

ClearSpace-1 In-Orbit Demonstration Mission

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Abstract

The ClearSpace-1 mission, as one of the main activity area of the European Space Agency's Active Debris Removal and In-Orbit Servicing cornerstone, will develop a demonstration to rendezvous, capture, secure and deorbit a non-cooperative client spacecraft. The client will be the PROBA-1 spacecraft, operating flawlessly meanwhile for more than 20 years. The mission is developed as an in-orbit demonstration mission funded by the European Space Agency.

The mission is the very first rendezvous and capture of an unprepared and uncooperative client satellite having no mechanical fixtures. The mission is incrementally demonstrating the key capabilities and functions required. It will demonstrate the GNC technologies required to approach an object in low Earth orbit into close proximity, inspect and characterise it to prepare its safe catching, demonstrate the capability of the servicer to avoid collision with the space object, demonstrate the safe capture of the space object with the servicer spacecraft in synchronised motion, and demonstrate the capability to relocate a space object.

The ClearSpace-1 servicer will use a claw-based caging system to embrace the client spacecraft and to capture it without physical contact before secure closure of the cage. This method allows to secure the client object independently of its attitude, and for a range of tumbling rates. Several sensors will be required to allow vision-based relative navigation and distance measurement before and during the approach to the client object.

The mission is developed under budgetary constraints, while meeting the applicable requirements for space debris mitigation and re-entry safety as well as guidelines for safe close proximity operations. The ClearSpace-1 servicer spacecraft is developed as minimum viable product demonstrating the principal approach to the active removal of unprepared and uncooperative space objects required to secure the useability of low Earth orbits for future space missions.

Keywords: Space debris, active removal, relative navigation, cage, proximity operations, capture system, and motion synchronisation

Acronyms/Abbreviations

ADRIOS	Active Debris Removal / In-Orbit Servicing
AOCS	Attitude and Orbit Control System
AOS	Acquisition of Signal
CAM	Collision Avoidance Manoeuvre
COP	Critical Operation Phase
CS1	ClearSpace-1
CSY	Capture System
ESA	European Space Agency
FAP	Final Approach Point
FDIR	Failure Detection, Isolation & Recovery
FKP	Formation Keeping Point
GNC	Guidance, Navigation & Control
GNSS	Global Navigation Satellite System
GSN	Ground Station Network
HDRM	Hold Down & Release Mechanism
IFOT	Integrated Flight Operations Team
IOD	In-Orbit Demonstration
IPP	Initial Proximity Point
IROD	Initial Relative Orbit Determination

KSAT	Kongsberg Satellite Services
LEO	Low Earth Orbit
LTDN	Local Time of Descending Node
MTL	Mission Timeline
MOC	Mission Operations Centre
NAC	Narrow Angle Camera
PFOBC	Platform OBC
PFST	Platform Support Team
PLOBC	Payload OBC
PLST	Payload Support Team
PROBA-1	Project for On-Board Autonomy - 1
RAAN	Right Ascension of Ascending Node
RCT	Reaction Control Thrusters
RDV	Rendezvous
RF	Radio Frequency
RPO	Rendezvous & Proximity Operations
RSO	Resident Space Object
RSOP	Routine & Supervised Operations Phase
SSO	Sun-synchronous Orbit
TMTC	Telemetry & Telecommand
WAC	Wide Angle Camera

1. Introduction

The Active Debris Removal / In-Orbit Servicing (ADRIOS) main activity area of the Space Safety Programme, executed through the ClearSpace-1 mission, will perform a demonstration to de-orbit and remove an unprepared and non-cooperative space object currently in orbit. ClearSpace-1 (CS1) will put a servicer spacecraft in orbit where it will inspect the space object during fly-arounds and validate its critical technologies, before rendezvous and capturing of the space object. The servicer spacecraft will use a claw-based caging approach to capture the space object. After having secured the stack, the stack will lower its orbit and undergo uncontrolled re-entry within five years in compliance with re-entry safety requirements.

The CS1 mission is conducted with the objective to demonstrate the GNC technologies required to approach an object to be removed from low Earth orbit into close proximity, inspect and characterise a space object in LEO to prepare its safe catching, demonstrate the capability of the servicer to avoid collision with the space object to be removed, demonstrate the capability to synchronise the motion of the chaser spacecraft with the space object to be removed, demonstrate the safe capture of an uncooperative space object with the servicer spacecraft in synchronised motion, and demonstrate the capability to relocate a space object.

The ESA-owned Project for On-Board Autonomy – 1 (PROBA-1) satellite is selected as space object to be removed. The satellite has completed its mission and can be reached within reasonable efforts in its low Earth orbit. Up to now PROBA-1 is fully operational without showing any degradation of its performance and, thereby, giving the opportunity to recover from an unsuccessful capture attempt by controlling its attitude to prepare for the next capture attempt. The client attitude, however, will not be controlled during the proximity operations to simulate an uncooperative space object. Furthermore, the PROBA-1 structural design is robust and able to withstand the contact loads predicted for the CS1 capture system.

This paper will give insight into the status of the project, and will explain the mission concept of operations, alongside with a discussion of system-level design and operational aspects such as the approach to the inherently safe operations, degree of spacecraft autonomy and the operational management of unexpected space object characteristics. The principal elements of the mission are described in section 2, followed by a detailed description of the Concept of Operations in section 3 and its subsections, complemented by a discussion of the Safety aspects of the mission in section 4, spacecraft autonomy in section 5, and conclusions drawn in section 6.

2. Mission Elements

The CS1 system consists of the Space Segment, the Ground Segment, the Client Spacecraft Segment and the Launch Segment (Fig. 1). The Space Segment, i. e. servicer spacecraft, is made of the following elements:

- Payload developed by the ClearSpace company providing all functions required for visual-based relative navigation to the client space object, a distance measurement function and a Capture System to encompass and secure the client space object.
- Platform based on the OHB Sweden InnoSat components, and a custom structure based on a design available at the prime contractor, providing all the functions to support the payload in successfully performing the mission. The platform maintains an S-band link to the Ground Segment, which is the nominal link for all mission critical and housekeeping data.

The Ground Segment is provided by the prime contractor and contains:

- Kongsberg Satellite Services KSAT / KSAT Lite Ground Station Network (GSN)
- OHB / ClearSpace Mission Operations Centre (MOC)

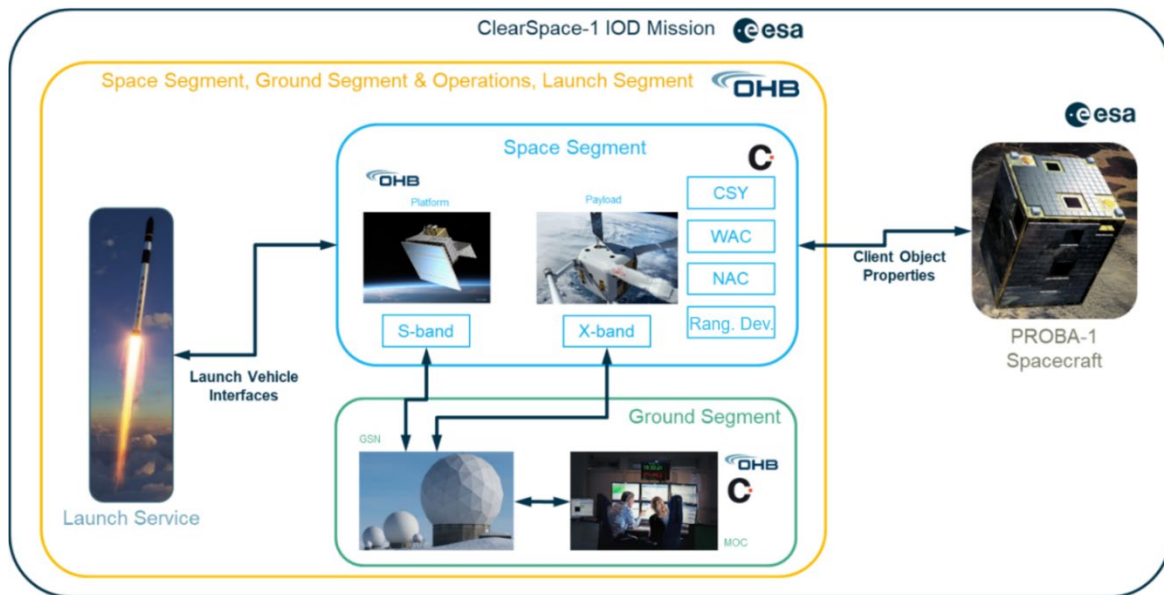


Fig. 1. ClearSpace-1 system overview

2.1 Space segment

Figure 2 provides an overview of the current CS1 servicer spacecraft design with the ClearSpace Capture System and its Capture Arms and Blocker Arms. An overview of the spacecraft design is given in Table 1. A detailed description of the spacecraft system design is presented in [1].

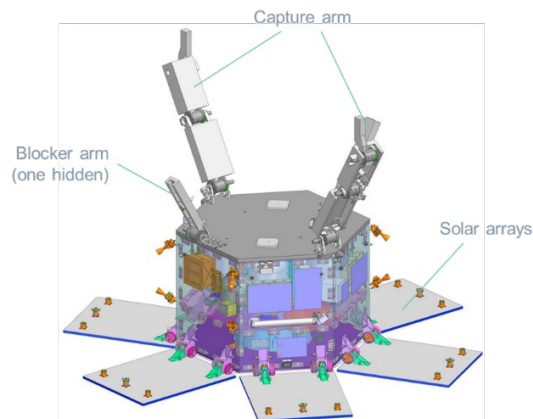


Fig. 2 CS1 servicer spacecraft with solar arrays and Capture System deployed

The space segment consists of the payload and the platform. The platform needs to be able to generate and distribute power, both to operate the payload and the platform itself. The platform performs the data handling of all platform units, but also between the platform and the payload. All housekeeping and mission critical data is downlinked via the platform's S-band communication system. All satellite uplink is performed via the S-band, as well. Next to the classical AOCS sensors, GNSS, sun sensor, gyro, star tracker, magnetometers, and actuators, reaction wheels and magneto torquers, it also features a six degree of freedom chemical propulsion system. In order to produce the high amount of power required by the payload and the difficult illumination conditions during the close proximity operations, the spacecraft has six solar panels attached to the bottom plate in a coronal configuration. To accommodate these panels both in stowed and deployed configuration, the spacecraft has a hexagonal base plate. The platform is responsible for planning and execution of all absolute attitude determination control and all orbital manoeuvres.

The payload provides all necessary functions for the visual-based relative navigation, the measurement of the distance to the client space object and the system to capture the client space object. The payload comprises the Payload OBC (PLOBC) running the payload GNC software and pose estimation algorithm, a Wide Angle Camera (WAC), a Narrow Angle Camera (NAC), a range measurement device, and a Media Camera. The ClearSpace Capture System (CSY) with its capture and blocker arms provides for the encompassing and securing the non-cooperative client object during the capturing. In addition, the payload has its own X-band communication system to establish a data downlink connection to the Ground Segment.

2.2 Ground segment and mission operations

CS1 operations will be performed by the industrial contractor team with OHB System, as the prime, providing the flight director and payload operations being performed by ClearSpace, while OHB Sweden will support platform operations and support the use of the RAMSES ground segment. This Integrated Flight Operations Team (IFOT) will operate from a common Mission Operations Centre (MOC) while both platform and payload aspects may be supported by independent user support centres. ESA will approve the entering into critical operational phases through GO decision points. ESA also supports the CS1 mission operations with its operations team, performing necessary telecommanding and monitoring of the PROBA-1 spacecraft as requested by the Contractor. As a minimum, PROBA-1 will be switched off before the rendezvous and capture operations. The overall organisation in mission operations is shown in Fig. 3. The distribution of tasks between the IFOT, the Platform Support Team (PFST) and the Payload Support Team (PLST) is provided in Fig. 4.

Requirements on Ground Station Coverage vary across the three main operational phases LEOP, Routine and Supervised Operations Phase (RSOP) and Critical Operation Phase (COP). Each of them leads to different coverage requirements in terms of Ground Station Pass duration, frequency and station redundancy. The KSAT GSN is currently baselined to provide the required tracking time which is especially demanding during critical operations where reliable and uninterrupted long duration passes are required for supervision and safety reasons.

An agreement with Starlink Services, LLC, will be fostered to ensure cooperation in case of a predicted conjunction with one of the Starlink satellites requiring a Collision Avoidance Manoeuvre (CAM) during Rendezvous and Proximity Operations (RPO).

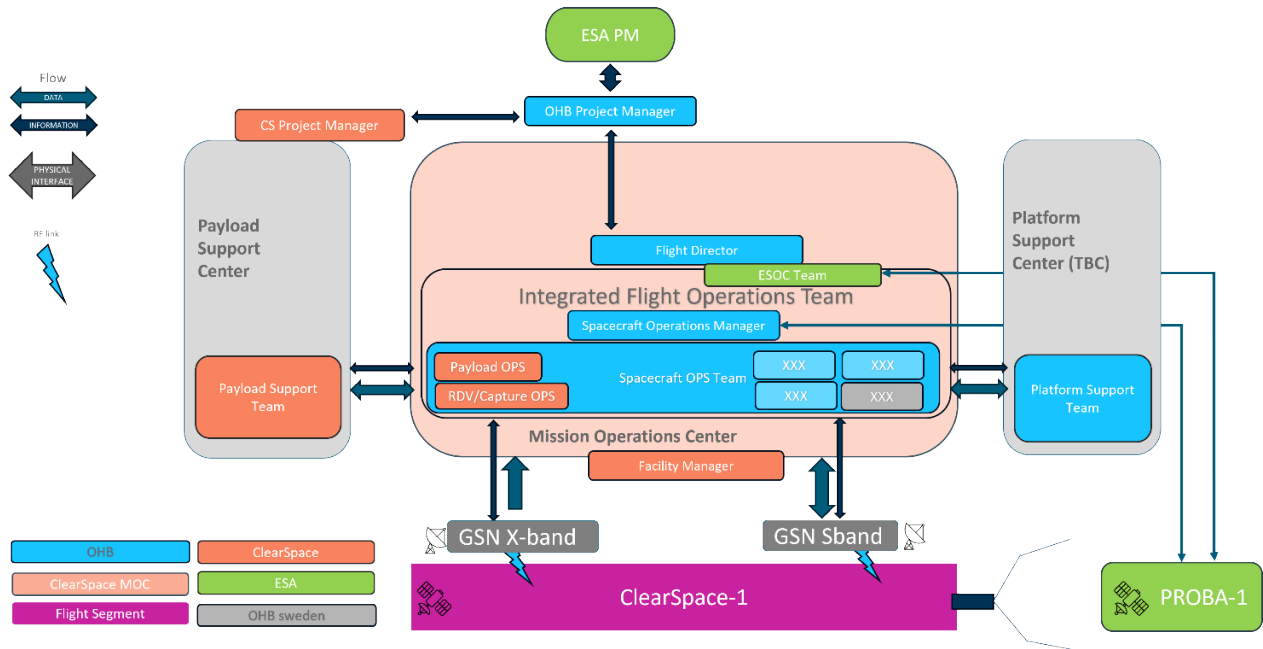


Fig. 3 CS1 mission operations overview

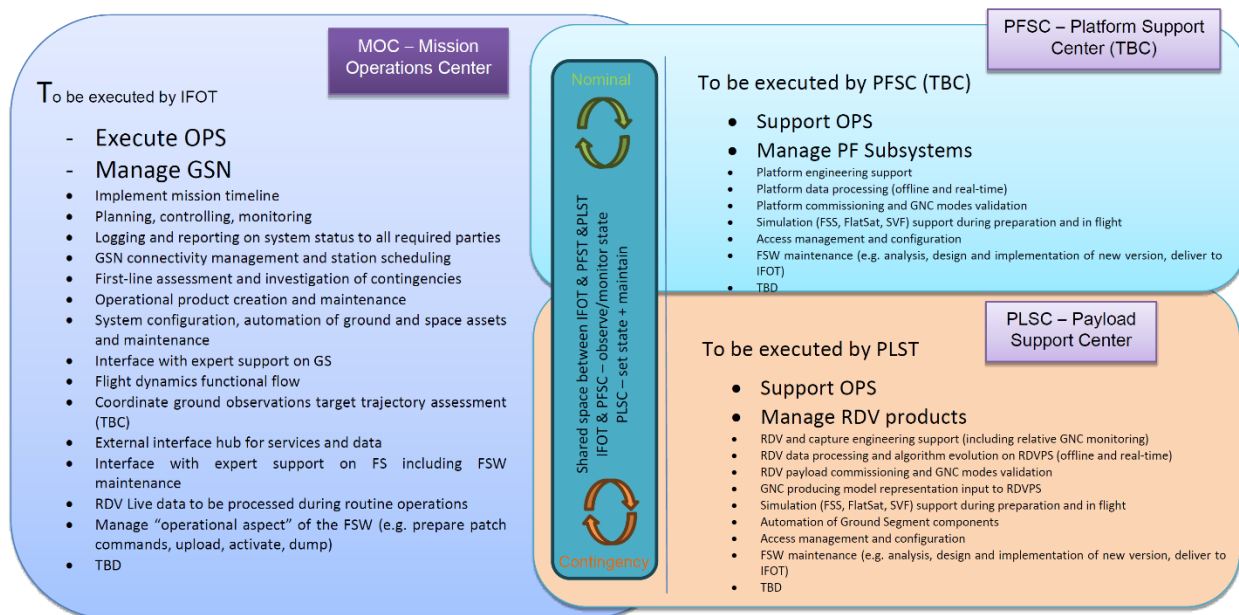


Fig. 4 CS1 operations team tasks

2.3 Client spacecraft

The ESA-owned PROBA-1 spacecraft is selected as client of the CS1 mission. PROBA-1 was developed by a consortium led by Verhaert Design and Development N. V. The spacecraft structure resembles a box with dimensions of 60 x 60 x 80.5 cm of conventional aluminium-based honeycomb design with body-mounted solar panels on five sides. The solar arrays are GaAs covered with borosilicate glass. The spacecraft total mass is 95.18 kg including the payload mass and the launch interface ring attached to the platform. The spacecraft design life is 2 years. PROBA-1 provides full on-board flight dynamics and orbital navigation computation, as well as automated onboard functions handling nominal spacecraft operations and control and resources management. The client spacecraft characteristics are summarised in Table 3, PROBA-1 itself is depicted in Fig. 5.

Table 2. PROBA-1 spacecraft design overview

Subsystem	Properties
Mission	Nominal operational orbit: 542 x 657 km LEO SSO, LTDN 10:30 Mission duration: 2 years Launch: 22 October 2001
Payload instruments	Compact High Resolution Imaging Spectrometer (CHRIS), Space Radiation Environment Monitoring (S-REM), DEbris In-orbit Evaluator (DEBIE)
Structure	Mass: 95.18 kg (including launch interface ring) Dimensions: 60 cm x 60 cm x 80.5 cm (excluding the launch interface ring)
Attitude Control System	Attitude control: 3-axis stabilized. Sensors: Dual head star tracker, 3-axis magnetometer, GNSS receiver Actuators: 4 magneto torquers, 4 reaction wheels
Power Control system	Solar panels: 5 body mounted GaAs panels; 90 W peak Battery: 36 Li-ion cells, 9Ah, 25 V, 1.9 kg Power conditioning system: 28V regulated power bus
Thermal Control System	Thermal control: Passive
TT&C	Interfaces: RS422, TTC-B-01 Uplink communications: Hot redundant S-band receivers Downlink communications: S-band transmitters Communications protocol standard: CCSDS
Avionics	Processor: ERC32 RISC processor Memory: 8 MByte RAM, 2 MByte FLASH
Software	Operating system: VxWorks, self-developed data handling software

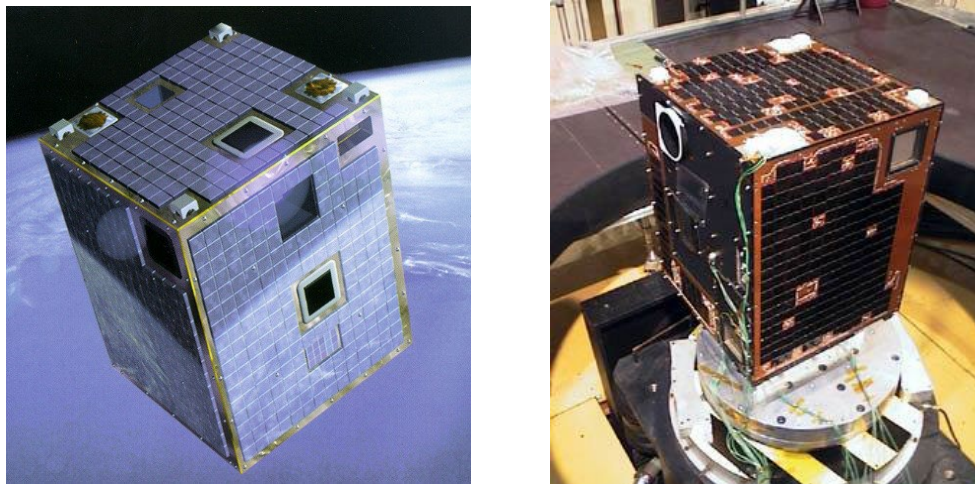


Fig. 5 PROBA-1 spacecraft

The CS1 servicer features a Capture System which is designed specifically for spacecraft of the size of PROBA-1. The static enclosure geometry provided by the two capture arms and two blocker arms matches the PROBA-1 geometry, taking into account the GNC accuracy. The expected contact forces stay below the force limit specified for PROBA-1. Until today PROBA-1 remains fully operational with attitude controlled. In order to simulate a non-cooperative space object, the PROBA-1 Attitude Control System will be switched off in preparation of the capture operations.

2.3 Launch segment

CS1 shall be directly injected into an orbit near the client space object by a dedicated single launch. This approach avoids the need for additional propellant and saves operation time required for phasing into the target orbit. Due to the budgetary constraints of the CS1 mission, a dedicated launch is only affordable with a microsatellite launcher, either one of the European microsatellite launchers currently in development, or with the already available Firefly Alpha from the United States. A rideshare launch with Vega-C would be feasible in principle, provided the launcher is launching by the time of need, and a direct injection in the correct orbit can be offered. This scenario does not seem to be likely now so that both launchers may only be considered in an opportunistic approach in case none of the prime and backup candidate solutions work.

Reflecting the upcoming microsatellite launch supply in Europe, assessing launch service proposals received, and considering the participation of ESA Member States in the project, the CS1 spacecraft is designed to be compatible with RFA ONE launched from Saxavord Spaceport, ISAR Spectrum launched from Andøya Space Center, and PLD Space MIURA 5 launched from Guyana Space Centre out of which the baseline launch vehicle will be selected. As a backup, the CS1 spacecraft shall be compatible with the Firefly Alpha launch vehicle from Vandenberg Space Launch Complex 2. The final selection of the launch service provider and associated launch vehicle is made at the preliminary design review.

The required injection orbit will not be accurately known until shortly before launch, as the orbit elements depend on the propagation of the client orbit, depending to a large extent on the solar activity in the next years. Best and worst-case orbital parameters as described in are taken into account when selecting the Launch Service Provider. To avoid a conjunction with the client spacecraft, a safety margin of 10 km is applied. Hence, the nominal injection orbit would be 10 km below the Client orbit. The preliminary mean orbital parameters at Launch epoch are summarised in Table 3.

Table 3. Client spacecraft mean orbital parameters at Launch epoch

Solar Activity Case	Max	Ave	Min
Semi-major axis [km]	6901.28	6912.49	6924.15
Eccentricity [-]	0.004976	0.005527	0.005834
Inclination [deg]	98.02	98.01	98.01
Right ascension of ascending node [deg]	41.22	37.19	32.29
Argument of periapsis [deg]	19.16	31.86	45.17
True Anomaly [deg]	217.81	279.31	101.57
Apogee altitude [km]	557.48	572.56	586.41
Perigee altitude [km]	488.80	496.15	505.62

3. Concept of Operations

The CS1 servicer will use a claw-based caging system to encompass the client spacecraft and to capture it without physical contact before secure closure of the cage. This method allows to secure the client independently of its attitude, and for a range of tumbling rates. Several sensors will be implemented to allow vision-based relative navigation and distance measurement before and during the approach to the client.

After separation from the launch vehicle upper stage and a short phasing for orbit change and correction, CS1 will inspect PROBA-1 during fly-arounds to validate its visual-based navigation algorithms and functionality of the Capture System, in preparation of rendezvousing with PROBA-1 and performing catching operations. Following catching, the servicer-client stack will need to be stabilised and secured. Finally, the servicer-client stack will lower its orbit and undergo uncontrolled re-entry within five years in a timeline as described in Fig. 6.

Note that for all following sections the launch date is assumed to be the 31 December 2028 based on the stated intent to launch the mission before end of 2028. All dates listed in the following are based on this launch date as a baseline.

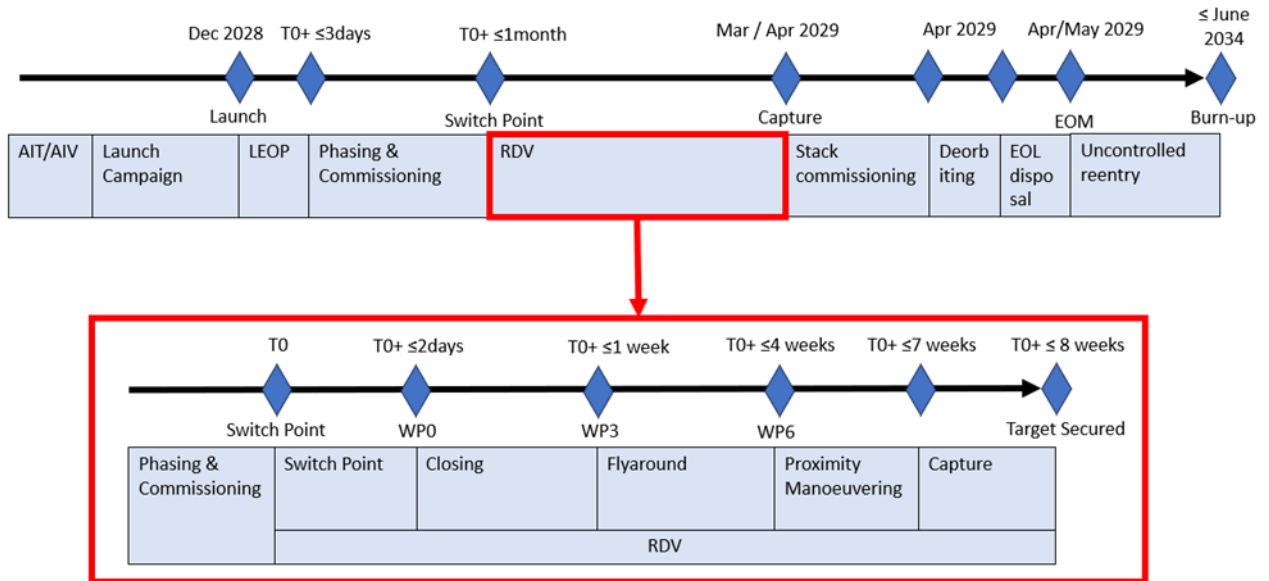


Fig. 6 ClearSpace-1 mission timeline

After launch and separation, the ClearSpace-1 spacecraft begins the LEOP phase, which will last at most 3 days. At the end of this phase the basic spacecraft functions are commissioned, including the AOCS. At this point, the servicer will enter the “Phasing & Commissioning” phase, during which the spacecraft will start approaching the client object position by performing a phasing manoeuvre. During this phase, which will last at most 30 days, the spacecraft will also conclude the commissioning of the platform and start the payload commissioning. At the end of this phase, the servicer will match the client object orbit at a distance of around 30 km from PROBA-1.

Subsequently, around end of January 2029, the servicer will enter the “RDV” phase, whose objective is the securing of the client object and the formation of a detumbled and power positive stack with the client. This phase will last at no longer than 8 weeks, and is divided in six more sub-phases, the “Switch Point”, “Closing”, “Flyaround”, “Proximity Manoeuvring”, and the “Capture”.

With the stack detumbled and power positive, it is possible to enter the next phase, “Stack Commissioning & Capture Images Downlink”, expected around end of March / early April 2029 in the current baseline. The stack will be commissioned to perform the final orbit lowering manoeuvre. Before that manoeuvre, the images of the close proximity operations and capturing obtained by the Media Camera will be sent to ground.

After around one week, the stack will be ready for the next phase, “Deorbiting”, during which, within 3 days the stack will lower its perigee altitude to 350 km. In addition, the apogee altitude is lowered below the Starlink shell to 530 km.

The final phase is “EOL disposal”, with the passivation of the spacecraft. This phase will last at most one day and conclude the mission. The date, at the current baseline, is around mid-April 2029. The stack is then left in its orbit and will re-enter within 5 years, concluding its life as intended.

3.1 LEOP, Phasing and Commissioning

The LEOP is expected to last 1 day, 3 days in non-nominal conditions. At the end of this phase the spacecraft will have absolute attitude, position and basic guidance capability, thermal control system, basic communications, Reaction Control Thrusters (RCT) commissioned, thus having the ability to perform a Collision Avoidance Manoeuvre (CAM) to avoid impact with the Residual Space Object (RSO). This status is expected to be achieved in January 2029.

The first objective of this phase is to correct the RAAN drift, performed with change in inclination or altitude to reverse or stop the drift of the servicer with respect to the client. This correction shall be performed as soon as possible, to prevent the manoeuvre becoming too expensive. Another task that must be performed as early as possible during the phase is the firing of the Hold-Down and Release Mechanism (HDRM) which secure the Capture System during launch. This has to be performed at latest 7 days after launch, to prevent cold welding between the snubbers and the arms of the Capture System.

At this point the phasing itself can begin. During this period, the spacecraft will perform an orbital change of the remaining RAAN, as well as the true anomaly. On top of the orbital parameters change, during phasing, the spacecraft

will complete the platform commissioning and start the payload commissioning. These tasks are carried out already in this phase in order to save time. Concerning payload commissioning, after the commissioning of the PLOBC and the X-band communication system, the CS-1 spacecraft is expected to cycle all the different configurations of the Capture System, to perform a function check of the RDV sensors and a loop of its use with ground. If possible, all GNC modes can also be tested during this phase.

After the required time has passed, the spacecraft is expected to perform an orbital manoeuvre to match the client object orbit. The arrival point is set to around 30 km from the client object in v -bar, where the Switch Point has been fixed. After reaching PROBA-1's orbit, it is possible to complete all commissioning task left, if the phasing was too short. It is also possible to execute the Initial Relative Orbit Determination (IROD), necessary for the RDV phase. At the end of the Phasing & Commissioning, the CS-1 spacecraft will have the platform fully commissioned, all the necessary payload functions and equipment, not relying on client's close proximity, commissioned, and the possibility to perform the switch from absolute navigation to relative navigation. Before moving to RDV phase a commissioning review can also be expected.

The Phasing & Commissioning will last at most one month. Based on the current baseline, the CS-1 spacecraft will reach the Switch Point, 30 km from PROBA-1, in February 2029.

3.2 Rendezvous Phase

The RDV is the core operational phase of this in orbit demonstration mission. Its main objective is to capture PROBA-1 and taking on a power positive configuration of the CS-1 / PROBA-1 stack, in order to be ready for moving to a lower orbit which is the objective of the next phases. The RDV is divided into six sub-phases and is expected to last at most 8 weeks. Each sub-phase is detailed below. During the RDV, a concept of passive safety is implemented based on proper separation of eccentricity and inclination vectors following [2].

3.2.1 Switch from absolute navigation to relative navigation

Line of sight observations provided by the NAC are used on ground for the initial relative orbit determination function while still in Normal Mode. Once the relative navigation filter is successfully initialised using the ground calculated IROD, transition to Relative Orbit Mode (Keplerian) is commanded. This phase starts with a GO/NOGO. After upload of the IROD parameters, algorithms are run on-board for relative orbit determination in closed loop. GNC parameters and sensors data are downlinked and processed on the ground for validation. This validation relies on servicer and client orbit determination from ground.

3.2.2 Closing to the client spacecraft

A gradual reduction of range to client object from 30km, in a passively safe relative orbit is performed. The range to client object is slowly reduced by controlling the relative semi-major axis of the formation in a spiralling approach consisting of a 3D elliptical motion with periodicity of one orbit. The diameter of the circular motion is gradually reduced throughout the approach (Fig. 5). The closing subphase is divided into multiple waypoints which also serve as validation checkpoints. Along the way, the servicer will switch from velocity pointing to target pointing to ensure that the client object remains in the sensor's field of view. At each waypoint, GNC performances and system health and status are checked. When downlinking data for rendezvous sensors commissioning purposes, the ground station pointing will result in RDV measurement data gaps to the GNC. Similarly, during eclipse there will be RDV optical sensors measurement gaps. Ending with a 3D relative motion around the client object with a range of minimum 100 meters. The servicer is constantly target pointed. System health is under frequent live check and offline assessment. This phase starts with a GO/NOGO command to be given by the MOC.

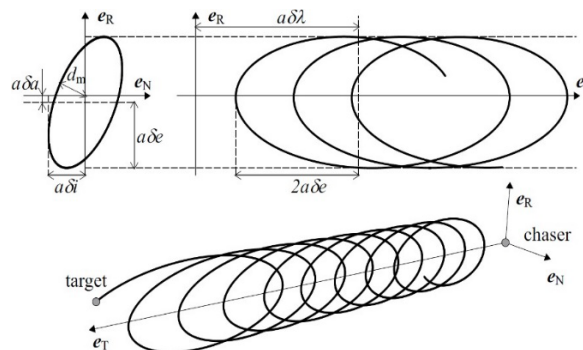


Fig. 5 Passively safe rendezvous parameterized with relative orbital elements

At the last waypoint, the ranging device is used to improve navigation providing a window of validity in which the 3D relative navigation is commissioned. The remaining part of sensors commissioning that were not available prior to this point are performed. In visibility of ground, the GNC mode transition is commanded for 3D navigation to be used to maintain final waypoint.

3.2.3 Fly around

Multiple waypoints centred on the client object at gradually decreasing ranges will be passed until the working range of each sensor is reached. While doing this, the sensors will be characterised regarding noise, working range, and behaviour with varying illuminations conditions, and verified for use. Collected data will also be used to visually assess the status of the client object. Collected data on ground will be used to cover the client object inspection and characterisation objective. The phase will also include testing Failure Detection, Isolation and Recovery (FDIR) functions accounting for the mid/close-range navigations and controls. The anticipated profiles in Fly Around Phase will allow for data collection in varying illumination and background conditions.

At the end of Fly Around Phase, Payload Operations and Support Teams start commissioning of 6D navigation. Since the elliptical trajectories encountered during Fly Around are not fully representative of the trajectory followed during capture, the full commissioning of the close-range navigation will be first achieved during the subsequent Proximity Manoeuvring phase.

3.2.4 Proximity Manoeuvring

Contains final commissioning steps of close proximity GNC based on offline verification by Payload Operations and Support Teams. Followed by Forced Motion trajectories in the client object reference frame. The relative orbit is no longer passively safe. Multiple excursions are planned from the Formation Keeping Point. Proximity manoeuvring slots require station keeping and software initialisation at about 10 m range from the client. A certain minimum range is adhered to, monitored by FDIR and passively safe orbit reached upon breaching this threshold through client CAM. Conditions apply, such as strict sun-client-servicer angles and Earth not visible in the background. The close-range navigation cannot be maintained in eclipse.

Proximity manoeuvres contain slots that cover close range navigation commissioning and capture rehearsals. Rehearsals will be planned for capture with and without motion synchronisation. The Proximity Slots are composed of complex operations requiring a high level of preparation and planning. These preparatory activities are done while the formation is autonomously maintained at the Formation Keeping Point (FKP). These activities include the configuration of the capture system, a Proximity Slot timeline compilation and uplink. A nominal mission timeline, including close proximity operations is uplinked to a disabled sub-schedule as well as a mission timeline containing a return to FKP instead. The latter is the default active timeline. All forced motion manoeuvres are calculated onboard according to the defined profile.

Once the software initialisation is successful, the relative navigation is autonomously switched to close-range precise navigation based on pose estimation. A GO command needs to be received from the Integrated Flight Operations Team enabling execution of the nominally planned mission timeline. If not received, the mission timeline executes the return to FKP. The Proximity Slot nominally ends when servicer and client enter eclipse when an impulsive hop back manoeuvre is executed from the mission timeline. Upon eclipse exit, the FKP is re-acquired and the formation keeping is activated.

In the orbits following each proximity manoeuvre slot, RDV data is downlinked through X-band and used for further commissioning and planning of future slots. During all operations, the baseline close-range navigation is used to monitor safety and trigger client CAM when required.

3.2.5 Capture

After having completed all rehearsals during approximately three weeks, the CS-1 servicer will position itself again on the FKP and will be ready to start the “Capture” subphase. The Capture System allows to capture PROBA-I from two sides along the client spacecraft’s longitudinal axis, either from the side with the launcher adapter ring, or from the opposite direction. This allows for relatively high flexibility in terms of illumination conditions. From the FKP the spacecraft will once again go to about 10 m distance from the client, perform software initialisation and path planning, and downlink the results. After receiving GO from ground, the servicer approaches the client object, with the motion synchronisation strategy, if required due to client motion, following a constrained path defined between the Initial Proximity Point (IPP) and the Final Approach Point (Fig. 6). This time however the spacecraft will go all the way through triggering the Capture System sensors, completing the enclosure of PROBA-1 and securing it. This sub-phase

will last at most 2 full days including all the preparation work on ground and is the most critical part of the entire mission.

Near-real-time TM is available through S-band during approach from IPP, capture and during the start of detumbling. A thorough system check is done during and after the next ground station pass based on deferred/stored TM downlink with higher rate acquisitions where needed, and a continuous TM history. Next to near-real-time TM, it will be possible to download low resolution images from the capture sensors or media camera at very low rates during this phase.

Ground intervention during capture until point of no return are possible, but not considered to add any safety, as onboard FDIR take care of intervention until point of no return. The autonomous functions are robust to the uncertainties on moment and inertia and centre of gravity of the combined stack after capture without the need of any ground activities.

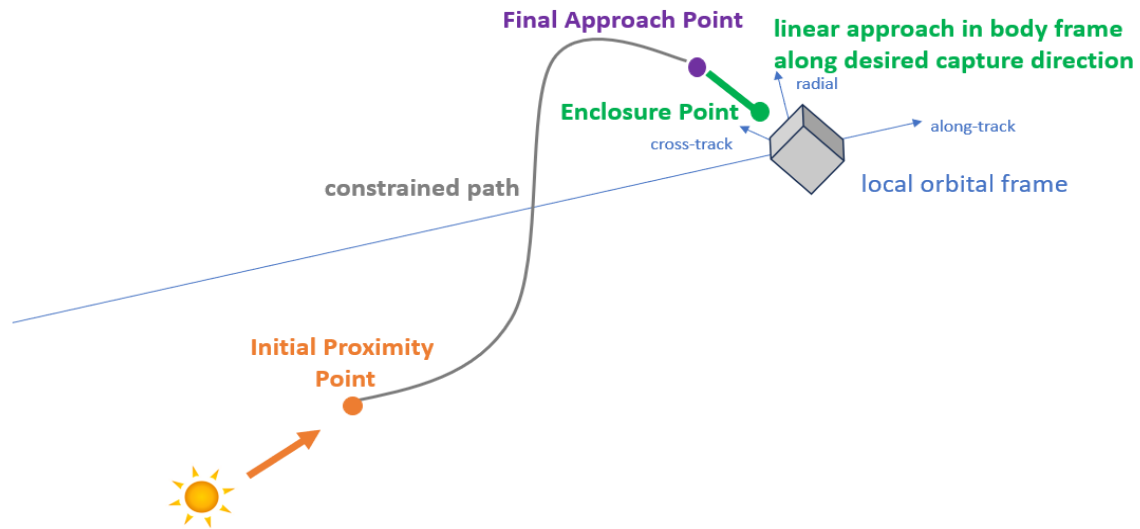


Fig. 6 Nontrivial motion synchronisation trajectory

The “Capture” sub-phase is followed by the sixth and final sub-phase, “Detumbling / Sun Pointing”, during which in at most half a day the stack will be detumbled and assume a power positive attitude. This will conclude the RDV phase, for a total duration of at most 8 weeks.

3.2.6 Stack commissioning, deorbiting and disposal

With a power positive attitude, the stack will be able to finalise its commissioning, in particular concerning the thrusters with the new mass, moments of inertia and centre of gravity (MCI). During this phase the servicer will also send the images to ground which were captured by the Media Camera during the RDV phase. This phase will last no longer than 1 week. With the thruster control fully commissioned with the new MCI, the stack will be able to perform the orbital manoeuvre required to lower the perigee orbit to 350 km. The overall duration of this Deorbit phase is not expected to exceed 3 days. The final phase of the mission consists in the full passivation of the CS1 spacecraft. This means, in particular, the passivation of the propulsion subsystem, of the battery and the reaction wheels. This should not take more than one day and effectively concludes the ADRIOS ClearSpace-1 mission. Given the new orbit of the stack, the two satellites are expected to re-enter and burn up in the atmosphere within a 5-year timeframe required.

4. Safety of mission operations

The Space Debris Mitigation requirements and Safety requirements are applicable in full and without modification [3-7]. The project will also implement the available guidelines for safe proximity operations and verification of the Space Debris Mitigation requirements [8-9].

The ClearSpace-1 mission is conducted in the LEO protected environment [10]. Within this region the creation of space debris is defined a critical event, requiring an adequate spacecraft and mission design as specified in [3]. In particular, the servicer spacecraft is expected to ensure a probability of unintentional contact of 10^{-4} until the initiation of the capturing.

However, the criticality of feared events in the CS1 mission is driven by eventual impacts on the re-entry casualty risk and expectation of an uncontrolled re-entry of the servicer spacecraft or the servicer/client stack. For the CS1

mission “catastrophic” events as in [3] are feared events with impact on safety on population at re-entry or on crewed vehicles through a collision. The Servicer spacecraft standalone and the Servicer / Client stack will be designed for an uncontrolled re-entry. Therefore, the predicted casualty risk for re-entry shall be below 10^{-4} , and any exceedance of this limit understood as “catastrophic” consequence. In missions like ClearSpace-1, in which the servicer spacecraft requires a significant amount of propellant and in which the re-entering mass is also driven by the client spacecraft as part of the stack, the compliance with casualty risk requirement is a particular challenge when aiming for an uncontrolled re-entry. The risk of collision with crewed vehicles, on the other hand, is deemed very low.

The mission and system design will control the “critical” event of space debris generation by specific measures:

- Intrinsically safe approach trajectories are selected during far and mid-range operations making use of eccentricity-inclination separation between Servicer and Client spacecrafts.
- A collision with the Client spacecraft will be protected against by CAM manoeuvre function. The CAM manoeuvre function is provided with one-fault tolerance, making use of the specific CS1 system architecture.

One crucial aspect of the CS1 mission is the RSO CAM. By requirement, this task needs to be single failure tolerant and, thus, requires a redundancy in the computing hardware which executes this CAM. Both the PLOBC and the PFOBC are non-redundant. Therefore, these two computers provide the redundancy for each other and are both able to execute a CAM.

Instead of the CAM also a retreat may be used as a recovery option. This is because a CAM is a very impactful action which will break the formation and will require re-approaching the client, consuming substantial amount of delta-v, i. e. 10% of the total mission delta-v.

By design the CAM is followed by a safe mode, under platform authority. Safe Mode aims at keeping a power- and thermal-safe sun-pointing attitude, using reaction wheels and magneto torquers to control the spacecraft. Thrusters are not actuated to not increase risks of collision and evaporation. The authority to resume the RDV is only handed back to the payload once the failure has successfully resolved by a decision from ground. During recovery the IFOT will work together to resolve the issue together identifying the cause and developing solutions to resolve the problem and resume the mission timeline. The relative position of the chaser relative to the client depends on the duration it takes to regain control and recover the spacecraft to nominal mode. Once the RDV phase is re-started, the spacecraft will need to again perform all the required phases.

5. Spacecraft autonomy

Due to the design to cost approach the ClearSpace-1 mission shall employ autonomy as much as possible in order to decrease cost of operations while also decreasing risk. Operator supervision is introduced where activities are complex, hard to predict or never done before. Autonomy will be applied to different parts of the spacecraft operations, (1) autonomous mode transitions, (2) FDIR, and (3) assisted autonomy during rendezvous. Autonomous mode transitions are available from launch until end of life. The spacecraft launches being switched off. After detection of separation after launch, the spacecraft autonomously transitions into Spacecraft Initialization Mode and performs the auto-sequence after separation. This initial transition including the execution of the auto-sequence is only performed once after detection of separation. If during the mission the spacecraft enters Survival Mode, it will continuously try to regain three-axis attitude knowledge and, if successful, subsequently autonomously transition into Safe Mode. This autonomous transition is active from separation until end of life.

The implemented FDIR function is available after separation until end of life. FDIR autonomously tries to recover a failure based on a hierarchical approach going from unit to sub-system, to system level. Failures that cannot be recovered on lower-level lead to an FDIR-triggered transition to Safe Mode. In case the spacecraft cannot estimate its current inertial attitude, FDIR triggers a transition to Survival Mode.

Autonomy on board is paramount for RPO and capture. In a demonstration mission, processes are supported and monitored from ground where required. The processing of IROD is a function executed by ground at the switch point from absolute to relative navigation, enabling an autonomous angles only navigation once initiated. All RDV phases provide the same profile of ground-supported onboard autonomy:

- System status, including onboard recording of deferred TM, data gathering and assessment
- Servicer and client position determination and propagation
- GSN booking and communications planning
- MTL gather / collection / validation / ready based on timelines and procedure
- Uplink of MTL
- System readiness check and go ahead
- Monitor autonomous process, intervene if flight rule dictates it
- Repeat System status, etc.

The MTL loaded onboard is the default status of the autonomous system. In Capture phase for example the default is that the servicer will return autonomously to FKP in case the go-ahead command from ground for capture is not received at IPP. The Ground command only enables that part of the MTL that activates the autonomous control loops for GNC and priming Capture System for proximity sensor triggering. During angles only navigation in closing phase, the impulsive manoeuvres are also autonomously determined onboard.

6. Conclusions

Following the successful implementation of the CS1 project, important technologies will be proven and ready to be used to implement more efficiently a policy aimed at reducing the harmful effects of space debris. This could also open new and promising market opportunities to industry, not only through the association of industrial entities to the successful implementation of the CS1 mission but also, in the future, in the framework of other missions dedicated to servicing satellites in, or debris removal from, outer space to be conducted on behalf of clients from the public or private sector.

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