A systems theory approach for evaluating the cascading collision potential of orbital shells

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ABSTRACT

Understanding the probability and the impact of cascading collisions in earth's orbit turns out to be one of the more controversial topics in space sustainability and risk management. A lot of work invested over the past decades and especially in the last years has led to a better understanding of fragmentation and collision processes [1][2]. The fragmentations and collisions which took place during that time served as real-life examples to validate or falsify model approaches, and to refine them. So far, we have not seen cascading collisions leading to what has been described as the "Kessler syndrome" decades ago [3][4]. Similar to climate change, it is not possible to determine exactly when the tipping point will be reached, but we know we are moving closer to it every day.

Using a systems theory approach, the goal of our research was to enable a perspective which is not meant to be contrary, but rather complementary to existing astrophysics and astrodynamics approaches which mostly care about conjunctions and collisions as risks for single objects, their dynamics and interaction with other single-object items.

We show how we can learn from available data and its correlations rather than feeding Monte-Carlo method results into theoretical models. We show how we can use traffic lane analogies from a system traffic point-of-view rather than from a moving-object perspective only. We show how understanding impacts of internal and external changes to orbital shell systems can provide added value for decision-makers that designing better-than-required criteria as thresholds for space sustainability awards on a per-object basis cannot yield.

We use existing measurement data, collected and assigned to altitude- and time-based systems of space objects, for analyzing the interactions of space objects and their evolution over time. This leads us to parameters describing the risk and the potential of cascading collisions. Other than the collision risk obtained by traditional astrophysics and astrodynamics methods [5][6], this cascading potential does not tell something about single object risks, but says something about the overall system, about the likelihood an "infected" object can "infect" further objects. Such potential analyses can be performed for different orbital shells and object types with the cascading potential change over time allowing an interpretation of the past, of the current situation and for future scenarios.

We show that for the calculation of the cascading potential, there is a difference between an object repeatedly meeting the same other object, and an object meeting many different other objects on its daily journey. Like in epidemiology, the risk of spreading an infection in a population is much bigger if there is a bigger exchange between many. (Note that this is different from the other perspective of the individual risk of getting infected [7][8].)

The resulting parameters and their variation over altitude and time can be used to identify trends, to assign priorities and, therefore, to support decisions e.g., in Active Debris Removal (ADR) planning, but also for life-time extension and Post-Mission Disposal (PMD) considerations [9]. All of these are important tasks on the way to a sustainable use of outer space by our and future generations, which is the guiding vision to which we dedicate our efforts.

1. SPACE TRAFFIC DATA

Most Space Environment Reports today – like those produced by Space Agencies [10] [11] – sum up the number of and the mass of objects in orbits. The result is like an inventory where the objects are listed including some classifications. Looking at the traffic situation from an *advocatus diaboli* position, such reports do not make any distinction whether all parts are orbiting in the same direction with stable distance to each other or whether all parts are flying in a direct collision course.

Fig. 1 below shows the total amount of objects in orbit, differentiated by the object class.

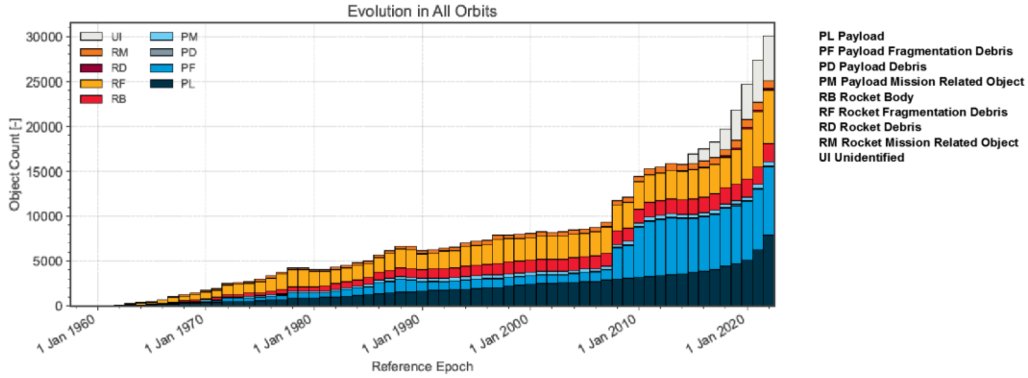


Fig. 1. Evolution of number of objects in geocentric orbit by object class (Source: ESA [12])

These reports neither show the dynamics (interactivity) of the objects in space-as-a-system, nor do they show the risk resulting from the objects' kinetic energy. For comparison: In road traffic, the risk of collision at a crossroad depends on the number of conjunctions of cars in a specific time and on their relative speeds. Making this information accessible and processing it in addition to the existing data is the key to a holistic understanding of orbital risk.

2. SYSTEMS THEORY

Hall et al. [13] describe a system as "a set of objects together with relationships between the objects and between their attributes."

Systems theory [14] provides a useful approach to the interaction of orbital entities, since it not only offers a framework to describing the boundaries, as well as the interactions within a defined system, but also the effects on entities outside of the system i.e., "the environment".

In this context, systems are defined by
- their borders in Space and Time,
- the correlations and inner interaction of the elements within the system,
- the system interaction with the environment.

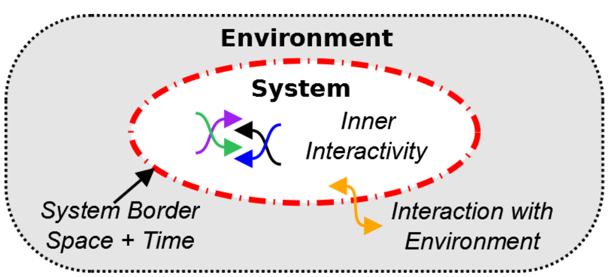


Fig. 2. System Definition

As shown in Fig. 2 above, the system is defined as
- a group of internally interacting elements (inner environment),
- embedded in an "outer environment".

The (interaction) events within the system's space and time boundaries represent the *System Process*.

When viewing *Space as a System (SpaaS)*, the focus changes from the description of individual elements - usually with the unspoken goal of achieving an exhaustive collection of exact data to describe and predict behaviors in a 1:n relationship - to a holistic approach that introduces a clearer picture of areas of potential interaction: in the specific case of collision risk, a heat map of the m:n interaction potentials.

The underlying questions which drive the description of *Space as a System (SpaaS)* are in the areas of

- the cybernetics to regulate the "uncontrolled" system processes,
- the system behavior description of the interaction of the elements with possible risk scenarios,
- the description of system effects not covered by traditional case-by-case risk analytics to reach a point of impact descriptions,
- the definition of first metrics of impact and likelihood scales to obtain a system vulnerability rating.

3. RISK

ISO defines risk as the effect of uncertainty on objects [15]. Since the goal is to create a quantifiable and verifiable framework for a *System Risk* (not the risk as an attribute of individual entities) (cf. also [16]), a few more definitions are needed:

- Spatial boundaries: *System Space* – the (physical) volume of space in which the system-relevant entities reside. For our purposes these will be orbital shells.
- Temporal boundaries: *System time* – the interval for which data will be analyzed.
- Individual risk: the amount of event-trigger risk that an entity carries within the defined *System Space and Time*.

With the above definitions, the System Risk of a conjunction can now be determined as a consequence of the orbital shell (*System Space*) and time (e.g., 24h – *System Time*) and by calculation of the number and distance of the conjunctions within this system (Interaction as a process).

Every conjunction within the above *System Definitions* contributes to the system risk. Therefore, every element involved in a conjunction in the space and time boundaries given carries an *Individual Risk* describing the probability of a close conjunction *within the System* [17].
The *System Risk* is the aggregate risk that all the individual conjunctions contribute to. Note that, in addition to the number of conjunctions per day, also the relationships of conjunctions to each other (spatial and temporal distribution) have an influence on the *System Risk*.

4. CONJUNCTIONS AND COLLISIONS

For assessing conjunctions in context of our current work, we use a system definition of orbital shells of 50km thickness and a 24h time span (see Fig. 3 below).

The interacting elements are the objects approaching each other closer than 5km, taken from the TLEs made available by space-track.org, including their given specification from the public catalogue (all-to-all conjunction analytics) [18].

Each conjunction of two orbital objects is recorded as one event with all relevant conjunction data e.g., time, location, direction.

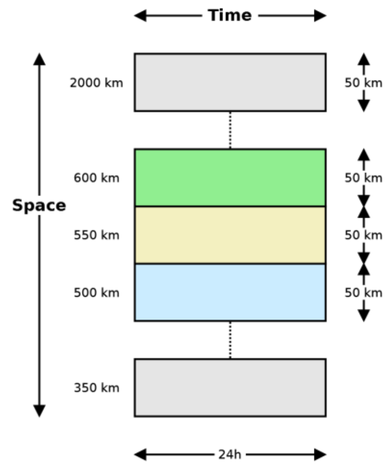


Fig. 3. Orbital Shell Definition

A conjunction is not equal to a collision, but the collision risk is connected to the probability of a close conjunction.

In the context of this paper, collisions are of interest because they usually lead to fragmentation effects i.e., turning one larger object into a significant number of smaller objects, thus multiplying the potential for further interactions within the system.

The specific outcome (amount, size and directions of objects created) of a collision depends on the kinetic energy and hence, on the mass and on the relative velocity of the colliding objects. Since the relative velocities of objects in earth orbit usually are in the range of up to 15 km/s, a collision without physical fragmentation is quite unlikely.

With the quadratic impact of velocity in kinetic energy, even small objects of limited mass carry a lot of destructive potential and can shatter other object to pieces by a single impact [19][20]. At the orbital height of the ISS (around 400km), a small wrench carries as much kinetic energy as a high velocity anti-tank shell (assuming a 200g wrench in a 400km orbit vs. a General Dynamics KE-W A1 tungsten penetrator for a 120mm tank gun weighing approx. 4kg [21].

5. CASCADE EFFECT

Objects which are shattered to debris and interact with more than one other object within the system have the potential to shatter other objects and initiate a cascade effect soon after the initial fragmentation.

If the initial or secondary fragmentation produces enough debris, the cascade can spread rapidly and “infect” other orbital shells as well, leading to a runaway cascade.

While modeling the problem one has to be aware that the data available gets more unreliable the smaller the parts involved are. ESA experts put the estimation at about 1 million parts between 1 cm and 10 cm in orbit, in addition to the about 35,000 parts bigger that 10 cm [22]. Overall, only about 25,000 objects are regularly tracked in their orbits, which is, according to the above estimates, only about 2.5% of the “risky” parts.

However, since bigger objects tend to have more mass, as well as in most cases having a larger surface for impact, the main focus should be on the “NOT-SMALL” category. The probability of hitting an adjacent object also depends on the size of the objects.

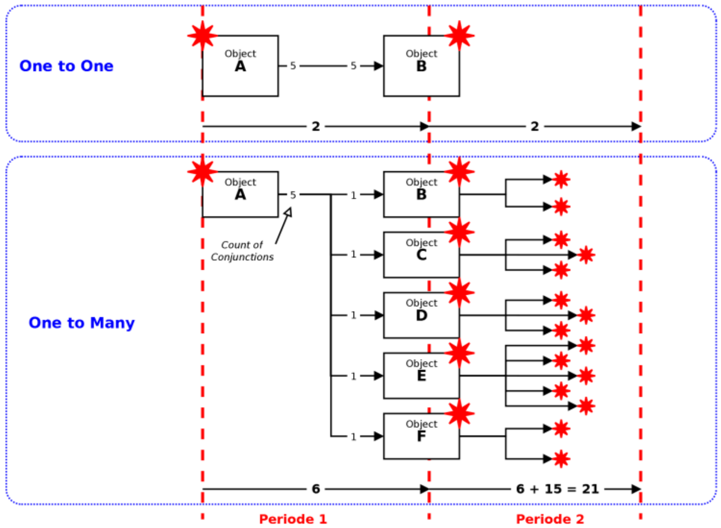


Fig. 4. Cascade Effect

If an object (or an object cloud originating from a previous fragmentation) just meets (in the meaning of undergoing a conjunction within 5km distance) one other single object within the given system boundaries, the impact in the context of a cascade effect dissipates.

However, if a fragmentation cloud meets more than one other object within the system boundaries the fragmentation cloud particles have the potential to hit more than one object, which can initiate (or further develop) a cascade effect. The evolution of the cascade effect depends on the count of conjunctions within “near time” of the initial fragmentation and on the conjunction distance.

In order to obtain indicators for the cascade risk, each individual conjunction risk has to be calculated and then accumulated per object as part of the system risk.

6. THE SYSTEM RISK OF A CONJUNCTION

The *System Risk* of a conjunction can be defined by the orbital shell (*System Space*) and time (e.g., 24h – *System Time*) and by calculation of the number and distance of the conjunctions within this system (Interaction as a process). Every conjunction within the *System Definitions* contributes to the system risk. Therefore, every element involved in a conjunction in the space and time boundaries given system carries an individual risk describing the probability of a close conjunction *within the System*. The *System Risk* depends on the distribution of the conjunction distances of all conjunctions per day.

The following Fig. 5 represents the expected number of conjunctions <10m per day within the defined orbital shells.

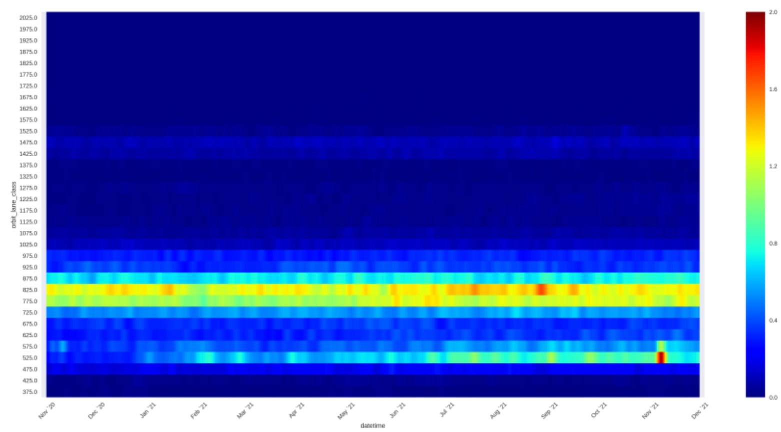


Fig. 5. Expected Number of Conjunctions <10m per Day

The numbers represented in the heatmap above are proportional to the daily risk of a conjunction for each object being part of the system. This probability depends on the number of conjunctions within the system and on the distance to each other.

In Fig. 5, we show 447 subsequent days of data. In this analytic timeframe we have ~8.5 million data sets, only for the LEO orbital shell from 375km to 2,000km as shown.

7. CASCADE RISK INDICATOR 1

The risk can now be distributed to each single conjunction, and then accumulated per individual object being part of the system risk.

In an ideal system setting the system is closed (without external influence from the *environment*) and the minimum counts of individual objects involved is two. The other ideal setting (open system) would be if the number of involved objects is twice the number of conjunctions. The correlation of involved objects over the number of conjunctions gives one approach indicating the *cascading risk* (or *risk spread*) within the system. So, it is a first indication of the probability of the system inner propagation of the risk to the involved objects.

Fig. 6 shows the resulting heat map of the cascade risk indicator 1 where red stands for a more *closed* system (so less unique objects with regular repeating conjunctions) and green for a system that is *open*.

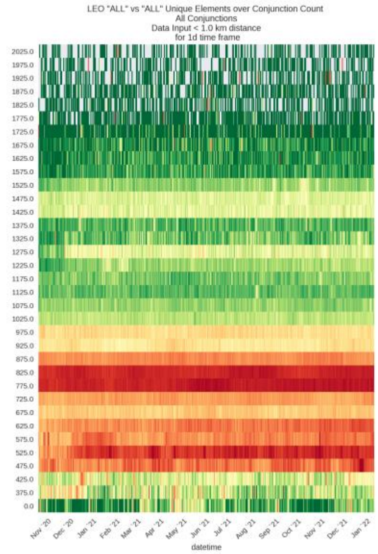


Fig. 6. Cascade Risk Indicator 1

Fig. 7 shows the same indications and color setting as before, but for SMALL vs SMALL, SMALL vs NOT-SMALL and NOT-SMALL vs NOT-SMALL. The risk of NOT-SMALL to be "infected" is shown in the middle figure and the catastrophic scenarios (NOT-SMALL vs NOT-SMALL) are shown on the right side.
(TLE categorizes the objects according to their radar cross-section (RCS) as SMALL, MEDIUM and LARGE [23]. For our analyses, we have chosen to merge MEDIUM and LARGE into a NOT-SMALL category.)

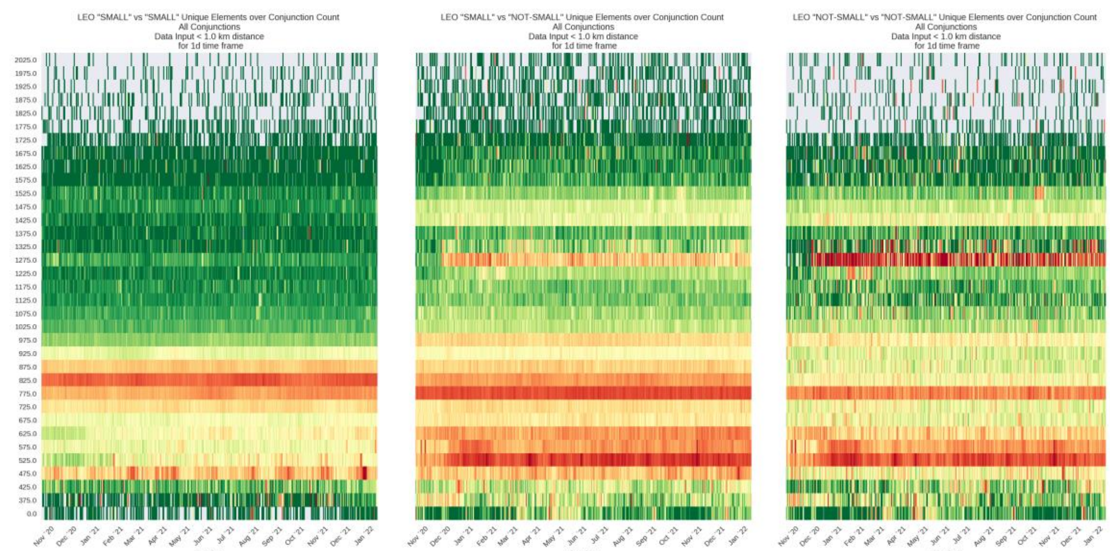


Fig. 7. Unique Elements over Conjunction Count

These graphs allow for good high-level identification of higher-risk orbital shells as well as identification of the impact of individual occurrences on the system risk.

8. CASCADE RISK INDICATOR 2

Another approach to get an indication of the cascade effect can be retrieved from the number of conjunctions per object within the system definitions.

A histogram plot of one day out of the above shown figures gives an indication of the distribution of the count of NOT-SMALL object conjunctions, per object.

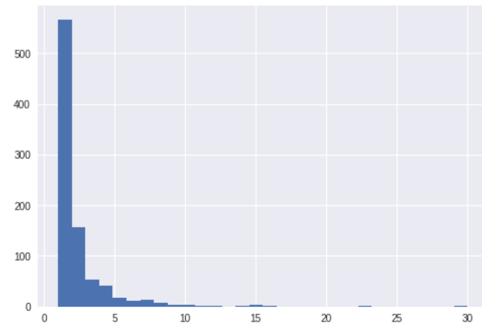


Fig. 8. Conjunction Count Distribution

Fig. 8 shows various distributions of counts of conjunctions of objects < 5km per day and per individual object in the orbital shell of 525 km on the day 2021-11-28. The numbers show a majority of 566 counts only involved once in a conjunction, 156 two times and at the other end one object with 24 conjunctions and one object with 30 conjunctions per day.

9. CASCADE KEY PERFORMANCE INDICATOR (KPI) EVOLUTION

One key indicator of orbital risk is the number of conjunctions in the different orbits in the context of space sustainability due to earlier collisions and fragmentation events. Here not only the inner interactivity within the system (orbital shell) is relevant but also the interactivity of the system (cross-traffic) with its environment (neighboring shells).

The other key indicator is the number of individual objects in the same orbital shell or orbital lane (*System Space*) as a metric how *closed* or *open* the system is (how much exchange happens within the system). That gives an indication of the risk to be “infected”.

Fig. 9 shows the conjunction counts and the number of individual objects involved in conjunctions as a line graph. The green line represents the daily inventory of space objects comparable to the inventory bar plot from ESA in Fig. 1.

Remarkable here is the overall correlation of the number of objects with the count of conjunctions. Nevertheless, the figure also shows clear some deviations of the overall correlation.
If the number of conjunctions can be used for interpretation of a collision system risk in outer space the number of objects in outer space seems not to be an adequate and accurate KPI for collision system risk.

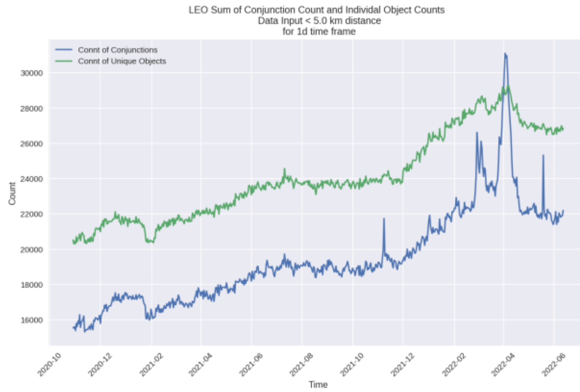


Fig. 9. Space Traffic showing as line graph conjunction count and individual object counts

Fig. 10 shows the conjunction counts and the number of unique objects for NOT-SMALL objects in the orbital shells 350km to 2000km between 2020-10-29 and 2022-06-13.

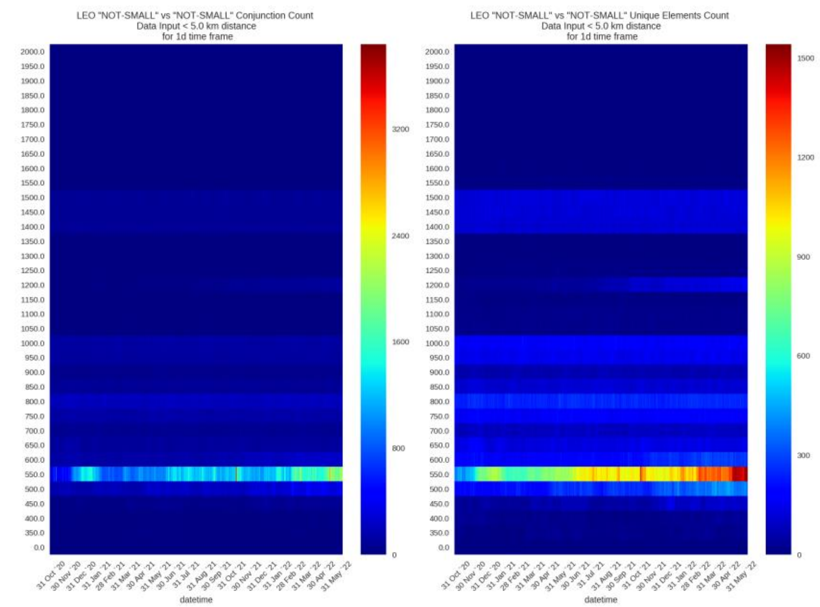


Fig. 10. Heat map of conjunction count and individual object counts for LEO

10. EMPIRIC DATA

Fig. 11 shows a “Conjunction Diary” for one satellite on one single day. The x-axis shows the time and the y-axis shows the distance to the conjunction partners.

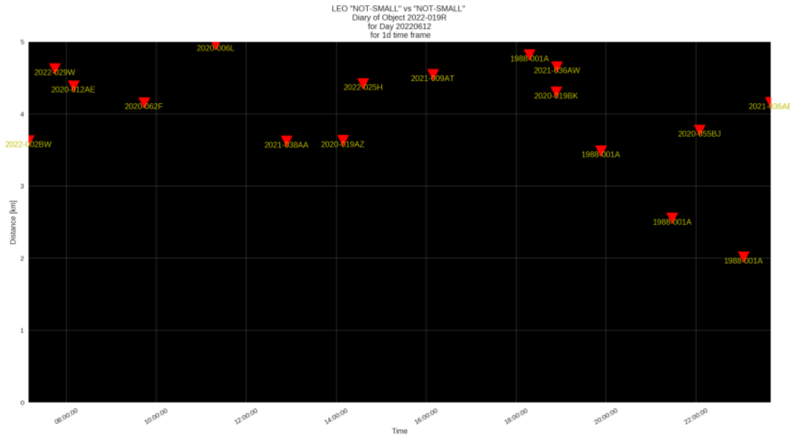


Fig. 11. 24h "Conjunction Diary"

The table in Fig. 12 below shows the series of conjunctions within the given sample day of the selected object including the repeated conjunctions with one of the objects (highlighted in cyan).

The sample object [Object ID = '*2022-019R*'] within the list is represented with a count of total 17 conjunctions with 14 individual other objects on the day *2022-06-13* in the orbital shell *550*.

datetime [2022-06-13]	Object ID Conjunction with [2022-019R]	distance [km]	Velocity angle [°]	Radial velocity [km/s]	Tangential velocity [km/s]
07:09:36	2022-002BW	3.626	7.630	0.000	1.009
07:44:29	2022-029W	4.624	136.903	0.010	14.125
08:09:30	2020-012AE	4.386	134.820	0.007	14.017
09:43:34	2020-062F	4.152	127.398	0.008	13.609
11:19:15	2020-006L	4.959	72.570	0.005	8.984
12:53:50	2021-038AA	3.619	123.091	0.005	13.347
14:08:56	2020-019AZ	3.629	93.812	0.000	11.086
14:35:54	2022-025H	4.417	147.011	0.011	14.563
16:09:02	2021-009AT	4.541	143.052	0.009	14.401
18:17:36	1988-001A	4.815	179.334	0.003	15.168
18:53:24	2020-019BK	4.298	71.634	0.003	8.884
18:54:22	2021-036AW	4.651	122.378	0.007	13.302
19:52:47	1988-001A	3.485	179.463	0.003	15.168
21:27:58	1988-001A	2.551	179.592	0.003	15.168
22:04:38	2020-055BJ	3.770	126.727	0.007	13.571
23:03:09	1988-001A	2.012	179.720	0.003	15.168
23:39:26	2021-036AE	4.154	130.654	0.008	13.796

Fig. 12. Empiric Data

Count of conjunctions: 17
Count of individual conjunction partners: 14
Series of conjunction Partners:
['1988-001A','2020-006L','2020-012AE','2020-019AZ','2020-019BK','2020-055BJ','2020-062F','2021-009AT','2021-036AE','2021-036AW','2021-038AA','2022-002BW','2022-025H','2022-029W']

11. CASCADE POTENTIAL CALCULATION

A cascade index depends on the number of individual conjunctions, and on the size of the objects.

In a sustainability context, **two satellites which meet only each other represent a lower risk than a satellite enjoying conjunctions with a whole series of different satellites.**

Consequently, we define an indicator for the overall number of conjunctions of an object in the *System Boundaries* (*System Space* and *System Time*), and an indicator for the number of individual conjunction partners. To get an indication of the risk per involved object, we need to put those two indicators in a relation to each other.

We define the *Individual Cascade Potential (ICP)* as the product of the **number of conjunctions (*N_{conj}*) of the object** and the **count of individual conjunction object partners (*Z_{ind}*)**:

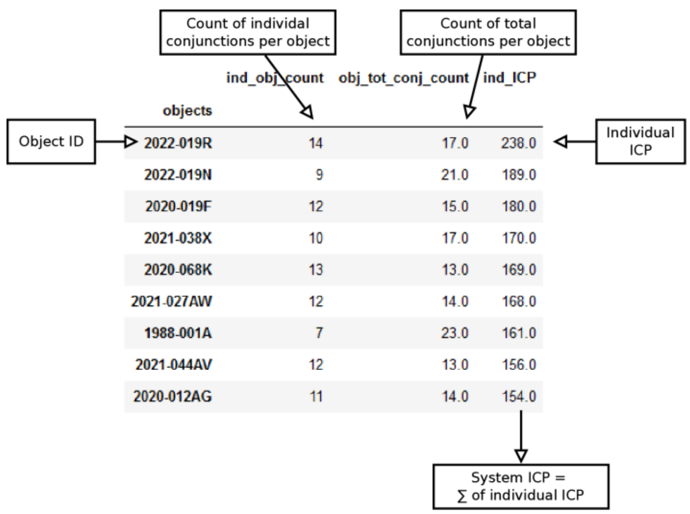
$$ICP = N_{conj} \times Z_{ind}$$

The number (count) of individual conjunctions expresses the risk of a cascading collision as the cloud of the parts meets the next satellite(s). The shorter the time to the next conjunction, the more compact the "parts cloud".

The formula uses the product of the count of individual conjunctions and the count of the total conjunctions to get the individual CP (ICP) and sums the ICP within the system to the *System Cascade Potential (SCP)*.

$$SCP = \Sigma_i\, ICP_i = \Sigma_i\, (N_{conj} \times Z_{ind}\,)_i$$

Fig. 13 shows the per-object count of individual conjunctions, the count of total conjunctions per object and, as a result, the calculated *Individual Cascade Potential (ICP)*.



objects	ind_obj_count	obj_tot_conj_count	ind_ICP
2022-019R	14	17.0	238.0
2022-019N	9	21.0	189.0
2020-019F	12	15.0	180.0
2021-038X	10	17.0	170.0
2020-068K	13	13.0	169.0
2021-027AW	12	14.0	168.0
1988-001A	7	23.0	161.0
2021-044AV	12	13.0	156.0
2020-012AG	11	14.0	154.0

Fig. 13. Individual Cascade Potential (ICP) Table

12. INDIVIDUAL CASCADE POTENTIAL

Fig. 14 shows exemplarily a line graph of 300 days per space catalog a number as KPI per object and day for five selected objects: the Individual Cascade Potential (ICP). This KPI helps distinguish different behavior properties of individual objects with the possibility to set management and/or operation actions to reduce cascading collision risks on object level.

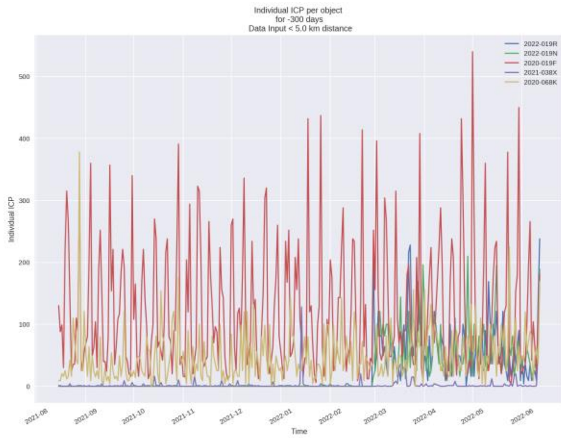


Fig. 14. Individual Cascade Potential

As a remarkable example the behavior of object 2020-19F shall be mentioned: It shows a long-lasting 7-day periodicity in the Individual Cascade Potential regardless of the extraordinarily high peaks in this KPI. A possible obvious interpretation of the behavior is that this specific object carries a high risk to initiate and/or further spread a cascading collision. In the wording of the COVID pandemic, this object would be called a “super-spreader”.

13. SYSTEM CASCADE POTENTIAL

In contrast to the Individual Cascade Potential (ICP) the System Cascade Potential (SCP) focuses on the system behavior and its possible system impacts on a per-day basis. This KPI helps distinguish different behavioral properties of individual system parts (e.g., orbital shells on a per-day basis) with the possibility to set management and/or operation actions to reduce cascading collision risks on system level.

Fig. 15 shows the System Cascade Potential (SCP) evolution over time.

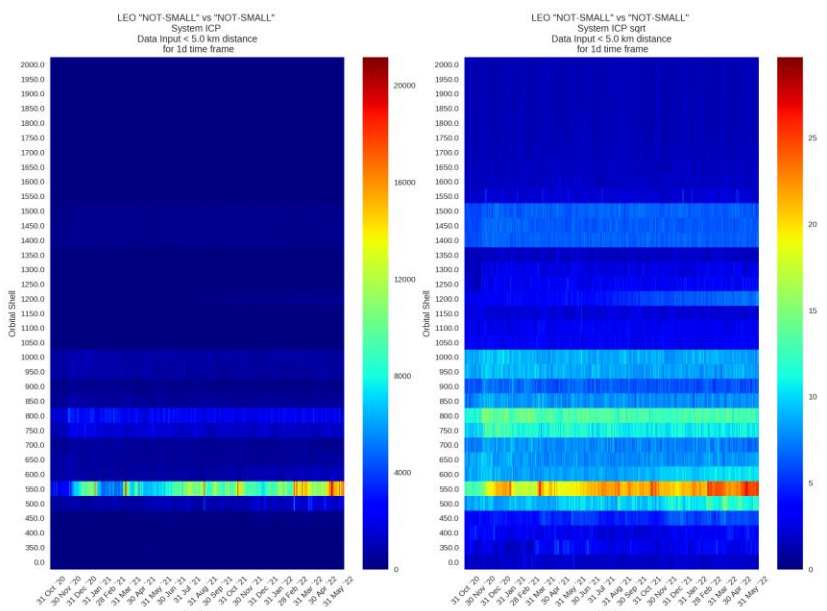


Fig. 15. System Cascade Potential (SCP) – left side: absolute value, right side: square root of SCP (linearizing an assumed quadratic dependency)

As a remarkable example note the behavior in the orbital shell at 550km (rages from 525km to 575km): The increasing KPI value in the beginning of the Starlink constellation deployment end of 2020 is clearly manifesting as a number of significant peaks.

Fig. 16 shows a zoom into Fig. 14, highlighting the SCP peaks in the orbital shell at 550 km from October 2020 to June 2022.

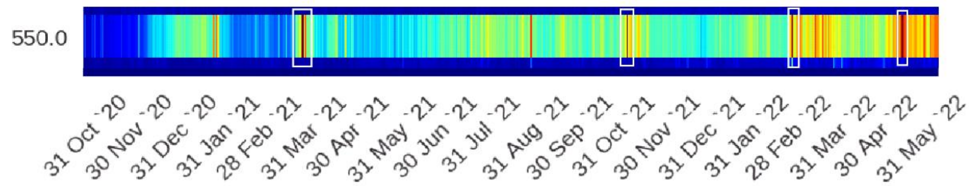


Fig. 16. System Cascade Potential (SCP) peaks

14. THE TRIGGER

Black Swan events, as Nassim Nicholas Taleb calls them in his book "The Black Swan" [24], are extremely unpredictable events that have a massive impact on our societies and the course of history. The trigger for cascading collisions in outer space could be initiated by unintended or intended events. Unintended events could be asteroids, solar flux, wrong surveillance data or just technical failures/errors/mistakes in the operations of a mega constellation [25][26]. Intended trigger events could be from military source or from hackers interfering on one or more points of the operations chain [27][28].

The consequences of this would be detrimental to society, as Olga Sokolova and Matteo Madi describe in their paper "A View of the New Space Sector Resilience" [29].

15. CONCLUSION

In our paper, we presented an approach to use altitude- and time-based systems of space objects for analyzing the interactions of space objects and the evolution over time. This led us to parameters describing the risk and the potential of cascading collisions.

Other than the collision risk obtained by traditional astrophysics and astrodynamics methods, this cascading potential does not tell something about single object risks, but says something about the overall system, about the likelihood an "infected" object can "infect" further objects. Such potential analyses can be performed for different orbital shells and object types with the cascading potential change over time allowing an interpretation of the past, of the current situation and for future scenarios.

We have shown that for the calculation of the cascading potential there is a difference between an object repeatedly meeting the same other object, and an object meeting many different other objects on its daily journey. Like in epidemiology, the risk of spreading an infection in a population is much bigger if there is a bigger exchange between many.

This is different from the perspective of the individual risk of getting infected. It is different from and therefore complementary to the traditional conjunction risk approach.

A complementary, holistic approach using existing data is possible and feasible. It is of fundamental value in establishing the *awareness* of "epidemiological" risk in space, for *mitigation* of high-risk areas and activities [30], and for establishing future *disaster preparedness* [31]. It provides a perspective for a more sustainable handling of the "**orbital environment as a finite resource**" [12].

16. OUTLOOK

An important next step in developing and implementing this new approach to space sustainability will be to validate the current results against data generated by existing stochastic approaches such as MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) and DRAMA (Debris Risk Assessment and Mitigation Analysis) [32], which in combination use object clustering and Monte-Carlo simulations to provide risk analysis for individual objects in orbit.

17. ACKNOWLEDGEMENTS

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Per aspera ad astra.

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