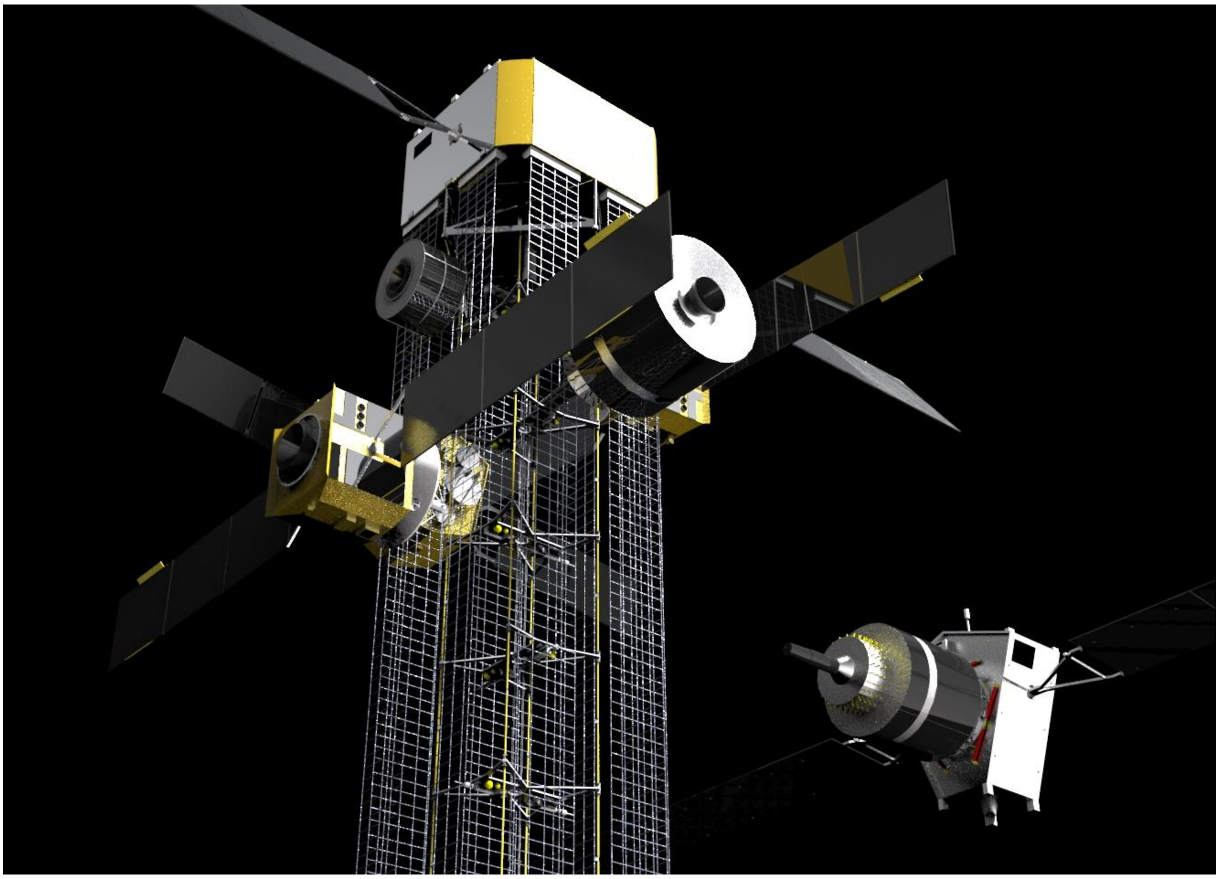

The Necropolis System

Sustainable Disposal of End of Life GEO Satellites

Issue: 1

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Guest Associates (Europe) Ltd. (GAE) was founded in 1992, initially as a subsidiary of Guest Associated Incorporated in the USA. Subsequently GAE became wholly owned by the company founder – Roger Longstaff – and for over 20 years has been a vehicle for administering his aerospace consultancy services to industry, institutions and government.

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Hempsell Astronautics Limited (HAL) was started in 2014 as a vehicle for the consultancy work and projects of Mark Hempsell. It can provide consultancy services on all aspects of astronautical systems engineering drawing upon on a wide range of experience in all kinds of space systems. It has all the tools necessary for design and analysis at the concept and feasibility stage stages and has a proven capability to produce concept level spacecraft designs. The company's special expertise is applying systems engineering processes to space projects.

Sustainable Disposal of End of Life GEO Satellites

Final Report on NSTP2 Grant for Exploratory Ideas Study

Contract Number: RP10GO348E65

Issue: 1 - 22nd Sept 2016

Written by

Roger Longstaff – Guest Associates (Europe) Ltd.

Mark Hempsell – Hempsell Astronautics Ltd.

Sustainable Disposal of End of Life GEO Satellites

Executive Summary

In 2002 ESA calculated that there could be a 1 in 25 chance of a collision in geosynchronous orbit by 2030, however, fourteen years later it appears that this calculation may have underestimated the threat. Such a collision would produce a shower of fragments that would perpetually intersect the geostationary arc, causing damage to operational satellites, or even destroying them, and producing more fragments and an exponentially growing debris field that could spread around the geostationary arc and make this unique resource unusable for the indefinite future. All current uses of this most favoured and valuable orbit would cease, and ambitious plans for the future would become impossible.

This study has provisionally determined that a mission to demonstrate the preservation and maintenance of the geostationary orbit is feasible and could be undertaken with a single Ariane launch. The mission, called Necropolis, would use two spacecraft; a "Hunter" spacecraft to collect non-functional satellites in geosynchronous orbit and take them to a "Terminus" satellite, where they would not be a hazard to navigation. Such missions would reduce the probability of collision in geostationary orbit, release "slots" for new satellites and provide a safer disposal for non-functional satellites than the currently unregulated (and ultimately unsustainable) "graveyard orbit". In addition, satellites coming to the end of their lives could be directly re-orbited to the Terminus spacecraft, resulting in a more sustainable disposal strategy. At least 6 long-non-functional satellites – including UK owned satellites such as Skynet 1 – could be deposited of to a safe location, and also that 6 satellites that naturally came to the end of their lives during the mission could be safely disposed of at the same location.

The study also identified the value of a precursor mission called "Scout" to reduce the uncertainties in the position and condition of non-functioning satellites and to validate some of Hunter's technologies and mission design. This would be a small satellite, probably with electrical propulsion which moves between geostationary and graveyard obits visiting potential target satellites.

The study also established that the UK upstream space industry could have a significant role in the production of the space segment of the Necropolis. Some technologies such as harpoon and the T6 ion engine are unique to the UK. At the system level the study found that the Hunter spacecraft could be based on the BepiColumbo Mercury Transfer Module, in which the UK has significant involvement and expertise.

Finally, the study recommends that this disposal concept should be externally evaluated, and that if found to be of merit should be progressed into a larger feasibility study phase, while opening discussions with other spacefaring nations, institutions and international regulatory bodies, with a view to gaining a consensus on the threat to geostationary operations, updating the regulatory regime and devising a common strategy to mitigate the threat.

Sustainable Disposal of End of Life GEO Satellites

Contents

Acronyms

AOCS, Attitude and Orbit Control System
ABM – Apogee Boost Motor
EP - Electric Propulsion
GAE - Guest Associates (Europe) Ltd
GEO - Geostationary Earth Orbit
GNC – Guidance Navigation and Control
GSO - Geosynchronous Orbit
GYO - Graveyard Orbit
HAL - Hempsell Astronautics Limited
ITU - International Telecommunications Union
LEO - Low Earth Orbit
MTM - Mercury Transfer Module
TriDAR - Triangulation and LIDAR Automated Rendezvous and Docking
UK - United Kingdom
USIS – Universal Space Interface Standard

Terminology

Necropolis – the satellite collection and storage system, consisting of:

Hunter – the spacecraft that collects non-functioning satellites
Terminus – the satellite that stores the non-functioning satellites
Scout – a pre-cursor reconnaissance spacecraft demonstration mission

Sustainable Disposal of End of Life GEO Satellites

1. Introduction

This document is the final report of the study into the Sustainable Disposal of End of Life GEO Satellites, which was supported by an NSTP2 Grant. This study had the objective of undertaking a preliminary evaluation of a concept to collect and store geostationary satellites that are dead and currently in uncontrolled orbits at or near geostationary altitudes.

Over almost half a century there have been about 1,500 launches into the geostationary equatorial orbit (GEO). This Earth orbit, with an altitude of 35,786 km over the equator, is a mathematical singularity that allows satellites to appear motionless over the surface of the Earth, allowing fixed antennas to relay data and communications for civil and military purposes. To date it has been by far the most favoured location for spacecraft operations; the most saturated orbit; and, the only profitable one. It therefore has limited capacity. Moreover, as of 1st January 2016, only 471 of the spacecraft launched into GEO remained under active control, with over 1000 "non-functioning" and drifting in the geostationary region (Ref. 1).

2. The Threat to GEO

When a satellite in GEO comes to the end of its life one of two things can happen: it either "dies" and ceases to obey commands from the ground station or it is boosted into a "graveyard orbit" (GYO). Since 2010, the International Telecommunications Union (ITU) has mandated that satellites coming to end of life must retain sufficient control and propellant to boost the satellite out of GEO, and into an orbit with a perigee at least 300 km above GEO, thus releasing the "slot" for a new satellite (Ref. 2). However, if an earlier launched satellite simply ceases to function it will remain in geosynchronous orbit (GSO), with a period of one sidereal day, and start to drift.

When a non-functioning satellite drifts it will retain its period (there is no air drag in GEO) but its orbital inclination will increase under the gravitational influence of the Sun and the Moon. The inclination will increase to about 15 degrees, and then decrease again, with a period of about 50 years. The satellite will also drift in an East/West direction around the equator, eventually settling at a "libration point" – a gravitational well consequent upon the non-uniformity of the Earth's gravitational field. There are two libration points – one at 105 degrees West and one at 75 degrees East. Figure 1 shows the ground tracks of 5 long-dead satellites at the Western libration point.

The satellites shown in Figure 1 are listed in Reference 1 as having settled at the 105W libration point, with periods that show they were never boosted out of GEO and that they have very similar altitudes. The intersecting ground tracks clearly show the possibility of collision. There are 48 other satellites stable at the 105W libration point and 75 satellites stable at the (75E) Eastern libration point (ref. 1). In 2002 an ESA study (ref.3) calculated that in a "worst case" scenario *"….there could be as many as 1700 satellites in the Geostationary orbit by the year 2030. 79% of these could be uncontrollable giving a 3.7% risk of collision, or 1 in 25 chance".* As reference 1 reports that in 2016 there are about 1500 objects in geosynchronous orbit it would appear that by 2030 the probability of collision could be significantly higher than 1 in

25! It is also important to note that every year active satellites are now being moved in orbit when tracking data indicates that another object will make a close approach.

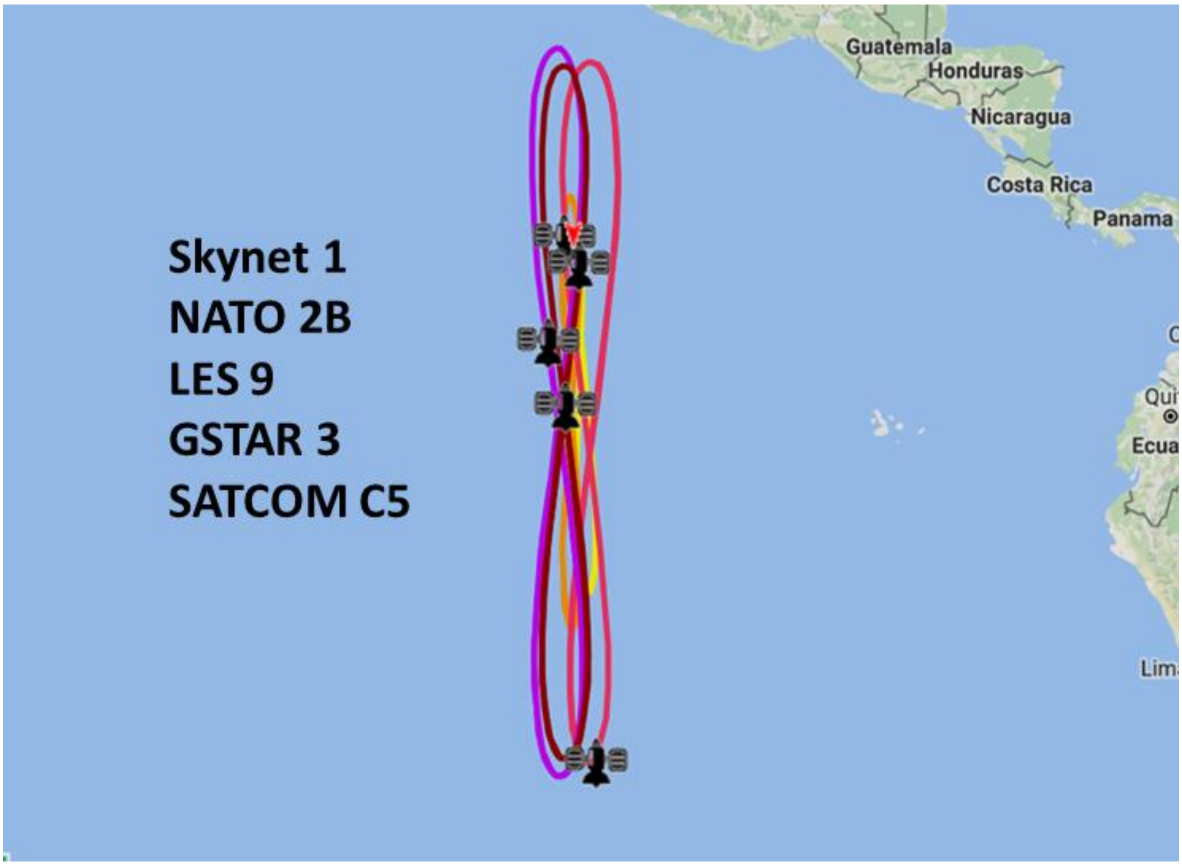

Figure 1: Ground Tracks of 5 of the 53 Satellites at Western Libration Points (credit: N2YO.com & Google Maps)

The consequences of a collision of two objects in GSO are unknown. While there have been observed instances of collisions in LEO (Low Earth Orbit) – for example including an Iridium satellite (ref. 4) – no objects have yet been observed to collide in GSO. However, if two objects in GSO each have inclinations of 15 degrees they could collide with a relative velocity of up to 1,591 m/s, which would shatter and fragment the spacecraft, producing a shower of debris that would intersect the geostationary orbit once every day. This could theoretically lead to a "Kessler Syndrome", where a debris cloud could spread around the geostationary arc that could interfere with or destroy all satellites in GEO and make it unusable for the indefinite future. In this case all of the current usage of the geostationary orbit would cease, and ambitious plans for the future, such as solar power satellites and orbital elevators, would become impossible.

At the present time not all of the GEO satellites that come to end of life are being boosted into a graveyard orbit, as some "die" in operation, thus denying a re-boost opportunity. Consequently, the number of non-functional and drifting objects in GSO is continually increasing, making the potential problem worse. There is also a conceptual problem with the graveyard orbit solution itself - the GYO is completely unregulated, such that if current operations continue indefinitely a collision within the GYO becomes more probable, potentially creating a debris field that itself could intersect the geostationary orbit below and cause a Kessler Syndrome in GEO.

3. The Necropolis Concept

This preliminary study examines a novel concept that could reduce the risk of collisions in GEO and enable continuing operations for decades and centuries to come. Clearly, either the objects need to be de-orbited to burn up over the Earth's ocean or to be physically removed to a safe location, where they can be monitored and will not be a hazard to navigation. As a deorbit manoeuvre to return to Earth would require sufficient propellant at end of life to impart a velocity change of 1,492 m/s (requiring a satellite to retain about 60% of its end of life mass as propellant) the preferred solution is a re-boost to an altitude sufficiently above GEO where collision becomes impossible. There have been several studies that have examined such spaceflight operations (eg. ref. 3).

This study will, however, examine a novel solution called "Necropolis" (a graveyard at a remote location) that uses a "Hunter spacecraft" to capture non-functioning satellites from GEO and GYO, and takes them not to an unregulated and potentially dangerous graveyard orbit, but to a "Terminus satellite" orbiting above the current graveyard orbit, where multiple objects could be secured in a safe location, preventing future mutual collisions and reducing the overall collision cross section.

In addition operational satellites coming to the end of life could rendezvous directly with the Terminus satellite, rather than re-orbit to the potentially dangerous graveyard orbit.

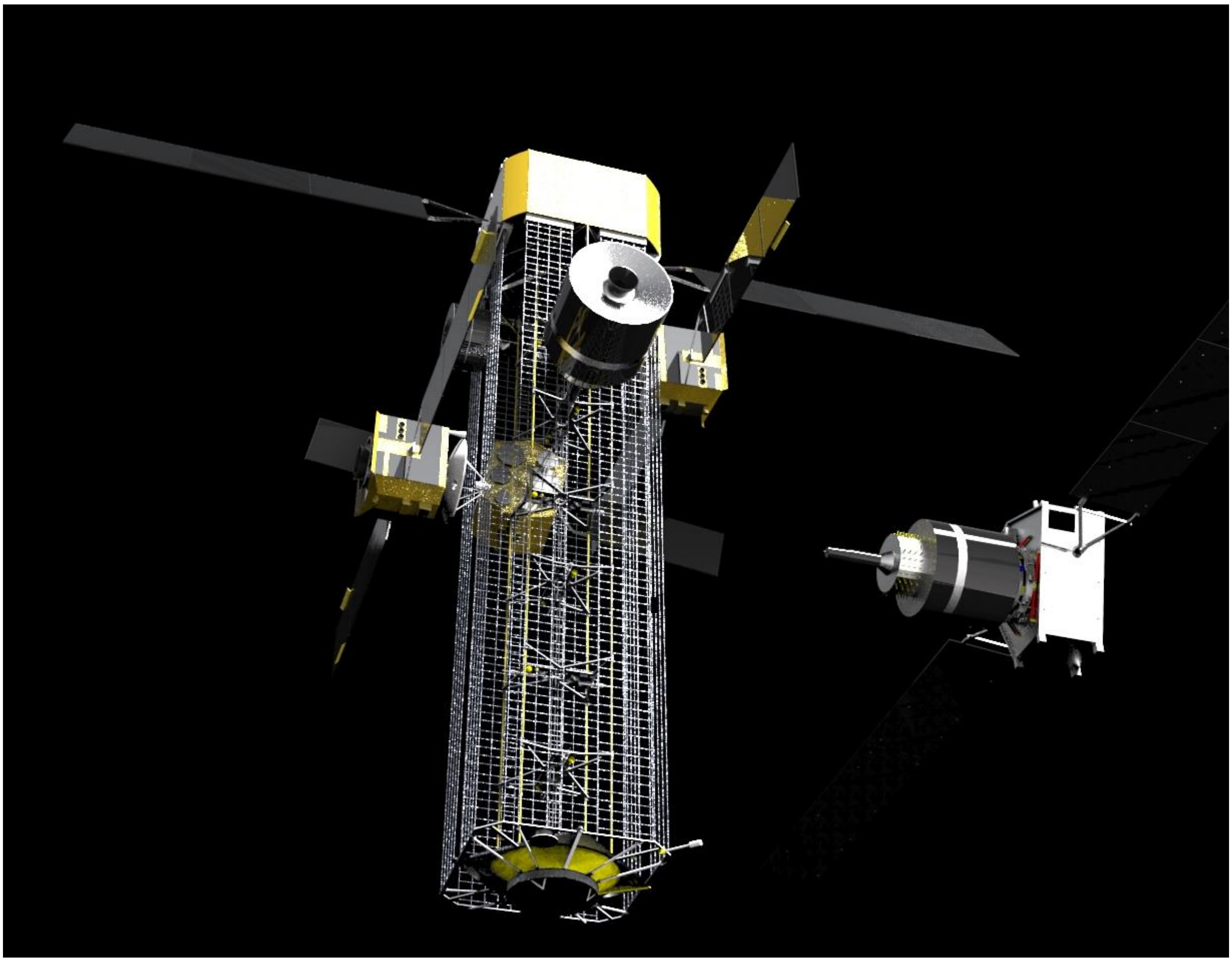

Figure 2: Necropolis System; Hunter Approaches Terminus with Non-functioning Satellite.

4. A Demonstration Mission

The focus of this study is that it may be possible to launch a demonstration mission, on either a single Ariane 5 or Ariane 64 launch vehicle, that could re-locate at least 6 dead satellites (with relevance to UK responsibilities and potential liabilities) to a Terminus satellite. A further goal was added during the study – that an equal number of current satellites that were coming to the end of their operational lives could be directly re-orbited to the Terminus, rather than to a GYO. It was initially decided that the Terminus should orbit 600 km above GEO in order to be clear of the currently employed GYO.

The Necropolis demonstration flight could then lead to either:

- expansion of the demonstration systems,
- repeat builds of the demonstration system,
- the development of more capable operational system .

5. Target List

A selection of long dead target satellites, either owned by the UK (e.g. Skynet 1), or with a UK relationship (e.g. NATO 2b, METEOST 1) was selected from the UK Registry of Outer Space Objects (ref. 5). This list was discussed with the responsible department of the UK Space Agency and agreed as a satisfactory objective for re-location. The list is shown in Table 1.

Table 1: Target List (agreed with UKSA)

NAME	DESIGNATION	Semi-Major Axis (km)	Inclination (degrees)	Longitude (degrees)
SKYNET 4b	1988-109a	42,314	15.4	57.7E
SKYNET 1a	1969-101a	42,164	8.3	105W
NATO 1	1970-021a	42,163	8.9	105W
NATO 2b	1971-009a	42,164	9.9	105W
SKYNET 2b	1974-094a	42,171	11.8	75E
METEOSAT 1	1977-108a	42,194	13.1	75E

Note that there was an attempt to re-orbit the first satellite on the list (Skynet 4b) to a GYO at end of life. However, the satellite did not achieve the minimum altitude gain required by Reference 2, and achieved an orbit only about 150 km above GEO. As such, this satellite has been selected as the first target for re-location, as if the operation resulted in a catastrophic failure the resulting objects would not threaten the GEO directly.

6. System and Operational Concept

A single Ariane 5 or Ariane 64 launch vehicle can place up to 10,500 kg into a geosynchronous transfer orbit, and a virtually identical payload into a super-synchronous transfer orbit with an apogee 600 km above GEO altitude. Into this orbit it is proposed to launch a spacecraft stack, that will circularise itself using on board chemical propulsion into an equatorial, circular, super-synchronous orbit 600 km above GEO. The stack will be comprised of:

a) A “Hunter spacecraft”, that will detach from the injected stack and proceed to rendezvous with target satellites, capture them and return them to;

b) A “Terminus spacecraft”, that will secure the target satellite, once released in close proximity by the Hunter.

The process will then repeat itself for the other target satellites.

While the Hunter is in the vicinity of the Terminus it will secure end of life satellites that have re-orbited themselves directly to the vicinity of the Terminus by capturing them and then re-locating them, as described above. These processes will repeat themselves until the Hunter’s propellant supply is exhausted, when in a final act it will be attached itself to the Terminus.

7 Mission Analysis

The mission begins when the spacecraft stack has been injected into a circular, equatorial orbit of 36,386 km altitude (600 km above GEO). The Hunter and Terminus spacecraft will separate and the Terminus will deploy its tower, containing 12 harpoon capture systems (see section 8).

The first target satellite in GSO will be selected from a trajectory optimisation analysis that cannot be performed until a launch date and time has been decided. The targets right ascension of ascending node, and argument of perigee, will determine the most propellant efficient mission sequence. Once the selection of a first target has been determined the Hunter spacecraft will use its electric propulsion subsystem to increase its inclination to match that of the target. This will involve the Hunter firing its electric propulsion (EP) T6 ion engines normal to the orbit plane, for 60 degrees around the equatorial node, then firing its engines for 60 degrees around the following equatorial node, also normal to the orbital plane but in the opposite direction. Thus the engines will thrust for 240 degrees for each 24 hour orbit, and this will continue until the Hunter has achieved the same orbital inclination as the target.

Section 8 will show that the Hunter spacecraft has an initial mass of 2,400 kg, and depending on the target sequence, the inclination of the targets and the mass of the target the transit time of this operation is calculated to take between about 80 and 145 days. Once the Hunter has matched the inclination of the target it will fire its EP engines continuously in a retrograde direction to initiate a continuous spiral decent until it matches the altitude of the target, when a rendezvous and capture procedure will be performed (see section 8).

When the target has been secured by the Hunter the EP propulsion will be fired in a prograde direction, raising the stack to the altitude of the Terminus. An inclination change will then be performed and the target will be released in the vicinity of the Terminus in order to be permanently secured to the spacecraft.

The performance of the T6 EP system has been discussed with the UK manufacturer – QinetiQ – and it was agreed that the following parameters were a reasonable representation of a single engine:

Thrust: 145 mN
Exhaust velocity: 42,000 m/s
Total impulse: 11.5 MNs

The Hunter will employ 4 T6 thrusters, with 2 firing at any one time, in an identical manner to that employed for the Mercury Transfer Module (MTM) of BepiColumbo.

A computer program has been written that is based on the mathematical approach developed in Reference 6. This uses analytical, rather than numerical, integration and was discussed with a specialist at Airbus, who provisionally approved the methodology. The results for a complete mission sequence are shown in Table 2.

Table 2: Mission Analysis Results

SATELLITE	Inclination (deg)	Round Trip dV (m/s)	Target Mass (kg)	EP Prop. Mass (kg)	Thrust Time (days)	Transit Time (days)
SKYNET 4b	15.4	2026	929	135.1	256.5	339.7
SKYNET 1a	8.3	1112	237	61.9	103.8	155.6
NATO 1	8.9	1190	237	64	107.3	160.9
NATO 2b	9.9	1318	237	68.4	114.7	172.1
SKYNET 2b	11.8	1562	237	77.9	130.6	195.8
METEOSAT 1	13.1	1730	452	86.7	145.4	218.1

In summary, the total Xenon propellant expended in the mission is calculated to be 494 kg, with an accumulated total thrusting time of 858.3 days and the total impulse is 21.51 MNs., showing that the Hunter design, with T6 EP thrusters, is capable of transferring all of the target satellites with a total transit time of 1,287 days (3.5 years). Once time for rendezvous and capture, orbit phasing, and relocation of newly arrived satellites at the Terminus has been added to the transit time it is estimated that the total elapsed mission time will be roughly 5 – 6 years. The existing MTM spacecraft, tested, integrated and awaiting launch, would appear to be an ideal foundation for the proposed Hunter spacecraft, as the MTM has a Xenon propellant capacity of 581 kg. fuelling four Qinetiq T6 ion engines.

8 Spacecraft Design

8.1 Overall Configuration

The overall Necropolis system consists of two independent spacecraft - Terminus, that creates the controlled store location, and Hunter, that collects the target satellites and brings them to Terminus. These two satellites are launched together on a dedicated Ariane 5 or 64 (Figure 3). The Ariane places the stack into a transfer orbit with an apogee at 36,386 km altitude. The internal propulsion of the Terminus places the stack into the operational circular orbit. The Hunter then separates from the stack to start its satellite collecting operations.

The Hunter is placed on top of the Terminus in the launch stack because it is the lighter spacecraft and because the MTM, on which it was based, is designed to carry a much lighter load and the structure would need altering if it were to be placed at the bottom.

The maximum launch mass of the stack into GTO was taken to be 10.5 tonnes which is compatible with Ariane 5 ECA and Ariane 64, which will be able to deliver 11 tonnes if it meets its performance targets. So the 10.5 tonnes was judged a conservative launch mass specification. The full payload mass budget is shown in Table 3.

Table 3: Launch Mass,

	Mass (kg)
Hunter	2400
Terminus	6510
USIS Adaptor	200
System Margin	1390
Launch Capability	10500

Figure 3: Terminus and Hunter on the Ariane Launch System

Even though this estimate is very crude this budget suggests that the Necropolis system could be launched on an Ariane launch system. The system margin (13% of the launch mass) is on top of the margins in the spacecraft mass estimates.

A consequence of the 10,500 kg launch mass, with an estimated Centre of Mass 2.8 m from the interface plane, is that none of the standard spacecraft connectors shown in the Ariane 5 User's Manual [Ref. 7] can handle that mass – the strongest being the 1666S rated for 9,000kg at 2.5 m Centre of Mass. It follows that a special adaptor will be needed and this was assumed to be a Universal Space Interface Standard (USIS)

The Necropolis system has used the USIS for all its space system to space system connection. USIS is a proposal from Hempsell Astronautics Ltd and Reaction Engines Ltd for a standardised universal interface for space system to space system physical interface, this includes launching, docking and berthing for both crewed and robotic systems [8]. In the context of Necropolis the important feature is that the use of a USIS as the launch interface also provides the spacecraft with a passive docking interface, giving the possibility of satellite servicing including easier end of life disposal.

Three studies (Fig. 4) have been conducted into USIS and they have established the basic viability of the concept. In Necropolis the Hempsell Astronautics concept was used; being the latest and most advanced in technical detail.

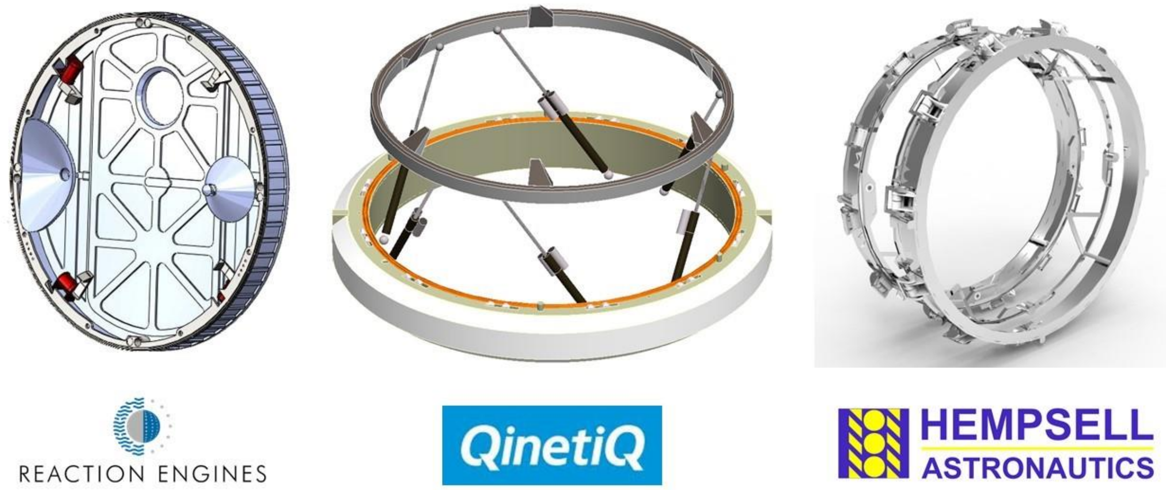

Figure 4: Three USIS Concepts

The first use of a USIS connection on the Necropolis is as the launch connection between Terminus and Hunter. Both sides have a passive docking version of the standard with a one off clamp release on the Terminus side. In addition to providing the structural connection the USIS will also enable power and data to be transferred between the spacecraft when they are connected together.

The use of USIS over a non-standard special connection in this role has very little mass impact and a considerable potential cost saving. However the main advantage is that once Hunter has completed its mission it will reconnect with Terminus and the composite will then have passive docking connections at both ends. These enable the Necropolis to be expanded and become the starting point of a growing facility, either manned or robotic, for the servicing of satellites in Geostationary orbit.

The second use is to enable the Hunter and Terminus to form an integrated system in the final phase of the operational mission. The concept configuration has also used the USIS as the interface with the Ariane launch system with another passive docking version. This will mean a new Ariane payload mount will be needed, but this would be part of the implementation of USIS as a standard launch system and therefore would not be a one-off special but be one of Ariane's standard launch interfaces. This approach is to enable the Hunter to use the active docking USIS located on its upper floor used to dock with Terminus at the end of its mission. This approach has the following advantages

- It provides early demonstration of automatic docking with USIS which is proposed as he long term means of collecting dead satellites.
- It provides a data and power connection enabling Hunter's systems to support Terminus, increasing the resiliency and life time of the Necropolis.
- It provides a known reliable structure connection which is important if Necropolis is to later become part of the larger facility.

8.2 Hunter Configuration

Hunter (Fig. 5) is required to rendezvous with the target satellites, physical capture them, return them to Terminus, then hold the satellite while it is harpooned and then release it. To do this Hunter is required to have:

- a propulsion system with a total impulse capable of the manoeuvres;
- a navigation system capable of rendezvous with an uncooperative target;
- a mechanism capable of capturing and then releasing the target satellite;
- an attitude control system capable of handling Hunter and target during capture and joint flight.

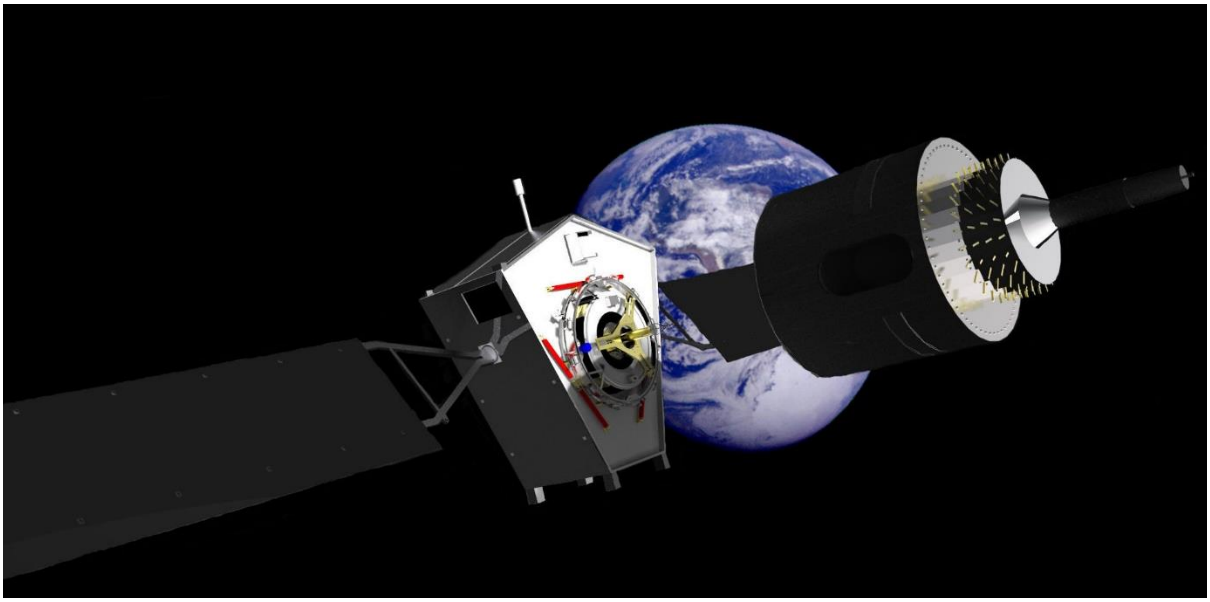

Figure 5: Hunter Approaching a Meteosat

Hunter was assumed to use a stinger system that uses the apogee boost motor or the Marman clamp ring as the physical capture point. MacDonald, Dettwiler and Associates in particular have patents for both types of system [Refs. 9 to 12]. The one shown on the study concept (Fig. 6) is based on a MacDonald, Dettwiler and Associates 2005 patent for a device that uses the apogee motor as the guide and attachment point but incorporates three way interface ring clamp for the final mechanical connection, which can accommodate 937mm and 1194 mm diameter rings.

Assuming that spin stabilised satellites, such as Meteosat or early Skynets, are still spinning at their operation speeds of 50 rpm, then their angular momentum will be around 3000 - 5000 N sec. To accommodate this the capture mechanism is mounted on a spin table that would match the speed of the satellite before connection. Once captured the capture mechanism would be despun and the angular momentum taken out by the Hunter's reaction control thrusters consuming about a kilogram of propellant.

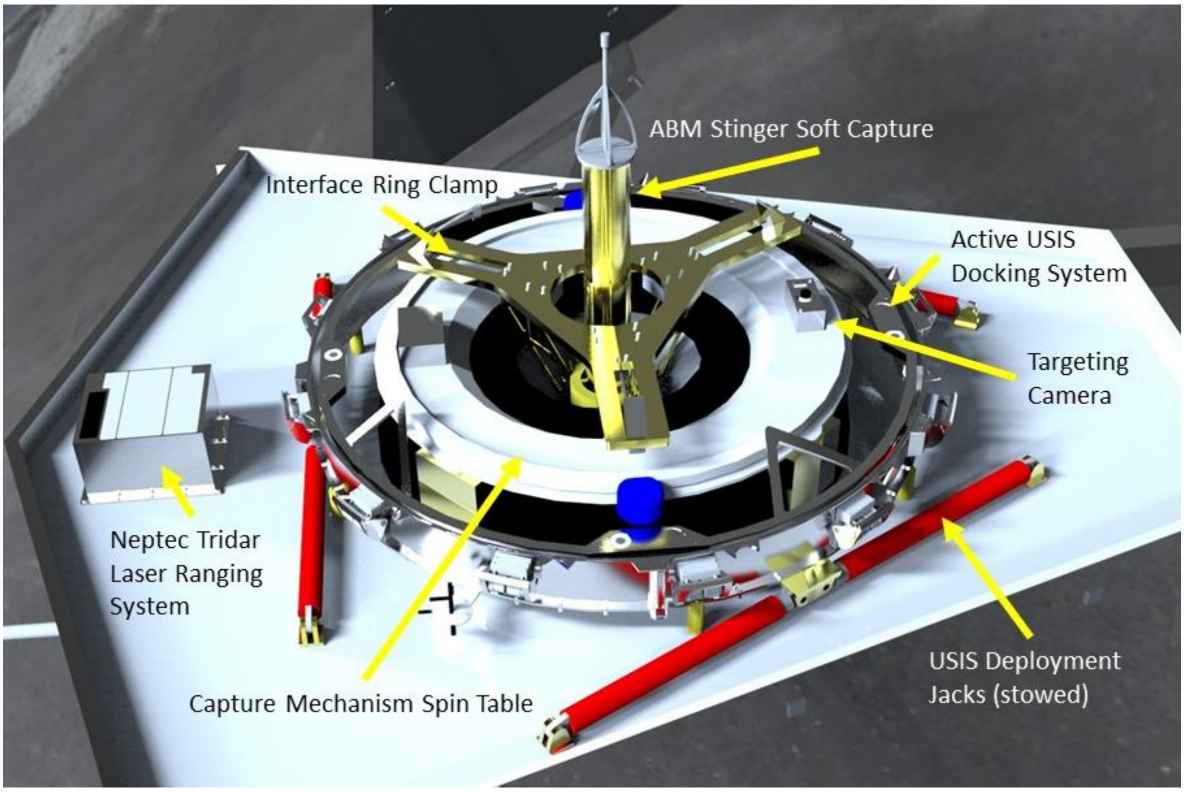

Figure 5: Capture Mechanism Concept

During the study it was established that the Mercury Transfer Module (MTM), developed to propel the BepiColombo spacecraft to Mercury, would provide the propulsion capability required and provide a suitable structure and power supply system for Hunter. Indeed in the experience of the study team the first impression of the suitability of the MTM for this role is unprecedented for a system developed for such a different mission. However there would need to be some alterations,

- the1660 launch system interface replaced with a USIS (with almost identical diameter),
- new attachments for the additional units required,
- change the top interface to allow mounting of an active docking USIS and the capture mechanism,
- a reduction of the thermal control provision,
- it is probable the expensive high temperature solar array would be altered to a lighter and cheaper version.

The MTM does not have complete communications, data management, or attitude control electronics as these functions are contained in the Mercury Planetary Orbiter. So all these functions would need to be added for the Hunter, but many of them could in essence be provided by standard units.

The MTM has a very capable set of bipropellant reaction control thrusters and a substantial propellant supply. However the need for extensive attitude changes on each orbit for the ion engine thrusting strategy and the control required during the capture operation requires the addition of reaction wheels. A very provisional analysis suggest that the 3 Axis controlled satellites, if they have a rotation around 1 rpm, would require about 200-300 N sec of momentum to be taken out. These lead to a proposal for three large (around 100 N sec) wheels in roll, one each in pitch and yaw and a sixth wheel at 45 degrees to all axis for redundancy.

No reaction wheels this size have been found so a parametric mass figure of 15 kg a wheel has been used, making a total of 90 kg.

The additional avionics needed were based on studies for an upper stage that included a docking capability.

The mass estimate for Hunter (Table 4) assumes the MTM mass would not alter after the revisions for its new role although in practice there may be some scope for mass reductions due to reduced structure and thermal requirements.

Table 4: Hunter Mass Estimate

	Mass (kg)
MTM basic mass dry	1134
Lower Interface convert to passive USIS docking	25
Upper interface active USIS Docking	75
Upper face Stinger capture mechanism	100
Additional Avionics	80
Reaction Wheels	90
TOTAL (dry)	1504
Margin (8% on MTM, 20% on other items)	158
Xeon main propellant	581
Reaction Control Propellant	157
TOTAL LAUNCH	2400

8.3 Terminus Configuration

The Terminus spacecraft (Figure 7) is required to:

- carry the Hunter spacecraft to its operational orbit (launch interact and apogee insertion);
- take target satellites from the Hunter and provide permanent controlled storage;
- maintain station and perform collision avoidance manoeuvres.

On order to fulfil these roles it requires:

- mountings for the Hunter during launch and orbit insertion
- a propulsion system for apogee orbit insertion
- a storage location for 12 non-functioning satellites
- a connection for Hunter at the end of its mission

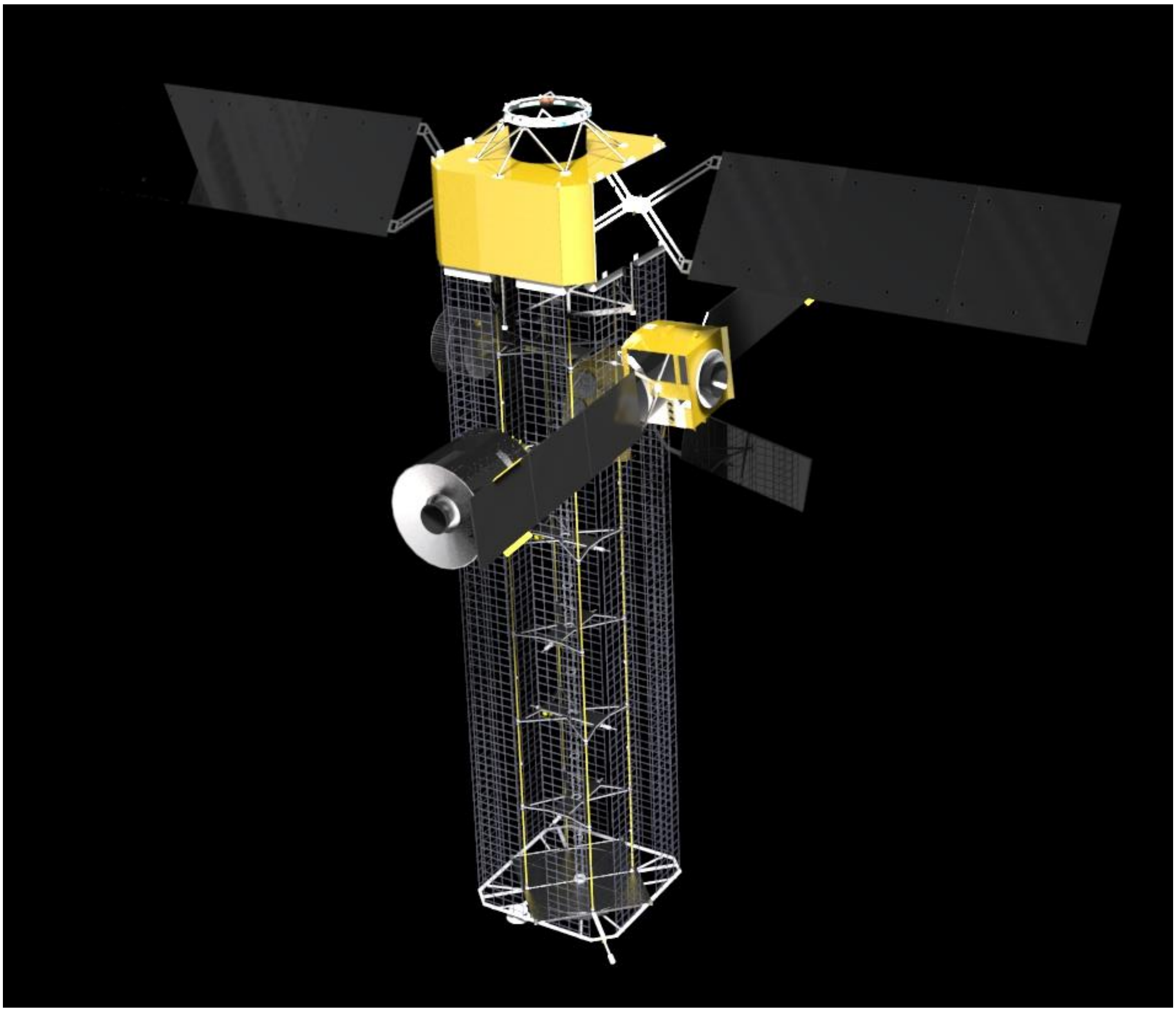

Figure 7: Terminus with the Tower Deployed

The main body of the Terminus spacecraft in the concept design had a 3588mm square cross section, chamfered to fit within the launch envelope and a height of 1900mm. It is a classic form of a central cylinder with shear walls supporting the outer panels configuration supplemented by struts taking tanks and other very high loads directly to the USIS interface ring. Mounted on top of the main body is the deployable tower and a load bearing structure that encloses the stowed tower to carry the loads from the top structure and the Hunter during the launch.

Once on station and after the separation of the Hunter the tower is deployed its full height of nearly 15 metres. The Tower has six floors 2 meters apart and on each floor are two capture harpoons. The key objective of the tower is to securely hold the dead satellites as closely together as possible. The tight packing being required to both reduce the size and hence mass of the mast and to maximise the shielding effecting of satellites with each other; minimising the overall cross section. For three axis satellites with deployable arrays the arrays will need to be orthogonal to the tower or the total tower length would rapidly become unviable. The arrangement is selected for a square cross section with satellites mounted on all four sides but staggered so their arrays do not clash. The key sizing constraint is the satellite body which in turn is constrained by the launch system envelope. Most satellites that would be the customers for the systems were launched on early Arianes, Deltas and Shuttle/PAM-D, which had payloads envelopes with diameters around 3.5 meters and to ensure compatibility the satellite buses and hence the body dimensions were designed to fit the smaller of the available launchers.

The concept design assumed that the Hunter would have attached to the satellite at its base, and that the best target point for the Terminus's harpoon would be the top of the satellite. Although this is the usual location for antenna which would prevent the main body of the satellite being drawn hard against the tower structure, it would generally bring it closer than if the sides, with solar arrays or side mounted antennas, were used. The concept design draws the satellite into nets on the outside of the Tower.

The Harpoon capture is under development by Airbus Defence and Space with support from ESA Clean Space programme. It was selected against the thrown net solution (also under consideration) because a net may ensnare the Hunter as well as the satellite it is carrying. The technical information provided by Airbus on the harpoon is given in the Annex. For the Necropolis role a number of changes are required to this specification.

i. The capture distance can be reduced from 25 metres to around 12 metres.
ii. The load can be reduced from 8 tonnes to 4 tonnes.
iii. Only one Projectile/Deployer in each system.
iv. A tether retraction system is required to draw the satellite into the nets.

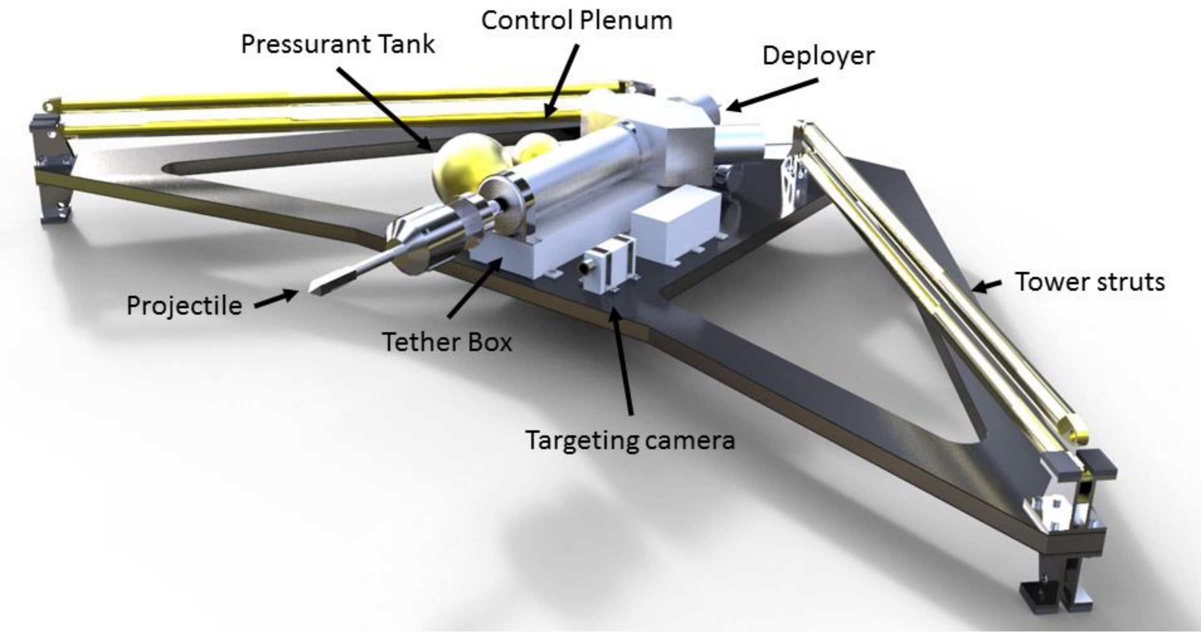

Figure 8: Airbus Harpoon as Installed on the Concept Design

The mass for the three Projectile/Deployer is based on the ground breadboard and would be reduced in a flight system. In this study a mass of 45 kg per Projectile/Deployer system was used on the mass estimate.

The Terminus spacecraft estimate mass is shown in Table 5. It is very provisional with guesses that the power requirement would be 4 kW and that the system would gravity gradient stabilise. Most masses are derived from general parametrics and the uncertainty this creates is why a 30% margin on the dry mass is included.

Table 5: Terminus Mass Estimate

	Mass (kg)
Structure and Mechanisms	730
Propulsion	270
Thermal	40
Avionics	60
Power (arrays, batteries and distribute)	290
Tower including harpoons and nets	700
Top section (including RF link)	220
TOTAL (dry)	2310
Margin (30% of dry mass))	700
Propellant	3500
TOTAL LAUNCH	6510

8.4 The Potential UK Contribution to a Demonstration Mission

During the development of the Study's concept design it became apparent that there is considerable scope for the UK's upstream industry to contribute the creation of the Necropolis system.

The unique and specific UK elements in the mission proposed are the electric propulsion system for the Hunter spacecraft produced by QinetiQ Ltd. in Farnborough, and the harpoon system for the Terminus satellite being developed by Airbus Defence and Space Ltd. in Stevenage.

The Hunter spacecraft design is based on the Mercury Transfer Module (MTM) spacecraft, for which Airbus D&S has the prime contract. This spacecraft was (at least in part) assembled in the AIT facility in Stevenage, therefore this facility has overall system engineering expertise in such a project and could take the prime contract for the Hunter spacecraft, if appropriate.

The additional subsystems required for the Hunter spacecraft (AOCS, GNC, communications, etc.) can all be produced in the UK - either by Airbus Defence and Space. or SSTL Ltd. - or otherwise procured directly from the other elements of ESA's BepiColumbo spacecraft composite.

The Terminus satellite is a new design and build, and again Airbus D&S Ltd, and SSTL Ltd. are capable of designing and building the structures and subsystems that will be required, and even taking the prime system engineering role if even more UK content in the mission was required.

In the concept design produced the Hunter use the TriDAR (Triangulation and LIDAR Automated Rendezvous and Docking) system as part of the rendezvous and docking system.

This unit is produced by the Canadian company Neptec Design Group as apart of wide range of relevant products. The company have recently set up a UK division at Harwell, this would enable the UK to have a significant role in many aspects of rendezvous docking and AOCS.

9. Scout Precursor Mission

During the course of the study two issues arose that provide justification for a small precursor mission early in the system development. This mission would rendezvous with satellites in geosynchronous and graveyard orbits, concentrating on potential targets and making detailed images of them.

The first issue is a lack of knowledge of the state of the target satellites after half a century in the space environment and decades in an uncontrolled state. Key concerns are the spin behaviour of targets, do spin stabilised satellites retain their spin or de-spin over time, or even tumble? Do 3 axis satellites develop a spin or tumble? Another concern is the state of the thermal blankets and other parts that will be impacted by the recovery process.

In addition to the specific information required for the detailed design of the Necropolis the mission would also provide valuable general information for the design of satellites for the geostationary environment - in particular the alteration of thermal finishes over time.

The second issue is the desirability of demonstrating rendezvous with non-functioning satellites at geostationary altitudes and proving the procedures for safe approach to target satellites. This mission would also confirm and refine the accuracy of the ground tracking of spacecraft in geosynchronous orbit. It was also thought to be a valuable opportunity to assess the capability of the laser range finder and its ability to support the capture process.

It is currently envisaged as a small spacecraft with a payload of a couple of cameras and a Tridar laser range finder. It is suggested that an electric propulsion system could be included to rehearse the rendezvous Hunter’s mission profile but it would not be necessary for Scout to match orbits will all its targets as in many case a flyby will be sufficient to get the required information.

The intention is this would be a fast track mission separate from the main Necropolis development, in order for its information to be available during the earlier stages of the Necropolis detailed design phase.

The Scout spacecraft is a stand-alone element, possibly to be launched on a small launcher or as a "piggy back" on a GTO comsat mission, and the UK has the ability to design and build all of the components of that spacecraft, and even take the prime system engineering role, if required and prudent. If the spacecraft has an EP subsystem then QinetiQ will be the obvious choice of supplier, possibly with the flight-proven T5 thruster that was successfully flown on the GOCE mission."

10 Conclusions

The study has demonstrated the basic feasibility of an Ariane launched mission that could re-locate at least six long non-functioning satellites, for which the UK carries some liability, out of geosynchronous orbit where they are currently a hazard to navigation and potentially a cause of collisions with active satellites.

The mission examined could have a large UK content, employing existing electric propulsion engines and much of a spacecraft design that is currently awaiting launch (Mercury Transfer Module).

The mission examined would also provide a safe repository of current generation satellites that are naturally coming to end of life.

The study also identified the value of a precursor mission called “Scout” to reduce the uncertainties in the position and condition of non-functioning satellites and to validate some of Hunter’s technologies and mission design.

International agreement will be necessary when proceeding with such a mission, with agreement on the liability of satellite owners in the event of collisions.

A business case for such a mission needs to be developed.

11 Recommendations

11.1 Technical

This study has shown that the basic concept is technically viable. The next stage of work should have the following objectives.

- The results of the study should be reviewed by the UK Space Agency, and/or its agents, for both conceptual validity and technical viability.
- The magnitude of the threat from collisions in the geostationary arc should be quantified. A thorough survey of past work should be undertaken and relevant parties contacted in an attempt to reach a consensus among space-faring nations.
- The concept design should be refined to the point where scoping cost estimates can be made as an input to the business plan
- If it is decided that the mission described in this report has both conceptual and technical merit a longer study, leading to a Preliminary Requirements Review (PRR) after one year, should be undertaken. The PRR should be organised by the UKSA, with ESA as technical auditors, and by attended by other HMG departments.

11.2 Legal Studies

This preliminary study has not considered the important legal and regulatory aspects of non-functional satellites damaging or destroying active satellites in the geostationary orbit and damaging the spatial environment, and where the responsibility and liability lies in such circumstances. It is crucial that further study in this area considers these aspects, as a matter of priority.

It is of importance because it is the foundation to the business case. The service that is provided is the reduction or elimination of legal liability for collisions. Thus establishing who has that liability establishes who the customers are. And establishing the amount of that liability establishes the value of the service, for price / cost comparison.

The legal study is also of direct importance to the UK are situations where:

- A UK owned non-functioning satellite collides with and destroys an active satellite;
- UK owned non-functioning satellite collides with another non-functioning satellite and debris destroys/disables one or more active satellites creating harmful contamination in the GEO;
- Responsibility, ownership and liability of non-functioning satellites.
- Environmental protection and the development of appropriate measures for a model code for the removal of these objects.

Consideration of these issues may require changes to current regulatory requirements, and may even result in changes to the Outer Space Act 1987.

11.3 Business Case

The business case for embarking on a programme to preserve and maintain the geostationary orbit and to free up space within the spatial environment for new satellites has not been considered in this preliminary study.

The results of the further work on technical and legal aspects will enable a broad business case to establish the financial viability of undertaking the enterprise.

It also needs to establish early on the structure of the business. There would appear to be at least three primary scenarios:

i. a purely institutional programme, consequent upon regulatory changes to the Outer Space Act 1987;
ii. a purely commercial programme, where an operator sells services to satellite owners/operators;
iii. a Public / Private Partnership.

Future study is required in order to examine these alternatives and gain consensus from the international, space-faring community.

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Annex – Airbus Harpoon Data Sheet

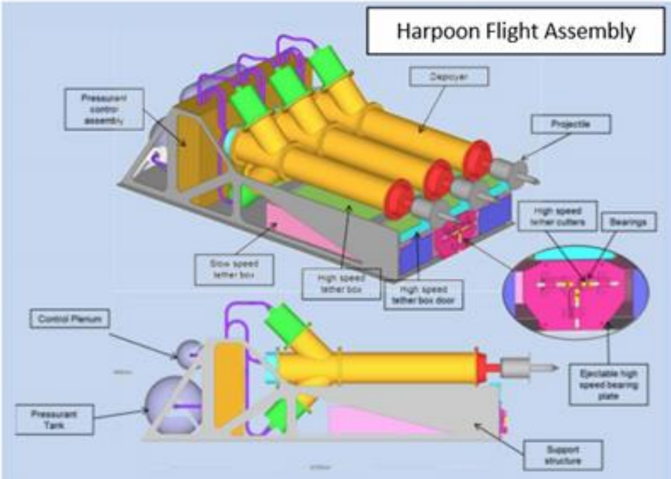
AIRBUS DEFENCE & SPACE

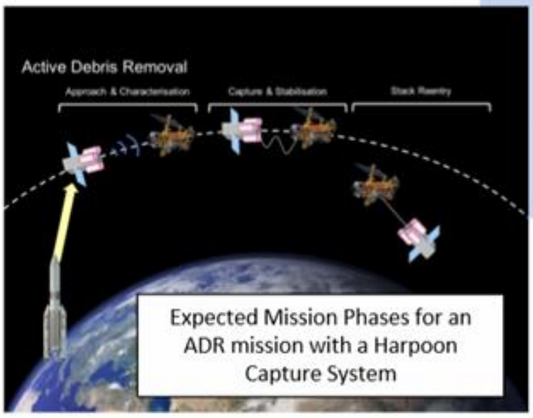
Clean Space Harpoon

esa

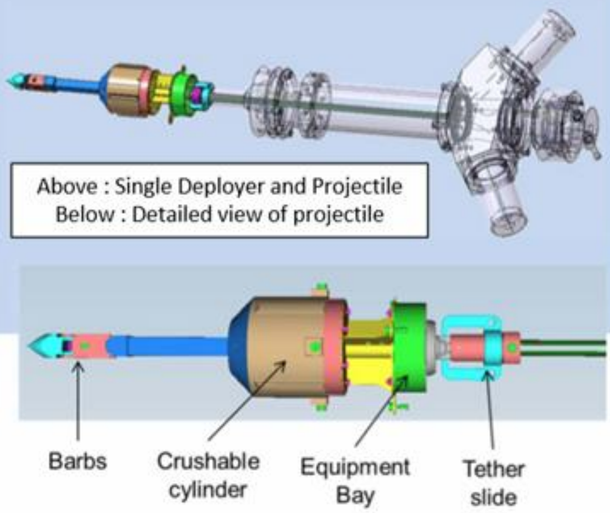
Summary : The Clean Space Harpoon is a technology development activity funded by ESA GSTP. The aim of the project is to design, develop and test a Harpoon Capture System capable of capturing large, intact debris items such as defunct satellites. At the end of the project, a complete specification for the Harpoon Capture System will be developed to allow for consideration on future flight systems. The bradboard will reach TRL 5/6.

The major elements of the capture system are the deployer, which is charged using a classical pressurant control system and the projectile. The system is designed to capture targets over a 30 m distance using a projectile with inbuilt capture sensors. The complete system is currently envisage as a one use device and does not incorporate any winch. The major innovation rests in the projectile which has a unique locking and energy absorbing system to limit penetration to the skin of the satellite.





Expected Mission Phases for an ADR mission with a Harpoon Capture System



Above : Single Deployer and Projectile
Below : Detailed view of projectile

Type	Value
Mass Harpoon Capture System – 3 deployers incl. tether [kg] :	≈ 140 kg
Mass Projectile [kg] :	≈ 2.5 kg
Capture distance [m]	≈ 25-25 m
Typical deployer firing speed [m/s]	15-20 m/s
Target maximum mass [kg]	8000
Target maximum spin rate [deg/sec]	5 deg/sec in any direction
Crushable energy attenuation [J]	200

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