VERIFICATION AND VALIDATION OF RENDEZVOUS AND PROXIMITY OPERATIONS SAFETY

Executive summary

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DOCUMENTARY REFERENCE SYSTEM

Applicable documents

Table 0-1 – Applicable Documents

[SoW]	Statement of Work: appendix 1 to ESA AO/1-11351/22/NL/AS Activity No. 1000034517
[CC]	ESA Draft Contract: appendix 2 to ESA AO/1-11351/22/NL/AS Activity No. 1000034517
[TC]	Tendering Conditions: appendix 3 to ESA AO/1-11351/22/NL/AS Activity No. 1000034517
[AD.1]	ESA-TECSYE-TN-022522 - Guidelines on Safe Close Proximity Operations, Issue 2, Revision 0
[AD.2]	ESA/ADMIN/IPOL(2014)2 - Space Debris Mitigation Policy for Agency Projects
[AD.3]	CONFERS Recommended Design and Operational Practices, Revised October 2022
[AD.4]	CONFERS Guiding Principles for Commercial Rendezvous and Proximity Operations (RPO) and On-Orbit Servicing (OOS), Revised October 2022

Reference documents

Table 0-2 – Reference Documents

[RD.1]	International Rendezvous System Interoperability Standards (IRSIS) Baseline- March 2019
[RD.2]	Rendezvous and Proximity Operations and On Orbit Servicing– Programmatic Principles and Practices (ISO 24330 standard, March 2022)
[RD.3]	JAXA safety standard for on-orbit servicing missions
[RD.4]	CONFERS On-Orbit Servicing (OOS) Mission Phases (October 2019)
[RD.5]	CONFERS Satellite Servicing Safety Framework – Technical and Operational Guidance document (April 2018)
[RD.6]	French Space Act, RT NG draft (December 2022)
[RD.7]	Guide des bonnes pratiques associées à la LOS (December 2022)
[RD.8]	The European Operations Framework (EOF) Principles & Guidelines for On-Orbit Services
[RD.9]	TN1: Guidelines on Safe Close Proximity Operations for cooperative clients
[RD.10]	TN2: Guidelines on Safe Close Proximity Operations for non-cooperative clients
[RD.11]	TN3: Verification and Validation Matrix for Sustainable Close Proximity Operations for cooperative clients
[RD.12]	TN4: Verification and Validation Matrix for Sustainable Close Proximity Operations for non-cooperative clients
[RD.13]	TN5: Case studies: Proposed methodology demonstration for verification and validation process

1 Introduction

Though the need for safety standardization has been identified by major agencies, the definition of accepted technical and safety standards for In-Orbit Servicing (IOS) to carry out in a safe and responsible manner these operations is still an on-going process. The economic context of these projects is challenging, and design rules and verification methods inherited from crewed rendezvous mission are probably over constraining. On the other hand, either from the space debris mitigation point of view or from a commercial and insurance service point a view, an adequate level of safety shall be implemented and demonstrated. Availability of adequate design and verification tool is thus considered essential to support in an exhaustive and cost effective way these verifications..

The main objectives of this study are to [SoW]:

- Derive rendezvous and proximity operations technical guidelines, requirements and best design practices for cooperative and non-cooperative clients which ensure sustainability of CPO. This activity correspond to Task 1 of [SoW] and is summarized in Sec.2.
- Identify the verification and validation method for each requirement, assess the state of the art for the various methodologies/numerical tools available for the identified verification methods, and perform a gap analysis and identify the methodologies/numerical tool(s) required. This activity correspond to Task 2 of [SoW] and is summarized in Sec.3
- Demonstrate the verification process/tools usage through case studies proposed by the Contractor. This activity correspond to Task 3 of [SoW] and is summarized in Sec.4

2 TASK 1: Critical analysis of [AD.1]

During the first task, different existing standards (i.e., IRSIS [RD.1], CONFERS [AD.3] [AD.4] [RD.4] [RD.5], ISO 24330 [RD.2], JAXA [RD.3], French Space Act [RD.6] [RD.7], and the European Operations Framework EOF [RD.8]) were analysed and compared with ESA CPO guidelines [AD.1] in order to propose updates to the existing ESA requirements.

2.1 Key Safety Requirements

The goal of [AD.1] is to propose guidelines to ensure mission safety without constraining the mission design. For uncrewed rendezvous mission such as IOS missions, mission safety mainly translates in avoiding the generation of any debris during the CPO. Debris could be generated due to:

1. Unintentional breakup of the servicer or the client.
2. Intentional generation of micro-debris during the servicing operations
3. Collision of the servicer or the client with third parties.
4. Unintentional degradation of the client (or the servicer) performance during servicing operations, preventing the client (or the servicer) from continuing its nominal mission and precluding the possibility of carrying out End-Of-Life disposal.
5. Collision of the stack with third parties.
6. Collision of the servicer with the client.

To avoid undesired collisions during CPO, the notion of zones is introduced. In [AD.1], two zones, centred at the Client's CoM (Center of Mass) are defined: **the Approach Zone (AZ)** and **the Keep Out Zone (KOZ)**.

The first zone encountered by the servicer during its approach is the AZ, with a size that is mission dependent, usually in the order of magnitude of some kms. The KOZ is smaller around the client, its size is mission dependent too, usually around a hundred of m. These zones can be entered only after the positive assessment of a set of condition that we will detail further. GO/NO-GO can be issued either from TC -requiring therefore Ground Station visibility-, or autonomously –implying a higher level of autonomy of the servicer. These decisions are taken in correspondence of *decision points.* Decision points are mission specific, defined by trajectory design, ConOPS and servicer performance. However, in order to ensure mission success and safety, a minimum set of decision points needs to be defined. These are the points where the servicer (either autonomously or through Ground communication) assess a set of conditions (i.e., GO/NO-GO conditions) before initiating an intentional entry in a zone and/or the initiation of the next rendezvous phase. Decision points represent -in the mission timeline- the boundaries between the different CPO phases, as detailed in the following paragraphs and pictured in Figure 1.

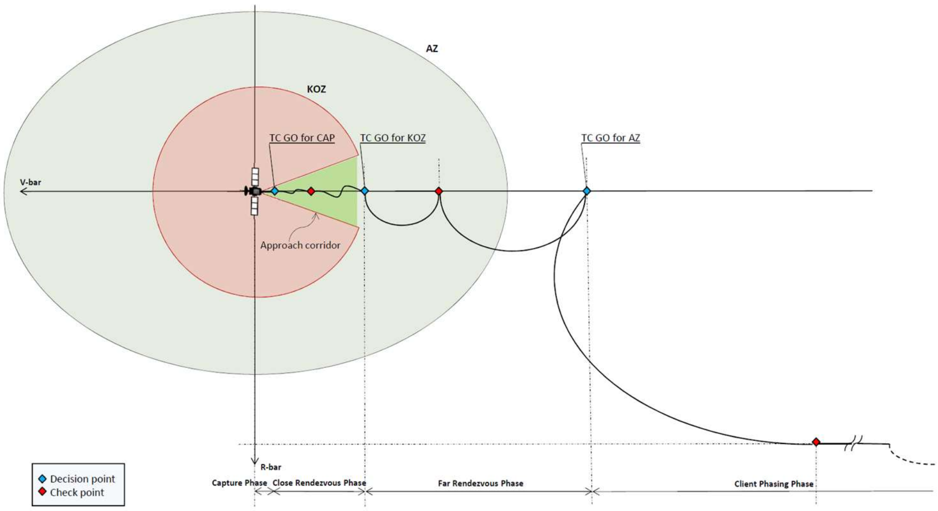

Figure 1: CPO Operational Phases, Zones, and Decision Points

Far Rendezvous Phase:
Before arriving at the AZ boundary, the servicer is in the Client Phasing Phase and it can still rely on absolute navigation, thus this mission phase is not considered part of CPO. When the servicer receives the GO allowing to proceed beyond the AZ boundary, the Far Rendezvous Phase (and CPO) begins. One of the condition for the servicer to enter the AZ is to perform relative 3DoF (Degrees-of-Freedom) pose estimation, i.e. the client has to have access to a reliable estimate of the relative client-servicer position. Within the AZ, the servicer can follow any trajectory: it's up to the mission design either to opt for an approach that follows passively safe trajectories or to rely on active orbit protection. In any case, inside the AZ, the servicer must ensure the capability to Abort or Cancel the approach either autonomously or from Ground TC. An Abort is an operation to safely terminate the CPO in the event that the **mission safety cannot be ensured**. The Abort command triggers a maneuver (e.g., a CAM) to put the servicer on a safe passive trajectory (if not already on such a trajectory). On the other hand, a Cancel is triggered when mission safety is not endangered but **mission success can no longer be ensured**, and it does not result in a CAM.

Close Rendezvous Phase:
When the servicer reaches the KOZ boundaries, it waits for the assessment of another set of condition for the GO/NO-GO to enter the KOZ zone. If the GO command is issued, the Close Rendezvous Phase starts. The KOZ can be entered only through the **Approach Corridor (ApC).** The ApC is a geometrical and dynamical envelope, generally understood as a cone originating from the client in which the servicer makes its approach. It encompasses several parameters, such as relative position, range, range rate, relative attitude and relative rotation rate. A violation of the ApC results at least in a Cancel. In order to enter the zone via the ApC, the servicer must ensure 6DoF relative control. Relative 6DoF control is mandatory in order to avoid potential collisions, since the KOZ is the zone in which the servicer performs closing maneuvers that approach the servicer and the client's clearance envelopes until potential tangency. Within the KOZ, the capability of executing an Abort must be fully autonomous (i.e., without the need of receiving any external command). Another corridor is defined in the KOZ, namely the **Abort Corridor (AbC)**, whose violation result in an Abort. Its definition is similar to the definition of the ApC, but might have a different range of acceptable parameters.

Capture Phase, Stack Configuration Phase, and Separation Phase:
During the Close RDV phase, the servicer can approach along the ApC until tangency of the vehicles clearance envelopes. Before proceeding with the *Capture Phase*, another assessment of condition has to be made to initiate the Capture Phase. During this phase the servicer approaches the client, so that the clearance envelopes cross and the servicer proceeds beyond the so called *Point-of-No-Return*, *i.e.*, the moment at which it is safer to continue with capture rather than performing a CAM. Autonomous Abort capability is conserved until this point. The Capture Phase ends with the actual capture (i.e., the action of establishing physical connection between the servicer and the client) and the establishment of a stable stack. After confirmation of capture, the *Stack Configuration Phase* is initiated. The servicer and the capture operations must be designed to avoid degradation of the servicer and client performance

(e.g., especially due to plume contamination and/or impingement, but not in case the client is a space debris). During the Stack Configuration Phase, the servicer (or the client) is able to control the orbit and the attitude of the stack, in compliance with the requirements for subsequent operations to be implemented. Among those functions, collision avoidance capabilities with third parties have to be ensured. Finally, if a *Separation Phase* is foreseen, the servicer must ensure that the release conditions are compatible with the control capabilities of both the servicer and the client. Moreover, the release mechanism/strategy has to be capable of providing a minimum impulse to either the servicer or the client to create an opening rate, which enables the two objects to move apart along a trajectory where any drift creates no risk of collision between them over a time frame compatible with implementation of a CAM.

2.2 Main findings

The critical analysis of the existing guidelines lead to an update of the ESA CPO guidelines [AD.1]. Additional requirements were proposed, especially covering two topics not fully addressed before which concern only the cooperative RDV: the compatibility of the end-to-end service with the client, and the interaction between the servicer and the client control centres. More details are in TN1[RD.9] and TN2[RD.10].

3 TASK 2: V&V process

During Task 2, two activities were preformed

- The V&V methodologies and tools have been detailed for each discipline and/or SC subsystem. The addressed topics are Mission analysis ,GNC, Operations, FDIR, RAMS, System engineering, Electrical Power System, Thermal System, Propulsion System, Mechanical engineering, TTC System, Software.
- The V&V process for each requirement have been detailed, focusing on the differences in the V&V process for the cooperative and the non-cooperative case.

The complete work can be found in TN3 [RD.11] and TN4 [RD.12]. Below, the main conclusions on the V&V processes and tool are summarized:

Mission Analysis:

- The adaptation of existing tools is mission dependent and in general does not require too much effort.
- There is some overlap for MA and GNC (as far as open-loop analysis are involved. When the loop is closed, it exits MA perimeter and it is only GNC). Therefore, there is an overlap also on the tools that can be used for a given analysis (they can come either from MA or GNC). See, for instance, the RTDV tool described in Sec.4.1.
- It is important to have good tools that propagate the uncertainties (both for the design and validation of passively safe trajectories and for collision risk assessment).

GNC:

- The validation of the validation tool is usually a problem:
  - Image processing:
    - Different synthetic image simulators are available in Europe, however there is a lack of information concerning the quality of the rendering with respect to real flight images. An ongoing ESA study (ESA 4000139071/22/NL/CRS/adu) with TAS is analyzing different metrics to evaluate the quality of a synthetic image and developing a methodology to compare it with real images.
    - The community would benefit from a mission to collect a dataset of space images.
    - A part of the validation of synthetic image generators can rely on test benches.
    - For thermal images (TIR), the validation is very complex (TVAC not easy to use in this scope)
  - Real time optimisation algorithms are difficult to V&V. ESA AO/1-10895/21/NL/CRS focuses on this topic.
- Collision risk:
  - Roadmap: to have some tool or method that everybody apply to demonstrate compliance with the probability of collision requirement (ALL-0100 of [AD.1]).

  - Compromise to be found between the feasibility of the computation (i.e., number of Monte Carlo (MC) simulations) VS reliability of the computed figures.
- Capture (and separation) sequence: there is a strong coupling between mechanical and GNC aspects which should be better investigated.

Operations:

- The main gaps are more in terms of procedures/methods rather than tools (i.e., sharing of data, identification of procedures,…).
- The CPO events tool, developed by GMV and described in TN5 [RD.13], fills existing gap in terms of tools, both for assisting the early phase trajectory design, and in-orbit trajectory monitoring to maintain mission safety.

4 TASK 3: Case studies

In the third task of this study, the verification and validation approaches are demonstrated through two study cases: a cooperative case study (Start-€, a concept for life extension services for GEO telecom satellites), and non-cooperative case study (ClearSpace-1, a mission to demonstrate the RDV, capture, and de-orbiting of a space debris in LEO). The application of the V&V methodology to each case-study is described in details in TN5 [RD.13].

4.1 Cooperative case study

This case-study allowed assessing the advantages and limitations of the RTDV (Rendezvous Trajectory Design and Validation) tool, a TAS internal tool for trajectory design and validation through stochastic analysis. The tool can provide a fast analysis solution to compare RDV strategies (safe trajectories, hold points definition, rendezvous sensors and navigation chain performance and trade-off), through Linear Covariance Analysis (LinCov) and Monte Carlo simulations (Figure **2**). The tool supports design and validation for passively safe trajectories, for nominal mission design and failure cases. It enables the implementation of multiple guidance algorithms to evaluate their performances in representative environment which implements representative onboard functions. Finally, it provides analysis capabilities for CAM trajectories performances, in terms of passive safety and probability of collision.

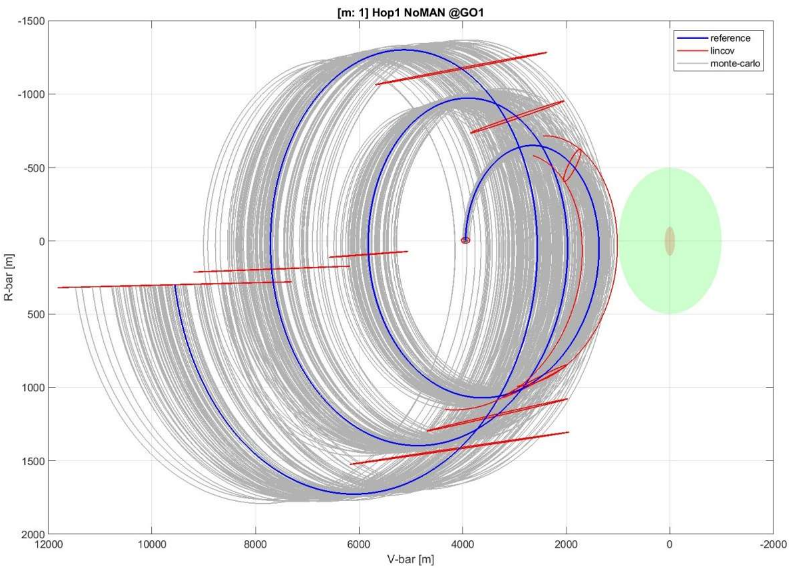

Figure 2: Example of RTDV trajectory result. The blue trajectory is the reference, the grey lines are the Monte Carlo runs and the red ellipses are the covariance ellipses computed with LinCov (for validation)

From a RAMS standpoint, it has been concluded that the relevant analyses for the current case-study are the Feared Event Analysis (FEA) and the Fault Tree Analysis (FTA) to assess the risk of collision during CPO. FEA has helped identifying feared events that could have an impact at mission level if nothing was done to alleviate them. It has been decomposed by phase and by subsystem. From these feared events, the FTA can be initialized. A methodology has been described in order to assess the risk of collision and verify the compliance to the Space Debris Mitigation requirements as well as Req. ALL-0100 [AD.1] for unintentional contact during CPO. The probability of collision has been computed between [4E-5;4E-4] for a one hour approach phase and depending on the SEE rate.

Finally, the use of the CPO event monitoring tool has been demonstrated on the Start-€ case study, including both the nominal trajectory as well as the results of the MC simulation.

4.2 Non-cooperative case study

ClearSpace-1 (CS-1) case demonstrates the definition of the requirements, the GNC solution and its validation for the capture of the VESPA payload adapter. The rendezvous phases are characterized by:

- Client Phasing: passively safe trajectories with ROEs, converging towards the client;
- Far Range Rendezvous: passively safe trajectories with ROEs, converging towards and naturally inspecting the client;
- Close Rendezvous: forced motion towards capture, with continuous monitoring of the approach corridor;
- Capture Phase and Stack Configuration Phase: capture of the client with the robotic arm and stabilization.

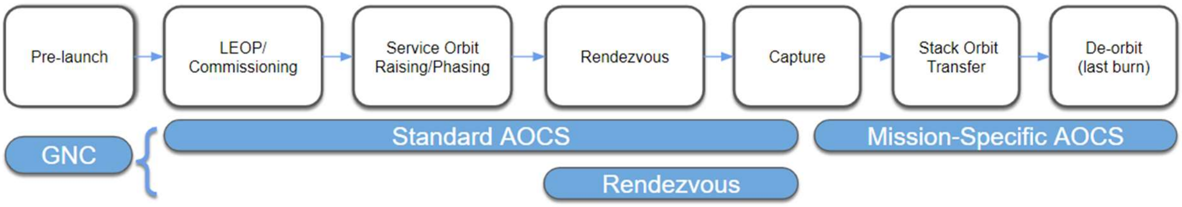

Figure 3: Phases of the ClearSpace-1 mission.

The requirements were defined and validated using approaches such as:

- Analysis tools for early assessment of the compliance with constraints:
  - Dedicated tool for controllability analysis of the rendezvous profile;
  - Mission analysis tools for illumination condition assessment.
- Control and Navigation solutions for non-cooperative scenarios:
  - Robust control to cope by design with uncertainties and disturbances, including actuation, navigation, and S/C non-idealities;
  - Navigation validated both with synthetic and optical test benches, taking the flexibility of the former, and the highest degree of realism of the latter;
- Guaranteeing overall mission safety:
  - Passively safe approach trajectory, using ROEs, to cope by design with safety during rendezvous, while also allowing for inspection;
  - Actively safe strategies, such as Abort and Cancel, to cope with collision avoidance during withdraw and passive safety of the subsequent drifting motion;
- Synergetic simulator analysis testing strategy:
  - Fast simulator for:
    - active safety (CAM) sizing and validation, extensively testing initial states;
    - strategic selection of worst-case conditions of Abort and Cancel;
  - High-fidelity simulator for detailed assessment of critical points of passively safe trajectories, of worst cases conditions of Abort and Cancel, and of capture approach performance;

The CS-1 case demonstrated that the guidelines are well posed and showed how to validate the requirements from the perspective of GNC, Mission Analysis and CONOPS.

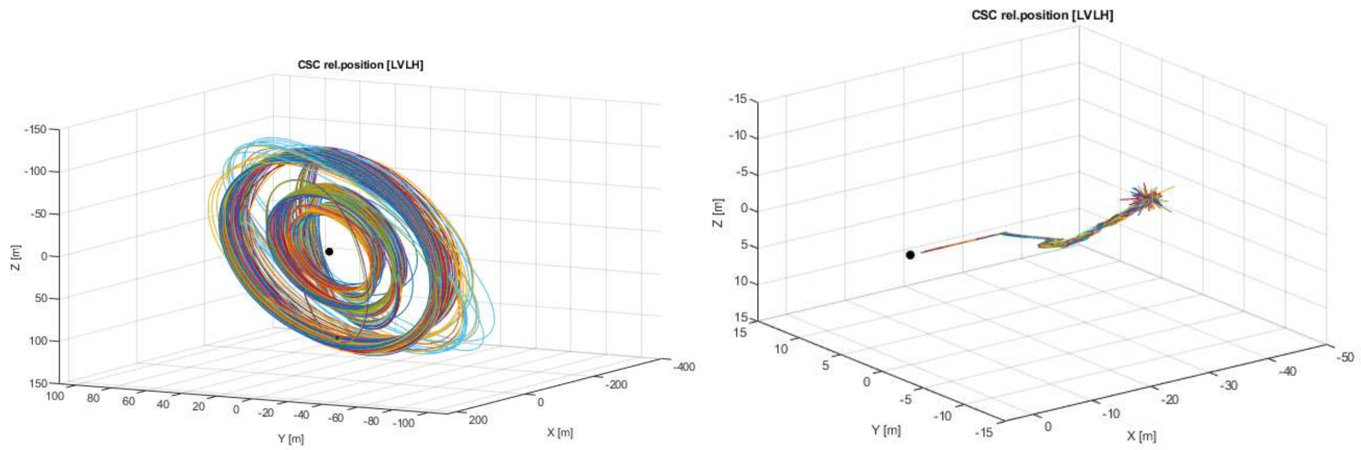

Figure 4: Rendezvous profile for Far Range [left] and Close Range [right]. The combination of fast and high-fidelity simulators assessed the properties of interest, such as flight envelope safety, proper zone transition, approach corridor compliance, passive and active safety of the approach, among others.