A MISSION TO DEMONSTRATE THE PRESERVATION OF THE GEOSTATIONARY ORBIT

R. Longstaff (1), **M. Hempsell** (2)

(1) Guest Associates (Europe) Ltd., 2 Alyson Villas, Vincent Close, Ilford, IG6 2FE, United Kingdom
Email: roger.longstaff@live.co.uk
(2) Hempsell Astronautics Ltd., 10 Silver Birch Avenue, Stotfold, Herts, SG5 4AR, United Kingdom
Email: mail@hempsellastro.com

ABSTRACT

A study conducted in 2016 explored a mission to demonstrate the preservation and maintenance of geostationary orbit which could be undertaken with a single Ariane launch. The mission, called Necropolis, would use two spacecraft; a “Hunter” spacecraft to collect non-functional satellites which pose a threat to the geosynchronous environment and deliver them to a “Terminus” satellite, where they would be permanently stored under control. Such missions would reduce the probability of collisions between the hundreds of derelict objects in geosynchronous orbit by providing a safer means of disposal than the ultimately unsustainable “graveyard orbit”. The study concluded that the mission was technically feasible with current technologies and systems and that at least six non-functional satellites could be stored and possibly more with either optimised mission planning for the Hunter or by end of life satellites making their own way to rendezvous with the Terminus. There were three unexpected conclusions. The first of these was the lack of knowledge about the geostationary environment and the state of state of derelict satellites, an issue which could be addressed by ‘Scout’ precursor mission. The second was the uncertainty regarding the legal liability of debris owners. The third was the impact of libration points on focusing debris locally, thereby increasing the collision risk. It was finally concluded that the removal of ten key derelicts would enable a significant decrease in the collision risk, and this could be achieved with this type of system.

1 INTRODUCTION

This paper describes a four month, new-look study to investigate a possible demonstration mission to actively remove and store inactive satellites in the geostationary environment that are posing a hazard to navigation in the region, as evidenced by the routine practice of moving active satellites in Geostationary Equatorial Orbit GEO to obviate the risk of collision [1].

The initial goal of the study was to devise a mission that could be launched on a single Ariane vehicle and would be able to remove at least six derelict satellites and transfer them to a co-located “graveyard”, orbiting above the current “graveyard orbit”, thereby greatly reducing the collision risk in the longer term. The system was called “Necropolis” – an archaeological term for a graveyard in a remote location away from active populations.

The study assumed it was addressing a long term problem that will arise for two reasons. The first reason is because the debris density in the “graveyard orbits” grows each year and will eventually reach a point where the collision risk reaches an unacceptable level, given that debris created by any collision at graveyard altitudes will reach the geostationary arc. Thus the study assumed that graveyard orbits are not a sustainable disposal option in the long term, which differs from the assumptions of previous studies such as ESA’s ROGER study [2].

The second reason is that not all satellites successfully reach a graveyard orbit and thus the debris density in geosynchronous orbit increases over time and will have to eventually be addressed by debris removal measures.

2 CONGESTION IN GEO

Over almost half a century there have been about 1,500 launches into the 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. 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 [3].

In 2002 ESA calculated that there could be a 1 in 25 chance of a collision in geosynchronous orbit by 2030 [2], however, fifteen 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,

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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.

As an example of the potential risk of collision, Figure 1 shows the orbits of five derelict satellites in geosynchronous orbits (all with a period of one sidereal day and therefore at the same altitude) in September 2016, with intersecting orbits at the Western libration point at longitude 105 degrees West.

(Credit: N2YO.com & Google Maps)

Figure 1: Ground Tracks of 5 of the 53 Satellites at Western Libration Point.

3 THE NECROPOLIS CONCEPT

3.1 System Objectives

The Necropolis objective is to create a system that could remove non-functioning from the geostationary environment to reduce the risk of collisions in GEO and enable continuing operations for decades and centuries to come. At the project start Necropolis was foreseen as a demonstration mission which could either then be repeated, or to revise the system design in light of the lessons learnt on the first mission.

The novel aspect of the Necropolis objectives was that, once captured, satellites should be brought to a single location and placed under permanent control; rather than released into a graveyard orbit uncontrolled.

As the study was part funded by the UK government the target satellites used in the study's reference mission were all ones that are the UK's responsibility; either owned by the UK (e.g. Skynet 1), or with a UK relationship (e.g. NATO 2b, METEOST 1). These were selected from the UK Registry of Outer Space Objects. The list is shown in Table 1. Although all these objects were on the UK Registry they were thought to provide a representative mission for any random group of satellites.

There was an attempt to re-orbit the first satellite on the list (Skynet 4b) to a graveyard orbit (GYO) at end of life. However, the satellite did not achieve the minimum altitude gain required by ITU regulations [4], 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 failure the resulting objects would not threaten the GEO directly.

3.2 The Necropolis System

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.

Table 1: Study Reference Mission Target Satellites

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

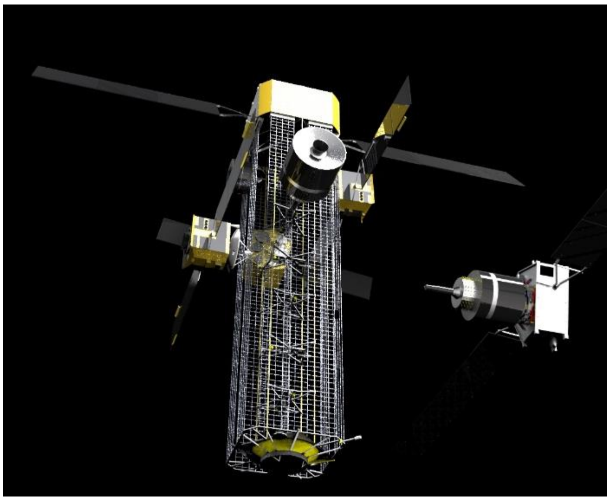


Figure 2: The Necropolis System in Operation. The Hunter (With a Recovered Satellite) Approaches the Terminus

This study examined a novel solution to achieve these objectives called "Necropolis" (Figure 2). This 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 in a super synchronous orbit 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.

The Necropolis system would be launched into Geostationary Transfer Orbit by either an Ariane 5 or an Ariane 64, as shown in Figure 3. The overall system launch mass breakdown is shown in Table 2.

Table 2: Necropolis Launch Mass Breakdown

Hunter	2400 kg
Terminus	6510 kg
Launch Adaptor	200 kg
System Margin	1390 kg
Ariane Launch Capability	10500 kg

3.3 The Hunter Spacecraft

The Hunter spacecraft has the task of rendezvousing with the spacecraft to be removed, capturing them and then taking them the Terminus for permanent storage.

Figure 3: The Necropolis System in Launch Configuration Packaged Within an Ariane Fairing with Hunter Being Stacked on Top of Terminus.

The concept design (Figure 4) for Hunter was based on the Mercury Transfer Module (MTM); a stage developed for ESA's BepiColumbo Mission to Mercury. This bus uses the four QinetiQ T6 Ion thrusters with two firing at any one time, in an identical manner to that employed for the MTM. Each engine has the following specification;

Thrust: 145 mN
Exhaust velocity: 42,000 m/s
Rated maximum total impulse: 11.5 MNs

The vehicle's usable propellant load is 581 kg of Xenon giving a system total impulse of 24.4 MNs. This gives it the large deltaV capability; required to undertake several capture missions.

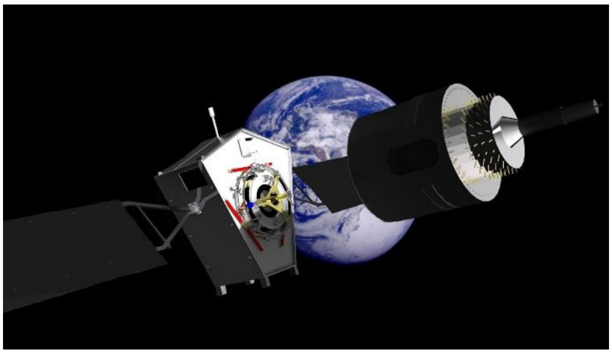


Figure 4: Hunter Spacecraft Approaches Target Satellite for Capture

To achieve this the Hunter has a spin table with a stinger capture mechanism (in order to capture spin stabilized derelicts) and a docking mechanism for spacecraft with compatible passive docking provisions. At the end of its life the Hunter uses the docking mechanism to permanently connect to the Terminus and remove itself from the uncontrolled debris population.

The mass budget for the Hunter is given in Table 3.

Table 3: Hunter Mass Budget

Item	**Mass (kg)**
MTM Basic Mass Dry	1134
Convert LV Interface to Passive USIS	25
Active USIS Docking Interface	75
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

3.4 The Terminus Satellite

The Terminus Satellite provides the long term controlled storage facility for the captured satellites

The Terminus satellite study concept was an all-new design as shown in Figure 5 in its deployed configuration with a height of 18 metres. Following a circularisation burn - using its own chemical propulsion system - the Terminus could store up to twelve satellites.

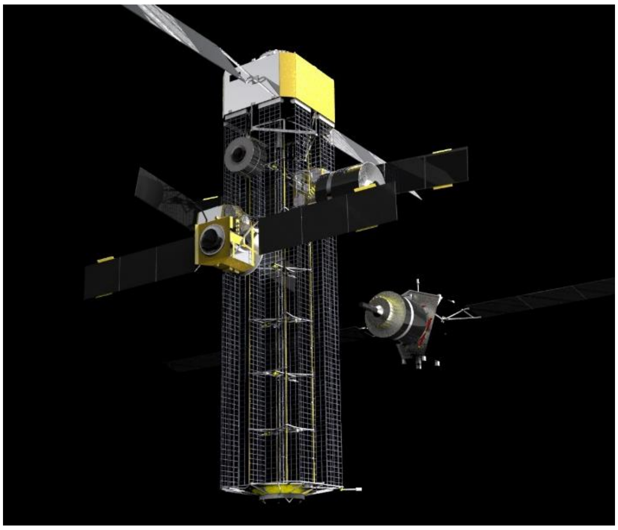


Figure 5: Terminus satellite with Tower Deployed

The satellites are attached to the Terminus tower using a variation of the Airbus D&S space harpoon (Figure 6). The Hunter will rendezvous with Terminus and then hold station presenting the satellite as target. The harpoon then fires; permanently ensnaring the satellite. The Hunter releases the capture mechanism and the satellite is then drawn into the net walls of the tower.

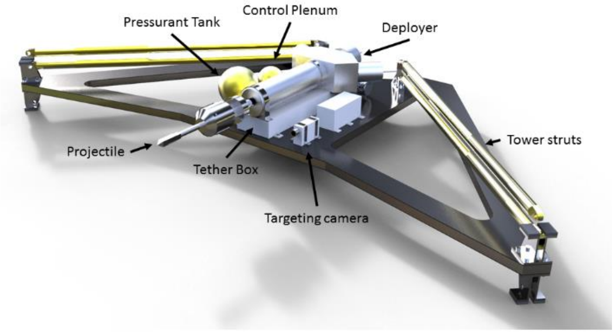


Figure 6: Airbus Space Harpoon in Terminus Tower Mounting.

The Terminus has a conventional bipropellant propulsion system for initial orbit insertion and orbit control. It also has two docking provisions at either end so it can be serviced and/or expanded indefinitely.

The Terminus mass budget is shown in Table 4

Table 4: Terminus Mass Budget

Item	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

4 MISSION DESIGN

4.1 Mission Outline

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) The Hunter; that will detach from the injected stack and proceed to rendezvous with target satellites, capture them and return them to;

b) The Terminus; 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 itself be attached to the Terminus.

4.2 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.

The first target satellite in Geosynchronous Orbit (GSO) will be selected from a trajectory optimisation analysis that cannot be performed until a launch date and time have been decided. The target's 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.

The Hunter spacecraft has an initial mass of 2,400 kg (Table 3), 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.

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.

A computer program has been written that is based on the mathematical approach developed in Reference 5. This uses analytical, rather than numerical integration. The results for a complete mission sequence are shown in Table 5.

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

Table 5: Mission Analysis Results

	Inclination	**Round Trip dV**	**Target Mass**	**EP Prop. Mass**	**Thrust Time**	**Transit Time**
	(deg)	**(m/s)**	**(kg)**	**(kg)**	**(days)**	**(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

that the total elapsed mission time will be roughly 5 – 6 years.

5 STUDY CONCLUSIONS

5.1 Conclusions Summary

The study achieved its main objectives in that it showed that the Necropolis concept was technically feasible with a single Ariane 5 or 64 launch, using available technology, and even suitable systems are available or under development. The degree to which the MTM was suitable to act as the basis for the Hunter was serendipitous and illustrates the required TRL level is very high. The capture mechanisms were judged to represent the areas of highest technical risk.

The mission analysis showed that at least six derelict satellites can be captured and transferred to the Terminus – perhaps more with optimised mission planning. Another six end of life satellites can directly transit to the Terminus during the mission for decommissioning.

However there were also thee conclusions that were not expected at the outset and lead to main areas for further work. These were;

i. lack of knowledge,
ii. unknown legal liability, and
iii. the impact of the libration points on collision risks.

5.2 Lack of Knowledge

The study established a number of unknowns which are critical to final system development:

- The physical condition of satellites, particularly surface finishes, after half a century in the GEO region is unknown.
- The dynamic behaviour (e.g. spin) of derelict objects is unknown.
- The actual debris environment is unknown.
- The reasons for apparent non-Keplerian behaviour are unknown.

It was concluded there would need to be a Scout mission to GEO to address these issues before end of Phase B development of the operational Necropolis system.

Although no work has been conducted to define the Scout it was envisioned as being a small satellite with a sufficient propulsion capability to reach out of equatorial plane targets and image them with sufficient resolution to establish the condition of the thermal blankets and other surfaces. There is already a USAF programme called the Geosynchronous Space Situational Awareness (GSSA) launching such satellites to monitor the geostationary arc. However this programme concentrates on active satellites within the equatorial plane and its results are classified.

The objectives of the Scout may also be accomplished by one of the geostationary satellite serving systems that are currently under study should they become operational.

5.3 Unknown Legal Liability

All States have an International Responsibility for activities of non-government entities operating in outer space, coupled with an obligation of continuing supervision. A review of this study has highlighted that States need to act now to address the potential debris risk to other satellites in GEO and to determine who will bear responsibility both for any damage caused and for clean-up activities.

The ITU has addressed removal to graveyard orbits, however, many satellites remain in geosynchronous orbit in cases where those regulations came too late, or have failed in GEO before removal was possible.

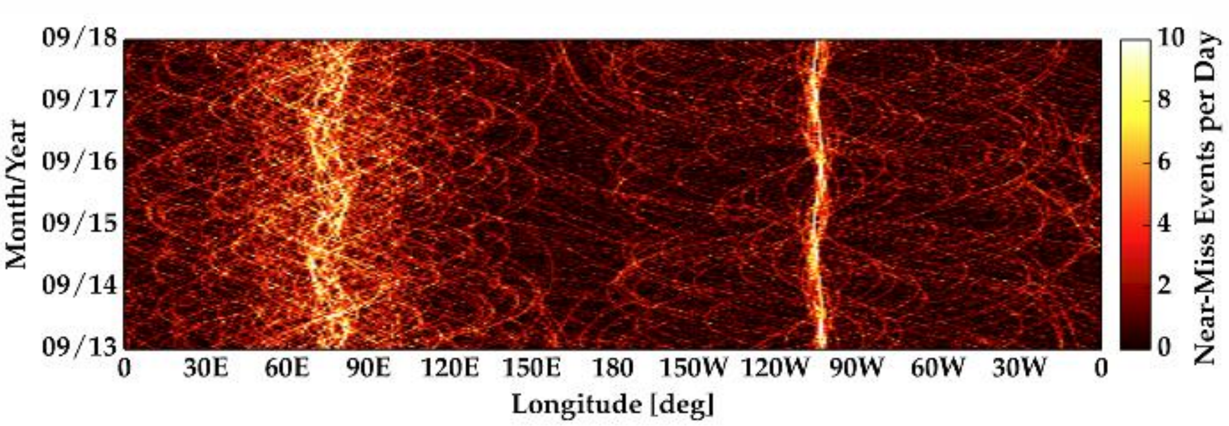
5.4 Orbital Motion Around Libration Points

During the study a number of satellites were noted at the libration points – especially the western point – greatly increasing the collision risk.

Subsequent work confirmed that about 25% of these objects in GSO were orbiting within 3 degrees longitude of the 105W libration point. This could be due to:

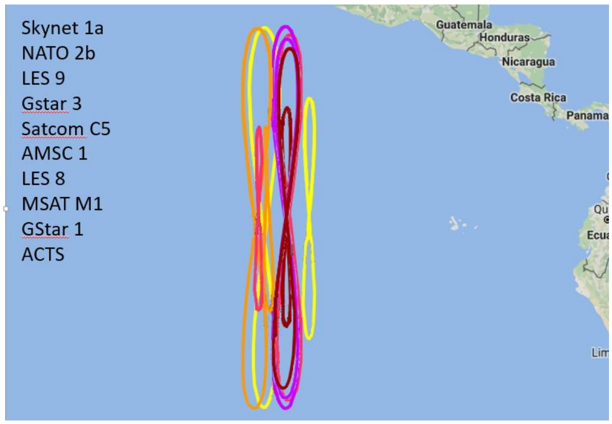
- loss of control and abandonment @ 105W, or
- deliberate re-location to 105W prior to abandonment, or
- an E/W "damping effect" in geosynchronous orbit, of an unknown nature.

Figure 1 showed the ground tracks of five derelict satellites in geosynchronous orbit, librating about the 105W libration point, in early September 2016. The libration period of these objects is about 2.2 years, therefore after about 6 months they should be at their maximum E/W excursion from 105W. However, they are shown again in Figure 7 in February 2017 – still within 3 degrees of the libration point – indicating a libration period of less than 3 degrees. Figure 7 also shows all the other satellites within 3 degrees of 105W – 10 objects in all.



(Credit: University of Colorado)

Figure 8: Collision Probability at Geostationary Longitude Over Time. [6]



(Credit: N2YO.com & Google Maps)

Figure 7: Uncontrolled Objects within 3 Degrees of 105 W on February 2017.

After the study concluded the authors became aware of the work of the University of Colorado, having already concluded that deterministic modelling was required in order to assess the real risk of collisions in the geostationary environment, rather than stochastic modelling, which had produced the conclusion that the risk of collision in GEO was at least 2 – 3 orders of magnitude less than in Low Earth Orbit.

Reference 6 concludes: "*Accumulation of uncontrolled objects around the gravitational wells at 75˝E and 105˝W is a well-known result... And the probability of collision in the vicinity of the gravitational wells is seven times larger than in surrounding regions at GEO*."

This is demonstrated graphically in Figure 8 reproduced from Reference 6.

The label "Near Miss Events per Day" refers to an object entering a notional torus around GEO, with a semi-minor axis of 100 km. The model run was for 5 years and included the effects of the Earth's gravitational harmonics, lunar and solar gravitational fields and solar radiation pressure. The greater number of incursions at the libration point of 105W and 75E are clearly shown in the figure.

Furthermore, a subsequent paper by the same team [7] stated: "*Nearly 60% of the total risk surrounding the Western well is attributed to 10 derelicts alone, which has critical implications for active debris removal (ADR) target selection*."

It is interesting to note the commonality of the list of satellites identified by this reference and the satellites identified by the authors as shown in in Figure 7. It is therefore possible to speculate that uncontrolled objects in geosynchronous orbit with small libration amplitudes are the major risk to the geostationary environment and that this risk may have previously been significantly underestimated.

It also shows that a system, like Necropolis, that can remove around ten satellites could have a dramatic impact on the overall collision risk in the geostationary region.

6 NEXT STEPS

The first step is to carry out detailed deterministic modelling in order to establish the real risk of derelict on derelict collisions in the geostationary environment. Also more work is needed to establish the long term viability of safely using graveyard orbits as a means of disposal.

At the same time the requirements for a Scout mission should be established, with the aim of a preliminary launch to determine the actual condition of satellites that have been derelict in the geostationary region for up to half a century. Another goal for the Scout mission will be to determine the small and fine particle environment in the region, as satellites may have been shedding their thermal blankets for decades.

While first steps are underway the Necropolis system should be refined by a Phase A study, to the level that a preliminary budget estimate may be obtained.

Finally, and in parallel with the above activities, the legal liability issues covering responsibility for derelict satellites and their "clean up" should be examined by national space agencies, the ITU and the United Nations, with the clear understanding that inaction is not an option if the geostationary orbit is to be preserved for future generations. Subsequently, a new regulatory regime needs to be discussed and agreed.

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