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Design of a Debris Removal & On-Orbit Maintenance Mission for Mega-Constellations

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Abstract— **This paper shows the results of the design of a mission providing a service of maintenance and removal of mega-constellations. The innovative concept inspiring the design of DeBROOM^2, Debris Removal and On-Orbit Maintenance Mission, is that a combination of different services can be performed in a modular and standardized way by a single unit servicing satellites in each orbital plane of the constellation. This is achieved through a servicer, which carries both the equipment to refuel target satellites and active-debris removal and propulsive kits, dedicated to the extension of the mission lifetime of cooperative OneWeb satellites, via the takeover of the attitude and orbital control system, as well as to de-orbit uncooperative faulty OneWeb satellites from LEO. The design covers all the areas of system level design, including the definition of system and mission requirements, concept of operations, and mission concept design, along with the design of the servicer and propulsive kits. The paper highlights and identifies the key challenges, the main drivers, and the major traded-off options during the mission concept design. Particular focus is given to the mission analysis aspects, with a computation of the delta-V that characterizes the key maneuvers necessary to serve one or a selection of orbital planes constituting the mega-constellation. The feasibility of the mission is demonstrated by the relevant budgets, along with the utilization of high TRL and COTS components in almost all the key elements of the mission.**

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1. INTRODUCTION

The advent of mega-constellations for satellite applications has revolutionized the Space Industry, with several major companies operating or planning to operate one to enter a promising and profitable market. Alongside their deployment, mega-constellations are causing an exponential growth of the number of satellites inserted in useful regions of near-Earth space, with the potential risk that such satellites will turn into space debris in the mid-long term. It is a fact that satellite lifetime relies on the amount of fuel they carry, and many satellites are forced to retire while otherwise completely functional because they run out of fuel or lose Attitude and Orbit Control System (AOCS) functionality [1]. Further, if for any reason these satellites become non-controllable (e.g., accidental failures, impact with space debris) the planned de-orbiting strategies might become ineffective, with uncontrolled satellites cluttering useful orbital positions and becoming a danger for the remaining constellation [2].

The aim of this paper is to propose a solution to this issue. DeBROOM[2], DeBris Removal & On-Orbit Maintenance Mission aims to provide a maintenance and removal service for mega-constellations. The innovative solution proposed in this concept is a combination of different services that can be performed, in a modular and standardized way, by a single unit servicing satellites in a mega-constellation. The present study focuses on servicing the OneWeb mega constellation. This is achieved through a chaser, which carries both the equipment to refuel target satellites and Attitude control and Propulsive Kits (APKs). The APK is a mini satellite unit that will be attached to target satellites to perform the following functions: extension of the mission lifetime of a cooperative OneWeb satellite in Low Earth Orbit (LEO), which will be achieved by the takeover of the Attitude and Orbital Control System, as well as to de-orbit an uncooperative, faulty OneWeb satellite in LEO by lowering its orbital altitude and reducing its orbital lifetime.

This paper focuses on and shows the results of the design of the demonstration mission, performed by a team of students from Cranfield University. The results of this exercise are critically discussed to highlight and identify the key challenges, the main drivers and the major traded-off options that occurred during the mission concept's design. The paper also provides an overview of the final baseline design of the servicer, APK, and concept of operations. Particular focus will be given to the mission analysis aspects, with a computation of the delta-V that characterizes the key maneuvres necessary to serve one or a selection of orbital planes constituting the mega-constellation. The feasibility of the mission is demonstrated by the relevant budgets, along with the utilization of high Technology Readyness Level (TRL) and Commercial-Off-The-Shelf (COTS) components in almost all the key elements of the mission.

The remaining part of this paper is organized as follows. Section 2 outlines the motivations and the eventual business case for proposing a mission for servicing mega-constellations. This gives the possibility of defining the mission's aim and objectives alongside the main top-level requirements of the mission. Based on these inputs, Section 3 shows the concept of operations of a possible demonstration mission. The overall mission analysis of the mission, with a service spacecraft servicing specific orbital planes of the OneWeb mega constellations, is presented in Section 4, where a trade space exploration is also carried on in order to select the best strategy to serve the highest number of satellites with one servicer. Section 5 and Section 6 outline the designs of the baseline service spacecraft and the APKs, respectively. The final section, Section 7, concludes the article by drawing some lessons learned from this investigation.

2. MISSION DEFINITION

This section provides the background and the motivation that has led us to analyze and develop a concept study for the removal and on-orbit maintenance of a mega constellation. The business case will then be used to define the mission statement and the eventual objectives of the specific mission, deriving top-level requirements that will shape the overall mission concept. The study uses and focuses on the servicing of OneWeb mega constellation, but the concept can be easily adapted to other constellations.

Motivation and Business Case

The increasing number of objects orbiting and operating in useful near-Earth regions impose new challenges in space traffic management and debris mitigation. With the recent deployment of mega-constellations the problem becomes even more relevant and opens a series of new needs that might create business opportunities in the near future. Among the different upcoming opportunities, the possibility of inspecting, upgrading, refueling, or extending the life of satellites seems to raise interest in the new space market alongside the actual removal of specific satellites when faulty or at their end-of-life [3]. According to the Northern Sky Research (NSR) forecast, on-orbit servicing will generate a revenue of $3.1B by 2029 and 78% of the total revenue will be attributed to life extension services for non-Geostationary Earth Orbit (GEO) satellites [4].

The nominal lifetime of satellites belonging to mega-constellations is relatively short, i.e., only 5 years of a nominal lifetime for OneWeb satellites [5]. The propellant carried on board does not allow for any mission extension or re-utilization of these platforms. These will be de-orbited at end-of-life. The eventual fleet renewal, operated by demising platforms at end-of-life and inserting new satellites in the same orbital positions, might become any more cost-effective in the long term. Other strategies that include life extension could potentially reduce the number of launches and, in the long term, the cost of maintaining the constellation operative with only specific components or propellent to be periodically changed or supplied, respectively. Such strategies might also be beneficial when for accidental reasons, the platforms cease operating. In most cases, only one of the subsystems is responsible for the failure, while the remaining parts of the spacecraft could still correctly operate. In such cases, takeover components could substitute the faulty subsystems to recover the nominal functions of the satellite. This is for example, the case of the AOCS takeover, or of the Electrical Power System (EPS) takeover.

In most of the planned mega-constellations, a large number of satellites will be inserted in already crowded orbits, with altitudes characterized by limited natural atmospheric decay, and in quasi-polar orbital planes, with the possibility of having close approaches among objects in adjacent orbit planes. These characteristics exponentially increase the risk of having collisions, especially if the satellites become non-controllable [2]. Accidental failures, impacts of space debris, or ineffective end-of-life strategies might result in non-operative objects cluttering useful orbital positions, limiting the eventual quality and profitability of the service offered by mega-constellations.

On the other hand, mega-constellations rely on standardized and mass-produced platforms. The similarity among the platforms helps define operations and tools that ease the eventual in-orbit servicing, refueling, and de-orbiting of such satellites. That is the case of OneWeb platforms, where specific docking interfaces, i.e., DogTag grappling fixture [6], have been included to facilitate eventual on-orbit recovery, servicing, or de-orbiting operations. Several studies have been carried on to explore eventual contingency plans for de-orbiting faulty OneWeb platforms, and commercial services, such as Astroscale, aim to lay down the fundamentals for a profitable business on active removal of such kinds of platforms [7].

Mission Aim and Objectives

Moved by the ingenuity and curiosity of exploring new mission concepts, a team of students at Cranfield University investigated the possibility of combining more than one of the eventual services needed to maintain mega-constellations. The overarching idea behind this project was to go beyond the current state-of-art of on-orbit servicing missions and to explore the possibility of having a sort of universal servicer able to provide all the necessary maintenance to make safer and more cost-effective the exploitation of the OneWeb mega-constellation. To work towards space sustainability and increase the cost-effectiveness of mega-constellations by servicing satellites in orbit and de-orbiting the ones that are no longer of use, the main goals of the project were:

- Design a servicing spacecraft to provide a range of services that includes inspection, life extension, and EOL active de-orbiting to the satellites of the OneWeb mega-constellation.
- Design a mission that can prove the concept of multi-purpose servicing of mega-constellations by demonstrating each service at least once and de-orbiting at least one target.

Mission Requirements and Constraints

Based on the objectives mentioned above, a list of top-level requirements was set to bound and shape the eventual design of the mission. Specifically, the following functional requirements were initially selected:

1. The mission shall provide AOCS takeover for at least one target OneWeb satellite
2. The mission shall provide refueling in orbit for at least one target OneWeb satellite to extend its life by 2.5 years.
3. The servicer shall visually inspect all the targets selected for the mission during the approach and servicing maneuvres
4. The mission shall de-orbit at least one target OneWeb satellite to bring it from its nominal orbit to a re-entring trajectory
5. The servicer shall perform at least one servicing operation per year

Alongside these top-level requirements, the following constraints were adopted:

1. The overall budget for the mission must not exceed £60M
2. The mission must last no less than 10 years
3. The mission must comply with the Inter-Agecy Space Debris Coordination Committee (IADC) mitigation guidelines at all stages [8].

3. MISSION ARCHITECTURE AND CONCEPT OF OPERATIONS

Given the broad scope of the mission and the numerous tasks to be accomplished, we systematically tackled the problem by first identifying the mission's main drivers and then trading off different options to obtain a suitable mission architecture that could fulfill the mission objectives and meet the imposed requirements and constraints.

Mission drivers and trade-offs

The mission objectives and requirements impose very strict interface requirements and drivers with the OneWeb satellite. OneWeb adopts an AIRBUS Arrow bus platform [9]. The mass of such a platform is up to 200 kg, with 100 kg available to host eventual payloads. The particular form factor, the location of the solar panels and antennas, and the positions of the DogTags allow in-orbit access and interface of only 3 out of the 6 sides of the central body. The main propulsion system is based on Hall-Effect Thruster (HET) technology and uses Xenon as a fuel [10]. The size of the main tank allows for carrying a total of 12 kg Xenon at begin of life with a blow-down feeding system.

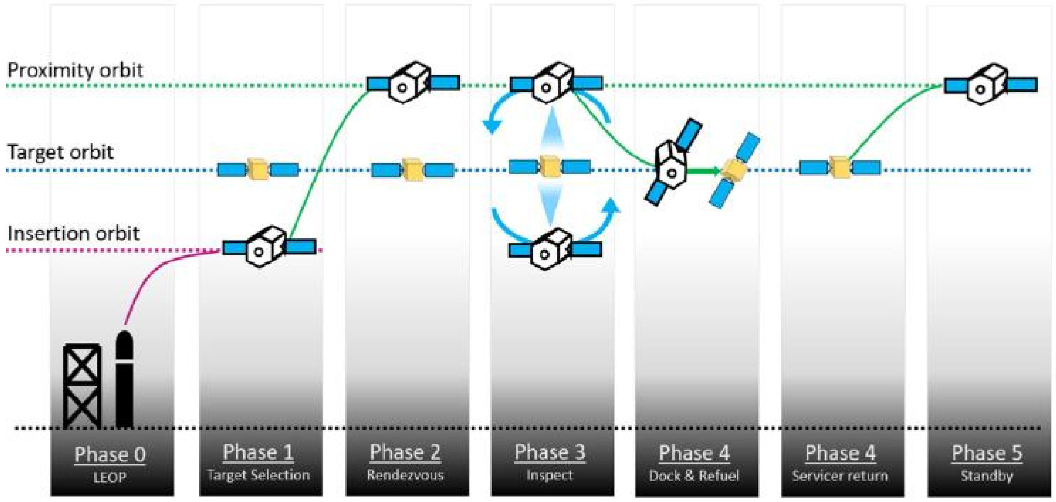


Figure 1 Mission operations - Refueling

Given the kind of operations to be performed, these characteristics drove the design and the selection of the baseline mission. For instance, even if a proper trade-off for selecting the capture mechanism was attempted, which included options such as tethered electromagnetic docking system, nets, harpoons, sticky materials, and trawling nets [11], these options couldn't provide the same level of convenience, reliability and high TRL as the option of using DogTags. Indeed, such devices are already used and installed on the target OneWeb satellites. Therefore, it appeared evident that this mechanism could be used as the primary way to capture the target, especially when this could cooperate during the operations, i.e., maintaining its nominal attitude. However, the case of having an uncooperative capture needed to be also taken into account to address all the situations when the targets might have tumbling conditions. Attempting a rendezvous with a DogTag in such conditions was not considered safe, and an alternative capture method was also included in the baseline design. The utilization of robotic arms was considered the best second option indeed, providing a certain degree of versatility to the capturing system even when there is a relative motion between the target and the chaser. Moreover, the arm could be used for grappling or attachment in all servicing scenarios, giving a more robust range of operations. For this reason, robotic arms were also included in the baseline configuration.

The selection of the methodology to perform the active removal task at end-of-life offered the opportunity of exploring quite interesting and, in some cases, innovative methods [11]. The options considered were: grappling arm, magnetic space tug, ground-borne laser, space-borne laser, brane-craft, solar/drag sails, expanding foam, soft projectiles, and propulsive kits. These options were traded in terms of their current TRL, the complexity of implementing them in space, the dangers and risks associated with their utilization, their adaptability to different non-nominal conditions, their effects on the overall system design, and the requirements imposed on specific subsystems. Propulsive kits to be attached to the target were considered the safest and most reliable option, which also had a sufficiently high TRL. Among the other pros, the utilization of de-orbit kits guarantees that the servicer does not take part directly in the de-orbit operations, thus providing the possibility to serve other satellites after having attached the kit to the target. Another advantage was found when a trade-off for an AOCS & EPS takeover was attempted. The same kit could include the necessary systems providing auxiliary AOCS and EPS capabilities if properly connected to the eventual faulty OneWeb satellite. For this reason, these kits were named APKs.

On the other hand, given the complexity of the refueling operations, which would also require robotic operations to use the fill and drain valves of the targeted satellites, we decided that these could be performed directly by the servicer. This would also reduce the number of units for storing, feeding, and pumping the Xenon fuel from the servicer to the target satellite. Tanks, feeding, and pumping systems could be easily located within the main servicer body, optimizing the available space of that platform.

Mission architecture and concept of operations

To meet the demonstration requirements, an initial mission was designed to service two satellites in a single orbital plane and de-orbit another satellite. This mission is therefore split into three distinct stages: refuel, AOCS takeover, and de-orbit, as illustrated in Figure 1, Figure 2 and Figure 3, respectively.

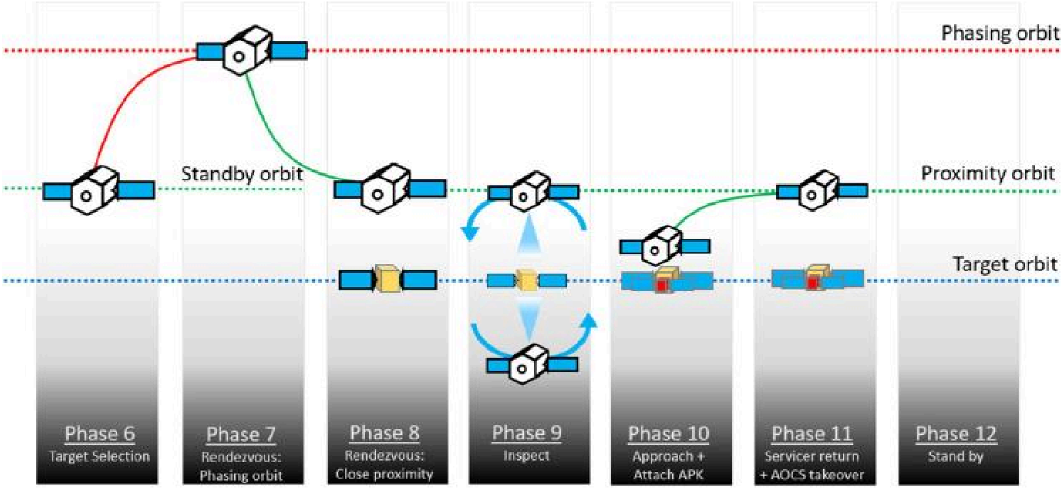


Figure 2 Mission operations – AOCS takeover

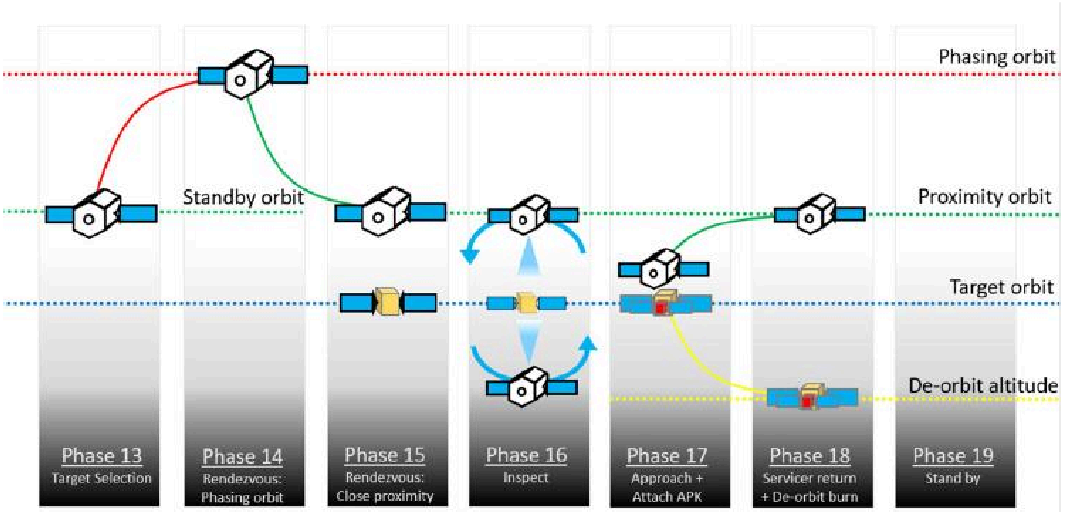


Figure 3 Mission operations – De-Orbit

The first stage begins at launch, where the servicer will be injected into a 550 km altitude at an inclination of 87°, before immediately performing a rendezvous maneouvre with the first target, as shown in Figure 1. This rendezvous brings the servicer into an orbit with a displacement of 1 km from the target spacecraft, at which point close proximity manoeuvres begin. The aim of these manoeuvres is to bring the servicer to a distance of 50 m with no relative velocity between the servicer and the target, by using low impulse monopropellant burns, to maintain a consistant, controllable movement rate and avoid collision with the target. The distance between the two bodies is measured using Laser Imaging, Detection and Ranging (LIDAR) system at all stages. At this point, visible and thermal spectrum cameras are used to detect surface condition and subsurface heat anomalies, such as cold spots indicating hardware failure and hot spots indicating overheating. The tumble vector and rate of the target is also detected to aid with docking, following detection of the target DogTag position. Once the target has been inspected, and for the purposes of demonstration it is assumed to be in operational condition and only in need of refuelling. At this stage the AOCS subsystem of the servicer brings it to within approximately 2 m of the target, at which point mechanical grappling can occur and the refuelling operation is undertaken.

Following the refuelling, the servicer returns to the close proximity displacement of 50 m, which acts as its standby position. This position is held as a balance between two criteria. The servicer must maintain a 50 m distance from any object not being serviced to prevent collision but must also be efficient in its use of propellant when distancing from a previously serviced body. After the selection of a viable second target, the servicer enters into a phasing orbit to change its true anomaly along the OneWeb orbit plane, and rendezvous with the new target, as illustrated in Figure 2. After having performed a rendezvous and inspected the second target, the second servicing method, namely the AOCS takeover takes place. The servicer attaches the APK to the target OneWeb satellite. For this, the AOCS system once again achieves a 2 m separation from the target, with mechanical grappling occurring using the target body as a fixture point. After being attached to the target satellite, the APK will immediately unfurl its solar panels and begin communications with a ground station to confirm it is operational. If the APK is confirmed to be working, servicer will return to the 50 m displacement zone. At this stage the APK will begin one of its two operations, in this case AOCS takeover. For this takeover mode, the APK will provide constant nadir pointing to the OneWeb satellite through its onboard AOCS system until a de-orbit manoeuvre is required at End-Of-Life (EOL).

The third phase of the demonstration mission concerns the de-orbit of a third pre-selected target. The servicer direct itself to rendezvous with a third target and follows an identical APK attachment procedure as before. However, the APK does not begin AOCS takeover but performs a de-orbit burn immediately after being released by the service, bringing the target into a controlled re-entry. Following this third stage the servicer remains in a stand-by orbit, where it can respond to future servicing and de-orbit requests from the client as required.

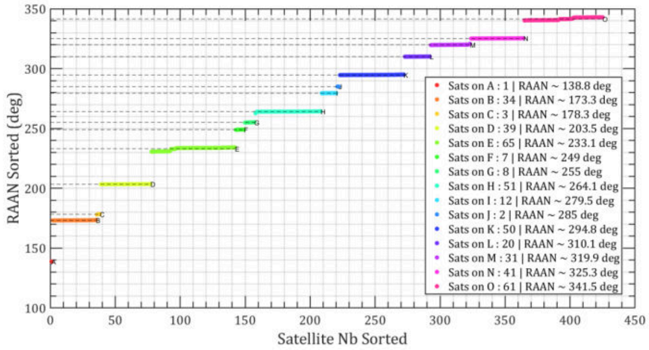


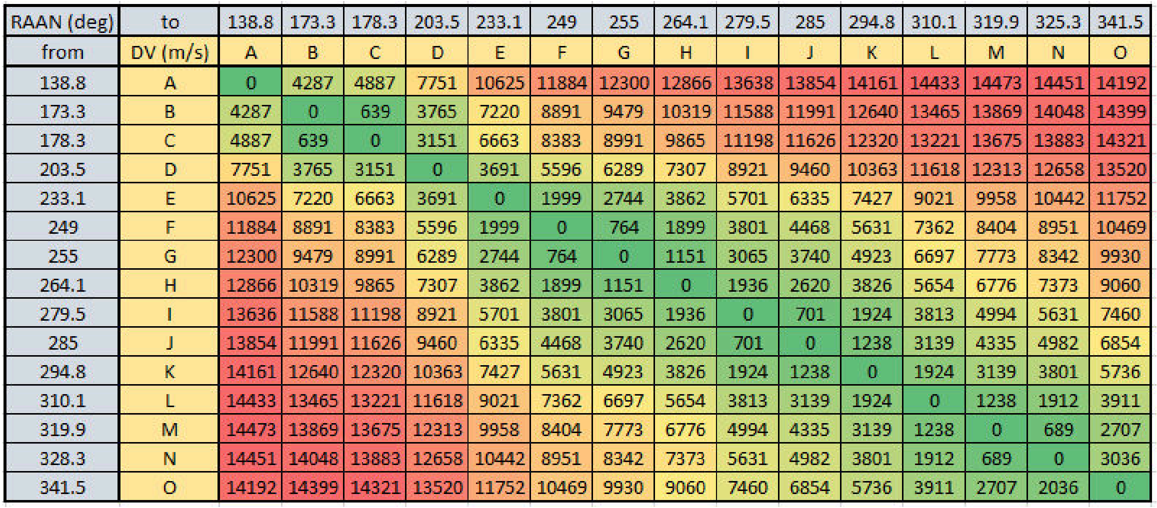
Figure 4 OneWeb orbital plane distribution

4. MISSION ANALYSIS

The complex series of operations of the demonstration mission translates into a set of required maneuvers that need to be accomplished by the servicer and the APK. A preliminary estimation of the required delta-V was performed, and different options were traded-off. This section summarizes this study's main findings and demonstrates the preference for having a servicer operating in each of the orbital planes of the OneWeb constellation.

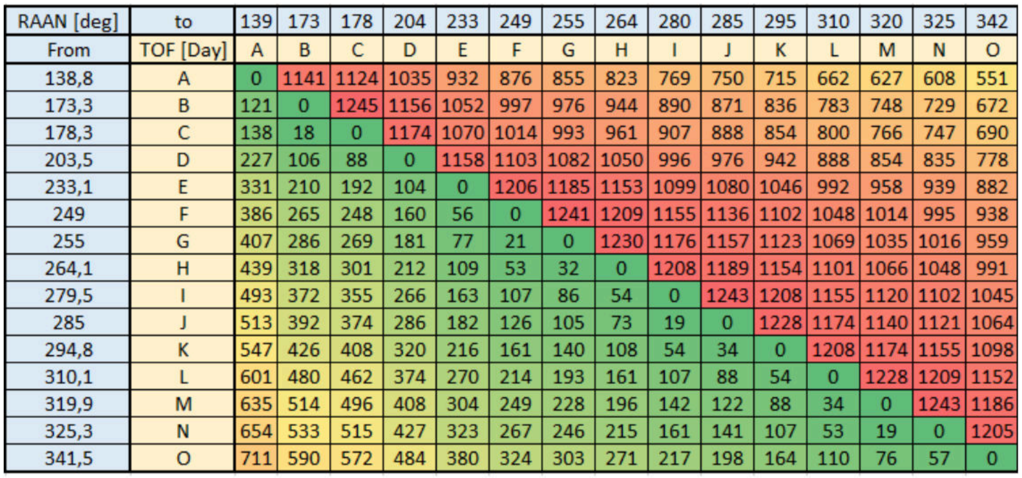
Analysis of the OneWeb constellation

The OneWeb constellation is defined as being composed of 15 orbital planes, named from "A" to "O". For simplifying the preliminary analysis, we assume that the nominal orbits are all circular and with an altitude of 1200 km, but differ only for their Right Ascentions of the Ascending Node (RAANs). At the time of this investigation, the OneWeb constellation was composed of 435 satellites, distributed as shown in Figure 4.



RAAN (deg)	to	138.8	173.3	178.3	203.5	233.1	249	255	264.1	279.5	285	294.8	310.1	319.9	325.3	341.5
from	DV (m/s)	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
138.8	A	0	4287	4887	7751	10625	11884	12300	12866	13638	13854	14161	14433	14473	14451	14192
173.3	B	4287	0	639	3765	7220	8891	9479	10319	11588	11991	12640	13465	13869	14048	14399
178.3	C	4887	639	0	3151	6663	8383	8991	9865	11198	11626	12320	13221	13675	13883	14321
203.5	D	7751	3765	3151	0	3691	5596	6289	7307	8921	9460	10363	11618	12313	12658	13520
233.1	E	10625	7220	6663	3691	0	1999	2744	3862	5701	6335	7427	9021	9958	10442	11752
249	F	11884	8891	8383	5596	1999	0	764	1899	3801	4468	5631	7362	8404	8951	10469
255	G	12300	9479	8991	6289	2744	764	0	1151	3065	3740	4923	6697	7773	8342	9930
264.1	H	12866	10319	9865	7307	3862	1899	1151	0	1936	2620	3826	5654	6776	7373	9060
279.5	I	13636	11588	11198	8921	5701	3801	3065	1936	0	701	1924	3813	4994	5631	7460
285	J	13854	11991	11626	9460	6335	4468	3740	2620	701	0	1238	3139	4335	4982	6854
294.8	K	14161	12640	12320	10363	7427	5631	4923	3826	1924	1238	0	1924	3139	3801	5736
310.1	L	14433	13465	13221	11618	9021	7362	6697	5654	3813	3139	1924	0	1238	1912	3911
319.9	M	14473	13869	13675	12313	9958	8404	7773	6776	4994	4335	3139	1238	0	689	2707
328.3	N	14451	14048	13883	12658	10442	8951	8342	7373	5631	4982	3801	1912	689	0	3036
341.5	O	14192	14399	14321	13520	11752	10469	9930	9060	7460	6854	5736	3911	2707	2036	0

Figure 5 Delta-V required to move within different orbital plane of the OneWeb constellation



RAAN [deg]	to	139	173	178	204	233	249	255	264	280	285	295	310	320	325	342
From	TOF [Day]	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
138,8	A	0	1141	1124	1035	932	876	855	823	769	750	715	662	627	608	551
173,3	B	121	0	1245	1156	1052	997	976	944	890	871	836	783	748	729	672
178,3	C	138	18	0	1174	1070	1014	993	961	907	888	854	800	766	747	690
203,5	D	227	106	88	0	1158	1103	1082	1050	996	976	942	888	854	835	778
233,1	E	331	210	192	104	0	1206	1185	1153	1099	1080	1046	992	958	939	882
249	F	386	265	248	160	56	0	1241	1209	1155	1136	1102	1048	1014	995	938
255	G	407	286	269	181	77	21	0	1230	1176	1157	1123	1069	1035	1016	959
264,1	H	439	318	301	212	109	53	32	0	1208	1189	1154	1101	1066	1048	991
279,5	I	493	372	355	266	163	107	86	54	0	1243	1208	1155	1120	1102	1045
285	J	513	392	374	286	182	126	105	73	19	0	1228	1174	1140	1121	1064
294,8	K	547	426	408	320	216	161	140	108	54	34	0	1208	1174	1155	1098
310,1	L	601	480	462	374	270	214	193	161	107	88	54	0	1228	1209	1152
319,9	M	635	514	496	408	304	249	228	196	142	122	88	34	0	1243	1186
325,3	N	654	533	515	427	323	267	246	215	161	141	107	53	19	0	1205
341,5	O	711	590	572	484	380	324	303	271	217	198	164	110	76	57	0

Figure 6 Waiting time within different orbital plane of the OneWeb constellation by exploiting the J2 effect

Out-of-plane maneuvres

A first investigation took place in order to assess the feasibility of having a servicer servicing more than one plane of the mega-constellation. The analysis was performed by considering two possible strategies [12]:

- *Impulsive maneuvres.* In this case, a delta-V is provided when the satellite is on the node given by the intersection of the initial and final orbital plane. This strategy allows for faster maneuvers among different orbital planes but results in higher values of delta-V needed, as shown by Figure 5.

- *Exploit the J2 effect.* In this case, the natural precession of the RAAN is used to change the orbital plane. This allows very low delta-V needed to perform the orbital change, with the main drawback of very long waiting time to pass from one plane to another, as shown in Figure 6. It is also worth noting that the precession drift allows for moving to orbits with lower values of RAAN, leading to an extremely long waiting time if the service should be provided to orbital planes of higher RAAN.

Unfortunately, these preliminary analyses showed that both strategies were unfavorable in terms of required delta-V or waiting time, respectively. This led us to consider, at least for the demonstration mission, that the servicer will operate only in one of the orbital planes of the mega constellation.

In-plane orbital maneuvres

Given the results in the previous subsection, the baseline mission assumes that the servicer will operate in a unique orbital plane. Keeping in mind that the selection of the orbital plane does not change the effectiveness of the maneuvres and the operations, for designing the demonstration mission and increasing the probability of servicing operations, we preferred choosing orbital planes where the satellites are more numerous. These led us to consider one among the D, H, K or N orbital planes for the mission's baseline, and in particular, we have chosen the N plane for this concept study. As a first analysis, two typologies of in-plane maneuvers were considered [12]:

- *Co-planar rendezvous.* This is a timed Hohmann to raise the orbit from the parking orbit at 500 km altitude to the OneWeb orbit at 1200km altitude to reach the first of the target satellites after launch. An illustrative

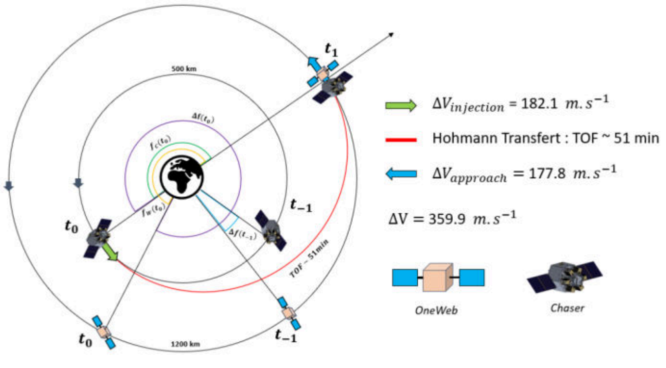


Figure 7 Co-planar rendezvous

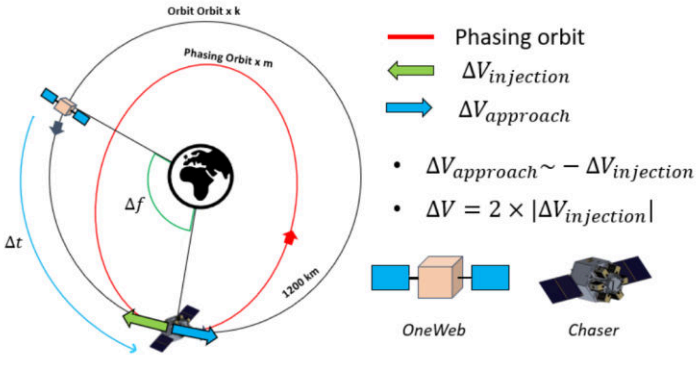


Figure 8 Co-orbital rendezvous

Table 1 Delta-V budget for the in-plane rendezvous maneuvres

Description	RDV Type	TOF [h]	ΔV [m/s]
RDV n°1	Co-Planar	$0.850 + \Delta t$	359.9
RDV n°2	Co-Orbital	359.017	12.3
RDV n°3	Co-Orbital	359.017	12.3
3 Oneweb	1 Co-O + 2 Co-P	$718.883 + \Delta t$	384.5
N Oneweb	1 Co-O + (N-1) Co-P	$N \times 359.017 - 358.167 + \Delta t$	$N \times 12.3 + 347.6$

sketch of such a maneuver is shown in Figure **7**.

- *Co-orbital rendezvous*. This is a re-phasing maneuver performed to move along different positions in the same orbit. A representation of such maneuver is shown in Figure 8.

Table 1 shows a first guess of the time for performing the maneuvers and the delta-V required for performing the rendezvous required for the demonstration mission. The numerical values are obtained under the assumption that the satellites are operating in their nominal orbits. The delta-V for co-orbital maneuvres has been calculated by assuming that the re-phasing is 180deg, which represents the worst condition for re-phasing maneuvres.

APK de-orbit maneuvres

The APK is equipped with a HET dedicated to de-orbit the compound formed by the OneWeb satellite and the APK itself. Given the non-impulse nature of the de-orbiting operation, AGI Systems Took Kit (AGI-STK) simulations were performed to estimate the time necessary for reaching a reasonable lower orbit, 210 km altitude, that could allow for passively de-orbit the system in 7 days. The simulation was set up so that the HET could operate in cycles of 70 minutes on-periods and 15 minutes off periods. It was estimated that the delta-V needed for performing such a maneuver is 525.7 m/s with a total time for maneuvering of 197 days.

5. APK DESIGN - OVERVIEW

The design of the APK followed a standard system engineering approach, with requirements derived from the overall mission concept and mission analysis but driven by the interface requirements with the servicer and the target satellite. Figure 9 shows the APK in its folded and unfolded configurations. The main body has dimensions of 0.96 m × 0.45 m × 0.96 m, while the solar panels reach 7.55 m wingspan, necessary for having enough power for the AOCS and EPS takeover of the OneWeb satellite. The figure shows also the configuration of the thrusters, with the HET located in the center of the outer face and 4 green monopropellant thrusters used for attitude corrections. One of DogTag is also visible on the top face of the system. Figure 10 shows the nominal interface configuration between the APK and the OneWeb satellite. The docking is performed through the magnetic coupling of the two DogTags. The final mass budget for the APK is shown in Table 2.

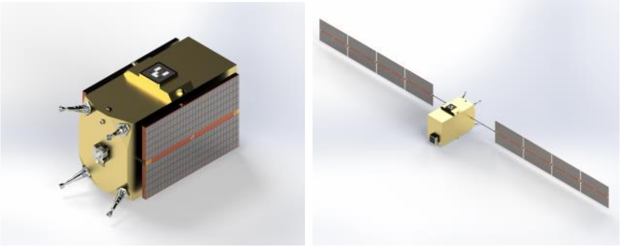


Figure 9 APK final design in its folded (left) and unfolded (right) configurations

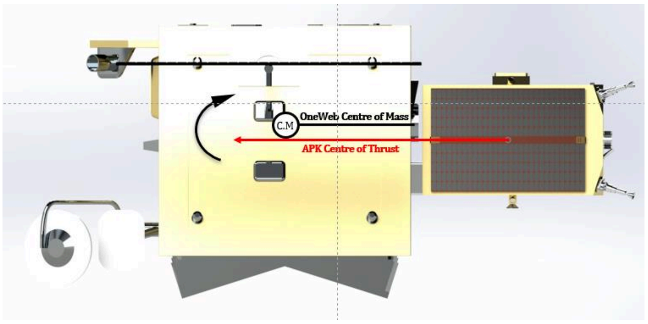


Figure 10 Mechanical interface between APK and OneWeb satellite

Table 2 Mass budget for the APK

Subsystems	Estimated Mass (kg)	Margin (%)	Total Mass (kg)
Structure	4.64	5.00%	4.87
Thermal	0.84	5.00%	0.88
Propulsion & De-orbit	7.74	5.00%	8.13
AOCS	3.32	5.00%	3.49
TT&C	1.60	5.00%	1.68
OBDH	0.10	5.00%	0.11
Power	22.84	5.00%	23.98
Total Dry Mass (without system margin)	42.37		43.13
Total Dry Mass (with system margin)	43.13	30.00%	56.07
Propellant			43.05
Total APK Mass			**99.12**

6. SERVICER DESIGN - OVERVIEW

The servicer spacecraft was designed to respond to the function of hosting the eventual APKs, the refueling system, the robotic arms, the eventual propulsion system, and enough propellant to perform the necessary maneuvers for the demonstration mission. The final configuration of the servicer spacecraft is shown in Figure 11. In the current configuration, the servicer is able to host 6 APKs, which are located on the top part of the bus and fixed to the main body of the spacecraft via specific adapters. Two robotic arms are also placed on top of a central cylinder to ease the eventual pick-and-place manipulations of the APKs and the eventual tools necessary for the refueling operations. Solar panels provide electrical power to the system. The main body of the spacecraft is a parallelepiped with hexagonal base of 2.8 diameter and 3.8 height in its stowed configuration. When the solar panels are deployed, they span for 7.85 m.

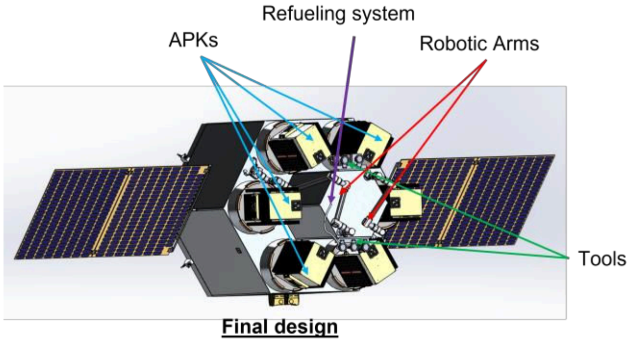


Figure 11 Final configuration of the servicer

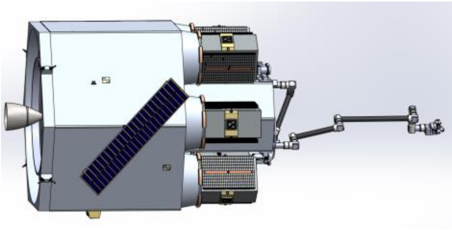


Figure 12 Refueling configuration

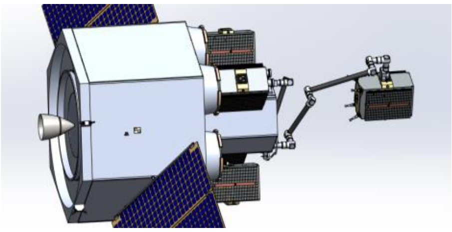


Figure 13 APK docking configuration

Figure 12 shows the servicer in its refueling condition, with the robotic arm extended and ready to refuel the eventual OneWeb satellite. Figure 13 sketches the eventual docking operation of the APK to the OneWeb satellite.

The final mass budget for the servicer is shown in Table 3. The overall weight of the system and the actual dimensions allow for being launched as one of the payloads of Falcon 9 [13].

Table 3 Mass budget for the Servicer and Total Mass at Launch Calculation

Subsystems	Estimated Mass (kg)	Margin (%)	Total Mass (kg)
Structures & Mechanisms	628.50	5.00%	659.93
Thermal	68.82	10.00%	75.71
Power	87.68	5.00%	92.06
TT&C	10.19	5.00%	10.70
AOCS & GNC	92.02	5.00%	96.62
Propulsion	245.25	5.00%	257.51
Other	85.97	5.00%	90.27
Total Dry Mass Servicer (without system margin)	1221.43		1282.80
Total Dry Mass Servicer (with system margin)	1282.80	30.00%	1667.64
Payload (Refuelling & Inspection)	78.54	5.00%	82.47
Payload (6 APKs)			594.72
Propellant	865.2	10.00%	951.72
Total Mass @ Launch			**3296.55**

7. FINAL REMARKS

The presented mission concept represents a first tentative towards the solution of the issues connected to the recent deployment of mega-constellations. With this preliminary study, we didn't want to find a definitive and optimal solution to these issues but explore and, perhaps, outline some of the key issues and considerations to be kept in mind for an eventual future and more detailed implementation of similar concepts. The key lesson learned during this process is twofold. The design demonstrates, in principle and under the boundaries defined by the assumptions made, the viability of a mission that provides multiple services to satellites of mega-constellations. However, the complexity of the operations and the amount of propellant necessary to perform multiple rendezvous in relatively low orbits undermines the profitability of an eventual business. A first estimate of the overall cost of the mission, based on Small Satellite Cost Model (SSCM) [14] for the APKs and the Unmanned Space vehicle Cost Model (USCM) [15] and QuickCost for the Servicer, provided a cost around £182M for the overall mission, which was way above the threshold initially imposed as a constraint. However, the extensive utilization of COTS components, which strongly characterize the new space economy, might produce sensible reductions in these cost estimates. For example, in

[17], it is optimistically predicted that the reduction due to the use of COTS components might lower the total costs of a mission by even a factor of 5, potentially bringing the cost under the £60M cap initially imposed by the mission requirements. Thus, utilizing new technologies and COTS components would definitively increase the profitability of such servicing missions and, therefore, the business growth associated with them.

An indirect benefit of this study has been the involvement of around 14 postgraduate students. This study benefitted from their work and creativity, and the students have been exposed to some of the challenges they will face during their careers in the space industry over the next few decades. Many in the space sector are working to make the use of space sustainable. New challenges, such as the one addressed in this paper, require us to be creative and go beyond standard practices and conventional solutions, and we offer this study as another step toward that goal.

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REFERENCES

[1] A. H. Sánchez, T. Soares and A. Wolahan, "Reliability aspects of mega-constellation satellites and their impact on the space debris environment," 2017 Annual Reliability and Maintainability Symposium (RAMS), 2017, pp. 1-5, doi: 10.1109/RAM.2017.7889671.

[2] J. Radtke, C. Kebschull, E. Stoll, Interactions of the space debris environment with mega constellations—Using the example of the OneWeb constellation, Acta Astronautica, Vol. 131, 2017, pp. 55-68, https://doi.org/10.1016/j.actaastro.2016.11.021 .

[3] M. Luu, D. E. Hastings. "Review of On-Orbit Servicing Considerations for Low-Earth Orbit Constellations," AIAA 2021-4207. ASCEND 2021. November 2021, https://doi.org/10.2514/6.2021-4207

[4] Northern Sky Research "In-Orbit Satellite Services Pave The Way To Manage Space Assets," 2020. Accessed: Oct. 13, 2021. [Online]. Available: https://www.nsr.com/nsr-report-in-orbit-satellite-services-pave-the-way-to-manage-space-assets/

[5] H.G. Lewis, T. Maclay, J.P. Sheehan, M. Lindsay, "Long-Term Environmental Effects of Deploying the OneWeb Satellite Constellation", 70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019, IAC-19-A6.2.4

[6] T. MacLay, J. Goff, J.P. Sheehan, E. Han, (2020). "The development of commercially viable ADR services: Introduction of a small-satellite grappling interface". Journal of Space Safety Engineering. 7 (3): 364–368. doi:10.1016/j.jsse.2020.08.002. S2CID 208652675.

[7] J. Forshaw, R.d.V. van Steenwijk, S. Wokes, S. Ainley, A. Bradford, J. Auburn, Preliminary Design of an End-of-life ADR Mission for Large Constellations, 70th International Astronautical Congress (IAC), Washington DC, US, 21-25 October 2019, IAC-19,A6,6,9

[8] Inter-Agency Space Debris Coordination Committee, "IADC-02-01 Space Debris Guidelines revision 3", Accessed: Oct. 13, 2022 [Online]. Available: https://www.iadc-home.org/documents_public/view/id/82#u

[9] Airbus D.S, "Arrow Platform Brochure", Accessed Oct. 13, 2022 [Online]. Available: https://airbusus.com/wp-content/uploads/2021/06/ARROW_Brochure-US-06.28.21.pdf

[10] H.J. Kramer. OneWeb Minisatellite Constellation for Global Internet Service. URL: https://directory.eoportal.org/web/eoportal/satellite-missions/o/oneweb. (last accessed: 05.04.2022)

[11] A. Ledkov, V. Aslanov, Review of contact and contactless active space debris removal approaches, Progress in Aerospace Sciences, Vol. 134, 2022, https://doi.org/10.1016/j.paerosci.2022.100858

[12] V.A. Chobotov, Orbital Mechanics, third ed., American Institute of Aeronautics and Astronautics, Reston, Virginia, 2002, https://doi.org/10.2514/4.862250

[13] Space X, "Falcon User's Guide", September 2021, Accessed: Oct. 13, 2022. [Online]. Available: https://www.spacex.com/media/falcon-users-guide-2021-09.pdf

[14] E. Mahr, A. Tu, and A. Gupta, "Development of the Small Satellite Cost Model 2014 (SSCM14)," 2015.

[15] J. Wertz, D. Everett, and J. Puschell, Space Mission Engineering: The New SMAD, Microcosm Press

[16] NASA, "Cost Estimating Handbook", Accessed: Mar. 13, 2022, [Online]. Available: https://www.nasa.gov/content/cost-estimating-handbook

[17] B. Fox, K. Brancato, and B. Alkire, "Guidelines and Metrics for Assessing Space System Cost Estimates.", Mar. 13, 2022 [Online]. Available: https://www.rand.org/content/dam/rand/pubs/technical_reports/2008/RAND_TR418.pdf

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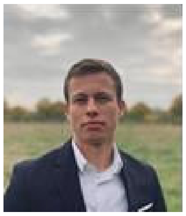

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