LONG-TERM DATA ANALYSIS FOR IMPROVED RISK ASSESSMENT REGARDING ORBITAL ASSETS

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ABSTRACT

In our paper, we try to show the added value of a holistic approach to risk assessment regarding orbital assets – not as opposed to, but – as a complementary approach to the commonly established analysis and forecast of single events and their respective criticality. Applying emerging technologies and procedures such as long-term data analysis through Big Data processing, we present the concept of a Space Pandemic Dashboard to be used for visualizing, monitoring and analysing the overall risk and criticality in the "system" of anthropogenic outer space critical infrastructure. In addition, we outline a way how this approach can be embedded in the existing UN-SPIDER disaster management framework, to support Space Traffic Management and the enforcement of Long-Term Sustainability in Space.

1 BACKGROUND

Most of today's Space Surveillance and Tracking (SST) solutions [16] and their usage scenarios consider risk assessment in the form of forecasting single events on a day-to-day basis, such as supporting collision risk analysis by providing conjunction prediction messages. While this represents a highly adequate quick-response process triggering the appropriate crisis management actions, this approach usually neither considers past events and historical anomaly evolutions nor does it lead to further forecasts beyond the single events in focus.

Big Data (BD) analytics helps approach the problem in a different manner. Like for satellite telemetry and satellite communications [14][15], long-term data archives of orbital data and resulting multiple conjunction prediction data can be evaluated under the rules of systemic principles, logical constraints and methodological procedures to reveal insights on highly complex dependencies. These insights are seen as a potential key to performing an assessment of a "global" risk in outer space activities, to describing its history, and – considering relevant scenarios – to forecasting its potential future evolution.

Various efforts are made around the world to implement a Space Traffic Management (STM) [9][10] with the goal to comply with the UNOOSA COPUOUS Long-Term Sustainability Guidelines [1]. These efforts show:

- the absence of a subordinate guiding methodology and framework structuring and coordinating all activities,
- missing metrics to measure success, deviations with comparable key performance parameters (KPI's)

To eliminate the shortcomings a worldwide accepted framework, the UN-SPIDER Sendai Framework [2], is proposed. This disaster management framework requires in Priority 4 (Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction) the monitoring of the actual risk of hazards.

In our paper, we also discuss the path towards a Space Pandemic Dashboard (as an analogy to current climate change and corona virus visualizations) and how historical data and its analysis can contribute to predicting future evolutions. Like in the relation between weather forecasting and climate analysis, like in the relation between medical status and epidemiological scenarios, the steps described represent the advancing from Space Debris Event Monitoring to Space Debris Risk Management.

We draft the elements for a "global" risk estimation process and attempt to visualize the various risk drivers and their interrelations. When we speak about risk in this context, we need to distinguish between the risk on the pure orbital infrastructure, i.e., the risk on the investment, and the operability of orbital objects including the availability, reliability and integrity of the services realised using these assets, i.e., the operational risk (which, as we know, leads to the business continuity risk).

Our current analyses are performed on the basis of publicly available data such as the TLEs provided by CelesTrak / Space-Track [11][12][17][18]. We shall discuss the advantages and limitations of this current range of data and their sources, and also the advantages and limitations of using further – parallel as well as complementary – data sets. This includes a critical view on the aspects of data integrity, data correctness and data usefulness and present an outline of possible future developments.

Proc. 8th European Conference on Space Debris (virtual), Darmstadt, Germany, 20–23 April 2021, published by the ESA Space Debris Office
Ed. T. Flohrer, S. Lemmens & F. Schmitz, (http://conference.sdo.esoc.esa.int, May 2021)

2 AVOIDABLE AND UNAVOIDABLE CONJUNCTIONS

At Space Analyses (Vienna), we performed a data analysis of roughly 2.75 million conjunctions < 5 km over an observation time of 164 days from autumn 2020 to spring 2021, as shown in Figure 1. It shall, of course, be noted that a conjunction does not necessarily always result in a collision, but that each close conjunction represents a high risk of an actual collision.

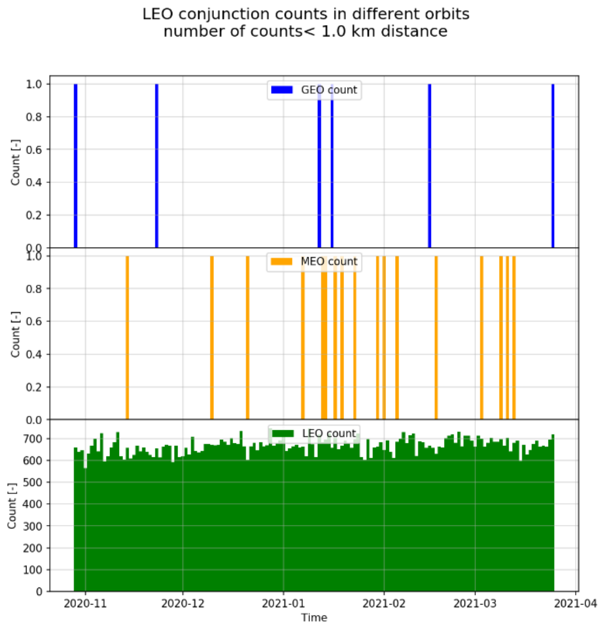


Figure 1: Conjunction counts in the different orbital regimes (GEO, MEO, LEO)

With this analysis, we found a set of developments which could enrich the current discussions on Space Traffic Management (STM) and Space Environment Management (SEM) [3]. The systemic look to the conjunctions should bring answers, e.g., identifying "regions" of increased collision risk, and show actual trends.

In outer space, we can distinguish between **avoidable conjunctions** (i.e., conjunctions where at least one of the two objects is manoeuvrable) and **unavoidable conjunctions** (debris potentially hitting other debris or any other non-manoeuvrable object).

There seems to be no publicly available data on which types of objects in the common databases (still) have active propulsion systems, but using the age and type of the object, we can make an assumption that, in LEO, only relatively new objects which are of a certain size qualify as "payload with propulsion".

In addition, the concept of "traffic lanes" in outer space helps distinguish certain areas with different risk levels. In the given model, steps of 50 km in orbit heights are chosen as "orbital lane" definition. These two main classifications build the frame to look on different aspects of conjunctions in a daily timeframe. The data used as input is the publicly available TLE data from Space-Track and although there is a limitation on the accuracy of single objects, the data is usable for long period analyses (~20,000 objects of a diameter > 10 cm).

3 CONJUNCTION PROBABILITY

As an approach to get a general view of the actual situation in outer space orbits, the probability of a statistical conjunction <10m ("close") was considered as a basis for evaluating collision risk (based upon actual accuracy of the space object position). The relative object dynamic of the space objects to each-other gives an estimate of that risk. Figure 2 shows the initial analysis results of such close conjunctions over time.

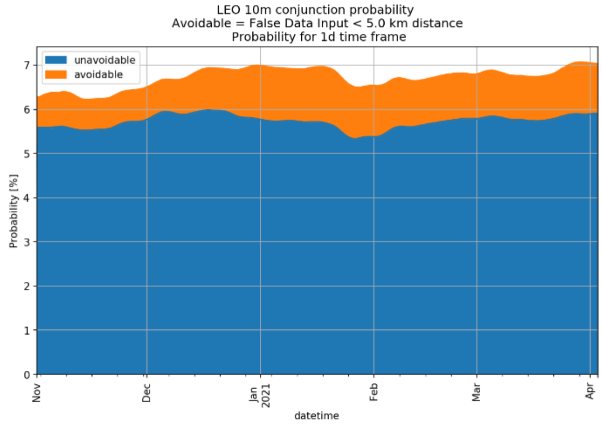


Figure 2: LEO 10m conjunction probability

This means not only the number of objects in the lane/area, but also the relative position of all objects in the "swarm" influences the collision risk. The daily probability of a <10m conjunction for all orbits in early 2021 turns out to be around 7% which means that statistically, each second week, two objects are <10m apart. The probability at the end of November 2020 was around 6.2%.

The statistical time between two subsequent conjunctions <10m (in a similar sense as the mean time between failure (MTBF) of a system) at the end of November was 2 days longer than today. This means that the probability of conjunctions (and, hence, the probability of collisions) increases as the time between conjunctions gets shorter.

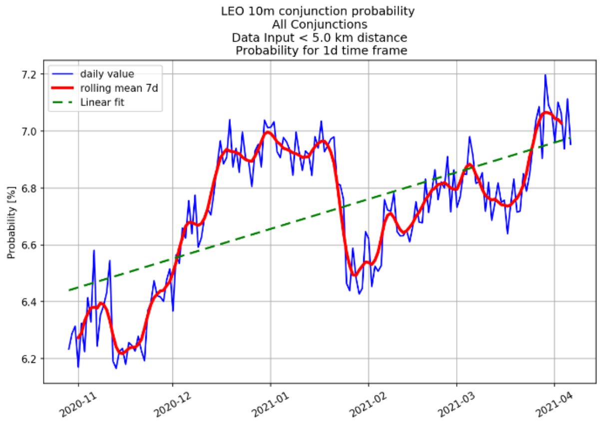


Figure 3: LEO 10m conjunction probability evolution over time

The graph in Figure 3 shows the daily probability in blue, the running mean of 7 days in red and the progression line in green.

If we now separate the avoidable and the unavoidable conjunctions, we arrive at Figure 4 for the avoidable conjunctions and Figure 5 for the unavoidable conjunctions.

Assuming a linear fit, the increase of unavoidable conjunction probability is slow, but steady. On the other hand, the increase of avoidable conjunction probability seems to be the main driver of the overall increase in conjunction probability. Let us note this for now; we will come back to this finding later.

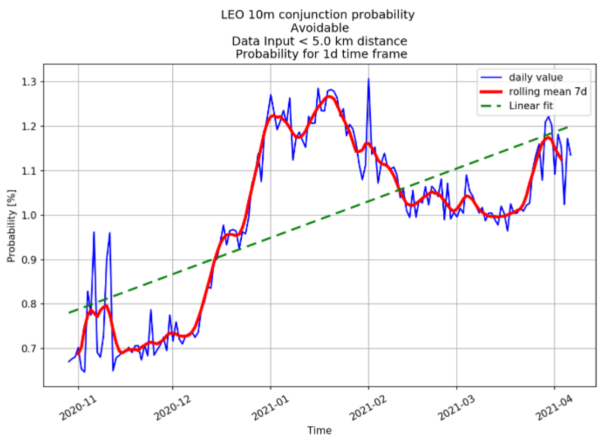


Figure 4: LEO 10m conjunction probability evolution over time (Avoidable)

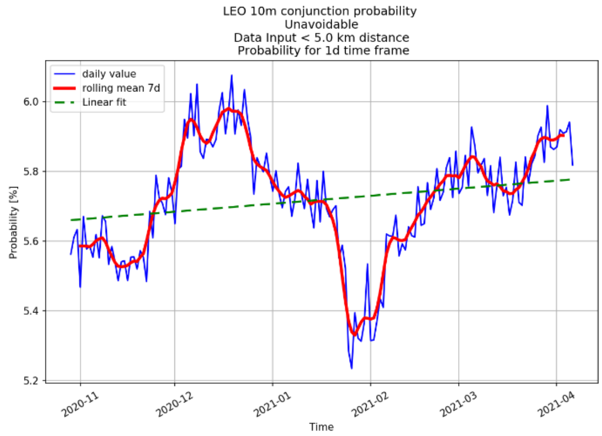


Figure 5: LEO 10m conjunction probability evolution over time (Non-Avoidable)

4 OBJECT AGE

In a next step, we looked at the question how long objects involved in conjunctions have already been up in space. Answering this question can help distinguish between the risk in a more-or-less settled "space system" – including follow-on risks by collision and fragmentation events in that system – and the additional risk contributions by adding further anthropogenic input such as large amounts of small satellites as part of megaconstellation installations.

We define the age of an object by the time since the launch date of the object noted in the object ID. (This means in case of a fragmentation event all fragments are considered to be of the same age as the original object.) Resulting from this, we can draw a scatter plot for conjunctions by putting the object age on the x and y axes, respectively, and then counting the number of conjunctions with objects of same age regimes, displaying the result of this count as the size of a bubble in the plot.

When we further distinguish the avoidable conjunctions on the right-hand side of Figure 6 from the unavoidable conjunctions on the left-hand side of Figure 6 in separate diagrams, we can see that those diagrams expose information pertaining to the aforementioned distinction between the more-or-less settled "space system" and the additional risk contributions by adding further anthropogenic input.

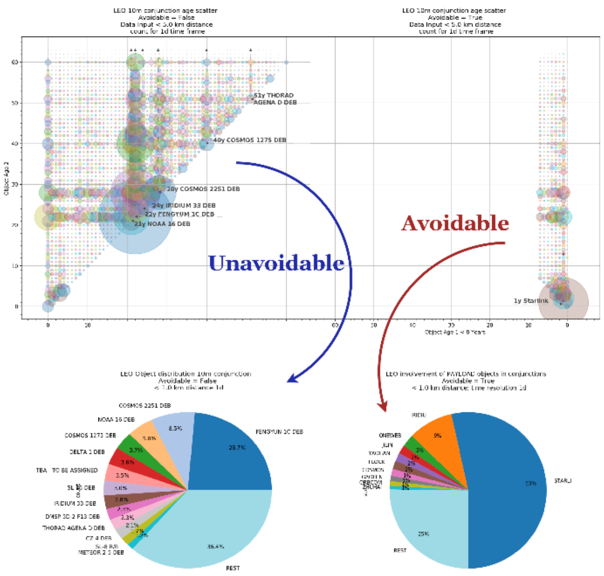


Figure 6: LEO 10m Conjunctions sorted by object age

This object-age related plot exposes some very interesting and significant findings.

Some – mainly unavoidable – conjunctions involve items that have been orbiting for >60 years in space, which means items from the very beginning of space exploration. The age of Fengyun 1C, for example, is 23 years, NOAA 16 is 22 years and Cosmos 2251 is 27 years. Most of these items are defunct or at least non-manoeuvrable by now, which is why they appear on the left part of Figure 6. This gives some indication of the involved objects and their impact to conjunction counts leading to some kind of "natural growth" of debris.

The distribution of objects in the left pie chart of Figure 6 shows that the "well-known suspects" such as Fengyun 1C debris, Cosmos-2251 debris and NOAA 16 debris lead to the majority of the conjunctions.

The small bubble close to the origin shows conjunctions involving items from the recent 1-2 years – stuff such as upper stages meant to re-enter within a couple of months to years, but also satellites which have failed or disintegrated within a short time after launch.

The age scatter plot for avoidable conjunctions (right-hand side) gives a clearer picture of how new (and thus manoeuvrable) items interact with each other and with the existing objects in orbit. The diagram is filtered for conjunctions where at least one of the objects is younger than 8 years, mainly because this is the age band for which we expect that more or less all of the objects are still manoeuvrable.

The largest bubbles (i.e., the highest conjunction probabilities) are close to the origin of the right part of the diagram extending over about 1-2 years. This leads to the interpretation that most of the conjunction risk in avoidable conjunctions is between the most recent satellites.

The distribution of origins in the right pie chart of Figure 6 shows that the majority of those "newcomer" conjunctions are caused by mega-constellations such as Starlink and OneWeb. The Iridium constellation also plays a role here, on the one hand considering the number of satellites in the constellation, and on the other hand considering the contribution of the Iridium NEXT constellation upgrade over the past few years.

Does this explain the increase in overall (and most of all, avoidable) conjunction probability of more than 60% over the time period considered for the present analyses? It seems to fit into a pattern, but first, a few further investigations need to be made.

5 CROSS TRAFFIC

In the analyses and discussion presented here, we define an **orbital lane** as a shell of 50km thickness around the Earth. This systemic view is comparable to a traffic lane on a highway.

Like in a traffic lane, in collisions which happen between two objects moving more or less in the same direction (rear-end collisions) the velocity difference (relative impact velocity) is comparably small and so is the kinetic impact energy. The diffraction cone of the resulting fragments is rather limited too. Due to the limited velocity delta, those collisions are also easier to estimate.

Head-on collisions have the highest velocity delta, adding the velocities of both objects, and therefore also a high kinetic impact energy. However, since the uncertainty ellipsoids are more or less parallel to each other, like for the rear-end collision, the time dimension is not as relevant as with other collision angles. The challenging parameter in this case the collision probability and its dependency on the accuracy of the orbit data.

But the really nasty collisions are those with cross traffic cutting sideways through the lane. For orbital lanes, this is even worse, as the cross traffic can cut through in "three dimensions". The event of a cross traffic collision has a high potential to spread the items into other orbits or, if it is in the same (mega) constellation plane, to spread over the complete constellation.

Looking at the avoidable conjunction angle distribution (Figure 7), a "porcupine"-like picture leads to the following possible interpretation: Sharper peaks are more regular and repeat. Very regular conjunctions are most probably from the same constellation and not from debris. In the given chart the conjunctions at 40° and 50° are within the same constellation. The peak at 100° seem to be rocket bodies and the rest are conjunctions with other items or debris. The peaks between 135° and 170° are classical debris conjunctions as they show the distribution of the collision cone in the conjunction angle.

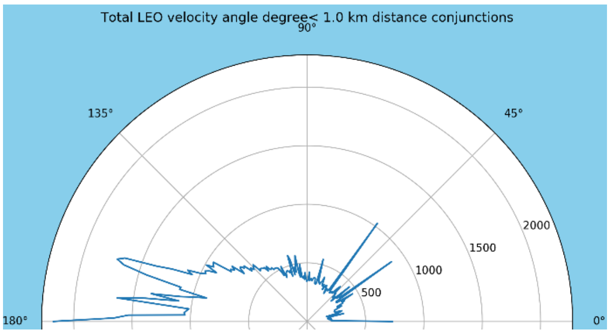


Figure 7: Conjunction angle distribution (avoidable conjunctions)

The plot of the unavoidable conjunctions (Figure 8) shows no sharp peaks which appears to be a logical conclusion as the distribution of space debris is not controlled and thus spread out in several directions. It also shows a clear peak in the directions between 160° to 180° i.e., nearly frontal with velocity deltas up to 14km/s or above.

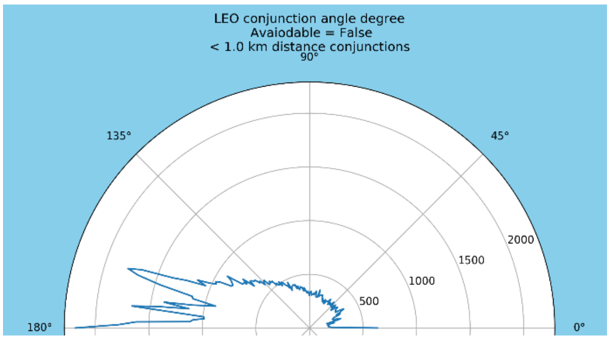


Figure 8: Conjunction angle distribution (unavoidable conjunctions)

6 ORBITAL LANE CONJUNCTION PROBABILITY

The split of the risk of a <10m conjunction into orbital lanes, the recalculation of the conjunction probability for each lane per day separately in the plot (Figure 9) shows the distribution is per lane and how it changes over time. The <10m conjunction probability has a similarity to the number of conjunctions but not in the same form.

The number of days between a conjunction is the inverse value of the daily conjunction probability, multiplied by 100. The conclusion here is that using TLEs does not show a significant risk of a conjunction or collision as, for example, in the 600km orbit lane the conjunction probability is only 0.2% which leads to a statistic time gap of 500 days.

The given data is based on the TLEs which represents more or less all parts >10 cm.

Smaller parts (we call them "noise") are not included in the probability calculations. There are estimates of 600,000 to 800,000 of space debris parts >1cm. The kinetic energy of a 1cm³ aluminium part with a speed of 14km/s represents the impact of 4.5kg steel with the speed of an artillery shell so also these small parts can destroy or significantly damage a (dead or active) object in space and produce additional space debris in an unknown factor. If now this "noise" (unknown small objects) is taken into the probability calculation the actual status can be multiplied by something between 28 and 38 (or the time gap between two <10m conjunction events as above described divided by this factor). The factor between 28 and 38 is the relation between the number of parts >1cm and the number of parts >10cm.

If such "system noise" (estimating all items >1cm) gets added to the evaluation, the time gap is reduced to 14 days.

An interesting detail that can be retrieved from longer-term analysis of the orbital lane conjunction probability is that changes in this probability become very visible (see Figure 9).

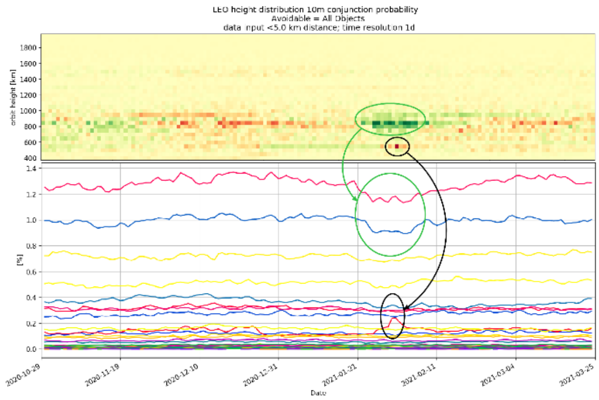


Figure 9: Orbital Lane conjunction probability over time

The reason for the changes is not always as easy to find out, and further work is required to correlate these findings with known manoeuvres and incidents, in order to rule out the known part and get closer to understanding the unknown part of the risk.

7 A CLOSER LOOK ON MEGA-CONSTELLATION CONJUNCTIONS

Using the previously mentioned details of each object, it is possible to use the information as filter criteria to produce specific analysis diagrams for specific questions.

As an example, we tried to get a view of all conjunctions of the Starlink constellation, as shown in an orbital lane conjunction probability diagram (Figure 10) in which we marked

- all constellation-internal conjunctions in red colour,

- all conjunctions of a constellation member with an external object in yellow colour
- and all other avoidable conjunctions in grey.

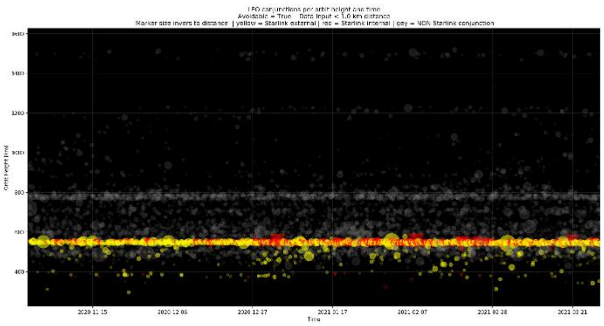


Figure 10: Orbital Lane conjunction probability over time, focusing on Starlink constellation

The high-risk events within the given constellation are represented by the size of the bubbles (higher risk is bigger size). The regularity of the internal conjunctions within the constellation appears as red lines in the same orbit height. In the given data set the closest conjunction was between STARLINK-1206 and STARLINK-1618 as happened on the 2021-01-02.

Note that the diagram in Figure 10 corresponds with the data presented in Figure 9. The filtering approach is a possible path to a stepwise assessment of the aforementioned probability deviations detected over time.

8 A SPACE PANDEMIC DASHBOARD

Combining the various views presented in this paper we propose to visualize the regularly updated information in a "Space Pandemic Dashboard". This is in analogy to pandemic dashboards in epidemiology, which most of us have become acquainted to over the past years.

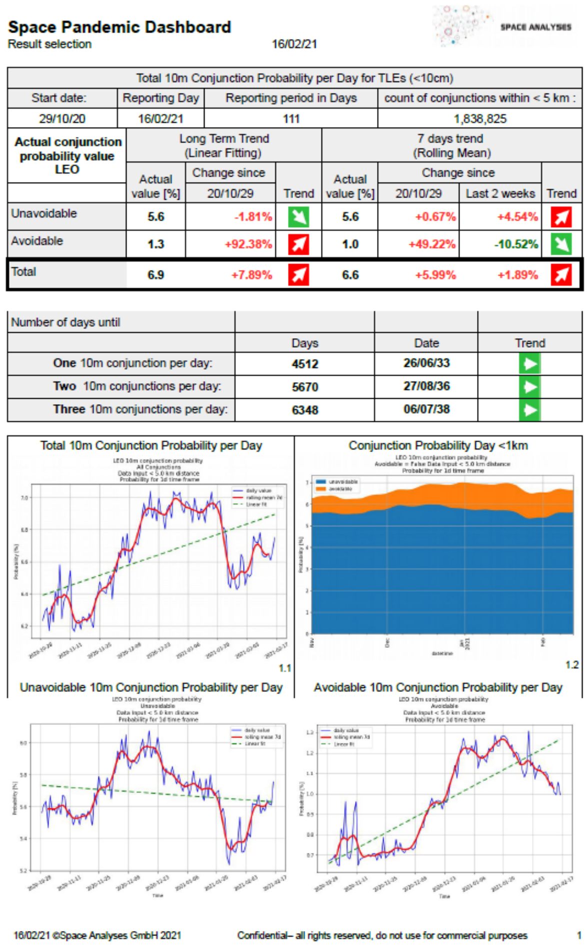
What is the difference between a Space Pandemic Dashboard and a Space Situational Awareness Dashboard (e.g., as used by EUSST [13])?

A pandemic dashboard takes its information from historic data logs, trying to figure out the most likely trend. It does not focus on single events and it does not focus on highly complex mathematical algorithms to calculate as exactly as possible the further evolution of single events.

A pandemic dashboard is a top-down statistical approach, not a bottom-up algorithm. Statements derived from such a dashboard are always based on statistical probabilities of a large sample rather than uncertainties about single objects and their movement.

A pandemic dashboard, as the name says, describes a pandemic behaviour. A normal operator dashboard would assume everything is in order until single events pop up as notifications of deviations from the normal situation. A pandemic dashboard starts from the systemic assumption that there is an ongoing deviation from a desirable state (which is more like a vision, such as: no collisions at all) and this ongoing deviation is represented by the assessment of a risk and, in case the risk materializes, by the assessment of the damage and the subsequent change in overall risk as a result of the materialization.

A pandemic dashboard is therefore more like a stock exchange ticker rather than a management console. The conclusions derived from the dashboard information are not meant to trigger immediate emergency actions, but influences to the mid- to long-term strategic planning and orientation – of a satellite operator, a Space Traffic Management or Space Environment Management organization, a spacefaring nation or, in the overall consequence, the worldwide space community.



Total 10m Conjunction Probability per Day for TLEs (<10cm)							
Start date:	Reporting Day	Reporting period in Days		count of conjunctions within < 5 km :			
29/10/20	16/02/21	111		1,838,825			
Actual conjunction probability value LEO	Long Term Trend (Linear Fitting)			7 days trend (Rolling Mean)			
	Actual value [%]	Change since 20/10/29	Trend	Actual value [%]	Change since 20/10/29	Change since Last 2 weeks	Trend
Unavoidable	5.6	-1.81%		5.6	+0.67%	+4.54%	
Avoidable	1.3	+92.38%		1.0	+49.22%	-10.52%	
Total	6.9	+7.89%		6.6	+5.99%	+1.89%	

Number of days until	Days	Date	Trend
One 10m conjunction per day:	4512	26/06/33	
Two 10m conjunctions per day:	5670	27/08/36	
Three 10m conjunctions per day:	6348	06/07/38	

Figure 11: Space Pandemic Dashboard (example)

An example for such a Space Pandemic Dashboard is presented in Figure 11. Part of the dashboard is dedicated to presenting changes in trends in comparison to previous days or weeks, part of it is used to present the longer-term evolution of the data itself, including categorization, proposed filtering and identified correlations. The dashboard can be a concise representation in one page, or it can be a regular report of a number of pages, including all of the different views as presented in the previous sections of this paper.

9 THE UN-SPIDER SENDAI FRAMEWORK AS A USEFUL CONTEXT

The event of a sudden outage or a slow evolution to an outage of the satellite infrastructure leads to significant changes in the socio-economic living on Earth, at least for the technology depending societies and represents a disaster according the UN-SPIDER disaster-risk definition: *“the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity”* [2].

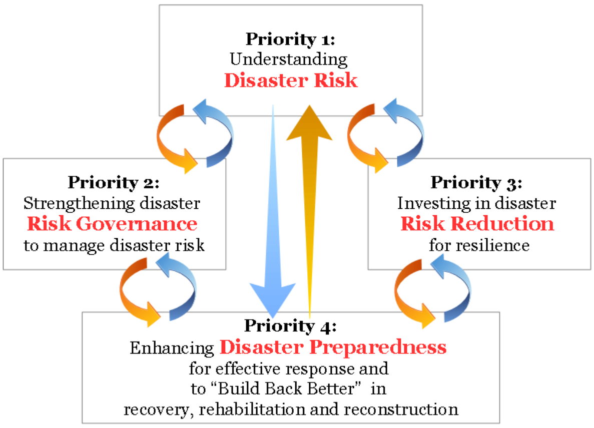


Figure 12: UN-SPIDER Sendai Framework

Taking the UN and disaster risk reduction approach the following priorities are applicable (see Figure 12):

- Priority 1: Understanding disaster risk
- Priority 2: Strengthening disaster risk governance to manage disaster risk
- Priority 3: Investing in disaster risk reduction for resilience
- Priority 4: Enhancing disaster preparedness for effective response and to “Build Back Better” in recovery, rehabilitation and reconstruction

10 PRIORITY 1: UNDERSTANDING DISASTER RISK

In the context of the Sendai Framework, the single outage of one spacecraft would not yet represent a disaster, but it can lead to a significant degradation of the “system” in service provision or of the overall usability of outer space.

Going back in history, the NOAA polar orbiting environmental satellite fragmentations, the end-of-life troubles of Envisat, the Cosmos-Iridium crash and the Fengyun-1C anti-satellite missile test are examples of such incidents over the past 20 years.

These events do not fall under the classification of a “disaster” as they can be seen as single “local” events without an immediate influence to the total system.

With the launch of the first mega-constellations with their thousands of satellites, the risk of a chain collision becomes significant. In the event of a chain collision, the subsequent degradation of services and of the usability of outer space will happen in the order of occurrence:

- Terrestrial monitoring/measurement of space objects (debris and active satellites) will be curtailed due to the enormous number of new parts in the scenery resulting in a loss of perceptive faculty of discrimination
- Outage of the services from the infected mega-constellation in the same “orbital lane”
- Spread of the infection to other “orbital lanes” from orbital objects in cross traffic
- Outage of other services like Earth observation and telecommunication
- Necessary evacuation of the ISS due to a loss of space debris monitoring capability and possible debris spreading
- Infection of complete LEO orbit section
- Infection of MEO orbit section
- Infection of GEO orbit section

Sokolova & Madi show in their 2019 paper [4] the vulnerability of assets depending on the outer space system infrastructure. Taking Figure 13 as a guidance, the socio-economic impact to the society is enormous.

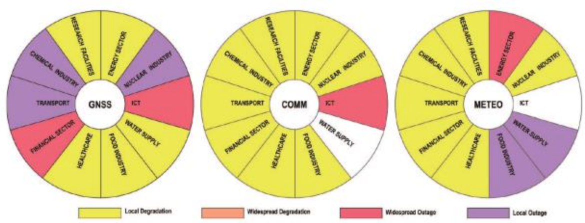


Figure 13: Terrestrial critical disruptions caused by the loss of multiple space assets loss (Source: Sokolova et al. [4])

The above event series have the characteristics of a disaster according UN-SPIDER risk description.

11 PRIORITY 2: STRENGTHENING DISASTER RISK GOVERNANCE TO MANAGE DISASTER RISK

In context of outer space, the UNOOSA COPOUS Long Term Sustainability Guidelines (LTS) [1] cover the clear vision. A number of national states (but by far not all) have already implemented national space laws with the vision of the LTS to cover the plans and competence.

The problem lies in the multi-nationality and in the definition of outer space as "common heritage of mankind" [5] to find a way for clear plans, competence, guidance and coordination of all countries and cultures. Never the less it is possible to implement laws on national level to create rules for behaviour in outer space and/or in connection with space missions, so that operators acting within this specific national state or their partners/suppliers/service providers have to comply to these national LTS space law implementations.

Actual Disaster risk governance in outer space covers prevention, a certain amount of mitigation, little preparedness and, so far, not much concerning response, recovery and rehabilitation. This will have to be tackled in the coming years (see, e.g., [8]).

12 PRIORITY 3: INVESTING IN DISASTER RISK REDUCTION FOR RESILIENCE

Today a number of activities for prevention and mitigation of risks in outer space exist. Funding for different projects of ESA (e.g., Clean Space, CREAM), of EU (e.g., EUSST) or of different national projects for space debris removal shall be mentioned here, as well as all military activities limited to surveillance of the space objects by private investments in space debris and object measurements. A global problem is that the major capacities in optical monitoring assets (telescopes and laser ranging) are operated by scientific organisations and cannot offer a guaranteed day-to-day data collection which is necessary for safe space operations.

According to [6], the US government spends $15 million to provide basic Space Situational Awareness (SSA) data and basic Space Traffic Management services to the public, based on the publicly releasable portion of the Department of Defence catalogue supported by the US Space Policy Directive-3 dated 18 June 2018 focus specifically on STMsdfootnote4sym [7].

Activities like the ESA space weather and near-earth object reporting are also an important contribution to the safety of space craft operations and to the governance of long-term sustainability guidelines for space.

13 PRIORITY 4: ENHANCING DISASTER PREPAREDNESS FOR EFFECTIVE RESPONSE AND TO "BUILD BACK BETTER" IN RECOVERY, REHABILITATION AND RECONSTRUCTION

In the context of an outer space disaster, we need a reliable and resilient cooperation of complementary levels/entities

- Governments, industry and research institutions
- Operators, manufacturers and regulators
- Global and local levels
- Employed professionals and volunteers
- Administration and public

This cooperation needs to be based on appropriate data sources, processing capabilities, guidance instruments and most of all, a mutual open approach to regularly exchange information and opinions, to trust each other in the joint preparation for and handling of space-related disasters.

14 OUTLOOK

The systemic and open approach of analysing, correlating and visualizing jointly measured long-term data regarding orbital assets (or rather, all anthropogenic objects in orbit) presented in this paper is proposed to serve as a solid background to establish and maintain such cooperation.

Further matching with the proposed use of the UN-SPIDER Sendai Framework for Disaster Risk Reduction needs to be elaborated and matched with the legal, technical and political realities, deriving inputs for the further implementation steps both on governance and on technology side.

Of course, the use of long-term data analyses of anthropogenic orbital objects is not limited to earth orbits. A similar approach could also be applied to e.g., Lunar or Martian orbital regimes. We may not have too many objects orbiting around Moon or Mars so far, but this is quite likely to change significantly over the next decades.

15 GENERAL CONCLUSIONS

We have shown how the holistic approach can help use existing as well as emerging technologies and procedures in a broader context, promoting the use of long-term, global data and modelling information. This should become an input for decision making in the governance implementation of political, administrative and economic institutions.

It can serve as an initial contribution triggering further research and discussion in the move from Space Situational Awareness to Space Traffic Management, and from Space Sustainability Guidelines to an operational implementation of Security in Outer Space (which ESPI defines as "Protection of the Space Infrastructure against natural and man-made threats or risks, ensuring sustainability of Space activities.").

16 REFERENCES

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