RemoveDebris Preliminary Mission Results

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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. RemoveDebris is a low-cost mission funded jointly by the European Commission (EU) and 10 partners: the University of Surrey (UK), Airbus (France, Germany, UK); Ariane Group (France); Surrey Satellite Technology Ltd, (UK); Innovative Solutions In Space (Netherlands); CSEM (Switzerland); Inria (France); Stellenbosch University (South Africa). The mission will utilise two CubeSats as artificial debris targets to demonstrate the technologies. In early 2018, the main 100-kg satellite was launched to the International Space Station (ISS) and deployed via the NanoRacks Kaber system into an orbit of around 400 km. The mission comes to an end in early 2019 with all space entities having been de-orbited.
This paper reports on the LEOP and commissioning phase of the mission in preparation for experimental tests due to begin end of 2018.
Keywords: space debris, debris removal, ADR, commissioning, net, harpoon, vision-based navigation, dragsail

1 Introduction

An extensive literature survey in the field of active debris removal has been presented in a recent papers [1].

1.1 Mission Overview

The mission concept consists of a main mini satellite platform of approximately 100kg mass that once in orbit will release two 2U cubesats which will act as space debris simulators (more details on the mission can be found in [2, 3, 4]). Four key technologies, to be used at different stages of a typical Active Debris Removal (ADR) mission will be tested: Vision Based Navigation (VBN) as a tool to observe and quantify the relative dynamics between an uncooperative debris and the platform preparing for its retrieval; two technologies for debris capture, namely a net and a harpoon; and finally a de-orbit sail, to increase the satellite platform drag, thus reducing its speed and orbit altitude until it burns up in the Earth's atmosphere.

One of the cubesats, after low speed ejection from the satellite platform will be observed using the VBN to prove its hardware and algorithm, whilst the CubeSat also relays attitude data to the satellite platform for validation. The second cubesat, after ejection, will inflate a structure to increase its size to make it comparable to that of larger debris becoming a more size-representative target for the net capture experiment i.e. a net will be launched by the platform to envelope and capture the cubesat. A small panel of material analogous to that used in standard satellites construction will then be deployed using a boom that will position this panel at a 1.5 meter distance from the platform. This panel will be the target for the harpoon experiment (i.e. a tethered harpoon is going to be fired by the satellite platform to hit this panel). The last experiment to be performed will be the drag sail. During a real mission this would be the last phase, when the platform and the debris that it has captured are deorbited together, destroying through burn-up.

Figure 1 shows the sequencing of the four experiments in the mission. 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.

The mission design has tried to ensure the payloads are representative as possible for future missions and have scalability potential to larger classes. In certain cases, the mission had to give priority to practicality, satisfying regulatory (licensing) requirements or safety requirements. For instance, sizing of the payload targets was selected to ensure the artificial debris would re-enter in a timely fashion whether or not the mission was successful, similarly a low altitude orbit was selected to ensure prompt disposal of the mission.

1.2 Paper Structure

This paper I structured into 5 sections. Section 1 provides the mission introduction and overview. Section 2 describes the spacecraft and hosted hosted payloads in greater detail. Section 3 presents the launch and deployment operations of the mission, with section 4 discussing the platform and payload commissioning acivities. Finally, Section 5 gives an overview of the experimental timeline as the mission moves to the payload demonstrations.

2 Spacecraft description

The platform and payloads are described in the next sub sections, and more details, including test activities can be found in [5].

2.1 Platform

The RemoveDebris satellite platform is based on the X50 satellite and utilizes internally developed avionics systems under the SSTL Fireworks programme. The X-Series platforms are being developed with some key drivers and principles in mind. These are a combination of (a) principles that SSTL have employed successfully in delivering small satellites in the last 30 years, and (b) new approaches that are enabled by SSTL's evolution as a company in the last 15 years, specifically the recently developed in house capabilities for batch/mass production and automated test.

The RemoveDebris platform has been modified to be compliant for ISS deployment including battery and

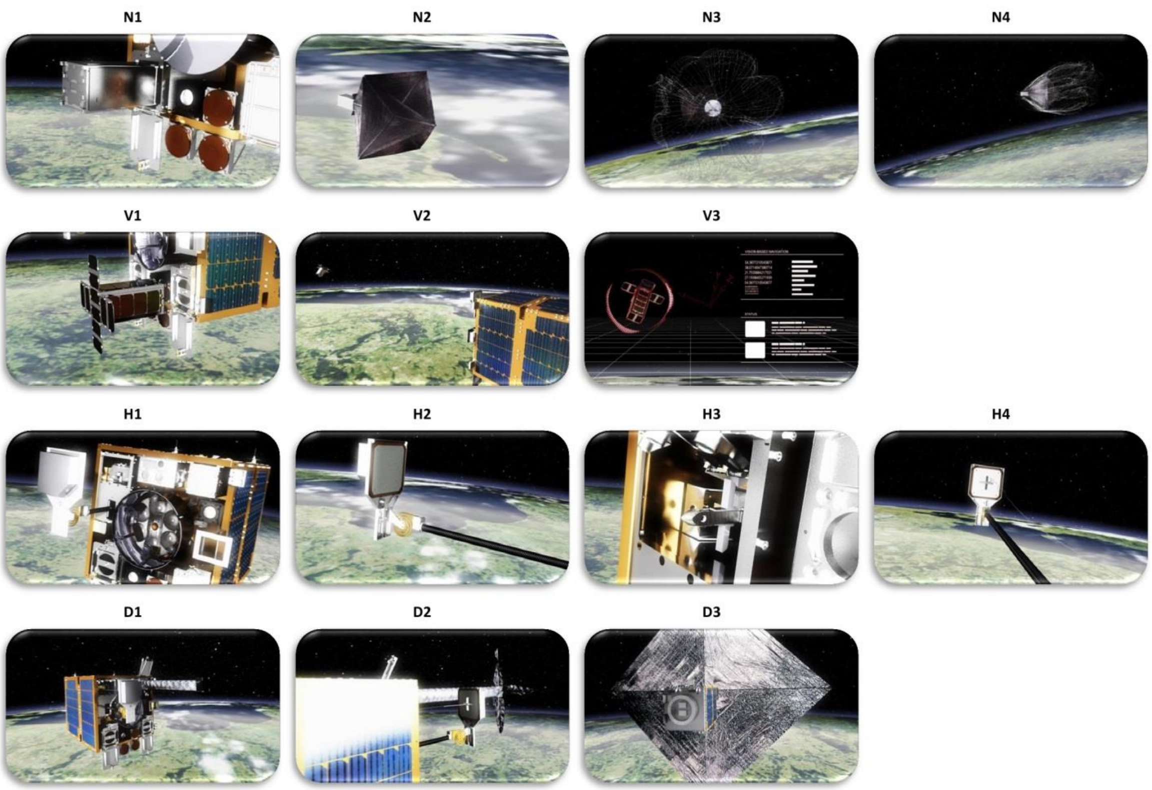

Figure 1. N1 to N4: net experiment, V1 to V3: vision-based navigation experiment, H1 to H4: harpoon experiment, D1 to D3: dragsail experiment.

activation safety features consisting of apply before flight items to be added by astronauts and additional delayed start-up system safeties. Further, certain elements of software for activation of payloads are to be uploaded once deployed from the ISS, rather than included at launch to ensure potentially dangerous commands cannot be sent be spurious commanding whilst in proximity to the ISS.

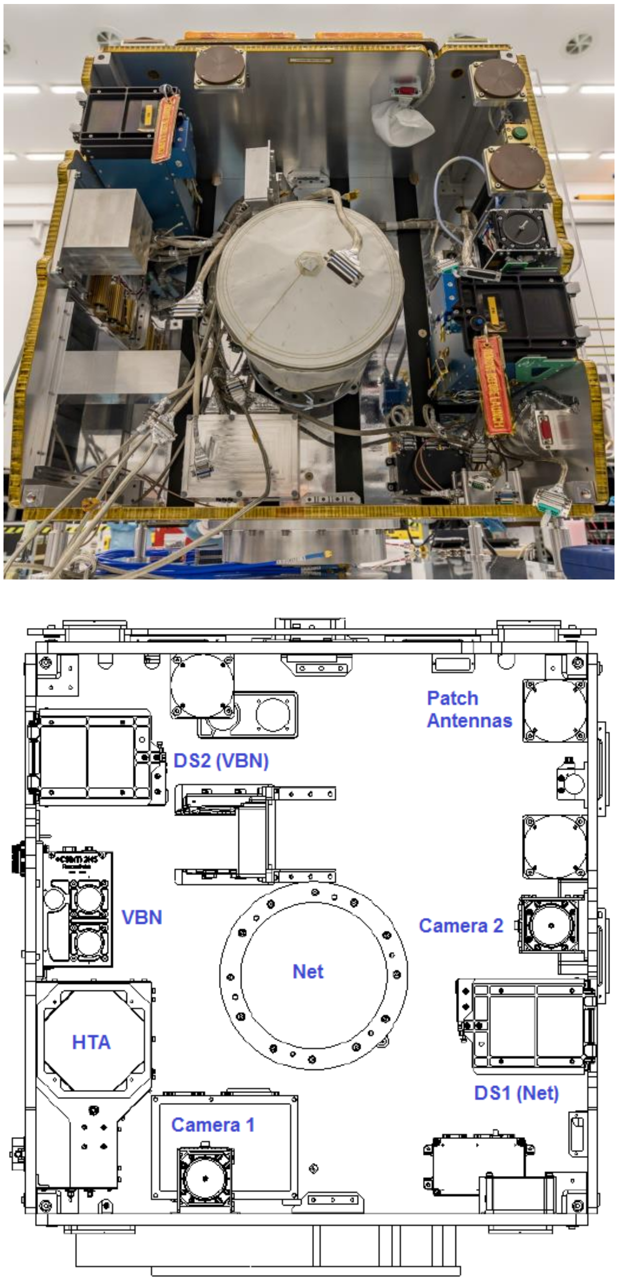

Figure 2. Platform - Payload Face. Top: platform under integration. Credit: SSTL, 2017. Bottom: CAD model view of the same face.

The platform, in the AIT hall, can be seen in Figures 2 and 3. Note that the back face of the spacecraft is covered with a solar panel for flight and that the dragsail has been reallocated to the back panel from former designs in [2]. A cutout is made in the back panel for dragsail deployment.

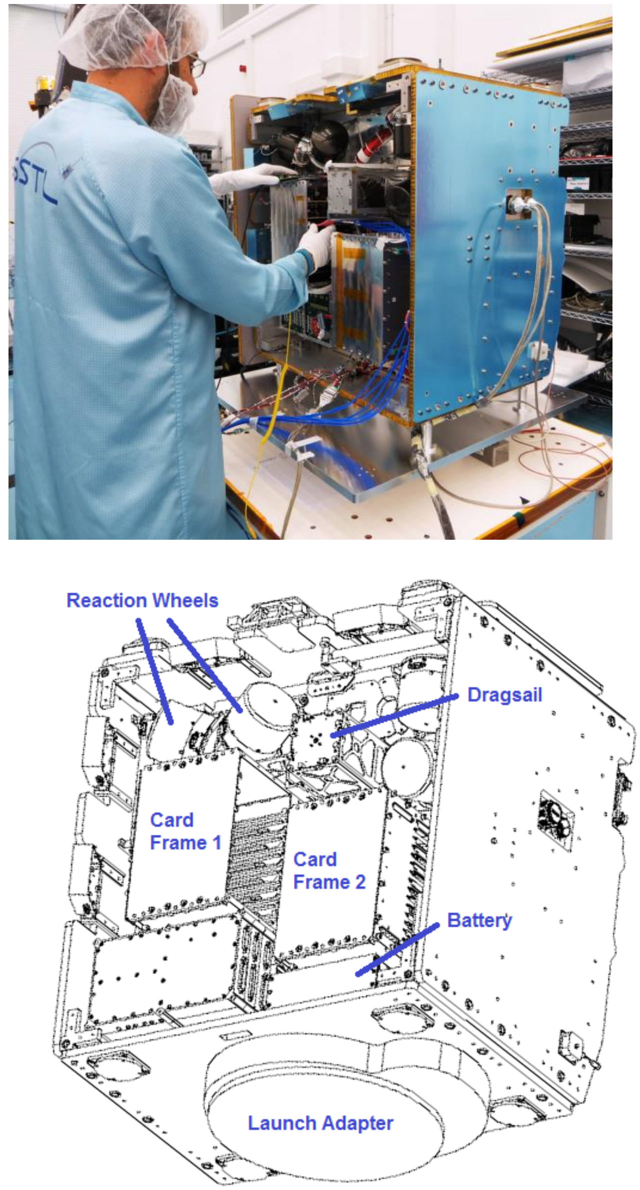

Figure 3. Platform - Back Face. Top: platform under integration. Credit: SSTL, 2017. Bottom: CAD model view of the same face.

2.2 Visual Based Navigation System

The Vision-Based Navigation is an experiment of proximity navigation between the satellite platform and a CubeSat, designated DS-2 [6]. At the beginning of the experiment DS-2 will be ejected by the platform and will drift gently away for several hours while the attitude is controlled to maintain a slow rotation. The main goal of the experiment is to evaluate navigation algorithms and a VBN sensor. The DS-2 CubeSat is a fully functional system and acts as an active target with integrated camera, GPS receiver and Inter-Satellite link (ISL). In this way, the VBN will capture navigation data of the position, orientation and relative velocity of the DS-2 CubeSat, which can be verified by the data and images captured by DS-2 and transmitted back to the mothership.

Dedicated image processing and navigation algorithms have been designed at Airbus Defence and Space and INRIA to meet the specific case of non-cooperative rendezvous [7]. Airbus Defence and Space is responsible for the overall VBN experiment and the navigation algorithms, while CSEM is in charge of the sensor.

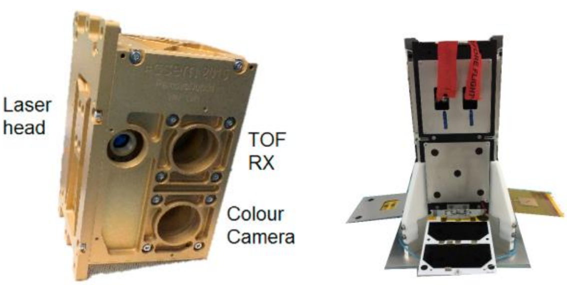

Figure 4. Left: Vision Based Navigation payload, Right: DS-2 target in deployed state

The University of Surrey have supplied the DS-2 target CubeSat with an attitude control system supplied by the University of Stellenbosch. The VBN sensor has two main subsystems: an off-the-shelf colour 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.

Figure 5 shows an image captured with the camera. The respective distance of the targets are quoted on the image. Below this, the figure 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. Performance requirements are verified by ensuring the hardware is capable of collecting the requisite number of images. The way in which the VBN algorithms are validated with respect to the VBN experiment and the tracking performance have been investigated in a separate paper[3].

Once integrated with the platform, the VBN experiment was verified through the system chain including transfer of images to the Payload Interface Unit (PIU) and transfer to operators.

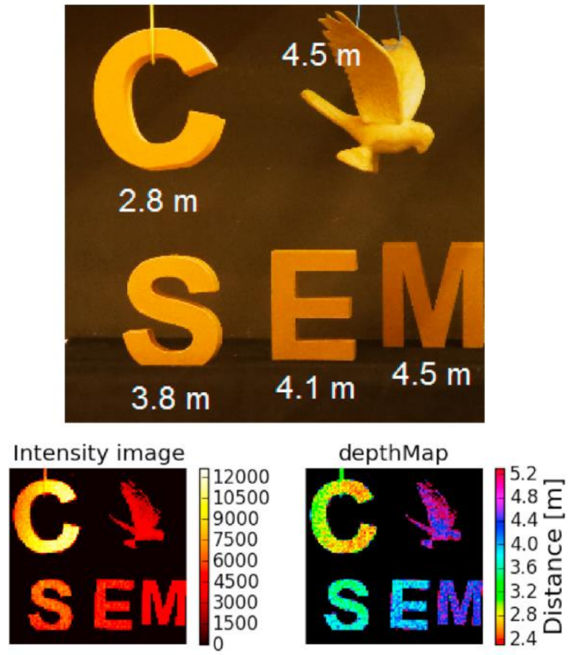

Figure 5. Top: test scene for VBN system, Bottom Left: showing image intensity in number of visible photons (more yellow objects are brighter). Bottom Right: 3D depthmap scene in metres.

The DS-2 target CubeSat includes an inter-satellite link (ISL), with a matching module integrated on the platform to collect data from the target. DS-2 streams GPS position, attitude data, imagery and general system telemetry one way over the ISL. On the platform, the ISL data is in turn streamed to the spacecraft PIU. Prior to integration, the ISL subsystems were extensively range tested on ground up to 500m with a 99% packet transfer success. Further, once integrated in to DS-2, the system was demonstrated at representative departure velocities performing all functions and streaming imagery and GPS location as expected on orbit.

2.3 Net Experiment

The NET payload will be the first in-orbit flight demonstration for a system catching large orbital debris via a high strength net. On the RemoveDebris mission artificial orbital debris of 2kg and 1m diameter will be captured, however, the 5m net used for this demonstration is already capable to capture debris in the 1.5m range and to return up to several hundred kilograms to Earth on a destructive trajectory. This experiment will be the next big step after successful demonstrations of the net deployment in both drop tower and on a parabolic flight.

The NET design is shown in Figure 6. The NET container has 275mm diameter and a height of 225mm. The total mass is 6kg.The high strength fiber net is deployed by concentric accommodated flight weights and a central lid, dragging the net. Motors and winches integrated within the weights are used to close the net after successful capture of the debris. The net deployment and closure will be achieved via redundant mechanisms. The NET will be released to capture the DS-1 debris target at 6m distance from the spacecraft.

Due to the complex dynamics of nets in microgravity, the NET has been tested on parabolic aircraft flights as well as a drop tower to verify correct opening and closing of the net.

As shown in **Figure 1**, the N2 stages involve the CubeSat, DS-1, deploying an inflatable sail system. The inflatable structure is constructed with five aluminum-polymer laminate cylindrical booms, with an average length of 45 cm. A set of four triangular polyester film segments or sails finish the structure. Initially the booms and sail are compacted into the satellite. The cutting of a burn-wire releases the booms and sail, whereby Cool Gas Generators (CGGs) activate to deploy the booms and side plates outwards and draw out the sail material. The central hub contains the un-deployed z-folded booms which are a two layer aluminum-PET membrane. To prevent the membrane from detaching during pressurization the ends of the booms are clamped between two aluminum disks. The principles of the deployable inflatable for the DS-1 experiment are explained in more detail in a separate paper[6]. The DS-1 CubeSat is electrically simple compared to DS-2, with only a power system and automated payload board to perform burn wire and CGG initiation. Repeated testing of the inflatables was performed to verify performance, including activation at the cold extreme case.

2.4 Harpon and target

The harpoon target assembly (HTA) is shown in Figure 7 and contains: structure, deployable boom mechanism, two frangibolts, target plate, harpoon and safety door. The full operation of the harpoon system has been detailed in other papers [1,7] The sequence for deployment of the target plate is as follows. Initially the target plate frangibolt is cut to release the outer plate. Then the Oxford Space Systems (OSS) deployable boom system is commanded to reel out the boom. The target plate is fixed to the end of the 1.5 meter boom and is pushed outwards. The OSS boom system consists of a carbon fiber boom rolled into a circle and unrolled outwards with a motor and guiding mechanism. Sensors are able to determine the length of the boom uncoiled and retraction is also possible, but not used on the RemoveDebris mission.

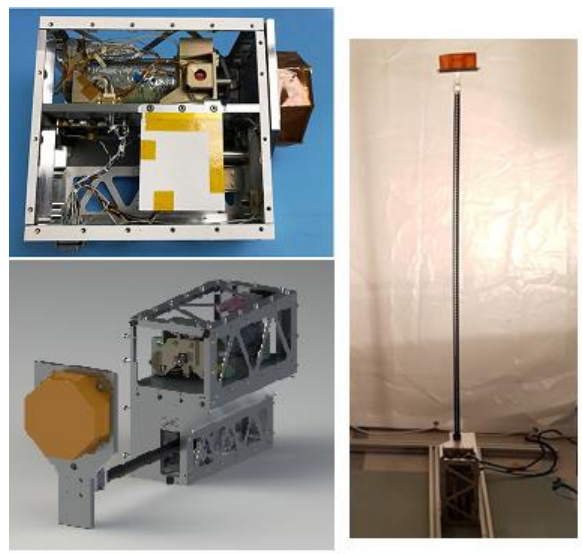

Figure 7. Top Left: inside the Harpoon target assembly (HTA); Bottom Left: CAD model of HTA with target partially deployed. Right: HTA with CPRF boom fully deployed during fire testing (HTA at bottom, target plate at top).

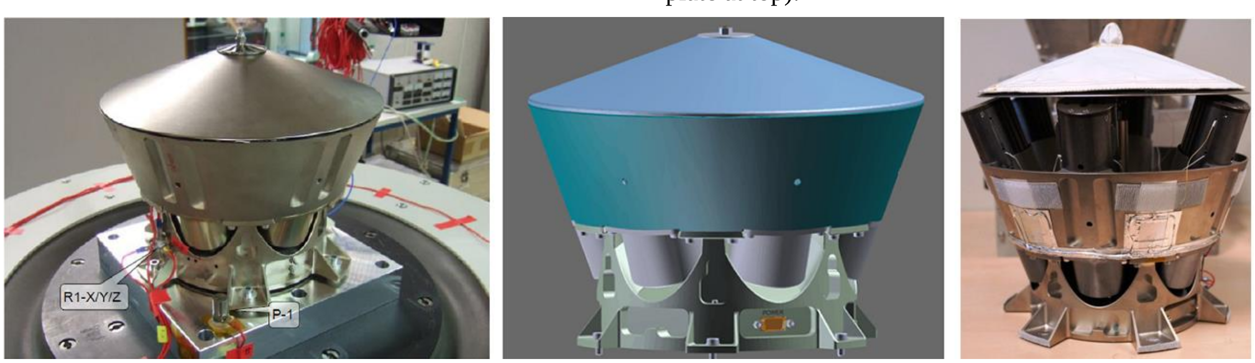

Figure 6. Left: NET undergoing vibration testing, Centre: NET CAD model; Right: Partially deployed system exposing flight weights.

Figure 7 shows the fully deployed boom system. Careful alignment is made on ground to ensure the harpoon is aligned with the centre of the target plate through use of a laser substituting for the harpoon. The plate is made of a metal honeycomb and is the same material the core of ESA's Envisat satellite is made of.

2.5 DragSail Experiment

The last experiment to be deployed is the dragsail. This system consists of two parts: an inflatable mast and a sail deployment mechanism located at the tip of the mast. Details of its development can be found in [8, 9].

The system utilizes a 'jack-in-the-box' deployment method, with a cool gas generator (CGG) that inflates the folded mast, and pushes the stored sail and its deployment mechanism out of its container. The inflatable cylindrical mast (1 m long, 90 mm diameter) consists of a tough aluminium-BoPET three-ply laminate. A BoPET bladder is used inside the cylinder to improve airtightness. Once full mast deployment and rigidisation has occurred, the inflation gas is vented symmetrically. The sail is then deployed using a brushless DC motor stored in the central shaft of the sail deployment mechanism which unfurls four 1.5 meter long carbon fiber booms, drawing the sail out

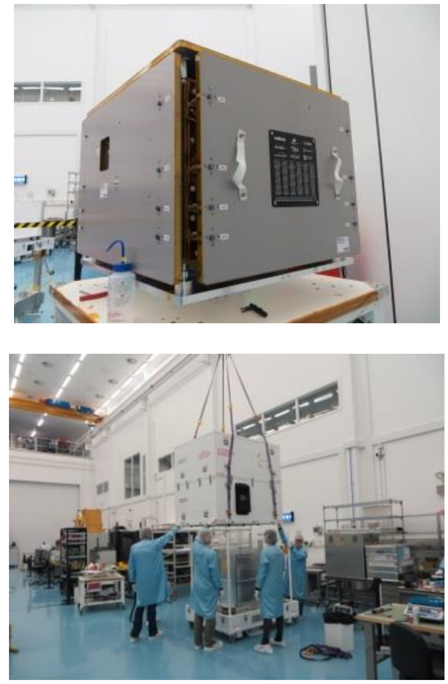

Figure 8. Top: RemoveDebris fitted with mounted handling panels; Bottom: RemoveDebris in shipping container

3 Launch and Deployment

After final system end to end and environmental testing, the RemoveDebris spacecraft was packaged for delivery and flight. 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 Cape Caneveral, the shipping container was removed and the RemoveDebris platform the platform was unpacked down to the clam shell, loaded into a cargo transfer bag (CTB) and embarked on to the CRS-14 Dragon as cargo in the pressurized section.

CRS-14 launched on 2nd April 2018 on a Falcon 9 launch vehicle, with the dragon capsule arriving and docking at the ISS two days on 4th April 2018. The RemoveDebris spacecraft was unloaded from the capsule pending the scheduled deployment.

After unpacking and removing the platform handling panels, the RemoveDebris satellite was loaded in to the Japanese Experiment Module (JEM) airlock on 6th June 2018.

Figure 9. Astronaut Richard Arnold loading the RemoveDebris spacecraft in to the JEM airlock

An airlock cycle was performed on 19th June 2018 and RemoveDebris transitioned externally to the JEM on the airlock slide table where the spacecraft was grasped by the Kaber interface on the Mobile Servicing System Special Purpose Dexterous Manipulator (MSS SPDM), detached from the slide table and transitioned to the deployment vector.

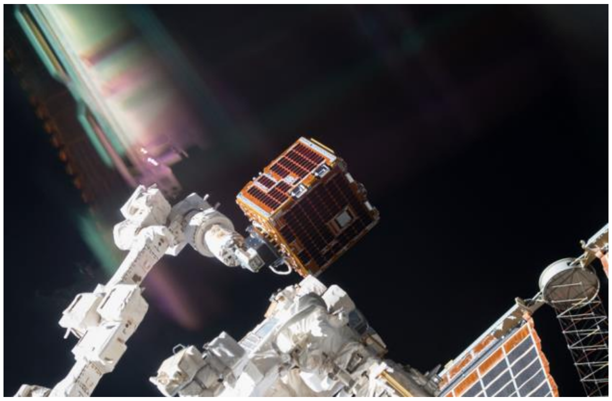

Figure 10. RemoveDebris mounted to the MSS SPDM ready for deployment

On 20th June 2018 RemoveDebris was deployed from the ISS with low tumbling rate allowing good observing conditions of the platform as it departed the station, as shown in Figure 11. Upon separation from the ISS, RemoveDebris powers up only a timer system which initialises the spacecraft system after 30 minutes to avoid any potential interference with the ISS.

Figure 11. Left: RemoveDebris observed from the ISS shortly after deployment, Right: Close up of platform

4 Commissioning Operations

4.1 Launch and Early Operations Phase (LEOP)

Deployment from the ISS marked the beginning of the RemoveDebris LEOP commissioning. Contact was made with RemoveDebris during the first pass after power up over the SSTL groundstation in Guildford, UK. This showed the spacecraft was performing nominally and the battery was fully charged. Initial commissioning progressed with switch on of the spacecraft OBC, followed by detumbling from the slow initial angular rate to a controlled attitude state. AOCS commissioning then progressed through higher order control modes until the platform was in a coarse Nadir pointing mode.

4.2 Platform Checkout

Key healthchecks were performed on key platform modules not already checked by virtue of moving to nadir pointing mode, including prime and redundant RF receivers, low rate transmitters and low level command links.

The spacecraft then performed a series of AOCS manoeuvres to verify performance against that required for executing payload experiments.

4.3 Payload Checkout

The critical data chains and experiment support systems were tested including verification of GPS, prime and redundant High Rate Transmitters (HRTs), Payload Interface Units (PIUs) and the Inter Satellite Link (ISL). This testing demonstrates full chain performance, from GPS/ISL to PIU to HRT to ground. The payloads are essentially "one-shot" systems, limiting the level of checkout that can be performed on the experiments themselves. All payload checkouts have shown good performance./

4.4 Payload Calibration and Characterisation

Once data paths had been established, commissioning moved on to calibration and characterisation of the imaging systems. The Supervision cameras and VBN 2D camera were tested over a range of exposures and frame rates which are planned for use on the experimental demonstrations. Imaging targets on the Earth were selected to check the bright and dark image signal levels. Typically, polar regions are used of the bright imagery, however due to the orbital inclination not reaching high latitudes, cloud tops were used instead for this purpose. Uniform zones such as the Sahara desert were also used to characterise the intrinsic sensor noise patterns.

Rehearsal sequences have been performed that include representative lighting conditions and spacecraft slews. An image captured during the Net experiment rehearsal is shown in Figure 12 showing the Earth partially in FoV, as expected.

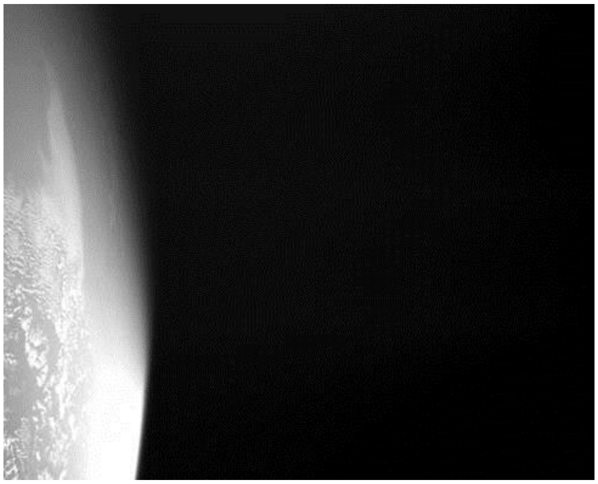

Figure 12. Supervision camera image captured during Net rehearsal operation

Spacecraft commissioning activities were completed end of August 2018.

5 Experimental Timeline

The RemoveDebris mission is now moving to the experimental demonstration phase, with the anticipated timeline given in the table below.

Table 1. RemoveDebris Experimental timeline

Event	NET Date	Description
Net Experiment	September 2018	Deployment and inflation of DS-1 CubeSat Deployment of Net and capture of DS-1
Visual Based Navigation Experiment	October 2018	Deployment of DS-2 CubeSat, transmission of imagery and attitude/position data Observation of departing DS-2 by VBN payload
Harpoon Experiment	February 2019	Deployment of Harpoon Target on end of boom Firing of harpoon into target Retraction of boom, target and harpoon
DragSail Experiment	March 2019	Deployment of Inflatable Boom and Sail Accelerated deorbiting of spacecraft

6 Conclusions

This paper has given an overview of the of RemoveDEBRIS mission, briefly describing the spacecraft and its experiments, and giving an update on the launch, deployment, and commissioning of the craft.

The RemoveDebris mission, now performing experimental payload operations, will be the first demonstration of key ADR technologies crucial to ensuring a space environment safe from space debris.

Acknowledgements

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