THE REMOVEDEBRIS ADR MISSION: PREPARING FOR AN INTERNATIONAL SPACE STATION LAUNCH

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ABSTRACT

Since the beginning of the space era, a significant amount of debris has progressively been generated in space. Active Debris Removal (ADR) missions have been suggested as a way of limiting and controlling future growth in orbital space debris by actively sending up vehicles to remove debris. The EC FP7 RemoveDebris mission, which started in 2013, draws on the expertise of some of Europe's most prominent space institutions in order to demonstrate key ADR technologies in a low-cost ambitious manner.

The RemoveDebris mission launches to the International Space Station (ISS) in late 2017 where shortly after it will be deployed via the NanoRacks Kaber system into an orbit of around 400 km. The mission will perform its core demonstrations sequentially, utilising two CubeSats as artificial debris targets: net capture, harpoon capture, vision-based navigation, dragsail de-orbiting. The mission comes to an end in 2018 with all space entities having naturally de-orbited.

This paper is split into the following parts: (a) an overview of the mission segments, (b) a discussion on launch procedures, (c) an overview of the operations sequence and demonstration timelines. The second section will focus on the specifics of the launch via NanoRacks and respective the NASA safety reviews. The third section will outline the planned operational timelines for the payloads. There will be a focus on what demonstrations will be performed and what types of data will be collected.

The RemoveDebris mission aims to be one of the world's first in-orbit demonstrations of key technologies for active debris removal and is a vital prerequisite to achieving the ultimate goal of a cleaner Earth orbital environment.

Keywords: debris removal; ADR; deorbiting; net; harpoon; vision-based navigation; dragsail.

1. INTRODUCTION

RemoveDebris is a low cost mission performing key active debris removal (ADR) technology demonstrations including the use of a net, a harpoon, vision-based navigation (VBN) and a dragsail in a realistic space operational environment, due for launch in 2017. For the purposes of the mission CubeSats are ejected then used as targets instead of real space debris, which is an important step towards a fully operational ADR mission. This paper examines the mission launch specifics and starts reviewing the operations timeline of the mission and the methodology in which the in-orbit demonstrations will be performed.

The project consortium partners with their responsibilities are given in Table 1.

1.1. Literature

One of the most active in the field of debris removal is the European Space Agency (ESA). ESA has produced a range of CleanSpace roadmaps, two of which focus on (a) space debris mitigation and (b) technologies for space debris remediation. A main part of these roadmaps is e.Deorbit, a programme spanning a host of phase studies examining removing a

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Table 1. ***RemoveDebris Consortium Partners****.* [†]*vision-based navigation*

Partner	Responsibility
SSC (Surrey Space Centre)	Project management, CubeSats, dragsail, harpoon target assembly
Airbus DS Germany	Net
Airbus DS France	Mission and systems technical lead, VBN[†]
Airbus DS UK	Harpoon
SSTL	Platform technical lead, operations
ISIS (Innovative Solutions in Space)	CubeSat deployers
CSEM	LiDAR camera
Inria	VBN algorithms
Stellenbosch University	CubeSat avionics

large ESA-owned object from space [4, 16]. This initiative started with ESA's service orientated ADR (SOADR) Phase 0 study involving the analysis of a mission that could remove very heavy debris from orbit examining both the technical challenges and the business aspects of multiple ADR missions [28, 29]. Progressing on, ESA has also now completed Phase A and Phase B1 studies [11, 30], with now several more mature designs now available. ESA's Satellite Servicing Building Blocks (SSBB) study originally examined remote maintenance of geostationary telecommunications satellites using a robotic arm [8]. The French space agency, CNES, is also widely involved in debris removal and has funded studies such as OTV which traded-off different ADR mission scenarios [25].

Regarding the development of capture technologies, there are several on-going efforts. Airbus DS capture designs include the robotic arm, net [2], and harpoon demonstrators for use in space [24]. The net, in particular, is considered by some studies to be the most robust method for debris removal, requiring the least knowledge about the target object [28]. The First European System for Active Debris Removal with Nets (ADR1EN) is testing net technologies on the ground with the aim of commercialising later on. A host of other capture technologies have also been proposed including: ion-beam shepherd [19], gecko adhesives and polyurethane foam [22, 9]. Aviospace have been involved with some ADR studies such as the Capture and De-orbiting Technologies (CADET) study which is examining attitude estimation and non-cooperative approach using a visual and infrared system [6] and the Heavy Active Debris Removal (HADR) study that examined trade-offs for different ADR technologies, especially including flexible link capture systems [3].

Although recently there have been advances in relative space navigation, the complex application of fully uncooperative rendezvous for debris removal has not yet been attempted. Vision-based relative navigation (VBN) systems, which would be necessary for future debris removal missions are currently being developed and will be demonstrated on RemoveDebris [23, 5, 33]. Other recent research specifically related to VBN for debris removal includes: TU Dresden [31], Thales [10], Jena-Optronik [17].

A range of de-orbitation technologies have been proposed previously but few have had in-flight testing. Research includes: dragsails (InflateSail, DeOrbitSail) [14], TeSeR (which proposes an independent modular deorbitation module that attaches to the satellite before launch) [32], BETS - propellantless deorbiting of space debris by bare electrodynamic tethers (which proposes a tether-based removal system), solid rocket de-orbitation (proposed D-ORBIT D-SAT mission) [1].

Regarding rendezvous in space, the Autonomous Transfer Vehicle (ATV) was one of the first times a spacecraft initiated and commenced a docking manoeuvre in space in a fully autonomous mode [27]. The Engineering Test Satellite VII 'KIKU-7' (ETS-VII) by JAXA in 1997 was one of the first missions to demonstrate robotic rendezvous using chaser and target satellites [34]. The AoLong-1 (ADRV) 'Roaming Dragon' satellite was also recently launched by CNSA (China National Space Administration) in 2016 in order to test target capture with a robotic arm; results are presently not available. Most recently JAXA's HTV-6 vehicle, which launched in early 2017, unsuccessfully attempted to deploy an electrodynamic tether under the Kounotori Integrated Tether Experiment (KITE) [7].

Upcoming missions to tackle debris removal include CleanSpace One by EPFL, which aims to use microsatellites with a grabber to demonstrate capture [26, 15]. The mission is still under design and launch is not foreseen for a few years. As mentioned previously, ESA's e.Deorbit will likely result in a large scale mission and is currently proposed for 2023. Of interest is AstroScale, a company based in Singapore, aiming to launch a mission with thousands of 'impact sensors' to build up knowledge of the magnitude of small fragments [21].

2. MISSION OVERVIEW

The mission timing can be seen in Figure 2. The four core events are launch preparation, launch to the ISS, ejection from the ISS and mission demonstrations. For further details about the concept and architecture of the mission refer to [12, 13].

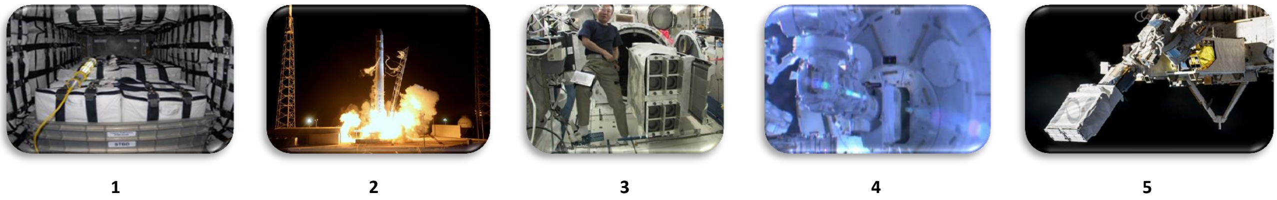

Fig. 1. ***Launch Sequence.*** *This figure shows the launch sequences for the mission to the International Space Station (ISS). Courtesy: SpaceX, NanoRacks, NASA [20].*

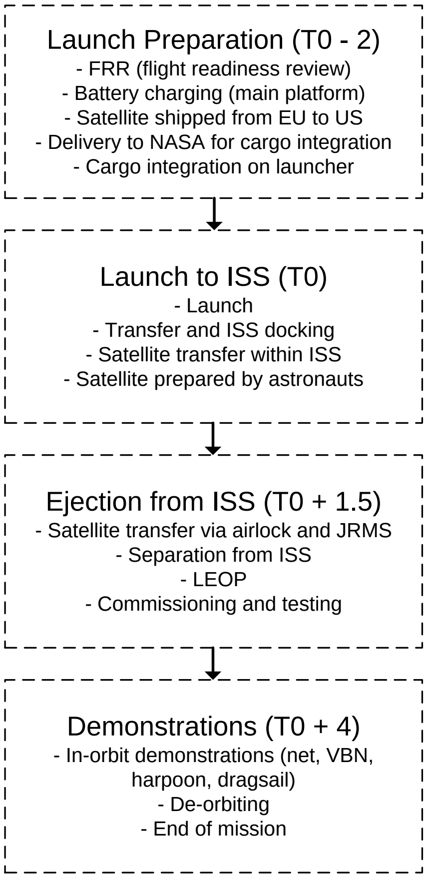

Fig. 2. ***High Level Mission Timing.*** *High level timing on the mission where times are in months and relative to the launch to the ISS (T0).*

2.1. Mission Segments

Figure 3 shows the mission space segment for the proposed launch. Operations for the RemoveDebris mission will be carried out from SSTL's Mission Operations Centre in Guildford. SSTL's standard operations procedures will be used, which are compatible with the SSTL designed platform operational requirements and characteristics. The primary communications dish is at Guildford, with a backup at Bordon; communications are at s-band level.

3. LAUNCH

The launch sequence for the RemoveDebris mission is an unconventional one. The solution uses NanoRacks as a supply agent to launch the final flight platform to the International Space Station (ISS) abroad a SpaceX cargo or Orbital ATK's Cygnus rocket. The mass of the platform, 100 kg, represents a new business line, in that past NanoRacks launches of systems from the ISS were of a much lower mass. The launch is expected to be in late 2017, but the launch manifest and weather disruptions will dictate the final launch date.

The use of the ISS scenario, launching to approximately 380 km, provides greater confidence to licensing agencies as to the mission safety, as if there were any issues, all the items would de-orbit very quickly. [12] and [18] give more information about the orbital lifetime of the objects calculated using both STELA and DRAMA, specialist end-of-life tools. They show that the main platform de-orbits within 2 years, even in case of the dragsail not deploying; smaller items, such as the CubeSats, de-orbit within a matter of months. Thus no further space debris is generated.

3.1. Launch Sequence

The launch sequence can be seen in Figure 1. Before launch (1), the platform is packaged into a crew or cargo transfer bag (CTB) inside a foam 'clam shell' which protects it. After the bag is launched to the ISS (2), the bag is unpacked by astronauts that install the platform on to the Japanese experiment module (JEM) air lock (3). The air lock then depresses and the slide table extends. The platform is grappled by the JRMS, a robotic arm system (4). Finally, the robotic arm positions and releases the platform into space (5), where commissioning and main operations of the mission can commence. Naturally, the ejection trajectory ensures that the satellite will not intersect the ISS orbit at a later time.

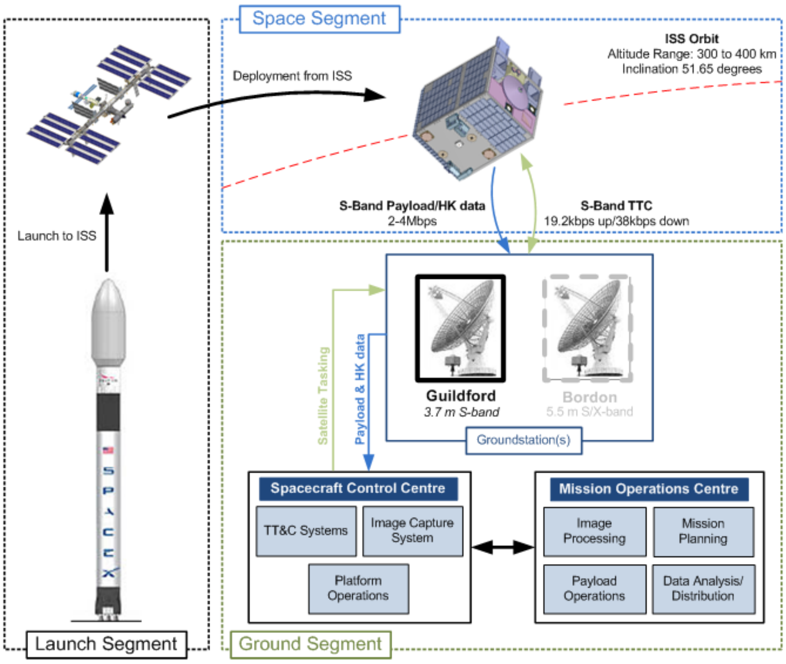

Fig. 3. ***Overview of Mission Segments.*** *This figure shows the three mission segments: launch, space, ground. From [12].*

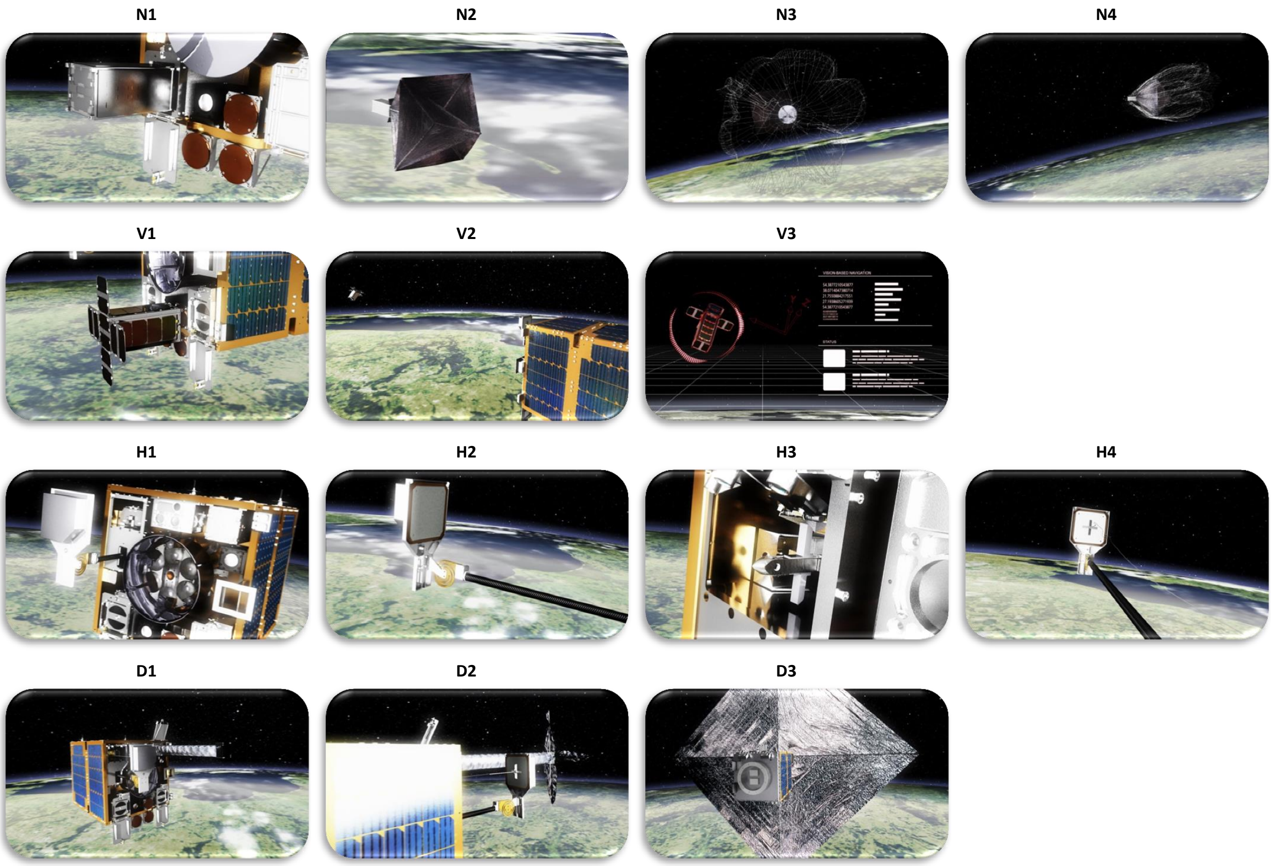

Fig. 4. ***Demonstration Sequence.*** *This figure shows the demonstration sequences for the net (N1 to N4), VBN (V1 to V3), harpoon (H1 to H4) and dragsail (D1 to D3).*

4. IN-ORBIT DEMONSTRATIONS (IOD)

4.1. Overview of Demonstrations

The four core mission demonstrations are shown in Figure 4. The net sequence is: (N1) DS-1 CubeSat ejection, (N2) inflatable structure inflation, (N3) net firing, (N4) net capture. The VBN sequence is: (V1) DS-2 CubeSat ejection, (V2) DS-2 drifts away, (V3) VBN system collects data. The harpoon sequence is: (H1) harpoon target plate extended, (H2) target plate reaches end, (H3) harpoon firing, (H4) harpoon capture. The dragsail sequence is: (D1) inflatable mast deploys, (D2) sail starts deployment, (D3) sail finishes deployment.

4.2. Net Demonstration

The proposed net demonstration sequence can be seen in Figure 5. The demonstration starts with checking the platform is ready to start the demonstration, and charging and turning on relevant platform services. Although the VBN demonstration comes after the net demonstration, the VBN requires calibration during the net demonstration and thus the full VBN image capture, transfer and download chain is performed to ensure the VBN is ready. The PIU (payload interface unit) on the platform is used to collect and process payload data. Part of the initial checks are that the supervision cameras have clear images - incorrect platform attitudes or poor lighting conditions (location in orbit) could mean images are obscured or too light or dark. There is therefore an opportunity to correct these before the demonstration begins.

On starting the main experiment the 3 platform supervision cameras activate and record the entire demonstration. At T0, the ISIPOD door opens releasing and translating the CubeSat into a locked position outside the ISIPOD. A timer cuts the CRS (CubeSat Release System) and the CubeSat is released. Shortly after, the DS-1 inflatable (via the CGGs) is inflated (Fig 4-N2), and the net is ejected to capture DS-1 (Fig 4-N3). The experiment closes with collection and download to Earth of the VBN and supervision cameras data. The net and DS-1 naturally de-orbit at a rapid rate due to the low altitude.

The main data collected in this experiment is the video of the experiment (from 3 sources). Various telemetry can also be acquired from the platform and the initial VBN experiment provides additional data sources.

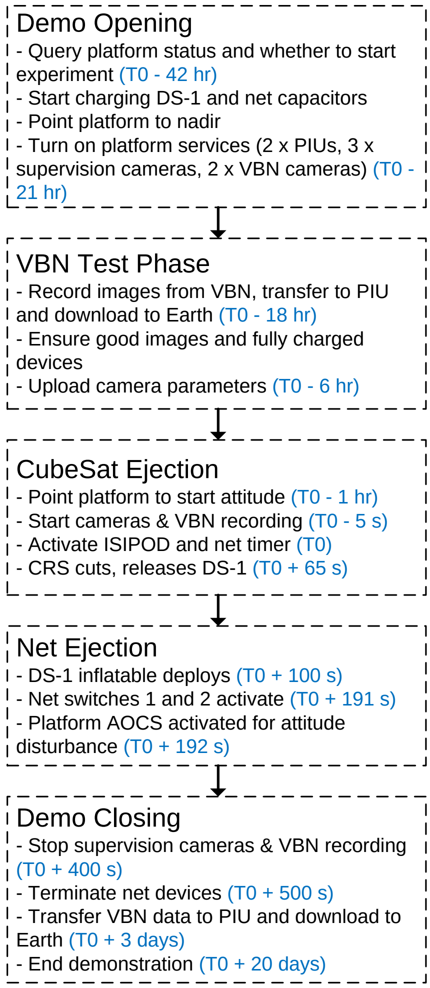

Fig. 5. ***Net Operations Sequence.*** *Relative to T0, ISIPOD activation (and start of CubeSat translation). Sequence is a simplification of the full sequence and is subject to change.*

4.3. VBN Demonstration

The proposed VBN demonstration sequence can be seen in Figure 6. The demonstration starts with checking the platform is ready to start the demonstration, and charging and turning on relevant platform services. For clarity, there are 3 supervision cameras on the platform and 2 VBN cameras (3d, 2d) but in the VBN demonstration only 2 of the supervision cameras are used. Similar to the net demonstration, the VBN requires a calibration and test phase where the full VBN image capture, transfer and download chain is tested.

At T0, the ISIPOD door opens releasing and translating the CubeSat into a locked position outside the ISIPOD. Different to the net demonstration, DS-2 is given time here to flip open the solar panels, start its on-board services, acquire a GPS lock and initiate the inter-satellite link between DS-2 and the platform (ISL) (Fig 4-V1). The VBN cameras start

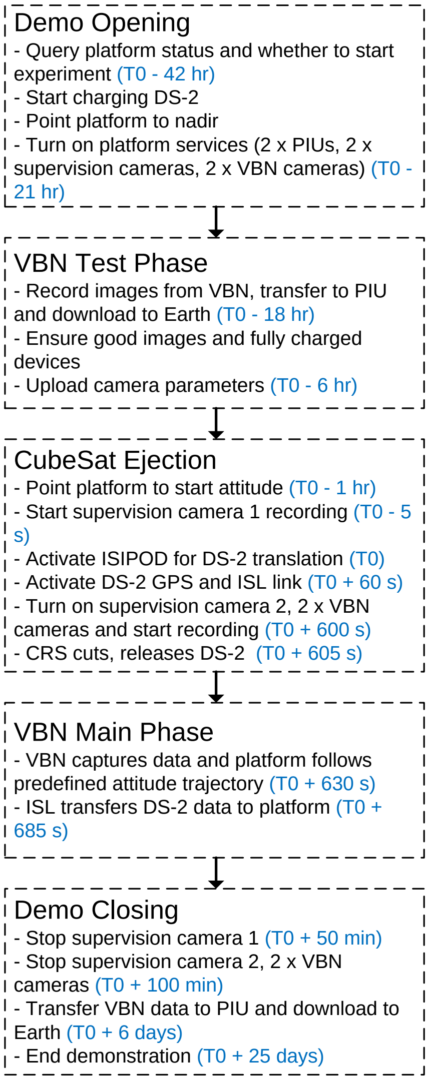

Fig. 6. ***VBN Operations Sequence.*** *Relative to T0, ISIPOD activation (and start of CubeSat translation). Sequence is a simplification of the full sequence and is subject to change.*

recording from this point. After this is completed, a timer cuts the CRS (CubeSat Release System) and the CubeSat is released.

Entering the main VBN phase, both CubeSat and platform attitude are adjusted as required for the demonstration. The VBN and supervision cameras collect data on the platform and the data collected on DS-2 (including GPS data) is sent back via the ISL to the platform (Fig 4-V3). The experiment closes with collection and download to Earth of VBN system data, the supervision cameras data, and the acquired CubeSat data. DS-2 naturally de-orbits at a rapid rate due to the low altitude.

The data collected in this experiment includes: the video of the experiment (from 3 sources), the VBN video and system data (from the 2 cameras), the CubeSat data which includes attitude sensor data, GPS data and housekeeping data. The GPS data and attitude data is also available from the platform. These data sets will allow post-processing of data to validate the VBN concept.

4.4. Harpoon Demonstration

The proposed harpoon demonstration sequence can be seen in Figure 7. The demonstration starts with checking the platform is ready to start the demonstration, and turning on relevant platform services. In the first phase, the target boom must be extended (Fig 4-H1), which involves cutting the frangibolt holding the target in place and deploying the boom. This phase is recorded. As per the other demonstrations, the platform needs to be re-pointed into the correct direction, the VBN must be calibrated and

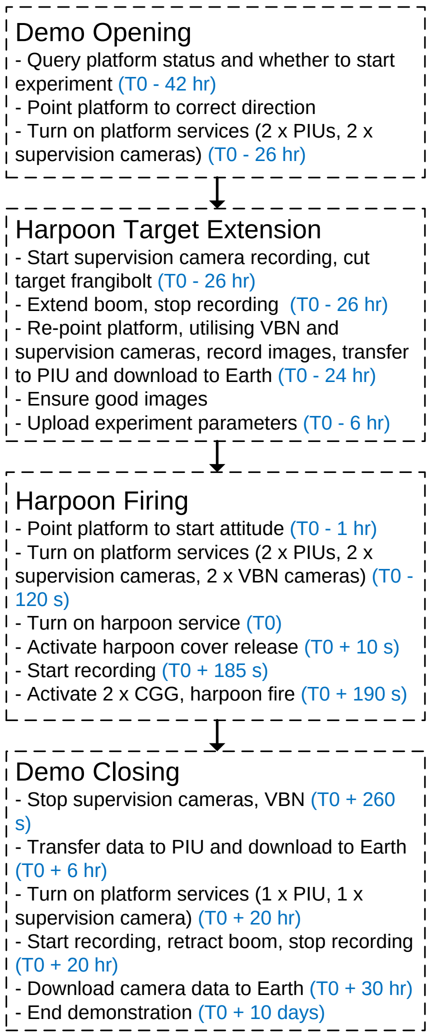

Fig. 7. ***Harpoon Operations Sequence.*** *Relative to T0, enabling of harpoon payload service. Sequence is a simplification of the full sequence and is subject to change.*

the supervision camera images checked ready for the main experiment.

In the main part of the demonstration, the platform services are re-enabled ready for the firing. At T0, the harpoon payload service is turned on (this is not the point at which the harpoon fires). Shortly after the harpoon protection cover is released (Fig 4-H3), recording is started and the 2 CGGs (cold gas generators) that fire the harpoon are activated. The harpoon aims to impact the target plate (Fig 4-H4).

The experiment closes with collection and download to Earth of VBN system data and the supervision cameras data. Before finishing the demonstration, the harpoon is retracted slightly (which is also recorded).

The main data collected in this experiment is the video of the experiment (from 2 sources). Various telemetry can also be acquired from the platform and the initial VBN experiment provides additional data sources. A thermal sensor is also embedded in the harpoon target assembly.

4.5. Dragsail Demonstration

The proposed dragsail demonstration sequence can be seen in Figure 8. The demonstration starts like the other 3 to check whether the platform and payloads are in a suitable position to start the demonstration. The supervision cameras are activated and the dragsail power switches are activated at T0 (this is not the point at which the dragsail starts deployment). Shortly after the dragsail burnwire is cut to enable the mast to deploy, the boom venting valve is closed (see [13] for more information), and the 2 CGGs are activated to inflate the mast. After this, the deployment motors are activated to unfurl the sail and carbon fibre booms. The experiment closes with the download of supervision camera data to Earth. After the dragsail is deployed, the platform will de-orbit at an accelerated rate. Due to the size of the sail, the platform does not guarantee unhindered communication or full power integrity (due to potential overlap of solar panels) after deployment; assessment of these is part of the demonstration.

The main data collected in this experiment is video from 2 camera sources. Various telemetry can also be acquired from the platform. In particular, the influence of the deployed dragsail on the platform can be assessed through attitude (and generic AOCS) data, power data and communications systems data. The platform de-orbit trajectory can be tracked from the ground and this can be compared with theoretical simulations of the de-orbit rate without a sail.

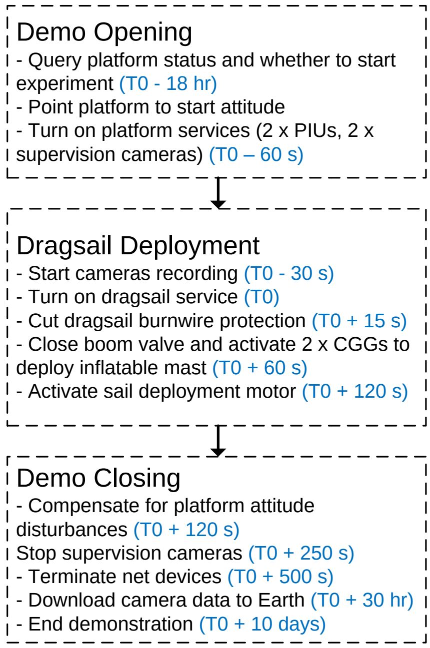

Fig. 8. ***Dragsail Operations Sequence.*** *Relative to T0, enabling of dragsail payload service. Sequence is a simplification of the full sequence and is subject to change.*

5. CONCLUSIONS

RemoveDebris is aimed at performing key ADR technology demonstrations (e.g capture, deorbiting) representative of an operational scenario during a low-cost mission using novel key technologies for future missions in what promises to be one of the first ADR technology missions internationally. The mission aims to be the first mission to demonstrate the use of a harpoon and net in space for debris capture, and the first use of CubeSats as 'artificial debris' targets. Additionally, the mission will be the world's first 100 kg satellite to be launched from the ISS.

This paper has presented an overview of the mission sequence, the launch procedure and sequence used for the mission, and the planned experimental timelines and operations for various payloads.

The key ADR technologies include the use of net and harpoon to capture targets, vision-based navigation to target debris and a dragsail for deorbiting. Although this is not a fully-edged ADR mission as CubeSats are utilised as artificial debris targets, the project is an important step towards a fully operational ADR mission; the mission proposed is a vital prerequisite in achieving the ultimate goal of a cleaner Earth orbital environment.

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