PROJECT FINAL REPORT

Grant Agreement number: 262824

Project acronym: ACCORD

Project title: Alignment of Capability and Capacity for the Objective of Reducing Debris

Funding Scheme: FP7-CSA-SA

Period covered: from December 2010 to February 2014 (Final Report)

Name of the scientific representative of the project's co-ordinator, Title and Organisation:

Dr Hugh Lewis
Faculty of Engineering and the Environment
University of Southampton,
Southampton SO17 1BJ
UK
Tel: +44 23 80 59 38 80
Fax: +44 23 80 59 30 58
E-mail: hglewis@soton.ac.uk

Project website address: http://www.fp7-accord.eu

4.1 Final publishable summary report

4.1.1 Executive Summary

Access to important regions of space is necessary for maximum political, economic and social return from space investments, yet the vulnerability of space assets to debris impacts results in a persistent threat to those investments. At the same time, the capability of space industry to apply debris mitigation measures to reduce the threat is constrained by financial, technological, informational and philosophical considerations in spite of efforts to establish comprehensive debris mitigation guidelines and standards. No system currently exists to identify, quantify or address these constraints, yet while they remain it is likely that the near-Earth debris population will continue to grow and therefore the risk to assets will increase. Thus, the removal of these road-blocks is essential for the long-term, sustainable use of space. Fundamentally, ACCORD was a diagnostic and alignment mechanism applied to the European space industry and the space environment it utilises. It has informed research efforts related to space debris mitigation and endeavours by industry to put mitigation measures into practice.

The objectives of the ACCORD project were realised by a 39-month programme of work comprising a management work package and the following four work packages (WPs):

- WP1: Surveying the capability of industry to implement debris mitigation measures, and identifying existing and future challenges
- WP2: Reviewing the capacity of mitigation measures to reduce debris creation using the University of Southampton's DAMAGE tool.
- WP3: Combining capability and capacity indicators within a new environmental impact rating system for spacecraft.
- WP4: Disseminating the findings to stakeholders through publications, presentations, outreach and public engagement.

The implementation of post-mission disposal, collision avoidance, and impact protection measures were identified in WP1 as being the most costly and technically challenging issues faced by the space industry. Further, post-mission disposal was found in WP2 to be, by far, the most effective debris mitigation measure in Low Earth Orbit and Geosynchronous Earth Orbit. As such, increased investment in R&D activities related to new deorbit technologies, especially for small satellites, and Design-for-Demise is needed to address these issues.

The ACCORD Environmental Impact Rating system was developed in WP3 to effectively communicate the impact of new spacecraft on the space debris environment, to identify aspects of spacecraft design and operation issues leading to negative (and positive) impacts, and to enable the spacecraft industry to align its mitigation efforts with best practice. The web tool was based on the capability and capacity results from the preceding WPs and user advice.

The dissemination activity in WP4 led to an engagement with the research community, industry, government departments (including the UK Space Agency, NASA and JAXA), international organisations (including the Inter-Agency Space Debris Coordination Committee and the International Standards Organisation), schools and the public. Through this activity, and beyond the end of the project, ACCORD will potentially lead to a European common mitigation practice and, ideally, one that is adopted at an international level.

4.1.2 Project context and main objectives

Access to important regions of space is necessary for maximum political, economic and social return from space investments, yet the vulnerability of space assets to debris impacts results in a persistent threat to those investments. At the same time, the capability of European and non-European space industry to apply space debris mitigation measures to reduce the threat is limited by financial, technological, informational and philosophical constraints in spite of efforts to establish comprehensive debris mitigation guidelines and standards. No system currently exists to identify, quantify or address these constraints at a European or global level. Yet, while they remain, it is likely that the near-Earth debris environment will continue to degrade and the risk to assets will increase as the space debris population increases. This global challenge should be addressed in order to bring debris mitigation practices to the requirements set by international guidelines.

The route to long-term, sustainable use of space is dependent on removing these roadblocks, strengthening the strategic capability across Europe and more widely, and ensuring industry has the appropriate information and tools to achieve this. Thus, the **main objective** of the ACCORD Support Action has been *to support research and development efforts being undertaken internationally and at European level, by providing a coherent and rigorous mechanism for communicating the efficacy of current debris mitigation practices and identifying opportunities for strengthening European capability*. This objective has been realised via a three-step approach:

1. Survey of the capability of industry to implement debris mitigation measures and the identification of existing and future challenges,
2. Review of the capacity of mitigation measures to reduce debris creation, and
3. Combination of capability and capacity indicators within an environmental impact ratings system, which communicates the effectiveness of mitigation practices and identifies opportunities for strengthening European capability and capacity.

The space debris mitigation guidelines of the United Nations (UN) Science and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space (COPUOS) represent a high-level account of measures that can be implemented during the design and operation of new (and, ideally, existing) spacecraft to reduce the generation of debris and are consistent with debris standards, codes of conduct, etc., applied (and enforced) at national and regional level. The UN guidelines are: (1) limit debris released during normal operations, (2) minimise the potential for break-ups during operational phases, (3) limit the probability of accidental collision in orbit, (4) avoid intentional destruction and other harmful activities, (5) minimise potential for post-mission break-ups resulting from stored energy, (6) limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-Earth orbit (LEO) region after the end of their mission, and (7) limit the long-term interference of spacecraft and launch vehicle orbital stages with the geosynchronous Earth orbit (GEO) region after the end of their mission.

Some of these factors have a greater capacity to reduce debris creation than others, and their implementation will be driven by a variety of spacecraft design characteristics such as size and orbit. However, with the publication of the (European) Code of Conduct, UN and IADC debris mitigation guidelines documents, and ISO debris mitigation standards, it is expected that the design and operation of future spacecraft will have to implement many of these measures in accordance with strict requirements.

The new environmental ratings system is now being directed at stakeholders from the public and private sectors across Europe to support their continuing efforts to address the growth of the space debris population and to encourage further investment for the future.

The appraisal of European space industry, with respect to the implementation of guidelines and standards, has enabled a better understanding of the challenges associated with the design and operation of spacecraft, and of opportunities for strengthening industrial capability in this area. In addition, this activity has also helped to establish the focus of future debris mitigation requirements development at the Inter-Agency Space Debris Coordination Committee (IADC) and International Organisation for Standardisation (ISO) organisations. Notably, aspects of spacecraft design and operation that can lead to *increased debris growth* have also been established, thereby providing further awareness of R&D opportunities and knowledge of criteria that could potentially be applied to support active debris removal architectures in the future.

The introduction of a quantitative information exchange mechanism, taking the form of an environmental impact rating, has complemented on-going efforts within the European Community to establish and publicise good practice. Of equal importance, is the profound effect that such ratings systems can have on the awareness and attitudes of European citizens and policy-makers, and this has now become a legacy target of the ACCORD Support Action. The spacecraft environmental impact rating has followed similar ratings schemes for vehicles operating in the atmosphere, for example, and is based on a number of measurable and verifiable factors.

To produce this ratings system, the methodology of the Support Action was divided into four distinct parts (Figure 1): (1) survey of the implementation of mitigation measures by industry, (2) a review of the role played by mitigation measures in reducing debris creation, (3) encapsulating the knowledge extracted in the environmental impact rating, and (4) the dissemination of the Support Action findings to stakeholders. The outcomes of the particular tasks were:

- *Encouragement of continued and improved compliance by industry with space debris mitigation guidelines and standards*
- *Introduction of a simple, yet effective means of communicating compliance with guidelines and standards, and the effectiveness of those mitigation practices*
- *Provision of a basis for the development of a roadmap for the long-term sustainable use of near-Earth space*

Dialogue with the space industry, articles published in leading scientific journals, presentations at major conferences and space debris meetings as well as the initiatives tackling compliance issues have been logical, measurable deliverables of this Support Action.

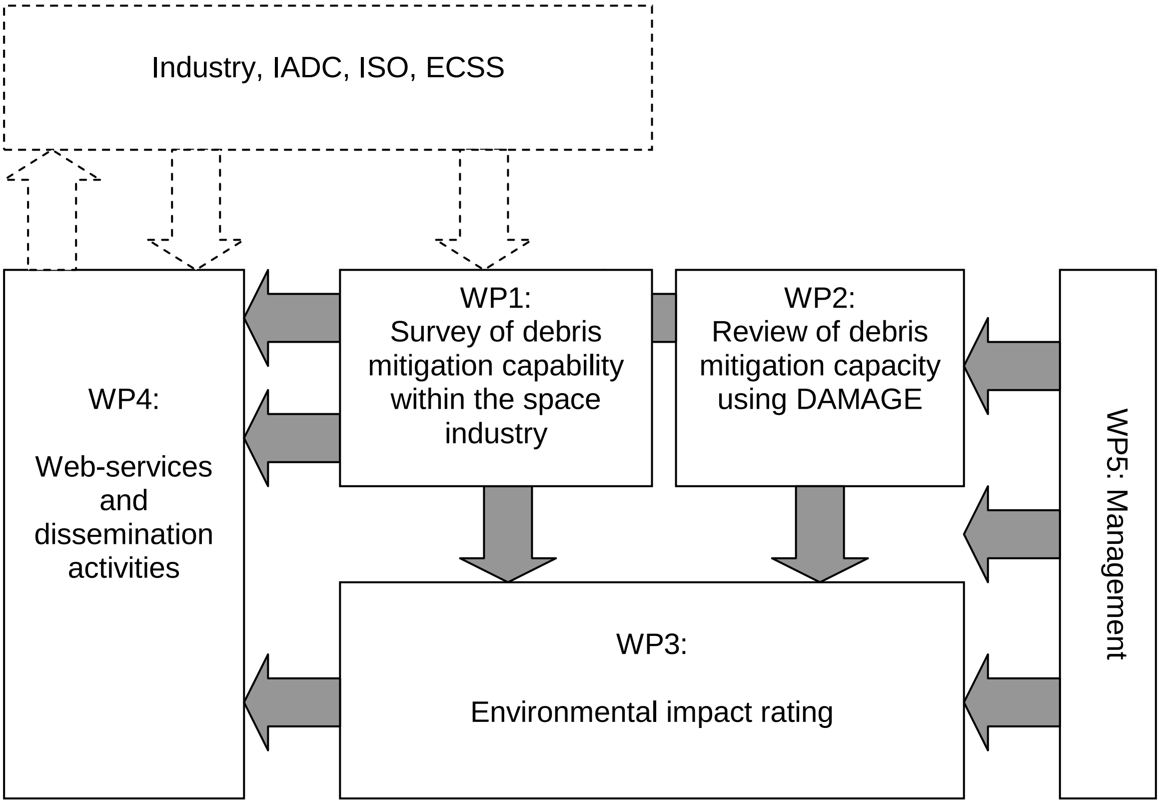


Figure 1 Key elements of the ACCORD Support Action shown as Work Packages and interactions between them.

4.1.3 Main scientific and technical results

4.1.3.1 Survey of debris mitigation capability within the space industry

The main objective of Work Package 1 was to perform a survey of the space industry to understand how space debris mitigation guidelines and standards are being implemented in the design and operation of spacecraft. This activity ran throughout the majority of the project (i.e. for 30 months) and was split into two phases. An interim deliverable report documented the first phase [1], which focused on the construction of the database and the collection and analysis of some preliminary data. In the second phase, greater effort was devoted to the data collection activity, with particular emphasis placed on the rapidly growing CubeSat class of unmanned spacecraft. Results from the entire activity should enable a better appreciation of the associated challenges and provide opportunities for strengthening industrial capability, which is a key requirement of the EC FP7 Space Work Programme. In particular, knowledge extracted from the survey should help to define the direction of European research in this field. Results from the survey should also help to identify if any of the current international debris mitigation guidelines and standards would benefit from some modification, e.g. because of practical difficulties in their implementation.

Another aim of the survey activity was to act as a stimulus for improved compliance with debris mitigation guidelines and standards. An awareness of the extent to which mitigation measures are being implemented across the industry should encourage greater participation from those designers and operators who have yet to adopt such measures.

The final objective of Work Package 1 was to extract statistical data from the survey to quantify the capability of industry to implement debris mitigation measures. This was a necessary input to the development of the environmental impact rating system in Work Package 3.

Survey Methodology

For the survey two questionnaires were designed to enable the collection of the required data from a wide range of spacecraft manufacturers and operators. One questionnaire focused on measures relating to the design of spacecraft, and the other addressed operations-related matters. To construct the questionnaires, PHS Space first reviewed the main debris mitigation measures from a variety of published guidelines and standards [e.g. 2 – 5] and used these as the basis for the questions that were asked in the survey. During the construction of the questionnaires, several draft versions were produced and reviewed by project members and key individuals in industry to ensure that the focus of the survey was correct. Questionnaires were distributed to survey participants with a covering letter, which was reviewed by the ethics committee at the University of Southampton, and a consent form. For ease of use, the questions were compiled into the following broad categories:

1) General Information
2) Mitigation Documents
3) Debris Release
4) Accidental Break-ups
5) Intentional Break-ups
6) Post-Mission Disposal
7) Prevention of Collisions
8) Miscellaneous

During the first phase of the survey activity, questionnaires were sent to approximately 40 space organisations either directly or through trade associations. In the second phase, a further 190 organisations were contacted. Awareness of the survey was also raised through presentations to a number of relevant international bodies, such as the ECSS, ISO and IADC. All responses to the questionnaires were subsequently entered into a 'Restricted' spreadsheet database, which is accessible only by the ACCORD project team and the European Commission. The overall response rate was 17.5%. For those organisations who did not respond to the survey, PHS Space obtained some of the requested data from a variety of other information sources, such as conference/journal papers and organisation websites.

In addition to the ‘Restricted’ database, an equivalent ‘Public’ database has also been compiled. However, this only contains information which survey participants have agreed to disclose publicly (by completing the ‘Disclosure’ sheet at the end of a questionnaire). Sensitive information, such as the name of the organisation or individual supplying the data, is automatically excluded from the public database. In recognition of the contribution made by those supplying data to ACCORD, the public database has been distributed to all organisations who have contributed to the survey. This has the added benefit that data in the database can be checked and updated as necessary.

Special Case of CubeSats

Within the past decade a new class of small satellite – the so-called ‘CubeSat’ – has come into prominence. Compared to larger satellites, CubeSats are relatively simple and can be built quite quickly. They are also inexpensive to launch. This has made them attractive to a wide variety of organisations who wish to establish a presence in space. For example, many of these newcomers to the space industry are academic institutions offering students ‘real-world’ experience of designing and operating a small satellite. It is not surprising, therefore, that there has been a dramatic growth in the number of CubeSats launched to date. Indeed, within the past six months the number launched into low Earth orbit has almost doubled. Consequently, this class of satellite deserves to be examined separately to other types of unmanned spacecraft. To address the special case of CubeSats, a subset of the final ‘Restricted’ version of the survey database was constructed.

Analysis of Survey Database (excluding CubeSats)

An important aspect of the analysis of the preliminary database has been to understand if there are any specific debris mitigation measures with which industry is having difficulty complying. Information on common compliance issues, their causes, and the main reasons why mitigation solutions have not been implemented was crucial for the calibration of the environmental impact rating system (developed in Work Package 3). This information is also useful for those organisations engaged in developing / maintaining guidelines or standards, as it will help to ensure that such documents remain relevant and useful to industry.

Excluding organisations involved exclusively in the manufacture/operation of CubeSats, the database comprises information on 111 distinct organisations. Of these, 24 responded to the survey. For the remainder, information was acquired through on-line searches. Since the year 2000, 61 of these organisations have designed spacecraft and 55 have been involved in spacecraft operations. The organisations listed in the database collectively account for a significant percentage of the satellite market since the year 2000.

Over half of the satellites are large (>1000 kg), while only 14% fall into the micro-satellite category (CubeSats are excluded). Approximately three-quarters of the satellites are civilian, with the rest being either military or dual purpose (i.e. civilian and military). Half of the satellites are LEO and nearly one-third are GEO. In terms of function, just over half of the satellites provide communications services.

Space Debris Mitigation Guidelines and Standards

To gauge the relative value of the guidelines and standards, survey participants were asked to identify which documents they have used and which ones they expect to use in the future. In this context the word ‘use’ means apply, consult or refer to. The results reveal that some long-standing documents, such as the IADC Space Debris Mitigation Guidelines and the European Code of Conduct for Space Debris Mitigation are less likely to be used in the future. At first glance this might seem rather surprising, especially with regard to the IADC Guidelines document which is one of the most well-known. One possible explanation is that some survey respondents will be shifting their focus to the newly-emerging ISO debris-related standards. The results confirm that there is likely to be an increase in the usage of these more recently published international standards. This is probably because the ISO standards are designed to be applied within the contractual arrangement between a customer and supplier, and so they are more suited to commercial spacecraft projects. Nevertheless, the IADC Guidelines remains a very important document as it is the foundation for the content of the ISO debris standards.

The database also reveals the relative usage of debris mitigation guidelines and standards among the individual survey respondents. A small number of organisations have used, and expect to continue using, just one document. These are generally national standards (or regulations) whose content is strongly consistent with that of ISO 24113, the top-level ISO debris standard. By contrast, most other organisations have used multiple documents and expect to continue doing so.

Limiting the Release of Space Debris during Normal Operations

One of the key debris mitigation requirements that manufacturers are expected to observe in the design of their spacecraft is to prevent or limit the release of space debris during normal operations. Survey participants were asked to identify which methods they had implemented, or were expecting to implement, in the design of their spacecraft. The results show that the majority of the manufacturers are already implementing design measures to prevent or limit the release of Mission-Related Objects (MROs) and solid products from pyrotechnic devices. Furthermore, in the future, it would appear that an even greater percentage of the manufacturers will be able to satisfy this goal. Most respondents indicated that the implementation of measures to prevent the release of MROs and pyrotechnic debris had little or no impact on the spacecraft design, although some impacts were noted.

With regard to the release of debris during normal operations, a small number of respondents said that they have not done this and do not expect to in the future. Of the remainder, almost 70% have been able to design their spacecraft to ensure that any debris released into the LEO protected region will stay there for less than 25 years. For the release of debris at GEO altitudes, 40% of the respondents had implemented measures to ensure any released debris remains outside of the GEO protected region. By contrast, almost 60% had allowed the option of releasing debris which would remain in the GEO region for up to 25 years. However, this option is not an applicable rule for many organisations.

An important source of small-size orbital debris is the release of ejecta from spacecraft surfaces as a result of various environmental factors. However, most respondents do not currently implement measures to limit the release of surface ejecta in the design of their spacecraft. The main reason given is that this is not a requirement in applicable standards. However, some organisations recognise the importance of reducing surface ejecta and stated that they expected to include such considerations in future spacecraft.

Avoiding Accidental Break-ups

Survey results show that 70% of manufacturers have calculated the break-up probability of a spacecraft, and another 8% said that they planned to do so. The publication of ISO 24113 in 2011 would appear to have had a positive effect in this regard, as confirmed by one of the respondents. Of those who had not calculated the break-up probability, 25% confirmed that they had assessed if there were any failure modes which could lead to accidental break-up. Thus, almost four out of five manufacturers have given some level of consideration to the possibility of accidental break-up during the design of a spacecraft.

The break-up probability of a spacecraft can also be calculated periodically during its mission life. The results show that 45% of operators either do this now or plan to do it in the future. The remaining 55% stated that they had no plans to perform this calculation. However, all operators monitor the condition of a satellite during its life to detect any malfunctions which could lead to an accidental break-up.

In the event that a malfunction is detected which could lead to a break-up, or the probability of accidental break-up is found to be greater than the specified maximum value during the operational phase, survey participants offered a range of responses for how they would deal with this problem. Not surprisingly, the answers show a degree of commonality. However, there is also some variation, which would seem to suggest that a standardised evaluation procedure might be beneficial. This is something that ISO and other standards bodies might wish to address.

To reduce the risk of accidental explosion it is essential to remove all major sources of stored energy from a spacecraft at the end of its life (or sooner if possible). This is known as passivation. Two items that require special attention are batteries and propulsion systems. Figure 2 reveals the most common approach among designers is to discharge batteries or subject them to a permanent electrical drain.

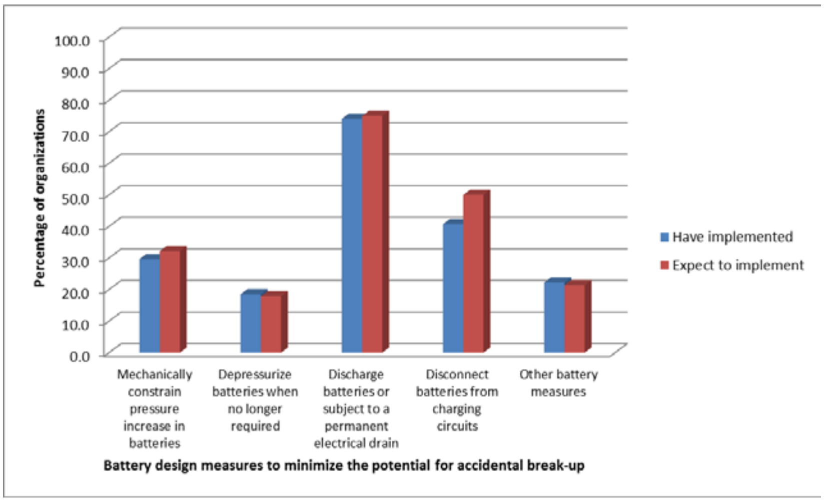


Figure 2 Battery design measures to minimise the potential for accidental break-up

Almost all operators have performed venting / depletion burns. However, only 44% of operators have taken steps to minimise the probability of collision with other space objects during this procedure. That said, in future it appears that a greater proportion of operators (over 60%) will endeavour to minimise the collision risk when performing venting / depletion burns. Typically, it takes in the region of a few hours or days to passivate all of the spacecraft subsystems (excluding fuel depletion). However, to remove all propellant can take several weeks.

Avoiding Intentional Break-ups

Most debris mitigation guidelines and standards state that the intentional break-up of a spacecraft is either not permissible or is to be avoided. However, some variation can be observed. The database reveals that all but two of the organisations involved in spacecraft operations have exercised the option of 'Intentional Destruction' for the post-mission disposal of their spacecraft. Both of these events occurred within the past decade and received significant publicity. Such incidents are rare and perhaps can be viewed as anomalous. When asked under what circumstances 'Intentional Destruction' might be included in an End-Of-Mission Disposal Plan (EOMDP), all but two organisations confirmed that there weren't any. One respondent stated that the only condition they could imagine would be if early break-up could allow for more complete demise of individual assemblies, thus reducing re-entry risk to less than 1 in 10,000.

Post-Mission Disposal

An effective way to preserve the Earth orbital environment is to remove spacecraft from the LEO and GEO Protected Regions at end of life. This is perhaps the most important of all of the measures listed in the various debris mitigation guidelines and standards. It requires that spacecraft have a reasonable probability of successful post-mission disposal. The survey results show that half of those involved in the manufacture of spacecraft have calculated the probability of successful disposal and a further 20% expect to do so. Thus, two out of three manufacturers have given some level of consideration towards ensuring the successful post-mission disposal of a spacecraft.

Whilst the probability of successful disposal calculation is commonplace during the design, it is less so during the operation of spacecraft. Only one-third of operators said that they had periodically performed the calculation during the operation of a spacecraft. The survey reveals that all operators have monitored the condition of a satellite and 98% have monitored the amount of remaining propellant so that the satellite can be successfully disposed. Of those who monitored propellant, 30% confirmed that they had encountered circumstances where their spacecraft had insufficient propellant to accomplish the desired disposal manoeuvre.

For the post-mission disposal of spacecraft in the LEO region, the most widely-accepted 'rule' is that removal should be accomplished within 25 years of the end of the mission, preferably by de-orbiting the spacecraft or alternatively by manoeuvring it above the LEO region. As shown in Figure 3, almost 80% of LEO spacecraft manufacturers confirmed that they had designed LEO spacecraft to be de-orbited according to the 25-year rule. Several organisations stated that they had used orbit propagation software tools such as NASA's DAS or CNES's STELA to confirm their spacecraft would be compliant with the 25-year rule. However, not everyone has considered uncertainty in the orbit lifetime prediction, which can ultimately lead to spacecraft remaining in orbit longer than the required 25 years. Over 75% stated they had performed a casualty risk analysis during the spacecraft design to understand the threat to public safety when a spacecraft re-enters (e.g. ensuring that the total casualty risk for an uncontrolled re-entry is less than a maximum specified value such as 0.0001).

For the post-mission disposal of spacecraft in the GEO region, the most widely-accepted 'rule' is that removal should be accomplished according to the IADC GEO re-orbit equation.

Of those involved in the design of GEO spacecraft, nearly 75% said they had designed GEO spacecraft to be disposed of in accordance with this equation (see Figure 4).

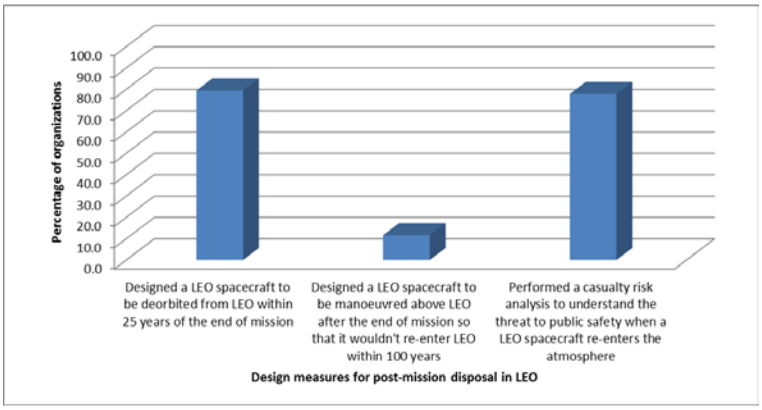


Figure 3 Design-related measures for post-mission disposal in LEO

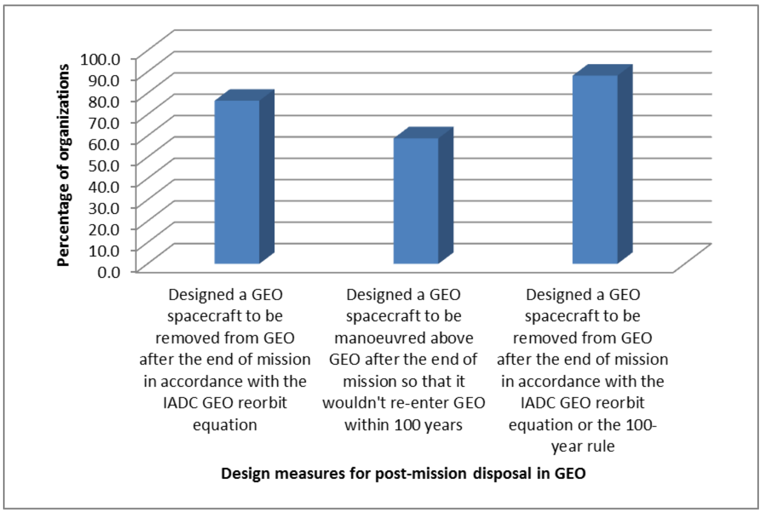


Figure 4 Design-related measures for post-mission disposal in GEO

A slightly different approach is to manoeuvre a spacecraft above the GEO region so that it won't re-enter the region within 100 years. Approximately 60% of the GEO spacecraft designers stated that they had incorporated this 100-year rule in the design of GEO spacecraft. Overall, nearly 90% of designers appear to have implemented either the IADC equation or the 100-year rule in their GEO spacecraft.

The results of similar questions were put to the operators of GEO spacecraft. 79% of operators have taken actions to dispose of GEO spacecraft in accordance with the IADC equation, and 60% have done so for the 100-year rule. Overall, 83% of the GEO operators said they had done one or the other.

Prevention of Collisions

During the design of a spacecraft it is possible to undertake a statistical assessment of the probability of accidental collision between the spacecraft and other known space objects. This can help to determine the number of collision avoidance manoeuvres that might have to be performed throughout the mission life, and therefore the amount of propellant that might be needed. The left-hand chart in Figure 5 shows that almost 71% of respondents have done such an analysis, and another 8% expect to do so in the future. Nearly 80% of manufacturers have included a capability for collision avoidance in the design of their spacecraft, i.e. the provision of additional propellant. Just over 40% of operators confirmed that they had coordinated collision avoidance manoeuvres with other operators, although a greater percentage said they were willing to do so if it was judged necessary.

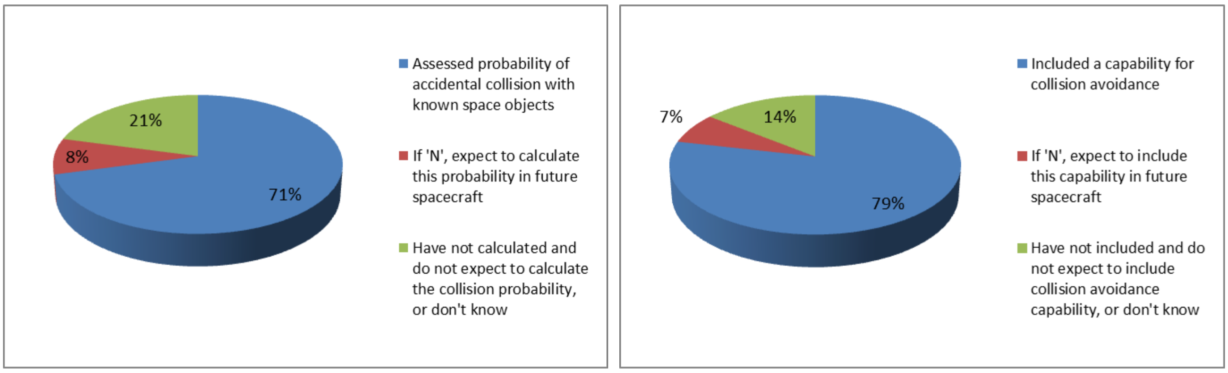


Figure 5 Design-related measures for collision avoidance

The growth in the population of small-size debris, particularly over the past decade, also presents a problem for spacecraft. Thus, it is becoming increasingly important that manufacturers calculate the probability of failure due to impact with small debris during the design of a spacecraft. Survey results show that 75% of the manufacturers had performed this calculation, and a further 8% expected to do so in the future. Of those who have calculated the failure probability, over 70% have subsequently made changes to the design of their spacecraft, e.g. adding localised shielding, to improve the impact survivability.

Effect of Debris Mitigation Measures on Spacecraft

A key aim of ACCORD was to understand the capability of a manufacturer and operator to implement debris mitigation measures in the design and operation of spacecraft. It is likely that some measures will be more difficult to incorporate because of the associated costs, whereas other measures will be technically challenging. To find out the cost and technical impact on the spacecraft design, survey participants were invited to provide a score out of 5 for each measure (where 1 is low and 5 is high). The results are shown in Figure 6.

It is clear that most respondents consider post-mission disposal to have the biggest cost impact on the design of a spacecraft. This is perhaps not surprising given that many spacecraft have to hold a significant quantity of propellant in reserve to perform such manoeuvres. Interestingly, the next most expensive measures to implement are jointly shared between impact protection and collision avoidance. These are also considered to be the two most technically challenging. The least problematic measure to implement from a cost and technical standpoint is to refrain from releasing debris during normal operations. For most organisations, the sector (i.e. whether the spacecraft is civilian or military) does not have a significant bearing on their ability to implement debris mitigation measures. By contrast, most designers observed that the size, orbit and function of a spacecraft influenced their ability to incorporate measures relating to post-mission disposal and collision avoidance / impact protection.

Overall, it would seem that the impact of the measures on operations (Figure 7) is not as pronounced as it is for the spacecraft design. Operators identified collision avoidance as having the greatest cost and technical impact. The lack of accuracy in current tracking data and collision risk assessments is a notable deficiency, especially for spacecraft in LEO. Post-mission disposal was identified by operators as having the second biggest cost impact.

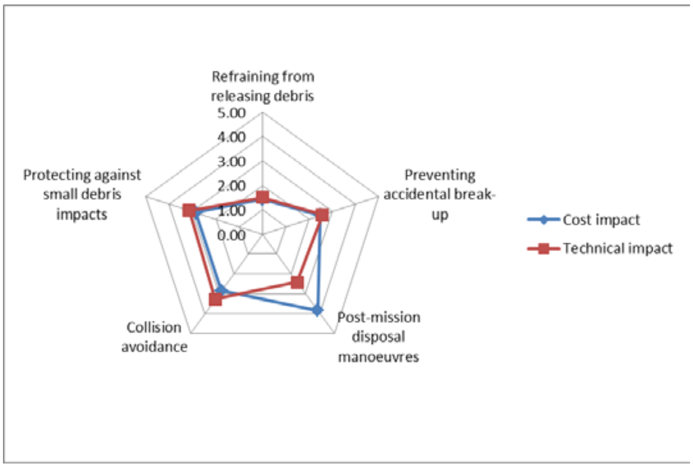


Figure 6 Effect of debris mitigation measures on spacecraft design

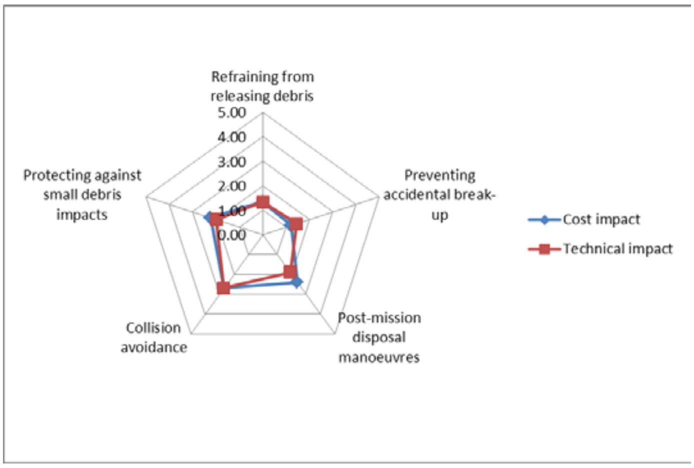


Figure 7 Effect of debris mitigation measures on spacecraft operations

Analysis of Survey Database relating to CubeSats

The CubeSat survey database comprises information on 118 distinct organisations involved in the manufacture and operation of CubeSats. Of these, 16 responded to the survey, and a further six agreed to participate in the survey but did not do so within the allotted timeframe. For the remainder, information was acquired via on-line searches. Approximately half of the CubeSat manufacturers are based in the USA, one-quarter are in Europe, and 8% are in Japan. Overall, these three regions account for 83% of organisations involved in CubeSats. 69% of CubeSat manufacturers are from academia, 19% are from industry, and the remaining 12% are governmental organisations (either civilian or military). The database reveals that the vast majority of CubeSats have been built for non-military purposes. Generally, the satellites have been designed to perform experiments or demonstrate technologies in LEO.

Space Debris Mitigation Guidelines and Standards (CubeSats)

The application of dedicated debris mitigation guidelines and standards, such as those published by IADC, NASA, and ISO, is sparse and does not compare favourably with the usage among manufacturers of larger satellites. There may be several reasons why some in the CubeSat community have not embraced debris mitigation guidelines / standards, including:

- A lack of awareness
- A lack of requirement imposed by an external customer or licensing authority
- A perception that CubeSats do not contribute significantly to the debris problem
- Difficulty in implementing debris mitigation measures, e.g. because of the small size of a CubeSat or the limited availability of low-cost launch opportunities

That said, many CubeSat manufacturers appear to be following the CubeSat standard [9]. Version 12 of the CubeSat standard contains the following debris mitigation related statement: the orbital decay lifetime of the CubeSats shall be less than 25 years after end of mission life. This is the most important mitigation measure for any LEO satellite. However, it is far from clear if all CubeSat manufacturers are implementing this particular requirement. The evidence from the following sub-section would appear to indicate otherwise.

Post-Mission Disposal (CubeSats)

Given the importance of the 25-year rule for post-mission disposal in LEO, the ACCORD project team placed a significant amount of effort in determining which organisations had launched CubeSats that would / would not comply with this rule.

80% of CubeSat manufacturers have launched at least one satellite that will deorbit within 25 years of the end of mission. Generally, this was achieved through the selection of an orbit that will decay naturally within this timeframe. The data also show that 15% of CubeSat manufacturers have implemented deorbit technologies to comply with the deorbit requirement. In contrast, almost 40% of CubeSat manufacturers have launched at least one satellite that will not deorbit within 25 years of the end of mission. This is a much more troubling statistic. It is clear evidence that the debris mitigation message, as promulgated in various guidelines and standards, has not been getting through to the entire CubeSat community. However, it would be unreasonable to point the finger of blame solely at some members of this community. One might also question the actions of those launch service providers who are enabling the deployment of CubeSats into inappropriate orbits. But perhaps the most important factor underpinning this problem is the lack of national regulatory oversight in many countries, especially those with emerging space capabilities.

Other Debris Mitigation Measures (CubeSats)

The small size and limited functionality of a CubeSat should mean that it is a relatively straightforward matter for the design to prevent or limit the release of debris during normal operations. Amongst the limited number of responses, there was compliance with all measures except for ejecta release. It is noteworthy that the CubeSat standard prohibits the use of pyrotechnics. This is a much stricter requirement than that found in most debris mitigation guidelines and standards.

To date, measures to limit propulsion-related accidental break-ups have been largely irrelevant since most CubeSats have avoided using propulsion systems. The absence of a propulsion system means that most CubeSats do not have a collision avoidance capability either. Therefore any measures in this regard will also be irrelevant. The main hardware item which could cause the break-up of a CubeSat is its battery. The most common measure is to discharge batteries or subject them to a permanent electrical drain. There is no reason why more CubeSats should not implement this particular measure in future.

Measures such as ‘putting critical equipment in less vulnerable positions’ and ‘distributing redundancy’ have been applied in some CubeSat designs. Given the size of a CubeSat, i.e. its small collision cross-section, one might not have expected such measures to be implemented. Nevertheless, it is reassuring to see this, since the impact damage from a 1 mm debris particle would be more likely to cause a CubeSat to fail than a much larger spacecraft.

Effect of Debris Mitigation Measures on CubeSats

Collision avoidance and impact protection are considered to be the most costly and technically challenging mitigation measures to implement within CubeSats closely followed by post-mission disposal (Figure 8). The fact that the ‘difficulty’ scores for these three measures were only in the region of 3 out of 5 would seem to suggest that the measures are not insurmountable. Therefore, one might expect the CubeSat community to achieve greater compliance with these debris mitigation measures in the future.

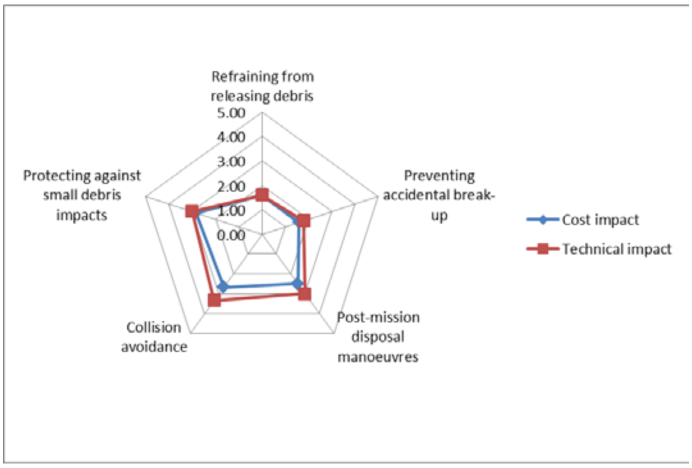


Figure 8 Effect of debris mitigation measures on CubeSat design

Recommendations and intitiatives

Another objective of WP1 was to identify initiatives for addressing the most common non-compliances in the survey data. Broadly, they encompass:

1. Suggestions for improvements to international debris mitigation guidelines and standards.
2. Options for better regulatory oversight.
3. Possibilities for future research and development.

Improvements to International Guidelines / Standards

Some of the common technical challenges stem from potential inadequacies in current international debris mitigation guidelines / standards. These include areas where guidance on the implementation of mitigation measures is either missing, incomplete, or impractical.

In the event that a malfunction is detected which could lead to a break-up, or the probability of accidental break-up is found to be greater than the specified maximum value during the operational phase, a standardised evaluation procedure might be beneficial. At the moment, ISO 16127:2014 [2] simply states that “In the event of in-orbit malfunctions which could lead to 1) break-up or 2) the loss of operating function, possible debris mitigation measures should be studied and implemented”. The inclusion of a standardised evaluation procedure in ISO 16127 would establish firm criteria against which judgements could be made about appropriate actions to take.

It would seem that the calculation of the probability of successful disposal is an area where some harmonisation might be beneficial. For example, the top-level ISO debris mitigation standard, ISO 24113:2011 [3], specifies that the probability of disposal must be calculated and discusses the basic equations for doing so, but it does not specify how to calculate the individual terms of the equations. This is, perhaps, something that ISO may wish to consider in future. Another factor concerns uncertainty in the prediction of post-mission orbit lifetimes for LEO spacecraft. The calculation of orbit lifetime is necessary to demonstrate compliance with the 25-year deorbit rule. Whilst there are a number of different software tools available to perform this calculation, not all of them cater for variability in the solar activity cycle. This uncertainty can have a significant effect on the orbit lifetime prediction, and therefore it should not be overlooked in the calculation. It is clear from looking at the IADC guidelines [4] and the ISO standards that further guidance is needed to address this issue.

Survey respondents indicated that the threshold of collision probability at which a manoeuvre might be performed ranged from 10^{-3} to 10^{-5}. Given the diversity of responses, the lack of clear guidance in the IADC guidelines and the ISO standards might be seen as a serious omission. Satellite operators have to judge whether satellites will come sufficiently close to each other by taking into account the accuracy of tracking data and orbit propagation before deciding whether a manoeuvre should be performed. Insufficient provision for space situational awareness at the present time means that the error margins can be significant. Until confidence in these factors is high enough, it is difficult for organisations such as IADC and ISO to specify thresholds for initiating collision avoidance. However, given the wide range of thresholds currently employed by operators, there is, perhaps, some scope for these organisations to provide more concrete guidance than that currently offered.

Assessing the feasibility of common shield design and test procedures aligns well with one of the outputs of the FP7-funded project ReVuS [6]. At the end of the project a number of design rules for implementing impact protection in unmanned spacecraft were proposed based on the investigations conducted earlier in the study [7]. These rules cover all aspects of impact protection, including procedures for designing and testing shields. Such guidance could potentially be implemented in an IADC guideline or ISO standard. One possibility might be to develop a standardised impact test procedure to evaluate the performance of a shield design, since no such procedure currently exists. Interestingly, ISO has recently published a standardised impact test procedure for the collection of data to characterise the ejecta released from oblique impacts on surfaces [8]. This defines all of the parameters for a test, such as projectile characteristics and the location of witness plates, and the measurements that should be taken before, during and after the test. Thus, it should be possible to use this ISO standard, together with experience from studies such as ReVuS, to guide the development of a standardised test procedure to evaluate shield designs.

ISO’s existing debris mitigation standards, such as ISO 24113:2011 [3], apply equally to all satellites irrespective of size. Small satellites are not exempt from any of the debris mitigation requirements. However, the ISO TC20/SC14 Space Systems and Operations Committee is considering the development of the following documents:

- Space systems — Small satellite best practices for operations and development
- Space systems — Design Qualification and Acceptance Tests of Small-scale Satellite and Units Seeking Low-cost and Fast-Delivery

These may contain additional guidance on how to implement debris mitigation in small satellites. If approved, the documents may become ISO Technical Reports rather than International Standards, i.e. their content may be informative rather than normative. The timescale to develop the documents would most probably be in the region of three years and the content will cover much more than just debris-related matters. In the event the documents are developed, an important point for consideration concerns the tendency for small satellites, such as CubeSats, to have lower quality / reliability compared to large satellites. This is usually for at least one of the following reasons:

- They are flown as technology demonstrators
- They are designed and built by student engineers as a learning tool
- Standard management and design practices are not followed
- Off-the-shelf components are used to keep costs down

Thus, these satellites, which might be considered as “experimental” in nature, can have a higher than normal probability of failure. This means that even if a post-mission disposal capability is included, there is a reasonable chance the satellite may fail before it has an opportunity to deploy that capability. Therefore, one might conclude that “experimental” LEO satellites, such as CubeSats, should be placed into orbits of sufficiently low altitude that they will be guaranteed to re-enter the Earth’s atmosphere within 25 years of the end-of-mission. The inclusion of a statement to that effect in a standard aimed at small satellites would be beneficial.

Options for Regulatory Oversight

Space debris mitigation guidelines and standards have existed for over a decade but there is clear evidence that a significant percentage of spacecraft designers and operators are failing to implement even the most basic measures; debris mitigation comes at a price and it is also technically challenging. Improvements to international guidelines and standards will certainly help, as will future technology developments. However, another part of the problem is that current guidelines and standards are voluntary, non-binding documents. There is no mandatory standard of conduct relating to debris mitigation with which the space industry has to comply. Until such time that one emerges, the compliance problem will persist. In the meantime, a couple of interim solutions are offered – one at a European level and the other at a global level – which may be worth exploring.

Within Europe there is no uniform regulation applied to the licensing of a satellite prior to its launch. Significant variation exists amongst the EU members. Some countries, such as the UK and France, have established strict requirements within their national legal frameworks while others have not. Differences in the licensing arrangements across Europe create an unbalanced commercial environment. Satellite manufacturers and operators based in countries with weak licensing arrangements have an unfair competitive edge over those located in countries with stricter arrangements. The variation in regulations across Europe also opens the door to the possibility of spacecraft flying under a ‘flag of convenience’. That is, to circumvent strict launch licensing rules in one country, some spacecraft owners may be in a position to seek a licence from another European country with a weaker licensing regime. It is understood that at least one CubeSat manufacturer has taken advantage of this situation to facilitate the launch of their satellite.

In view of these regulatory imbalances in Europe, there is an argument that the EU should take the necessary steps to introduce an EU-wide launch licensing regime. Not only will this establish a fair commercial environment within the European space industry, it will also ensure that Europe, which accounts for a significant proportion of the global satellite market, is acting in a coherent and unified manner to preserve the near-Earth space environment.

The number of CubeSats (and PocketQubes) launched in 2013 is comparable to the total number launched in the previous ten years, as shown in Figure 9. If this trend continues then by 2017 at least one-quarter of all active satellites in LEO will be CubeSats, with the numbers continuing to rise beyond that date. Amongst such a large and fast-growing community, many of whom could be classed as "enthusiastic amateurs", it is unlikely that international debris mitigation guidelines or standards will gain much traction. Evidence from the survey conducted in WP1 shows that almost 40% of CubeSat makers have failed to comply with the most fundamental of debris mitigation measures, namely the 25-year post-mission deorbit rule, in one or more of their satellites [1]. This is despite the fact that debris mitigation guidelines and standards have been around longer than CubeSats. Consequently it should not be assumed that compliance with guidelines and standards will increase over time. Indeed it could be the opposite. Even an intensive education campaign may be of limited value because of the rapidly changing composition of the CubeSat community.

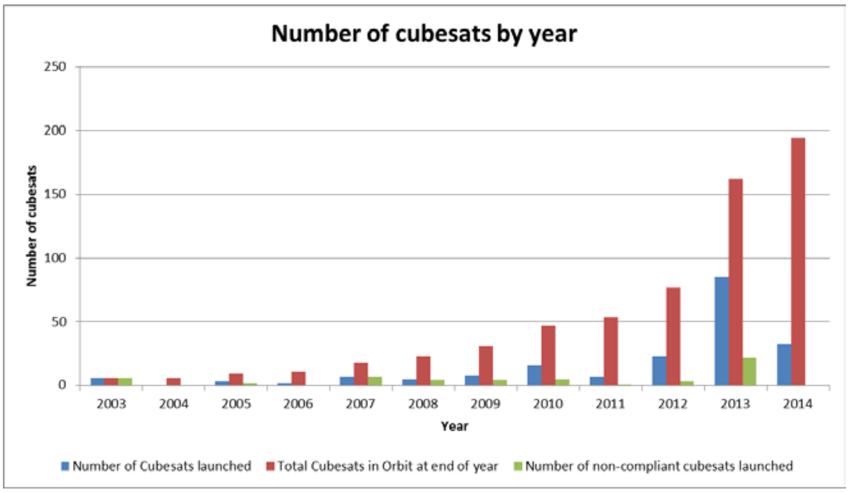


Figure 9 Number of cubesats launched per year

It could be argued that the easiest way to manage the LEO Protected Region is to shift the focus of attention onto those who provide access to this region of space, i.e. the launch service providers. These "gate-keepers" are professional organisations and are relatively few in number. Therefore, it should be easier to engage with that small, stable community rather than a large and fast-changing satellite community. For example, one approach might be to encourage launch service providers to sign up to an international Code of Conduct (or other legal instrument) in which they agree only to launch satellites that comply with national regulations or international standards relating to debris mitigation. This should not place a significant extra burden on the launch provider. Rather, it would be up to the satellite owner to demonstrate to the launch provider that their satellite is compliant.

Possibilities for Future Research and Development

One of the questions in the survey asked participants if the implementation of debris mitigation measures in the design and operation of spacecraft was a subject that required further research and development. The majority of the recommendations relate to collision avoidance, impact protection and post-mission disposal. These were also identified in the survey analysis report as being the most costly and technically challenging measures faced by the space industry.

In particular, for collision avoidance, there is a desire for improved accuracy of tracking data, better collision risk assessment, and clearer criteria for when to perform avoidance manoeuvres. In terms of European R&D, it is well recognised that space situational awareness capability needs to be improved, as this is a key component of debris mitigation in the future, and programmes are already in hand.

With regard to debris impact protection, investigations into better shielding materials and techniques of these aspects have already been undertaken within the FP7-funded ReVuS project [6]. At the conclusion of the project a number of important recommendations for follow-on work were made, which are worthy of consideration within the context of the EC's Horizon 2020 work programme on space. Another debris protection-related concern is the need for improved impact risk analysis models. Models, such as ESA's ESABASE/DEBRIS and NASA's BUMPER, were developed over two decades ago and their analytical capabilities are restricted to consideration of the penetration of exposed surfaces. Models, such as PHS Space's SHIELD tool, have been developed more recently to characterise the impact damage inside a spacecraft. The modelling techniques for evaluating internal impact damage are reasonably well-defined, but there is a lack of data to support them. This is an important issue that needs to be addressed. Another important issue, which is a common failing of most impact risk codes, is the lack of consideration of uncertainty in the modelling process.

In terms of post-mission disposal, the most popular suggestion from survey respondents relates to the need for new deorbit technologies. These might be attractive alternatives to propulsion systems, especially when used in small satellites, such as CubeSats, and so their development should be encouraged. Another concern is the need for studies on Design-for-Demise (DfD). The aim of DfD, which is a relatively recent innovation, is to minimise the survivability of a spacecraft during atmospheric re-entry, thereby ensuring fewer parts reach the ground. DfD is an especially important consideration in the design of a large LEO spacecraft that will be performing an uncontrolled re-entry at the end of its orbital life. Without DfD, there is little prospect that such a spacecraft will be able to satisfy the most commonly applied re-entry casualty risk threshold of 10^{-4}. In this situation the only alternative is to design the spacecraft to perform a controlled re-entry. However, this could be an infeasible proposition if the spacecraft has to deorbit from a relatively high altitude in LEO.

In summary, all of the above recommendations deserve serious consideration by those organisations involved in defining the direction of debris mitigation research programmes in Europe. It is hoped that countries outside of Europe will also find the information to be of similar benefit. Most of the recommendations would seem to fit within the scope of the Horizon 2020 funding programme.

4.1.3.2 The capacity of mitigation measures to reduce space debris

The main objective of WP2 was to determine the capacity of space debris mitigation measures to reduce debris. This objective was complementary to the objective of WP1 and the knowledge gained from both activities provides a clear understanding of the efficacy of mitigation practices. The objective was reached through the use of the University of Southampton's DAMAGE tool, which is a full 3D evolutionary model of the debris environment. Using DAMAGE, individual mitigation guidelines and standards were assessed for their impact on the future space debris population. In addition, DAMAGE was used to identify factors that lead to an increase in the debris population. Results from both work packages also provided important knowledge for the generation of an environmental impact rating system. WP2 comprised two key tasks:

- Determine the capacity of space debris mitigation guidelines and standards.
- Identify specific factors that can lead to increased debris creation.

Capacity of space debris mitigation guidelines and standards

Making use of the Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) 2009 reference population, provided by the ESA space debris office, a set of future scenarios were designed for simulation by the DAMAGE tool. This set comprised 16 scenarios based on a non-mitigation (or "business as usual") case, the implementation of individual debris mitigation guidelines (taken from the IADC space debris mitigation guidelines) or a combination of these Table 1). 100% compliance with each mitigation measure was assumed in order to understand the "best case" outcome.

Table 1: Description of mitigation scenarios

Mitigation Scenario	Short name	Description
Collision avoidance	CA	Satellites manoeuvred to avoid any collision within their operational lifetime (assumed to be 8 years from launch)
Mission-related objects	MRO	All mission related objects were removed from the future launch traffic
Passivation	PASS	All spacecraft and rocket bodies were passivated at End-of-Life (EOL) such that no explosions occurred
Post-mission disposal	PMD	At EOL, satellites and rocket bodies launched after 2009 were manoeuvred to a decay orbit with remaining lifetime of 25 years (with a tolerance of one year). A small proportion of satellites (~1%) at altitudes > 1400 km were placed in a graveyard orbit above LEO. These satellites were removed from the simulation.

For each scenario (100 Monte Carlo runs), DAMAGE was used to project the reference population into the future by 200 years, taking into account future launch and explosion activity (Table 2). A database holding the results from the LEO and GEO mitigation scenarios was constructed and is available through the ACCORD website (MEO scenarios were not included because no separate guidelines or standards were in existence for this region). The database includes, for each Monte Carlo run, and ordered by scenario):

- The effective number of objects ≥ 10 cm (total, by debris type and in altitude bands)
- The cumulative number of damaging, catastrophic and critical collisions (total and in particular altitude bands)
- The debris spatial density (#/km^3)

The capacity of each mitigation measure was quantified in terms of the percentage reduction in the ≥ 10 cm population in LEO and GEO. These results led to the ranking of the mitigation measures (and combinations of them), in terms of their effectiveness/capacity. In addition, the Normalised Effective Reduction Factor (NERF), was used [10]. This statistic compares the size of the debris population, $N(t)$, at time, t, with the 'worst-case' population, $N_1(t)$, (non-mitigation) and 'best-case' population, $N_2(t)$, (all mitigation measures). The result is a value between zero (not effective) and one (highly effective).

Table 2: Description of the non-mitigation scenario (BASE)	
Parameter	Value
Projection period	1 May 2009 to 1 May 2209
Traffic model (2009-2209)	Repeat 8-year (2001-2009) launch traffic
Future explosions (2009-2209)	Repeat 8-year (2001-2009) explosion cycle
Time-step	5 days
Minimum object size	10 cm
Collision prediction: cube size	10 km

With respect to the LEO results, the 'worst-case' scenario is the non-mitigation scenario (solid black line in Figure 10). In this case, the population increased by 288% over the 200 year projection period. In contrast, the 'best-case' LEO scenario, incorporating all four mitigation measures (solid grey line in Figure 10), resulted in a decrease in the population by 8.0%. The effectiveness of each scenario to reduce the overall LEO debris population by the end of the 200 year projection is shown graphically in Figure 11. The results suggested:

- Implementing fully all four mitigation measures significantly reduces the creation of new space debris in LEO.
- Post-mission disposal is the most effective individual mitigation measure in LEO.
- Passivation and limiting the release of mission related objects have a lesser (although still beneficial) impact on the LEO debris population
- Collision avoidance manoeuvres appear only to have a limited effect on the LEO environment as a whole. However, they remain pivotal to the protection of individual space assets

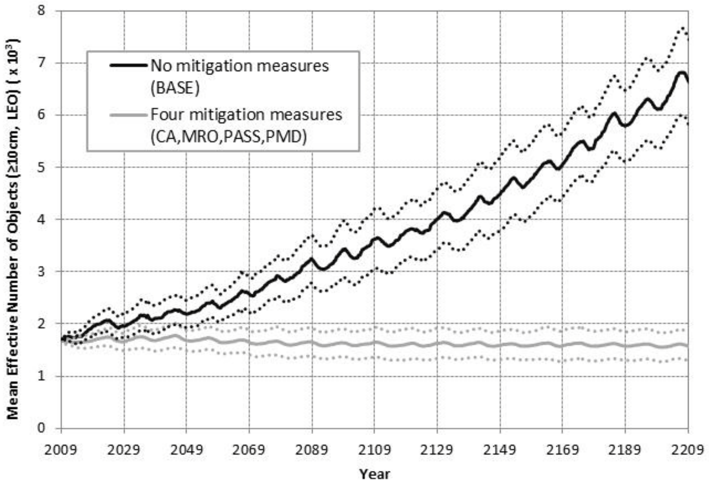


Figure 10 Effective number of objects in LEO (≥10 cm) for the non-mitigation scenario (BASE) and the best-case scenario (CA, MRO, PASS, PMD). Dotted lines represent one standard deviation.

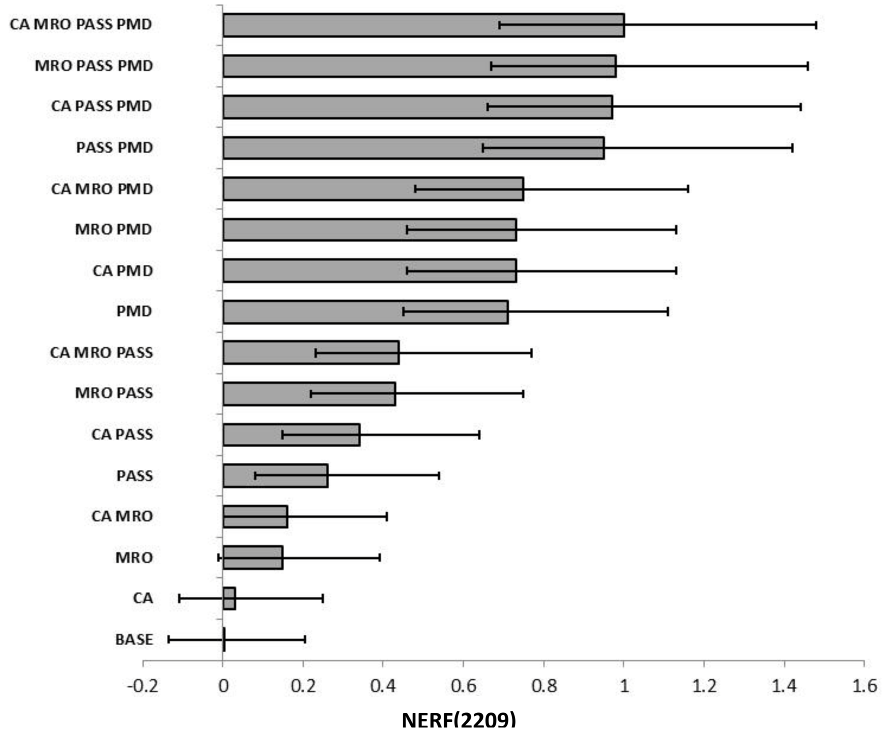


Figure 11 Effectiveness of mitigation measures in reducing the LEO space debris population, based on NERF values calculated for 1 May 2209.

For the assessment of GEO mitigation measures, the population of debris≥10 cm residing or intersecting the GEO regime on 1 May 2009 was used as the initial reference population. These objects were again derived from the MASTER 2009 reference population.

The implementation of individual mitigation measures within DAMAGE scenarios was similar to the implementation used for the LEO study. With respect to the post-mission disposal of GEO spacecraft, these were removed from the geostationary protected region and re-orbited to a higher graveyard orbit as defined by the IADC equation. As before, 100% compliance with each mitigation measure was assumed in order to understand the "best case" outcome. Each mitigation measure was investigated individually and a further scenario, with all mitigation measures implemented simultaneously, was also assessed. This led to six unique scenarios.

In the baseline, non-mitigation scenario (red line in Figure 12), the GEO population increased by 577%. Even in the best-case, full mitigation scenario, the population still increased by 188% over the projection period. The single most effective measure was Post Mission Disposal, producing results comparable to those obtained using full mitigation (population increase of 200%).

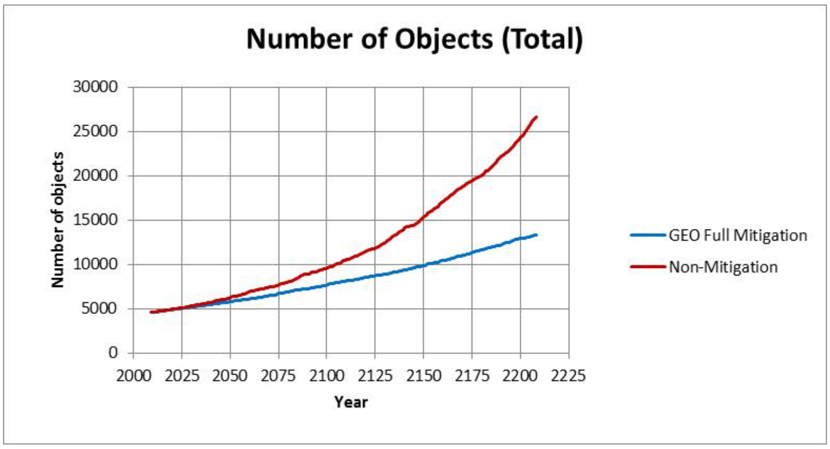


Figure 12 Effective number of objects in LEO (≥10 cm) for the non-mitigation scenario (BASE) and all four combined mitigation measures scenario (CA, MRO, PASS, PMD).

Table 3 Summary of key GEO results.

Scenario short name	Mean population increase (%)	Reduction in population size compared with BASE scenario (%)	NERF
BASE	477.1	0.0	0.0
MRO	492.3	-2.6	-0.052
PASS	467.7	1.6	0.033
PMD	199.9	48.0	0.961
CA	474.7	0.4	0.009
CA,MRO,PASS,PMD	188.6	50	1.0

Implementing fully all four mitigation measures significantly reduces the creation of new space debris in LEO and GEO, and post-mission disposal is the most effective individual mitigation measure in both regions. Given that the survey in WP1 identified this measure as being technically challenging and costly to implement, it is important to ensure that the initiatives identified in WP1 can be realised.

Factors that lead to an increase of space debris

Identifying particular factors which contribute to an increasing debris population is an important step towards the development of methods for Active Debris Removal (ADR) and for reducing collision risk, especially within LEO where the debris hazard is greatest. A particular challenge associated with ADR is in the selection of targets to be removed; debris removal may be most effective when identifying candidate objects which contribute to future collision activity and the growth of the debris population. By considering "close-approach" data recorded by DAMAGE whilst performing the LEO simulations for WP2, key factors were revealed which increase likelihood of collision. Some of these factors were then represented within ADR target selection criteria to assess their relevance for debris remediation.

The results from this task showed that orbital inclination, altitude and eccentricity were key factors in the occurrence of collisions and close approaches (Figure 13). In particular, orbital inclinations of 74°, 81-84°, 86.5° and 97-100°, eccentricities less than 0.04 and altitudes 700-1000 km, were related to an elevated collision probability, potentially leading to the generation of further debris. These orbital characteristics correspond with Sun-synchronous orbits and LEO satellite constellations. Object mass was also recognised as a critical factor in the generation of new debris, as large, intact objects lead to higher numbers of fragments upon collision.

Rocket bodies were identified as the primary contributors to the debris population. Targeting rocket bodies exclusively, for ADR, was as effective as a separate ADR strategy focussed on both rocket bodies and spacecraft. This suggests that ADR vehicles can be designed to remove similar objects from particular orbital clusters without significant loss of effectiveness. ADR targets were shown to be predominantly from Sun-synchronous orbits near 700 km altitude when no restrictions were placed on the target type. In contrast, targets at 83°and 720 km were preferred when removals were restricted to upper stages. Objects here can intersect Sun-synchronous orbits at high speed

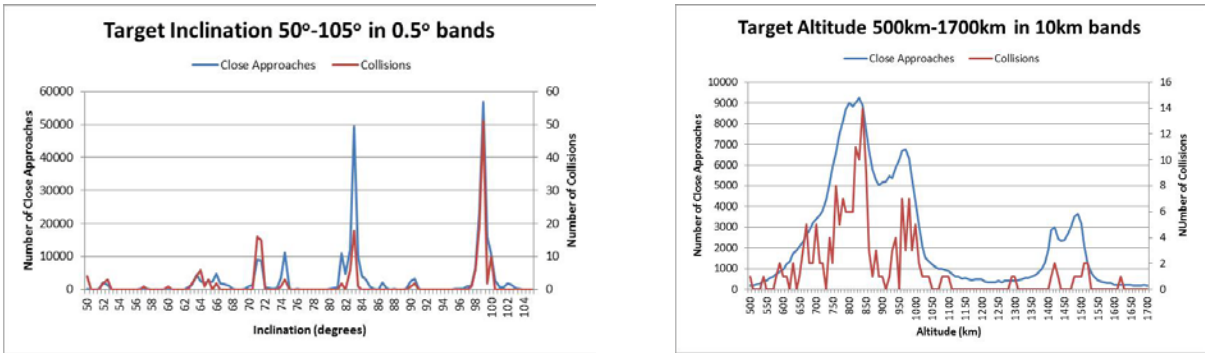


Figure 13 Orbital inclination (left) and altitude (right) of target spacecraft/debris in collisions and close approaches.

4.1.3.3 Communicating the efficacy of space debris mitigation measures

A key part of the ACCORD support action has concerned development of an environmental impact rating (EIR) system with respect to the LEO and GEO space debris environments. Development of the EIR system was the objective of WP3. The ultimate aim of this work is to supply industry with a multi-criteria tool to evaluate how spacecraft design and operation can impact the long-term debris environment, and how the environmental impact of a spacecraft could be improved through modification to design and operation. The EIR system uses indicators for capability (from WP1) and capacity (from WP2) along with other key measures to calculate a rating for a candidate spacecraft. The rating is presented as a score out of 100, whereby a ‘positive’ (beneficial) environmental impact yields a high score.

The individual components of the EIR system are shown schematically in Figure 14. These comprise:

A. A “debris score” for the relevant orbital region
B. The “capacity score” of applied mitigation measures to limit the generation of new debris (from DAMAGE simulations in WP2)
C. A “health score”, summarising how the prospective spacecraft affects the “health” of the relevant orbital region

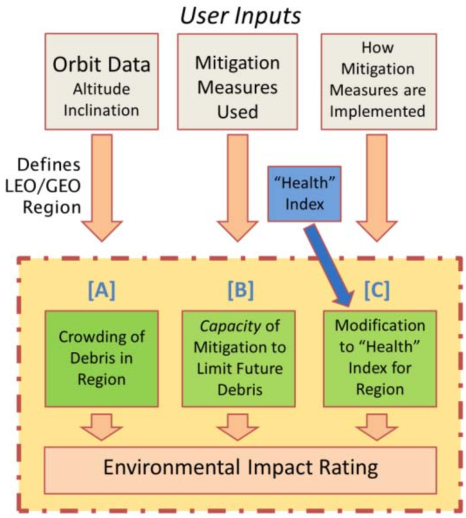


Figure 14 Schematic diagram demonstrating aspects which contribute to calculation of the ACCORD environmental impact rating.

A Space "Health" Index is calculated using a number of desirable traits or 'goals' which describe the "health" of the space environment, yielding a single score. This score is a reflection of the region's ability to support sustainable, long-term space activities (measured with respect to the debris environment) and is based on the compliance of spacecraft with space debris mitigation guidelines and standards. Within this framework LEO and GEO are separated into a broad number of regions based on orbital inclination, altitude (for LEO) and longitude (for GEO). The "health" of a region is measured according to particular *goals* which characterise the maximum "health" of a region and the ability of the region to achieve those goals (measured on a scale of 0 to 1). Two goals were defined: the first is focused on the widespread implementation of mitigation measures in active spacecraft, and the second is defined by the number of non-payload objects present in each LEO/GEO region. To calculate the score, the index uses an estimate of the current $\geq$ 10 cm debris population, together with data describing the typical compliance of satellite manufacturers and operators with mitigation guidelines and good practices. The index thus provides a "health" baseline against which the impact of a future mission may be measured.

The first component of the EIR, the debris score (A), is associated with the orbital region in which the prospective spacecraft is placed (either in LEO or GEO). This score is based upon how "crowded" the region of space surrounding the prospective satellite is, with data taken from ESA's MASTER-2009 debris population. The second component, the capacity score (B), is associated with the effectiveness of the identified mitigation measures to limit the generation of new debris. The Normalised Effective Reduction Factor (NERF, from WP2) was used here to quantify the reduction in the LEO debris population arising through the implementation of a particular combination of mitigation measures, compared with a business-as-usual case. Finally, the health score (C) represents the change to the "health" of an orbital region arising from the launch and deployment of the prospective spacecraft.

Capability metrics quantify the ability of spacecraft operators and designers to implement space debris mitigation measures and are an integral component of the health score. These metrics describe the technical and financial challenges associated with implementing individual measures and were derived from the survey conducted by PHS Space Ltd., whereby respondents from industry assessed the difficulty of implementing measures on a scale between 1 (low difficulty) and 5 (high difficulty) for the technical and cost impacts.

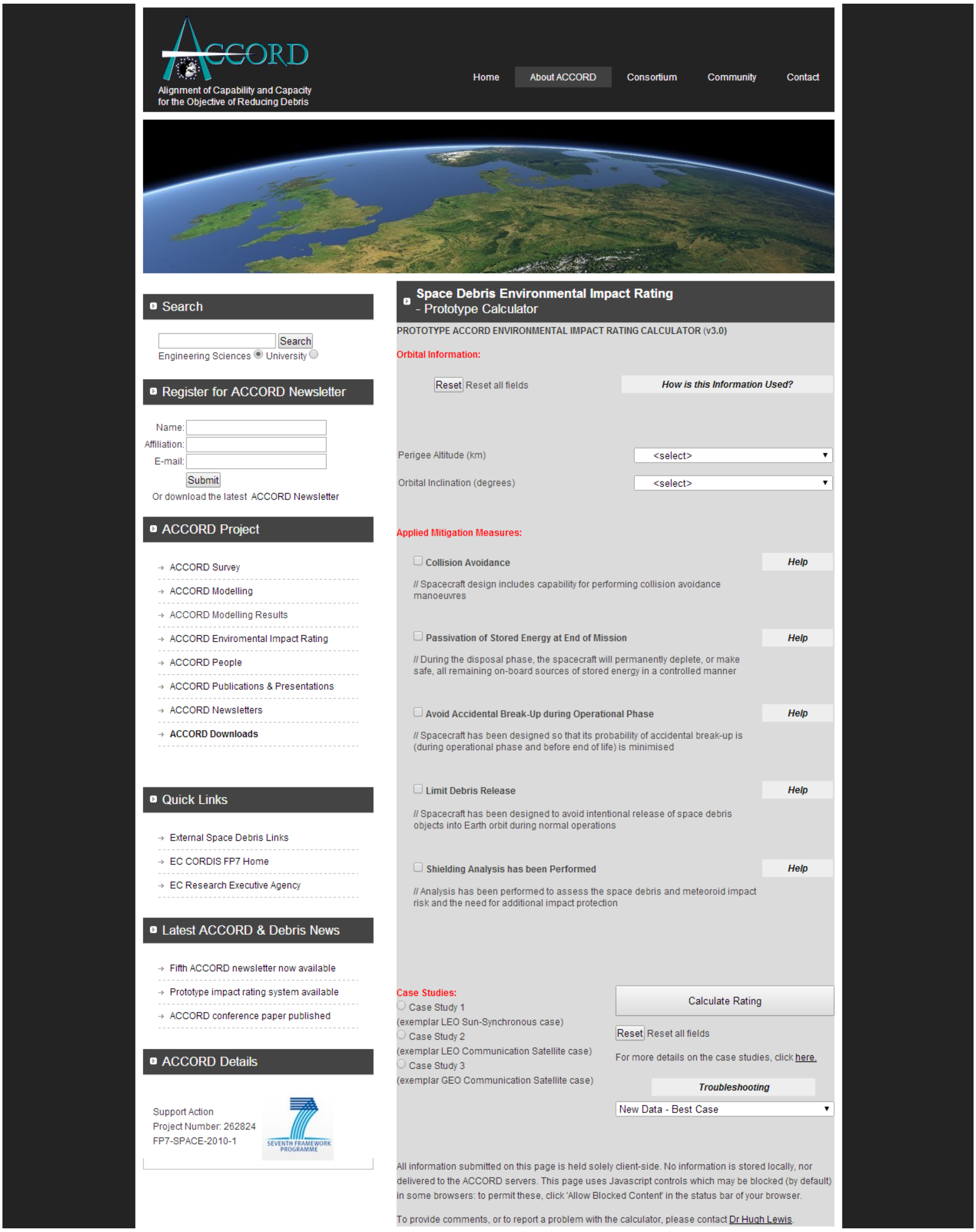
Calibration

The three component scores (A-C) were calibrated to ensure that they and the resulting EIR were meaningful to users of the system and in line with expected values. This was achieved through a testing and feedback process by selected industry partners, identified from those who participated in the survey carried out by PHS Space Ltd. The EIR system, implemented as a web tool, was updated based on the responses received. A feedback database was created to record these responses.

Environmental Impact Rating Web Tool

The final web tool takes the form of a simple webpage with embedded JavaScript functionality (Figure 15). This approach ensures that all calculations are performed client-side (i.e. on the user's computer). The ACCORD EIR web tool is available online at http://www.fp7-accord.eu/rating.

Through a mixture of text-entry boxes and multiple-choice queries on a web page, the EIR tool allows spacecraft manufacturers and operators to enter details of a proposed spacecraft and to see the projected impact on the space debris environment. Results are presented to the user with additional information and suggested actions that will improve the derived environmental rating. The EIR system is supported by a range of documentation including a user guide, exemplar case studies, Frequently Asked Questions and a help system. Users of the EIR web tool are also able to generate a PDF document containing a printer-friendly version of the output. This document is a performance certificate in the style of a commonly used eco-label (Figure 16).



Engineering Sciences ● University ○

Name:
Affiliation:
E-mail:

Or download the latest ACCORD Newsletter

- ACCORD Survey
- ACCORD Modelling
- ACCORD Modelling Results
- ACCORD Enviromental Impact Rating
- ACCORD People
- ACCORD Publications & Presentations
- ACCORD Newsletters
- **ACCORD Downloads**

- External Space Debris Links
- EC CORDIS FP7 Home
- EC Research Executive Agency

- Fifth ACCORD newsletter now available
- Prototype impact rating system available
- ACCORD conference paper published

Support Action
Project Number: 262824
FP7-SPACE-2010-1

Space Debris Environmental Impact Rating
- Prototype Calculator

PROTOTYPE ACCORD ENVIRONMENTAL IMPACT RATING CALCULATOR (v3.0)

Orbital Information:

Reset all fields

Perigee Altitude (km)

Orbital Inclination (degrees)

Applied Mitigation Measures:

☐ **Collision Avoidance**

// Spacecraft design includes capability for performing collision avoidance manoeuvres

☐ **Passivation of Stored Energy at End of Mission**

// During the disposal phase, the spacecraft will permanently deplete, or make safe, all remaining on-board sources of stored energy in a controlled manner

☐ **Avoid Accidental Break-Up during Operational Phase**

// Spacecraft has been designed so that its probability of accidental break-up is (during operational phase and before end of life) is minimised

☐ **Limit Debris Release**

// Spacecraft has been designed to avoid intentional release of space debris objects into Earth orbit during normal operations

☐ **Shielding Analysis has been Performed**

// Analysis has been performed to assess the space debris and meteoroid impact risk and the need for additional impact protection

Case Studies:

○ Case Study 1
(exemplar LEO Sun-Synchronous case)
○ Case Study 2
(exemplar LEO Communication Satellite case)
○ Case Study 3
(exemplar GEO Communication Satellite case)

Reset all fields

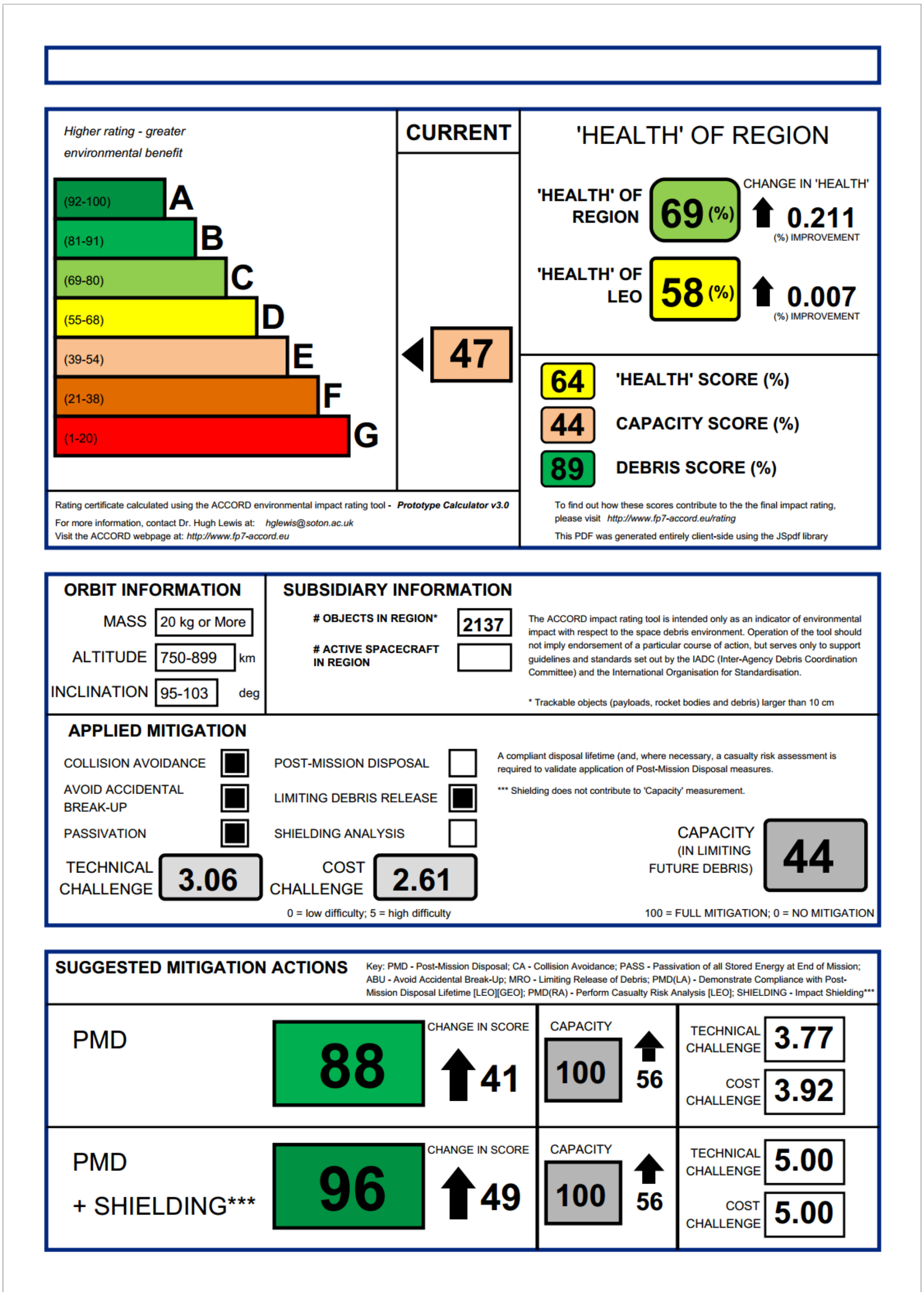
For more details on the case studies, click here.

New Data - Best Case

All information submitted on this page is held solely client-side. No information is stored locally, nor delivered to the ACCORD servers. This page uses Javascript controls which may be blocked (by default) in some browsers: to permit these, click 'Allow Blocked Content' in the status bar of your browser.

To provide comments, or to report a problem with the calculator, please contact Dr Hugh Lewis.

Figure 25 Screenshot of the ACCORD Environmental Impact Rating web tool input page.



Higher rating - greater environmental benefit

Range	Rating
(92-100)	A
(81-91)	B
(69-80)	C
(55-68)	D
(39-54)	E
(21-38)	F
(1-20)	G

CURRENT

◀ 47

'HEALTH' OF REGION

		CHANGE IN 'HEALTH'
'HEALTH' OF REGION	69 (%)	↑ 0.211 (%) IMPROVEMENT
'HEALTH' OF LEO	58 (%)	↑ 0.007 (%) IMPROVEMENT

64	'HEALTH' SCORE (%)
44	CAPACITY SCORE (%)
89	DEBRIS SCORE (%)

Rating certificate calculated using the ACCORD environmental impact rating tool - ***Prototype Calculator v3.0***
For more information, contact Dr. Hugh Lewis at: *hglewis@soton.ac.uk*
Visit the ACCORD webpage at: *http://www.fp7-accord.eu*

To find out how these scores contribute to the the final impact rating, please visit *http://www.fp7-accord.eu/rating*
This PDF was generated entirely client-side using the JSpdf library

ORBIT INFORMATION

MASS 20 kg or More
ALTITUDE 750-899 km
INCLINATION 95-103 deg

SUBSIDIARY INFORMATION

 # OBJECTS IN REGION* 2137
 # ACTIVE SPACECRAFT IN REGION

The ACCORD impact rating tool is intended only as an indicator of environmental impact with respect to the space debris environment. Operation of the tool should not imply endorsement of a particular course of action, but serves only to support guidelines and standards set out by the IADC (Inter-Agency Debris Coordination Committee) and the International Organisation for Standardisation.

* Trackable objects (payloads, rocket bodies and debris) larger than 10 cm

APPLIED MITIGATION

COLLISION AVOIDANCE ☒
AVOID ACCIDENTAL BREAK-UP ☒
PASSIVATION ☒
POST-MISSION DISPOSAL ☐
LIMITING DEBRIS RELEASE ☒
SHIELDING ANALYSIS ☐

A compliant disposal lifetime (and, where necessary, a casualty risk assessment is required to validate application of Post-Mission Disposal measures.

*** Shielding does not contribute to 'Capacity' measurement.

TECHNICAL CHALLENGE 3.06
COST CHALLENGE 2.61
0 = low difficulty; 5 = high difficulty

CAPACITY (IN LIMITING FUTURE DEBRIS) 44
100 = FULL MITIGATION; 0 = NO MITIGATION

SUGGESTED MITIGATION ACTIONS

Key: PMD - Post-Mission Disposal; CA - Collision Avoidance; PASS - Passivation of all Stored Energy at End of Mission; ABU - Avoid Accidental Break-Up; MRO - Limiting Release of Debris; PMD(LA) - Demonstrate Compliance with Post-Mission Disposal Lifetime [LEO][GEO]; PMD(RA) - Perform Casualty Risk Analysis [LEO]; SHIELDING - Impact Shielding***

		CHANGE IN SCORE	CAPACITY		TECHNICAL CHALLENGE	COST CHALLENGE
PMD	88	↑ 41	100	↑ 56	3.77	3.92
PMD + SHIELDING***	96	↑ 49	100	↑ 56	5.00	5.00

Figure 13 Example performance certificate showing the environmental impact rating and additional information.

4.1.3.4 References

[1] Stokes, H., Survey on the Implementation of Space Debris Mitigation Measures in Spacecraft (Final Report), Technical Note for EC FP7 ACCORD Project (# 262824), Issue 1.0, 7 February 2014
[2] ISO 16127:2014, Space systems – Prevention of breakup of unmanned spacecraft
[3] ISO 24113:2011, Space Systems – Space Debris Mitigation Requirements
[4] IADC Space Debris Mitigation Guidelines, IADC-02-01, Revision 1, September 2007
[5] Support to the IADC Space Debris Mitigation Guidelines, IADC-04-06, Issue 1, October 2004
[6] Dissemination Workshop for EC FP7 ReVuS Project (# 262156), Paris, France, 15 October 2013
[7] Stokes, H., Design Rules for Implementing Impact Protection in Unmanned Spacecraft, Technical Note for EC FP7 ReVuS Project (# 262156), Issue 3.0, November 2013
[8] ISO 11227:2012, Space systems – Test procedure to evaluate spacecraft material ejecta upon hypervelocity impact
[9] The CubeSat Program, Cal Poly SLO, CubeSat Design Specification, Revision 12, 1 August 2009.
[10] Lewis, H.G., Swinerd, G.G., Newland R.J., Arrun S., 2009, Active removal study for on-orbit debris using DAMAGE, *Fifth European Conference on Space Debris*, Darmstadt, Germany

4.1.4 Potential impact

The impacts (and potential impacts) of the ACCORD project were seen in four areas: the economy, knowledge, people and society (Figure 17).

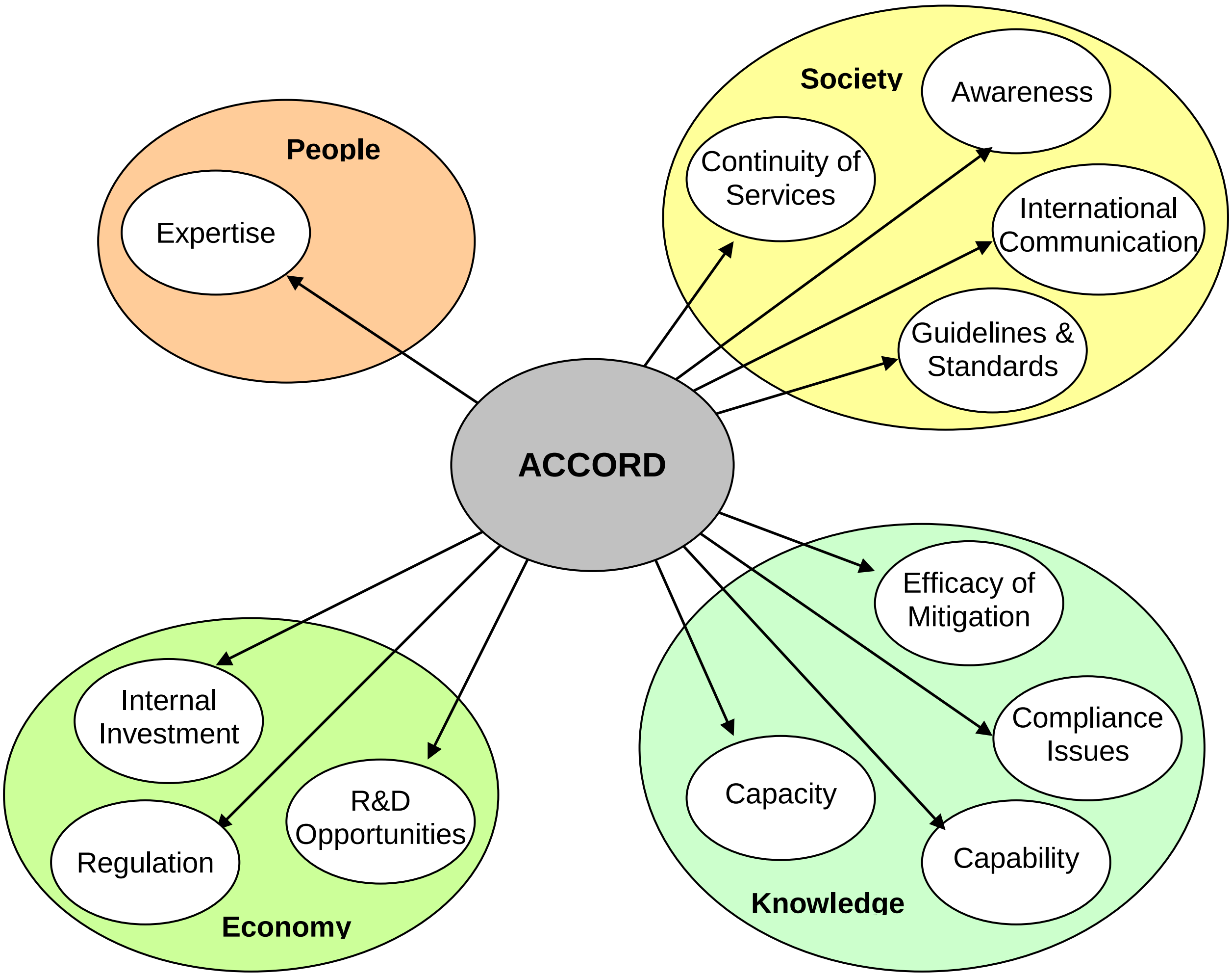


Figure 17 Impacts from ACCORD.

4.1.4.1 Socio-economic and wider societal impacts

Impacts on the economy

Through a survey of European and international spacecraft manufacturers and operators, the ACCORD project has identified compliance issues with debris mitigation guidelines and standards. These issues arise because of technical and financial reasons. The diagnosis of these issues has enabled the ACCORD project to identify important European R&D requirements, thereby providing an incentive for earlier and more complete adoption of debris mitigation guidelines and standards. In the longer-term, the awareness, knowledge and tools developed during the ACCORD project will directly support the activities of the IADC, ISO United Nations and other organisations in their efforts to encourage mitigation compliance. As such, the indirect impact of this Support Action will be to reduce the creation of space debris and thereby reduce the risks to spacecraft operating within the near-Earth space environment. The direct and indirect support provided by ACCORD will have financial benefits for the space industry at European and international level.

ACCORD has encouraged further investment by the European space industry to develop solutions to the space debris problem, by raising awareness of the steps they can take and the R&D needed to reduce spacecraft vulnerability. This has been achieved via the use of a simple Environmental Impact Rating system that delivers such information clearly and concisely to industry users. The Support Action has complemented work in the field of space situational awareness, and other research by ESA (e.g. within its Clean Space initiative) and across Europe. This coherent and effective approach has been enabled by a series of dissemination activities by the ACCORD consortium focused on the transfer of important knowledge coming out of the ACCORD project into these other research activities. This should encourage returns from future R&D investments and enhance the competitiveness of European industry.

The publication of space debris mitigation guidelines and standards in the past decade, by organisations such as the IADC, ISO and the UN, has provided the space industry with a clear set of goals to ensure the Earth orbital environment remains safe and usable for future generations. Industry has access to clear, measurable, and verifiable requirements and methods for realizing these goals. The availability of such documents places a significant expectation on industry such that, increasingly, manufacturers and operators will have to demonstrate the compliance of their spacecraft. The ACCORD Support Action has provided a mechanism for facilitating the interaction between industry and the bodies responsible for authorizing space launches. In addition, the knowledge gained from activities in WP1, WP2 and WP3 has been introduced into the technical discussions at the IADC, ISO and UN. This is already having a bearing on endeavors to update and improve mitigation guidelines and standards, to introduce a similar framework for remediation (including Active Debris Removal) and to initiate discussions on the regulation of CubeSats.

Impacts on knowledge

Debris mitigation guidelines and standards are both subject to periodic reviews to ensure they remain accurate and up-to-date. The review processes are at their most effective when data has been compiled on how the guidelines and standards have been implemented in practice, i.e. within space programmes. Currently, no formal mechanism is available for compiling and evaluating such data across the industry. Instead the data is collected in a piecemeal fashion. Thus, the data gathered and knowledge extracted during the ACCORD Support Action will now greatly assist those engaged in the periodic reviews and lead to consistent, robust guidelines and standards that are appropriate for future space activity. In addition, an understanding of the overall effectiveness of mitigation practices at European and international levels have been gained, as well as at the much finer level of a particular spacecraft. This multi-level understanding now provides a coordinated and coherent approach to international discussions in the context of space debris.

The knowledge of factors potentially leading to increased debris, gained from the tasks outlined in WP2, is supporting new and evolving research efforts directed at active debris removal. In particular, this knowledge has been critical in the assessment of the Ion-Beam Shepherd (IBS) removal method conducted for the FP7 LEOSWEEP project: in order to reduce the financial and technological demands placed on the IBS method (and any other debris removal architecture) there will be a requirement to target spacecraft or upper stages that are likely to contribute to future collisional activity. Consequently, the understanding of factors that enhance collision risk made available through ACCORD has provided a way to establish robust removal criteria.

Impacts on people

Four researchers (White, Blake, Schwarz and George) were employed at the University of Southampton during (and by) the ACCORD project; all have benefited from exposure to the ideas and concepts of ACCORD and from the interaction with industry. On the completion of his role within the ACCORD project, one researcher (Blake) commenced a PhD project looking at modelling issues raised by ACCORD. Through project tasks and dissemination activities, the researchers have generated contacts within the space industry, presented on the ACCORD project at international conferences, workshop and meetings, and have contributed to on-going research efforts in this domain. After leaving the ACCORD project, White was employed at the University to work on a space debris-related ESA contract, whilst Schwarz and George were employed on the FP7 LEOSWEEP project. The knowledge and expertise gained by these ACCORD members will benefit the community of space debris researchers if they choose to remain working within this field.

Through its established courses on Spacecraft Systems Engineering, the Astronautics Research Group at the University of Southampton regularly takes the opportunity to inform professionals within the space industry about the space debris problem. Since the commencement of the ACCORD project, Dr Lewis has delivered space debris lectures on three courses to industry professionals at its campus in Southampton, and on six courses to ESA staff at the ESTEC site. This activity has provided an important dissemination route for the knowledge gained from the ACCORD Support Action, in particular the findings from WP1 and WP2, which were used to provide important details about debris mitigation for half of the courses. Ultimately, these professional engineers, managers (and others) will be more conversant with debris mitigation guidelines, standards, and compliance issues; they will drive future R&D investment and efforts to tackle the space debris problem.

Dr Lewis also teaches undergraduate students on the Aeronautics and Astronautics degree courses at the University of Southampton. In particular, he teaches on the topic of space debris. Results from the tasks in the ACCORD project's WP2 were used directly in the lecture materials for the module “Astronautics” in the academic years 2011-12, 2012-13 and 2013-14 (approximately 60 students in total). The materials will be supplemented with results from WP1 for use within a new lecture module to be introduced in academic year 2014-15, entitled “Spacecraft Concurrent Design”. This module focuses on the design of an active debris removal spacecraft and features discussions of sustainability and sustainability issues. A fundamental part of the module will be to understand the design drivers coming from space debris mitigation guidelines and standards. A very high percentage of students on the Aeronautics and Astronautics are ultimately employed as graduate engineers in the aerospace industry. A significant proportion goes on to the space industry or takes on further space-related studies at other institutions. Their awareness of space debris issues, mitigation guidelines and standards (and corresponding technical and financial issues), means that they can and do become ambassadors for sustainability and debris mitigation.

Impacts on society

The ACCORD survey has revealed that some spacecraft manufacturers and operators are already able to demonstrate that their spacecraft comply with space debris mitigation guidelines and standards. However, the picture is not uniform across the industry and this is, perhaps, especially true for the CubeSat community. The situation is also complicated by the fact that each space faring nation has its own approach for authorizing the launch of a spacecraft. This means that consideration of debris mitigation, and the adoption of guidelines or standards, can vary significantly from country to country in spite of the fact that the guidelines have been in place for over a decade. ACCORD has provided a mechanism, through its Environmental Impact Rating system, to harmonise the information exchange at international level. ACCORD will potentially lead to a European common practice and, ideally, one that is adopted at an international level. Indeed the project could be a key step in supporting the development of an EU space debris mitigation policy as part of a wider EU policy relating to the preservation of the near-Earth space environment. A logical consequence of this would be for the policy to be promoted internationally through multi-lateral fora, such as the IADC, ISO and UN-COPUOS, and via bi-lateral arrangements, such as the EU-US space dialogue.

More widely, ACCORD will indirectly affect the quality of life of European citizens due the improved compliance with debris mitigation guidelines and standards it has encouraged (and continues to encourage), which will limit the growth of the debris population. Limiting this hazardous population will ultimately reduce the vulnerability of space assets providing services to the European Community (e.g. communications, navigation, and Earth observation), which are now embedded within our technological infrastructure.

ACCORD has raised awareness of the space debris problem and solutions among European citizens through its dissemination, outreach and public engagement activities. For example, the Astronautics Research Group at the University of Southampton has developed a flexible, interactive exhibit of the Group's research, incorporating activities focused on space debris. In particular, the DAMAGE simulations performed for ACCORD WP2, now running on touch-screen PCs, provide a visual, interactive exhibit (Figure 18 and Figure 19). At the same time, the ACCORD Environmental Impact Rating system now satisfies an important educational and outreach role, as it is available to students of all ages through the World Wide Web. Use of the EIR system has already been embedded within the new Spacecraft Concurrent Design module to be taught by Dr Lewis from 2014 onwards. The system will also provide a new interactive game for use in future outreach and public engagement events.

Figure 18 The Astronautics Research Group exhibition at the University of Southampton's Science and Engineering Day (March 2014). DAMAGE simulations used for the ACCORD project, running on a touch-screen PC (circled), provided an interactive exhibit. ACCORD researcher Simon George (centre, in red) is also shown explaining some of the Group's other research activities.

Figure 19 The Astronautics Research Group exhibition at the University of Southampton's Science and Engineering Day (March 2013). ACCORD researchers Simon George (right, in white) and Adam White (far right, in blue) demonstrating the space debris remover robot to visitors.

4.1.4.2 Main dissemination activities and the exploitation of results

The following lists identify the main dissemination (articles and presentations), outreach and public engagement activities during the project.

Articles

- Hugh Lewis, Simon George, Benjamin Schwarz, Hedley Stokes, **Space Debris Environment Impact Rating System**, 6th European Conference on Space Debris, Darmstadt, Apr 2013.
- Hugh Lewis, Adam White, Richard Crowther, Hedley Stokes, **Synergy of Debris Mitigation and Removal**, Acta Astronautica vol. 88 issue 1, Dec 2012.
- Hugh Lewis, Hedley Stokes, Adam White, **Debris Mitigation Capability and Capacity to Reduce Orbital Debris**, International Astronautical Congress, Naples, Oct 2012.
- Hugh Lewis, Adam White, Hedley Stokes, **The Effectiveness of Space Debris Mitigation Measures**, 16th Annual International Space University Space Sustainability Conference, Feb 2012.
- Hugh Lewis, Adam White, Hedley Stokes, **Synergy of Debris Mitigation and Removal**, International Astronautical Congress, Cape Town, Oct 2011.
- Hugh Lewis, Hedley Stokes, Clint Styles, **ACCORD – Alignment of Capability and Capacity for the Objective of Reducing Debris**, EU FP7 Space Conference, Budapest, May 2011.

Presentations

- Clean Space Workshop (Harwell, UK), Oct 2013.
- UK Space Conference (Glasgow, UK), Jul 2013.
- 6th European Conference on Space Debris (Darmstadt, Germany), Apr 2013.
- Defence, Science & Technology Laboratory workshop on Space Situational Awareness (invited), International Space Innovation Centre (Harwell, UK), Feb 2013.
- January 2013: Visit from Chief Executive and Chief Engineer from UK Space Agency (University of Southampton).
- Appleton Space Conference (Rutherford Appleton Laboratory, Harwell, UK) Dec 2012 (invited).
- Faculty of Engineering and the Environment EngD Conference (University of Southampton, UK), Nov 2012 (invited).
- International Astronautical Congress (Naples, Italy), Oct 2012.

- 2nd European Workshop on Active Debris Removal (CNES HQ, Paris, France), Jul 2012.
- Inter-Agency Space Debris Coordination Committee, Montreal, May 2012
- UKSEDS Conference (University of Kent, Canterbury, UK), Mar 2012 (invited).
- 16th Annual International Space University Space Sustainability Conference, Feb 2012.
- European Cooperation for Space Standardisation Space Debris Working Group, Paris, May 2011 and Sep 2011.
- International Organization for Standardisation Orbital Debris Coordination Working Group, Berlin, May 2011.
- Inter-Agency Space Debris Coordination Committee, Berlin, Apr 2011.

Outreach and public engagement events

- March 2014: Southampton Science & Engineering Festival 2014, Astronautics Research Group stand (University of Southampton)
- January 2014: Stargazing Live, Astronautics Research Group stand (University of Southampton)
- March 2013: Big Bang Solent Science Fair, Astronautics Research Group stand (University of Southampton)
- March 2013: Science & Engineering Day 2013, Astronautics Research Group stand (University of Southampton)
- January 2013: Learn With US, School Year 8 Workshops on ‘Space Systems Engineering’ activity (University of Southampton)
- January 2013: Stargazing Live, Astronautics Research Group stand (University of Southampton)
- September 2012: Bestival 2012 (Isle of Wight, UK), Astronautics Research Group stand [University of Southampton ‘Bringing Research to Life’ Roadshow]
- July 2012: Farnborough International Air Show 2012, Astronautics Research Group stand
- July 2012: 60@60 Community Open Day, Astronautics Research Group stand (University of Southampton)
- May 2012: InTech Science Centre (Hampshire, UK), Astronautics Research Group stand [University of Southampton ‘Bringing Research to Life’ Roadshow]
- April 2012: Big Bang Regional Science Fair (Ageas Bowl; Hampshire, UK), Astronautics Research Group stand [University of Southampton ‘Bringing Research to Life’ Roadshow]
- March 2012: Science & Engineering Day 2012, Astronautics Research Group stand (University of Southampton)
- January 2012: Learn With US, School Year 8 Workshops on ‘Space Systems Engineering’ activity supervisor (University of Southampton)
- March 2011: Science & Engineering Day 2011, Astronautics Research Group stand (University of Southampton)

Engagement with the media

During the life of the project, Dr Lewis engaged with the media to discuss and comment on space debris issues (although none of these items were associated specifically with the ACCORD project):

- BBC News Website (2011): http://www.bbc.co.uk/news/science-environment-14763668
- BBC World News Report (BBC TV, 2011)
- Discovery News Website (2012): http://news.discovery.com/space/history-of-space/sace-junk-carbon-dioxide-hazard-121111.htm

- Space Safety Magazine (2012): http://www.spacesafetymagazine.com/2012/11/12/climate-change-increases-space-debris-longevity/
- BBC News 24 (BBC TV, 2013)
- Warner Brothers Home Entertainment (2013), “Collision Point: the race to clean up space” DVD and Blu-ray special feature included with the film “Gravity”.