ESA's e.deorbit mission and its roadmap to Active Debris Removal

Robin Biesbroek
European Space Agency
e.deorbit study manager
ESTEC-TEC/SYE, PO Box 299, 2200 AG, Noordwijk, The Netherlands
Robin.biesbroek@esa.int

ABSTRACT

Since 2012, the European Space Agency (ESA) has studied a mission to perform Active Debris Removal (ADR) of a large space debris in Low Earth Orbit. The objective of the mission is to remove an ESA-owned heavy debris from the 800 to 1000 km altitude near polar region. The removal is performed by moving the target at high speed and high precision into the Earth's atmosphere allowing the target to burn up due to aerothermal dynamic forces. Several system studies have been performed, first internally in the form of pre-phase A studies done within ESA's Concurrent Design Facility, and also phase A studies done by large satellite integrators contracted by ESA. E.deorbit is now in phase B1 (detailed design phase). Apart from the system studies, several technology development activities have started and some other are planned to start. In-orbit testing may be required for several new technologies. All these activities together lead to a roadmap to a European capability to perform Active Debris Removal.

1 INTRODUCTION TO E.DEORBIT

1.1 Scope of e.deorbit

ESA wants to pave the way for future ADR missions by removing a single large ESA-owned space debris from the protected Low Earth Orbit (LEO) zone in the 2021-2023 timeframe.
The motivation for this project is that by now over 17,000 objects around Earth can be tracked from ground, and less than 1,000 of these objects are actual active satellites. Looking closely at Figure 1, a dense area close to Earth is the near polar region of orbits with altitudes between 600 km and 800 km.

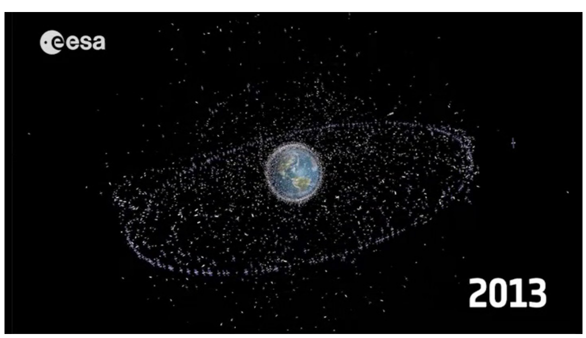

Figure 1: Overview of space debris in the year 2013

Several independent studies have shown that space debris with the largest probability of collision are the large objects located in dense areas, and it is generally considered that the growth of space debris can only be stabilized if give of those large objects are removed per year from these orbits.

1.2 What e.deorbit needs to do

The e.deorbit mission objective is to "Remove a single large ESA-owned space debris from the LEO protected zone".

From this objective, six different 'use cases' are defining all the main tasks the e.deorbit needs to fulfil in order to achieve the mission objective:

1. Launch into space
2. Perform LEOP and commissioning
3. Transfer and phase to target orbit
4. Rendezvous with target
5. Capture target
6. De-orbit target

Figure 2 gives an overview of the use cases.

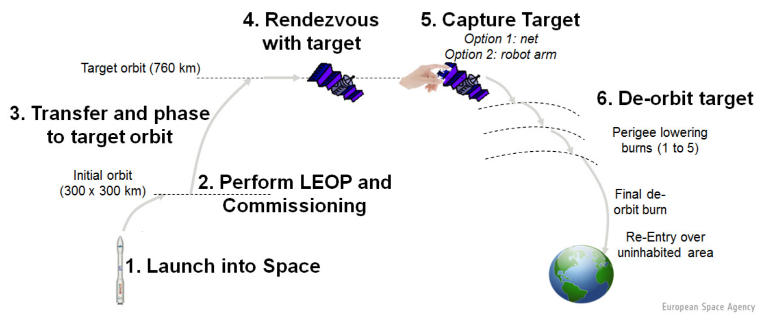

Figure 2: e.deorbit use cases

Ad 1. The launch into space is foreseen to be done by ESA's smallest launcher VEGA, using the 'VEGA-C upgrade'.
Ad 2. After launch, deployment of the solar panels (in case of deployable panels) will be done, initial contact with ground will be made and housekeeping data will be sent to Earth. Testing and calibration of the GNC (guidance, navigation and control) sensors and all critical equipment will be done during this phase.
Ad 3. Since e.deorbit will need to have a large propulsion system for the de-orbit use case, it is more optimal to have VEGA insert e.deorbit into a low altitude initial orbit (e.g. 300 km) and then use e.deorbit's own propulsion system to transfer to the target orbit. The target's orbit (as described in section 3.1 is estimated to be 760 km high). Based on position estimates of the target by ground tracking, the orbit of e.deorbit will be phased with that of the target, until the target can be picked up by the GNC sensors.
Ad 4. Based on the GNC sensors, E.deorbit can now calculate the relative position with respect to the target, and it will then perform several hops to get close to the target, until a hold point is achieved from which an inspection of the target can take place and the attitude and motion of the target is determined.
Ad 5. When a 'go ahead' is received from ground, the capture shall take place. This is either done by means of a net (i.e. a net is shot towards the target, and embraces the target), or by means of a robot arm (i.e. synchronize the motion of e.deorbit with the target, and capture the target at its launched interface ring). Since the target is likely to be rotating, the rotation needs to be stopped, either by pulling

the net via a tether in-between e.deorbit and the target, or by initiating a de-tumbling mode on e.deorbit, now with the target attached via a robot arm.
Ad 6. Once the correct attitude is obtained to initiate the de-orbit burns, the de-orbit phase will start. In order to minimize gravity losses, the de-orbit burn could be split into several firings of the main thrusters. The re-entry will burn up both target and e.deorbit during the aerothermal dynamics forces when the atmosphere is entered. Several re-entry zones are identified in the Pacific (North and South) and Indian Ocean, since some parts of the target could survive the re-entry and impact the water.

1.3 Organization of this paper

Four questions will be answered in the next four chapters: what the boundaries of e.deorbit? How is e.deorbit executed? How can we enable success? And what do we see when we re-assess e.deorbit on a regular basis?

2 BOUNDARIES OF E.DEORBIT

This chapter shows the organization, planning and stakeholders of e.deorbit, which all define the boundaries in which this project can move.

2.1 Clean Space

e.deorbit is a mission requested by ESA's Clean Space initiative. The objective of Clean Space is guaranteeing the future of space activities by protecting the environment. With the Clean Space initiative, ESA will devote increasing attention to the environmental impacts of its activities, both on Earth and in space [1]. Figure 3 shows the branches of Clean Space.

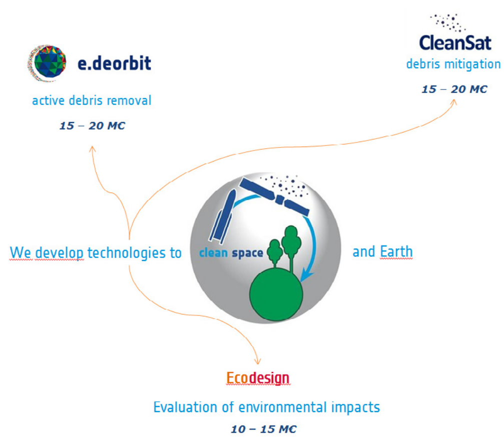

Figure 3: Clean Space and its branches

E.deorbit falls under the branch 'Active Debris Removal'. The budget allocated to this branch is between 15 and 20 M€ for the 2012 to 2015 timeframe. This allocation is for the system design studies and related technology developments. Within ESA, the management of e.deorbit is assigned to the Systems, Software and In-Orbit Demonstration department of the Technical and Quality management directorate, until the next ministerial conference.

2.2 Planning

The global plan of e.deorbit is shown in Figure 4.

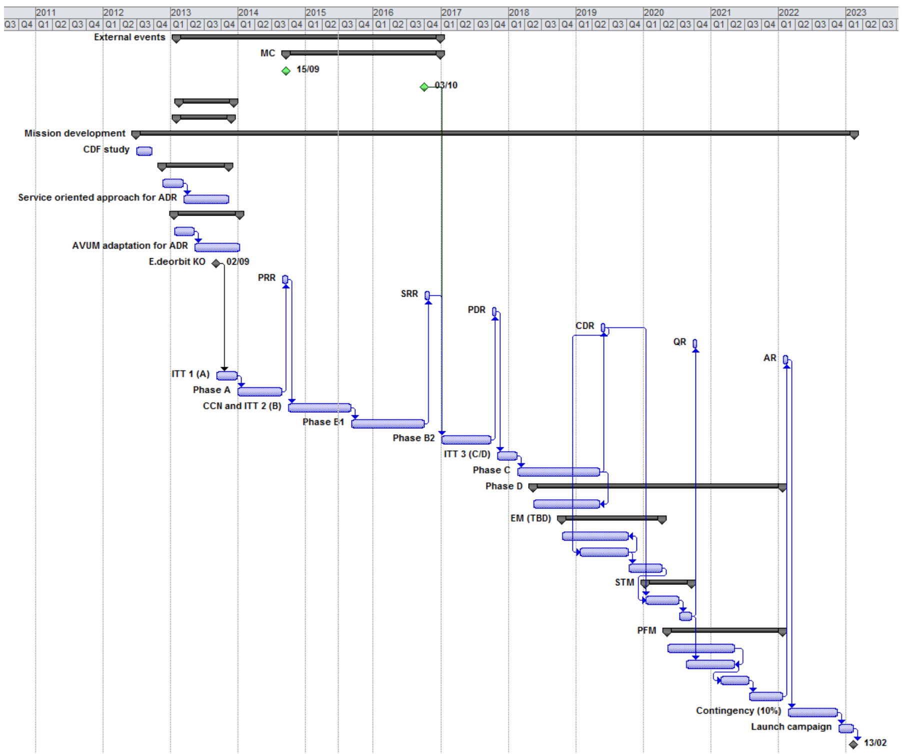

Figure 4: e.deorbit timeline

As every ESA mission, the Ministerial Council (MC) meetings dictate the plan. The next MC is expected to take place by end 2016. By this time, the first detailed design phase should have completed so that a dossier can be prepared as proposal for the MC.

Since 2012, several assessment studies have been performed ('e.deorbit CDF study', 'Service Oriented Approach towards ADR', 'ADR with AVUM', and the e.deorbit phase A study, all described in section 3.3). E.deorbit is, at time of writing this paper, finalizing the negotiations for the detailed design phase B1, which will start on 1 September 2015 and should lead to a Systems Requirements Review (SRR) in July 2016.

Pending approval to continue in the MC 2016, the phase B2 can start leading to the Preliminary Design Review (PDR) in end 2017, and the start of the phase C/D phase and the Engineering Model in 2018. Following extensive testing, the creation of the Structural and Thermal Model as well as the Flight Model can commence in 2020. The Acceptance Review is planned for early 2022 however as is normal in this early stage of the project, a 10% margin is set on the schedule, giving a launch date in early 2023.

2.3 Stakeholders

Until the phase A the system design studies, as well as most technology development studies, were performed within ESA's General Studies Programme. This typically implied that there were no restrictions

on the countries of the bidding companies. Starting the detailed design phase (B1), a switch to the General Support Technology Programme (GSTP) was implemented meaning that the funding is received from member states that subscribe to this activity, and bidding companies can only be from the participating countries. By early 2015, subscriptions were received from Germany, Belgium, Poland, Italy, Portugal, Sweden and Canada, and these are now the countries sponsoring and participating to the detailed design phase. Several technology development studies are also run within the GSTP programme with additional subscriptions from the UK and Spain.

Active stakeholders are therefore the European delegations, European industry itself. Within ESA, several directorates are stakeholders due their involvement in the system studies, such as the mission analysis team, operations team and space debris team at ESOC, German, as well as the TEC support team and communications office, and the General Studies Programme team, all at ESTEC, The Netherlands, plus the Clean Space team at ESA headquarters, France.

When the mission is launched, several stakeholders are active such as the Arianespace launcher provider, satellite operators and ITU (International Telecommunications Union).

Stakeholders such as media and other national agencies are affected and influencing the mission however it should not be forgotten that other space missions (both current and future) are influenced by e.deorbit as well because a potential candidate for generating many space debris objects in case of collision, is now safely removed from orbit.

3 EXECUTING E.DEORBIT

We will now go more in debt concerning how the e.deorbit contracts are executed and what are the main drivers for the design.

3.1 Target requirement

Selecting a target space debris for the mission is not an easy task. While no nation can claim that space debris exists exclusively in its territory, a launching state that puts an object into space has and keeps jurisdiction over that object, even if it turns into space debris. A target debris can therefore only be removed with the consent of the launching state(s) that put the debris object into orbit. Moreover, the launching states are liable for any damage caused on Earth from the re-entry, or any collision in case fault can be established. This means that if e.deorbit has a malfunction and causes either a collision in space or a damage on Earth, there may be major implications on the liability. For this reason, an ESA-owned target is proposed as ESA is a launching state. Furthermore, the object shall be in the (near) polar orbit region at an altitude between 600 km and 800 km, since this is a crowded orbit with space objects as shown in section 1.1.

For the requirements phase (i.e. phase 0 to phase B1), ENVISAT is chosen as target, for the following reasons:

1. It is one of the few ESA-owned debris in LEO
2. It has a heavy mass, roughly 8 tonnes
3. It is located in a crowded near polar orbit (Sun Synchronous Orbit at 800 km). Predicted altitude for 2023 is 760 km.

ENVISAT was launched on 1 March 2002 and its mission ended on 9 May 2012. Figure 5 shows an impression of a possible attitude by 2023.

Figure 5: Impression of ENVISAT; made using STK

A study performed by the university of Braunschweig [2] created a priority list for removal based on orbit, mass and size and not only was ENVISAT on top of this list, it also showed that ENVISAT's mass and size are similar to most other objects within the list (e.g. Zenith-2 stage 2). For this reason, ENVISAT marks an excellent opportunity to serve as a benchmark target for future debris removal missions. It should be underlined though that the final decision of the target will be made by end of 2016.

There are several challenges to be overcome related to this particular target choice, which could be a good test for future targets. As can be seen in Figure 5, the solar panel rotation mechanism is locked in such a position, that it complicates access to the launcher adapter ring (which is situated at the bottom of the model in the picture). Moreover, several observation campaigns have shown that ENVISAT is in a tumbling motion, and the current models do not conclude on the possible attitudes by 2023. Some models even predict rotations of up to 5 degrees per second, and therefore e.deorbit must be designed with these tumbling rates in mind. Finally, ENVISAT was still designed before the digital era, and finding details within the design is often complicated. This is enforced by the fact that many of the engineers who worked on the design of ENVISAT have retired by now.

3.2 E.deorbit driving requirements

The main driving requirements can be linked to the elements acting on e.deorbit, called 'actors'. Calling e.deorbit the 'space element', the main actors can be identified as:

- Launch element
- Ground element
- Target element
- Environment element

Note that the environment element here is both space and Earth, as the space environment will act on e.deorbit during its mission, and the Earth's atmosphere will act on e.deorbit during the re-entry. From the actors, an e.deorbit context diagram can be made showing the most important influences from and on e.deorbit, see Figure 6.

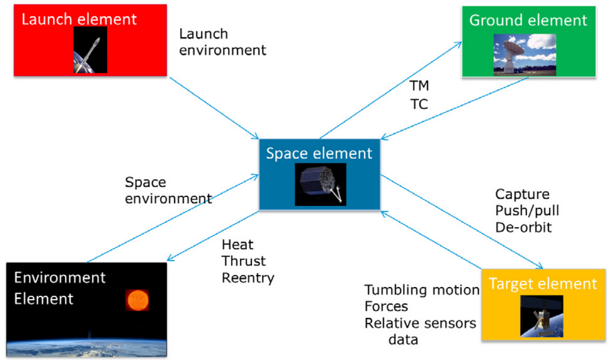

Figure 6: e.deorbit context diagram

The following technical design drivers are identified:

- *Launch environment*: the selection of a small launcher such as VEGA-C poses a strong constraint on the maximum e.deorbit wet mass.
- *TM/TC* (telemetry, tele-commands): when in the vicinity of the target, the communication link can suffer from interference by the target.
- *Capture*: the capture mechanism has a low TRL (Technology Readiness Level) for either net or robot arm option. In case of the robot arm, e.deorbit will need to get very close to a tumbling target and initiate a synchronized motion with the target in order to not collide with it.
- *Tumbling motion*: when the target is captured its tumbling motion needs to be damped. For the net case, this is done by pulling the tether in-between e.deorbit and target at the right times however this de-tumbling motion can only be initiated upon confirmation of capture. For a net curled around the target it will be extremely difficult to get this confirmation in time, and the de-tumbling should be initialized based on timers. For the robot arm case, de-tumbling may pose high torques on the robot arm's joints, and the attitude and control system needs to quickly adapt to newly calculated centre of mass of the stack (e.deorbit plus target connected).
- *Forces*: when any force is applied to the target, it must be ensured that no new debris is created (e.g. by parts braking off). This is in particular true for forces through points like the gripper on the robot arm, even if the foreseen contact point is confined to a small area. The net is likely to distribute its forces over the target, and could even contain large parts in case they break off.
- *Relative sensors data*: image recognition of the target is likely to be needed, which could require heavy processing on board the spacecraft.
- *Push/pull de-orbit*: when doing de-orbit burns by pulling the target (net capture) a special control scheme needs to be designed that keeps the tether from getting slack, avoid collision and keep the target rotation rates to a minimum. When doing the de-orbit burns by polling the target (robot arm capture), the system must calculate the centre of gravity and ensure that the thrust force is aiming at the centre of gravity, in order to avoid a spin-up of the stack.
- *Heat* will have a positive effect on the space element as it will burn up the target and e.deorbit. However some parts of the target may survive the aerothermal dynamic forces.
- *Thrust*: when thrusting using the net option, e.deorbit is actually thrusting towards the target (by 'pulling' the tether). It must be ensured that the tether does not burn up, or that the thrust initiates a tumbling motion on the target. This can be achieved by off-pointing the thrusters under an angle, but this has a negative effect on the propellant consumption.
- Finally, the *re-entry* has strong safety requirements, requiring complex planning including contingency cases, and additional redundancy on board e.deorbit.

3.3 Performed system studies for e.deorbit

Since 2012, several system studies have been executed both internally as externally (i.e. via contracts awarded by ESA).

In 2012 and internal assessment study was carried out by ESA's Concurrent Design Facility (CDF) [3]. The study focused on two capture techniques which were identified as most suitable for capturing non-cooperative targets, based on previous in-house studies. The first option was based on a capture using a clamping mechanism that embraces the target (like tentacles) and achieves a firm grip on the target. However it was shown that the accuracy with which the target could be captured was not enough for the attitude system to guarantee a de-orbit force going through the centre of gravity of the new stack, and a robot arm would be required to accurately place e.deorbit on the target. The second option was based on a net capture, where two net canisters were put into the design (one redundant), and the de-orbit burns are executed by a bi-propellant system. The study showed that the VEGA launcher could be suitable to launch e.deorbit.

Following the CDF study, three contracts were awarded after a competitive bid, to Airbus, Kayer-threde, and SSTL, with the aim to investigate a service oriented approach towards the implementation of e.deorbit, and to derive a business plan for future ADR missions [4], [5], [6]. The study showed the strong need of national and international agency sponsor at least one ADR mission, in order to lower implementation cost for future missions. The results of these studies were presented to the Technology Advisory Working Group at ESA HQ, Paris 2014.

The year 2013 ended with a conceptual design study of e.deorbit performed by ELV [7]. Since VEGA was considered as launcher for e.deorbit, the objective of this study was to assess if the upper stage of VEGA could serve as a satellite platform itself, on to which the capture and GNC equipment would be mounted as an 'AVUM proximity module', see Figure 7. The motivation was also that the VEGA upper stage already had a large bi-propellant propulsion system on board. The study concluded in December 2013 and an internal ESA review was executed in march 2014. The proposal was put forward to continue studying this option via ESA's GSTP programme, however so far no support was found.

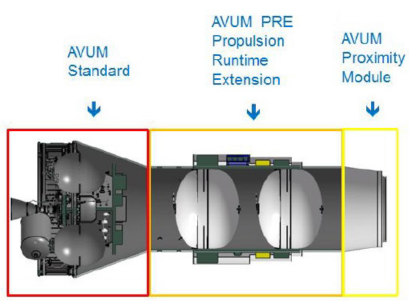

Figure 7: Using VEGA's upper stage as e.deorbit platform

In 2014 e.deorbit's phase A started. After a competitive bidding process, three companies were awarded a phase A contract, namely Airbus, Kayser-Threde and Thales Alenia Space. Each contractor was asked to study three system options: a de-orbit mission with a rigid capture method, a de-orbit mission with a flexible capture method, and a re-orbit mission. Two internal reviews were held, namely a Mission Baseline Review and Mission Design Review, before going to the Preliminary Requirements Review (PRR)

in September 2014. The PRR consisted of a technical panel and a review board. The review board, after evaluating the findings of the technical panel, recommended discontinuing both the harpoon and the re-orbit options for later phases. It also proposed to further study the development plan, consolidate mission requirements and the touching mechanisms design before proceeding with phase B1. Figure 8 shows the configurations for the rigid and flexible de-orbit missions proposed by the contractors [8], [9], [10].

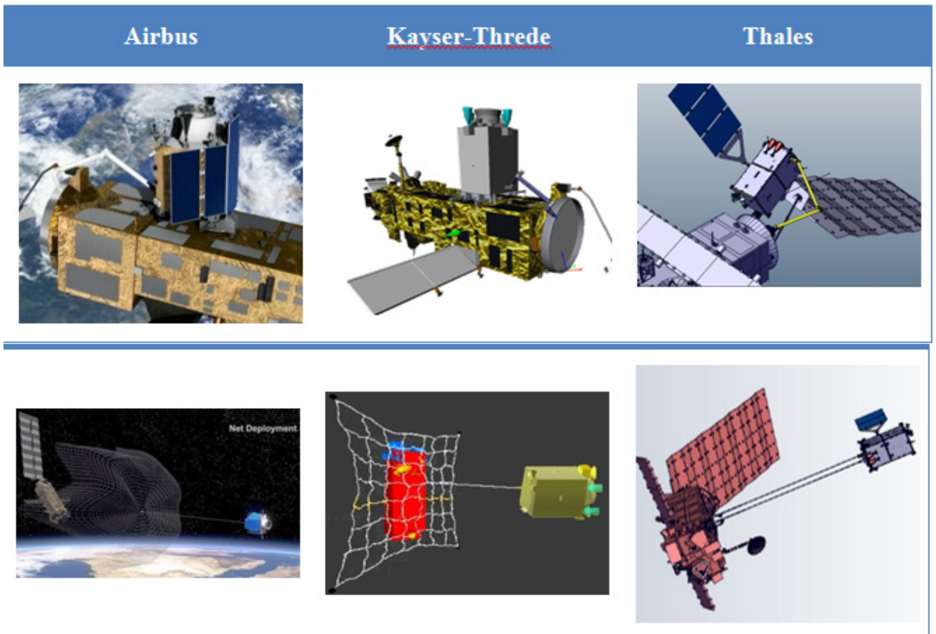

Figure 8: Phase A rigid (above) and flexible (below) design configurations

Following the recommendations of the PRR board, an extension of the phase A was offered to the contractors with the objective to 1) apply Model Based Systems Engineering (MBSE) in order to improve requirements generation and tracking, 2) update the technology development plans, and 3) improve the gripper or clamping mechanisms modelling. This extension came in handy, as it took a few months to issue the invitation to tender for the phase B1, and therefore the extension allowed to bridge the waiting time for the next design phase. Before the end of phase A, Arianespace released a new user manual of the VEGA launcher, showing a strong decrease in predicted launch mass performance. The project team decided, after discussion with ESA's launcher department, to assume that by 2023 the upgraded VEGA-C would be available, and select this as baseline launcher.

Meanwhile at ESA, the e.deorbit study manager, system engineers and risk engineers sat together to define the tasks of the detailed design phase, with the goal to link all identified risks from the phase A to tasks in the phase B1. At the end of phase A five main risks were identified:

1. Risk of collision between e.deorbit and the target
2. Risk of casualty on ground
3. Risk of an unsuccessful capture
4. Risk of generating more debris
5. Risk of schedule slippage

For each of these five risks, several performance indicators were identified and for each performance indicator a task was created to help mitigating the risk. For example, extra simulations were asked to model the rendezvous and capture phases. On top of this, a typical detailed design of a satellite using one capture option (to be proposed by the contractor) was to be performed in order to perform a cost estimate and achieve requirements mature enough for an SRR. The request to continue MBSE during phase B1, as well as the application of concurrent engineering and the use of collaborative design tools, accessible to both ESA and the contractors, enforced this. The low TRL of the capture technique and GNC software means extra monitoring of the total mission costs, including developments, and for the first time a cost ceiling was given at 150 M€ for the phase B2/C/D/E contract, excluding margins and launcher costs.
In May 2015, the invitation to tender for the phase B1 was issued by ESA after receiving sufficient subscriptions by member states (as described in section 2.3) and ESA received several proposals. At time of writing this paper, ESA started the negotiation phase with the aim to start the B1 phase in September 2015.

4 ENABLING SUCCESS

While typical ESA mission ideas are collected at ESA by means of a call for ideas to the scientific or telecommunication community for example, e.deorbit was never a mission proposed by ESA's member states, or science team to ESA. In contrast to this, e.deorbit came from a group of engineers within ESA who had studied sustainability options for space missions, and the mission was proposed to higher management within ESA who responded positively and together with other ideas to protect the environment, ESA member states were asked in the previous Ministerial Council to support the Clean Space initiative. So how did this mission study become so successful? The answer lies in teamwork, taking and aiming for decisions, and the cultural influence.

4.1 Teamwork

A strong success aspect is teamwork. At ESA a 'project like' support is pursued during the phase A and B1 studies. The team consists of the study manager, two systems engineers, cost engineer, risk engineer, Assembly Integration and Verification engineer, GNC, robotics, mechanisms, and space debris. Furthermore a strong link is held with the Clean Space manager, Clean Space system engineer, and direct higher management within ESA's TEC directorate. The team members were mostly present from the beginning i.e. active in space sustainability studies even before Clean Space was created.

The industry team consists of prime contractors and sub-contractors. During the phase A, the Airbus team consisted of ADS ST (Germany), ADS satellites (Germany), ADS SAS (France), SSTL (UK), GMV (Spain), DLR (Germany) and Aviospace (Italy). The Thales team consisted of TAS-F (France), TAS-I (Italy), MDA (Canada), Deimos Space (Spain) and GMV (Spain). The Kayser-threde team changed name to OHB during the phase A and consisted of OHB system (Germany), OHB Sweden (Sweden), DLR (Germany) and Polimi (Italy). ESA recommended frequent contact with industry, not only with the primes but also involving the sub-contractors. Videoconference tools and desktop tools such as Webex were used on a weekly basis. Some contractors voluntarily continued the use of concurrent engineering within their team. An e.deorbit symposium was held in May 2014.

4.2 Decisions

Several decisions have played and will play a major role in the success of e.deorbit. A first decision was to take a transparent approach, i.e. inform industry and member states on a frequent basis on the

current plans and the current achievements. The Clean Space team noted a positive reaction by industry as industry was often proposing to discuss at ESA results of the company's own internal studies and ideas. Another decision was not to narrow down system options, in particular related to the capture technique, too quickly. The phase A contained a mandatory set of three system options. The first phase A review (Mission Baseline Review) was to select for each of the three system options the capture technique, out of many options considered. While industry was asked to perform a trade-off between the three system options, it was decided to continue technology development studies for net, harpoon and rigid capture options, until the next Ministerial Council. The reason is that the final decision on the capture technique may not only be based on system engineering, but on the preference by participating member states, i.e. sponsors. Before PRR, a Mission Design Review was held to check if the design was mature enough for the PRR.
It was also decided that the robot arm capture solution would rely on a strong heritage of the German DEOS mission, which aimed at performing a capture using a robot arm in the 2017-2018 timeframe. Finally, it was decided to switch to an 'optional programme' already early in the design phase. While the phase A was under GSP funding and therefore only dependent on ESA internal funding, it was decided to propose phase B1 under GSTP funding, meaning that the phase B1 would only take place if ESA member states would actually subscribe and sponsor it. This entailed the risk of having no funding for the detailed design study, but was done on purpose to test interest before proposing the mission to the MC in 2016. Also during the MC, e.deorbit can only be proposed as an optional programme.

4.3 Culture

The e.deorbit mission is studied in a time where the culture puts more and more a focus on environment and its protection. While the majority still needs to realize that the Earth environment *includes* space until the Earth's sphere of influence, there is still a high amount of involvement, which becomes evident to the high coverage of e.deorbit videos and press releases on the Internet. Furthermore, when it is in the news that a space debris object is about to enter the atmosphere, there is a high amount of phone calls and emails received at ESA's debris office. Movies such as Warner Bros' movie "Gravity" certainly aid to the realization of the general public about the hazards of having debris in space. The e.deorbit mission and in particular the net tests and videos have received much attention on the ESA website. And both on-line newspapers as well as paper versions of newspapers often copied press releases.

5 RE-ASSESSMENT OF E.DEORBIT

While the progress of e.deorbit can be considered successful, it is good to stand still and re-assess the current situation and the projection on the future. How much did we mature really? What could be required if we did not or are not maturing enough? What can we conclude from the current strategy?

5.1 Maturity

As mentioned before, e.deorbit is supported by a wide range of technology development studies. The strategy is to continue these developments for net, harpoon and rigid options until the next MC decides with which capture method to continue.

The following technology development studies were pursued in the 2014 – 2015 timeframe:

Net studies

- Net debris capture and parabolic flights; this study studied the motion of net deployment, tested it in parabolic flights and modelled it in simulators.

- Bounced. Mathematical modelling of high elastic tethers.
- Elastic tethers; this study performs tests on elasticity of tethers of several materials, and the impact of the space environment.
- Harpoon characterization, bread-boarding and testing; this study creates test harpoons suitable for e.deorbit, and tests the harpoons for different impact conditions.

Robotics

- Clamping mechanism; trade-off of clamping mechanisms suitable of capturing the target without a robot arm.
- Robotics and GNC set-up; at ESTEC a set-up is created within the robotics laboratory that allows testing of GNC algorithms and sensors.

GNC And Debris Attitude

- De-tumbling solutions; a study on GNC algorithm and solutions to de-tumble e.deorbit with the target attached via a clamping mechanism.
- Advanced GNC solutions for ADR; this study developed first control algorithms to stabilize e.deorbit with a target attached via a tether.
- Image recognition and processing. Mathematical modelling on image recognition.
- GNC synchronized motion with robot arm. This activity studied GNC algorithms for a synchronized motion with robot arm.
- Debris attitude motion and measurements and modelling. In this activity observation campaigns are organized to determine attitudes of debris objects. ENVISAT is one of the objects to be studied. Based on the attitude motion, models will be developed to predict future debris attitudes.

The studies were executed with the aim to reach TRL 4 of the technologies. Most studies were executed within ESA's GSP programme or Technology Research Programme, allowing only internal approval within the need of member states contributions. Note that no robot arm technology developments were proposed. Instead it was assumed that these technologies would benefit from the heritage of the DEOS mission, as described in section 4.2.

For the 2016-2017 timeframe the following activities are proposed:

Net / Harpoon

- Net deployment prototype and sounding rocket test; this will allow testing of a net deployment in space.

Robotics

- Clamping mechanisms bread-boarding. The study will take the most promising clamping mechanism option of the phase B1 into account and create a breadboard version for testing purposes. Note that the requirement for the system study (phase B1) will be to select this particular clamping mechanism technique.

GNC & Avionics

- Hipnos & Comrade: advanced avionics, processing and collaborate control; these studies will focus on the mission vehicle management, processing power and avionics link between GNC and robotics.
- Consolidation of tethers advanced GNC algorithms; this is a follow up on the first study of control algorithms for de-orbiting debris via a net with a tether attached.
- Consolidation of active de-tumble solutions; this is a follow up on the first study of algorithms to de-tumble a stack connected by a rigid connection.

- Infrared camera for RDV; this study should investigate the requirements of camera equipment to be placed on the gripper of the robot arm.
- Miniaturized LIDAR; this study should start the development of a small light and radar sensor to determine the target's distance and attitude.
- Image recognition demonstrator; a demonstrator of the algorithms to determine the target's attitude and possibly distance from image recognition algorithms.
- Hardware in the loop testing; finally, GNC algorithms and robot arm should come together and be tested within one laboratory.

For the proposed studies, many studies are proposed in GSTP meaning they will require subscription of member states. This will also test the interest of the member states in that particular technology. In contrast, it could highlight no interest at all. For example, the miniaturized LIDAR has been proposed as GSTP study but no country has subscribed yet.

Some of the technologies could reach high TRL by doing an In-Orbit Demonstration (IOD). There has been much debate within the e.deorbit team about the necessity of IOD or not [11]. One could argue that many tests can be performed on ground (robotics, GNC sensors). The net behaviour cannot be tested on ground however a sounding rocket flight is foreseen to test the capture, and the tether dynamics could be tested in parabolic flights or free-flying equipment on board the International Space Station. Moreover, an IOD may cause a delay in the e.deorbit schedule, as well as increased overall cost. On the other hand there is the phenomenon of 'fear mitigation'; managers are more likely to sign for an expensive mission to remove a large debris, if it has been proven in space that a small debris can be removed. A small debris would pose no harm on ground, in case of a malfunction.

So far, the German agency DLR was pursuing a debris removal mission called DEOS, however the mission received no funding to go to phase C/D. In January 2015 a Memorandum of Understanding (MoU) was signed between DLR and ESA to study a joint IOD mission for ADR based on the DEOS capture technique (robot arm) and with a small ESA or DLR owned target (< 500 kg). An internal assessment study was done at ESA's CDF in February-March 2015, and the intention is to perform a phase A study for this potential IOD mission.

Other IOD missions have been studied under ESA contract. The first is ANDROID; a mission based on the PROBA platform which aimed to test both a net and robotic arm capture. This mission was studied on conceptual level with GMV as prime contractor, and could fit well within the constraints of an e.deorbit IOD (i.e. small target, launch latest at 2020). Also a cubesat based mission was studied by EPFL in Switzerland under ESA contract, called CADRE-1, which is a 12U satellite which brings its own target, and performs rendezvous experiments to test GNC sensors and algorithms related to the capture.

5.2 Strategy

Looking back on the decisions made (see section 4.2) and the work done, it can be concluded that as of today the system studies are on track to prepare a proposed for the implementation phase of e.deorbit the next MC in 2016. The start of phase B1 had suffered a small delay however the MC was also moved towards the end of 2016. There is the consequence though that, taking into account proper schedule margins, the predicted launch date has already shifted towards the end of the 2021-2023 timeframe.

The technology development studies were sometimes suffering from a late start due to the process of receiving funding, and sometimes due to overload on either the technical or contracts officers at ESA. While the late start of e.deorbit phase B1 means that the technology studies are more synchronized with

the system study, they still need to be put on a fast track in order to reach TRL 5 around the e.deorbit SRR.

Moreover, some countries are not represented in the phase B1 of e.deorbit. In particular countries like France, Spain, and the UK, who did participate to the phase A, are not supporting phase B1. This underlines the comment made by ESA's new Director General at the Paris air show of 2015 on the difficulty in getting member states to pay for 'waste removal'. It is typically far more interesting to give contribution to an interplanetary probe for example. Much work need to be done to convince the missing member states to contribute to the noble cause of e.deorbit.

6 CONCLUSIONS

E.deorbit is a challenging mission that requires new developments as capturing a uncooperative space debris using a spacecraft, and then de-orbiting it, has never been done before. It allows Europe to take the lead in ADR technologies.

E.deorbit started 'from scratch' as no ESA programme was requesting it, yet due to a motivated team of both ESA, industry and delegations, and the push of the Clean Space Initiative, the study matured to a phase B1 level. Continuation to implementation phase however will require strong motivation by the member states to finance waste management.

Much attention in the media is received (internet journals and TV shows) and an e.deorbit workshops was held with a high attendance of European industry, showing a high interest of many companies

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