RObotic GEostationary orbit Restorer (ROGER) Executive Summary ESA/ESTEC Contract No. 15678/01/NL/WK

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Duncan Smith

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Authorisation

Prepared by	Duncan Smith
Title	Technical Manager
Signature	
Date	
Location	Space Department, QinetiQ
Reviewed by	Dr Hedley Stokes
Title	Project Manager
Signature	
Date	
Authorised by	Dr Mike Jackson
Title	Director, Space
Signature	
Date	

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Abstract

The RObotic GEostationary orbit Restorer (ROGER) is a study focused on the need for and feasibility of a mission to control the threat from faulty satellites and large debris.
This report presents the work performed within the ROGER project. It has been prepared a team lead by QinetiQ, Space Department, and comprising OHB-System, Dutch Space and Esys, for the European Space Agency (ESA/ESTEC) under contract 15678/01/NL/WK.
The aim of the work is to examine the threat from overcrowding in GEO, determine possible mission scenarios and subsequently the justification for a RObotic GEostationary orbit Restorer, and finally to suggest a plausible technical implementation for such a mission and identify the necessary development and demonstration activities.
This final report comprises an executive summary report and six annexes describing the technical work performed in the project.

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1 Introduction

The future growth of space debris has been studied and characterised extensively for low Earth orbit and more recently for the geosynchronous orbital environment. For objects in geostationary or geosynchronous orbits the presence of even a relatively small number of satellites has a special significance given the small range of suitable orbital parameters. The unique operational characteristics of GEO mean that all users are constrained to the same narrow corridor of space.

Given that there is no natural sink for objects at GEO altitudes the number of objects in the corridor will continue to increase, enhancing the collision risk, unless some mitigation measures are implemented.

Sources of debris in GEO are primarily considered to be uncontrolled satellites that have either completed their propellant reserves or have failed, and launch vehicle upper stages. Additionally there is a small contribution from related objects, such as explosive bolts and lanyards, and the two explosive break-ups known to have occurred in GEO. Due to the distance involved for GEO observations and the resolution of most ground based systems the characterisation of the debris environment in GEO is not as mature as that in LEO.

1.1 Re-orbiting Policies of Operators

The unique orbital characteristics of the GEO ring make it a very valuable natural resource. In order to preserve this resource for future satellite operations users have been encouraged over the years to re-orbit their satellites at end of life. This involves boosting the satellite to a graveyard region above the GEO ring. Today this practice is not fully embraced by all satellite operators, indeed only one third of satellites that reached the end of their missions last year are believed to have successfully re-orbited.

Failed satellites, which could not subsequently be re-orbited, are believed to comprise a small but significant fraction of the total number of uncontrolled objects remaining in GEO.

1.2 Long and Short Term Risk and Need for Early Mitigation

The actual risk of a collision between two objects, be they operating satellites or otherwise, is at present still very low for objects in or crossing GEO. Studies performed to date suggest that on the basis of “business as usual”, future launch and explosion rates there are likely to be at most a few collisions between large objects over the next hundred years. However if it was intended only to curb this problem when the threat became very serious, the population of uncontrolled objects would have grown so much as to present an enormous task for an object removal programme. Thus prevention is more desirable than cure.

On this basis it is of real concern that a re-orbiting strategy should be adopted universally. Furthermore the proportion of satellites suffering total failures has not reduced as the market has grown so there is expected to be a growing population of uncontrolled objects regardless of the extent of regulation on re-orbiting policy.

1.3 Real Potential for a Re-orbiting Mission

There is a case for restricting the increase of uncontrolled objects in GEO. It is known that many satellites are not re-orbited at the end of their mission for a number of reasons. Previous studies have investigated the possibility of rendezvous and docking with an uncontrolled target and concluded basic technical feasibility. The possibility exists therefore that spent satellites could be removed to a graveyard orbit continually by one or more shuttle vehicles. This would reduce the increase in such objects and could even reduce the total number of objects depending on the vigour of the programme.

1.4 Likely Economic Case for a Re-orbiting Mission

The economic case for re-orbiting to graveyard has also been studied. One example was the removal of dead satellites on the basis of the direct threat they posed to operators. It was concluded in [3] that the fee that could be raised from commercial spacecraft operators as a subscription for satellite removal would not pay for the capital cost of a mission, as the threat is presently perceived to be low.

The concept was also studied of an operator hiring the services of a re-orbiting mission as a means of preventing wastage of propellant through uncertainty of the quantity remaining for a graveyard manoeuvre. The net effect would be to allow the operator to use the spacecraft until its propellant reserves were absolutely exhausted. It was perceived that the potential revenue from this concept was higher than the first case identified but again would not cover the capital cost of the mission.

1.5 Role of Regulation and Operator Policies

At present there are no enforceable regulations on the re-orbiting of satellites. The Inter Agency Space Debris Committee (IADC) has established a guideline for re-orbiting which has been incorporated into the draft European Space Debris Mitigation Standards (EDMS) document. This includes determination of the distance that an object should be removed from GEO based on its mass, cross-sectional area and reflectivity. Some states, e.g. the UK, have developed a licensing process for satellite operators requiring them to adhere to these guidelines and some operators may have adopted them as good practice. However whilst it is essentially voluntary the guidelines will likely not be adopted universally as there are many instances when an operator will not be able to replace a satellite and will wish to keep it in use as long as possible.

It is not inconceivable, though perhaps unlikely, that a sufficiently universal intergovernmental body could succeed in imposing an enforced re-orbiting requirement on the majority of operators. This could have the direct effect of causing the owners to undertake this themselves, or it could be undertaken by a dedicated re-orbiting mission.

1.6 Synergies from Other Fields

The GSV study [3] was aimed principally at the repair or recovery of a satellite struck by mechanical failure or in some other way stranded. The economic investigation concluded that a commercial service for this purpose could command high fees if successful. It acknowledged though that the opportunities for such intervention are rare or at least randomly distributed.

The study suggested that a plausible composite mission would be feasible with the revenue stream obtained partially from a re-orbiting mission and partially from an imaging or servicing mission.

It may be possible to reduce the growth of hazards in GEO with a dedicated re-orbiting mission though it may only be viable as a joint mission. It may therefore become necessary to study the economic and technical feasibility of ancillary tasks in order to determine the case for the primary objective.

This study thoroughly investigates the tangible requirement for a re-orbiting mission and takes advantage of the technical synergies with servicing missions in order to determine a workable technical and economic solution.

1.7 Programme description

This technical work is divided into three major work packages as shown in figure 1-1. The final work package, WP 5000, has been devoted to the production of a video, a brochure and web pages describing the project. Figure 2-2 shows the applied study logic. The remainder of this document summarises the key issues developed in the course of the study.

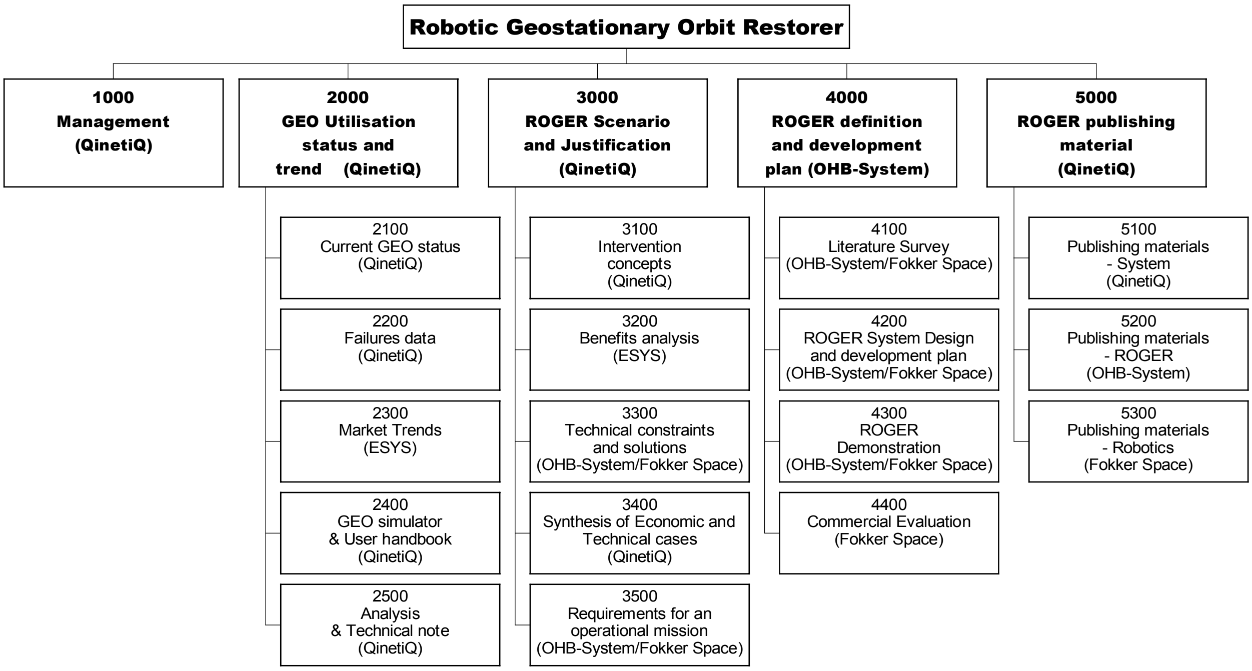

Figure 1-1 Work Breakdown Structure (high-level)

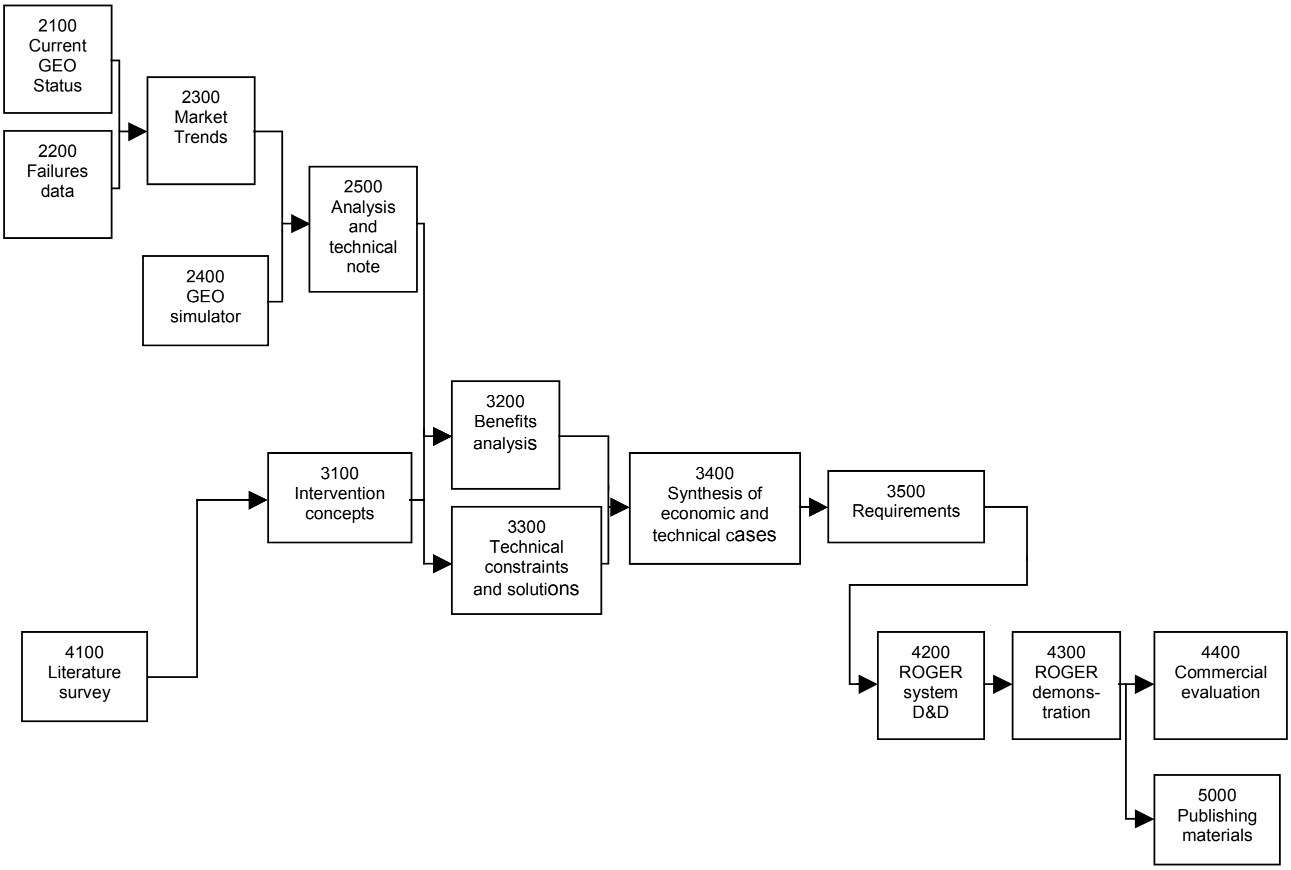

Figure 1-2 Study Logic Diagram

2 GEO Utilisation Status & Trend

The aim of the first major study task is to provide the basis for possible mission scenarios and the justification for a Robotic Geostationary Orbit Restorer.

2.1 Current GEO Status

The current population of objects residing in, or crossing, the GEO region has been determined by querying ESA's DISCOS database. Analysis has categorised the use and occupancy of the longitude slots in GEO by mission classification, country of origin and control status.

Key results include:

- As of January 2002 there are 900 reported objects in GEO of which ~ 28% are controlled, operational satellites. A significant proportion of the population, ~ 10%, are military satellites and rocket bodies that do not have publicly available orbital elements. Analysis of the distribution of objects around the GEO ring showed the most heavily utilised longitude slots are ~ 75ºE and ~ 105ºW due to a combination of natural orbital perturbations and mission requirements. Figure 2-1 shows the distribution of objects by longitude and status.

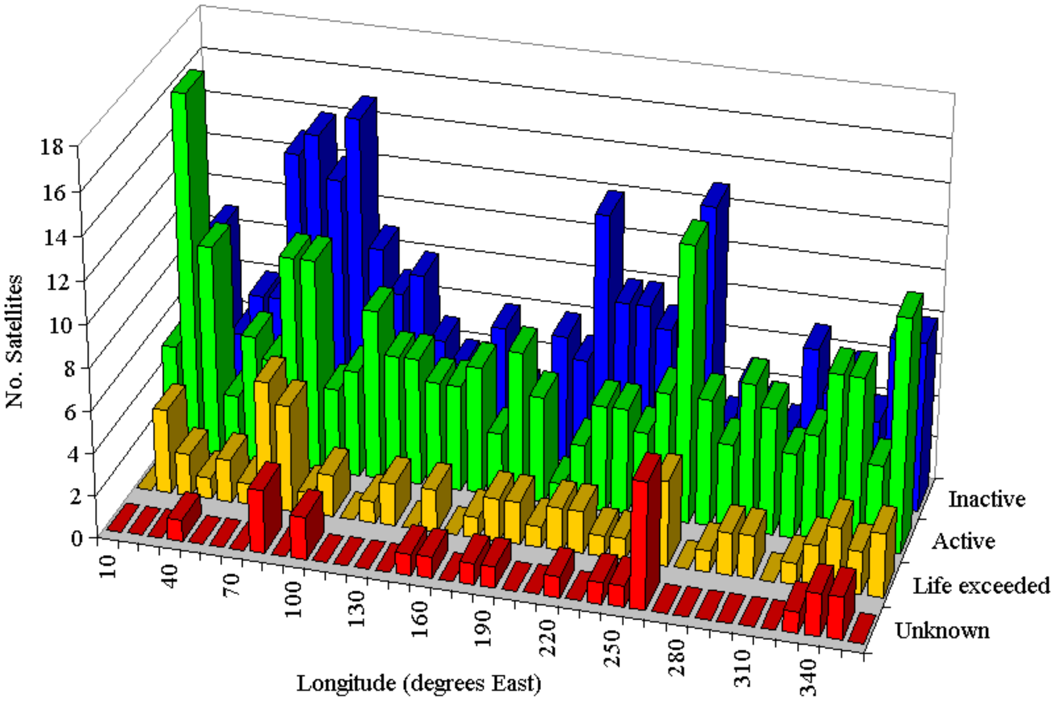

Figure 2-1 Distribution of satellites in GEO by status (derived from DISCOS data [4])

- By far the most dominant mission type at GEO is telecommunications - commercial and military services combined constitute ~ 85% of the satellite population.
- Additional analysis revealed 239 objects in GTO orbit that regularly intersect the operational GEO region, noting that the injection accuracy of launch vehicles could play a significant role in determining the potential hazard such objects pose to the geostationary orbit.

These population inputs will be used as the basis for a traffic model upon which the threat from overcrowding may be determined.

2.2 GEO Spacecraft Failures Data

The traffic model will project growth in utilisation according to current market research. In order to support the use of this model a satellite failure analysis has been performed. This has determined a range of parameters, including the probability of satellite failure at a given stage in its mission, the average design lives for several mass and functional categories, the proportion of satellites being re-orbited at the end of their operational lives and the rate of occurrence of failures with some potential for servicing.

All the results have made use of data available in the QinetiQ SpaceBase database of satellites and in-orbit events [5], which contains data on 6000 satellites and 1800 events. Some other sources were also used, notably the published review of re-orbiting success conducted annually by ESA based on the DISCOS database [6,7].

Key results include:

- The probability of satellite failure at a given point of the mission has been determined and this indicates that most satellites considerably exceed their formal design lives. See Figure 2-2.

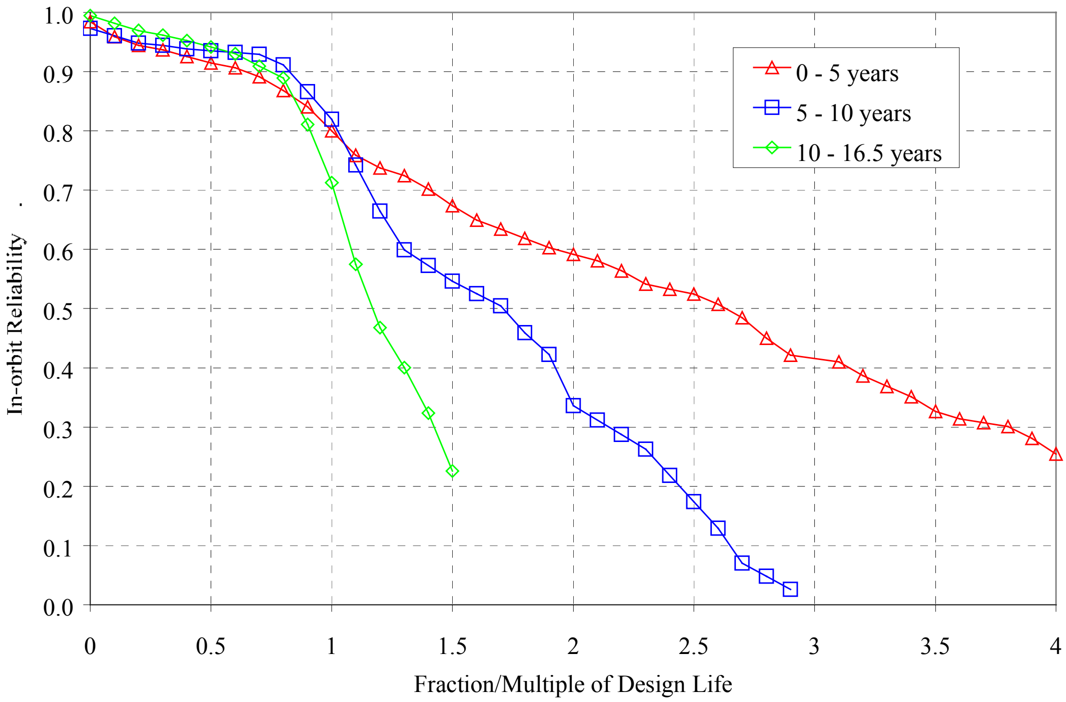

Figure 2-2 Probability of successful satellite operation (derived from SpaceBase data [5])

- Nearly 40% of all geostationary satellites are not re-orbited at the end of their design lives and only 30% are re-orbited in accordance with the IADC guideline, see Table 2-1. Approximately 3 – 4% of GEO satellites could not be re-orbited even if the operators were prepared to do so, due to onboard failures.
- Some satellites do develop failures with servicing potential. The most common types of event are appendage deployments and permanent failure to maintain attitude and longitude, which have occurrence rates of 3.3% and 2.9% respectively.

	Abandoned	Inadequate	Re-orbited	Total
1997	6	5	7	18
1998	8	6	7	21
1999	6	2	4	12
2000	3	3	2	8
2001	5	7	2	14
	28	**23**	**22**	**73**

Table 2-1 End of life actions for GEO satellites between 1997-2001 (derived from [6,7])

2.3 Market Trends

The evolution of the geostationary orbital region is contingent on the future GEO satellite population. A GEO satellite population model has been developed, which can statistically predict the number of satellites placed in GEO over the coming years.

The period of interest was determined to be the time of initiation of the study, 2002, through to 2030 thus enveloping the period of operation anticipated for the ROGER mission.

The starting point for the model was taken as the market baseline, which includes the current population of satellites in GEO, their distribution around the geostationary ring and estimates of satellite failure and re-orbiting rates, as discussed above.

The model is able to extrapolate forward in time from this initial population by replacing satellites that have failed and introducing additional satellites that reflect increased market demand.

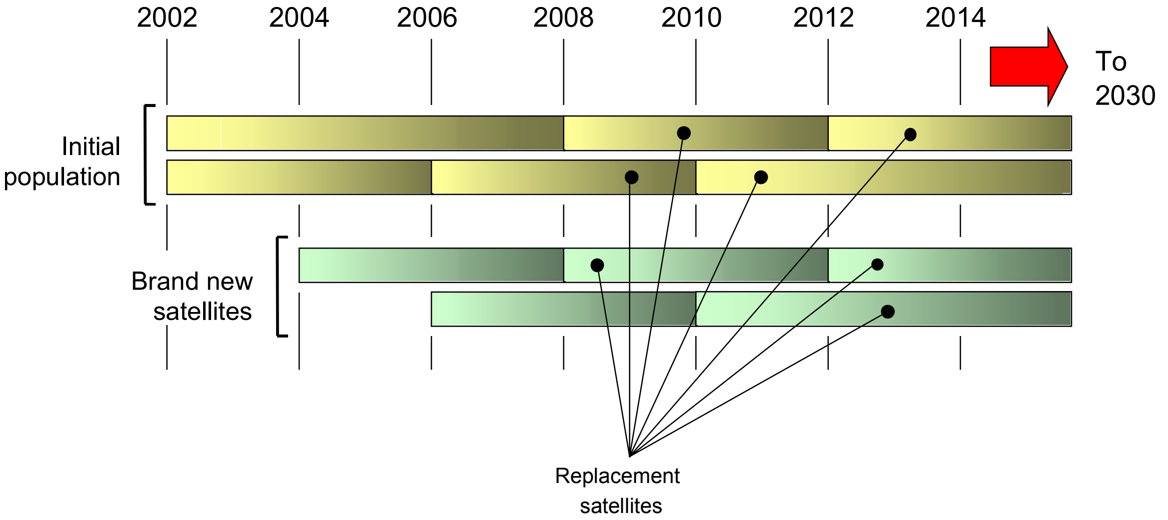

Figure 2-3 Satellite replacement and augmentation

Wherever possible, independent predictions of the future values of parameters such as launch rates and the mass distribution of satellites from 2001- 2010 have been used [8]. The output from the model is a comprehensive data set of satellites introduced into GEO, between 2002 and 2030, for a number of different assumptions regarding re-orbit policy and launch traffic rate.

The traffic scenarios considered were as follows:

- nominal launch rate and re-orbiting behaviour
- lowest launch rate and nominal re-orbiting behaviour
- highest launch rate and nominal re-orbiting behaviour
- nominal launch rate and worst re-orbiting behaviour
- nominal launch rate and best re-orbiting behaviour.

The bounds for nominal best and worse re-orbiting behaviour were derived from Table 2-1. Those from the launch rate were deduced from [8]. Ten data sets of each case were produced with different random seeds governing the application of failure probabilities and replacement launches. As an example Figure 2-4 shows the progression in distribution over longitude slots from 2002 to 2030 under assumptions of nominal launch rate and re-orbiting behaviour. Note that this distribution does not include the natural evolution of the satellite's longitude.

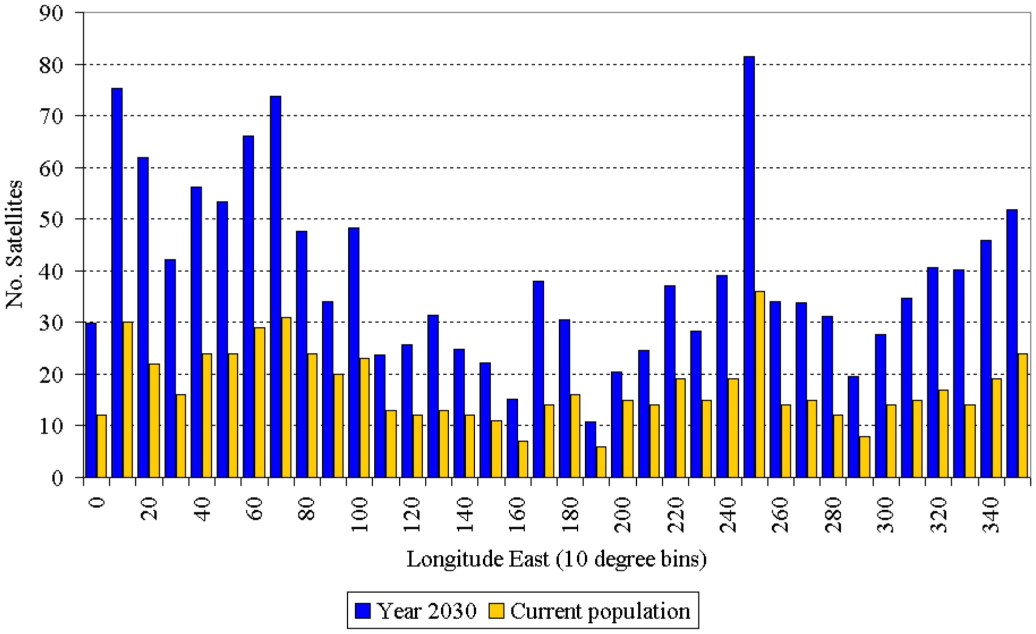

Figure 2-4 GEO longitude distributions for nominal launch rate and re-orbiting behaviour

2.4 GEO Simulator

To evaluate the consequences of future use and satellite failures on the geostationary environment, the future traffic projections have been combined with realistic orbital dynamics and a collision prediction algorithm to produce a computer simulation of GEO.

The GEO Simulator (GEOSIM) software tool was designed to provide an analysis of the effect on the geostationary ring of current and future satellite operations. This tool has been developed to ESA PSS-05 (lite) software engineering standards to run under the ESA standard desktop operating system, Windows 95, and is also compatible with Windows NT and 2000.

The model considers the region of GEO defined in Figure 2-5 and is based upon the GEO and GTO populations described in sections 2.1 and 2.3. Within the software, the object population is evolved over time using components of the QinetiQ Orbit Software Suite. This propagates the positions of objects to a high accuracy using numerical integration. The station-keeping cycles of operational satellites are modelled by an algorithm designed to represent generic cycles that are considered typical of current satellite operations.

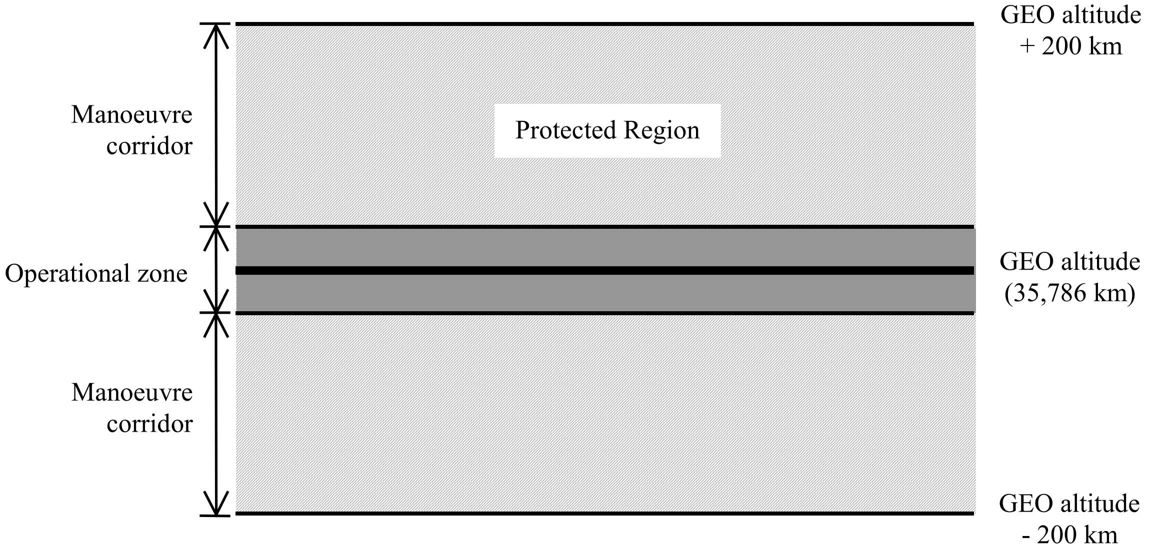

Figure 2-5 The operational GEO region as defined for GEOSIM

A close approach and collision prediction algorithm was designed to enable a quantitative assessment of the risk, making the best use of the publicly available orbital positions obtained during the analysis of the current population. The object position is conceptualised as in Figure 2-6 and an ellipsoid based on uncertainties in the along track, across track and radial positions is super-imposed over the nominal position.

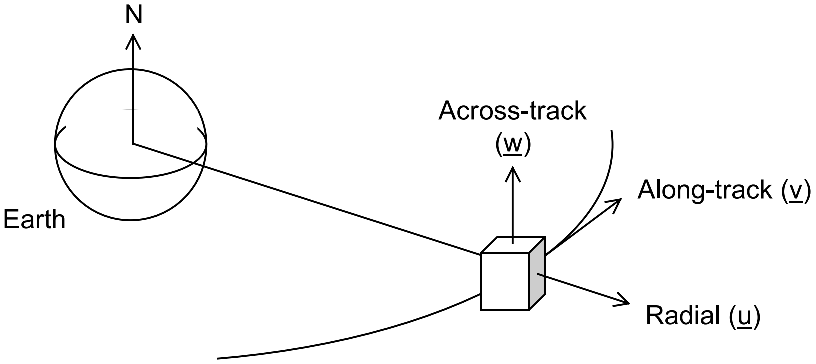

Figure 2-6 Satellite oriented co-ordinate system

The position of the object within its uncertainty volume is described using a normal distribution. By assuming that the along-track, across-track and radial errors are all independent of each other the probability density function may be described by three independent, one-dimensional distributions.

The probability of collision is determined on the basis of the intersection of each object with the uncertainty volume of the other object as in Figure 2-7. In this manner a collision probability for each object pair is determined for the period in which the uncertainty volumes intersect.

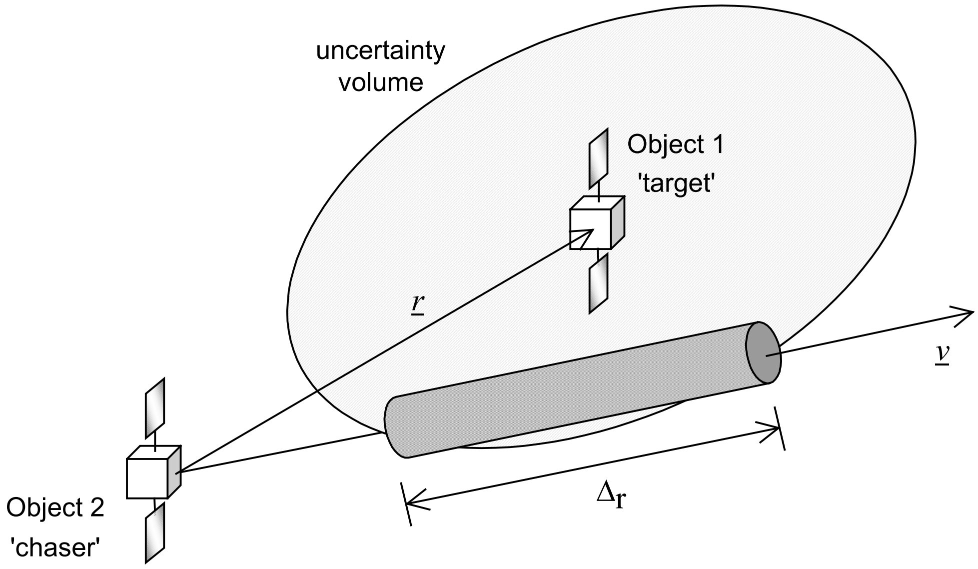

Figure 2-7 Determining the collision probability

2.5 Analysis of collision risk assessment

The GEO Simulator has been used to investigate the best and worst cases thought to apply in GEO over the period to 2030 and thus provide a quantitative assessment of the effect of future launch traffic and space debris mitigation policies.

Future Population Scenarios	**Probability of a Single Collision**
Nominal	2.83 ± 0.43%
Low launch rate	2.43 ± 0.30%
High launch rate	2.57 ± 0.25%
Best re-orbit rate	1.75 ± 0.33%
Worst re-orbit rate	3.71 ± 0.61%
Nominal excluding GTO objects	2.46 ± 0.32%

Table 2-2 The risk of a single collision occurring between tracked objects during the simulation

The results from the analysis with GEOSIM are given in Table 2-2. The key points include:

- there is a ~ 2.8%, or 1 in 35, chance of a collision occurring between two tracked objects in the GEO region in the period 2002 to 2030, assuming nominal launch traffic and re-orbit rates apply;
- this rises to 3.7%, or almost as high as 1 in 25, for the worst re-orbiting case
- the standard deviations shown are those resulting from the necessarily random element of the future traffic projection;
- a significant proportion of close conjunctions are between two controlled satellites, which is attributed to the similarity of manoeuvre profiles used;
- the overall risk of a collision does not drop significantly when GTO objects are excluded from the nominal case;
- by 2030 the number of uncontrolled objects populating the GEO region increases to 79% for nominal launch rate and re-orbiting assumptions.

As expected, significant numbers of objects collect around the most highly utilised orbital slots, see Figure 2-8, with a corresponding increase in the local collision risk. It should be noted that a small number of close conjunctions, having a high probability, could bias the collision probability at a given longitude.

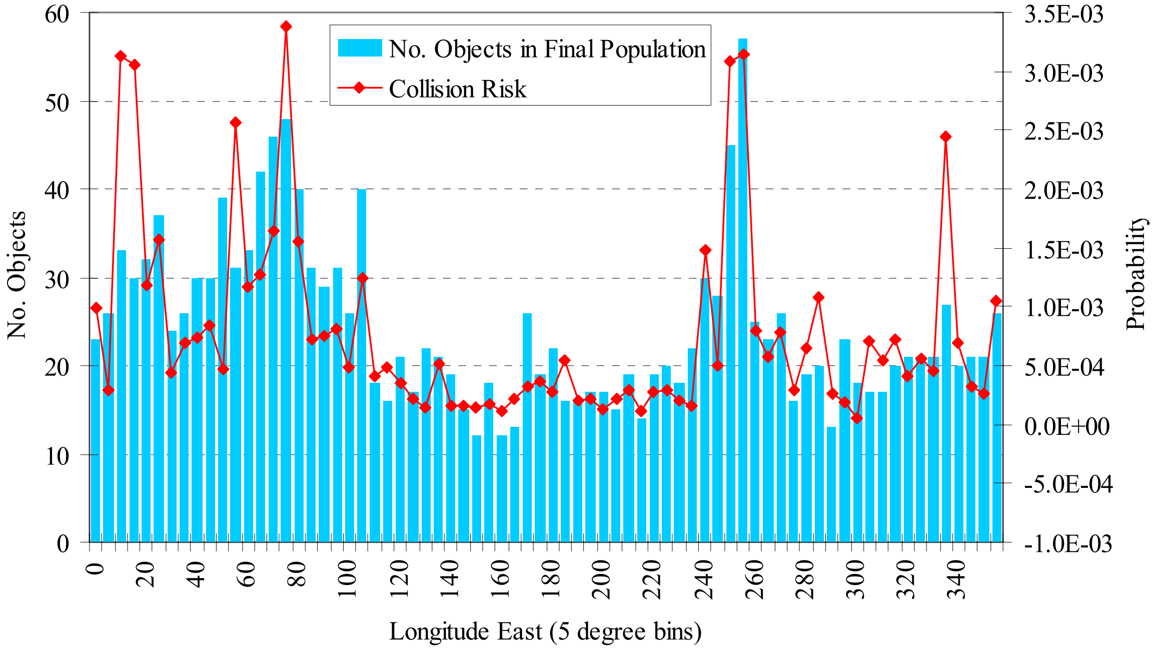

Figure 2-8 Correspondence between longitude distribution and collision risk

An investigation was also aimed at resolving the collision hazard resulting from a permanent manoeuvre failure of one satellite amongst a co-located cluster of satellites. This study was actually based on a the current Astra fleet at 19.2ºE. For this longitude it is determined that the risk to the remaining satellites of the cluster is not significantly increased in comparison to their background risk from other all uncontrolled objects. This result, which may vary according to longitude, occurs because the natural evolution of the failed satellite, due to orbital perturbations, will move it away from the vicinity of the cluster.

It is believed that these results are broadly compatible with other detailed studies into the collision risk at GEO. It is important to note that this result excludes any consideration of the untracked debris population in the geosynchronous region. The lower limit of object size for detection by the US Strategic Command Surveillance Network is 1m at GEO. Furthering our knowledge of the untracked population is key to providing a full understanding of the collision risk present at geostationary altitudes.

To summarise the six principal cases evaluated have suggested that:

1. The re-orbiting policy dominates collision probabilities, having a much greater influence on the evolution of GEO than expected variations in future launch traffic.
2. For the whole near term period from 2002 to 2030 there is a cumulative chance of collision over the 28-year period of 2.8% for the nominal re-orbiting case over all objects. This rises to 3.7% for the worst re-orbiting case. If GEO re-orbiting was implemented to its fullest the collision risk in the region may be almost stable with a cumulative chance of collision of 1.7% over the same period.
3. Variations in the predicted launch traffic rate (as derived by the ROGER GEO satellite population model) do not play a significant role in decreasing or increasing the collision risk over the next 30 years.

4. The results indicate also that the role of GTO objects for the collision probability in the GEO region is not significant.

3 ROGER Scenario and Justification

The aim of the second major study area is to determine plausible technical and economic scenarios for a Robotic Geostationary Orbit Restorer.

3.1 Intervention Concepts

The results from section 2.5 suggest the following policies for a re-orbiting programme:

1. mass removal is required for general GEO resident objects. Mass removal for GTO objects is less significant and GTO objects are not presently subject to the same re-orbiting guidelines as GEO objects;
2. mass removal effectively needs to keep the number of objects static. The earlier such a programme is started the less the future risk will be.

A scheme may therefore be based on removing objects as they become uncontrolled or removing objects in high-risk longitudes. There is no need to consider the removal of older objects with higher inclinations. Removal of objects as they reach the end of their controlled lives has the advantage that the operator will generally still exist as an entity and may be approached regarding the disposal. This achieves the required result and avoids the need to deal with issues of ownership, liability and payment from potentially defunct organisations. The predictions also suggest that mass removal of GTO like orbits need not be considered to a first order.

The principal mission of interest is re-orbiting. This mission is studied from a commercial and publicly funded perspective. The possibility of commercial funding of servicing missions is also examined to scope the possibility that commercial servicing could assist in the economic viability of a re-orbiting mission. This is based on the perception that servicing missions may have a high value in their own right and also have sufficient technical similarity to a re-orbiting intervention mission such that development costs and possibly even flight hardware may be shared.

A search of literature regarding servicing concepts and the related applications of robotics has been conducted. A number of recent and current satellite servicing system concepts have been reviewed and demonstrate:

- feasibility of proximity manoeuvres
- docking with ABM adapter
- relative expense of robotic technology
- teleoperation.

The following robotic concepts are perceived to have the strongest connection with the ROGER concept for spacecraft capture and servicing activities:

- DLR ROTEX experiment
- DLR/Japanese GETEX/ETSVII experiments
- ESA ERA.

A number of non-robotic concepts for spacecraft capture were also considered and thus the review looked for contemporary mechanical design concepts of interest:

- NASA inflatable lenticular antenna reflector

- Dornier telescopic mast
- tethers for orbiting object capture.

Some of the content of previous studies and experiments in servicing missions is directly relevant to the re-orbiting task as well as to servicing aspects of the ROGER concept, including:

- DLR ESS(T)/OSS mission studies
- DLR/Japanese GETEX/ETSVII experiments
- ESA GSV study.

The output of the literature search was used to generate several intervention concepts, distinguished by purpose and timeframe. The purposes are re-orbiting and servicing, and a number of servicing events are then considered based on their likelihood of occurrence.

The selected cases of intervention concepts for the ROGER spacecraft and mission are:

Case (i)a: Government or commercially funded re-orbiting mission using a minimum development route (e.g. with no reliance on robotics)

Case (i)b: Government or commercially funded re-orbiting using currently mature robotic technology (i.e. minimum development still consistent with servicing possibilities)

Case (ii): Commercially funded servicing mission using currently mature robotic technology

Case (iii): Commercially funded servicing mission using more advanced technology, expected to be mature in perhaps 10-15 years, aiming to take advantage of a wider range of servicing targets.

Thus cases (i)a and (i)b envelop the principle aim of re-orbiting and possible subsidy from servicing.

Servicing events considered under case (ii) are those that can be achieved with no more robotic technology than that required for rendezvous and docking without damage to the target. These are listed in Table 3-1 together with their probability of occurrence per geostationary mission as determined from [5]. The motivation for servicing case (ii) events is to use the same rendezvous and capture technology and possibly even the same spacecraft to provide revenue with which to support the capital cost of the hardware required for the re-orbiting missions.

Event type	**Probability per GEO mission**
Catastrophic premature fuel exhaustion or AOCS failure	2.9%
Deployment failure, e.g. stuck in GTO	0.8%
Uncontrolled spin-up, i.e. unsuccessful ESR	0.4%

Table 3-1 Case (ii) servicing event types (derived from [5])

Each of these event types has a well-known precedent. Orbital Recovery has been in the news recently for their programme for extending the life of GEO communications satellites. The Artemis and Astra 1K satellites were both victims of deployment failures, though with rather different final outcomes. The Olympus spacecraft suffered an uncontrolled spin-up in 1991. As indicated in the table the probability of events with a similarity to the Olympus case, and yet not finally being recovered by the operator, is actually quite low.

Servicing events for case (iii) are those listed in Table 3-2 and all require manipulation of some mechanical feature of the target spacecraft after capture. The motivation for case (iii) is to take advantage of a larger number of events.

Event type	**Probability per GEO mission**
Antenna or Solar Array Release	3.3%
Other mechanical or thermal alignment problems	0.6%
Other mechanisms, in service problems	1.3%

Table 3-2 Case (iii) servicing event types (derived from [5])

The value of correcting such events with a servicing intervention mission varies from case to case. A review of reported insurance payments from [5] suggests that typically those events resulting in whole mission loss could imply a value for correction of the order of €100-200M. Lesser events such as stuck antennas could still imply a value of €50-100M depending on the degree of services lost.

It was considered in early reviews of these event types that the basic appendage release category may itself not be particularly demanding from a robotic point of view. Typical actions could be the application of torques or cutting of release cables, if accessible. As a result this event type was thereafter considered to be potentially viable within the case (ii) near term servicing concept. This obviously puts an optimistic scenario on the case (ii) concept given the high probability and value of such events.

3.2 Technical Constraints and Solutions

The technical challenges implied by the intervention cases have been addressed to determine plausible solutions and establish any fundamental limits to that which may be achieved. In this section both robotic and non-robotic solutions are identified for certain cases together with the identification of system issues and generation of ROM costs.

An exhaustive review of technical constraints and potential solutions has been carried out for each phase in the mission of each of the intervention cases and event types identified in section 3.1. This concluded that there are only a few technical constraints and a few key design drivers and critical technologies identified for a GEO intervention mission. The most significant issues are the following:

3. the ability to safely capture a target satellite is constrained by the target satellite's dynamic behaviour, its shape and structure and the availability of solid capture and docking points,
4. the number of target satellites within a multiple target mission is technically limited by the OCS capability in terms of propellant mass and reasonable spacecraft reliability during mission design lifetime. Consideration should be given to the trade-off of transfer time and propellant mass for high Isp electric propulsion systems,
5. the ACS of ROGER has to be capable to control both the ROGER satellite and the tandem "ROGER plus target satellite" within all mission phases,
6. the ability to perform the intervention case (iii) and the related event types are constrained by the availability and capability of dextrous robotics,

7. the supervision, control and eventually tele-manipulation of ROGER from ground, especially during the close approach, capture and docking, taking into account the data turn-around latency for communication with GEO.

3.2.1 Capture

Beginning with the capture, for at least intervention case (i):

- the target will be non co-operative, e.g. abandoned spacecraft, upper stages or other debris,
- given the premise from section 3-1 the target objects can be limited to low inclination satellites reaching the end of their operational lifetime,
- the attitude and the dynamic behaviour (residual spin rate, spin axis) of the target is not controlled.
- the capturing approach is assumed to differ for re-orbiting compared to the other cases in respect of the risk of damage to the target satellite. Whilst an in-orbit collision must be avoided at all times it is clear that a re-orbiting only mission could tolerate a more severe capture than a servicing mission. i.e. a capture process that resulted in physical contact with delicate surfaces on the target such as second surface mirrors and thermal blankets should be acceptable for re-orbiting purposes. The guiding principle should be no new debris generation.
- for the servicing cases (ii) and (iii) either some special manoeuvring with the target or some manipulation of mechanical fixtures will be necessary. Both of these activities can be assumed to diverge from the re-orbiting manoeuvre required for case (i).

A number of non-robotic and robotic schemes have been reviewed for the capture phase. The non-robotic methods are the result of a deliberate exercise to generate some novel solutions and have in common the greater risk of damage to the target and have thus been excluded at the outset from case (i)b, (ii) and (iii).

All solutions require considerable stand-off between the chaser and target to allow access past appendages on a possibly rotating target whilst still maintaining a safe separation of the target from the chaser body.

Table 3-3 lists the basic capture options.

Mission type; Constraint	Distinguishing features
Case i) re-orbiting mission only	
Shooting Net, Bolas or a combination	Expanding net directed at target with weights to wrap around the target and snare on barbs on the weight cords or net. Requires a new net for each target. Non rigid connection between chaser and target and with dynamic control problem for chaser. Modest cost, mass and volume. Difficult to test in 1g. Potentially complex ejection mechanism.
Hinged hands or rakes	Inflatable hands or mechanical rakes hinged at shoulder on chaser spacecraft. See Figure 3-1. The closing torque is applied from the shoulder and the inflatable structure or rakes are simply intended to grasp the target making use of uneven surfaces for grip. Many variants possible. Maybe difficult to guarantee retraction of arms at mission completion. Modest cost, low stowage volume.
Octopus-tentacles	Several rigid and articulated, or semi-rigid, tentacles to encircle the body of the target; see Figure 3-2. Requires surveillance to control alignment of tentacles away from target appendages. Simple joints without precise control requirements. A semi-rigid capture that allows for pushing or towing during re-orbiting. Modest cost. Mechanism testable in 1g, low mass.
Robot arm with “simple” end-effector	Highly mobile arm with a capture tool; see Figure 3-3. Must be similar scale to ERA, i.e. multi-jointed and 11m reach in order to access the apogee engine grappling point.
Case ii) restoring service and Case iii) sophisticated servicing level	
Manipulator arm + universal capturing tool	Robot arm with capture tool and additional tool set. Probably heavier than ERA, capable to perform additional services.

Table 3-3 Summary of capture methods

All solutions have some challenge concerning the motion of the target spacecraft after first contact by the capture equipment. The apogee engine expanding nozzle clamp appears to be relatively certain though requires precise initial alignment. The octopus solution should avoid divergence of the target position as the first contact will be from the tentacle tips and thus result in motion contained within the cage of the tentacles.

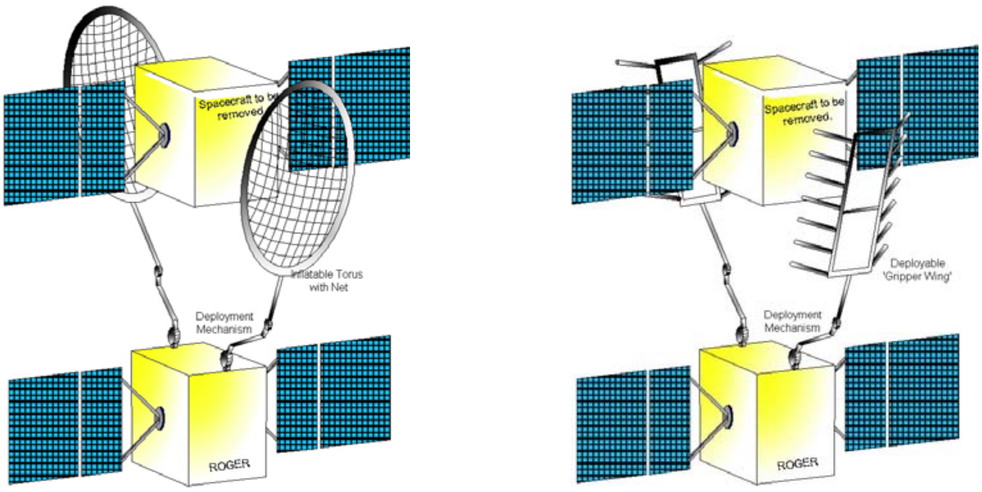

Figure 3-1 Large inflatable hands or mechnical rakes

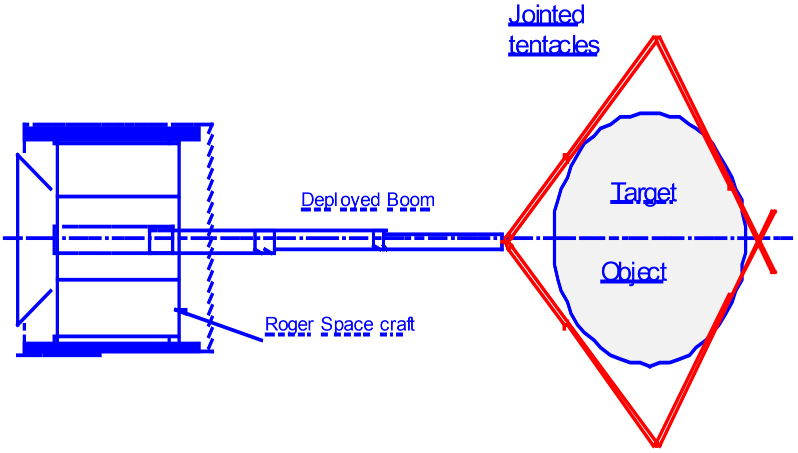

Figure 3-2 Capture of target using the Octopus tentacle solution

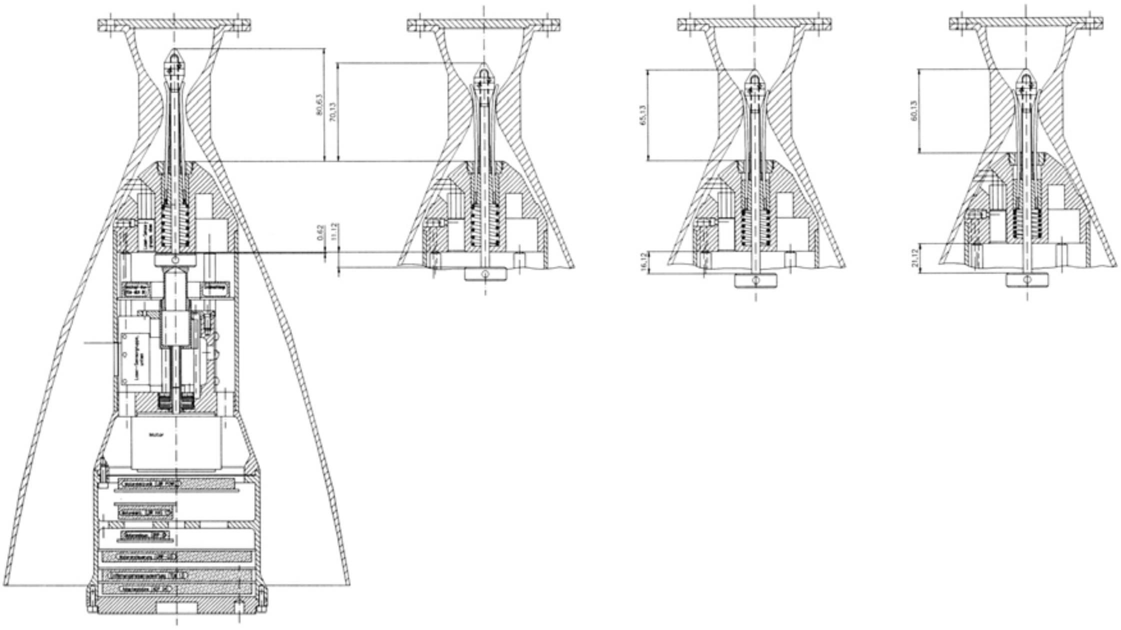

Figure 3-3 Apogee engine coupling tool of ESS/T [9]

The target object is most likely to be a satellite having previously adopted an Earth pointing mission and will also most likely have utilised some form of momentum bias for attitude stability. This presents an extra challenge for the capture phase, as this momentum bias will transfer into a body rate as the satellite becomes uncontrolled. This will result in a uniform rotation about the target's axis of greatest moment of inertia, i.e. a "flat spin", with any nutation having been naturally damped by flexible modes in the target.

The residual spin rate of a number of plausible targets has been assessed and is generally expected to be less than 1°/s. The implication for all forms of capture equipment is that spin rate matching between the chaser and the target will probably be necessary.

Trade-off of the non-robotic and robotic capture concepts considered cost, maturity, development time, ease of testing and operational features such as appllicability to different target types. The final selection favoured a non-robotic solution, the octopus tentacles, for the re-orbiting only case (i) on grounds of cost and simplicity.

The baseline choice of an ERA scaled manipulator arm was made for cases (i)b, (ii) and (iii). The latter cases (ii) and (iii) are then distinguished, as far as the payload is concerned, by the need for more complex end effectors to perform the various servicing activities.

3.2.2 Mission profile

The next most dominant trade-off is to define how many re-orbiting or servicing missions should be undertaken by a single ROGER spacecraft. This includes parameters such as the time and propellant required to perform the intervention and how rapidly the system can respond to a new requirement to re-orbit or service a client satellite.

Within this assessment some assumptions must be made over the orbital distribution of targets. It is reasonable to assume that the target could be located anywhere in longitude terms although the finer distribution will approximate to that suggested in Figure 2-2. Given that the re-orbiting action will cause the longitude of the ROGER spacecraft to drift it is reasonable to assume a worst case need for longitude harmonisation between re-orbiting events of 180º. The rate at which longitude changes are accomplished will drive the propellant budget.

The inclination of satellites requiring servicing are most likely to be low given that the majority of modern satellites are North South Station Kept missions. Uncontrolled objects however initially adopt an increasing inclination with time. Re-orbiting of objects with significant inclinations would be very costly for a ROGER spacecraft in propellant mass terms due to the plane changes involved. It has been noted in section 3-1 however, as a product of the hazard analysis that a workable strategy would be to limit re-orbiting to those targets just becoming uncontrolled at the end of their operational lives. In this case these objects are also likely to have a low inclination.

Thus it is probable that a typical intervention mission will be required to make a combination of a longitude change and a small inclination harmonisation. The mass of propellant required over a multi-target mission and the time taken to perform such a mission can then be determined for a given propulsion system. A propellant mass efficient electric propulsion system such as an ion thruster will generally require longer transfer times than an impulsive bi-propellant system. This is illustrated in Table 3-4.

Type and Number of Targets	**Mission duration (years, months)**				
	Monoprop	**Bi-prop**	**Arcjet**	**Ion thruster**	
	Valid for all intervention Concepts/ solutions			**non-robotic solution**	**robotic solution**
First Target	3 m			4 m	4.5 m
Each additional	2 m			3 m	3.5 m
10 Targets	1y 9m			2y 10m	3y 3m
20 Targets	3y 5m			5y 4m	6y 2m
30 Targets	5y 1m			7y 10m	9y 1m
40 Targets	6y 9m			10y 4m	12y

Table 3-4 Estimated mission duration and repeat rates

There is a strong cost advantage in selecting a high specific impulse electric propulsion system. Figure 3-4 shows the dependency of the ROGER mission costs of the number of re-orbited target spacecraft. Trade-studies have also looked at the relative merits of Arcjets, ion thrusters and stationary plasma thrusters (SPT), some details of which are given in section 4.

Figure 3-4 also usefully indicates the difference in system costs due to choice of payload type. The non-robotic Octopus tentacle solution is expected to be less expensive than a robotic manipulator and also considerably lighter, compounding the cost impacts. This result can readily be applied to distinguish case (i)a from cases (i)b, (ii) and (iii).

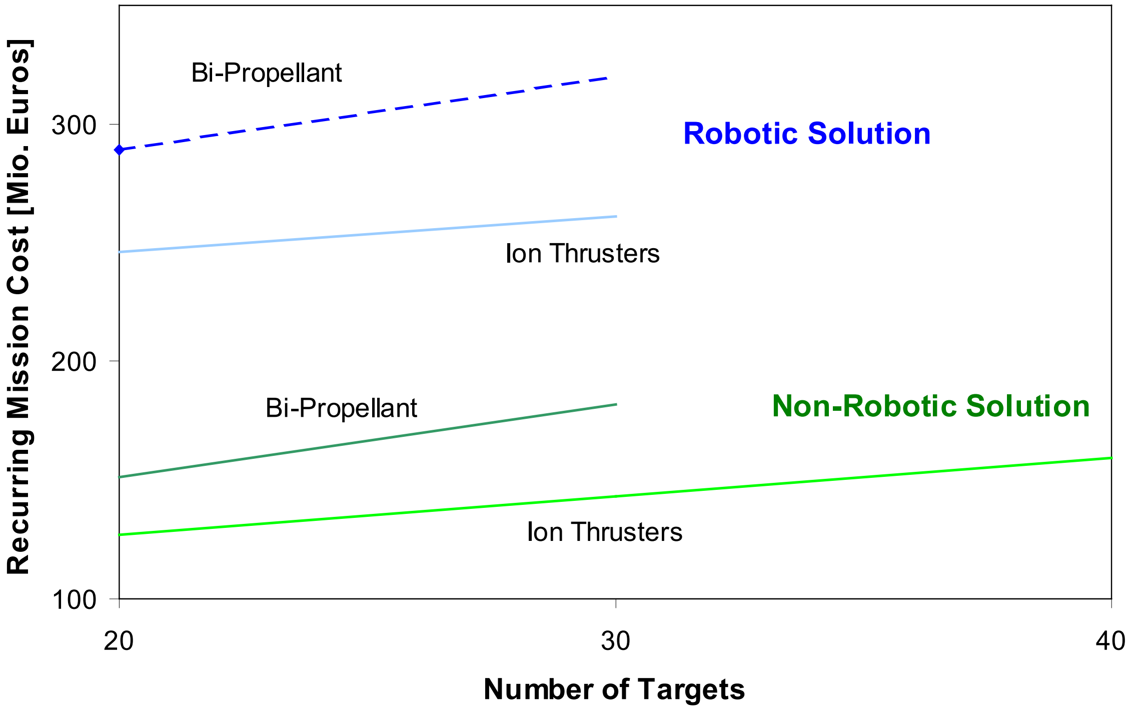

Figure 3-4 Dependency of ROGER mission costs of the number of re-orbited target S/C

3.2.3 Servicing specific topics

The servicing missions comprise two broad categories:

- case (ii), those requiring docking and manoeuvring permanent docking, such as deployment from GTO or re-provision of AOCS facilities;
- case (iii), those requiring docking and manipulation of mechanical features on the target spacecraft.

It is presumed, given the current maturity of robotic technology, that case (ii) missions are within reach of current mature technology and case (iii) are necessarily require significant technology development. Recall however the possibility that some relatively simple mechanical manipulations may be possible in the case (ii) timeframe.

Costs and system architectures for case (ii) missions are in the first instance assumed to correspond well with the robotic solution for re-orbiting outlined in the previous section. Divergence is likely however for the following reasons:

- provision of permanent 3-axis control and station-keeping to remedy premature fuel exhaustion or AOCS failure is likely to be a single target mission;

- recovery of a satellite from a failed deployment is likely to be very demanding in propulsion terms. This event category has been labelled “transfer from GTO” for convenience but this statistic in Table 3-1 is actually combined from launcher under-performance and spacecraft failures. Thus the design must be capable of a potentially very high delta V and also, to be useful, must be capable of delivery to orbit rapidly, requiring a dedicated launch and spacecraft available in ground storage;
- both of these mission categories are likely to require a rather stiffer connection between the servicing vehicle and target than can be afforded by a robotic manipulator and some form of semi-permanent coupling will be required;
- it is difficult to project total system costs for case (iii) missions though it is reasonable to assume that the potentially larger range of treatable event types may be of benefit in finding a cost effective application scenario.

3.2.4 System costs and summary

Table 3-5 indicates the effective cost per target visited for non-robotic and robotic capture solutions. These missions correspond to cases (i)a and (i)b respectively and the robotic costs also apply as a lower bound first estimate to the costs of the case (ii) servicing missions. General characteristics of the spacecraft assumed in this solution are given in section 4.

No. of Targets	**ROM Cost per Target [Meuro]**			
	Monoprop	**Bi-prop**	**Arcjet**	**Ion**
	Non-robotic solution			
20	First: **10.7** Recurring: **8.7**	First: **9.5** Recurring: **7.6**	First: **8.5** Recurring: **6.7**	First: **8.3** Recurring: **6.4**
30	†	First: **7.4** Recurring: **6.1**	First: **6.7** Recurring: **5.3**	First: **6.1** Recurring: **4.8**
	-	-	-	First: **5.1** Recurring: **4.0**
	Robotic solution			
20	†	First: **17.0** Recurring: **14.5**	First: **15.0** Recurring: **12.6**	First: **14.8** Recurring: **12.3**
30	†	†	First: **11.9** Recurring: **10.2**	First: **10.4** Recurring: **8.7**

† no solution with launch mass within bounds of dedicated Ariane 5 launch to GTO

Table 3-5 ROGER ROM cost per target

To summarise the key points of this part of the study:

1. all re-orbiting and servicing missions appear to be basically technically plausible
2. the basic choice between deployable bulk grappling structures and local grappling device attached to a robotic arm basically relates to the cost and mass implications of the latter. It appears that non-robotic devices can offer a plausible means of capture and thus are the preferred solution for a re-orbiting mission where the consequences of superficial damage to the target object are minor;
3. case (ii) servicing missions will require a robotic manipulator
4. the propellant fraction of system mass is a significant design driver. The main trade off in propulsion technology is that of propellant mass against time to complete

each re-orbiting transfer and there are factors such as thruster lifetime and technology readiness to consider.

Further significant issues include:

5. total system life is a significant issue limiting the cost effectiveness of any individual ROGER spacecraft.
6. generic GNC for ROGER is more complicated than typical space missions so in-orbit validation for concepts and system elements is required.
7. generalised spacecraft designs attempting to meet many mission types such as for case (ii) and case (iii) may become over-designed for any one given task, thus reducing their cost-effectiveness.

3.3 Benefits Analysis

An assessment has been made of the willingness to pay of various entities for each of the intervention concepts. These are compared with the event rates that drive the cases for re-orbiting and servicing. The potential costs of intervention missions suggested in the previous technical investigation are reflected in the plausibility arguments.

3.3.1 Concepts of beneficiaries, losses and willingness to pay

The direct beneficiaries of a re-orbiting mission are primarily mission owners, whether private or public. Users, insurers and general public represent significant direct and indirect beneficiaries. The primary benefit being supplied is immunity against collision and thus the probability and magnitude of this loss are key factors.

The probability of the loss has been given in section 2-5. The magnitude of loss can be expressed in terms of the asset costs, typically in the range €100-300M at launch or in terms of lost revenue. At the current time a review of the turnover of the 10 leading GEO satellite operators [10] suggests that the mean revenue per satellite is approximately €42M per annum per telecom satellite.

It is believed that satellite operators in general regard the risk of in-orbit collision as low, at least in respect of the evidence of Table 2-1. The insurance industry does not appear to have taken much interest in this field and on the basis of the above estimates for probability and impact of a collision insurance premiums could be expected to be low.

Presently there is no legal compulsion for satellite owners to re-orbit their satellites when no longer in use. There is no means of enforcement for the current IADC guideline that would create a market for a re-orbiting service such as ROGER.

As a natural resource, governments have an interest in the management of GEO however the “public”, i.e. governments, are unlikely to pay for re-orbiting as the hazard is not sufficient to pose a significant threat to individual businesses or global trade in the time-scale studied. This assumes that until a collision actually occurs the likely-hood will be perceived low. It may actually take a collision resulting in litigation, perhaps because of one of the objects being owned by a commercial entity, to really stir public or government concern.

The “polluter pays” principle could be seen as reason enough to strengthen re-orbiting guideline into an enforceable regulation. It is believed however that such a change is not likely in the foreseeable future and so a remaining option is for government investment to generate improved conditions for commercial market

3.3.2 Voluntary re-orbiting practice

On the basis of Table 2-1 there are between 8 and 21 “end of operational life” events per annum, of which 30% may result in successful re-orbiting and perhaps an additional 30% at least attempted a re-orbiting manoeuvre.

A re-orbiting manoeuvre to 300km above GEO requires energy equivalent to an 11ms^{-1} impulsive delta-V. On the basis that a typical North-South Station Keeping mission requires an annual delta-V budget of 45ms^{-1} per year just for inclination control it may be assumed that the re-orbiting manoeuvre costs the operator about a quarter of a year’s revenue. When combined with mean revenue values this suggests that an operator sacrifices about €10M revenue to re-orbit each satellite.

It is then a simple step to propose that a commercial re-orbiting service would be viable if it could price each re-orbiting mission at less than this value. A number of questions may be raised against such an argument, such as over the revenue estimate, the uncertainties in remaining propellant and the propulsion technology in use though this value is believed to be a reasonable benchmark at present and perhaps also for the foreseeable future.

As a precaution the nature of the satellites recently being re-orbited was reviewed as a first estimate to future behaviour. For example, if a satellite suffered a major payload failure the operator could perform the re-orbiting at no further loss of revenue yet that case would bias the Table 2-1 statistics. Conversely a manoeuvring failure would prevent re-orbiting even if the operator could be supposed, through its track record, to have intended a re-orbiting. Finally, some operators who actually perform re-orbiting themselves at present are government organisations rather than commercial and thus may not have commercial pressures to continue revenue earning operation to the last possible moment.

This review considered each end-of life event for the satellites contributing to the data in Table 2-1 and attempted to assess, by cross checking [4] and [5], whether there really had been a conscious sacrifice of station-keeping propellant in order to perform the re-orbiting. This review concluded that between 16% and 44% of recent end of life events could be associated with a will to pay for re-orbiting. This is equivalent to between 2 and 6 opportunities for a ROGER mission per year.

Recurring costs for a re-orbiting only mission are in the region of €130-160M for the hardware, launch and operations of a mission capable of 20-30 re-orbiting targets. Consequently the cost per re-orbiting event, not including a margin for amortisation of development or the cost of capital, will be about €5-6M. The distribution of opportunities suggests that a single ROGER spacecraft could meet the demand.

3.3.3 Servicing

The case (ii) intervention, near term servicing, is characterised by events that will very likely require a new ROGER spacecraft for each event. The most attractive servicing case appears to be replacement provision of attitude and orbit control functions on the basis of the frequency of events and the value of the remedy.

Remedy of the type of failures that would allow the same servicing spacecraft to perform several missions appears limited, with current technology, due to the low number of such events.

The timeliness of response will improve the value of the single event type of mission and thus a joint re-orbiting and servicing mission could be considered. In this case a ROGER spacecraft would be launched into a re-orbiting role until such a time as an operating satellite suffered a manoeuvre related failure and then the ROGER spacecraft would be re-directed to remedy the situation.

However there would only be a benefit to the re-orbiting programme if sufficient profits could be generated from the servicing mission to pay for the capital cost of the ROGER spacecraft, thus subsidising the fee to be charged for re-orbiting. It appears however that the cost of a servicing mission could be as much as €250M, given that a robotic payload is required. Thus the profit margin compared to the likely total loss value of the failed satellite will be quite slender, if at all positive.

Thus it does not appear that there is a compelling argument for this form of servicing in its own right, particularly given the technical and commercial risks. The situation would improve slightly if many appendage release events could be solved with a general purpose manipulator and a small number of tools though it would be difficult to assess the proportion that was genuinely achievable. Thus the attraction of the Case (ii) servicing concept to assist in the operation of a re-orbiting programme is also not great.

The case (iii) intervention, longer term servicing, is characterised by frequent and high value opportunities. If it may be reasonably assumed that all appendage release failures may be remedied by such a mission then there could be as many as 2 events per annum associated with insurance payments of the order of €50-100M.

Thereafter the business model for case (iii) servicing are similar to case (ii) though there is a greater confidence in the availability of clients at a cost of higher technical risk and development effort.

The possibility of more advanced servicing concepts such as refuelling and ORU exchange has been considered but not specifically evaluated, being outside the scope of the study and there being a lack of information on which to base a market size. Such concepts also suffer from the circular problem that it is difficult to assess the market size because it doesn’t yet exist. There are however government initiatives in Europe, the US and Japan to progress the concept of in-orbit servicing and so this appears to be an area that should be monitored for developments.

3.3.4 Cost effectiveness of intervention for voluntary re-orbiting

The only plausible commercial model appears to be that based on operators that already voluntarily re-orbit as a policy. The benchmark of effectiveness has been assumed to be that an operator sacrifices €10M in revenue in the act of a voluntary re-orbiting. A key point is that there is considerable risk in this assumption, i.e. re-orbiting will be a high-risk business because of uncertainties over market depth.

An entirely commercially funded mission must use this revenue to pay for the development of the technology and spacecraft design, the recurring costs of manufacturing successive ROGER spacecraft and the interest on the capital used to fund the venture.

Thus it appears that the recurring cost per re-orbiting must actually be significantly lower than €10M and maybe rather lower than €5M after accounting for interest payments. The commercial model will thus only be plausible on the basis of revenue covering the cost of manufacture of successive ROGER spacecraft rather than the technology development and design activities that will precede the first commercial flight. The risks in the commercial and technical aspects are also such that private investment is unlikely until the technology and business cases are better quantified.

Government support is therefore required for development yet the public good case for re-orbiting is extremely long term. Some form of joint funding may be applicable in order to encourage private investment as the development programme gathers pace and interest is awakened amongst the operator community.

3.4 Summary and implications for an operational mission

To summarise:

1. the plausibility of non-robotic capture methods and their apparent cost effectiveness suggests that this would be a desirable basis for a re-orbiting mission. It is assumed that a risk of modest, non debris-producing, damage exists;
2. the concept of using a servicing mission to generate greater revenues with which to subsidise re-orbiting appears limited by the higher cost of the servicing missions, driven in part by the need to use a robotic capture method;
3. operationally re-orbiting and servicing functions may be conveniently combined though significant engineering challenges present in servicing missions may also cause them to diverge technically from a pure re-orbiting mission;
4. the recommended way forward for the design of a reference mission is re-orbiting only based on a non-robotic capture method. Such a mission will re-orbit several expired satellites for which the owner is willing to pay a fee for the service. It appears that there is a small market for this activity though there is significant commercial risk in estimating the number of opportunities and fee that may be levied.

It is important to note that this market is based on the observed trend of satellite operators to re-orbit satellites on a good citizen basis without the pressure of regulation and despite the apparently large financial sacrifice incurred.

Current estimates suggest that this market has a chance of supporting the recurring hardware, launch and operating cost of a re-orbiting mission but not the development cost. It is therefore proposed that government sponsorship be sought for the development of the programme with commercial partners being encouraged later to join in investment in anticipation of the first operational mission

The details of the transition from government development to commercial exploitation may be complex, particularly if there is no tidy boundary between orbital assets for the former or latter purposes, and some early consideration should be given to the appropriate form of Public Private Partnership for the implementation.

The following major assumptions and requirements were identified for the system design:

Operational lifetime:	up to 10 years
Number of targets:	approximately 30
Type of targets:	GEO satellites having recently become uncontrolled
Distribution of the targets:	any longitude, low inclination
Graveyard orbit:	GEO + ~300 km
Launcher compatibility:	ARIANE 5 shared launch (baseline)
Launch compatibility :	GTO injection (7° inclination)
Ground segment:	Global coverage required.

The mission profile is expected to comprise a deployment phase and then a mission cycle of 2-3 months for each target depending on the propulsion solution adopted.

Each re-orbiting mission then consists of

- a ground guided phase
- a target acquired homing phase
- a final approach
- the grappling manoeuvre
- the transfer to graveyard orbit
- the return to GEO to begin a new ground guided phase.

The translation of these requirements and assumptions into a reference solution is undertaken in the following section.

4 ROGER definition and development plan

The aim of the third major study activity is to determine a reference solution, taking account of development issues, for a ROGER system meeting the requirements and scenario developed in section 3.

The trade studies affecting critical items such as the grappling equipment, orbit transfer strategy and propulsion are described together with system budgets. The development cycle leading to the system implementation is described.

4.1 ROGER System Design

4.1.1 Overview

The ROGER spacecraft bus design is based on a new design rather than a current commercial GEO spacecraft bus primarily for ease of payload accommodation. It is shaped as an octagonal prism, with the telescopic payload boom mounted on the centre axis of the spacecraft. The solar generators are folded flat onto opposing surfaces of the bus, as are the tentacles of the octopus grappling equipment. The high specific impulse electric thrusters of the OCS system are mounted on the top surface of the bus. The launch configuration of the ROGER spacecraft design outside view is shown in Figure 4-

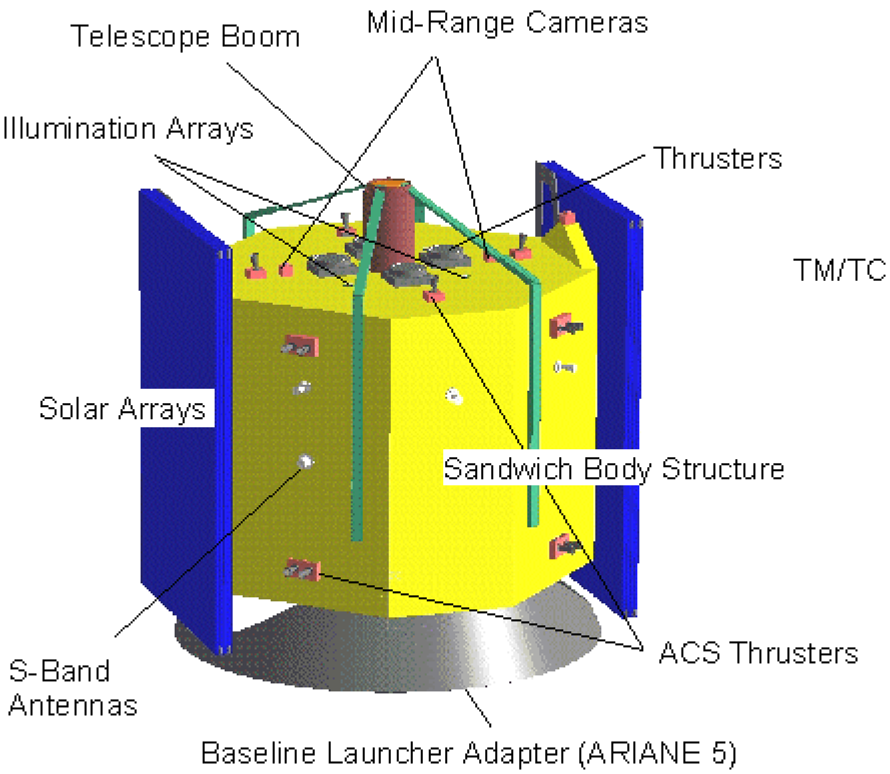

Figure 4-1 ROGER spaceacraft configuration outside view

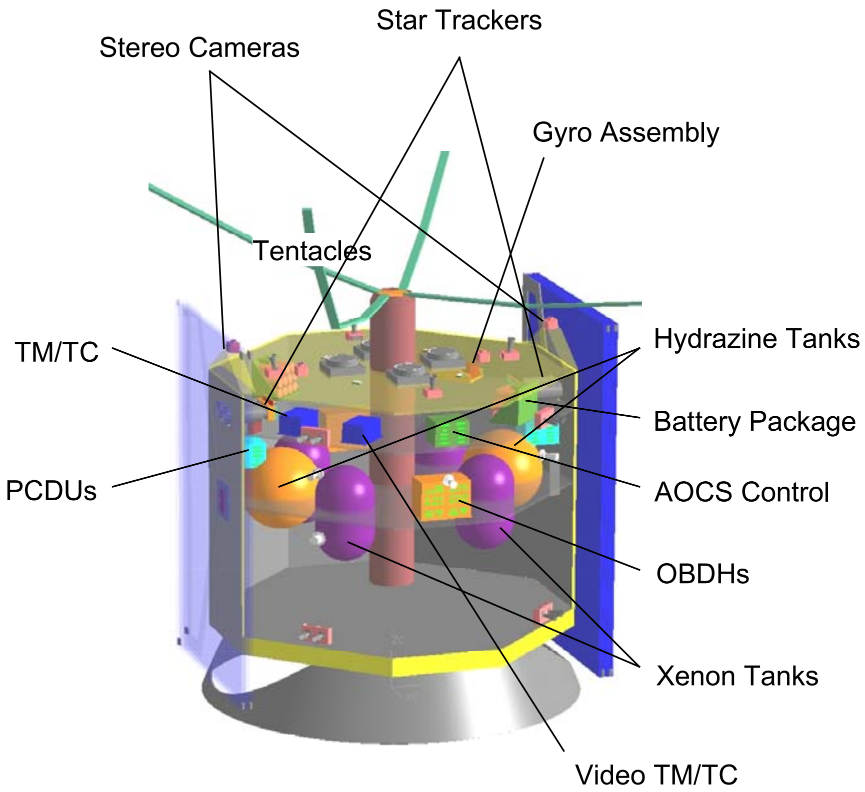

Figure 4-2 ROGER spacecraft configuration (cutaway view)

In Figure 4-2 a cutaway view of the ROGER S/C configuration is depicted. It shows:

- hydrazine tanks for the ACS thrusters
- Xenon tanks for high specific impulse electric thrusters
- AOCS and OBDH command processing unit
- star trackers and the gyro sensors
- PCDU units and the battery packages
- video and command TMTC processing units
- stereo cameras.

4.1.2 Grappling Equipment Payload

The principal payload element is the grappling equipment. The trade off for grappling equipment has lead to the adoption of a novel bulk capturing device dubbed the “octopus tentacle solution”, depicted in Figure 3-2. As a result of further design trades this is now defined by two main structural subsystems:

- telescopic boom subsystem
- tentacle subsystem

The telescopic boom is mounted on the Roger spacecraft and supports the tentacles, which perform the grappling action. At the end of the deployment the tubular segments of the boom are locked to make the joints stiff and to eliminate all undesired play. The end section of the boom is not locked, but spring loaded and allowed to be pushed back into the larger section to guarantee a soft contact with the target-object. The baseline for the telescopic boom is a telescopic aluminium mast with spring-assisted deployment.

There are four tentacles of sufficient reach to encircle any potential target-object and they can be operated simultaneously or independently. The tentacles consist of tapered articulated fingers with a soft surface on the contact side. In the hinges, springs have been added to provide the required local grappling torque, while a number of redundant memory metal wires, which contract when heated electrically, provide the opening torque. In this way loss of contact (grip) during a power drop is prevented and no power is needed during the long towing phase.

The example of grappling depicted in Figure 3-2 shows a target symbolically reduced to a sphere for clarity. It should be clear that the strength of this conceptual approach is that the tentacles may be orientated so as to close around the target body between appendages such as solar arrays and antennas.

Storage of the Octopus tentacle system during launch is illustrated in Figure 4-3. The telescopic boom is shown collapsed within the body of the spacecraft and the tentacles are wrapped around the spacecraft body with extra joints used only for deployment.

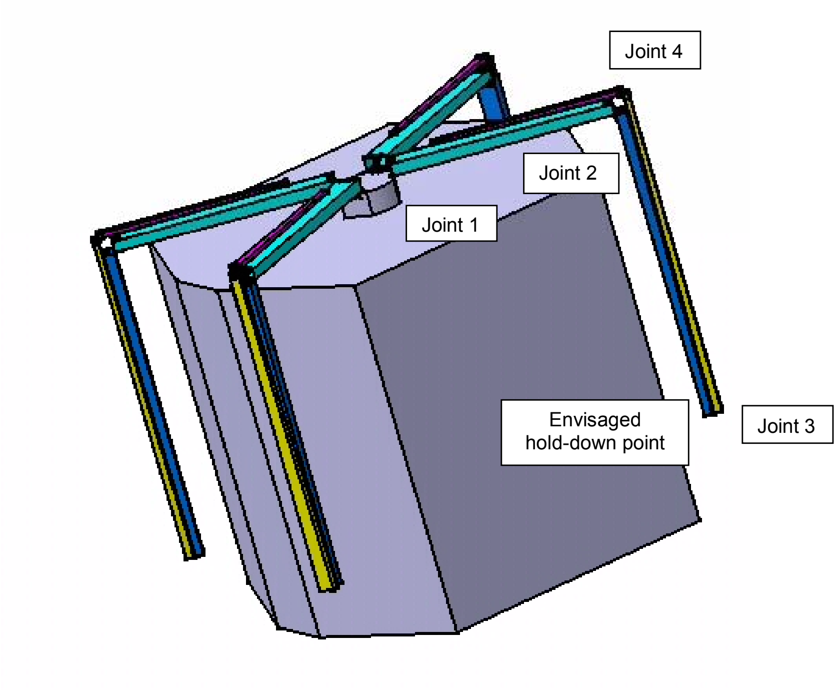

Figure 4-3 ROGER Stowed configuration

4.1.3 Rendezvous and Capture concept

The worst case situation for the approach sequence of the ROGER S/C to its target is the flat spin condition of the target. As the operational momentum vector of momentum biased GEO spacecraft is orbit normal (see Figure 4-4), the final orientation of the spin axis of the object after attitude control has ceased is an orbit normal flat spin.

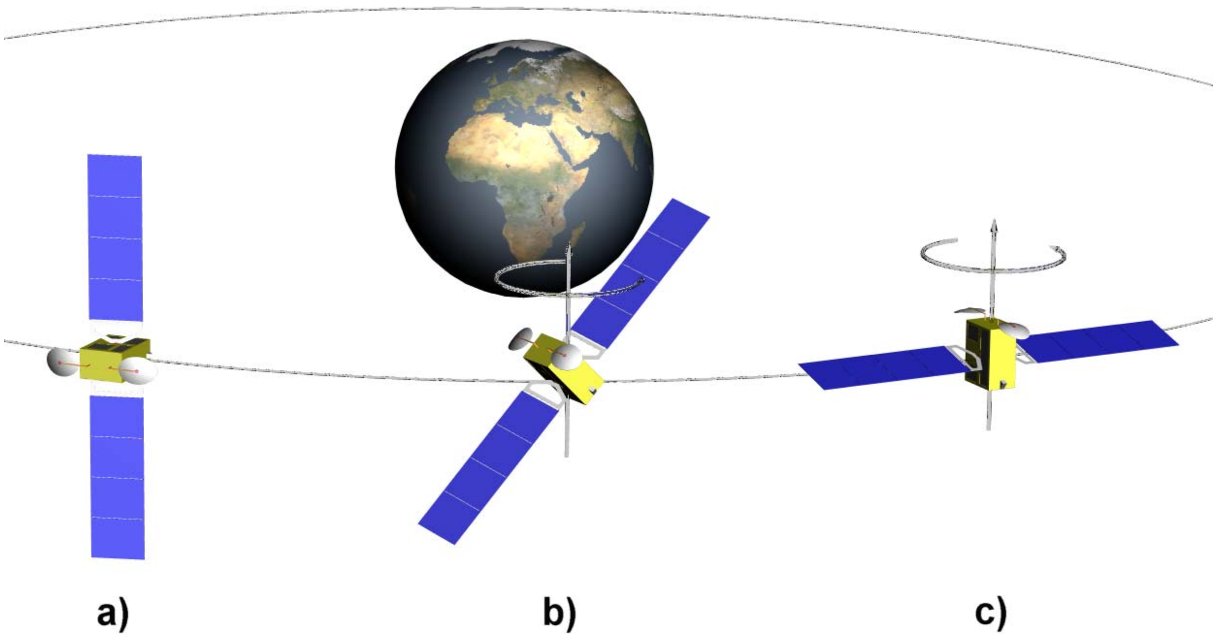

Figure 4-4 Transition of target from controlled status to flat spin

The approach for rendezvous thus has to take place from northern or southern directions. This is illustrated in Figure 4-5. Prior to the grappling of the target, a kinematic synchronisation of the two spacecraft's motions must also be performed.

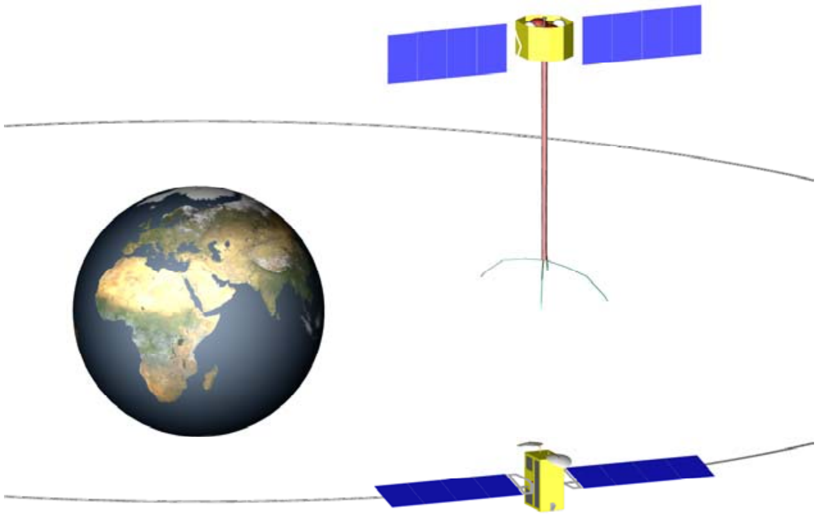

Figure 4-5 Approach to a target in a flat spin

4.1.4 Ranging, Guidance, Navigation and control

There are two principal GNC problems to solve: gross acquisition of the target and manoeuvring in close proximity to the target.

The first problem is solved with the use of a sequence of absolute and relative position determination sensors for both the chaser and target satellites. Figure 4-6 illustrates the necessity of handing over from one sensor suite to another as the range closes.

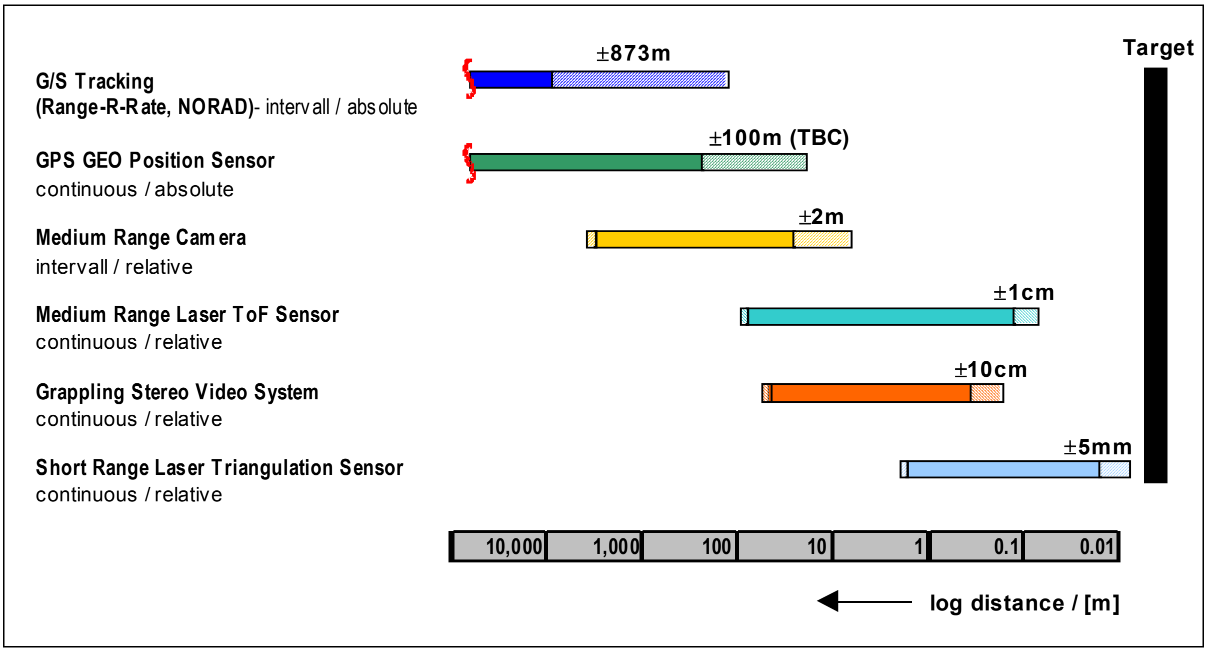

Figure 4-6 ROGER Position determination and data properties

Operations close to the target will be supported by a video system. The video system is essential for the ground-based teleoperation of the grappling equipment. It allows for close proximity distance estimations by the operator.

In the last phase of approach, the human operator on the ground will not be able to interact, because of the time delay in the communication between the ground station and the ROGER spacecraft. Therefore, the automatic short-range distance detection system has to be included. The focussing system for the camera lenses and for the adjustment of the two optical axes has to rely on an additional distance measurement system. The relative position sensors are laser based. Both signals are filtered and fed into the Guidance Controller, which commands the thruster controller of the AOCS system.

4.1.5 Propulsion issues

The trade-off for the primary re-orbiting propulsion system is further refined leading to the preferred option of the use of a high thrust electric propulsion system. A high specific impulse electric propulsion system is the baseline with the dual purpose of initial deployment of the ROGER spacecraft from GTO to GEO, see figure 4-8 for the example of the SNECMA patented transfer method, in addition to the function of re-orbiting. The motivation for this choice is to reduce overall system mass and cost. An outstanding area of this trade-off to re-visit in the detailed design phase is that of the radiation environment experienced during the transfer phase.

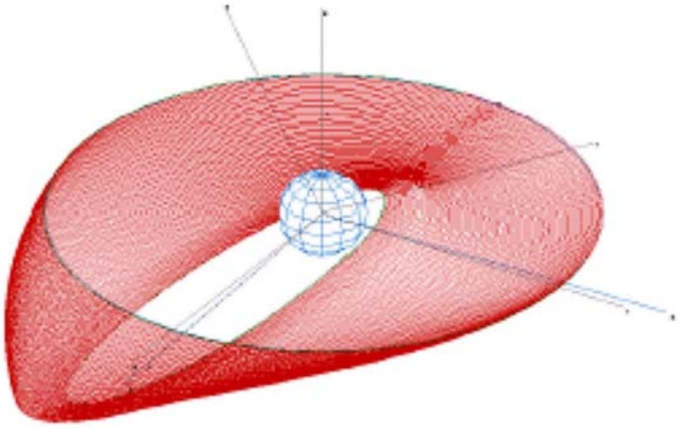

Figure 4-7 SNECMA continuous thrust transfer strategy [11]

The delta-V budget of the ROGER spacecraft is based on the following components:

- a worst case phasing capability of 180° in order to provide global service coverage, or
- an inclination harmonisation capability of approximately 0.7°, which includes the NSSK per target, plus
- additional altitude manoeuvre capability during homing & final approach, plus
- the transfer to graveyard orbit with an assumed value of 11 m/s.

And thus leaves scope for optimisation of target ordering according to inclination and longitude.

4.1.6 Other spacecraft details

Other characteristics of the preferred reference solution are given in Table 4-1.

Launch mass:	1,450 kg into GTO
In-Orbit mass:	1,250 kg wet GEO, 920 kg dry GEO
Launch dimensions:	2.7 x 2.7 x 2.9 m3
Deployed width:	17 m
Launcher:	Ariane 5 shared launch compatible
Power:	4,300 W EoL from 32 m2 GaAs Solar Array
TT&C:	S– Band
Data downlink:	S– Band (2 Mbit/s)
ACS:	24 mono-propellant hydrazine thrusters
OCS:	4 electric thrusters for GTO - GEO transfer and re-orbiting

Table 4-1 Key spacecraft parameters

The high level mass breakdown is given in Table 4-2

Item	**mass (kg)**
Spacecraft bus (inc. margin)	800
Payload - grappling hardware (Inc margin)	100
Payload – sensors and electronics	20
Propellant – ACS Hydrazine	120
Propellant – Re-orbiting Xenon	210
Propellant – GTO-GEO transfer Xenon	200
Total	**1450**

Table 4-2 High level mass breakdown for the ROGER spacecraft

The maximum total power demand of 3500W occurs during phases when the electric propulsion OCS is in use. This subsystem requires 3000W and operates during GTO-GEO transfer and re-orbiting, but not during eclipse phases.

The spacecraft maximum power during the next most demanding mode, grappling, amounts to 440 W and includes batteries sized to account for array shadowing during the capture sequence. Within this mission phase, all the telemetry and video subsystems are at their peak performance with a power consumption of 100 W. The communication and GNC subsystems consume 125 W of power during the mission phases of Homing, Grappling and Stabilisation. During the grappling process, the release heaters of the octopus tentacles are activated, consuming approximately 100 W of power. The grappling sensors (e.g. laser distance sensors) at the same time consume 100 W.

4.2 Development, Schedule and Cost

The study considered the various technical risks that resulted in a risk mitigation plan with test and demonstration events for the key elements of the system. The demonstration sequence, described in more detail in the next section, comprises the following elements:

- ground based software and hardware simulation, comprising EUROSIM, EPOS and neutral buoyancy simulation;
- Technology Flight Opportunities (TFO),i.e. piggy-back launch opportunities for critical subsystem components;
- ROGER in-orbit Demonstration Model, i.e. GEO demonstration of the following
  - GNC with an existing GEO target, i.e. sensors and ranging
  - ground planning and real time operations
- ROGER Model for Proto-Flight and Operational Missions
  - grappling, manoeuvring and towing of a real target
  - fully operational mission.

It is expected that the in-orbit demonstration model and proto-flight models will utilise the following conventional qualification philosophy:

- Structure and Thermal Model (STM)
- Engineering Model (EM)
- Proto-Flight Model (PFM).

On this basis the development cycle is expected to have a form similar to that shown in Figure 4-9.

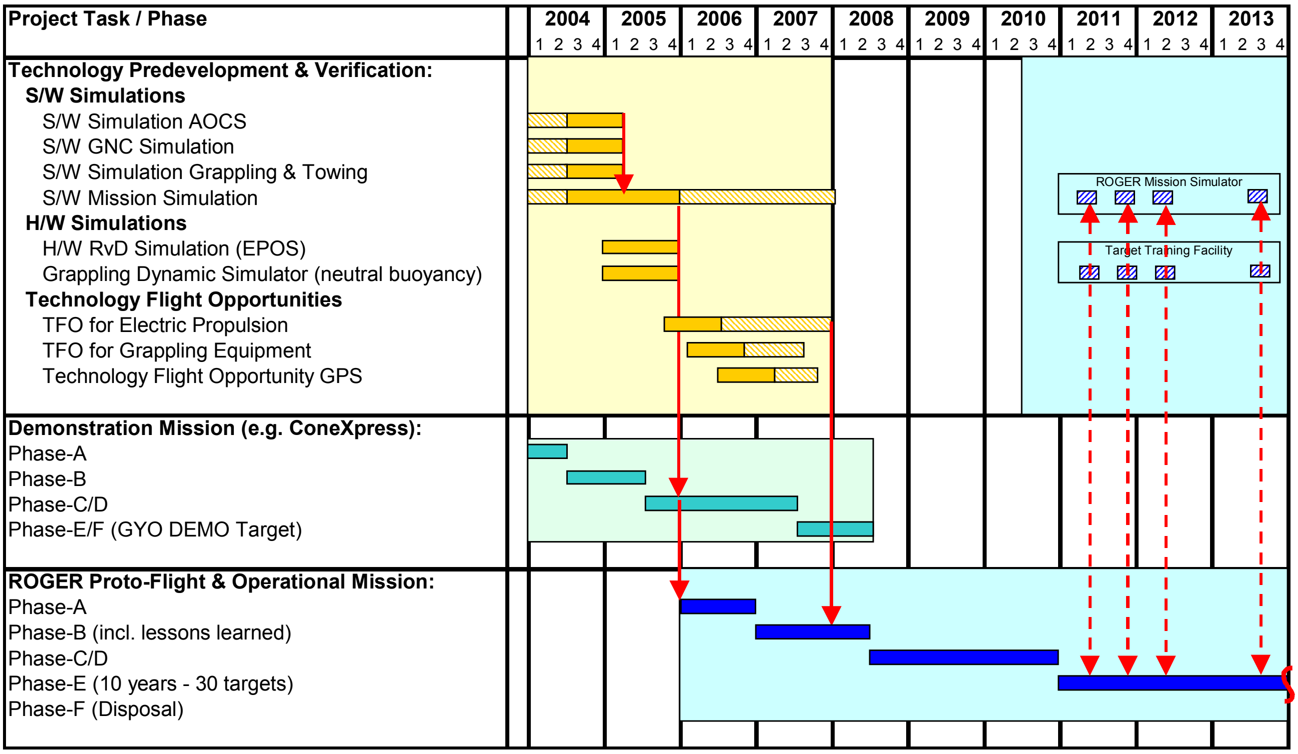

Figure 4-8 Proposed ROGER development schedule

Mission costs are summarised in Table 4-3.

Phase	Item	Cost Meuro
Development		
	Software simulation	6
	Hardware simulation	10.5
	TFO electric propulsion	17
	TFO Grappling equipment	17
	TFO GPS	14
	Demonstration mission (including launch and operations)	78.25
Protoflight	Design, manufacture and AIT	152.5
	Launch	40
	Operations	20.5
Total to protoflight		**355.75**

Table 4-3 Expected programme costs

4.3 ROGER Demonstrator Development

This part of the study identifies the critical enabling technologies for the mission described in the previous section and reviews the options for risk reduction.

The key risk items, identified through extensive mapping of the technology readiness of all mission, spacecraft and payload items, are considered to be:

- the selected re-usable capture device, to be tested for a multiple number of docking and undocking procedures;

- re-orbiting of a non co-operative target into the graveyard orbit
- satellite platform AOCS for the S/C compound, including the utilisation of an electrical propulsion system;
- the absolute distance ranging system and the relative distance measurement systems, which are essential for GNC;
- teleoperation from ground.

The demonstration methods considered sufficient to envelop all the risk areas are as follows:

- simulation facilities for hardware and software e.g. EUROSIM
  - AOCS, GNC, Grappling and Towing, Mission planning
  - GNC/video hardware model for the EPOS simulator,

- underwater simulation using neutral buoyancy models, test facilities and software simulators, for the grappling equipment;
- Technology Flight Opportunities, i.e. piggy-back launch opportunities for critical subsystem components;
  - electric propulsion, if required
  - grappling equipment
  - GPS sensor at GEO, if required

- in-orbit demonstration missions for GNC and rendezvous manoeuvres,
  - GNC with existing GEO target, i.e. sensors and ranging
  - ground planning and real time operations

- first target removal with a Protoflight Mission of a full-fledged ROGER spacecraft.
  - grappling, manoeuvring and towing of a real target
  - fully operational mission

For the orbital demonstrations, i.e. TFO and the in-orbit GNC demonstrator, consideration has been given to the needs and benefits of reduced scale models and of using orbits other than GEO for the demonstration.

The evolution of the risk levels is described in Table 4-2. In summary, the grappling equipment will be demonstrated by software simulation, neutral buoyancy tests and a TFO, which may be performed in LEO. The final full scale “end to end” hardware demonstration with a representative target will occur in the first protoflight capture and comprises the following elements:

- grappling of a realistic and non co-operative target
- towing of the target to graveyard orbit, including the adjustment of the AOCS to the conditions of the coupled system.

Though by this stage all critical subsystems will already have been individually proven.

The GNC elements have the highest risk level of all critical ROGER subsystems. The readiness for the rendezvous and close approach of a GEO target, including the hand-over between absolute and relative navigation, is considered to remain poor without a dedicated GEO demonstration mission. Risks related to ranging, medium and short range position sensors, orbital and finally attitude synchronisation will be mitigated by software simulation, subsystem testing in EPOS and with the GEO in-orbit demonstration. This dedicated in-orbit GNC demonstrator has no need for a full-fledged ROGER satellite platform and grappling equipment. It is therefore foreseen that the GNC demonstrator can be based on an available and cost effective GEO platform such as ConeXpress

Table 4-4 shows the progressive reduction of risk during the programme due to the various development and demonstration activities. The tests listed along the top row are ordered as expected in the schedule and thus in the final column on the right each of the technical risk areas is seen to have evolved to proven design status.

A – feasible in theory **B – working lab. model** **C – based on existing non-flight engineering)** **D – extrapolated from existing flight design** **E – proven design:** E- proven by simulation E+ proven in praxis (E) - critical subsystems proven		**S/W Simulation AOCS**	**S/W Simulation GNC**	**S/W Simulation Grappling & Towing**	**S/W Simulation Mission**	**H/W Simulation with EPOS**	**H/W Simulation with Neutral Buoyancy**	**TFO – Electric Propulsion**	**TFO – GPS**	**TFO – Grappling Equipment**	**Demo Mission – GNC & Ranging in GEO**	**Proto Flight Mission**
Risk Element	**Initial Risk Level**	**Risk Level After Simulation / Demonstration**										
AOCS: standard functions	D, high	»E+	E+	E+	E+	E+	E+	E+	E+	E+	E+	E+
AOCS: control parameter adjustment for target S/C	A, high	» B	B	» C	C	C	C	C	C	C	C	E+
Video Ranging System for medium range position & attitude processing	C, high	C	C	C	C	»E-	E-	E-	E-	E-	»E+	E+
Short range distance sensor (LASER triangulation)	C, high	C	C	C	C	»E-	E-	E-	E-	E-	»E+	E+
Medium range distance sensor (LASER ToF)	C, high	C	C	C	C	»E-	E-	E-	E-	E-	»E+	E+
Ground guided manoeuvres & ranging in GEO, incl. target	C, high	C	C	C	C	C	C	C	C	C	»E+	E+
GNC in GEO:												
- Phasing & orbit synchronisation	D, high	D	»E-	E-	E-	E-	E-	E-	E-	E-	»E+	E+
- Attitude synchronisation	C, high	C	»E-	E-	E-	E-	E-	E-	E-	E-	»E+	E+
- Rendezvous & Close Approach	A, high	A	» B	B	B	B	B	B	B	B	»E+	E+
Ground segment for teleoperation	C, high	C	C	C	C	C	» E-	E-	E-	E-	»E+	E+
Grappling of a non-co-operative target	A, high	A	A	» B	B	B	»C	C	C	»D	D	E+
Towing of target to GYO	A, high	» B	B	» C	C	C	C	C	C	C	C	E+
Long term use of Electric Propulsion	D, high	D	D	D	D	D	D	»E+	E+	E+	E+	E+
GPS H/W & availability in GEO	B, low	B	B	B	B	B	B	B	»E+	E+	E+	E+
Grappling Technology: **Tentacle structure** **Release Actuator** **Boom** **Stereo Video System**	C, high	C	C	C	C	C	E-	E-	E-	(E+)*	(E+)	E+
Gimballed boom mounting	C, med.	C	C	C	C	C	E-	E-	E-	(E+)*	(E+)	E+
Mission & Operations planning	C, high	C	C	C	»E-	E-	E-	E-	E-	E-	»E+	E+

Table 4-4 Evolution of risk levels during ROGER development

5 Conclusions

The RObotic Geostationary orbit Restorer (ROGER) is a study focused on the need for, and feasibility, of a mission to control the threat from non-operational satellites and large debris.

The aim of the work has been to examine the threat from overcrowding in GEO, determine possible mission scenarios and subsequently the justification for a Robotic Geostationary Orbit Restorer. Finally, the study has suggested a plausible technical implementation for such a mission and identified the necessary development and demonstration activities.

The risk of overcrowding in GEO has been investigated. An assessment of the current population, expected future launch traffic and the impact of spacecraft failures has been made. This data has been used to drive specially written collision risk analysis software, which has been used to predict collision probabilities.

The probability of a single collision occurring during the period 2002 to 2030 is predicted to be 2.8%. This rises to 3.7% for the worst case assumptions regarding spacecraft operators re-orbiting success. If the best possible re-orbiting effectiveness is assumed, such as could be achieved with a ROGER system, then the collision probability reduces to 1.7% over the same period, approximately level with the current risk.

A study of possible intervention missions has been undertaken. The aim is to look at technical and economic issues that could affect the need and justification for a mission to re-orbit uncontrolled objects in GEO. This has been a broad study and has investigated other mission types with the aim of looking for cost sharing opportunities.

It is concluded that missions based on either robotic principles or more novel bulk capture solutions are technically feasible. This latter category of mission appears to be achievable at a lower cost than the robotic approach. The commercial prospects for such a mission are modest and subject to difficulty in assessing the future market depth.

There are undoubtedly plausible flight opportunities though it is not obvious that there will be the number of opportunities required to bring per-mission costs down to attractive levels. The costs in any case are such that government support will be required for the development of the programme, with the aim that commercial revenue will support the cost of each operational mission.

A solution has been studied in detail based on the favoured concept amongst the non-robotic bulk capture solutions previously reviewed. This reference mission comprises a satellite with an injection mass of 1450kg into GTO and capable of re-orbiting approximately 30 objects from GEO over a five to ten year period.

A number of development issues are highlighted, principally for the capture equipment and for guidance, navigation and control during the rendezvous and capture phase.

A programme for the implementation has been planned assuming a programme start in 2004. The key points are that the development cost including first protoflight mission is expected to cost of the order of €355M with a launch in 2011. Subsequent flights may cost in the region of €148M plus launch.

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7 Glossary

ACS	Attitude Control System
AOCS	Attitude and Orbit Control System
EM	Engineering Model
EOL	End of Life
EPOS	European Proximity Operations Simulator
ERA	European Robotic Arm
Eurosim	European Real Time Operations Simulator
GaAs	Gallium Arsenide
GEO	Geostationary Earth Orbit
GNC	Guidance Navigation and Control
GPS	Global Positioning System
GTO	Geostationary Transfer Orbit
GYO	Graveyard Orbit
IADC	Inter-Agency Space Debris Co-ordination Committee
LEO	Low Earth Orbit
NORAD	North American Aerospace Defense Command
NSSK	North-South Station Keeping
OBDH	On-Board Data Handling
OCS	Orbital Control System
PCDU	Power Conditioning and Distribution Unit
PFM	Proto-Flight Model
PPP	Public-Private Partnership
ROGER	RObotic GEostationary orbit Restorer
SPT	Stationary Plasma Thruster
STM	Structural and Thermal Model
TFO	Technology Flight Opportunity
TMTC	Telemetry and Telecommand

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10a. Abstract. (An abstract should aim to give an informative and concise summary of the report in up to 300 words).

The RObotic Geostationary orbit Restorer (ROGER) is a study focused on the need for and feasibility of a mission to control the threat from faulty satellites and large debris.
This report presents the work performed within the ROGER project. It has been prepared a team lead by QinetiQ, Space Department, and comprising OHB-System, Dutch Space and Esys, for the European Space Agency (ESA/ESTEC) under contract 15678/01/NL/WK.
The aim of the work is to examine the threat from overcrowding in GEO, determine possible mission scenarios and subsequently the justification for a Robotic Geostationary Orbit Restorer, and finally to suggest a plausible technical implementation for such a mission and identify the necessary development and demonstration activities.
This final report comprises an executive summary report and six annexes describing the technical work performed in the project.

10b. Abstract classification:	FORM MEETS DRIC 1000 ISSUE 5

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