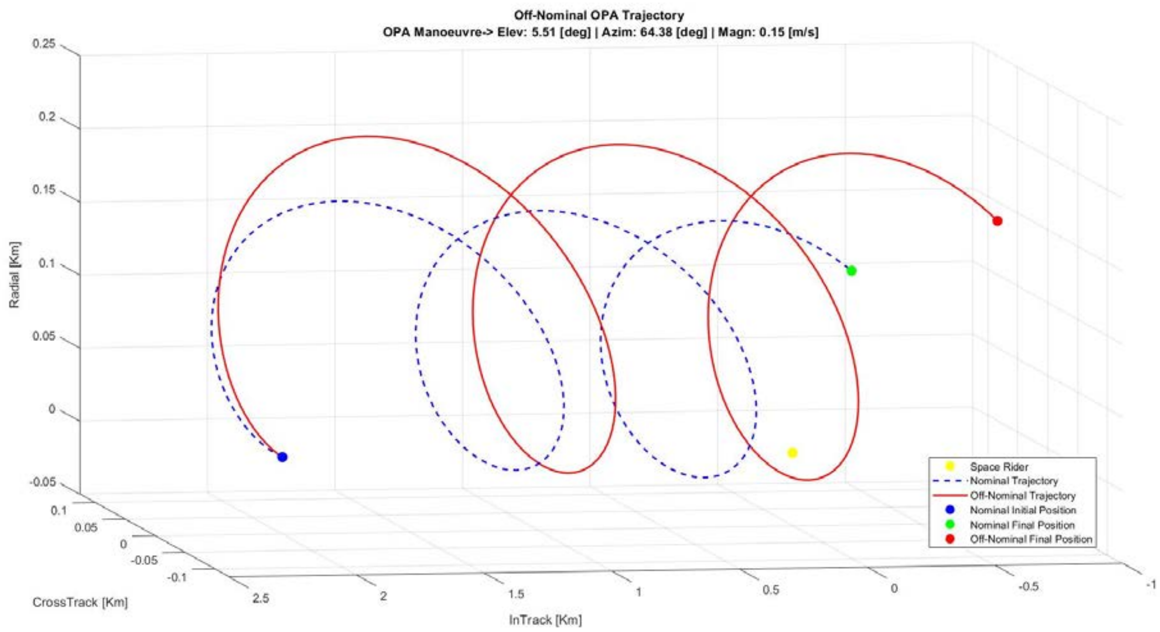


Figure 135: OPA Off-Nominal Direction – worst Final Position

Table 74: OPA Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	0.51	5.51
Azimuth [deg]	69.38	64.38
Magnitude [m/s]	0.15	0.15
OPA Final Position [m] (module and RIC frame components)	158.6 [150.9 9.4 -47.8]	40.6 [-13.0 32.0 -21.5]
Time to the min Range [hr]	4	3.03

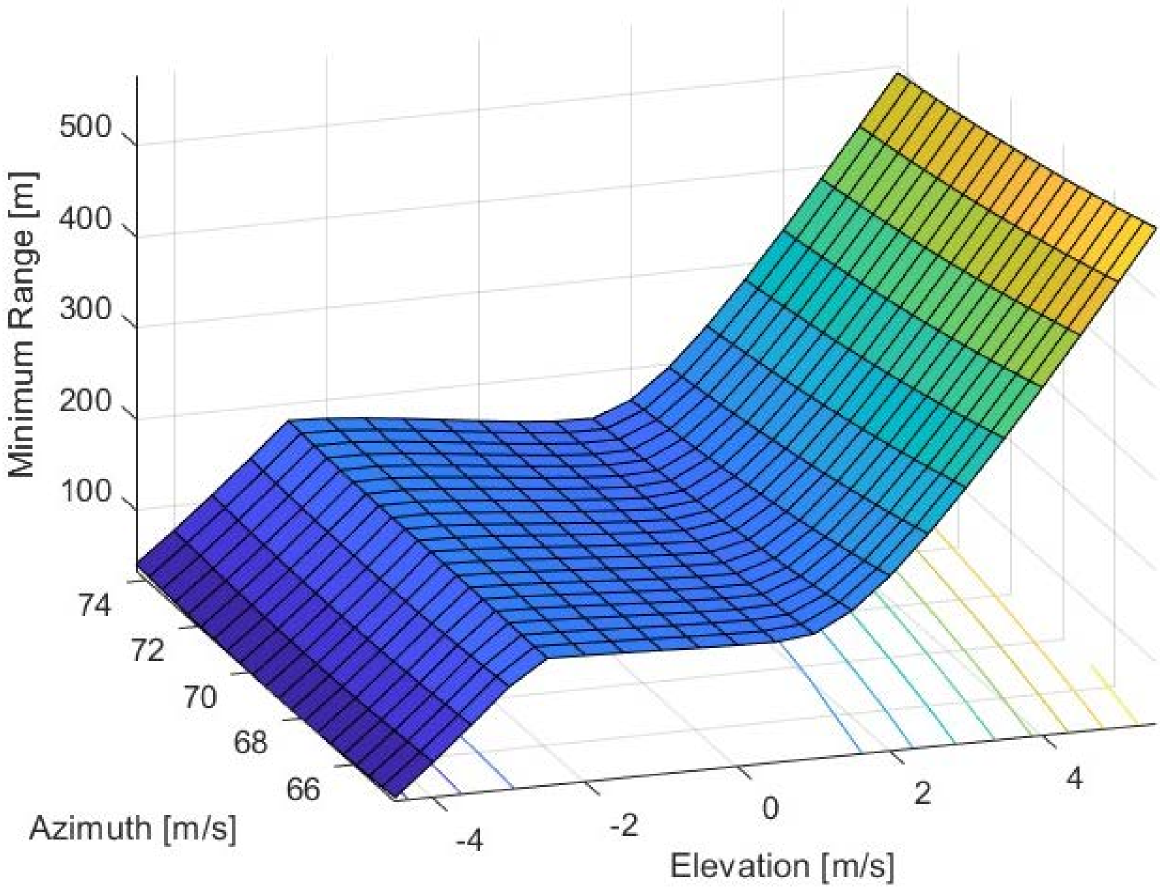


Figure 136: Scatter plot Direction errors – OPA Opt 2

Magnitude errors

A manoeuvre magnitude higher or lower than the nominal value involves a different final position at the end of the OPA, which, as for errors on the direction, will be respectively in the negative or positive part of the InTrack. Therefore, also in this case it is necessary to evaluate the error that involves the minimum distance between the two spacecraft and the error that involves the greatest difference between the final position reached and the desired one. The minimum distance during the OPA trajectory is achieved for an off-nominal manoeuvre more intense than 25%. The relative distance between the two spacecraft is 13.8 m. Furthermore, the final position in this scenario is in the negative InTrack direction, due to the greater manoeuvre magnitude. For this reason, if SROC did not perform any other manoeuvres, a second pass should be expected near SR, during the drift away motion which would be resumed after a short period. However, this second passage would not cause high collision risks, because in the meantime SROC would continue to lose altitude, increasing the relative distance along the Radial direction and, possibly, it would perform some correction manoeuvres. The off-nominal relative trajectory is shown in Figure 137 and Table 75 resumes the manoeuvre values and the relative final components.

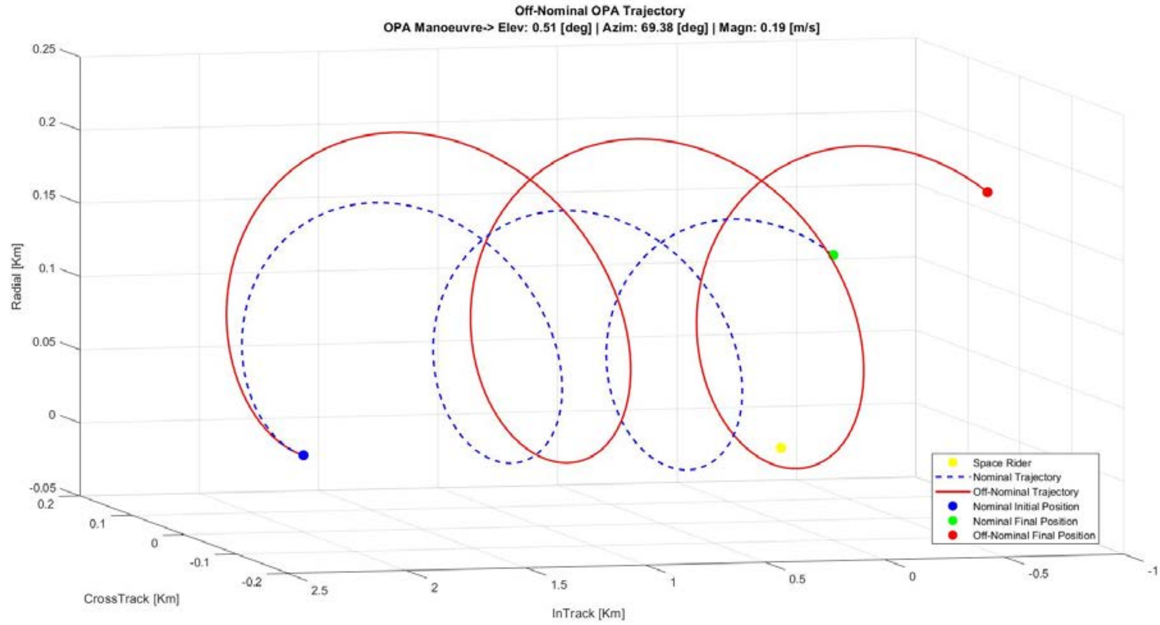


Figure 137: OPA Off-Nominal Magnitude – minimum distance

Table 75: OPA Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	0.51	0.51
Azimuth [deg]	69.38	69.38
Magnitude [m/s]	0.15	0.19
OPA min Range [m] (module and RIC frame components)	158.6 [150.9 9.4 -47.8]	13.8 [-13.4 -3.3 1.3]
Time to the min Range [hr]	4	3.08

The OPA final position with the greatest distance compared to the desired one is obtained when the insertion manoeuvre in the OPA is performed with double of the nominal magnitude value. The minimum distance during the OPA would be 275.9 m, this case does not introduce higher risk since the minimum distance reached is out of the KOZ. The off-nominal trajectory is shown in Figure 138.

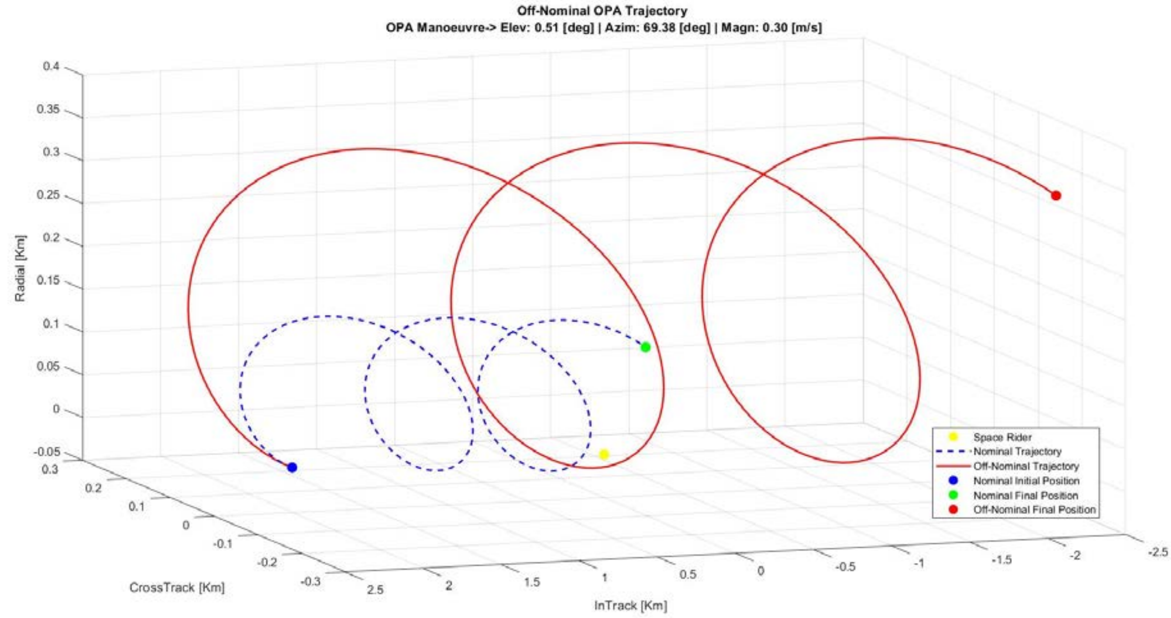


Figure 138: OPA Off-Nominal Magnitude – worst Final Position

Table 76: OPA Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	0.51	0.51
Azimuth [deg]	69.38	69.38
Magnitude [m/s]	0.15	0.30
OPA Final Position [m] (module and RIC frame components)	158.6 [150.9 9.4 -47.8]	275.9 [5.7 262.4 -85.2]
Time to the min Range [hr]	4	1.45

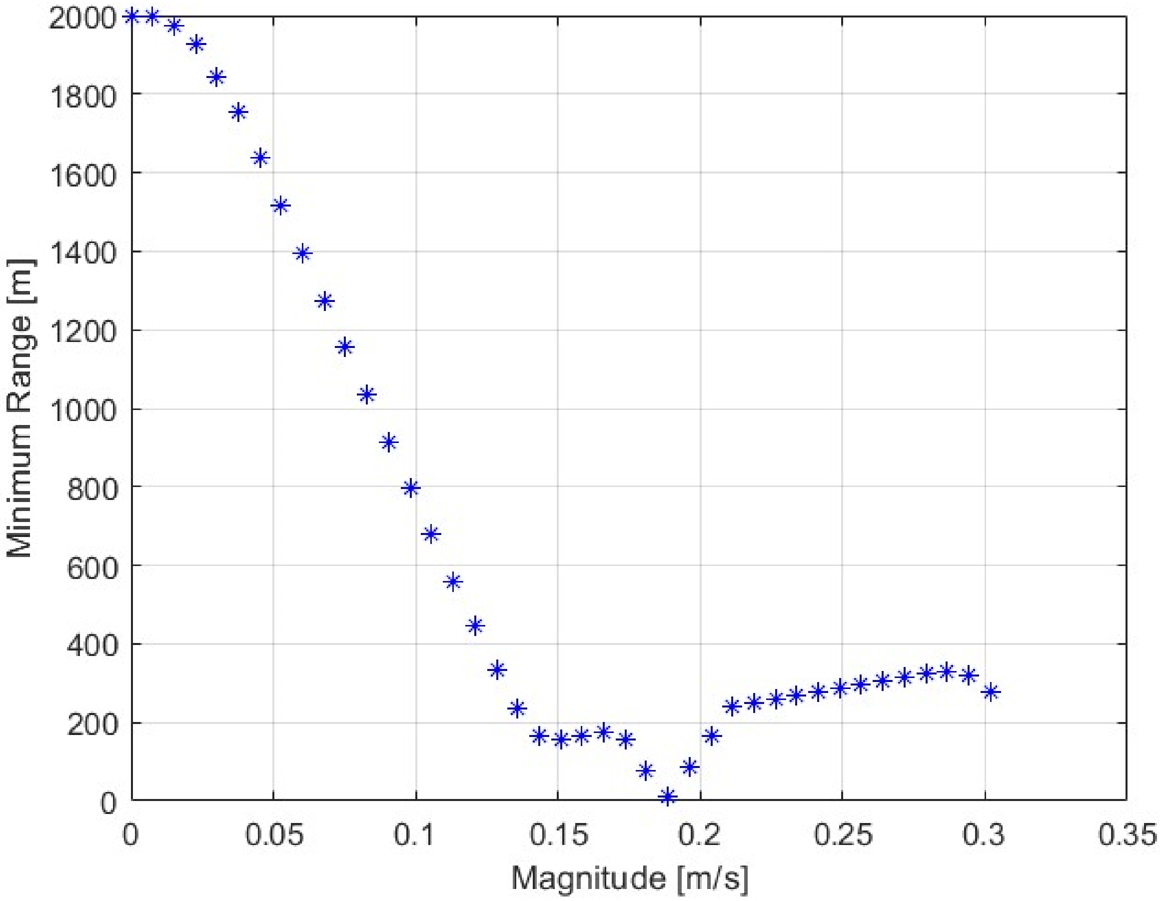


Figure 139: Scatter plot Magnitude errors – OPA Opt 2

Direction and magnitude errors

Combining errors in direction and magnitude of the thrust, the minimum distance is 6.5 m for an off-nominal manoeuvre with an error of -2.5 deg for the elevation, -5.0 deg for the azimuth and a magnitude increased by 90%. The resulting trajectory and some parameters are shown in Figure 140 and in Table 77:

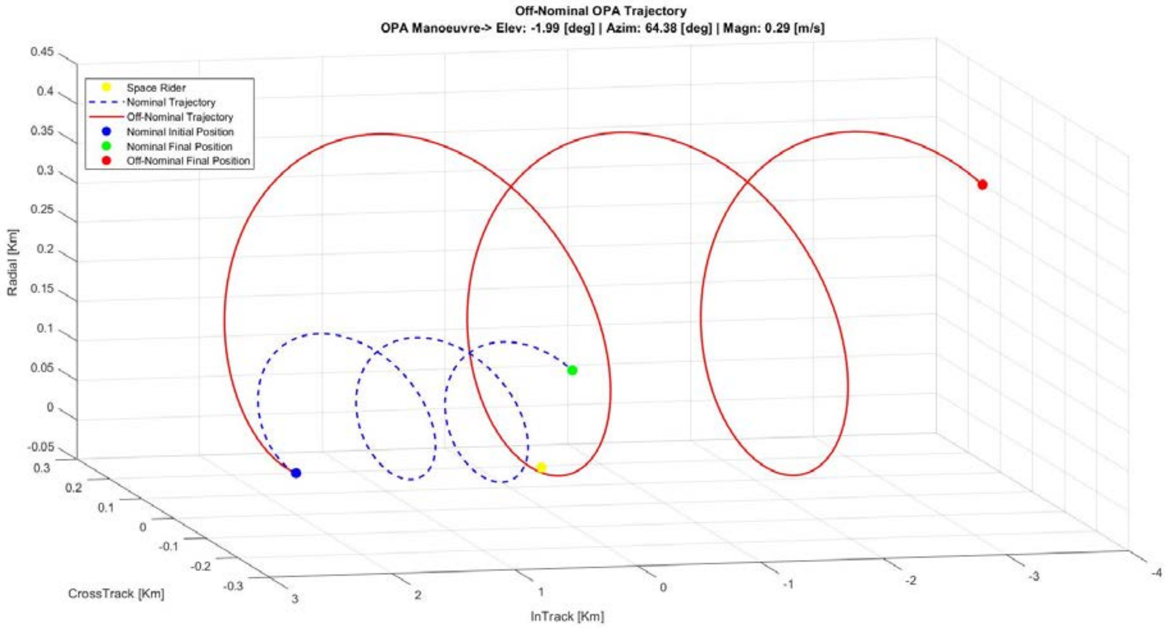


Figure 140: OPA Off-Nominal Direction and Magnitude – minimum distance

Table 77: OPA Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	0.51	-2
Azimuth [deg]	69.38	64.38
Magnitude [m/s]	0.15	0.29
OPA min Range [m] (module and RIC frame components)	158.6 [150.9 9.4 -47.8]	6.5 [-6.5 0.2 -0.6]
Time to the min Range [hr]	4	1.54

The OPA final position with the greatest difference from the nominal one occurs with an elevation error of +5 deg, an azimuth error of -5.0 deg and a magnitude 100% higher than the nominal one. In this event the minimum range between the two spacecraft during the rendezvous is 89.4 m. The relative trajectory is shown in Figure 141:

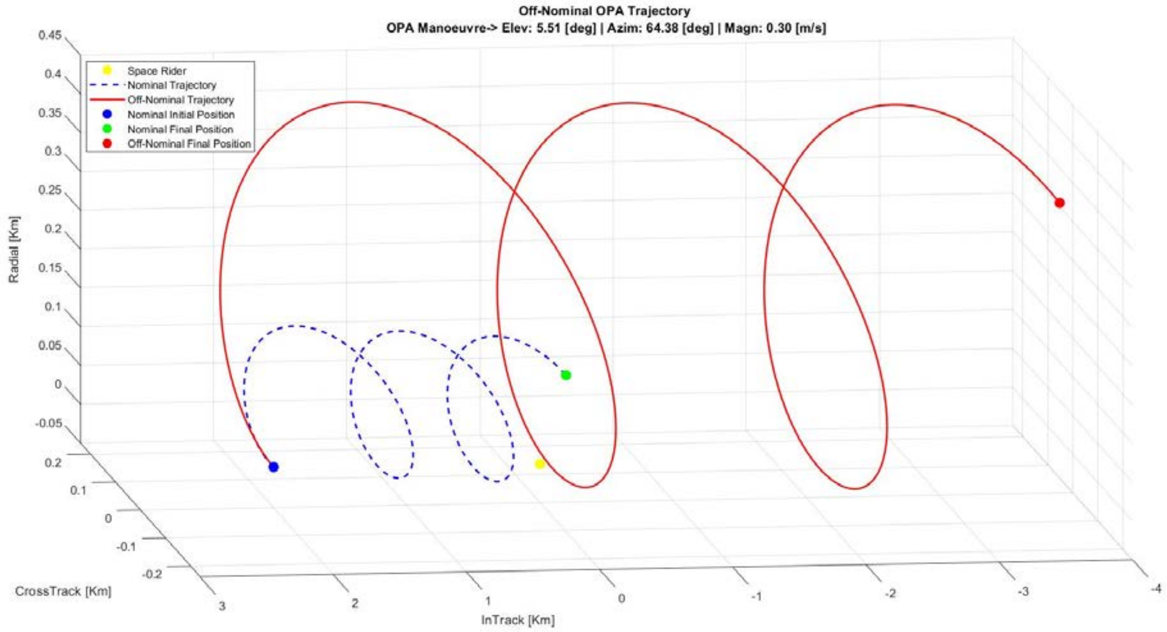


Figure 141: OPA Off-Nominal Direction and Magnitude – worst Final Position

Table 78 resumes this off-nominal scenario.

Table 78: OPA Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	0.51	5.5
Azimuth [deg]	69.38	64.4
Magnitude [m/s]	0.15	0.3
OPA Final Position [m] (module and RIC frame components)	158.6 [150.9 9.4 -47.8]	89.4 [-1.1 -80.9 38.1]
Time to the min Range [hr]	4	1.58

4.2.5 Off-Nominal manoeuvre Closing

To approach Space Rider after the inspection phase and start the docking phase, SROC performs an out-of-plane manoeuvre to execute the Hold Point 3. After the Free Flight phase SROC executes an out-of-plane trajectory toward SR and reaching the *InTrack Target* (150 m in the nominal scenario), SROC performs a holding phase finite manoeuvre close to SR to maintain this relative position during the HP#3. Hereafter, (Table 79) are reported the ΔV vector for the nominal scenario and some other parameters useful to compare the off-nominal scenarios to the nominal one:

Table 79: Closing Nominal Manoeuvre Values

Elevation [deg]	Azimuth [deg]	Magnitude [m/s]
13.0	-0.35	0.11
min Range [m]	150	
Time to the min Range [hr]	10.6	
Next Manoeuvre ΔV [m/s]	0.3	

It must be noticed that the minimum range for the nominal mission profile is the InTrack target. Furthermore the "next Manoeuvre ΔV" includes the entry manoeuvre in the HP#3 trajectory and the finite manoeuvre needed to maitain this relative position. Both depend on the execution of the Closing. Figure 142 shows two different views of the nominal Closing trajectory, while Figure 143 highlight the out-of-plane nature of the Closing trajectory.

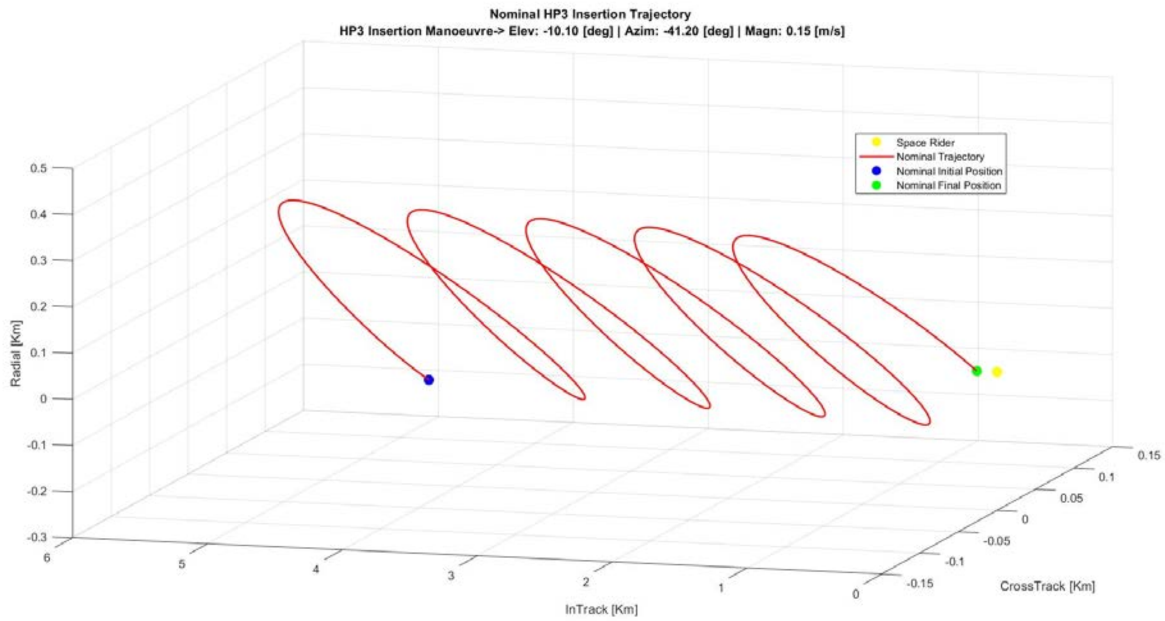


Figure 142: Closing Nominal Trajectory

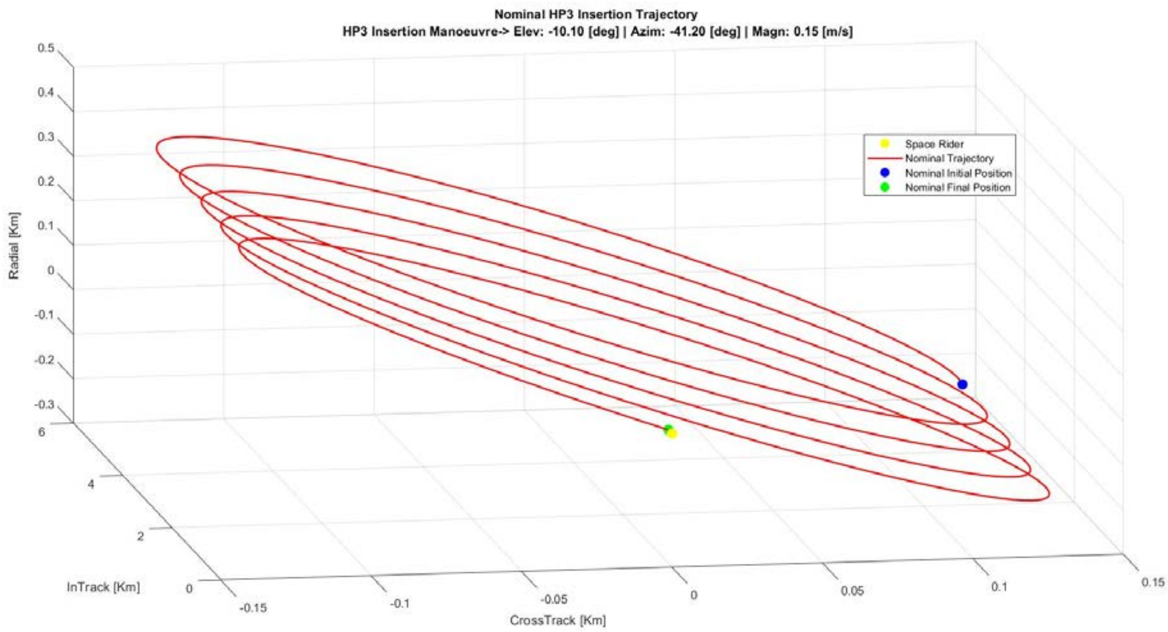


Figure 143: Closing Nominal Trajectory – Out-of-Plane View

As for the Option 1 HP#3 the off-nominal Closings are therefore evaluated with respect to the minimum distance with the target spacecraft during the entire trajectory.

The off-nominal analysis was performed by varying the angles of ± 5 $[deg]$ from the nominal value, with a step of 0.5 $[deg]$, the magnitude of ± 100% from the nominal value, with a 5% step, and the combinations of the two errors were also considered. Since the Closing is a trajectory towards the target spacecraft out of its orbital plane, performing an off-nominal manoeuvre could increase the risk of collision with the target itself. Therefore, the objective of the analysis is to determine the maximum permissible errors so that the Closing is still considered valid, even if no longer optimized. Moreover, for an off-nominal HP#3 Insertion it is necessary to evaluate the minimum distance reached with respect to SR.

Direction errors

Committing some errors on the manoeuvre direction could increase the risk of collision with SR, since the final position to be reached is close to the target spacecraft. However, similar considerations as reported for the Option 1 Closing off-nominals must be taken into account. Two cases of particular interest are reported below. The minimum distance during the the Closing trajectory is for an off-nominal manoeuvre with -3.5 deg for the elevation angle and -0.5 deg for the azimuth with respect to the nominal values. The minimum distance is achieved at the end of this approaching phase and the module of the minimum distance is 4.9 m. The worst off-nominal mistaking the direction leads to a collision to SR after 10.6 hr (about 7 orbits). The off-nominal trajectory is shown in Figure 144 and some values are resumed in Table 80.

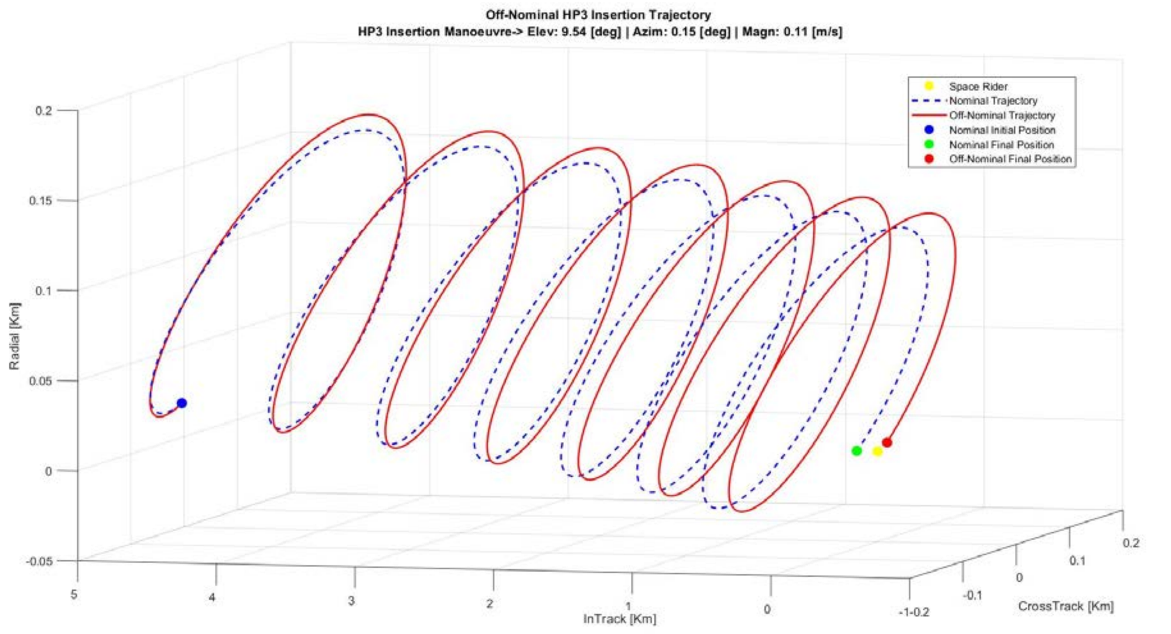


Figure 144: Closing Off-Nominal Magnitude – minimum distance

Table 80: Closing Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	13.0	9.54
Azimuth [deg]	-0.35	0.15
Magnitude [m/s]	0.11	0.11
Closing min Range [m]	150.0	4.9
(module and RIC frame	[0.0	[4.7
components)	150.0	1.0

	0.0]	-0.5]
Time to the min Range [hr]	10.6	10.6

Another case of particular interest concerns the final position with the greater error than the nominal one. This occurs for an off-nominal manoeuvre mistaken by +5 degrees for the elevation angle and -5 degrees for the azimuth angle. The final position reached is 340 m away (in module) from the desired position along the Intrack axis. The trajectory is shown in Figure 145 and some parameters are reported below (Table 81).

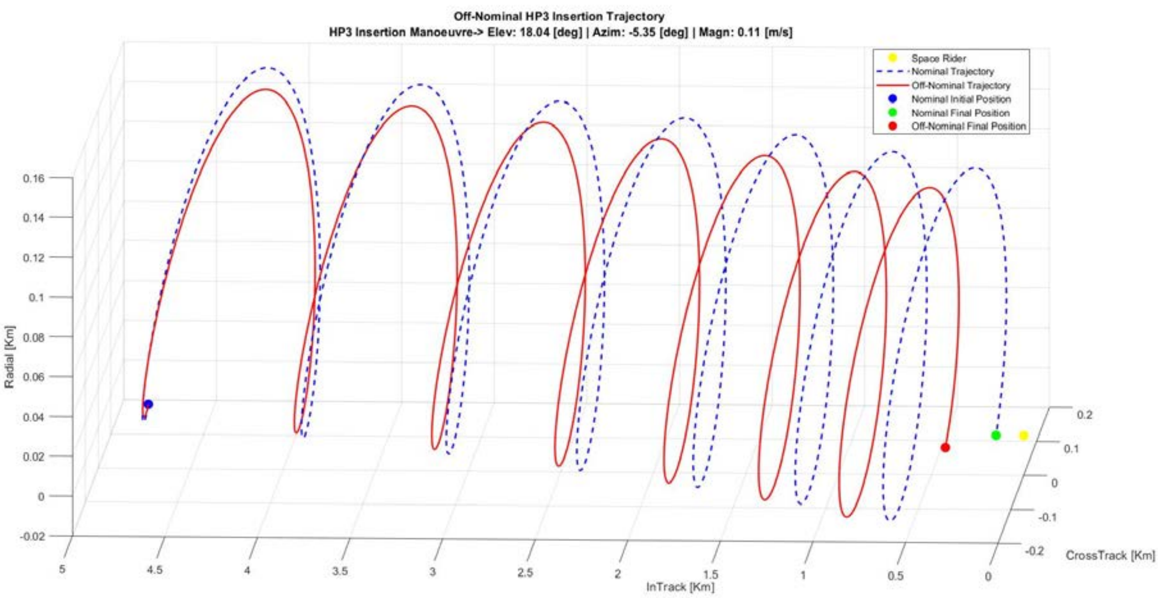


Figure 145: Closing Off-Nominal Magnitude – worst Final Position

Table 81: Closing Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	13.0	18.0
Azimuth [deg]	-0.35	-5.35
Magnitude [m/s]	0.11	0.11
Closing min Range [m] (module and RIC frame components)	150.0 [0.0 150.0 0.0]	492.1 [2.3 490.7 36.6]
Time to the min Range [hr]	10.6	10.55

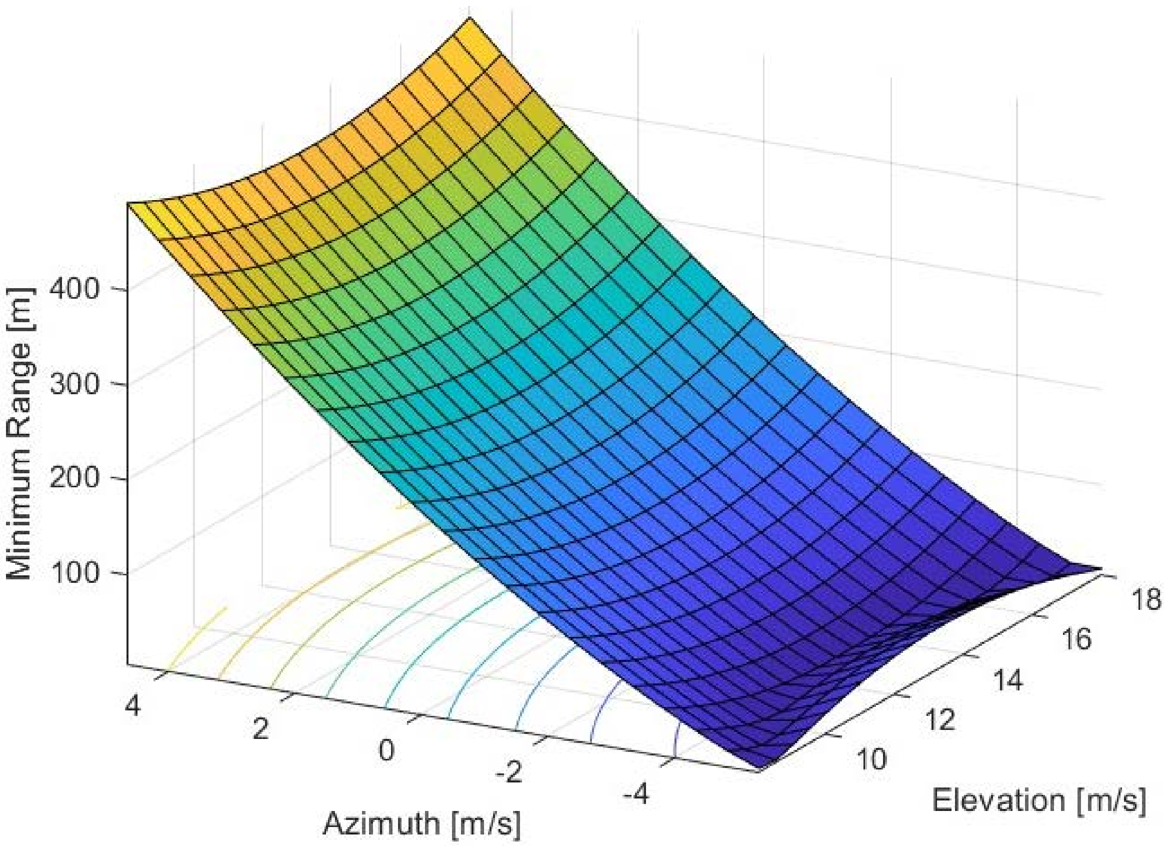


Figure 146: Scatter plot Direction errors – Closing Opt 2

Magnitude errors

The minimum distance during the Closing trajectory is achieved for an off-nominal manoeuvre more intense than 5%. The relative distance between the two spacecraft is 40.5 m. Furthermore, the final position in this scenario is in the negative InTrack direction, due to the greater manoeuvre magnitude. For this reason, if SROC did not perform any other manoeuvres, a second pass should be expected near SR, during the drift away motion which would be resumed after a short period. However, this second passage would not cause high collision risks, because in the meantime SROC would continue to lose altitude, increasing the relative distance along the Radial direction and, possibly, it would perform some correction manoeuvres. The off-nominal relative trajectory is shown in Figure 147 and Table 82 resumes the manoeuvre values and the relative final components.

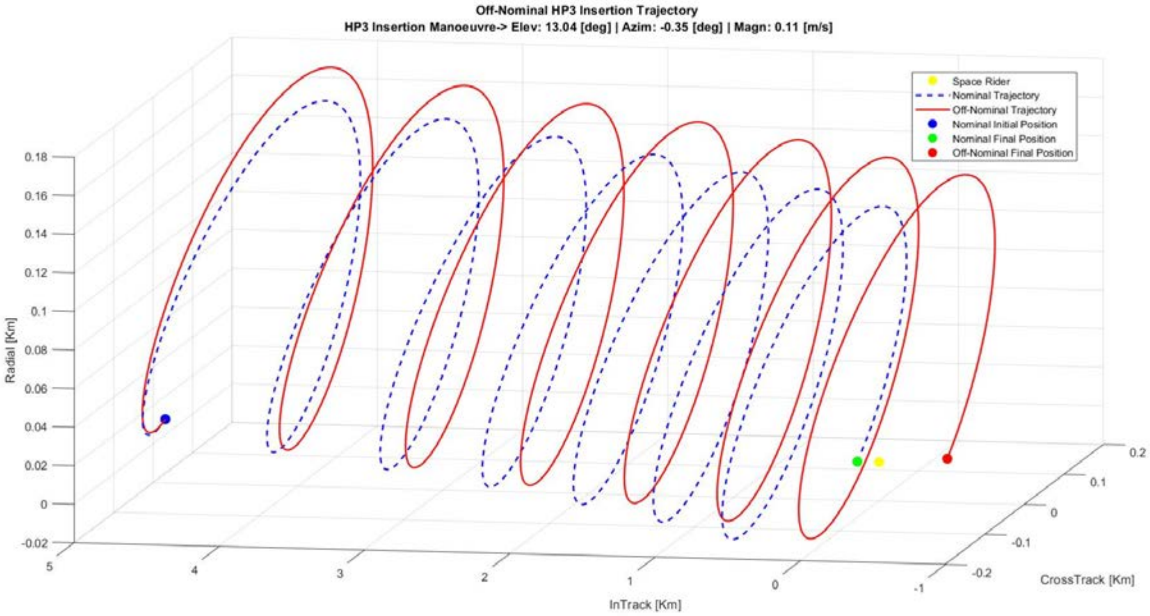


Figure 147: Closing Off-Nominal Magnitude – minimum distance

Table 82: Closing Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	13.0	13.0
Azimuth [deg]	-0.35	-0.35
Magnitude [m/s]	0.11	0.11
Closing min Range [m] (module and RIC frame components)	150.0 [0.0 150.0 0.0]	40.5 [9.9 39.3 -1.6]
Time to the min Range [hr]	10.6	9.07

The Closing final position with the greatest distance compared to the desired one is obtained when the insertion manoeuvre in the HP#3 is not performed at all (0% of the nominal value), this off-nominal manoeuvre does not cause any risk of collision. In fact, the minimum distance during the Closing would be 4.6 km, reaching a final position which differs from the nominal one of 4.47 km along the Intrack direction. The off-nominal trajectory is shown in Figure 148 and it can be noticed that it is the continuation of the previous Free Flight trajectory.

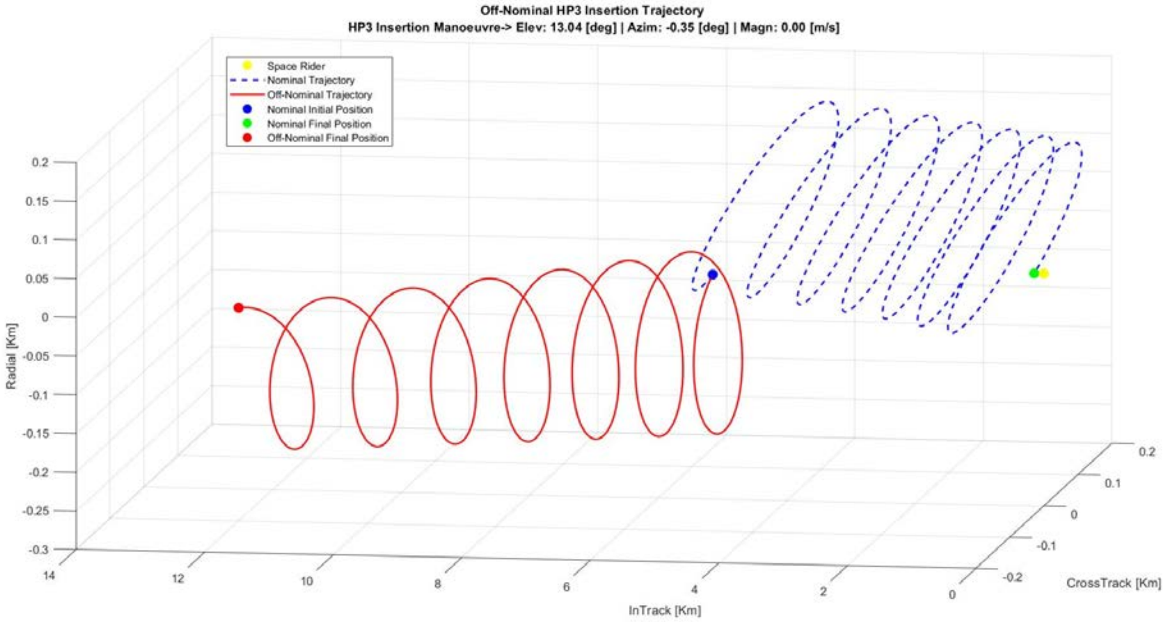


Figure 148: Closing Off-Nominal Magnitude – worst Final Position

Table 83: Closing Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	13.0	13.0
Azimuth [deg]	-0.35	-0.35
Magnitude [m/s]	0.11	0.0
Closing min Range [m] (module and RIC frame components)	150.0 [0.0 150.0 0.0]	$4.62 \cdot 10^3$ [-23.9 $4.62 \cdot 10^3$ -149.5]
Time to the min Range [hr]	10.6	0.17

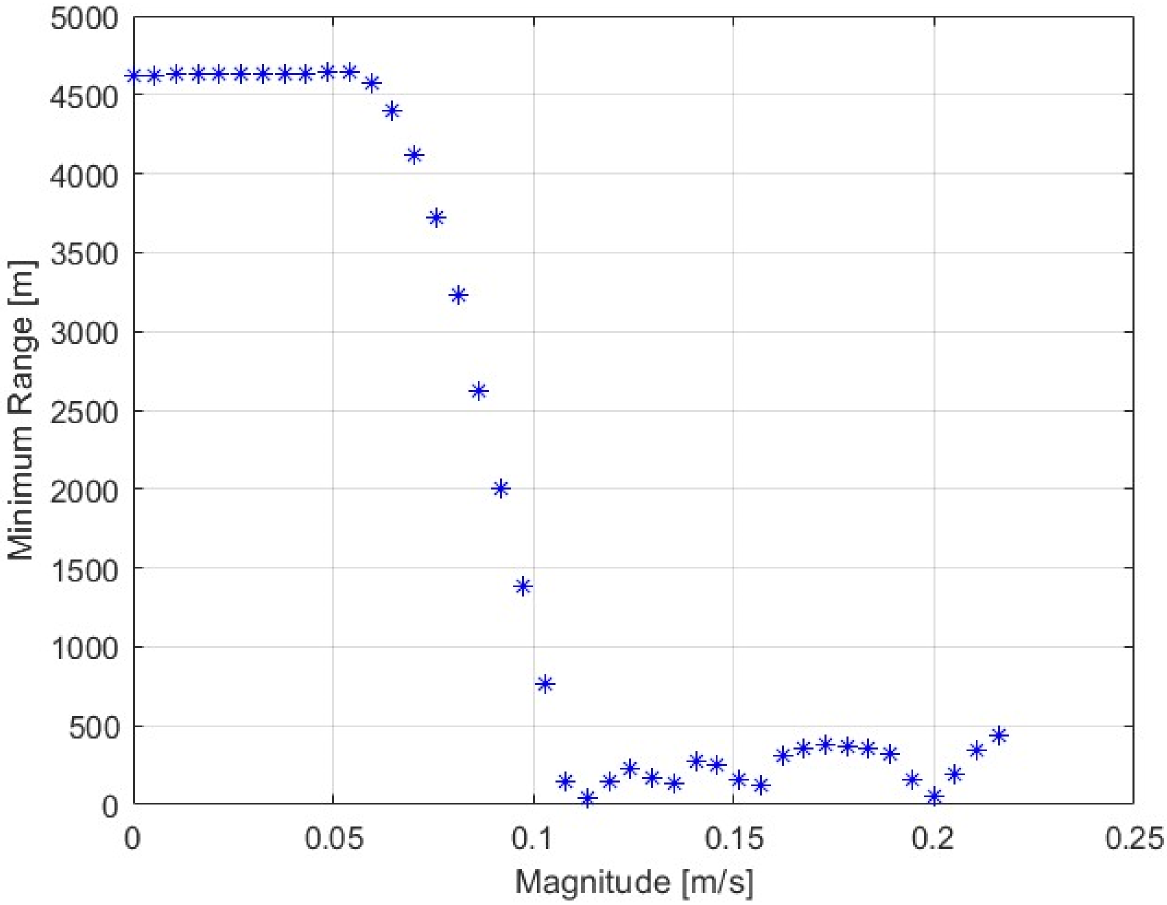


Figure 149: Scatter plot Magnitude errors – Closing Opt 2

Direction and magnitude errors

Combining errors in direction and magnitude of the thrust, the minimum distance is 4.9 m with the major component along Radial (4.7 m), for an off-nominal manoeuvre with an error of -3.5 deg for the elevation, +0.5 deg for the azimuth and the nominal magnitude value. The resulting trajectory and some parameters are shown in Figure 150 and in Table 84:

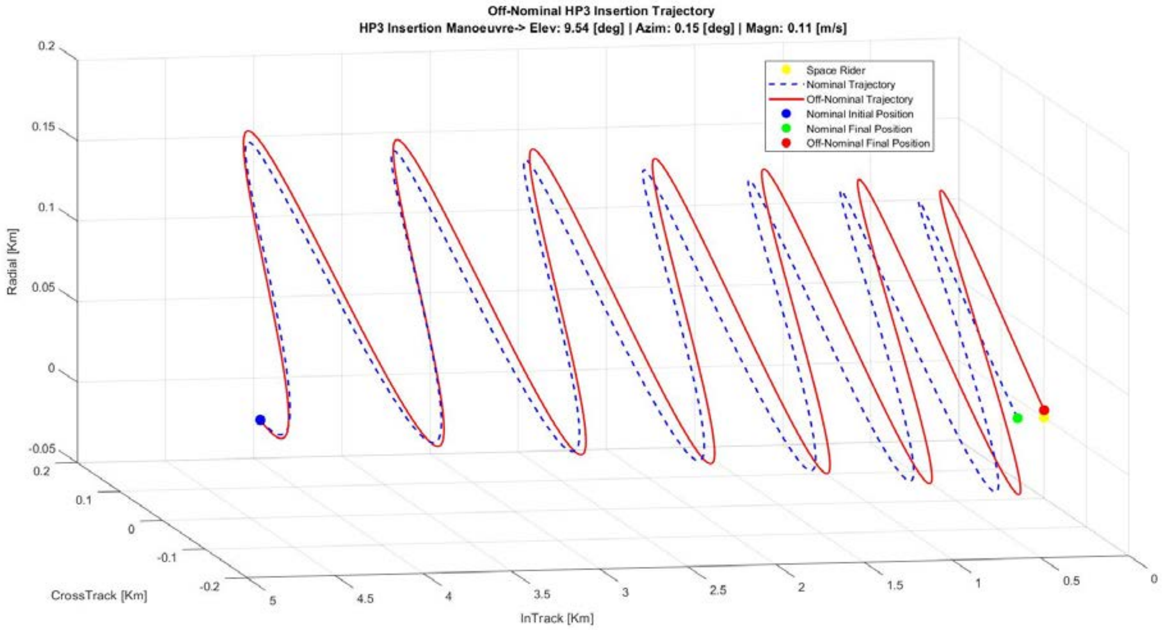


Figure 150: Closing Off-Nominal Direction and Magnitude - minimum distance

Table 84: Closing Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	13.0	9.54
Azimuth [deg]	-0.35	0.15
Magnitude [m/s]	0.11	0.11
Closing min Range [m] (module and RIC frame components)	150.0 [0.0 150.0 0.0]	4.9 [4.7 0.1 -0.5]
Time to the min Range [hr]	10.6	10.6

The Closing final position with the greatest difference from the nominal one occurs with an elevation error of -5.0 deg, an azimuth error of +0.5 deg and a double magnitude compared to the nominal one (+100%). In this event, the minimum range between the two spacecraft during the rendezvous is 474.2 m. The relative trajectory is shown in Figure 151:

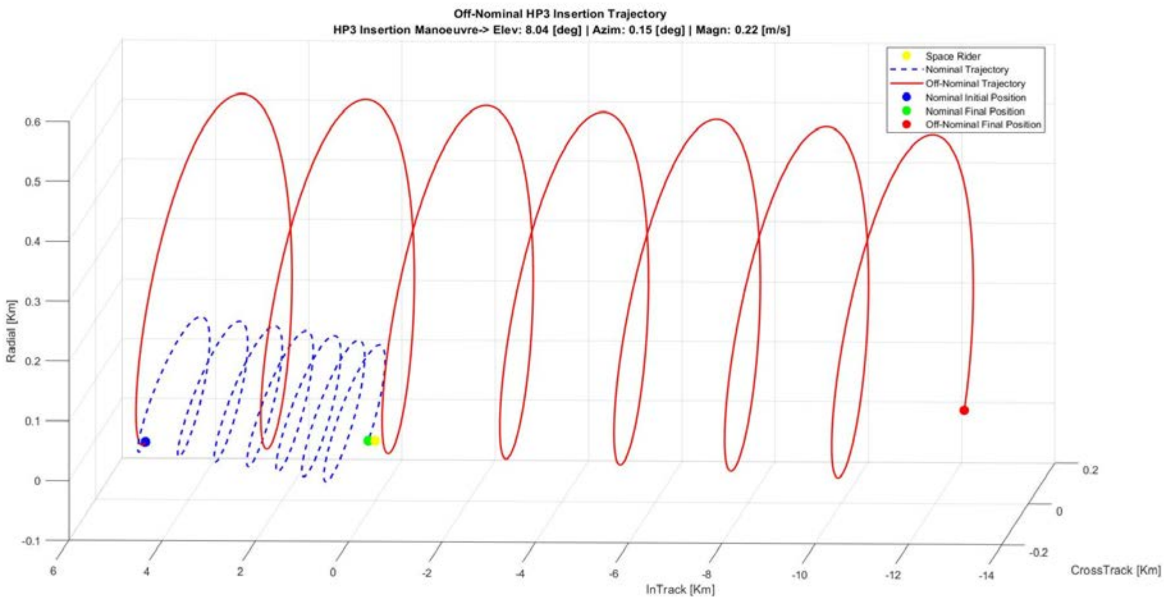


Figure 151: Closing Off-Nominal Direction and Magnitude – worst Final Position

Table 85 resumes this off-nominal scenario.

Table 85: Closing Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	13.0	8.0
Azimuth [deg]	-0.35	0.15
Magnitude [m/s]	0.11	0.22
Closing min Range [m] (module and RIC frame components)	150.0 [0.0 150.0 0.0]	474.2 [430.3 -124.6 155.4]
Time to the min Range [hr]	4.5	2.55

4.2.6 Off-Nominal manoeuvre entering the Hold Point 3

The entry manoeuvre in the HP#3 is performed at the end of the Closing phase. This manoeuvre stops the relative motion along the Intrack axis at a desired value (*Intrack target*) of 150 m with respect to SR. Figure 152 shows the nominal relative trajectory during the HP#3. A relative motion is still present, but it is small compared to the distance being examined.

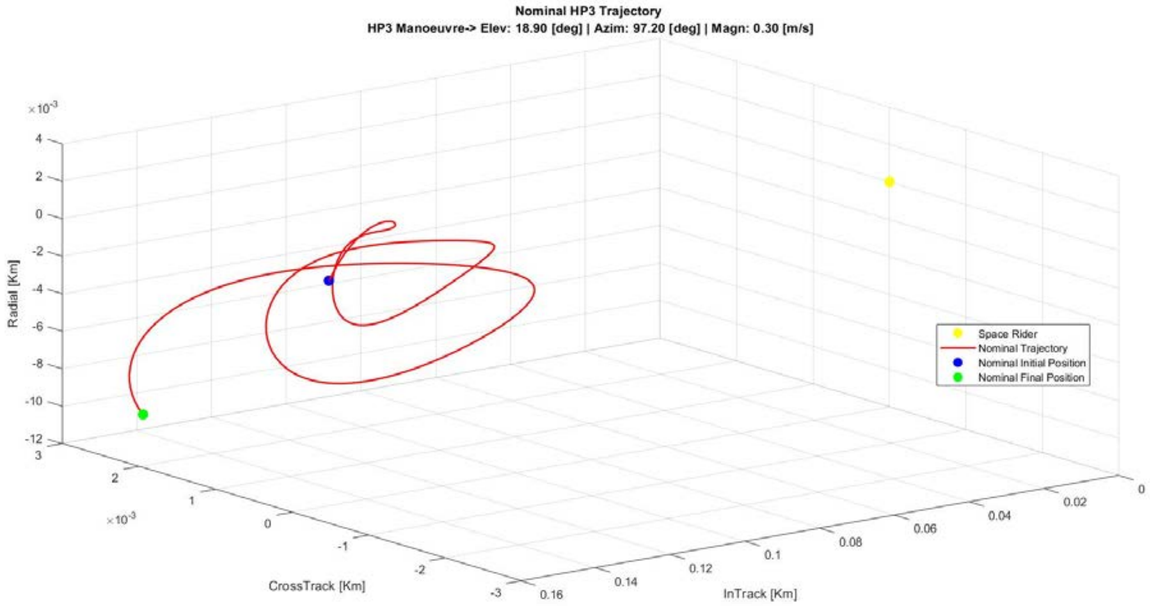


Figure 152: HP#3 Nominal Trajectory

Hereafter (Table 86) are reported the manoeuvre values for the nominal mission and some other parameters useful to compare the off-nominal scenarios to the nominal one:

Table 86: HP#3 Nominal Manoeuvre Values

Elevation [deg]	Azimuth [deg]	Magnitude [m/s]
18.9	97.2	0.3
min Range [m]	123.5	
Time to the min Range [hr]	2.62	

The off-nominal analysis was performed by varying the angles of ± 5 $[deg]$ from the nominal value, with a step of 0.5 $[deg]$, the magnitude of ± 100% from the nominal value, with a 5% step, and the combinations of the two errors were also considered.

Direction errors

Committing some errors on the manoeuvre direction could increase the risk of collision with SR, since the minimum distance to be reached could be close to the target spacecraft. The minimum distance during the HP#3 trajectory is for an off-nominal manoeuvre with -2 deg for the elevation angle and -3 deg for the azimuth with respect to the nominal values. In this scenario the minimum distance is 0.5 m that for sure would lead to a collision after one orbit if no correction manoeuvre would be performed. This is the worst off-nominal manoeuvre for the HP#3 mistaking only the direction with respect to Space Rider. The off-nominal trajectory is shown in Figure 153 and some values are resumed in Table 87.

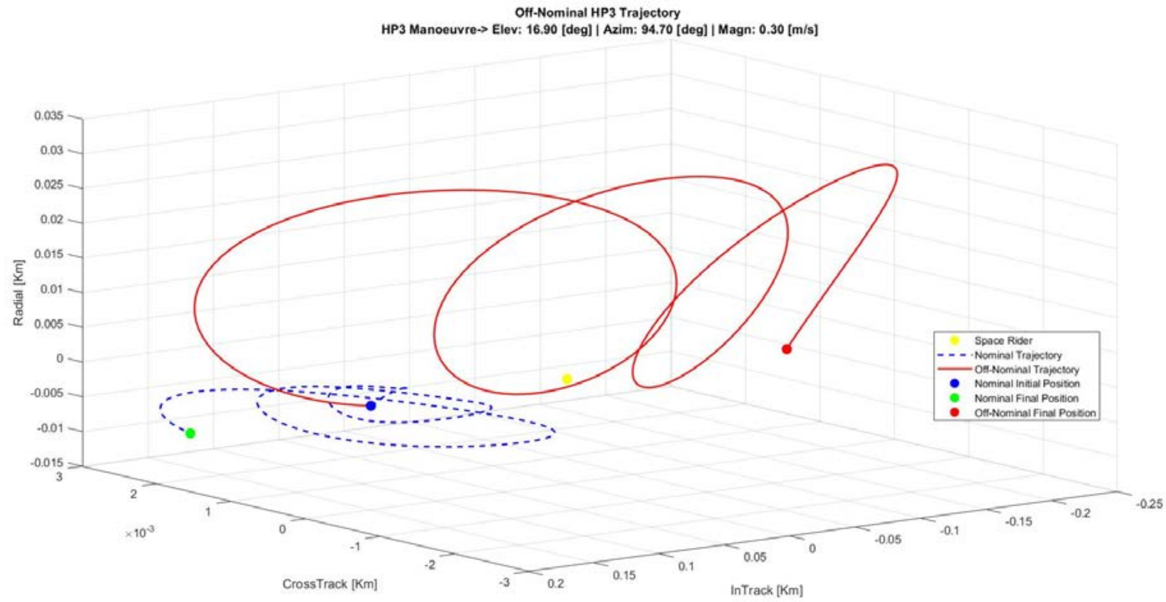


Figure 153: HP#3 Off-Nominal Direction - minimum distance

Table 87: HP#3 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	18.9	16.9
Azimuth [deg]	97.2	94.7
Magnitude [m/s]	0.3	0.3
HP#3 min Range [m] (module and RIC frame components)	123.5 [-1.2 123.5 1.3]	0.5 [0.2 0.4 -0.2]
Time to the min Range [min]	2.62	1.45

The final position with the greater error than the nominal one occurs for an off-nominal manoeuvre mistaken by -5 degrees for the elevation angle and +5 degrees for the azimuth angle. The minimum range is comparable to the nominal one and this scenario would not increase the collision risk. Nevertheless, this case would result to a higher ΔV and mission delay since a new approach will be required. The trajectory is shown in Figure 154 and some parameters are reported below (Table 88).

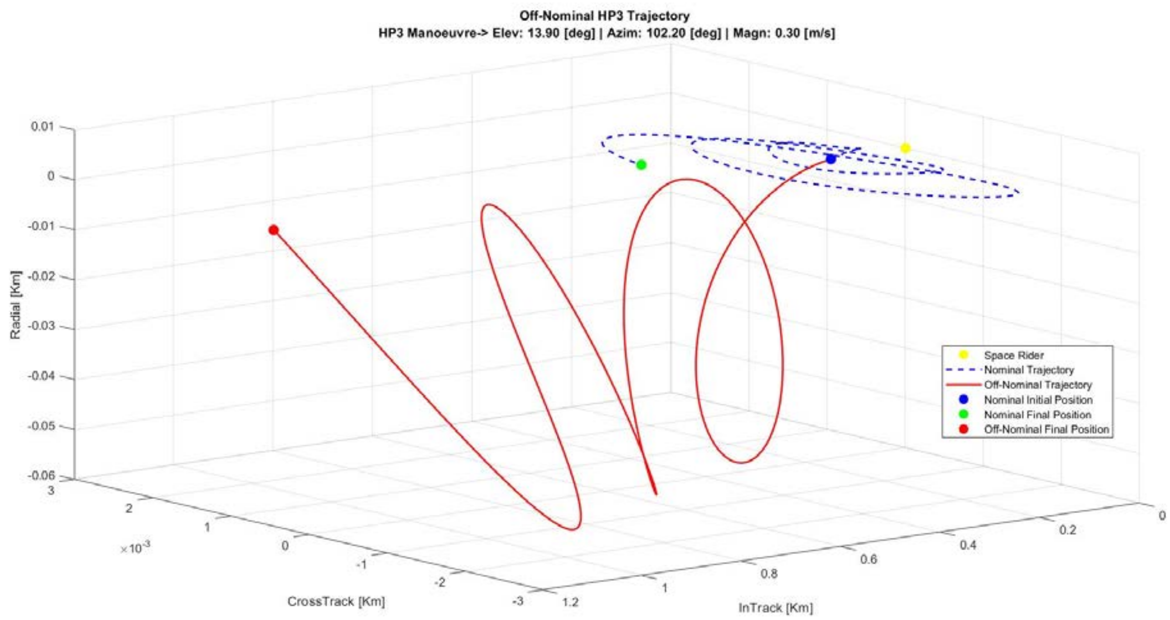


Figure 154: HP#3 Off-Nominal Direction - worst Final Position

Table 88: HP#3 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	18.9	13.9
Azimuth [deg]	97.2	102.2
Magnitude [m/s]	0.3	0.3
HP#3 min Range [m] (module and RIC frame components)	123.5 [-1.2 123.5 1.3]	147 [-6.9 146.9 0.6]
Time to the min Range [min]	2.62	0.1

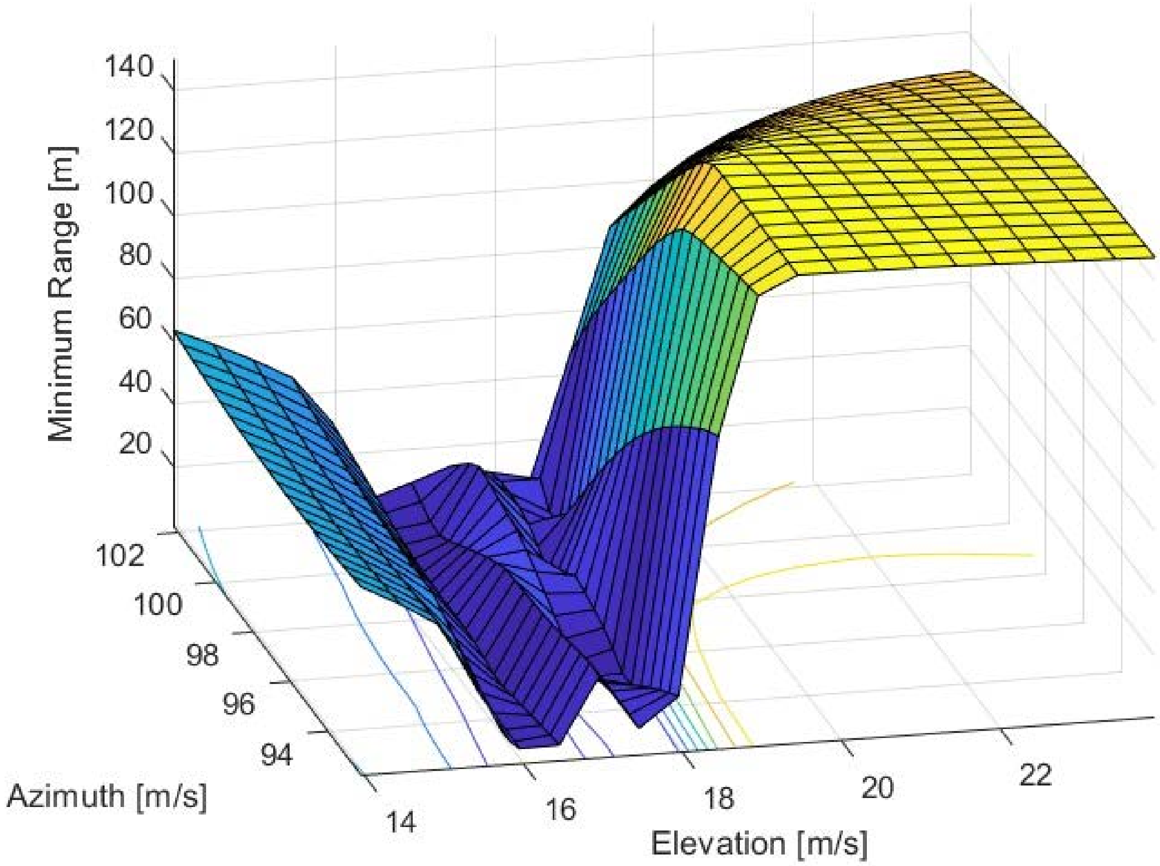


Figure 155: Scatter plot Direction errors – HP#3 Opt 2

Magnitude errors

The minimum distance during the HP#3 trajectory is achieved for an off-nominal manoeuvre less intense than 65%. In this case nonzero Intrack velocity component from the previous segment would lead to a minimum distance between the two spacecraft is 2.8 m and, even in this case, considering the SR size and geometry this off-nominal scenario would lead to a collision after one orbit. The off-nominal relative trajectory is shown in Figure 156 and Table 89 resumes the manoeuvre values and the relative final components.

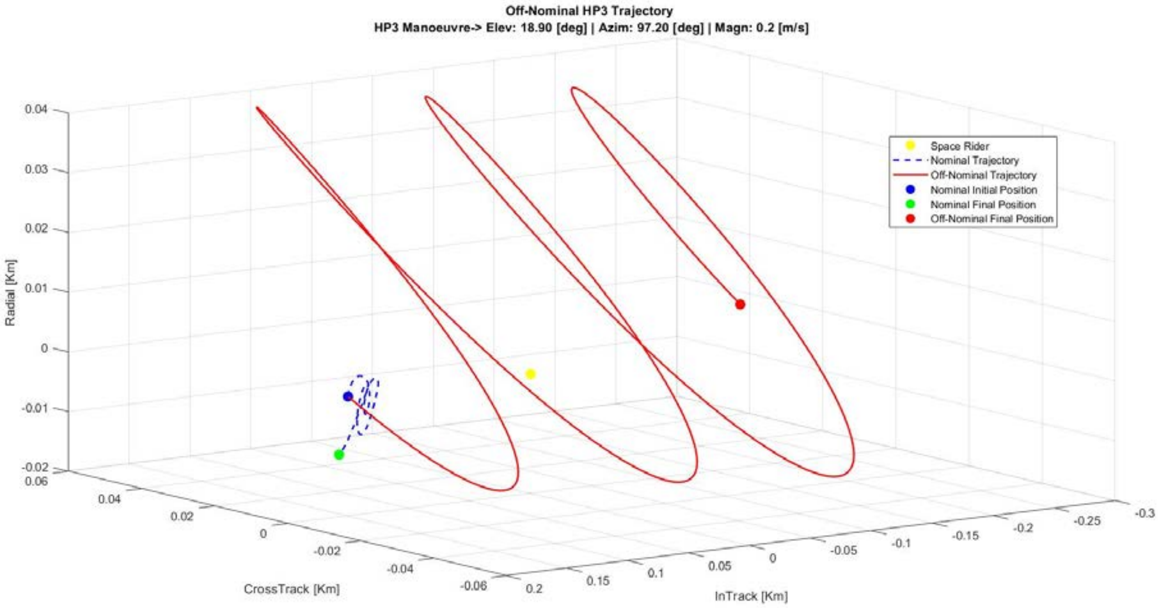


Figure 156: HP#3 Off-Nominal Magnitude - minimum distance

Table 89: HP#3 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	18.9	18.9
Azimuth [deg]	97.2	97.2
Magnitude [m/s]	0.3	0.195
HP#3 min Range [m] (module and RIC frame components)	123.5 [-1.2 123.5 1.3]	2.8 [-2.7 -0.2 0.9]
Time to the min Range [min]	18.9	1.53

The HP#3 final position with the greatest distance compared to the desired one is obtained when the manoeuvre is mistaken by +100%, this off-nominal manoeuvre does not lead to increased risk of collision. In fact, the minimum distance during the HP#3 would be 100 m, reaching a final position which differs from the nominal one of about 1.1 km. The off-nominal trajectory is shown in Figure 157.

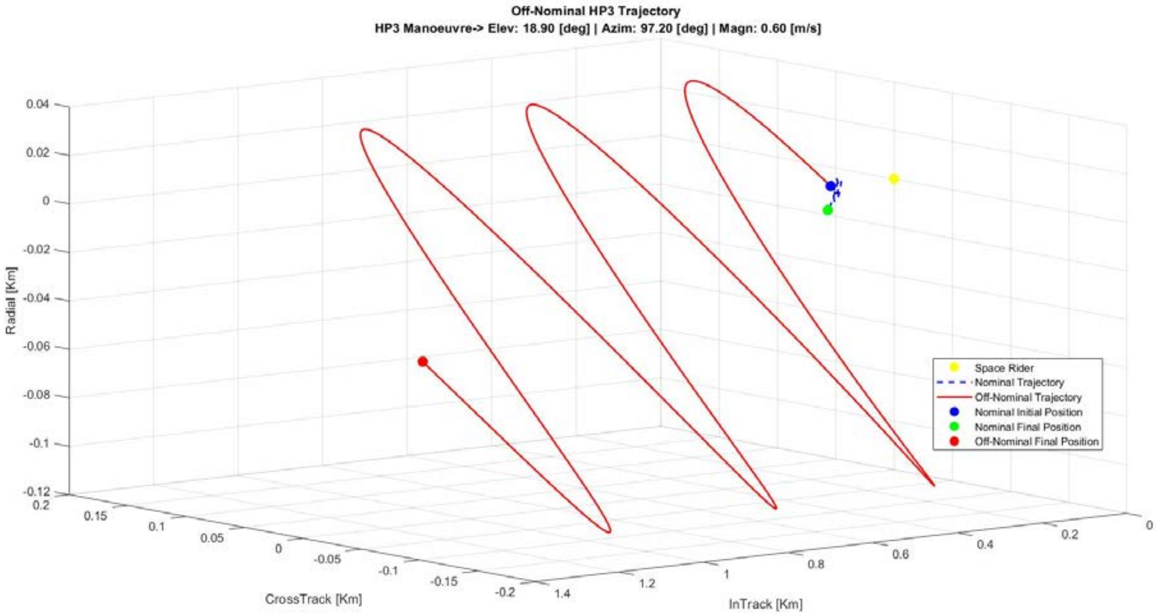


Figure 157: HP#3 Off-Nominal Magnitude - worst Final Position

Table 90: HP3 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	18.9	18.9
Azimuth [deg]	97.2	97.2
Magnitude [m/s]	0.3	0.6
HP#3 min Range [m] (module and RIC frame components)	123.5 [-1.2 123.5 1.3]	100.2 [-53.9 59.8 59.7]
Time to the min Range [min]	18.9	0.67

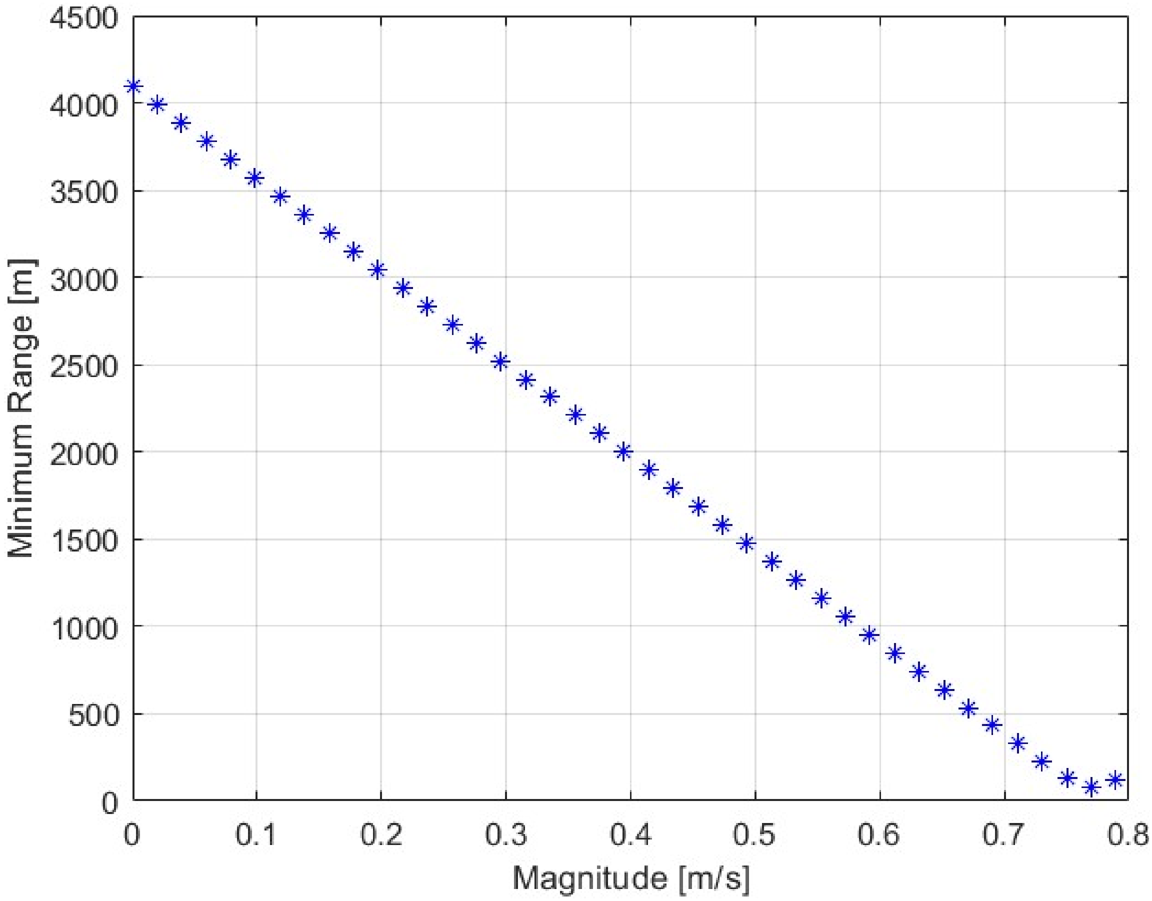


Figure 158: Scatter plot Magnitude errors – HP#3 Opt 2

Direction and magnitude errors

Combining errors in direction and magnitude of the thrust, minimum distance is 0.4 m for an off-nominal manoeuvre with an error of +2.5 deg for the elevation, -2.0 deg for the azimuth and a magnitude increased by 45%. The resulting trajectory and some parameters are shown in Figure 159 and in Table 91:

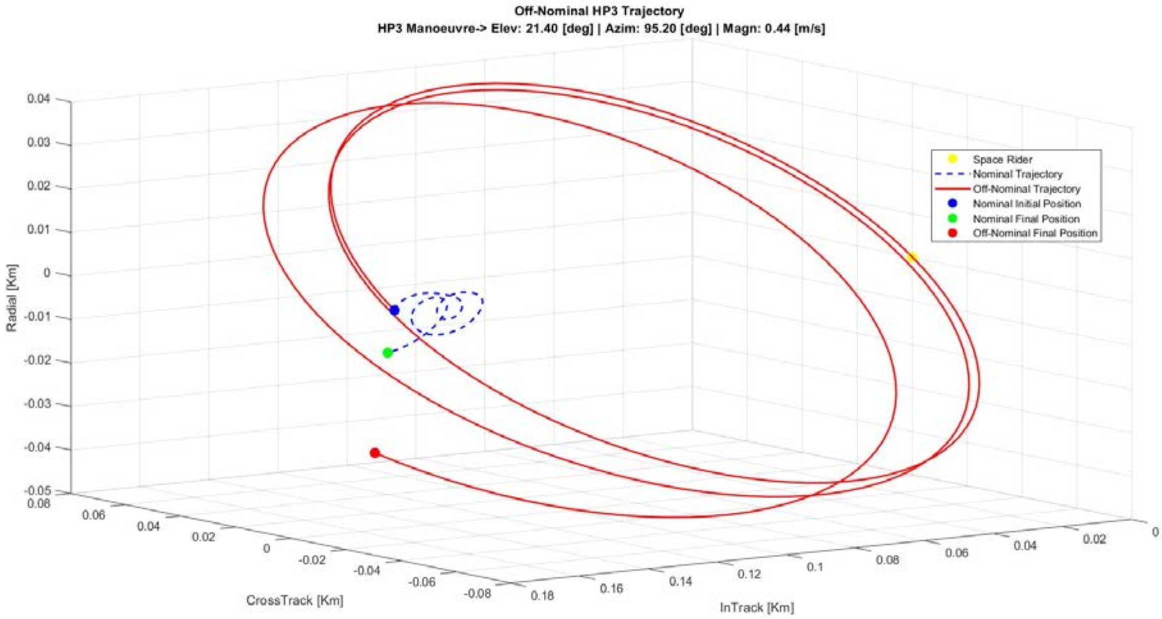


Figure 159: HP#3 Off-Nominal Direction and Magnitude - minimum distance

Table 91: HP#3 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 1
Elevation [deg]	18.9	21.4
Azimuth [deg]	97.2	95.2
Magnitude [m/s]	0.3	0.435
HP#3 min Range [m] (module and RIC frame components)	123.5 [-1.2 123.5 1.3]	0.4 [0.3 0.3 -0.2]
Time to the min Range [min]	18.9	46

The HP#3 final position with the greatest difference from the nominal one occurs with an elevation error of - 5.0 deg, an azimuth error of +5.0 deg and a double magnitude compared to the nominal one (+100%). In this event, the minimum range between the two spacecraft during the rendezvous is 142.1 Km. The relative trajectory is shown in Figure 160:

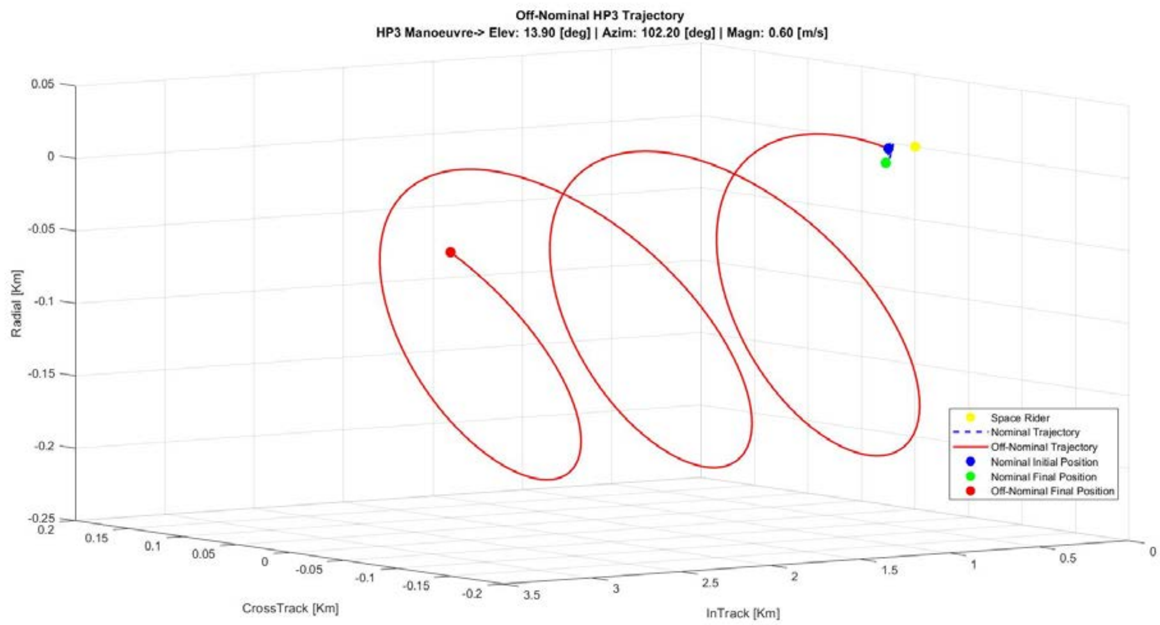


Figure 160: HP#3 Off-Nominal Direction and Magnitude - worst Final Position

Table 92 resumes this off-nominal scenario.

Table 92: HP#3 Off-Nominal Manoeuvre Values Comparison

	Nominal	Off-Nominal 2
Elevation [deg]	18.9	13.9
Azimuth [deg]	97.2	102.2
Magnitude [m/s]	0.3	0.6
HP#3 min Range [m] (module and RIC frame components)	123.5 [-1.2 123.5 1.3]	142.1 [3.7 133.4 48.8]
Time to the min Range [min]	18.9	4.45

5 BASELINE SCENARIO AT SRR

According to both the nominal and off-nominal analyses the Observe & Retrieve Quasi-Equatorial (5 deg) Orbit is proposed as Baseline mission scenario, while regarding the Rendezvous and Docking strategies the selected trajectories of SROC are composed as follow:

1) Deployment
2) 5 days Commissioning
3) Hold Point 1 (HP#1)
4) In-Plane Approach Rendezvous (IPA)
5) Hold Point 2 (HP#2)
6) Out-of-Plane Approach Rendezvous (OPA)
7) Walking Safety Ellipse (WSE)
8) Free Flight
9) Closing
10) Hold Point 3 (HP#3)

The **deployment** has been chosen to be coplanar, with a 10 degrees inclination with respect to the Radial axis toward negative Intrack axis; the DeltaV applied is **0.5 m/s**. Once deployed, the scenarios have been propagated for **5 days** (target scenario) in order to simulate the required time for the operations of detumbling, check and calibration of SROC Commissioning Phase.

The **Hold Point 1**, as well as the HP#2 and the Intrack HP#3, have been chosen to be in positive Intrack direction because the natural effects of the perturbations make SROC to drift away from SR. The HP#1 will last for about **4.5 hr.**

The **In-Plane Approach** (IPA) Rendezvous is conceived to reduce the relative distance reaching the Intrack target of **2 km**. This segment will last for **5.7 days**.

At the end of this segment an Out-of-Plane trajectory is performed to correctly reach the next segment starting point after **4.55 hr**. The **Hold Point 2** (HP#2) is a **4.5 hr** long segment during which SROC will maintain a relative distance of **2 km** from SR along the Intrack axis. During this phase SROC will execute the navigation sensors switch, as well as the SR locking while waiting for the "go/no-go" command from Ground.

The Rendezvous Phase is resumed with an **Out-of-Plane Approach** (OPA) whose purpose is to correctly reach the Observation starting point. After **4 hr** SROC will reach a position along the negative Intrack axis with non-zero out of plane components, where executing the observation segment insertion manoeuvre.

The SR observation will be carried out with a **Walking Safety Ellipse** (WSE), that is a passively safe trajectory with a drift velocity component toward positive Intrack. The SR observation will last for **6 hr**, during this amount of time SROC will obtain a cumulative SR surface coverage higher than 90%. According to the performed analyses the WSE geometry that ensures higher performance while reducing the ΔV cost is a 150-150 m wide ellipse.
The Observation Phase is concluded with a **Free Flight** segment, a passive safe continuation of the WSE executed without any additional manoeuvre that will permit to the data downlink, wait for "go/no-go" command to start another Observation cycle (if needed) or to start the Docking & Retrieval Phase. In any case, SROC will not exceed a relative distance of 5 km in order to retain the SR locking, so this segment duration will be less than **15 hr**.

The Docking and Retrieval Phase is characterised by four main segments: the **Closing** segment is required to stop the drift away from SR, thus to re-approach it with a passively safe out-of-plane trajectory and reaching the designed position for the HP#3 after **10.6 hr**.
Regardless of the docking axis, the **Hold Point 3** (HP#3) will permit SROC to enter the Keep Out Zone with a passive safe trajectory, maintaining a relative distance between **100 and 150 m** with respect to SR for about **4.5 hr**, required to wait “go/no-go” command, as well as good illumination conditions and ground station visibility. The docking axis choice declines into two strategies that are equivalent from a performance point of view:

- Intrack Docking: SROC will wait with null relative motion along the Intrack axis performing a finite burst manoeuvre to correct the orbit disturbances. The Final Approach is straight line trajectory along Intrack axis.
- Radial Docking: SROC will perform a passive safe out-of-plane trajectory, leading the spacecraft in the proximity of a virtual point, the Final Approach Point (FAP), that is conceived as a way point towards Final Approach and Mating.

To conclude, the selected Baseline ensures SROC to pursue all the mission objectives with high safety levels during all the mission phases, in compliance with the [7]. The overall DeltaV budget is 5.3 m/s (with margins), well below the 20 m/s maximum threshold imposed by the applicable requirement. Nevertheless, for this scenario a concern was presented and described on the Ground Stations Visibility Section (8.8), indeed due to the low orbit inclination only four Ground Stations are available for communication with the two spacecraft during the mission. This could result in mission delays due to increased time needed to complete communication both uplink and downlink after the Observation Phase. Moreover, a precise synchronization for SROC trajectory, illumination condition and Ground Station coverage to correctly and safely executes the Docking & Retrieval Phase.
A possible solution to this could be an additional antenna placed between the Malindi and the Sri Lanka Ground Stations, so as to guarantee a Ground Stations take over and a higher continuous communication window. This solution will rise the communication window up to 17 minutes.

6 AKNOWLEDGEMENTS

"*Hope is the possibility of always having something to achieve.*" – Luca Parmitano

I do not remember the exact day when my fascination for space was first sparked, but I still feel apprehensive about everything related to it. At the completion of this thesis project, I feel thankful: thankful that the academic course is coming to an end, thankful for the chances for development the university has provided, and thankful for the opportunity to serve as a crucial member of the SROC team.

I want to express my gratitude to the entire research team, including my mentor Catia Speranza, my supervisors Sabrina Corpino and Giorgio Ammirante. The months have been demanding, packed with work and deadlines, but most of all, they have been rewarding.
SROC gave me the chance to work alongside professors, researchers, and engineers more experienced than myself. I was able to witness first-hand the dynamics of a multi-partner project, and I gained knowledge and experience from both the industrial and academic sectors, thanks to Tyvak's engineers, the European Space Agency's engineers, and the involved professors and researchers from the Polytechnic of Turin and the University of Padua.

All that remains is to wait for SROC's flight.

Finally, I would like to express my sincere gratitude to my parents and brother, who have always been and will continue to be my intangible sources of inspiration and support. Along with that, I would like to thank all of my university friends and colleagues, both current and past.

7 BIBLIOGRAPHY

[1] Statement of Work – Development of the Space Rider Observer Cube Phase B1 ESA−TECMPA−SOW−017273 (30/07/2021)

[2] User Guide for the Space Rider Re−usable Free Flyer Platform ESA−STS−SR−TN−2018−0002 (09/09/2021)

[3] Tailored ECSS Engineering Standards for In−Orbit Demonstration CubeSat Projects TEC−SY/128/2013/SPD/RW (24/11/2016)

[4] Space Debris Mitigation Policy for Agency Projects ESA/ADMIN/IPOL(2014)2 (28/03/2014)

[5] Space Rider System – Payload Safety, Space Debris and Collision Avoidance Requirements ESA−STS−SR−ST−2022−0001 (21/04/2022)

[6] D1.1 – Assessment of the SROC mission and preliminary functional specification – DIMEAS/ASSET/2019/020/ESA−SROC/TN/D1.1−Mission/I3R0 (30/10/2020)

[7] Space Rider Observer Cube (SROC) Mission Requirements Document −ESA−TECMPA−RS−023426 Iss.1 Rev.3 (30/07/2021)

[8] Safe Close Proximity Operations ESA−TECSYE−TN−010228 Iss.1 Rev.1 (30/09/2018)

[9] Mission Concept of Operations Document SROC−PTO−SYS−TNO−007 (13/05/2022)

[10] Fehse, W. (2003). Automated Rendezvous and Docking of Spacecraft (Cambridge Aerospace Series). Cambridge: Cambridge University Press. Doi:10.1017/CBO9780511543388

[11] TEC−SY/77/2016/POL/RW − System Margin Policy for ESA IOD CubeSat Projects

[12] D'Amico, S. (2005). Relative orbital elements as integration constants of Hill's equations. DLR, TN, 05−08.

[13] D111 – System Technical Specifications – SROC−PTO−SYS−REQ−001 (10/06/2022)

[14] D212 – Mission Concept of Operations Document – SROC-PTO-SYS-TNO-007 (10/06/2022)

[15] D122 – SROC System Design Justification File – SROC-TVK-SYS-DJF-004 (10/06/2022) + Annex to D122

[16] *Nanosats Database*, https://www.nanosats.eu/ – Accessed 20/11/2022

[17] *CubeSat Design Specification (CDS),* Rev. 14.1 Updated on February 2022, *https://www.cubesat.org/cubesatinfo – Accessed 20/11/2022*