IAC-17,A6,6,4,x37324

THE REMOVEDEBRIS ADR MISSION: LAUNCH FROM THE ISS, OPERATIONS AND EXPERIMENTAL TIMELINES

Jason L. Forshaw[1], Guglielmo S. Aglietti[2]

Surrey Space Centre, University of Surrey, Guildford, UK

Thierry Salmon

Ariane Group, Bordeaux, France

Ingo Retat [a], Alexander Hall [b], Thomas Chabot [c], Aurélien Pisseloup [c]

Airbus: [a] Bremen, Germany; [b] Stevenage, UK; [c] Toulouse, France

Daniel Tye

Surrey Satellite Technology Limited (SSTL), Guildford, UK

Cesar Bernal [f], François Chaumette [g], Alexandre Pollini [h], Willem H. Steyn [i]

[f] Innovative Solutions In Space (ISIS), Netherlands; [g] Inria, France; [h] CSEM, Switzerland; [i] Stellenbosch University, South Africa

ABSTRACT

The EC FP7 RemoveDebris mission aims to be one of the world's first Active Debris Removal (ADR) missions to demonstrate key technologies in-orbit in a cost-effective ambitious manner, including: net capture, harpoon capture, vision-based navigation, dragsail de-orbitation. The mission will utilise two CubeSats as artificial debris targets to demonstrate the technologies. In early 2018, the main 100 kg satellite will launch to the International Space Station (ISS) where it will be deployed via the NanoRacks Kaber system into an orbit of around 400 km. The mission comes to an end in 2018 with all space entities having been de-orbited.

Previous papers have outlined the mission architecture and design, the demonstrations, and the test campaign. This paper continues by initially overviewing the pre-flight final configuration of the payloads and platform. The second section will focus on the specifics of the launch via Space X / NanoRacks, and compliance to the NASA safety reviews. As the satellite is being transported to the ISS as cargo, it will require manipulation by astronauts to ready it for deployment. The final section will detail the planned operational timeline, including the timeframe for the experiments, an overview of the operational sequences to be performed and the desired mission results.

Future mega-satellite constellations are now being proposed, where hundreds to thousands of satellites are being launched into orbit. A coherent strategy, along with technological and platform developments, is needed for de-orbiting, re-orbiting, or servicing of such constellations. The RemoveDebris mission is a vital prerequisite to achieving the ultimate goal of a cleaner Earth orbital environment, and is a core step in the development of active removal vehicles, or on-orbit servicing vehicles of the future.

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

I. 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 and a dragsail in a realistic space operational environment, due for launch in early 2018. 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 manufacture of payload hardware and both functional and environmental testing undertaken. Many of these payload concepts have never been tested in space before, and consideration is given to aspects of the test (and design) regime that differs from a conventional satellite.

*Corresponding Author. Tel.: +44 (0)1483 68 6025
Email addresses: j.forshaw@surrey.ac.uk, g.aglietti@surrey.ac.uk
URL: www.surrey.ac.uk/ssc/
[1]Consortium Dissemination Manager, Research Fellow II
[2]Principal Investigator, Professor of Spacecraft Structures

For former details about the mission refer to: website [1], first major mission paper [2], mission analysis [3], functional and environmental experimental results [4, 5], former mission and launch update [6].

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

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

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

I.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 large ESA-owned object from space [7, 8]. 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 [9, 10]. Progressing on, ESA has also now completed Phase A (feasibility) and Phase B1 (PDR) studies [11, 12], 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 [13]. 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 [14]. DLR's (German space agency) DEOS (Deutsche Orbital Servicing Mission) went as far in design as PDR level and aimed to rendezvous with a non-cooperative and tumbling spacecraft by means of a robotic manipulator system accommodated on a servicing satellite [15].

Regarding the development of capture technologies, there are several on-going efforts. Airbus capture designs include the robotic arm, net [16], and harpoon demonstrators for use in space [17]. 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 [9]. 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 [18], gecko adhesives and polyurethane foam [19, 20]. 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 infra-red system [21] and the Heavy Active Debris Removal (HADR) study that examined trade-offs for different ADR technologies, especially including flexible link capture systems [22].

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, 24, 25]. Other recent research specifically related to VBN for debris removal includes: TU Dresden [26], Thales [27], Jena-Optronik [28].

A range of de-orbitation technologies have been proposed previously but few have had in-flight testing. Research includes: dragsails (InflateSail, DeOrbitSail) [29], TeSeR (which proposes an independent modular deorbitation module that attaches to the satellite before launch) [30], 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) [31].

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 [32]. 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 [33]. 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) [34].

Upcoming missions to tackle debris removal include CleanSpace One by EPFL, which aims to use microsatellites with a grabber to demonstrate capture [35, 36]. 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, aiming to launch a mission with thousands of 'impact sensors' to build up knowledge of the magnitude of small fragments [37] as well as testing a chaser for capture of a 'boy' target in their ELSA-d mission [38].

I.2. Review of Mission

On the RemoveDebris mission there are 4 main experiments that utilise the two CubeSat targets DS-1 and DS-2. The mission features are summarised in Table 2.

Table 2: **RemoveDebris Mission Features**. †inter-satellite link, *payload interface unit

Platform	Structure	X-50M
	AOCS	SS, magnetometers, GPS, RW, magnetorquers
	Comms	S-band, ISL†
	Power	Fixed solar array, flight battery
	Avionics	OBC dual redundant, PIU*, CAN bridge
Targets	DS-1 CubeSat (net)	1 × passive CubeSat, inflatable structure, low-speed 5 cm/s deployer
	DS-2 CubeSat (VBN)	1 × active CubeSat with AOCS, GPS, ISL, deployable solar panels, low-speed 2 cm/s deployer
	Deployable target (harpoon)	OSS deployable boom, fixed target plate
Payloads	Net	1 × net fired on DS-1 in open-loop at 7 m
	Harpoon	1 × harpoon fired on target plate at 1.5 m
	VBN	LiDAR, 2-D camera pointing at DS-2 for analysis from 0 to 1800 m
	Dragsail	Dragsail deployable to 9 m^2 on platform
	Supervision cameras	2 × dual-redundant cameras recording experiments

I.3. Paper Structure

Section II focuses on the final payload and platform configuration for the mission. Section III examines the nature of the launch. Section IV examines the operational timelines of the mission and demonstrations. Finally, Section V concludes the paper and outlines key contributions to the field.

II. PRE-FLIGHT FINAL CONFIGURATION

This section will discuss the final pre-flight configuration of the platform and payloads. Any additional information about final functional or environmental testing not presented in [5] will be discussed here.

II.1. Platform

The platform, in the AIT hall, can be seen in Figures 1 and 2. Note that the dragsail has been reallocated to the back panel from former designs in [4]. The platform is undergoing final payload integration, system-end-to-end testing (SEET) and environmental testing in the soft launch clam shell (final vibe and TVAC). Expected shipping to launch site would be around October 2017, ready for a launch in early 2018.

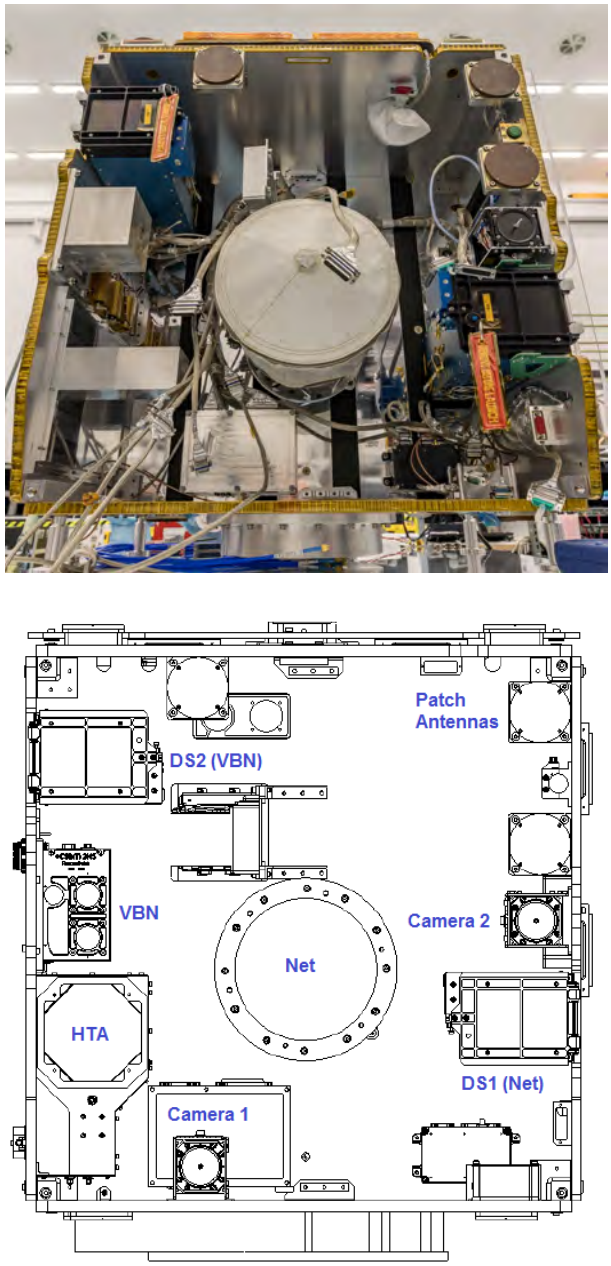

Fig. 1: **Platform - Payload Face.** This figure shows the platform from the payload face. Top: platform under integration showing: 2 × CubeSat deployers, net, 1 × camera, patch antennas. Mass dummies integrated for the HTA and VBN subsystems. Credit: SSTL, 2017. Bottom: CAD model view of the same face.

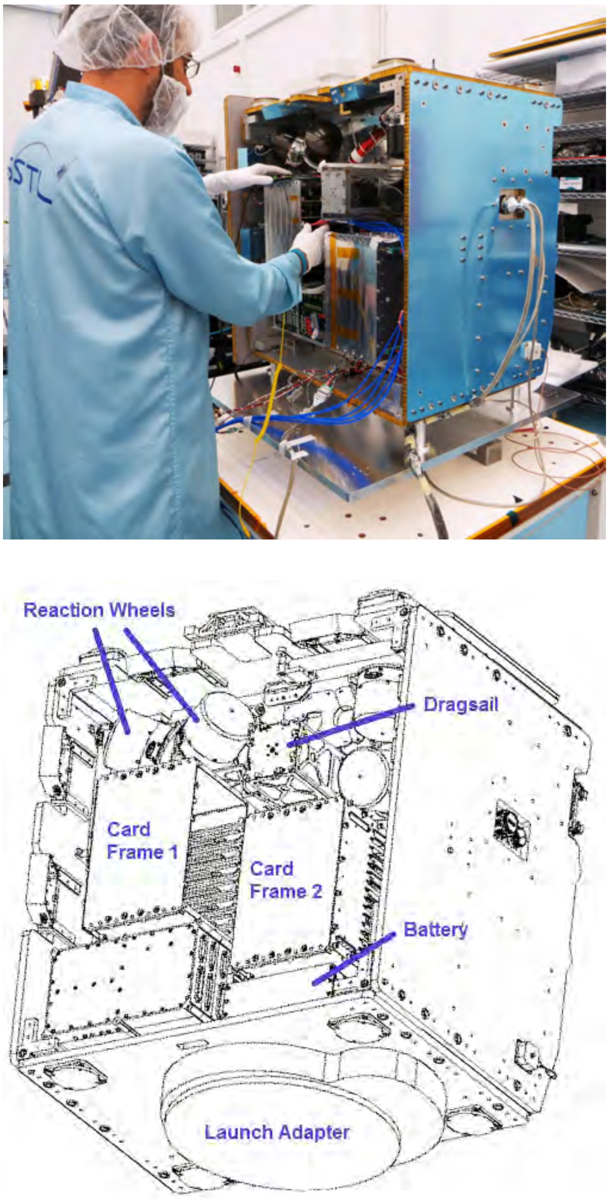

Fig. 2: **Platform - Back Face.** This figure shows the platform from the back face. Top: platform under integration. Credit: SSTL, 2017. Bottom: CAD model view of the same face.

II.2. Payloads - CubeSats, Dragsail

The CubeSats and Dragsail have been fully tested and integrated into the platform as of June 2017.

II.2.1. System End-to-End Tests

The SEET (payload level) for DS-1 is shown in Figure 3. The CubeSat showed correct and full inflation, with gravity compensation, before it was repacked for transportation to the integration hall.

Figure 4 shows a hardware-in-loop SEET (payload level), using the DS-2 CubeSat to photograph a simulated image of the platform (replicating its view in space), and transmit camera and sensor data back over the inter-satellite link (ISL) in real-time to a simulated platform. The CubeSat DS-2 was placed on

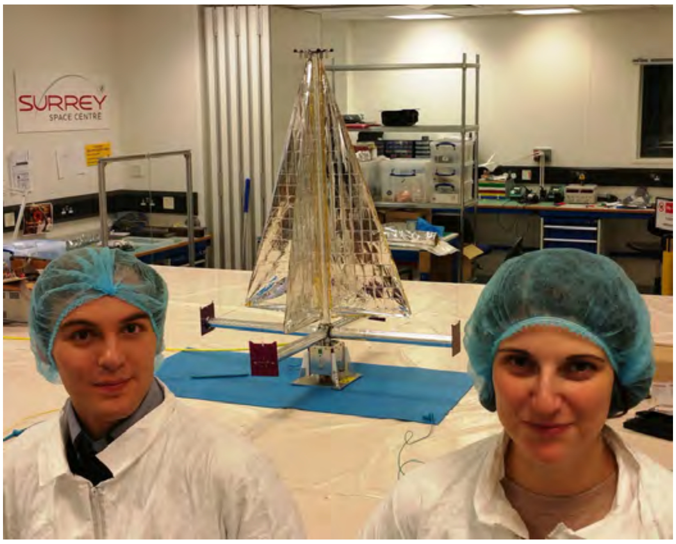

Fig. 3: **FM DS-1 CubeSat.** This figure shows the DS-1 CubeSat under a final deployment test as part of the SEET.

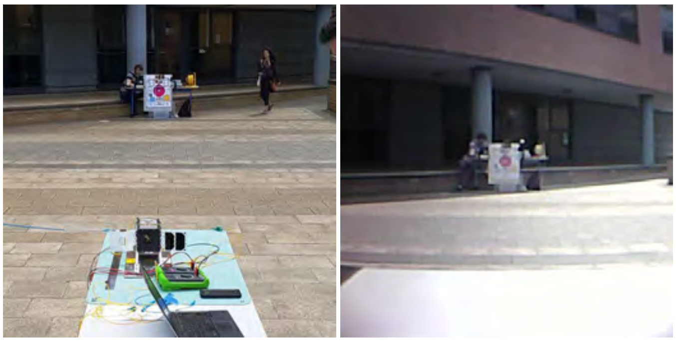

Fig. 4: **FM DS-2 and ISL SEET.** Full end-to-end DS-2 CubeSat (containing camera, sensors and inter-satellite link) test transmitting data back to a simulated platform. Left: test setup with CubeSat shown on surface. Right: view from CubeSat camera (as transmitted back to the platform).

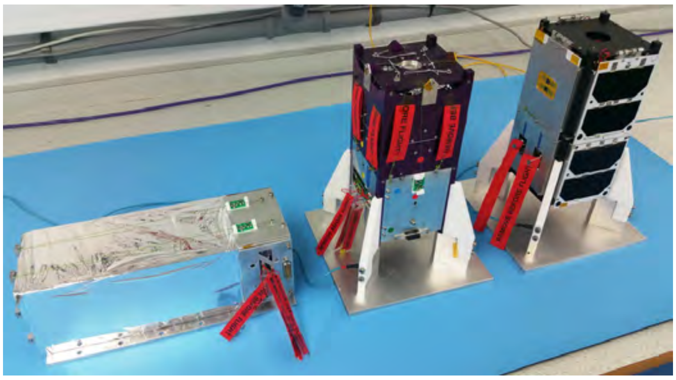

Fig. 5: **FM CubeSats and Dragsail.** This figure shows the payloads from SSC. Left to right: Dragsail, DS-1 (Net), DS-2 (VBN).

a surface and rolled backwards at the same speed as CubeSat ejection on the actual mission. The data collection rate was the same as on the actual mission. The test shows the type of images and nature of data expected from these initial stages of the DS-1 demonstration. In addition to this HILS test, the ISL link underwent independent RF range testing (which showed good performance even beyond the required 400 *m* range requirement) and a 90 hour soak test to burn in the components.

II.2.2. Flight Models

The three payloads from SSC can be seen in Figure 5. Here, the dragsail is ready for integration on to the platform and DS-1 and DS-2 are visible, before integration into the deployers. Figure 6 shows DS-1 and DS-2 isometrically.

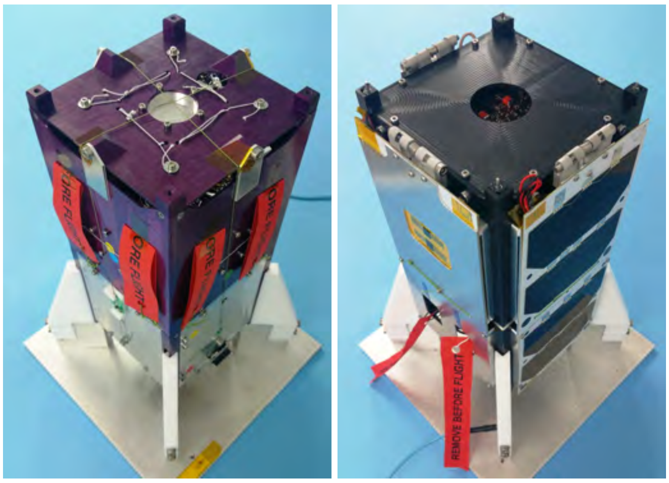

Fig. 6: **FM DS-1 and DS-2 CubeSats.** This figure shows DS-1 (left) and DS-2 (right).

II.3. Payloads - Deployers

After the flight preparation and successful test campaign of the ISIPODs (RemoveDebris deployers), they were brought to SSTL facilities in order to perform the integration in the RemoveDebris platform together with the other payloads and subsystems. The CubeSat Release Systems (CRS) is the system in charge of ensuring the CubeSats are released from the platform with the required velocity. After the fine tuning of the CRS flight models together with the actual flight models of the CubeSats they were also ready to be brought for the final integration.

II.3.1. CRS Integration

During the integration activities first the CRSs were integrated on to the CubeSats as shown in Figure 7. After pertinent checks the CubeSats were loaded into the correspondent deployers as shown in Figure 8.

II.3.2. Platform Integration

Finally the deployers were installed on the RemoveDebris platform performing the necessary mechanical and electrical checks to ensure the correct function of them in space. The ISIPODs were the first payloads to be integrated on the platform. The ISIPODs are in readiness to be actuated in orbit releasing the CubeSats with the required low velocity in order to contribute to successfully perform the net and VBN experiments of the RemoveDebris mission.

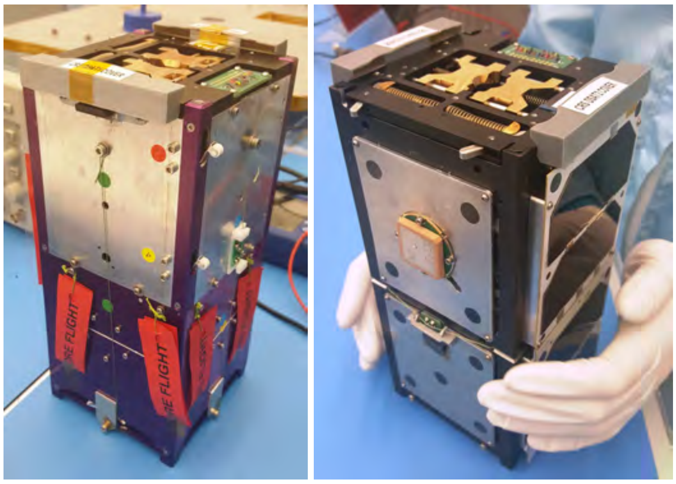

Fig. 7: **CRS insertion on to CubeSats.** This figure shows DS-1 (left) and DS-2 (right) with the CubeSat Release Systems (CRS) attached (on top).

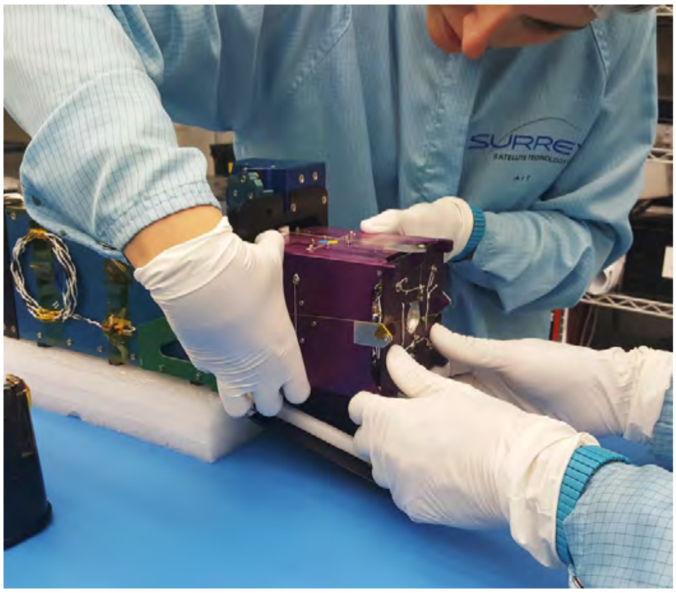

Fig. 8: **CubeSat insertion into Deployers.** This figure shows DS-1 being inserted into ISIPOD-1.

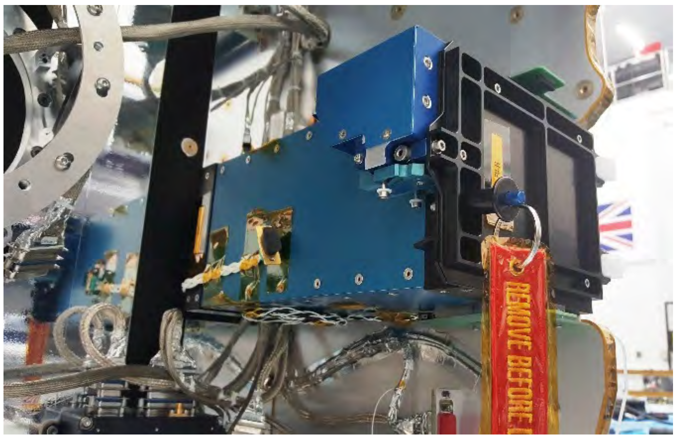

Fig. 9: **Deployer insertion on to Platform.** This figure shows ISIPOD-1 for the net experiment integrated on the platform.

II.4. Payloads - Net

Figure 10 shows the FM net payload. Since progress demonstrated in [39, 5], post-environmental testing, the payload was sent for integration in the platform. The full SEET deployment will be conducted using the FM platform but with an EQM net, as the FM is a single-use deployment.

Fig. 10: **FM Net.** This figure shows the final net flight model with ejection springs unloaded.

II.5. Payloads - Vision-based Navigation (VBN)

The Vision-Based Navigation is an experiment of proximity navigation between the satellite platform and an artificial mini satellite (DS-2). At the beginning of the experiment DS-2 will be ejected by the platform and will drift gently away for several hours. The main goal of the experiment is to evaluate navigation algorithms and a VBN sensor. Dedicated image processing and navigation algorithms have indeed been designed at Airbus and INRIA to meet the specific case of non-cooperative rendezvous. Airbus is responsible for the overall VBN experiment and the navigation algorithms, while CSEM is in charge of the sensor. For the latest in VBN developments see [40, 5].

II.5.1. System End-to-End Tests

A set of functional tests have to be conducted with the VBN sensor PFM aiming at taking images with the camera and the LiDAR, and uploading these images from the sensor to an unit simulating the platform PIU.

Figure 11 presents an image captured with the camera. The respective distance of the carton targets are quoted on the image. Figure 12 presents the same scene captured with the LiDAR. The LiDAR provides 2 images: a B&W intensity image similar to any standard camera, and a distance image or depth map that is a 3D image of the scene of interest or target.

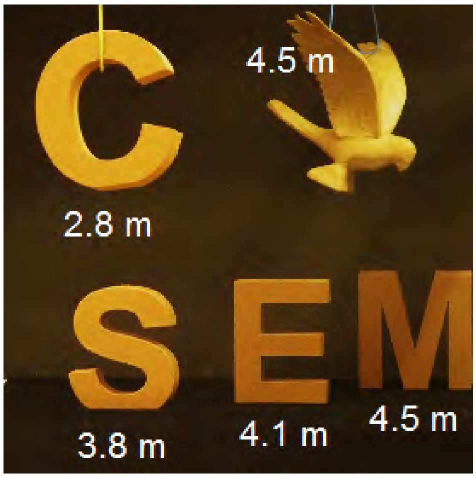

Fig. 11: **VBN: Image from Camera.** Using the letters 'CSEM' from the partner's name. Provides an indication of the targets' distances. From [5].

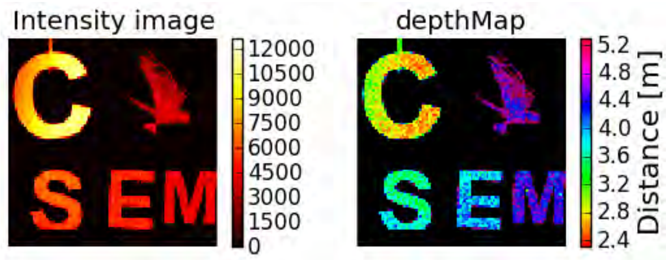

Fig. 12: **VBN: Image from LiDAR.** Left: showing image intensity in number of visible photons (more yellow objects are brighter). Right: 3D depthmap scene in metres. From [5].

Following the environmental tests, and before delivery, the PFM is calibrated. The goal is to determine the geometrical parameters of both vision-based subsystems to correct optical aberrations.

II.5.2. Flight Model

The sensor has two main subsystems: an off-the-shelf color camera and a flash imaging Light Detection And Ranging device (LiDAR) developed by CSEM. Its main functionality is to capture images of DS-2 with both vision-based devices according to a predefined timeline defining snapshot times and integration times. It is foreseen to use the sensor for the harpoon, the net and the VBN experiments. The VBN sensor has the most complex set of functionalities and interface with the S/C amongst the payloads. A proto-flight model (PFM) has been made for the project and can be seen in Figure 26.

II.6. Payloads - Harpoon

In the past year the harpoon experiment has been manufactured, assembled and tested ready for flight. The Harpoon Target

Fig. 13: **PFM VBN.** This figure shows the final VBN flight model.

Assembly (HTA) experiment will deploy a target on a carbon fibre boom to 1.5 *m* and capture it with a tethered harpoon. This experiment will demonstrate the use of a harpoon to capture large pieces of space debris, although initially envisaged to capture defunct satellites other targets could include spent rocket casings. Upon impacting a target two barbs are deployed, seen in Figure 14; these secure the chaser to the target and allow it to be dragged out of orbit. The experiment will be filmed using high-speed cameras on-board the spacecraft, these will observe the flight of the harpoon and the position of impact.

Fig. 14: **Harpoon Barb Mechanism.** This figure shows the projectile with the barbs deployed.

II.6.1. *Firing Tests*

The harpoon is fired by a piston propelled by gas. The point at which the piston releases is determined by a tear-pin within the casing, this allows the firing speed to be modified. To verify the harpoon accuracy, multiple firing tests were performed. A laser placed on the tip of the harpoon was used to predict the impact location, once aligned the harpoon was fired upwards into a honeycomb panel. The position of predicted impact was compared to the actual impact in order to characterise the accuracy. An impact can be seen below in Figure 15.

The harpoon strikes the target within a 20 *mm* diameter circle, including the size of the harpoon tip. As the target is 100 *mm*

Fig. 15: **Harpoon Impact.** This figure shows a harpoon impacted into a target.

there is enough margin for variations of the target position in space compared to on ground. A plot of the flight model (FM) impacts can be seen in Figure 16.

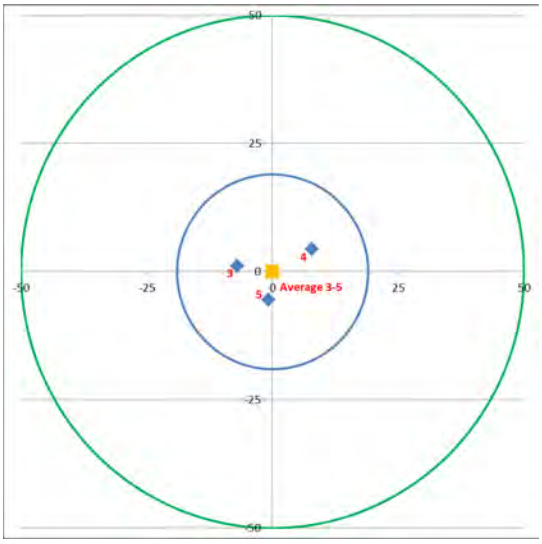

Fig. 16: **Harpoon Impact Locations.** This figure shows the distribution of impact points for the FM. Note that minimal firing tests were performed on the FM compared to the qualification model (QM), preventing excessive wear of the flight firing mechanism.

II.6.2. *Safety*

A main concern for the payload was accidental activation of the gas generators. To prevent this, a protective door restrains the harpoon before firing. If the gas generators are activated before the door is opened, the door will hold the harpoon until a burst disc ruptures releasing the pressurised gas. This was tested and shown that the door can withstand pressures up to the rupture point of the burst disc, allowing safe transportation of the HTA assembly.

Another risk was the possibility of the harpoon missing the target, if the harpoon tether snapped there is a chance that the projectile could reach the same orbit as the ISS. A test was performed firing horizontally with no target, the tether mounting pins were undamaged and the tether did not snap or fray at any point.

II.6.3. Flight Model

After the firing tests the harpoon assembly was finished, with the completed build shown in Figure 18 and the target deployed in Figure 17. Once the harpoon accuracy was characterised, the harpoon was integrated into the experiment chassis. The chassis houses the target, deployable boom and all the electronics necessary to run the experiment. The harpoon was aligned with the target using the laser tool and information generated from the accuracy tests. In order to deploy the target in a representative position to that in space, the target was removed from the boom and deployed facing downward. This minimised the gravitational pull on the boom and allowed it to settle in the correct position.

The payload was subjected to environmental tests, representing the conditions it would face during launch and in orbit. The most strenuous of these were the vibration tests which prove the payload can survive launch to the ISS. However, as the satellite is launched using a SpaceX Dragon capsule, a human rated capsule, the load requirements were relatively small. Thermal-Vacuum cycling was performed after vibration. This test sequence was used as micro-fractures caused by vibration will propagate through the structure during thermal cycling, showing failures not found if TVAC was tested first. Following environmental tests functionality testing was performed to verify the integrity of the payload.

The FM HTA payload, seen in Figures 19 and 20, has now been integrated onto the spacecraft ready for EVT testing. The RemoveDebris mission will be the first to test a debris capturing harpoon in space.

Fig. 17: **FM Boom - Deployed.** This figure shows the harpoon target assembly (HTA) and the boom fully deployed to 1.5 *m* with gravity assistance.

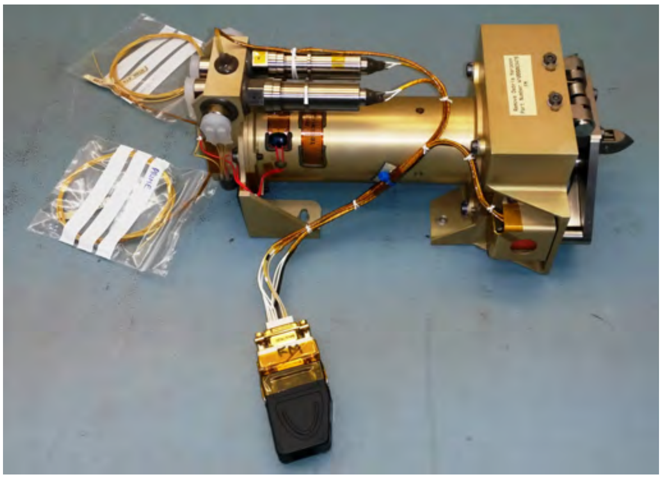

Fig. 18: **FM Harpoon Payload.** Showing the harpoon payload (no MLI) without the harpoon target or casing.

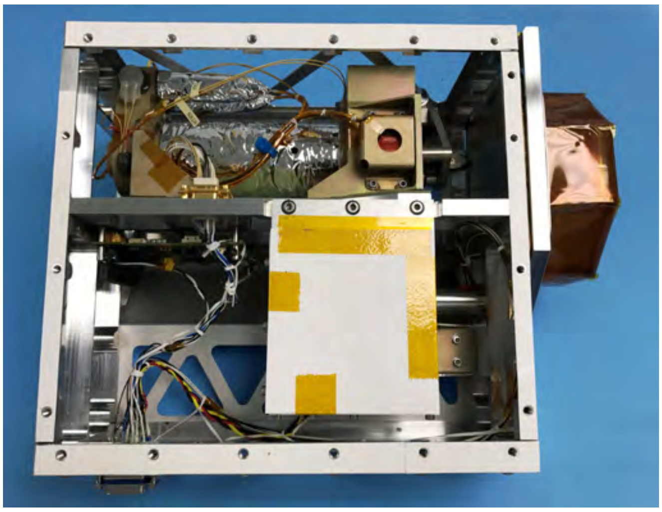

Fig. 19: **FM HTA - 1.** This figure shows the harpoon target assembly (HTA) from the right side.

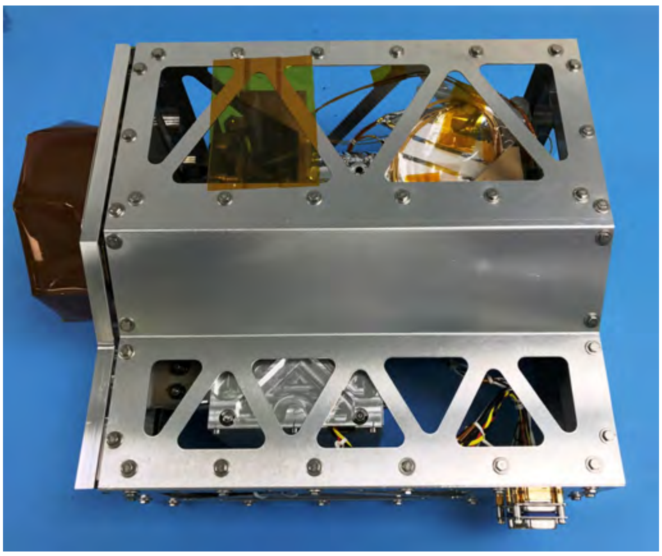

Fig. 20: **FM HTA - 2.** This figure shows the harpoon target assembly (HTA) from the left side.

III. LAUNCH AND SAFETY REVIEWS

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 Dragon capsule. 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 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. [2] and [3] 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.

III.1. Shipping and Flight Preparations

The RemoveDebris platform will be loaded on to the Dragon as cargo. The main platform is protected by a series of concentric encasements for shipping. Firstly cover panels screw into the platform structure and protect the solar panels. Secondly the panelled structure is placed within a clam shell. This clam shell is placed into a metal protective box and the box is put into the shipping container. On arrival at the launch facility, the platform is unpacked down to the clam shell and the clam shell is loaded into a cargo transfer bag (CTB) and then on to the Dragon as shown in Figure 22 (right). Figure 22 (left) also shows just the clam shell placed around a structural model of the platform.

Fig. 22: **Clam Shell.** Left: the clam shell (foam) that encompasses a RemoveDebris structural model. Credit: SSTL, 2017. Right: loading of the Dragon capsule with a cargo bag. Credit: NASA, SpaceX from [42].

III.2. Launch Sequence

The sequence of operations can be seen in Figure 21. Before launch (1), the cargo bag is loaded into the Dragon capsule as cargo and strapped down. After the cargo is launched to the ISS (2), the clam shell and outer protective panels are unpacked by astronauts, which install the platform on to the Japanese experiment module (JEM) air lock table (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.

III.3. NASA Safety Reviews

Launching to the ISS requires NASA safety reviews have to be passed. NASA impose certain constraints on the overall platform design to ensure safety to the astronauts on the ISS. As well as more common requirements, such as the platform not having sharp edges, several other requirements have introduced extra design effort in to the mission. These are detailed as follows.

After ejection from the ISS, the main platform is inert for up to 30 minutes before booting on. This is to protect the ISS from interference, or in case of any issues. All batteries on the mission must have triple electrical inhibits and thermal runaway protection. This includes the main platform battery and the two batteries in the CubeSats. The CubeSats also can only turn on when three separate deployment switches are activated, which is only physically possible when the CubeSats have left their respective pods. Mechanically, all the payloads require an inhibit.

Significant effort has been extended to ensure astronaut safety. The harpoon can only fire with an 'arm and fire' sequential command sequence (which would of course require power to the system - which already has a triple electrical inhibit). Without this command, there is no way the cold gas generator (CGG), which propels the harpoon, could be powered, and thus no way in which the harpoon could fire. Furthermore, the safety door in front of the harpoon only opens before firing and must be manually commanded to be opened. In front of the safety door is the main target plate which presents another mechanical barrier. A final mechanical barrier is the Kapton box in front of the target plate which prevents fragments of debris escaping into space during the harpoon experiment.

IV. OPERATIONAL TIMELINES

The mission timing can be seen in Figure 23. The four core events are launch preparation, launch to the ISS, ejection from the ISS and mission demonstrations.

IV.1. Overview of Demonstrations

The four core mission demonstrations are shown in Figure 24. 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.

Fig. 21: **Launch Sequence.** This figure shows the launch sequences for the mission to the International Space Station (ISS). Credit: SpaceX, NanoRacks, NASA [41].

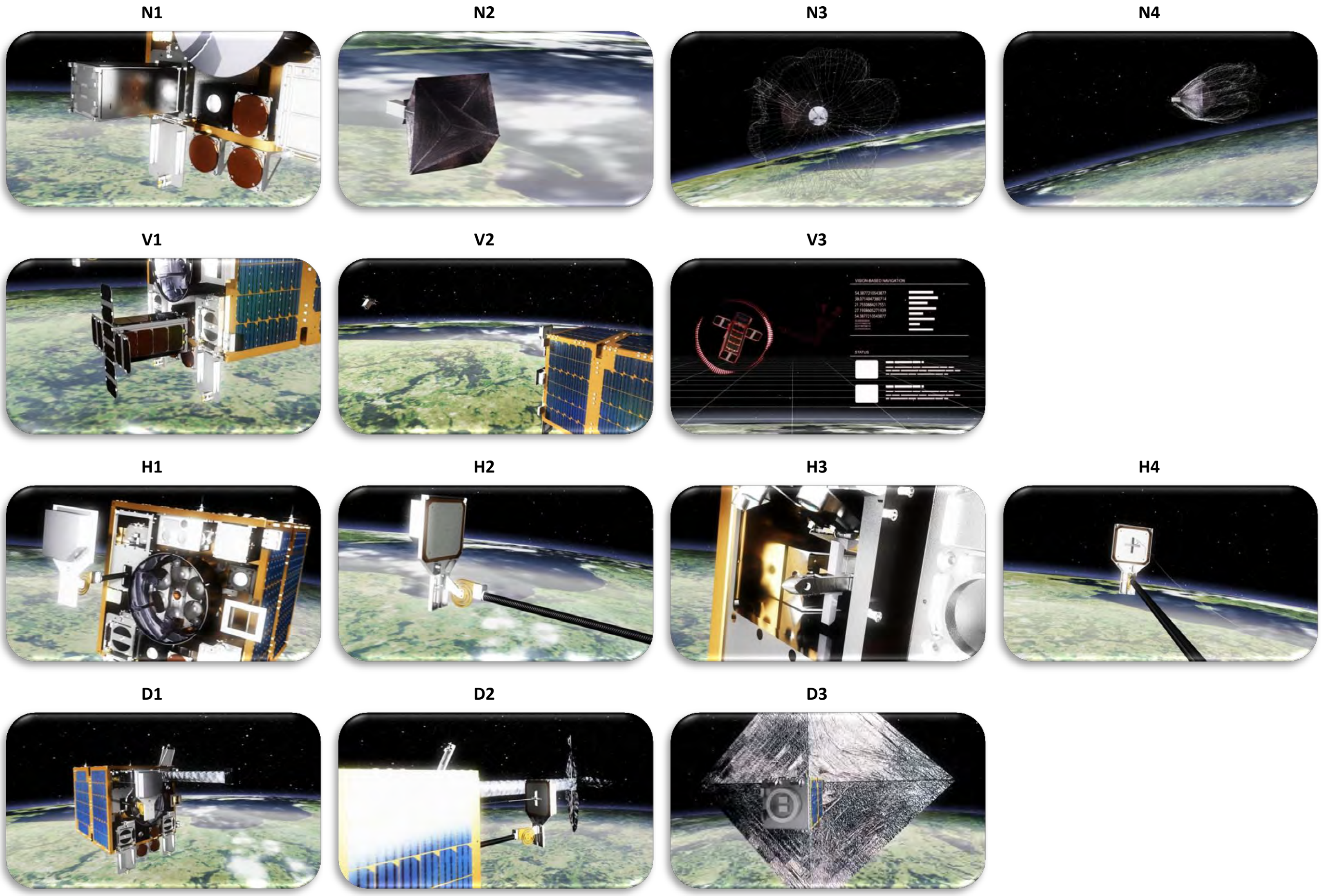

Fig. 24: **Demonstration Sequence.** This figure shows the demonstration sequences for the net (N1 to N4), VBN (V1 to V3), harpoon (H1 to H4) and dragsail (D1 to D3). Note: visualisation is only an approximation of the mission - subsystems may be positioned differently or have cosmetic differences, compared with flight model.

IV.2. Net Demonstration

The proposed net demonstration sequence can be seen in Figure 25. 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 24-N2), and the net is ejected to capture DS-1 (Fig 24-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

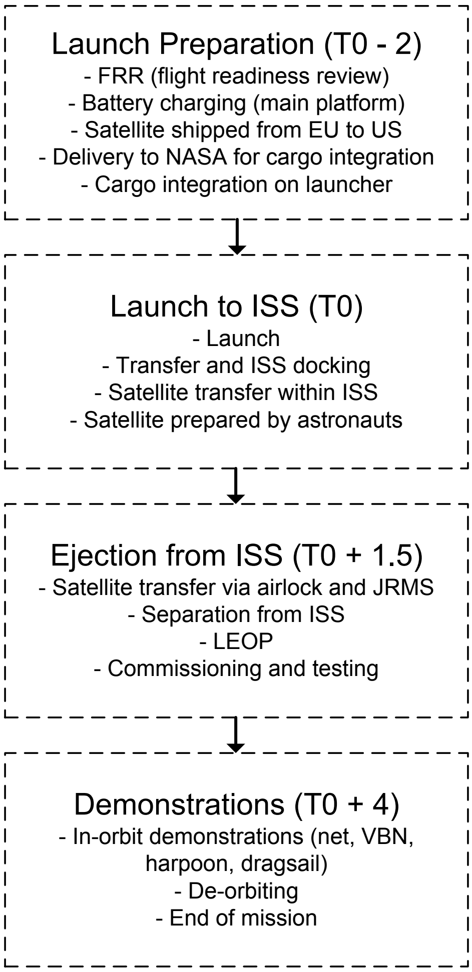

Fig. 23: **High Level Mission Timing.** High level timing on the mission where times are in months and relative to the launch to the ISS (T0).

the experiment (from 3 sources). Various telemetry can also be acquired from the platform and the initial VBN experiment provides additional data sources.

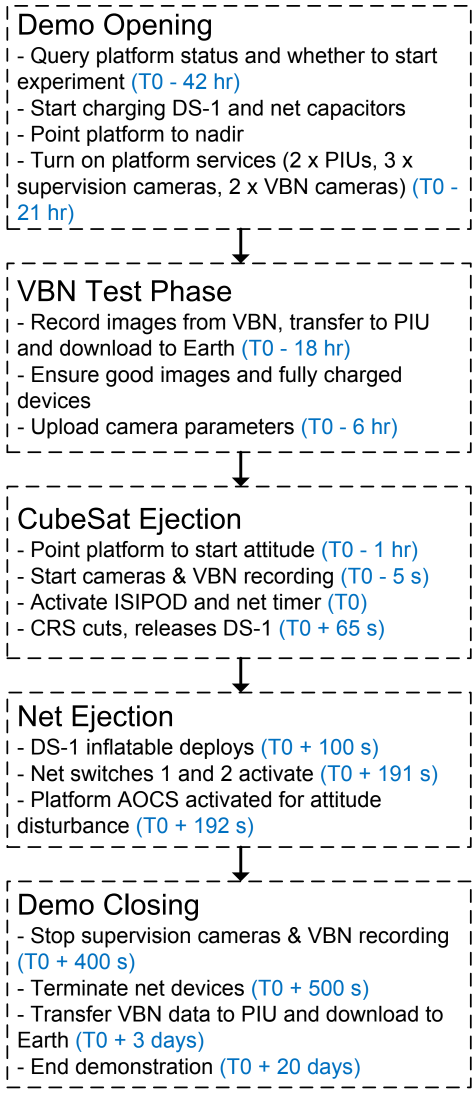

Fig. 25: **Net Operations Sequence.** Relative to T0, ISIPOD activation (and start of CubeSat translation). Sequence is a simplification of the full sequence and is subject to change.

IV.3. VBN Demonstration

The proposed VBN demonstration sequence can be seen in Figure 26. 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 2 supervision cameras on the platform and 2 VBN cameras (3d, 2d). 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 24-V1). The VBN cameras start 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 24-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 2 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 and algorithms.

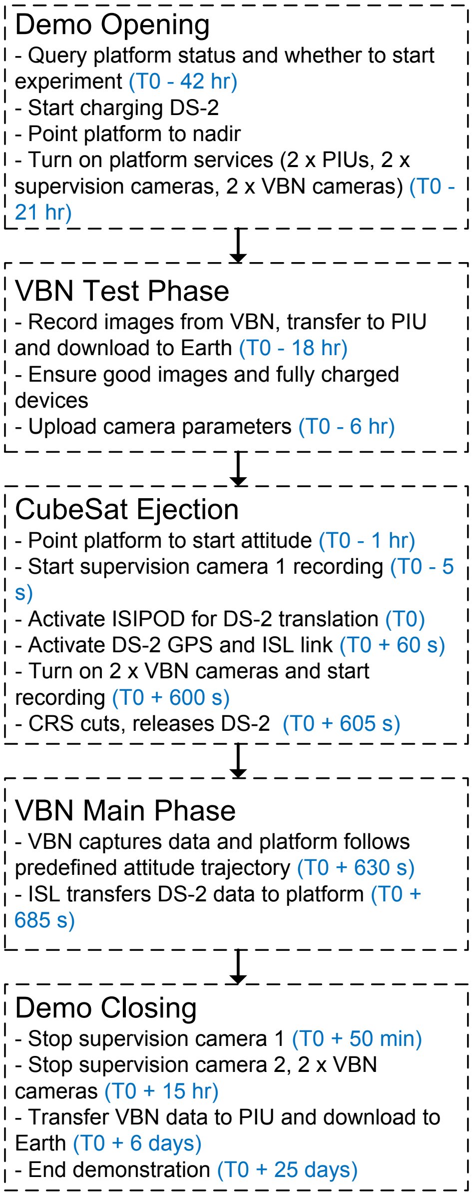

Fig. 26: **VBN Operations Sequence.** Relative to T0, ISIPOD activation (and start of CubeSat translation). Sequence is a simplification of the full sequence and is subject to change.

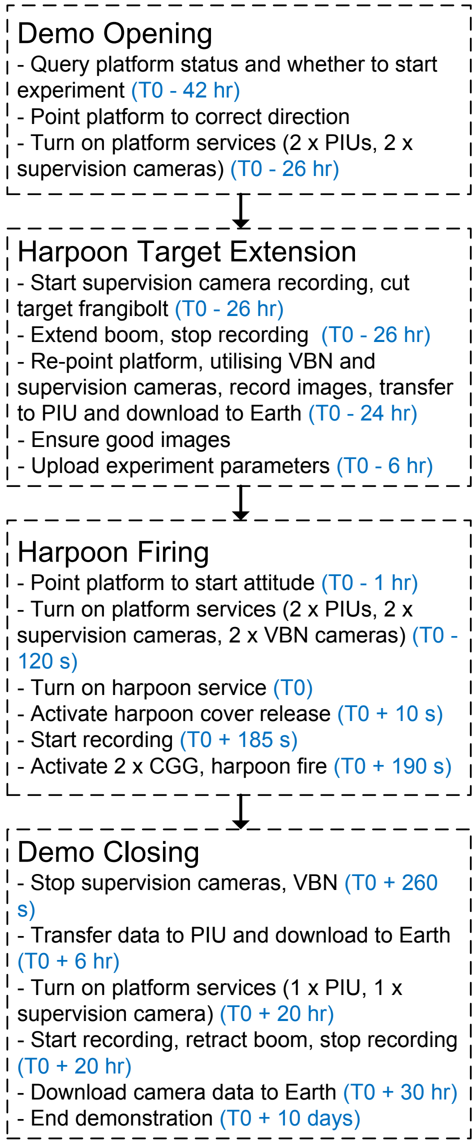

Fig. 27: **Harpoon Operations Sequence.** Relative to T0, enabling of harpoon payload service. Sequence is a simplification of the full sequence and is subject to change.

IV.4. Harpoon Demonstration

The proposed harpoon demonstration sequence can be seen in Figure 27. 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 24-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 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 24-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 24-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.

IV.5. *Dragsail Demonstration*

The proposed dragsail demonstration sequence can be seen in Figure 28. 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 [4] 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.

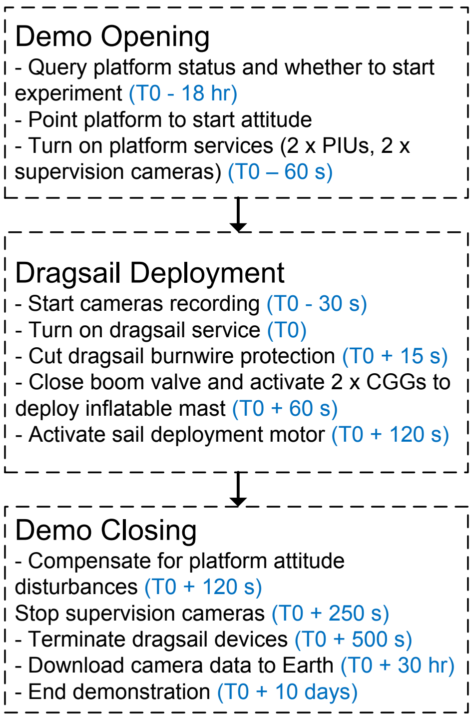

Fig. 28: **Dragsail Operations Sequence.** Relative to T0, enabling of dragsail payload service. Sequence is a simplification of the full sequence and is subject to change.

V. 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 the first ADR technology mission internationally.

This paper has provided a pre-launch overview of the mission - from the final configuration of the payloads and platform - to the expected mission operations.

The key ADR technologies include the use of net and harpoon to capture targets, vision-based navigation for rendezvous with 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.

VI. ACKNOWLEDGEMENTS

This research is supported by the European Commission FP7-SPACE-2013-1 (project 607099) 'RemoveDebris - A Low Cost Active Debris Removal Demonstration Mission', a consortium partnership project consisting of: Surrey Space Centre (University of Surrey), SSTL, Airbus GmbH, Airbus SAS, Airbus Ltd, Ariane Group, Innovative Solutions in Space (ISIS), CSEM, Inria, Stellenbosch University.

REFERENCES

[1] Main Website, `www.surrey.ac.uk/ssc/research/space_vehicle_control/removedebris/`.

[2] J. L. Forshaw, G. S. Aglietti, N. Navarathinam, H. Kadhem, T. Salmon, A. Pisseloup, E. Joffre, T. Chabot, I. Retat, R. Axthelm, S. Barraclough, A. Ratcliffe, C. Bernal, F. Chaumette, A. Pollini, W. H. Steyn, RemoveDEBRIS: An in-orbit active debris removal demonstration mission, Acta Astronautica 127 (2016) 448 – 463. doi:10.1016/j.actaastro.2016.06.018.

[3] E. Joffre, J. L. Forshaw, T. Secretin, S. Reynaud, T. Salmon, A. Pisseloup, G. Aglietti, RemoveDebris - mission analysis for a low cost active debris removal demonstration in 2016, in: 25th International Symposium on Space Flight Dynamics (ISSFD), Munich, Germany, 2015.

[4] J. L. Forshaw, G. S. Aglietti, T. Salmon, I. Retat, M. Roe, T. Chabot, C. Burgess, A. Pisseloup, A. Phipps, C. Bernal, F. Chaumette, A. Pollini, W. H. Steyn, Review of final payload test results for the RemoveDebris active debris removal mission, in: 67th International Astronautical Congress, Guadalajara, Mexico, 2016.

[5] J. L. Forshaw, G. Aglietti, T. Salmon, I. Retat, M. Roe, C. Burgess, T. Chabot, A. Pisseloup, A. Phipps, C. Bernal, F. Chaumette, A. Pollini, W. H. Steyn, Final payload test results for the RemoveDebris active debris removal mission, Acta Astronautica 138 (2017) 326 – 342. doi:10.1016/j.actaastro.2017.06.003.

[6] J. L. Forshaw, G. Aglietti, T. Salmon, I. Retat, C. Burgess, T. Chabot, A. Pisseloup, A. Phipps, C. Bernal, F. Chaumette, A. Pollini, W. H. Steyn, The RemoveDebris ADR mission: preparing for an international space station launch, in: ESA 7th European Conference on Space Debris, ESOC, Germany, 2017.

[7] R. Biesbroek, A. Wolahan, Maturing the technology for ESA's e.Deorbit mission to remove a large, heavy space debris from low earth orbit, in: CNES 4th International Workshop on Space Debris Modelling and Remediation, Paris, France, 2016.

[8] L. Innocenti, Clean space - an overview, in: ESA Clean Space Industrial Days, ESTEC, Netherlands, 2016.

[9] C. Saunders, J. L. Forshaw, V. J. Lappas, A. Chiesa, B. Parreira, R. Biesbroek, Mission and systems design for the debris removal of massive satellites, in: 65th International Astronautical Congress, Toronto, Canada, 2014.

[10] C. Saunders, J. L. Forshaw, V. J. Lappas, D. Wade, D. Iron, R. Biesbroek, Business and economic considerations for service oriented active debris removal missions, in: 65th International Astronautical Congress, Toronto, Canada, 2014.

[11] S. Estable, Envisat removal by robotic capture means - results of the airbus ds led e.Deorbit Phase B1 ESA study, in: ESA Clean Space Industrial Days, ESTEC, Netherlands, 2016.

[12] M. Scheper, e.deorbit Phase B1 System Overview (OHB), in: ESA Clean Space Industrial Days, ESTEC, Netherlands, 2016.

[13] C. Cougnet, B. Gerber, C. Heemskerk, K. Kapellos, G. Visentin, On-orbit servicing system of a GEO satellite fleet, in: 9th ESA Workshop on Advanced Space Technologies for Robotics and Automation 'ASTRA 2006', ESTEC, Netherlands, 2006.

[14] A. Pisseloup, T. Salmon, C. Cougnet, M. Richard, ADR concepts from CNES funded study OTV, in: 64th International Astronautical Congress, Beijing, China, 2013.

[15] D. Reintsema, B. Sommer, T. Wolf, J. Theater, A. Radthke, W. Naumann, P. Rank, J. Sommer, DEOS - the in-flight technology demonstration of german's robotics approach to dispose malfunctioned satellites, in: ESA 11th Symposium on Advanced Space Technologies in Robotics and Automation, ESTEC, Netherlands, 2011.

[16] Astrium Space Transportation, ROGER Phase-A Final Report Executive Summary, Tech. Rep. ROG-SIBRE-EXS, Astrium Space Transportation (2003).

[17] A. Pisseloup, S. Estable, K. Pegg, E. Ferreira, R. Delage, J.-M. Pairot, T. Salmon, A. Ratcliffe, M. Frezet, Airbus defence and space's vision and activities in active debris removal and on-orbit servicing, in: CNES 4th International Workshop on Space Debris Modelling and Remediation, Paris, France, 2016.

[18] M. Merino, E. Ahedo, C. Bombardelli, H. Urrutxua, J. Pelaez, L. Summerer, Space debris removal with an ion beam shepherd satellite: target-plasma interaction, in: 47th AIAA Joint Propulsion Conference & Exhibit, San Diego, US, 2011.

[19] A. Parness, Orbital debris removal with gecko-like adhesives; technology development and mission design, in: 66th International Astronautical Congress, Jerusalem, Israel, 2015.

[20] C.Trentlage, E.Stoll, The applicability of gecko adhesives in a docking mechanism for active debris removal missions, in: 13th Symposium on Advanced Space Technologies in Robotics and Automation, ASTRA 2015, ESTEC, Netherlands, 2015.

[21] A. Chiesa, G. Gambacciani, D. Renzoni, G. Bombaci, Enabling technologies for active space debris removal: the CADET (CApture and DEorbiting Technologies) project, in: CNES 4th International Workshop on Space Debris Modelling and Remediation, Paris, France, 2016.

[22] M. Bicocca, Debris capture technologies overview, Tech. rep., Aviospace (May 2014).

[23] A. Petit, E. Marchand, K. Kanani., Tracking complex targets for space rendezvous and debris removal applications, in: IEEE/RSJ Conference on Intelligent Robots and Systems, IROS'12, Vilamoura, Portugal, 2012.

[24] T. Chabot, E. Kervendal, N. Despre, K. Kanani, P. Vidal, E. Monchieri, D. Rebuffat, S. Santandrea, J. L. Forshaw, Relative navigation challenges and solutions for autonomous orbital rendezvous, in: EuroGNC 2015, Toulouse, France, 2015.

[25] A. Yol, E. Marchand, F. Chaumette, K. Kanani, T. Chabot, Vision-based navigation in low earth orbit, in: i-SAIRAS 2016, Beijing, China, 2016.

[26] A. Sonnenburg, Image recognition and processing for navigation (irpn), in: ESA Clean Space Industrial Days, ESTEC, Netherlands, 2016.

[27] N. Deslaef, J. Christy, Rendezvous sensors and navigation, in: ESA Clean Space Industrial Days, ESTEC, Netherlands, 2016.

[28] Jena-Optronik, The rvs3000 and rvs3000-3d lidar sensors for rendezvous and docking and space robotics, in: ESA Clean Space Industrial Days, ESTEC, Netherlands, 2016.

[29] J. L. Forshaw, C. Massimiani, M. Richter, A. Viquerat, E. Simons, R. Duke, G. Aglietti, Surrey Space Centre: A survey of debris removal research activities, in: 66th International Astronautical Congress, Jerusalem, Israel, 2015.

[30] P. Voigt, C. Vogt, B. Barthen, H. Stokes, C. Underwood, A. Knoll, K. Ryden, M. Macdonald, E. Kerr, et. al., TeSeR - technology for self-removal - a horizon 2020 project to ensure the post-mission-disposal of any future spacecraft, in: ESA Clean Space Industrial Days, ESTEC, Netherlands, 2016.

[31] S. Antonetti, D-SAT mission: An in-orbit demonstration of autonomous decommissioning capabilities in changing space debris mitigation requirements scenario, in: CNES 4th International Workshop on Space Debris Modelling and Remediation, Paris, France, 2016.

[32] I. A. Sanchez, D. Paris, F. Allard, N. Frischauf, The navigation and communication systems for the Automated Transfer Vehicle, in: IEEE 49th Vehicular Technology Conference, Vol. 2, 1999, pp. 1187–1192. doi:10.1109/VETEC.1999.780535.

[33] K. Yoshida, ETS-VII Flight Experiments For Space Robot Dynamics and Control, Vol. 271, Experimental Robotics VII, Springer, 2001.

[34] S. Clark, Japanese Cargo Ship Ends Mission after Space Debris Experiment Flounders, spaceflightnow.com, 2017.

[35] M. Richard, L. Kronig, F. Belloni, S. Rossi, V. Gass, C. Paccolat, J. Thiran, S. Araomi, I. Gavrilovich, H. Shea, Uncooperative rendezvous and docking for microsats: The case for CleanSpace One, in: 6th International Conference on Recent Advances in Space Technologies (RAST), Istanbul, Turkey, 2013.

[36] B. Gorret, L. Mtrailler, L. Moreau-Gentien, P.-A. Musli, A. Guignard, M. Richard, M. Lauria, Status of the development of the CleanSpace One capture system, in: CNES 4th International Workshop on Space Debris Modelling and Remediation, Paris, France, 2016.

[37] N. Okada, ADRAS 1: Spacecrafts EOL solutions and debris removal, in: CNES 4th International Workshop on Space Debris Modelling and Remediation, Paris, France, 2016.

[38] M. Okada, A. Okamoto, K. Fujimoto, M. Ito, Maximizing post mission disposal of mega constellations satellites reaching end of operational lifetime, in: ESA 7th European Conference on Space Debris, ESOC, Germany, 2017.

[39] R. Axthelm, B. Klotz, I. Retat, U. Schlossstein, W. Tritsch, S. Vahsen, Net capture mechanism for debris removal demonstration mission, in: ESA 7th European Conference on Space Debris, ESOC, Germany, 2017.

[40] T. Chabot, K. Kanani, A. Pollini, F. Chaumette, E. Marchand, J. Forshaw, Vision-based navigation experiment on-board the RemoveDebris mission, in: GNC 2017: 10th International ESA Conference on GNC, Salzburg, Austria, 2017.

[41] NanoRacks, Space station CubeSat deployment services, Tech. rep. (February 2015).

[42] SpaceX, COTS 2 mission press kit, Tech. rep. (October 2011).