Collision Avoidance Decision Making Based on Risk and Consequence Metrics

2nd Space Capacity Allocation for the Sustainability of Space Activities Workshop

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Contents

This work was carried out by a consortium consisting of GMV and Politecnico di Milano, within the framework of ESA-funded "*Space Debris Assessment to Improve Collision Avoidance Metrics for Telecommunication Spacecraft*" (TELCOLA) activity.

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Introduction

Limitations in current CA and COLA practices

Problems derived from the enormous increase in the population of Earth-orbiting objects:

- CAM decision criteria driven by operational thresholds applied to geometrical/probability metrics
- **Collision consequences not considered** in CA practices and CAM decision
- Higher number of events requiring mitigations at the same time; **need to prioritize event mitigations**

Introduction

Objectives

1. Extension of current **CAM decision** process to account for **consequence metrics**, evaluating the impact of a collision both from an **environmental** and **economic** perspective
2. Derivation of a **prioritization strategy** based on the **aggregation of risk and consequence** metrics

CAM Decision Logic

Current practices

- Satellite operators define a **combined risk criteria** based on **operational thresholds**, considering **only risk metrics**
  - Usual metrics:
    - Remaining time to TCA
    - Remaining time to take a CAM decision
    - Miss-distance and relative RTN position at TCA
    - Mahalanobis distance at TCA
    - Collision probability at TCA
  - CAM planned when combined criteria is violated
  - Collision consequences disregarded

CAM Decision Logic

Aggregation of Consequence Metrics – Decision Framework

- **Normative** approach based on **decision** and **risk theories** to make choices under risk and uncertainty
- Policy: Choose **optimal** action in terms of **expected utility**

$$\mathbb{E}[U(x)] = \sum_i \mathbb{E}[p_i]U(x_i)$$

  - p_i: Probability of outcome x_i for this action
  - Utility function $U(x)$ can be tunned to model **risk aversion attitudes**

- "**No-CAM**" action:

$$\mathbb{E}[No\ CAM] \approx P_C \cdot U(C_{Coll})$$

- "**CAM**" action:

$$\mathbb{E}[CAM] \approx U(C_{CAM}) + P_{C,post-CAM} \cdot U(C_{Coll})$$

- "**Wait**" (until mission's CAM decision time) action:

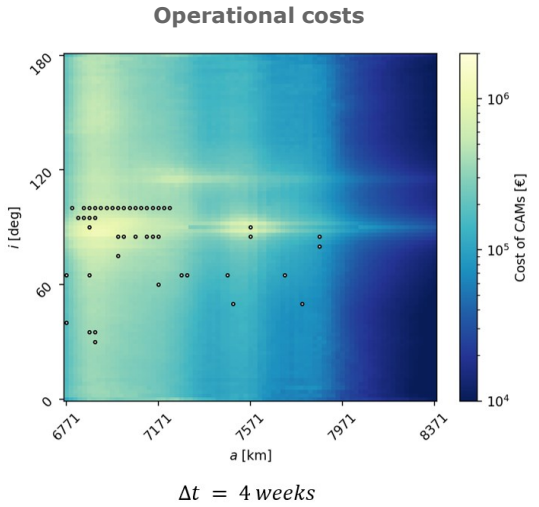
$$\mathbb{E}[Wait] \approx U(C_{Wait}) + P\left(P_C' \geq P_{C,thr}\right) \cdot \mathbb{E}[CAM] + P\left(P_C' < P_{C,thr}\right) \cdot P_C' \cdot U(C_{Coll})$$

- P_C: Collision probability
- $P_{C,thr}$: Collision probability threshold
- $P_{C,post-CAM}$: Target post-CAM probability (≈ 0)
- P_C': Predicted P_C at mission CAM decision time
- C_{Coll}: Cost of collision
- C_{CAM}: Cost of performing CAM
- C_{Wait}: Cost of waiting until mission CAM decision time

CAM Decision Logic

Aggregation of Consequence Metrics – Decision Framework

- **Costs** definition**:**
  - C_{Coll} accounts for **mission-related** and **environment losses**
    - Spacecraft + operations losses
    - Operational CAMs costs triggered by fragments of the collision (depends on the orbital region, expected number of fragments and the timeframe)
  - C_{CAM} accounts for **mission-related** losses when CAM is performed
    - ΔV cost (impact on the remaining ΔV budget for the mission)
    - For typical ΔV_{CAM}: $C_{CAM} \ll C_{Coll}$
  - C_{Wait} accounts for **operational losses** due to delaying the decision



- **Risk attitude** modelling**:**
  - Risk **neutral** attitude: $U(x) = x$ (being $x < 0$ a cost)
  - Risk-**averse** attitude: Concave $U(x)$ ($U''(x) > 0$; marginal increase in disutility as losses grow)

CAM Decision Logic

Aggregation of Consequence Metrics – Events Prioritization

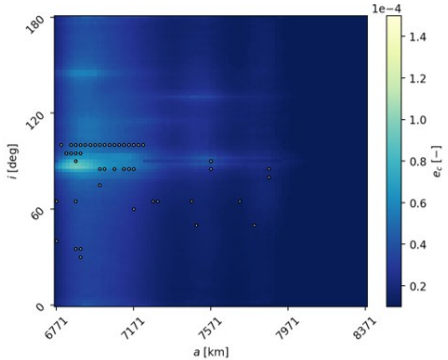
- **Risk** and **consequences** can be used to prioritize events requiring a mitigation (CAM)
  - **Risk factors** computed for metrics used in the **CAM decision** and remaining **time to TCA** T

$$RF_i = \begin{cases} \sigma\left(\log_{10}\left(\frac{M_i}{M_{i,thr}}\right)\right) & if\ M_i\ is\ probabilistic \\ \sigma\left(\ln\left(\frac{M_{i,thr}}{M_i}\right)\right) & if\ M_i\ is\ geometrical \end{cases} \qquad RF_T = \frac{T_{max} - T}{T_{max} - T_{Decision}}$$

  - Non-dominated sets (**Pareto layers**) computed for all events to be prioritized **based on risk factors**
  - Events in the same Pareto layer ordered based on a **score metric** γ aggregating both **risk** and **consequences** (environmental + economic)

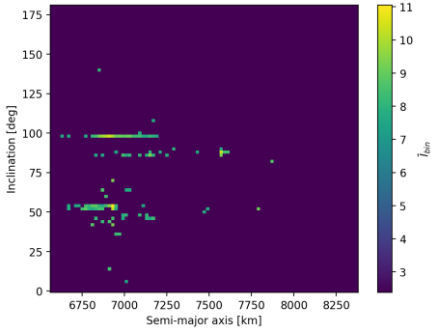
$$\gamma = e_c \bar{I}_{bin} \left(\frac{1}{N}\sum_{i=1}^{N} RF_i\right) f(RF_T), \qquad f(RF_T) = e^{2\ln(2)RF_T}$$

Fragmentation effects e_c



$\Delta t = 4\ weeks$

Orbital slot value $\bar{I}_{bin}$



Conclusions

- Novel **CAM decision framework** aggregating both **risk** and **consequences** (environmental + economic) derived from general decision and risk theories (**normative approach**)
- **Aggregation** of risk and consequences **allow** satellite operators to establish **event prioritization** (triage) strategies for situations with several events requiring a CAM at the same time
- New CAM decision and event prioritization logic to be implemented in ***Arcade*** SW prototype and validated as part of TELCOLA activity

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Thank you

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