A SPACE ENVIRONMENT HEALTH SITUATION REPORT

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ABSTRACT

Historically, satellite situation reports were summaries of the orbital object population. Today, numerous sources offer similar outputs, such as the European Space Agency's Space Environment Report. These show a wide variety of data relating to the orbital object population. New index formulations, offering added value in relation to space debris, safety, or sustainability, are being sought. An objective of these is to offer awareness of how well the space environment supports current and future space activity, analogous to "health". This paper addresses how such index formulations might be designed to better align with an understanding of space sustainability and to communicate environmental concerns more readily to broad audiences. Using a comparison of hazard-based approaches with a new approach based on a reserve index, it shows how consideration of objectives and audience is needed before appropriate modelling approaches can be identified.

1 INTRODUCTION

Before the advent of the Internet, knowledge of the space environment was shared by NASA via satellite situation reports containing some summary statistics (e.g. a "box score") and lists of satellites in-orbit and decayed (Fig. 1) [1]. At the time, these situation reports were the only reliable source of information upon which the status of the space environment could be evaluated. Now, the same information is available via the World Wide Web from numerous providers, such as Space-Track. Additionally, several organisations and individuals have fused different data sources, including the satellite catalogue, to provide a rich source of information about the objects that have been added to the catalogue through the years since the beginning of the space age (e.g., the European Space Agency's (ESA's) Database and Information System Characterising Objects in Space (DISCOS) and Jonathan McDowell's Space Pages). Furthermore, the European Space Agency and the Inter-Agency Space Debris Coordination Committee (IADC) now publish annual reports evaluating the status of the space environment [2, 3]. These reports include time-series of the number, mass, and cross-sectional area of objects in orbit, distributions of the number, mass, and area in altitude, categorisation based on the use and owner/operator and estimates of the compliance with the space debris mitigation guidelines (e.g. of the IADC or the ESA Zero Debris Charter), amongst many other valuable statistics.

SPACE OBJECTS BOX SCORE

	OBJECTS IN ORBIT	DECAYED OBJECTS
AUSTRALIA	1	1
CANADA	8	0
ESA	4	0
ESRO	1	9
FRANCE	54	26
FRANCE/FRG	2	0
FRG	9	3
INDIA	1	0
INDONESIA	2	0
INTERNATIONAL TELECOMMUNICATIONS SATELLITE ORGANIZATION (ITSO)	22	0
ITALY	1	4
JAPAN	27	0
NATO	4	0
NETHERLANDS	0	4
PRC	6	14
SPAIN	1	0
UK	11	4
US	2928	1523
USSR	1439	4456
TOTAL	4521	6044

Figure 1. Satellite Box Score from December 31, 1977 Satellite Situation Report [1].

Whilst these existing reports offer valuable information relating to the status of the space debris environment, they mostly lack a simple means of representing the environmental status that appeals to a wide audience and can be communicated easily. To address this gap, the IADC, ESA, and other entities have sought to develop a space environment index. In this context, an index is a **model** – a conceptual tool – that explains how a satellite or system of satellites contributes to the environmental state, or "health". The model might transform multiple measurements into a simple, single, and meaningful representation of the environment. The objective of the work being undertaken by the IADC, for example, is to identify the measurements needed to assess the effects of a space mission on the environment and to assess the overall health of the environment in the context of long-term sustainability. The measurements can be seen as environmental "**vital signs**" that reflect essential functions of the environment in supporting space activity, analogous to those typically identified in the field of healthcare. The role of the measurements and their transformation into an index is then analogous to the use of a patient vital signs monitor [4] by healthcare professionals to interpret and evaluate the overall health of a patient (Fig. 2). Finally, a situation report can present a concise assessment of the environmental health, based on a combination of the vital sign measurements and the index, rather than an expansive list of data and statistics. Reporting in this way can offer value to broad audiences not typically reached by the reporting that is currently undertaken by ESA, the IADC, and others.

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

Figure 2. Patient Vital Signs Monitoring [4].

1.1 Health in the human context

In the human context, we understand that there are several, fundamental indicators needed to capture what we mean by "health". For example, we might measure blood pressure, heart and respiration rates, oxygen saturation, and body temperature, amongst several others. Each of these offers a unique and important measure of a different factor of human health. They are related to body systems and organs that provide vital and life-supporting functions. Hence, their label as vital signs. We have experience of how each of these measures relates to the functioning of those systems and, through them, our health. Each measurement is expected to sit within a particular range if a person is considered as healthy. We recognise that there are also risks to our health that can disrupt the normal function of body systems. Hence, if measurements fall outside the acceptable range, a variety of health management actions might be taken to restore the healthy function of the affected system. We can also appreciate how these measures taken together embody our current health and its trajectory into the future. Additionally, we have the means to access direct measurements of these vital signs, meaning it is generally a simple task to understand one's health situation (although, of course, there are situations when this is not the case).

1.2 Health in the context of long-term sustainability

The 1987 Brundtland Report defined sustainable as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [5]. Fundamental sustainability thinking has now become the notion of three dimensions: environmental, social and economic sustainability. These have been drawn in a variety of ways, as concentric or overlapping circles, or as pillars (Fig. 3).

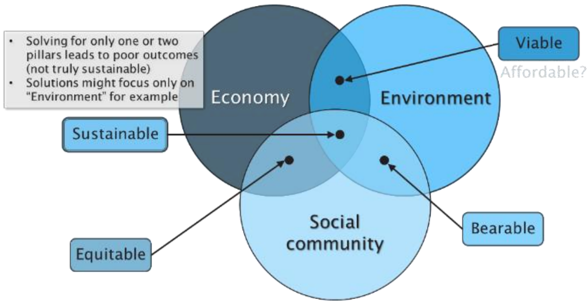

Figure 3. The three pillars of sustainability, physical, economic, and social sustainability, drawn as three overlapping circles. Adapted from [7].

Similarly, the United Nations (UN) definition of space sustainability reflects the Brundtland definition of sustainable development and the importance of these three dimensions [6]:

> *"The long-term sustainability of outer space activities is defined as the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations."*

Arguably, this way of representing sustainable development is imperfect because it suggests that trade-offs can be made between the environmental, social and economic dimensions of sustainability. In practice, decisions by governments, businesses, and other actors have tended to place more weight on the economy than the other dimensions of sustainability, leading to advancing environmental degradation rather than the opposite. There is a recognition that greater emphasis needs to be placed on environmental sustainability to better balance the model [7].

In a terrestrial context, the concept of "critical natural capital" has emerged to describe elements of the environment that cannot be traded off. These are parts of the natural environment that perform vital and irreplaceable functions, mainly associated with life-support and ecological services [8]. Likewise, the planetary boundaries framework identifies nine processes that are critical for maintaining the stability and resilience of the Earth system [9]. A recent update to the framework found that six of the nine boundaries have been transgressed, and that "Earth is now well outside the safe operating space for humanity" [9] (Fig. 4).

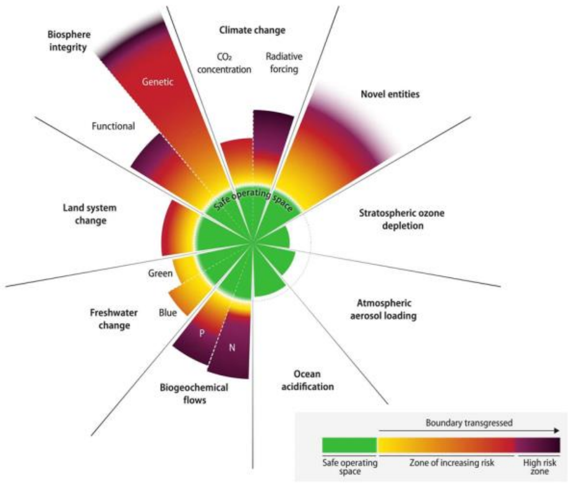

Figure 4. Current Status of Control Variables for All Nine Planetary Boundaries. The Origin Represents Mean Holocene Conditions and The Planetary Boundary Is Represented by The Dotted Circle. Wedge Lengths Are Scaled Logarithmically [9].

1.3 Criteria for good indicators

In its definition of space sustainability, the UN placed substantial importance on the objective of "access to the benefits of the exploration and use of outer space". If we were to adopt the commonly held assumption that limitations to space activity are of a purely technical and economic nature, then one might consider the essential functions of the space environment are to provide and support such access. This would tend to drive research aiming to measure the overall health of the space environment to focus on risks arising from space debris. Whilst there is a growing consensus that space activity presents broader environmental concerns, which point to the existence of additional limits to space activity, there is some uncertainty in the significance of these other environmental impacts in the context of long-term sustainability. For this paper, the focus will remain on space debris risks, but the work presented may be seen as illustrative of a more general approach that can be applied once the uncertainty in the significance of some environmental impacts has been resolved.

Identifying the elements of the space environment that are essential for accessing "the benefits of the exploration and use of space", i.e., the critical *orbital* capital, is akin to identifying the essential life-supporting functions of the human body, i.e., the vital signs. With these analogies in mind, the following general criteria for good indicators can be recognised (adapted from [10] and [11]):

1. **Specific** – specific indicators for specific elements.
2. **Objective** – measured in absolute, unequivocal terms.
3. **Reliable and repeatable** – measurements yield similar results under similar conditions.
4. **Related to use or activity** – level of use, type of use, location of use, or behaviour.
5. **Sensitive** – indicators should respond proportionally to use.
6. **Manageable** – indicators should be responsive to and help determine the effectiveness of management actions (so that indicators can be maintained within prescribed standards).
7. **Efficient and effective to measure** – easy and cost-effective to measure on a regular basis.
8. **Significant** – indicators help define the quality of the user experience.
9. **Unique** – measurements have a low correlation with others that capture the same characteristic.

Ideally, the space environment's vital signs would meet these criteria. However, the space environment is distant and many objects residing within it are difficult or impossible to access. We may need to rely on measurements that are either old (e.g., taken before launch), remote, incomplete, uncertain, or all of these. Additionally, some characteristics that may be valuable for evaluating the health of the space environment are not measurable directly – for example, the likelihood of a collision in orbit is often cited in risk assessments of the space environment but it is a quantity that cannot be determined simply by observing the objects in the space environment. It requires a model with some predictive capability, able to project the objects forwards in time from their current positions, considering the orbital perturbations that can affect their trajectories (which also require prediction of things like the solar activity and space weather), to identify possible close approaches.

These points mean that some important measures may be difficult, impossible, or costly to obtain. In such instances, one might turn to proxies for the desired set, characteristics that can be measured more easily and directly, but with the inclusion of some error or loss of sensitivity.

1.4 Accessible environmental measurements

The European Space Agency's Space Environment Report [2] offers a substantial and very broad range of possible measurements of the space environment at a high level. Additionally, the websites Space-Track.org, Celestrak.org, KeepTrack.org, ESA's DISCOS database, and Jonathan's Space Pages provide information about catalogued objects. The reader is encouraged to refer to these websites for details of the specific data available. This section shows a set of plots of environmental measurements that are readily accessible and that can be used to inform a space environment index.

Fig. 5 is a plot of the change in the number of active satellites through time. The size of the current population of active satellites is nearly 12,000. The growth in the number of spacecraft has been driven primarily by the deployment of satellites into large constellations in low earth orbit (LEO).

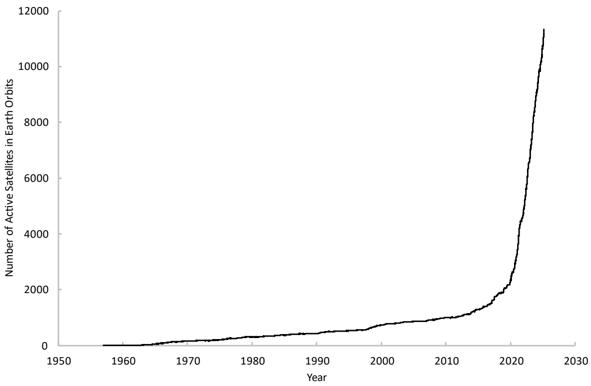

Figure 5. History of Active Satellites from Jonathan McDowell's Space Pages.

Fig. 6 gives the spatial density of intact objects from the 28 March 2025. Four regions with high concentrations of payloads stand out: (1) below 600 km, (2) 600 km to 1000 km, (3) 1140 km to 1260 km, and (4) 1340 km to 1560 km. The Starlink constellation at about 340 km to 560 km is the cause of the peaks in region 1. The Iridium NEXT constellation and several, large fragmentation events are the cause of the high concentration in region 2, and the OneWeb constellation is the cause of the peak at 1200 km. The atmospheric density in region 1 is relatively high and the drag will remove large fragments and derelict objects with high area-to-mass ratios quickly. Objects in region 2 will take decades to decay into region 1, while large fragments in region 3 will take centuries to decay into region 2. Large, intact objects in regions 3 and 4, and large fragments in region 4 will likely take thousands of years to decay into the lower regions.

Fig. 7 is a plot of the cumulative number of collisions as recognised on Jonathan's Space Pages. Two lines are needed to account for uncertainty in the identification of some collisions. The gradients of the trendlines represent the collision rates. For example, current collision rates between 0.52 per year and 0.94 per year are indicated (alternatively, about one collision every 1 to 2 years).

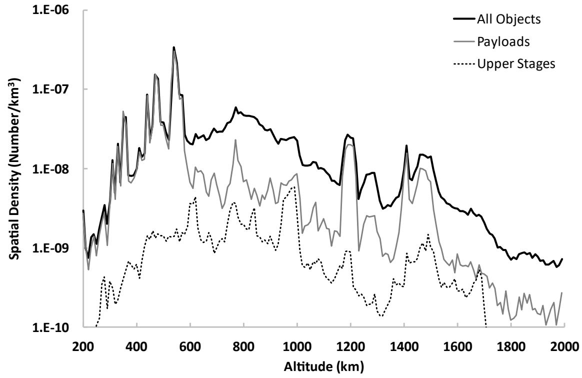

Figure 6. Spatial Density of Upper Stages, Payloads, and All Objects from a March 2025 Catalogue.

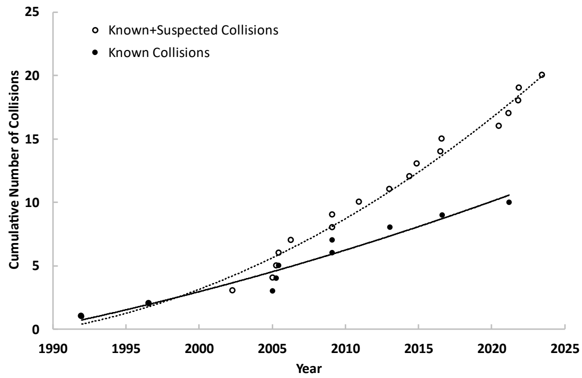

Figure 7. Cumulative Number of Known and Suspected Collisions Since 1957 from Jonathan McDowell's Space Pages. The Gradients of the Quadratic Trendlines provide the Time-Varying Collision Rates.

2 HAZARD-BASED APPROACHES

Through a comprehensive review by IADC members of many different approaches for generating a space environment index [12], some common ingredients and methodologies emerged. These are reflected in similar reviews conducted independently. Findings show many approaches to be focused on parameters and models for performing **hazard analysis**. Generally, in these approaches, the objective is to measure the **degree of loss or harm** arising. This is determined through consideration of the possible hazards, their likelihood and consequences if they occur. The space environment index formulations represent the degree of loss in absolute terms or in relative terms, following normalisation by a reference case.

In general, the individual risk, R_i, arising from the occurrence of an incident, i, can be computed as the product of the potential loss, L_i, and its probability of occurrence, $p(L_i)$,

$$R_i = L_i p(L_i) \tag{1}$$

The expected risk, R_{exp}, is defined as the sum over the individual risks,

$$R_{exp} = \sum_i R_i \qquad (2)$$

In the context of a space environment index, the expected risk is represented through the summation (**aggregation**) of individual risks calculated for each payload and debris object in orbit, as per Eq. 2.

In this framework, losses arise because of the occurrence of a hazard, i.e., an incident or mishap affecting a satellite. It makes sense, therefore, to consider collisions and the losses resulting from them. This is consistent with the environmental harm that is generally considered to be the primary concern in relation to space debris. In this case, the loss, L_i, can be measured in terms of the catastrophic breakup of a satellite impacted by debris, the degradation of space-based services resulting from a collision, or financial values associated with either. The probability of occurrence, $p(L_i)$, is the collision probability. Hence, the environmental risk might be the expected number of satellites lost through collisions or the cost to replace them.

A benefit of this approach is that the contribution by a specific object to the overall environmental health can be readily evaluated. This offers a way to understand the significance, or **criticality**, of each object to the overall environmental health, opening possibilities for licensing or determining third-party liability insurance requirements, for example. However, due to the difficulties in measuring some parameters easily, many versions of this approach use simplifications regarding both the degree of loss or harm and the probability of occurrence, e.g., by representing them through proxies or other abstraction, such as using object mass as the loss term or spatial density or flux in lieu of the probability. This results in an error that might be small when considering the individual risk to a satellite but potentially grows through the aggregation process in Eq. 2 to become significant in the expected environmental risk. It can additionally result in strange outcomes that are difficult to communicate. For example, a risk that uses mass as a proxy for the degree of loss (also referred to as the "severity" in this context) will have units of kilogrammes, which is not intuitively perceived as a loss or a harm.

All models make some simplifying assumptions, and it is impossible to build a fully accurate model. Models tend to achieve accuracy through high complexity, but this limits their transparency and flexibility and requires substantial parameterisation. In contrast, simple models are more easily parameterised, understood, and adapted, but may have insufficient accuracy. Yet even the most complex model will make some simplifying assumptions. The level of complexity needed will depend on the objective, the level of precision or generality required, the available data, and the time frame by which results are needed.

We want models that are **suited to their purpose** and capture the **essential** features of a system, whilst achieving an appropriate balance of accuracy, transparency, and flexibility. Fig. 8 shows six different representations of a house. It is unlikely that the leftmost representation would be viewed as capturing the essential features of a house. In contrast, the rightmost representation is likely to be quickly and easily identified as a house, because it includes what might normally be recognised as the essential features. At the same time, the two representations in the centre of Fig. 8 might also be easily identified and could be considered to have captured the essential features, without the need for any further complexity.

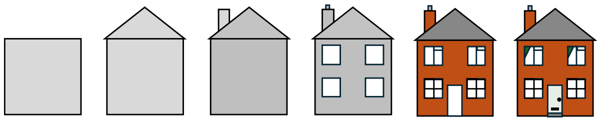

Figure 8. Six Representations, Or Models, Of A House with Complexity – And Accuracy – Increasing from Left To Right. Which One Is a Sufficient Representation and Captures the Essential Features?

The hazard-based approach defined in Eqs. 1 and 2 is appealing because it mimics the way in which a long-term, space debris evolutionary model functions, by determining the risks associated with individual objects through time and aggregating these over the entire orbital object population. Yet, this also means that the environmental risk can only be measured in terms of the risk to individual objects. There is no meaningful sense of a measure that encompasses the objective of "access to the benefits of the exploration and use of outer space" without some further transformation. Arguably, it means that such models may be ill-suited to the purpose of evaluating the overall health of the space environment.

Several hazard-based approaches reviewed attempt to overcome this limitation by using a comparison with a reference case, often one that describes a "sustainable" outcome or one that describes a "non-sustainable" outcome [12]. The comparison is typically achieved through normalisation, e.g., the expected risk calculated from Eq. 2 for a scenario of interest (e.g., a projection of current space activity into the future) is divided by the expected risk for a reference scenario. Whilst this enables the environmental health to be measured in relative terms, there is no absolute understanding of health. This process ultimately obscures the knowledge of the intrinsic conditions of the space environment that are being measured, and which are of value to the audience. Even without this normalisation, an environmental risk that is framed in terms of the risk to its constituent objects may require substantial efforts to translate into a form and a language that are meaningful to the audience. Hence, such models may lack the appropriate balance of accuracy, transparency, and flexibility.

3 A RESERVE-BASED APPROACH

A method that is more closely aligned with the UN space sustainability objective is desirable, one that uses a measure more directly associated with access to the benefits of the exploration and use of outer space. This can be achieved if the space environment is considered to be a finite but renewable resource and if exploration and use of space consumes it. Such resource framing is commonplace in the literature and media. In this framework, one can also see debris remediation as a renewal of the environmental resource.

This paper proposes the use of an environmental **reserve** to fulfil the requirements of a space environment index that is aimed at measuring the overall health of the space environment [13]. In this context, the most relevant definition of "reserve" is "a supply of a commodity not needed for immediate use but available if required." The "commodity" in question is literally the outer space needed to accommodate desirable levels of exploration and use. A healthy space environment is therefore one that has sufficient reserves to "meet the needs of the present generations while preserving the outer space environment for future generations." A space environment that is unhealthy is one where there is **overshoot** of the reserves and renewal is necessary to restore them.

The reserve, Δ_i, is defined with respect to the number of intact objects, N_i, maintained in orbit above some altitude, h_1,

$$\Delta_i = {}_{R}N_i - N_i \tag{3}$$

where ${}_{R}N_i$ is the critical number of intact objects above h_1 producing a runaway environment [14, 15],

$${}_{R}N_i = \frac{4\pi a^3 V_o \rho_a C_D}{N_0 W (m/A)_a V \sigma_f} \tag{4}$$

and $a = r_e + h_1$, with r_e the radius of the earth, V_o is the orbital velocity, ρ_a is the atmospheric density, C_D is the drag coefficient, N_0 is the number of fragments generated by the collisional breakup of an intact spacecraft massive enough to break up another intact spacecraft, W is a weighting factor accounting for elliptical orbits, $(m/A)_a$ is the average mass-to-area ratio, m/A, over the fragment m/A distribution, V is the average relative velocity that transforms spatial density into flux with a value of about 7.5 km/sec, and σ_f is the collision cross-section between an intact object and a fragment.

The critical number of intact objects was calculated using values adopted by [14]. For the LEO region below 1020 km: $N_0 = 90$, $(m/A)_a = 125$ kg/m^2, $\sigma_f = 14$ m^2, $W = 1.1$, and $C_D = 2.2$. For the LEO region between 1350 km and 1550 km the following changes were made to account for smaller intact sizes and fewer fragments: $(m/A)_a = 100$ kg/m^2 and $\sigma_f = 2.3$ m^2. For the region between 1020 km and 1350 km, the averages of the values adopted for these two regions were used. Atmospheric densities were from the CIRA-72 atmospheric model under the assumption of average solar activity [15].

Fig. 9 is a plot showing the regions below 1020 km where the March 2025 population of intact objects exceeds the critical number needed for a runaway environment, based on the stability model parameters listed above. The region between 720 km and 1000 km is well above the runaway threshold while the region below 700 km is well below the runaway threshold. In the former region, there is overshoot of the reserve, and renewal is needed (Fig. 10), whereas the reserve is preserved in the latter region for use by current and future generations.

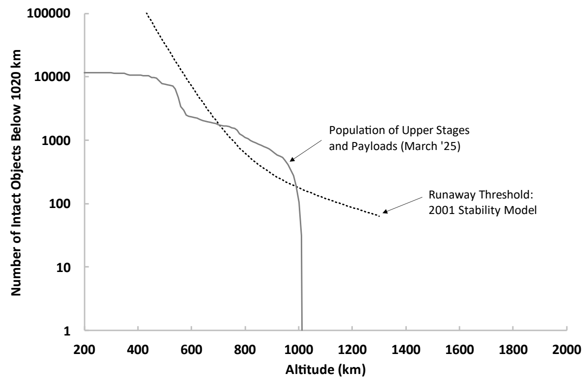

Figure 9. Regions Where the Current Population Exceeds or is Under the Runaway Threshold.

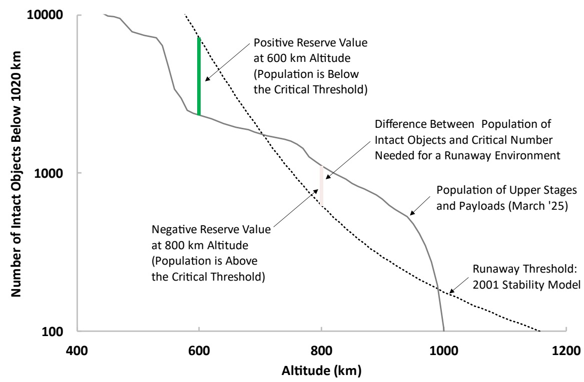

Figure 10. Altitudes Showing Preservation (Green) or Overshoot (Red) of Environmental Reserves.

3.1 Static Reserve Index

The **static reserve index** [13] is a measure of how long before there is overshoot in the reserve (i.e., how long it will last) if used at a constant rate, U,

$$SRI = \frac{\Delta_i}{U} \tag{5}$$

In this context, U is the annual **net increase** in the number of intact objects, N_i, above altitude h_1, which is referred to as the annual orbital consumption rate. It is not the launch rate.

Fig. 11 is a plot of the number of intact objects below 1020 km for the years 1999, 2009, 2016, and 2025. It shows generally exponential increases in the annual consumption rate over this period at all altitudes below 1000 km, but with differing growth rates. Increases are also seen in the populations above 1000 km.

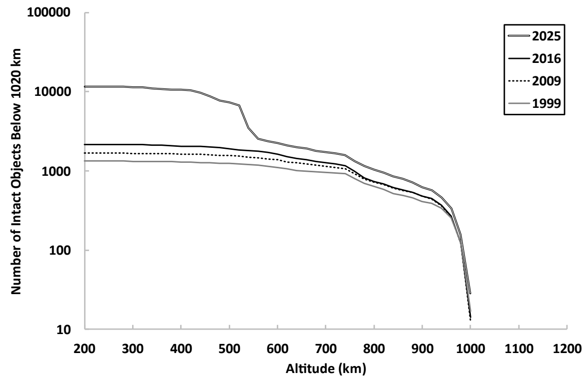

Figure 11. Number of Intact Objects Below 1020 km for Populations from 1999, 2009, 2016, and 2025.

3.2 Exponential Reserve Index

If the rate of resource use is increasing, the reserve cannot be calculated by simply taking the current known reserves and dividing them by the current annual consumption rate (Eq. 5). Hence, the **exponential reserve index** [13] determines how long the reserve will last assuming a constant annual rate of growth, G, in consumption of the orbital resource, starting from U. In cases where there is overshoot, the exponential reserve index can also determine how long it will take to **renew** the reserve assuming intact objects are removed from orbit at an initial frequency of D objects per year, with the removal frequency also growing annually at a rate G,

$$ERI = \begin{cases} 0, & \Delta_i = 0 \\ \dfrac{ln\left(1 + \frac{\Delta_i}{U} G\right)}{ln(1+G)}, & \Delta_i > 0 \\ -\dfrac{ln\left(1 + \frac{-\Delta_i}{D} G\right)}{ln(1+G)}, & \Delta_i < 0 \end{cases} \tag{6}$$

In Eq. 6, ERI is positive, indicating a reserve remaining, when the population of intact objects above altitude h_1 is less than the critical number of intact objects needed for a runaway environment. ERI is negative when there is an overshoot, the number of intact objects above h_1 is above the critical number needed for a runaway environment. In this instance, the magnitude, $|ERI|$, gives the minimum time needed to renew the reserve using active debris removal.

4 RESULTS

The values listed above were used in Eq. 4 to calculate the critical number of objects needed for a runaway environment, ${}_RN_i$. These were identical to the values used in [1]. The difference between ${}_RN_i$ and the number of intact objects in orbit on 28 March 2025 was used to calculate the reserve values, Δ_i, for all LEO regions, based on Eq. 3. The values of the annual orbital consumption rate, U, were obtained for all LEO regions by differencing the counts shown in Fig. 11, normalising by the number of years, and averaging over the four periods. This led to the plot in Fig. 12 of the annual consumption rate.

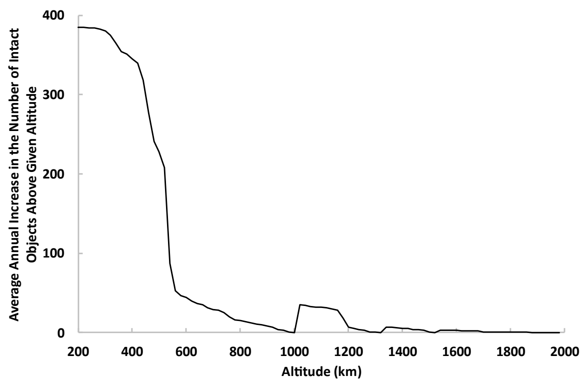

Figure 12. Annual Orbital Consumption Rates for All LEO Regions Based on the Average Annual Rates for the Period 1999 through 2025.

The large values seen in Fig. 12 for the region below 600 km are associated with the Starlink constellation. The peak between 1000 km and 1200 km is due to the OneWeb constellation. Assuming orbital consumption as per Fig. 12 where there is reserve remaining, and debris removal at an initial rate of 5 intact objects per year, with both increasing at an annual growth rate, G, of 5%, we obtain the exponential reserve index values in Fig. 13.

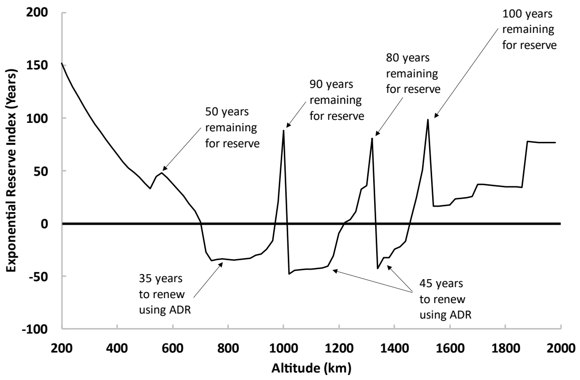

Figure 13. Exponential Reserve Index Values Calculated for the March 2025 Satellite Catalogue Assuming an Annual Growth Rate of 5% in Orbital Consumption from 2025. Horizontal Lines Above Zero Show Years Remaining Before Overshoot. Horizontal Lines Below Zero Show Years to Renew the Reserve Using ADR.

Fig. 13 shows two key regions with orbital reserves remaining: below 720 km and above 1460 km. There are two other small regions where reserves remain, estimated to last between about 80 years and 90 years. The exponential reserve values indicate no more than about 50 years before there is considerable overshoot in most LEO regions for altitudes above 520 km, and the removal of intact objects will need to be considered. Even so, recovery from overshoot could take about 50 years. Elsewhere, regions of LEO already in overshoot are: (1) 720 km to 980 km, (2) 1000 km to 1220 km, and (3) 1340 km to 1460 km.

The exponential reserve index across all LEO regions indicates that the orbital resource should last for about 24 years, on average, before substantial remediation efforts will be needed.

4.1 An initial space environment health situation report

Potential indicators of the health of the space environment are presented in Tab. 1, using values from section 1.4 above and from the exponential reserve index results. Care needs to be taken to present this information in a manner that is easily understood by a broad audience. Some of the indicators selected for Tab. 1 require explanation and may pose difficulties for some audiences. Perhaps one way to approach this is to see the first two indicators – the number of active payloads and the interval between collisions – as analogous to specific measurements in a healthcare context, such as heart rate and blood pressure, and the exponential reserve index as equivalent to an estimate of the patient lifespan arising from a combination of lifestyle choices, genetics, etc.

Table 1. Potential Indicators of the LEO Space Environment Health for March 2025.

Indicator	Value
Number of active payloads	About 11,300
Interval between collisions	Less than 1 year
Time remaining for orbital reserve	24 years

4.2 Preliminary analysis

The use of hazard-based approaches for measuring the overall health of the space environment is problematic because of the typical way in which they are used. The risks associated with individual satellites, based on the hazard from collisions, are aggregated into an expected environmental risk value, supposedly to represent the environmental losses or harms. This output is arguably poorly suited for representing the environmental health because it can only capture the environmental risk in terms of the hazard to individual objects. Additionally, the aggregation process may be computationally intensive, especially for large populations of satellites.

The exponential risk index does not rely on aggregation, saving on computing power, but is instead associated with the consumption of the orbital resource, which is finite (but renewable), as a product of humanity's exploration and use of space. This means it is more closely aligned and well-suited to the objective of measuring health in terms of "access to the benefits of the exploration and use of outer space," as defined by the UN [6]. At this level of abstraction, it is also more straightforward to incorporate elements of economic and social sustainability, thereby addressing the fundamental pillars of sustainability.

The reserve-based approach still makes use of a model, which needs to be selected carefully to ensure a good balance of accuracy, transparency, and flexibility. In the work presented here, the stability model first presented in [14] was used to estimate the orbital reserve. Other models can be used to do the same, such as those based on equilibrium (e.g., system dynamics or so-called "source-sink" environment models). Indeed, such equilibrium-based approaches ultimately lead to models that have much in common with the stability models used here. Some additional care is needed, however, as all these models are based on assumptions that might not always hold true and require parameterisation that can be challenging (e.g., see [15]). This is particularly true for the assumption of exponential growth in the consumption rate. Over a relatively short period of time, this is perhaps not inaccurate. However, the assumption breaks down after longer time spans, when consumption rates reach unrealistic levels. A logistic function may be a better approximation.

The values of the parameters used for the stability model and for calculating the exponential reserve index will have a strong influence on the overall assessment of the health of the space environment. The values shown above are based upon published values (e.g., for the stability model and for the debris removal frequency) or on recent trends (e.g., the orbital consumption rate). Further work is needed to establish the reliability of these values, perhaps through the use of a sensitivity study. Initial investigations have shown that the quantities needed to calculate the critical number of intact objects needed for a runaway environment (Eq. 4) are quite robust to new data sources [2], meaning that changes in the reserve value (Eq. 3) would arise predominantly because of changes in the number of intact objects in the orbital population. Similarly, the values of the consumption rate, U, and its growth rate, G, do not affect the regions in overshoot but can affect the time outputs considerably.

A considerable benefit of the exponential reserve index is that it frames environmental health in terms of **time**. I.e., the time remaining before the orbital resource is used up or the time needed to renew the resource. This shift, from the losses or harms that are outputs from the hazard-based approaches, ensures that its use as an environmental health indicator better fits the UN definition of space sustainability, which centres sustainability in terms of time [6]:

*"The **long-term** sustainability of outer space activities is defined as the ability to maintain the conduct of space activities **indefinitely into the future** in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of **the present** generations while preserving the outer space environment **for future** generations."*

This framing also moves away from the perception of a limit on the number of satellites, which is associated with "orbital carrying capacity." Additionally, the exponential reserve index avoids presenting an overshoot – where the number of intact objects exceeds the runaway threshold – as something permanent. It uses the same formulation to offer a timeframe for the renewal of the orbital resource. Hopefully, this encourages optimism and enables the role of debris remediation to be evaluated consistently and reliably.

The exponential reserve index also highlights the importance of effective debris mitigation, specifically post-mission disposal (PMD). An important proportion of the change in consumption rate over the period 1999 to 2025 is due to the abandonment of intact objects in the LEO region. If there is widespread adherence to the IADC post-mission disposal guidelines, then the consumption rate would truly reflect the use of space rather than being, as it is now, a reflection of relatively poor behaviour in orbit. Such adherence would lead to a one-in-one-out scenario and the number of intact objects would only change in response to an increasing deployment of active satellites.

Future work will aim to adapt the model to account for some of the issues identified above and to incorporate economic and social sustainability elements. Additionally, sensitivity studies on the parameters used for the stability model and the environmental reserve index will be conducted, to assess the variability and reliability in the approach. Finally, further effort will be expended to identify the essential features of the health of the space environment – the vital signs – and to communicate them in the form of a regular situation report.

5 CONCLUSIONS

Rather than reviewing the extensive literature that now exists on different approaches for evaluating the health of the space environment, this paper has presented a high-level analysis and critique of the commonly used, hazard-based approach. This analysis found that this approach is perhaps poorly suited for measuring space environment health in a manner that aligns with the widely adopted definition of space sustainability. An alternative approach, based on the use of a reserve index, was presented and evaluated. The concept of a reserve and its basis in time, offer several advantages over other ways of measuring environmental health. This includes a much closer alignment with the UN definition of space sustainability.

An initial implementation of the reserve index approach was presented, which used the stability model of Kessler and Anz-Meador to estimate the reserve. When applied to the current population of intact orbital objects, the results suggested that relatively large regions of LEO, at low altitude and at high altitude, have maintained a reserve that will last for some decades. However, regions of LEO between 720 km and 980 km, and 1000 km to 1220 km, will require remediation actions to be maintained over an equivalent duration to renew them.

The work has addressed some of the challenges of measuring the health of the space environment in the context of long-term sustainability. It has additionally highlighted the need to enhance efforts to tackle the space debris problem, particularly through existing debris mitigation measures, and the need to deploy debris remediation technologies into the LEO region to restore the environment.

6 ACKNOWLEDGEMENTS

The research presented in this paper made use of information from Space-Track.org and Jonathan McDowell's Space Pages. The author acknowledges the use of these databases, and the efforts of the teams and individuals involved in their maintenance and operation.

The authors would also like to thank Megan Perks, Rob Garner, and Sam Diserens for sharing their valuable insights and suggestions.

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