SPACE DEBRIS ENVIRONMENT IMPACT RATING SYSTEM

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ABSTRACT

As part of the European Union Framework 7 ACCORD (Alignment of Capability and Capacity for the Objective of Reducing Debris) project, concepts for an environmental impact rating system for the space environment have been devised, and details of a candidate prototype system are presented and discussed in this paper. The system aims to combine the capacity of mitigation measures to reduce the future debris population and the capability of industry to apply such measures. Using a holistic index of "health" of the space environment, the rating system subsequently produces a single score reflecting the impact of a candidate spacecraft on the environment. The system focuses on the state of the debris environment, the implementation of mitigation measures, and also takes into account the cost and technical difficulty associated with applying mitigation measures. The goal is to supply industry with a tool to evaluate how spacecraft design and operation can impact the long-term debris environment, and how improvements in environmental impact may be obtained through modification of these factors.

1 INTRODUCTION

Operation of space missions in a variety of important regions of Earth orbit is necessary for deriving maximum return from space assets for a wide range of users and investors. However, the space debris environment typically represents a significant risk to space operations and renders such assets vulnerable to the persistent threat of collision. The route to long-term, sustainable use of space is dependent on forging a balance between the drive to launch and operate important missions in Earth orbit and maintaining efforts to ensure the sustainability of such operations in a risk environment.

It has been shown [1] that the implementation of a number of mitigation practices can limit the increase in the debris population in the long term. Through funding from the European Union Seventh Framework Programme (FP7), the Alignment of Capability and Capacity for the Objective of Reducing Debris (ACCORD) project supports on-going research of the benefits provided by mitigation measures and the challenges involved in implementing them in spacecraft design and operation. In particular, this support activity is focused on quantifying the efficacy of current mitigation practices, communicating these results to spacecraft manufacturers and operators and strengthening European capability in this area. The objectives of the ACCORD project are four-fold:

1. Surveying the *capability* of industry to implement debris mitigation measures, and identifying existing and future challenges
2. Quantifying the *capacity* of mitigation measures to reduce debris creation
3. Combining *capability* and *capacity* indicators within an *environmental impact rating* system to provide a quick and simple means of quantifying the ability of a spacecraft to implement debris mitigation measures, whilst taking into account the environmental effectiveness of those measures
4. Disseminating the findings to stakeholders

In this work, the ACCORD consortium (comprising a UK team composed of the University of Southampton and PHS Space Ltd.) introduces preliminary results from the development of an environmental impact rating system for spacecraft in the context of the debris environment and the implementation of debris mitigation measures. A number of concepts for a rating system have been considered, and a set of key criteria have been identified (against which environmental impact may be measured). A prototype candidate system has been developed and some initial testing using exemplar spacecraft has been performed. 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.

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The prototype system uses indicators for *capability* and *capacity* 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 prototype system is directed at stakeholders within both public and private sectors from across Europe to support continuing efforts to address the growth of the space debris population and to encourage further investment for the future. Engagement with industry and the debris community is anticipated in order to improve the prototype system.

2 DEVELOPMENT OF PROTOTYPE SYSTEM

There is currently an increasing interest within the space community to establish methods of describing the environmental impact of spacecraft. Many of these systems have been motivated by the need to identify suitable targets for Active Debris Removal (ADR). In particular, ESA's Clean Space initiative promotes awareness of the environmental impacts of space activities on both Earth and the orbital environment; this involves the assessment of ESA's efforts to minimise negative impacts on these environments in four domains: Eco-design, green technologies, space debris mitigation and technologies for space debris remediation. In addition, an approach to Life Cycle Assessment for spacecraft is discussed by [2], including discussion of figures of merit and particular metrics.

The prototype ACCORD space debris environment impact rating has its basis in systems and indices that are operated in other industries. For example, in energy-efficiency ratings for household appliances (ecolabelling), life cycle assessment of vehicles or environmental impact assessment of buildings. The system comprises two stages, demonstrated schematically in Fig. 1: a Space "Health" Index, and an Environmental Impact Rating System. Within this framework, the LEO environment is divided into distinct regions and the "health" of these regions is examined.

The 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 (currently measured with respect to the debris environment). To calculate this score, the index uses an estimate of the current $\geq$ 10 cm debris population, together with data describing the 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.

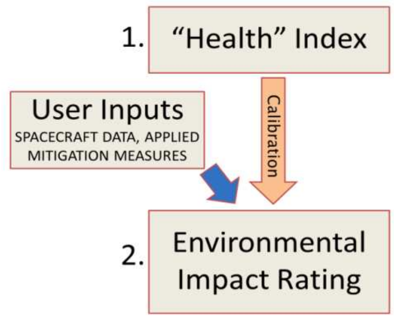

Figure 1. Schematic diagram depicting the primary stages of the space debris environment rating process

The subsequent aspect of the system is associated with the calculation of the environmental impact rating. At this stage, a future spacecraft may be rated for its ability to improve the "health" of its local LEO region based on performance with respect to a number of key goals based on compliance with mitigation guidelines and practices. The calculation is performed through a multiple-criteria algorithm which combines data on the current implementation of mitigation measures within industry (obtained through the use of an industry survey conducted by PHS Space Ltd. [1]) and results obtained using the University of Southampton's evolutionary model, the Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) [3].

The finalised ACCORD environmental impact rating system will be a voluntary, interactive, web-based tool for use by industry stakeholders, developed in order to improve engagement with spacecraft manufacturers and operators and to encourage increased compliance with mitigation practices. With this in mind, efforts were made to avoid significant complexity in construction of the prototype system, to provide a platform for further development and future iterations of the system, following feedback from the community and industry.

2.1 Space "Health" Index

The approach described here represents an initial effort to generate a measure of the current "health" of the LEO environment. By considering key traits and measurements of the environment, a unique score is derived which provides the basis for understanding how future spacecraft will impact on the "health" of the region.

To calculate the "health" index, the LEO environment was divided into 35 regions. These regions were differentiated according to 5 inclination bands and 7 altitude bands (Tab. 1). The inclination bands were chosen using definitions used within the Union of Concerned Scientists' Satellite Database, and the altitude bands were divided according to the distribution in the perigee altitudes of current active satellites.

Table 1. Definition of LEO altitude/inclination bands

Inclination (°)		Perigee Altitude (km)
Equatorial	0-19	100-449
Intermediate	20-84	450-599
Polar	85-94	600-749
Sun-Synch.	95-103	750-899
Retrograde	104-180	900-1049
		1050-1399
		1400-1700

The environment traits used to establish the preliminary "health" index were focused on key aspects of the space debris environment:

- The number of debris objects
- The level of implementation of mitigation measures and good practices amongst manufacturers & operators, relating to:
    - Post-mission disposal (PMD)
    - Passivation
    - Limiting the release of mission-related objects (MROs)
    - Collision avoidance
    - Impact shielding
- The technical and financial challenges of applying mitigation measures

The technique adopted to calculate the space "health" index follows a method similar to that of the Ocean Health Index [4]. Desirable *goals* are defined which characterise the ideal, best "health" of a region, and the ability of the region to achieve those goals is measured on a scale of (0-1). The score for a region is then calculated from the average of the present status (in achieving the defined goals) and a predicted 'near-future' status, to derive a score (from 0-1) for each LEO region. A score for the "health" of the full LEO environment is then derived by calculating the average over all regions. Scores are communicated as a percentage.

Following the method described by [4], the *present status* of a goal, x, is calculated relative to a specified (and current) reference point. The predicted 'near-future likely status', x', is then

$$x' = x[1 + \beta T + (1 - \beta)(R - C)], \quad (1)$$

where T is the change of the status, or trend, over the preceding five years (expressed as a percentage), R and C are the weighted average of *resilience* and *pressure* indicators, respectively [4], and β is a weighting factor (0.67) that favours the historical trend.

Resilience indicators are factors that facilitate a goal. For example, the existence of well-defined and supported mitigation guidelines for LEO spacecraft encourage compliance. Pressure indicators are factors that impede movement towards a goal and are primarily associated with technical and financial challenges of applying mitigation measures. The resilience and pressure indicators are represented numerically, with values between zero (no effect) and one (strong effect). A diagram showing how these components contribute to the goal is shown in Fig. 2.

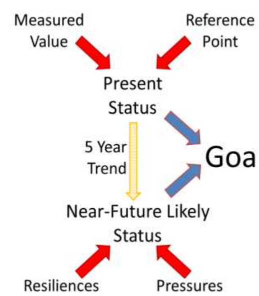

Figure 2. Diagram demonstrating the components which contribute to the measurement of a single goal.

Table 2. Construction of Space "Health" Index

Goal	Sub-Goal	Value	Resilience Indicators	Pressure Indicators
1. Widespread Implementation of Mitigation Measures	1A. Protection of Services	Percentage of spacecraft in region applying mitigation measures (shielding, CA) *[ACCORD survey]* Reference: 100% compliance for all spacecraft in region	Availability of data, tools, techniques and supporting guidelines	1. Technical challenge of applying relevant mitigation measures in design & operation; *[ACCORD survey]* 2. Monetary challenge of applying relevant mitigation measures in design & operation; *[ACCORD survey]*
	1B. Legacy of Services	Percentage of spacecraft in region with mitigation measures (PMD, PASS, MRO) *[ACCORD survey]* Reference: 100% compliance for all spacecraft in region	Availability of data, tools, techniques and supporting guidelines	
2. Benign Space Debris Environment		Number of debris objects in region *[MASTER 2009]* Reference: Number of objects in region in 2009 population	Compliance with mitigation guidelines *[ACCORD SURVEY]*	

Two principal goals were identified. Details of these goals and their constituents are presented in Tab. 2.

2.1.1 Goal 1: Widespread Implementation of Mitigation Measures

Goal 1 is focused on the current implementation of mitigation measures in active spacecraft and on the challenges existing in implementing these in spacecraft design and operations. It is formed of two sub-goals, *Protection of Services* (1A) and *Legacy of Services* (1B), which are defined according to the level of compliance with, or implementation of, mitigation measures among manufacturers and operators. Sub-Goal 1A focuses on mitigation measures and design practices that are aimed at avoiding loss during operations, whereas Sub-Goal 1B focuses on mitigation measures that are implemented to preserve the space environment.

Data on compliance and implementation of these measures and practices were obtained through the ACCORD survey. These data determine the proportion of operators (from all respondents) currently implementing each measure, or whether they expect to do so in the future. The former provides the present status whilst the latter establishes the trend and, therefore, contributes to the near-future likely status. The reference (ideal) point for both of these sub-goals was 100% compliance in the LEO region with all mitigation measures (PMD, passivation, limiting the release of MROs, collision avoidance and shielding).

For these sub-goals, the sole resilience indicator used was the availability of well-defined mitigation guidelines, standards or other best practices. As there are many such guidelines for LEO, this indicator was set to 1. Pressure indicators for these goals were represented by the cost and technical difficulty of applying each mitigation measure within the design or operation. These indicators were derived from the ACCORD survey, in which the cost and technical difficulty were rated on a scale from one (low difficulty) to five (high difficulty), averaged over the mitigation measures relevant to that goal and normalised to provide the pressure indicator value.

2.1.2 Goal 2: Benign Space Debris Environment

Goal 2 considers the "health" of the debris environment in terms of the number of non-payload objects present in each LEO region, and future trends. As a reference point, the Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) 2009 population of objects ≥ 10 cm was used to provide the baseline. The DAMAGE tool was used to derive the short-term trend data, based on a single Monte-Carlo projection from 1 May 2009 through 1 May 2014, in which no mitigation was applied and in which there were no collisions.

As before, the technical difficulties associated with the implementation of debris mitigation measures were quantified and the average (across all the measures considered) was used as a pressure indicator. The requirement for active spacecraft to comply with mitigation guidelines and/or standards was used as a resilience indicator for this goal.

Using the technique presented with the data currently available, a "health" index for the LEO space environment of 58% was derived, comprising of the average of the individual region scores presented in Tab. 3.

2.2 Environmental Impact Rating

Following the development of a prototype "health" index for the LEO environment, first efforts have been made to develop a system which can be used by satellite manufacturers & operators to calculate the environmental impact rating of a prospective spacecraft mission. The prototype rating system currently uses the following simple manufacturer inputs to calculate the rating of a proposed spacecraft:

- On-orbit mass
- Perigee altitude

Table 3. "Health" index scores for LEO regions

		Inclination (degrees)				
		0-19	**20-84**	**85-94**	**95-103**	**104-180**
Perigee Altitude (km)	**100-449**	0.309940	0.704183	0.730048	0.728120	0.730876
	450-599	0.729115	0.694829	0.724832	0.721108	0.313592
	600-749	0.729378	0.702418	0.722517	0.707206	0.313512
	750-899	0.312958	0.697571	0.723341	0.695169	0.313574
	900-1049	0.312944	0.709064	0.311909	0.725773	0.313546
	1050-1399	0.312927	0.720217	0.729357	0.723162	0.730865
	1400-1700	0.313496	0.713579	0.313557	0.724246	0.313698

- Orbital inclination
- Mitigation measures implemented
- How individual measures are implemented in the design

These inputs, together with the baseline provided from the "health" index, are used to calculate three aspects of the environmental impact rating:

a. A debris score for the relevant orbital region (*how "crowded" the region is*)
b. The capacity of applied mitigation measures to limit the generation of new debris (*from DAMAGE simulations* [1])
c. How the prospective spacecraft affects the "health" index in the relevant orbital region (*determined by re-calculating the "health" index*)

The combination of these individual scores provides the final environmental impact rating for the prospective satellite, expressed as a score out of 100. The maximum environmental benefit is denoted by a high score, whereas a low score reveals little environmental benefit. The contribution of the individual aspects to the environmental impact rating is shown schematically in Fig. 3.

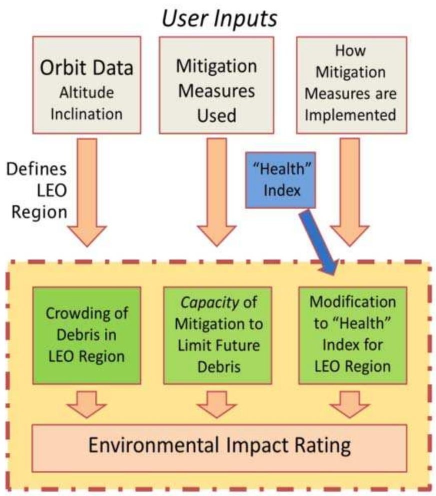

Figure 3. Schematic diagram demonstrating aspects which contribute to calculation of the impact rating

The first rating parameter (a) is associated with the operating region of the spacecraft, whereby the user-determined altitude and inclination place the prospective spacecraft into one of the 35 pre-determined orbital regions. A score is assigned based upon the number of debris objects present in this region (determined from the MASTER 2009 population).

User-supplied information on the applied mitigation measures and design practices contribute to the remaining two aspects of the rating, associated with the effectiveness of the identified mitigation measures (b) and the resulting modification of the "health" index (c) of the operating region (due to the addition of the user's spacecraft).

The capacity of mitigation measures to limit the generation of new debris was calculated using a separate DAMAGE study to evaluate four key mitigation measures (and combinations) [5]:

1) Limiting the release of mission-related objects
2) Passivation of spacecraft at end of mission life
3) Performing collision avoidance manoeuvres for operational spacecraft
4) Post-mission disposal of spacecraft and rocket bodies according to the "25-year" rule.

The capacity of each measure to reduce debris was quantified using a Normalised Effective Reduction Factor (NERF), which quantified the reduction in the LEO debris population compared with a baseline, non-mitigation case. The NERF is delivered in the range [0, 1], whereby the baseline, non-mitigation case produces a value of 0 and the best mitigation scenario (where all four measures are implemented with an assumed 100% compliance or success) produces a value of 1. Details of this process, and a full list of NERF values is provided in [5].

To determine how a prospective satellite will affect the "health" index of the relevant orbital region (c), specific details of how the mitigation measures and design practices are implemented are collected from the user. These inputs are similar to those requested by the ACCORD survey [1] and are, thus, used to modify the "health" index. More precisely, these inputs modify measured values of sub-goals 1A and 1B and affect the resilience indicator for the Goal 2. The change in "health" of the region occupied by the prospective spacecraft is then compared with the maximum change possible for an ideal spacecraft.

In addition to the environmental impact rating, two other indicator values are calculated and communicated to the user: firstly, the change in the overall health of the LEO environment as a result of adding the proposed spacecraft (with the applied design), and secondly the increase in the number of ≥ 10 cm objects in the operating region if it were to be involved in a catastrophic collision with an average-mass object from that region. The first indicator is calculated using revised calculation of the "health" index and the second indicator is determined from an implementation of the NASA breakup model [6].

Finally, the environmental impact rating system provides the user with an indication of how improvements to the rating (and, hence, increased benefits for the space environment) could be achieved through the application of further mitigation measures.

These recommendations are provided with an indication of the expected cost and associated technical impact.

An alpha-numerical score, designed to reflect the results in a straightforward manner, is used to relay the output of the environmental impact rating system to the user. In this respect, the prototype system assumes an environmental rating scored out of 100, following the method of the "health" index. This scheme is augmented through the use of colours (red to green) and the full information set can be ultimately presented in the form of a performance certificate.

3 PRELIMINARY RESULTS

The calibration of the rating system is vital, in order to maintain the relevance and applicability of the environmental impact rating system to industry stakeholders and users. The final system must be balanced to ensure that modifications made by the user to the input parameters (for example, to reflect the implementation of mitigation measures) will update the calculated rating in an appropriate fashion, based on the estimated improvement to the debris environment. To this end, an exemplar spacecraft was selected in order to test the system and to provide an initial calibration.

The exemplar was a generic Earth observation spacecraft, mass 1000 kg, placed in a sun-synchronous orbit with perigee altitude of 795 km and inclination of 97°. No efforts to replicate any past, or existing, spacecraft were made in selection of the exemplar. It was assumed that the spacecraft implemented three mitigation measures: limiting the release of mission-related objects, passivation and collision avoidance. All three measures were applied with 100% success. No measures for post mission disposal or impact shielding were included.

The scores received by the exemplar spacecraft and the final environmental impact rating are listed in Tab. 4.

Table 4. Calculation of environmental impact rating for exemplar spacecraft.

Environmental aspect/indicator	Score	Environmental impact rating
Debris score	0.8847	23.21%
NERF score	0.4420	
Health score	0.5937	
Change in LEO "health"	0.01%	
Increase in debris population in the region following a catastrophic collision	44%	

A representative, environmental impact rating certificate is presented in Fig. 4. It makes use of an alphabetic rating system and illustrates how the output of the rating system may look when the system is finalised.

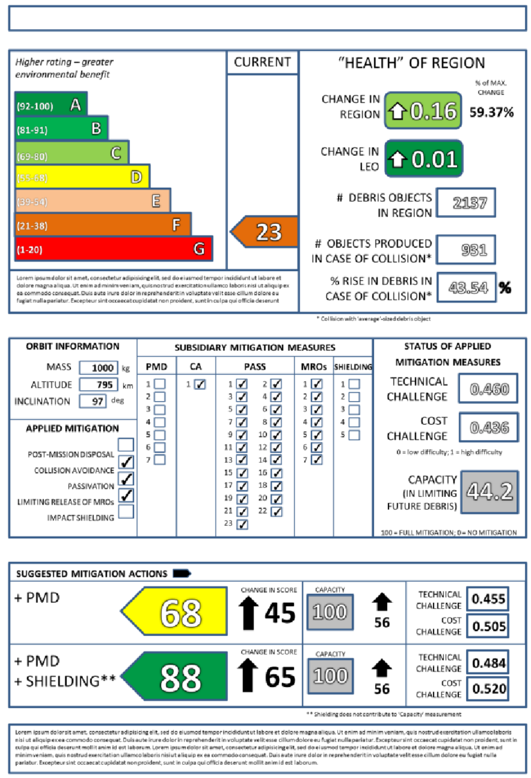

Figure 4. Illustrative output from the environmental impact system in the form of a performance certificate.

The system suggests two potential improvements to the exemplar spacecraft that could be implemented to achieve an improved rating (presented in the 'Suggested Mitigation Actions' section of the certificate in Fig. 4). The first suggested action is to implement a post-mission disposal strategy. If implemented fully, this would result in an environmental impact rating of 68%, with a relative cost impact of 0.455 and a technical impact of 0.505. These values reflect the capacity of post-mission disposal to reduce the generation of debris [5], and the technical and financial challenges involved in incorporating this into spacecraft design and operations [1]. The second suggested action is to add impact shielding in addition to post-mission disposal. In this case, the impact rating would increase to 88%, with a relative cost impact of 0.484 and a technical impact of 0.520. These suggestions aim to encourage design changes that have strong benefits on the space environment, whilst providing information about their relative cost.

4 CONCLUSIONS AND FUTURE WORK

The environmental impact rating system presented here represents a prototype of the ACCORD rating system. Through further development, it is expected that a rigorous mechanism will emerge for communicating the efficacy of current debris mitigation practices and demonstrating how modification to design may benefit the environment. The current version of the environmental impact rating system can summarise the condition of the LEO environment effectively. With further refinement, the system will account for other Earth orbital environments, including Medium Earth Orbits and Geosynchronous Earth Orbits.

The release of the final environmental impact rating system will be through an online web tool, allowing spacecraft manufacturers and operators (amongst others) to input details of a proposed spacecraft and calculate the projected impact on the space debris environment. In doing so, privacy of sensitive data will be ensured by use of a JavaScript-style web tool which retains all data at client-side with no storage of user data on the ACCORD web servers.

The current prototype includes a number of assumptions and there are limitations in some datasets currently used in the prototype calculation. In particular, there is not yet a complete picture of compliance amongst a wide range of users based on responses collected by the ACCORD survey, and the resolution of the data is not yet sufficient to draw conclusions about variations in the implementation of mitigation measures in individual LEO regions. Work is continuing to address these issues. In addition, community and industry engagement is anticipated and being actively sought to improve the relevance of the space "health" index and environmental impact rating system. Given the primary objective of the ACCORD project, to support the European space industry, such engagement is a necessary part of the work. In addition, the intention is to introduce the ACCORD environmental impact rating system as a voluntary tool only.

Transparency is paramount in both construction and operation of the system, and an important purpose of this paper lies in initiating and stimulating a wider discussion within the community. As such, the ACCORD project team welcome further involvement of industry and the space debris community to improve construction of the "health" index and rating system.

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