FROM TRACKING TO WRECKING: PRACTICABILITY OF ORBITAL RISK KPIs FOR SPACE DOMAIN MANAGEMENT DECISIONS

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ABSTRACT

Half a century after the first conquest of earth orbits with human-made satellites, a new rush to space has started, populating earth orbits with an unprecedented number of objects, delivered by an unforeseen number of players, creating a risk environment mandating sustainable behaviour by all actors, not as a beauty contest, but as a matter of survival.

When trying to assess and enforce behaviour which is compliant to defined rules, we usually identify a set of key performance indicators (KPIs) which, together with a set of thresholds for these KPIs, pave the way to establishing a policy that can be looked after by the operators and by defined national or international regulators, agencies, or committees.

However, many KPIs identified so far are barely practicable for deriving appropriate Space Domain Management (SDM) decisions. In this paper, we try to show why, and we present an approach to establish verifiable long-term sustainable behaviour of space actors.

1 NEW SPACE – NEW RACE

The dramatic change in human exploitation of space resources over the last few years, commonly summarized as “New Space,” has led to a changing situational perception regarding valuable assets placed in earth orbits.

The “New Space” (R)Evolution has many aspects:

- Liberalization of markets
- Commercialization of space activities formerly restricted to government and military
- Scalability technology leap: small Sats, Cube Sats, Nano Sats
- Launch from almost anywhere
- Scalability of launchers
- Industrialized satellite production replacing the single satellite workshop
- Multiple satellites per day instead of single satellite per month.

The combination of all the above is the key to commercial and the industrial feasibility of mega-constellations.

The corresponding evolution of possible usage scenarios shifts a big portion of the focus of new satellite launches from Geostationary Earth Orbits (GEO) to Low Earth Orbits (LEO).

Putting this in sync with the next evolutions in mobile communication (5G, 6G) unleashes overwhelming potential in automated communication (Internet of Things (IoT)).

2 TRAFFIC, RISK AND ELEMENTS OF SUSTAINABLE BEHAVIOUR

2.1 Traffic

In the same way as traffic increases by at least an order of magnitude, the related risk of and for the assets placed in orbit, and in the end, the overall risk for the society changes.

The main questions asked by stakeholders are:

- **Risk-Taking:** What is the risk the current orbital object population infers on a single object?
- **Risk-Making:** What is the risk a single object infers on the other objects in orbit?

2.2 Risk

Space services have become an integral part of the social life in our industrialized world. Most of the time we may not notice it, but our day-to-day life vitally depends on services such as satellite communications, time services, navigation, earth observations and weather information. Any impact to, or even outage of, these services need to be considered to have a significant impact to society.

Following the philosophy of law, any threat to society shall be judged based on the behaviour of one or more persons or legal entities. To enable a resilient living together, behaviour rules are established with the aim of preventing society from threats. These rules are converted into laws and regulations by the legislation, implemented by the administration, and executed by

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jurisdiction.

In a simple example, driving under the influence or driving at excessive speed is recognized as a risk to society. Therefore, rules and regulations have been established to keep our living together safe. The behaviour of the actors is monitored, non-compliant (“wrong”) behaviour is punished while those who behave correctly are allowed to move their vehicles.

In Space Operations, the behaviour of the “operator person” (person or legal entity) shall become measurable based on Key Performance Indicators (KPIs). It is important that those KPIs can be monitored by the operator and, as independent and neutral as possible, by the administration.

For what concerns threats to society, any risk-making in space operations needs to be measurable and put in a relation to the impact. Taking an example from sea traffic the impact differs a lot if there is a private sailing boat sinking or if it is an oil-super-tanker.

Most current approaches base their definition of risk on the term “interference” (denoting either physical interference or also including spectrum interference), and try to establish “a quantitative metric to describe the risk of interference” [1].

To reduce the complexity of measurable KPIs in space operations, we focus in this paper on the physical interference and leave out radio frequency and light interference, even in the awareness that they are very important topics.

Bringing it to the point, the most important behaviour threats in space are:

- Owning, operating, or inserting outer-space objects which are
  - Difficult to locate
  - Unable to avoid collisions
  - Not subject to 24/7 operations
- Owning, operating, or inserting a series of outer-space objects (“constellations”) possessing the potential for uncontrolled serial collisions

This corresponds to the questions

- “Which loss-of-mission risk is placed on other operators due to the behaviour of a given mission?” and
- “What is the contribution of a given mission to the Kessler syndrome?”

as presented e.g., by [1].

Further below, we will discuss whether an object-centred or mission-centred approach is sufficient for the implementation of a sustainable space behaviour policy. We will show that, from the systemic perspective, it may be better to not only look at the damage-related risk (cf. [1]: “Environment capacity is defined as the term for resource usage of the space environment as quantified by the integral over all Environmental Consequences of Orbital Breakups (ECOB) values of objects in the space environment that implies a sustainable future.”), but to also include the “endangering” as a part of unwanted behaviour.

Converting the threats to parameters which are measurable at any time for the operators and for the administration is a necessary task for enabling efficient law and regulation formulation.

2.3 Sustainable Behaviour

Sustainable behaviour in space, as described in the United Nations’ Guidelines for the Long-term Sustainability of Outer Space Activities [2], needs to be turned into binding legal and contractual implications, into a set of actionable rules of world-wide validity and consensus. Otherwise, all guidelines remain nice suggestions and all rule becomes a dead letter.

The rules, in turn, need to be backed by an objective evaluation of an appropriate set of Key Performance Indicators (KPIs). Those KPIs can be based on the parameters as shown below.

Table 1. KPI Base Parameters

<table>
<tr><th colspan="2">Object</th><th colspan="2">Operator</th></tr>
<tr><td></td><td colspan="2">Properties</td><td></td></tr>
<tr><td></td><td colspan="2">Capabilities</td><td></td></tr>
<tr><td colspan="2">Dynamics</td><td colspan="2">Behaviour</td></tr>
</table>

This means that KPIs are linked to objects and operators. Objects and operators can be described in terms of properties (such as object mass or physical dimensions, operator location, etc.), in terms of capabilities (such as object manoeuvrability, operator ground station availability, etc.) and in terms of object dynamics (such as object attitude changes) and of operator behaviour (operational manoeuvres, etc.).

3 SPACE DOMAIN MANAGEMENT

Space Traffic Management is the government responsibility regarding licensing and co-ordinating the actual traffic of objects operated by various persons or legal entities.

Space Domain Management is the administrative responsibility. KPIs relevant for Space Domain Management describe the Risk-Making to Society. We will therefore concentrate on this risk aspect, in the context of the Sustainability of a System.

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Note that in most publications so far, the term "Space Domain Awareness" is used (e.g., [3]). We use "Space Domain Management" in this present paper to make it clear that this is an active responsibility and not just a passive monitoring duty.

4 TYPES OF EVALUATION

There are the following basic types of evaluation, verification, and assessment of KPIs:

Table 2. Types of KPI Evaluation

Trust	based on a Maturity Model, assessing the Process Definitions. The analysis mainly looks at static information, ISO certification, reporting, mission design, etc.
Monitoring	of actual Actions vs. defined Rules. Monitoring means measurability. It delivers the raw data which, in conjunction with the KPIs and defined thresholds (see Rules), can be used as evidence in assessing the compliance to rules and laws (or rather, to identify deviations from the compliance).
Rules and Laws	define the formal basis for a Feedback loop to be established so that the Administration can track the actors' compliance via the KPIs and so that it can (re)act appropriately in case of deviations and violations. A pro-active approach would also include some kind of Credit System and/or Market Model in order to create a merit vs. punishment system based on Forecast Compliance.

5 RISK ASSESSMENT

5.1 KPIs

The following parameters are currently used in space operations to describe threats to the environment and therefore to society by harming the continuity and resilience of services provided or supported by space infrastructure.

Parameters originate from

- Asset Management (e.g., object properties)
- Operations (e.g., object trajectories)
- System (e.g., orbital shell "container")
- Domain (e.g., overall relation to the object and operator community)
- Risk for Society (e.g., impacts on continuity and resilience of space-based or space-assisted services)

They can describe interactions of/with

- Single objects (single events and impacts thereof)
- Constellations
- Fields (describing the orbital population as a density function)
- Statistical Ensembles (sum of objects weighted by selected properties, potentially leading to some kind of entropy definition)
- Systems (model-based, empiric, or both)

5.1.1 KPI requirements

The requirements for KPIs for legislation, administration and jurisdiction can be summarized in the following points:

Table 3. KPI Requirements

The monitoring of the KPIs shall be possible for the space operator as well as for the administration, using similar or comparable tools, used independently from each other.
The KPIs shall be available for very different time intervals as summary as well as for specific events.
The risk expressed in the KPIs shall easily express the risk-making to the environment / to the society.
The KPIs should be retrievable from different tools expressing the same metric (comparability).
The KPIs shall allow to refer to persons or legal entities per event / time period.
The KPIs shall have the quality to be used in administration and jurisdiction (evidence-based, representing empiric perceptions).
The KPIs shall allow to judge a deviation from rules and regulations (Yes / No) and to what extent the deviation was found evident (in the best case, in numbers from the metrics).

5.1.2 Conjunction probability

Conjunction probability shows the probability of a conjunction in a specific case of two objects. It is a look into a short period of time. In the context of a behaviour of an operator it could be used how the operations reacts on the threat. In the above-mentioned threats, it could be assessed if operations are successful in reducing the risk to the environment. The number itself does not help to judge right of wrong behaviour. In the best case the operator and the administration must do the conjunction probability assessment for a conjunction based on standardized measurement methods and compare it with defined thresholds. The drawback here is that the administration must build up a significant own infrastructure including experts to monitor a possible thousands of conjunctions daily.

5.1.3 Space capacity

The given index known by the authors refers to the model developed and used by ESA [1]. It is based on Monte Carlo simulations of object populations including break-up scenarios and represents future scenarios.

In the context of operator behaviour judgement, it could serve to assess areas used by the operator. The drawback here is that the day-to-day monitoring seems difficult based on regulations. In the best case it could be used to assess licence conditions given by the regulator based of simulations.

5.1.4 Data Sharing

To share data is a wide accepted practice to enable, minimize and optimise the actions of space craft operations to avoid unnecessary manoeuvres. It is in fact a measurable behaviour indicator in context of operations. The draw back here is that it seems hard to measure without a cooperation of the respective operator. Data sharing seems to be a second-tier indicator indirectly reducing the threats to the resilience of space services. In the best case the administration could be involved in the communication / data sharing loop and develop own KPIs to measure the number and quality of the data sharing activities. The pro here would be that the administration also gets the data of the space activities without judging what the administration is doing with it.

5.1.5 Detectability

To know the position and moving vectors of space objects the detectability plays a major role in space domain awareness and is the precondition for safe

Table 4. Overview of KPI Monitoring Services

Reports	**Time dynamic**		**Time relevance**			**Spotlight to**		
	Static	**Dynamic**	**Empiric**		**Model**	**Single Events**	**Group**	**System Behaviour**
			Past	**Near-Real-Time**	**Future Scenarios**			
ESA Environment Report [7]	Yearly		X		X***			X
NASA ODQN [8]	Quarterly		X					X
AstriaGraph / Privateer [9]		Actual		X		X		
Space Sustainability Rating (SSR) [10][11]	Per Mission Phase	Limited*		Limited*	X		X	
LeoLabs Quarterly Report [12]	Quarterly		X				X	X
ShareMySpace Monthly Report [13]	Monthly		X			X		
EUSST Conjunction prediction [14]		Actual		X		X		
EUSST fragmentations [14]		Actual		X		X		
EUSST re-entry [14]		Actual		X		X		
STROM: Space Traffic Reports for Orbital Management (see Outlook section)	X	Daily	X	X		Limited**	X	X

Notes:

* The future implementation is not clear at the current stage

** The implementation depends on the available data and the used algorithm to predict the orbits

*** The ESA environment report refers to “The simulation of the future evolution of the debris population can be used to assess the efficacy of proposed mitigation actions and of current behaviours.” in two scenarios (“No future launches” and “Extrapolation of current behaviour”)

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behaviour in outer space. The detectability of a space object is measurable on day-to-day bases without a cooperation of the operator. The precondition to measure the detectability is an infrastructure to measure. Same as the data sharing it seems to be a second-tier indicator as unknown objects represents definitely a risk to other space infrastructure and so also to the society.

5.1.6 Environment reports / bulletins

These reports or bulletins shows in their parts numbers and lists in longer and shorter intervals. At the end all these reports are aiming to describe the environment in different perspectives like number/mass of objects total and in different classifications (e.g., owner, type), some of the reports also list the number of conjunctions, others provide lists of conjunction probabilities. In the context of operators' behaviour assessment these numbers have a very limited capability to bring in a regulation correlation for the administration and jurisdiction.

In the best case the data could be used to get (mainly general) information about fragmentation events.

5.1.7 Simulations of short and long-time space environment

Simulations using statistical methods like Monte Carlo simulation algorithms represent model implementations used for future predictions with a limited meaning in reference to evidence used in jurisdiction topics.

Judgements based on probabilities are very problematic in administration use. Compare this to judgments based on probabilities of future crime incidents (e.g., the science fiction idea of establishing a "department of pre-crime" [4]).

In most modern justice systems, judgements are based on facts and afterwards (ex-post), not in advance (ex-ante). Reference is made to the factual evidence, and not to potential future evidence. Laws are meant to provide a frame for moving and in doing so already represent the safeguard. Penalties become effective only for deviations, for exceeding thresholds of the frame.

Administration and jurisdiction rely on evidences and facts which represent the empiric.

In the best case, simulations could be used in the process of licensing before launch where the rules are defined under which circumstances the space object operations should happen.

6 CYBERNETICS: A SYSTEMIC APPROACH

The problem about most of the current risk assessment methods in the space domain is that they in fact describe the relation, interaction and behaviour of objects or operators to other objects or operators.

This can hardly be named as a cybernetic or systemic point of view. Interpreting ESAs MASTER SW implementation [5] as a systemic view to the environment, the look to the systemic interaction of the elements is based on stochastic theories leaving aside the active behaviour of the elements controlled by humans or computers.

But the relation, interaction and dynamics of objects owned by and the behaviour of the operators towards a system, towards the public, towards society in general, requires to see sustainability in conjunction with the public, with society.

The one-to-one analysis is often a necessary abstraction to avoid that the system model would get too complex.

Cybernetics, the systemic approach, defines a model for the risk to the overall system (including the service users on ground) rather than attempting to create a model for the system itself. That way, it avoids the aforementioned complexity problem.

The price for this is a lower accuracy compared to the other methods – which is one of the reasons why we consider both approaches not mutually excluding each other, but complementary.

In addition, the use of Cybernetics allows to define rules to reduce risk to the system. From a Space Domain Management point-of-view, this would answer the question of what is endangering space-as-a-system, with the involved elements including their properties.

When modeling the risk from empiric data, there is a lot to learn about the dynamics of the system.

The graph below shows the object and conjunction count for objects originating from Cosmos-1408, the former Soviet satellite which was destroyed in November 2021 through a Russian Anti-Satellite Weapon Test (ASAT).

As can be seen from the graph, the number of objects is not necessarily a good risk indicator and the number of close conjunctions is clearly not only depending on it – while one might have expected a direct correlation.

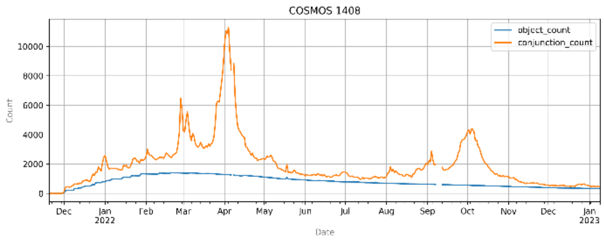

Figure 1. Example Object vs. Conjunction Count <5km (Cosmos-1408)

7 CYBERNETICS KPIs

As stated above, there are two main differences to the other KPI approaches:

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- Modelling the Risk instead of Modelling the System
- Risk is not only collision or breakup risk, but also includes endangerment

Therefore, each close approach of two objects beyond a defined threshold already counts as an event of risk-making.

A Cybernetics KPI for risk modelling of operator behaviour towards the system could for example be the Number of Conjunctions < 1km (or 500m or other threshold distance) for the operated satellite or constellation. This is a measurable KPI in the area of governance vs. person. The figure below shows an example of a monthly statistics of such close conjunctions, filtered for selected fleets/operators, expressing the number of endangering incidents in the responsibility of the respective operator.

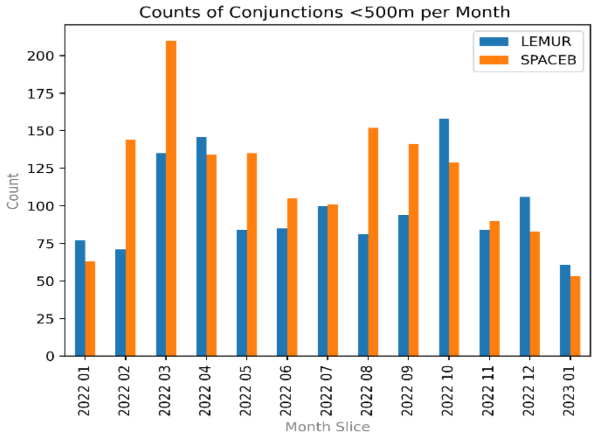

Figure 2. Example Monthly Statistics of Conjunctions <500m for selected fleets/operators: LEMUR (Spire) and SpaceBEE (Swarm Technologies)

A second Cybernetics KPI, targeting the operations of large constellations is the Cascade Potential KPI we presented at the AMOS conference 2022 [6]. Considering analogies to epidemiology, we discover the important difference between repeated conjunctions with the same other object versus conjunctions with many different objects. From this, we derive both an Individual and a System Cascade Potential KPI. In the context of the present paper, the Individual Cascade Potential KPI is of interest.

8 OUTLOOK

First implementations of these KPIs are currently done in the STROM (Space Traffic Reports for Orbital Management) software which is developed in co-operation with the European Space Agency who supports it with a GSTP De-Risk activity.

In a next step, these parameters should be made available on a day-to-day basis. This would allow to study the impact of such parameters to space operators and their behaviour, and possibly allow extending the view also to the entire space industry. On the other hand, the impact of the application of these KPIs in the light of the resilience of space services needs to be further studied.

9 CONCLUSIONS

In this paper we showed and compared existing established parameters used in space operations to express threats to the environment. We assessed them for usability in the context of requirements from law-making, administration and jurisdiction. We also introduced a new parameter retrieved from the requirements and combined it with an already published one representing threats to the environment.

Following the philosophy of law, any threat to society shall be judged based on the behaviour of one or more persons or legal entities. To establish and to safeguard a sustainable and resilient living together, behaviour rules are established with the aim of preventing threats to society. These rules are converted into laws and regulations by the legislation, implemented by the administration, and executed by jurisdiction.

The proposed Cybernetics KPIs could be used to regulate endangerment to the well-being of society. Moreover, deviations to laws and regulations can be identified on the merits and to the extent. This enables the possibility to judge the behaviour of space actors – based on the proposed KPIs – as compliant, or as negligent or even intentionally endangering the sustainable and resilient well-being of society.

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