Simulating Space Policy Implications on Collision Avoidance Decisions Using the Environment-Vulnerability-Decision-Technology Framework

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Self-Introduction

Jonathan Wei

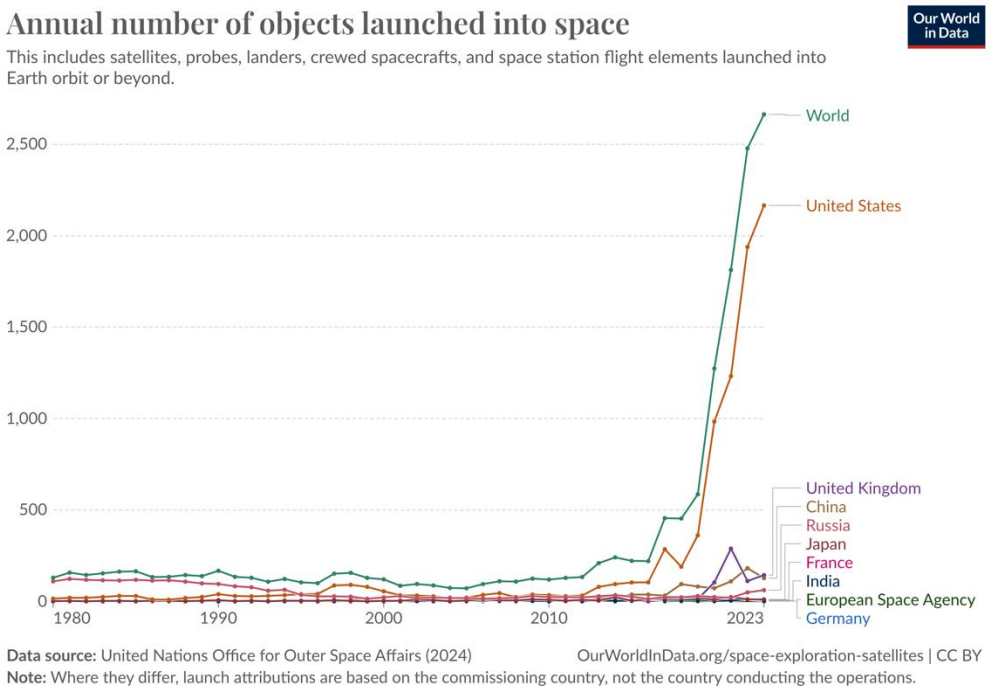
- BSc Microengineering, EPFL, 2018-2021
- MSc Microengineering, minor in Space Technologies, EPFL, 2021-2024
- Co-founder & systems engineer, EPFL Xplore
- Master's thesis, MIT, 2024

Co-authors:

- William E. Parker (MIT, Astrodynamics, Space Robotics, and Controls Lab (ARCLab))
- Jacqueline H. Smith (MIT, Space Enabled Research Group)
- Sina Es Haghi (Politecnico di Milano)
- Danielle Wood (MIT, Space Enabled Research Group)

Motivation

- Exponential increase in the number of objects launched into space
- More than 25’000 objects larger than 10 cm, ~1 million between 1 cm and 10 cm[1]
- Congestions in some orbital regions lead to more attention required on collision avoidance activities



[1] ESA, https://sdup.esoc.esa.int/discosweb/statistics/

Thesis Aim

- Lack of “international space traffic rules”
- Need of better understanding the implications of such traffic rules
- What parameter do we use to decide if a maneuver is required? What factor do we consider to decide who maneuvers (in case of spacecraft spacecraft conjunction)

2 Specific Cases:

If we use the **same probability of collision (Pc) and time of maneuver threshold** for both spacecrafts in conjunction, how would different thresholds impact the resulting number of maneuvers?

If we have a space traffic law that takes the **socio-economic impact** of the spacecraft into account in the decision of who maneuvers, what would be the implications of it on the number of maneuvers of each spacecraft?

What is COLA-EVDT?

- **COLA-EVDT 1.0**: MATLAB software → Collision avoidance Decision Support System that takes into account the socio-economic impact of the spacecrafts in conjunction

- **COLA-EVDT 2.0**:
  - Added space policy study capabilities
  - Take TLEs and CDMs as input
  - COLA-EVDT 2.0 designed to specifically answer the 2 above questions, but modular

EVDT Framework

System Architecture Framework, developed at the Space Enabled research group at MIT Media Lab, used to create decision support systems for sustainable development applications

- **Environment model**: "What is happening in the natural environment?”
- **Vulnerability model**: "How will humans be impacted by what is happening in the natural environment?”
- **Decision model**: "What decisions are humans making in response to environmental factors and why?”
- **Technology model**: "What technology system can be designed or acquired to provide high-quality information that supports human decision-making?"

EVDT Framework

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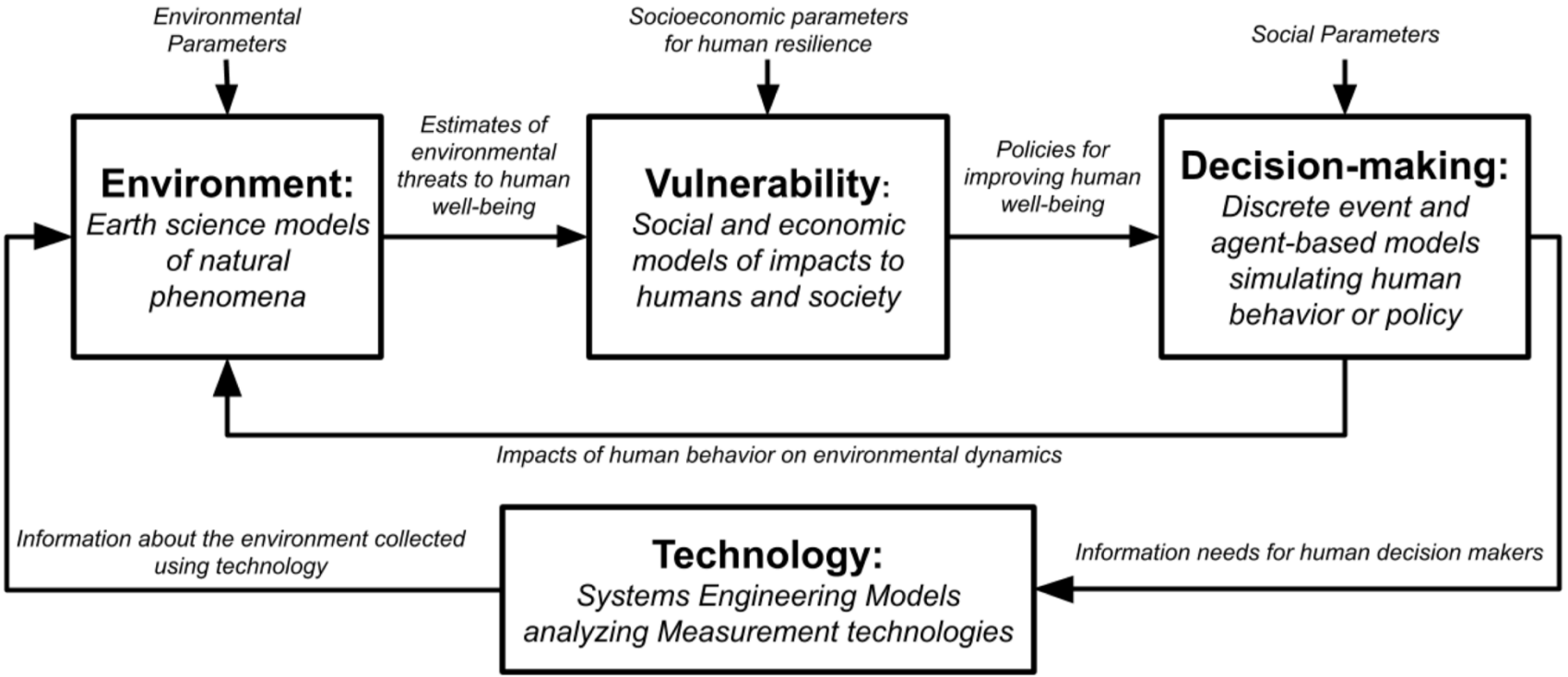


Fig.: Jack B. Reid and Danielle Wood. “Decision Support Model and Visualization for Assessing Environmental Phenomena, Ecosystem Services, Policy Consequences, and Satellite Design Using Earth Observation Data”. In: AIAA (2020).

EVDT Framework – COLA-EVDT

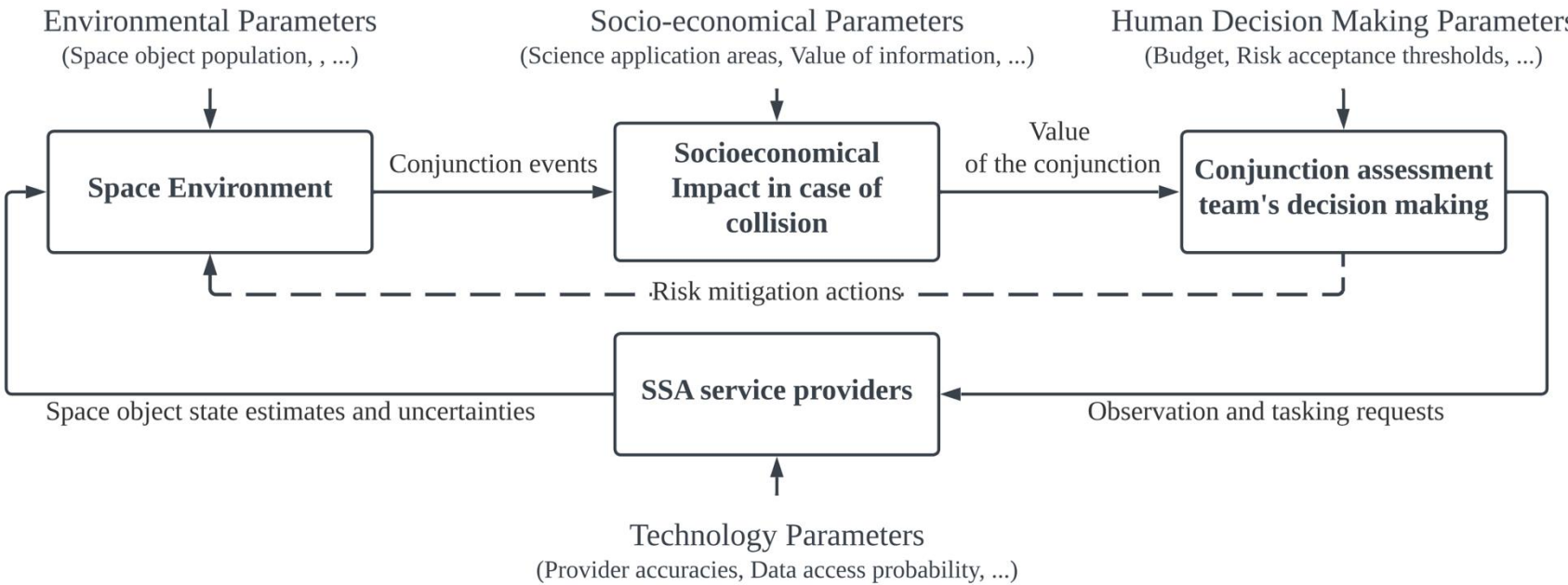
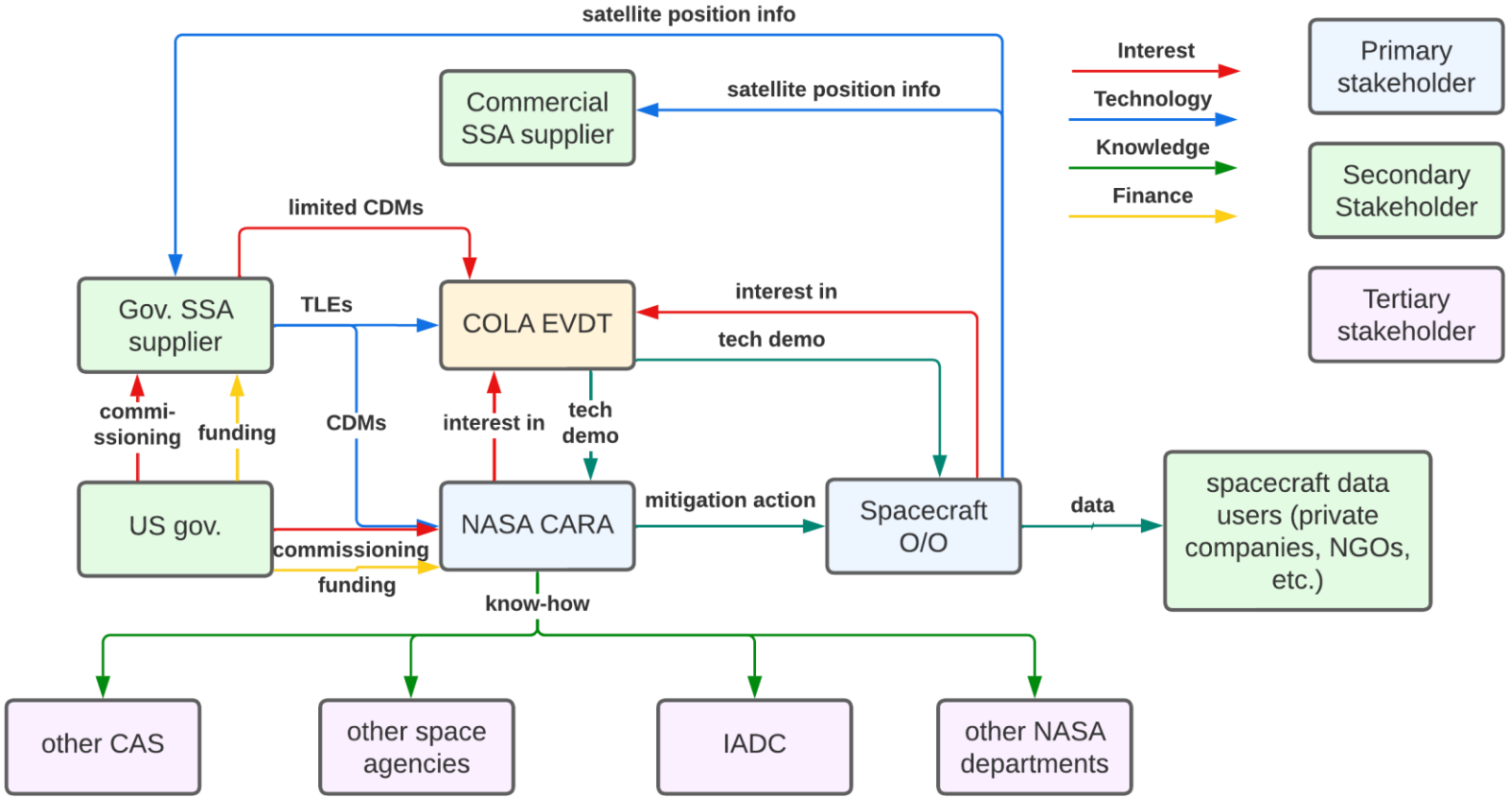


Fig: Sina Es Haghi. Implementing the environment-vulnerability-decision-technology framework to space collision avoidance applications. url: https://www.politesi.polimi. it/handle/10589/203214.

Decision Model

	NASA CARA	Rules4CREAM / CASCADE	COLA-EVDT
	NASA CARA (Conjunction Assessment and Risk Analysis)	**Rules4CREAM** (Collision Risk Estimation and Automated Mitigation) **CASCADE** (Collision avoidance, satellite coordination assessment demonstration environment)	**COLA-EVDT**
Main Characteristics	Advanced decision process used for **real time conjunction assessment** for NASA and US satellites	Long term **space pop. scenario**, suggest **bilateral STM rules**, give information about chosen ruleset **consequences**	Flexible space policy study tool aimed at understanding implications of **international STM rules**, including **socio-economic impact**
Primary Stakeholder(s)	NASA CARA, US O/O	Future use by spacecraft O/O	Policy makers, NASA CARA

Stakeholder Relationships – What it is



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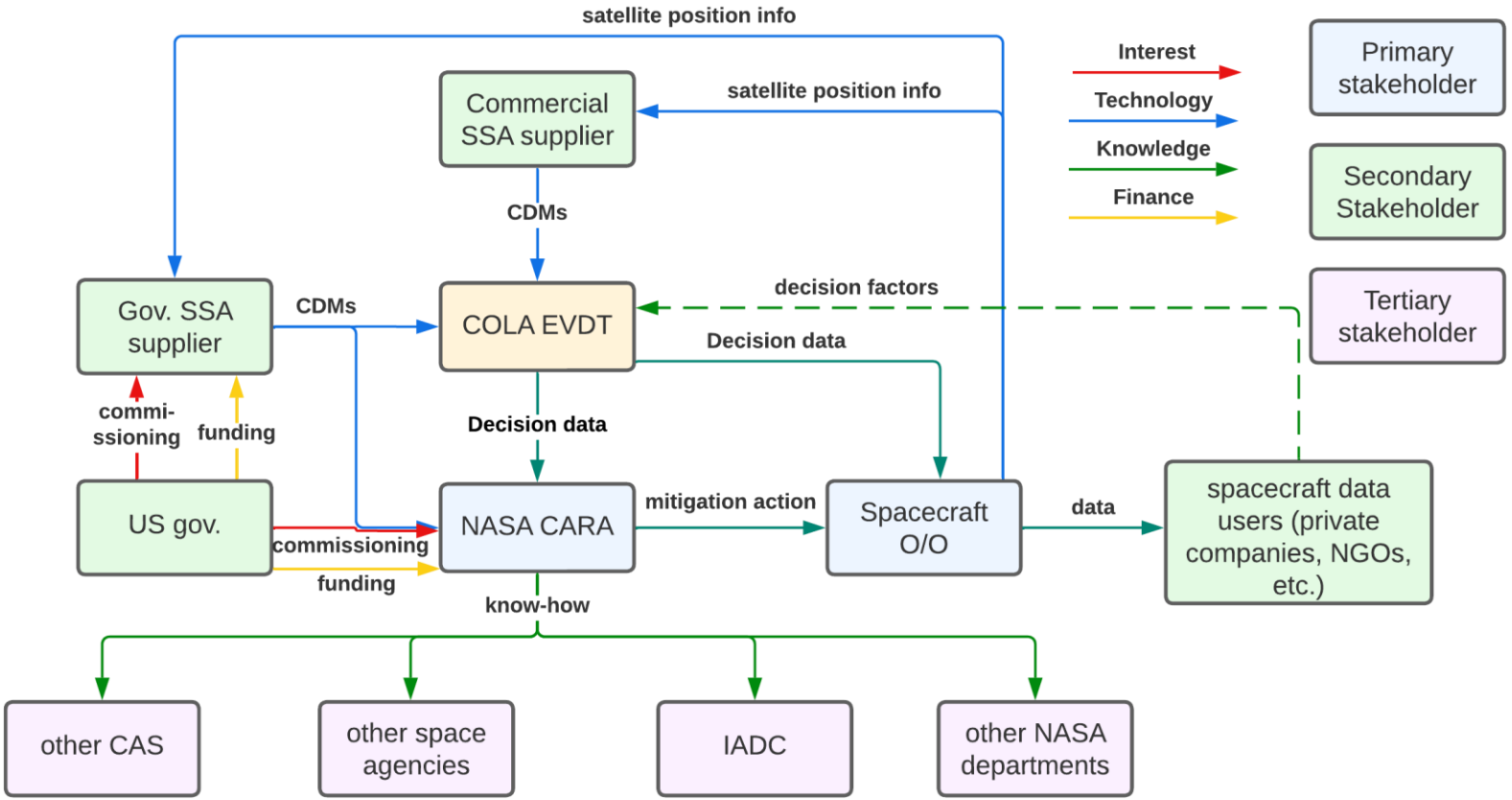
Stakeholder Relationships – What it could be



Vulnerability Model – Spacecraft Ordinal Ranking

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Main Application	Earth Observation	Scientific Research	Communication	Navigation
Score S_{ma}	10	10	5	5

General Category	Human Spaceflight	Military	Civil	Commercial
Score S_{gc}	10	7.5	5	2.5

Socio-economic Score S_{se}

$$S_{se} = 0.3 \cdot S_{gc} + 0.7 \cdot S_{ma}$$

Scaled Socio-economic Score S_{sse} *(for R_e>10)*

$$S_{sse} = \frac{S_{se}}{R_e \cdot \alpha}$$

R_e redundancy level

α redundancy scaling factor

Vulnerability Model – Spacecraft Ordinal Ranking

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Cost Score S_c

$$S_c = \begin{cases} \frac{C_{hw}}{10^8} & \text{if } C_{hw} \leq 10^9 \\ 10 & \text{if } C_{hw} > 10^9 \end{cases}$$

C_{hw} hardware cost (USD)

Total Score S_{tot}

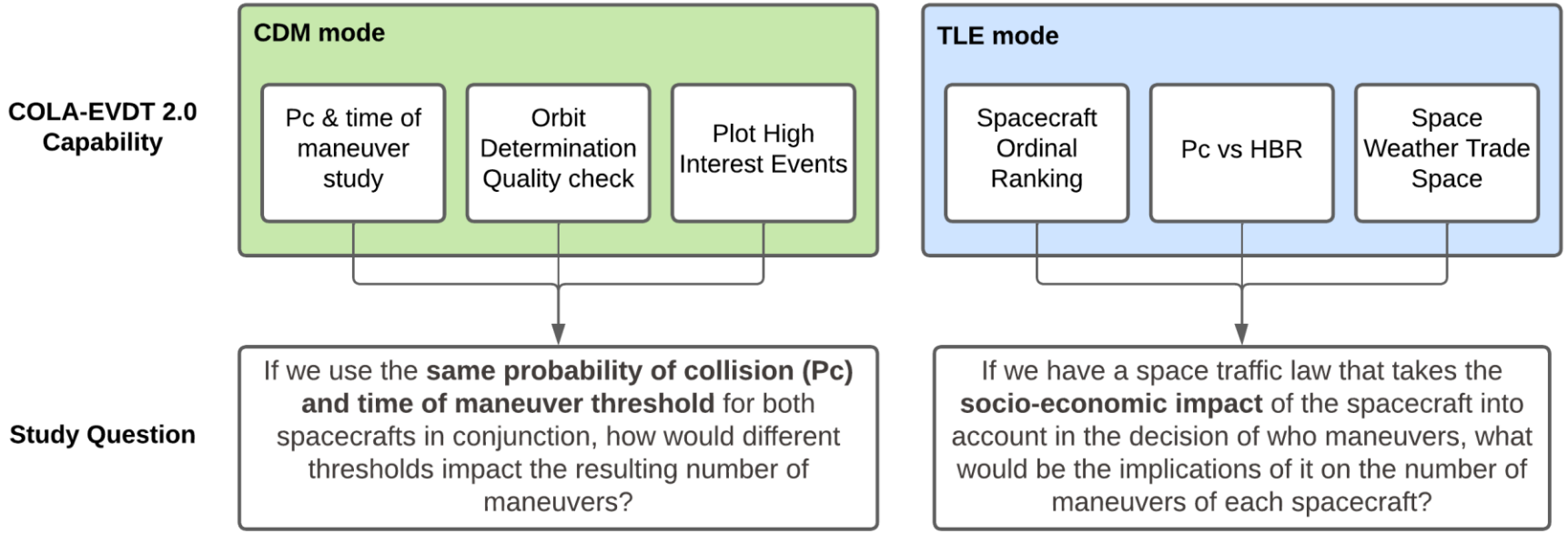
$$S_{tot} = 0.5 \cdot S_{sse} + 0.5 \cdot S_c$$

Scaled Total Score S_{stot}

$$S_{stot} = \begin{cases} S_{tot} \cdot R_l & \text{if } R_l \geq 0.5 \\ S_{tot} \cdot 0.5 & \text{if } R_l < 0.5 \end{cases}$$

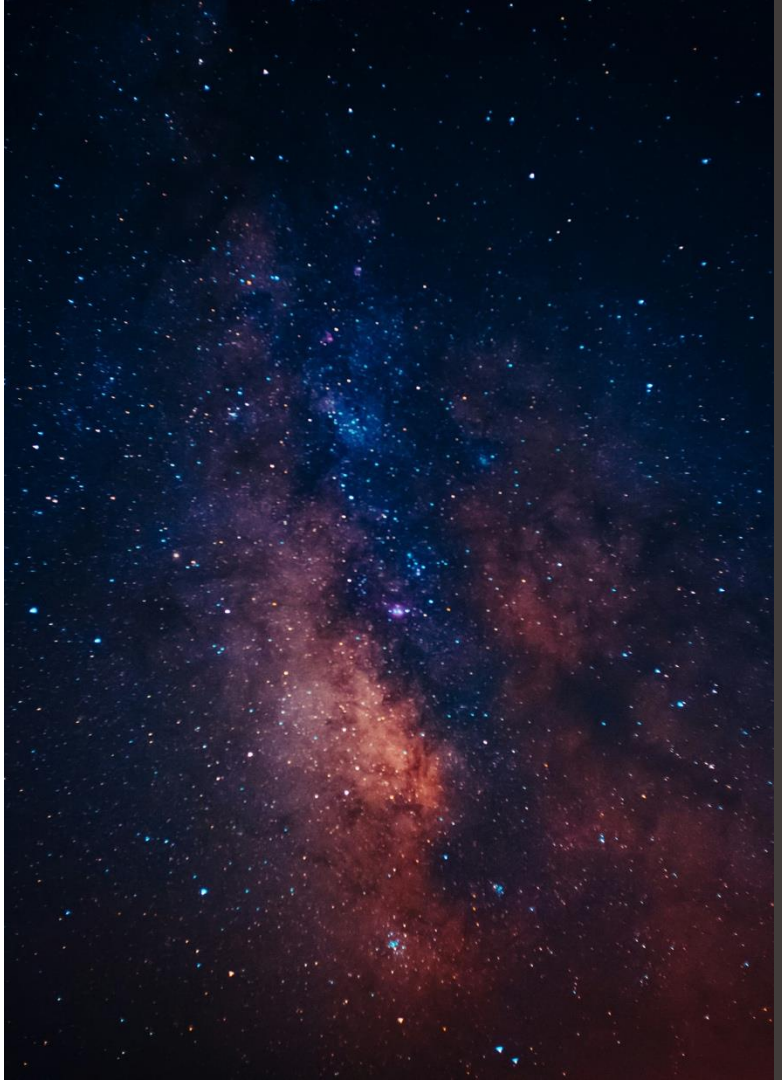
R_l remaining expected lifetime (0-1)

COLA-EVDT 2.0 – Improvements Summary



Mapping CDMs to the 1st question and TLEs to the 2nd question is advantageous:

- For question 1, we need **realistic Pc value** that are only available in CDMs
- For question 2, we need to be able to **choose the primary spacecraft freely**



Results

1. Datasets

2. Policy Study: Common Pc and Time of Maneuver Threshold

3. Policy Study: Ordinal Ranking based Maneuver Decision & Socioeconomic Factor Sensitivity Analysis

Datasets

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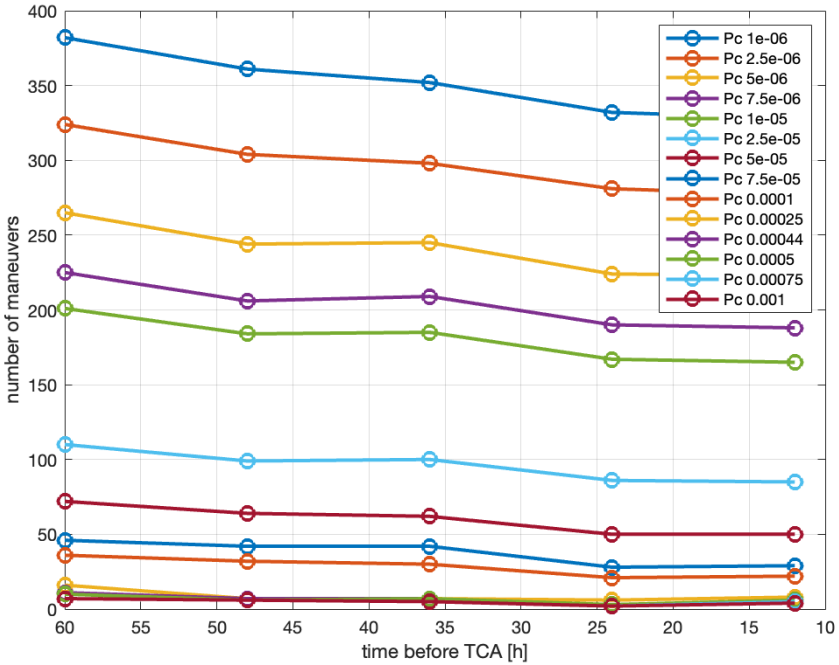
List of primary spacecrafts (TLE mode):

Spacecraft	NORAD ID	General Category	Main Application	Remaining Lifetime	Redundancy Level
Landsat 7	25682	Civil	Earth Observation	0	3
Terra	25994	Civil	Earth Observation	0	1
Aqua	27424	Civil	Earth Observation	0	1
ICEYE X-14	51070	Commercial	Earth Observation	0.75	34
SWISSCUBE	35932	Commercial	Communication	0	1
AEROCUBE 11-R3	43849	Commercial	Communication	0.5	2

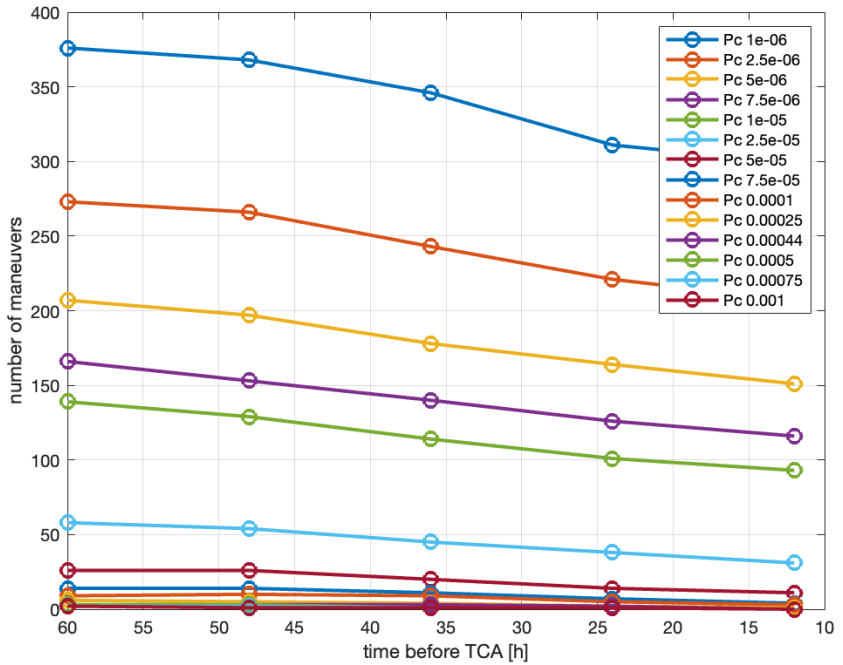
Available CDM datasets:

Dataset Number	Start Date	End Date	NORAD ID	Spacecraft
1	1/1/2015	12/31/2015	25682	Landsat 7
			25994	Terra
			27424	Aqua
2	1/1/2023	6/30/2023	25994	Terra
			27424	Aqua
			43613	ICESat-2

Policy Study: Common Pc and Time of Maneuver Threshold



CDM Dataset 1 (2015)



CDM Dataset 2 (2023)

Policy Study: Common Pc and Time of Maneuver Threshold

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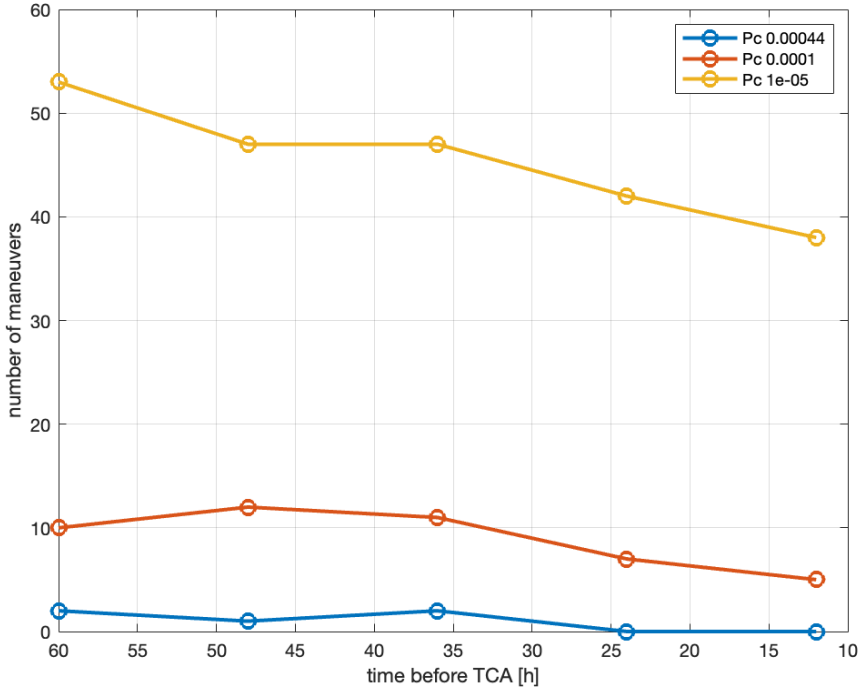
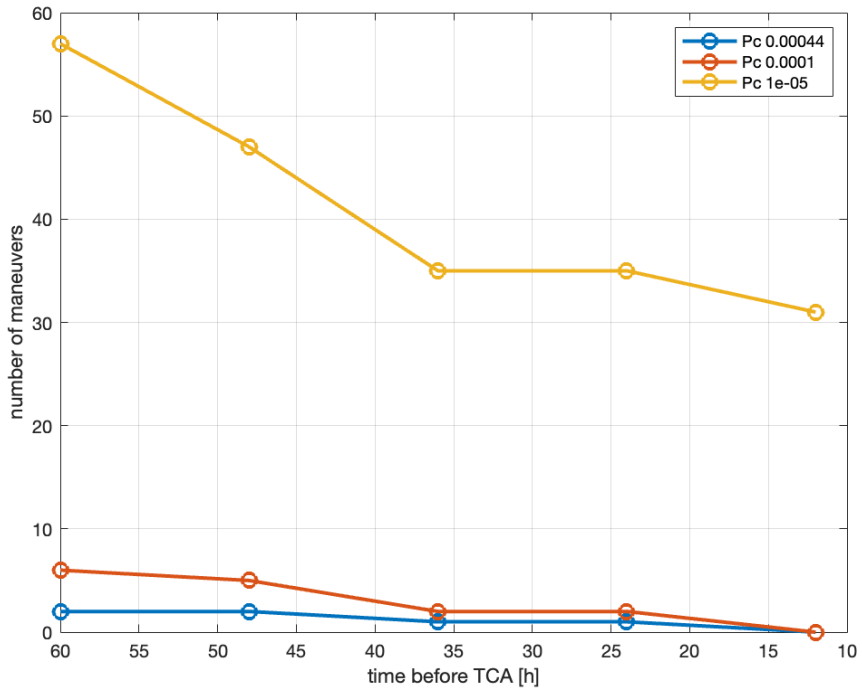
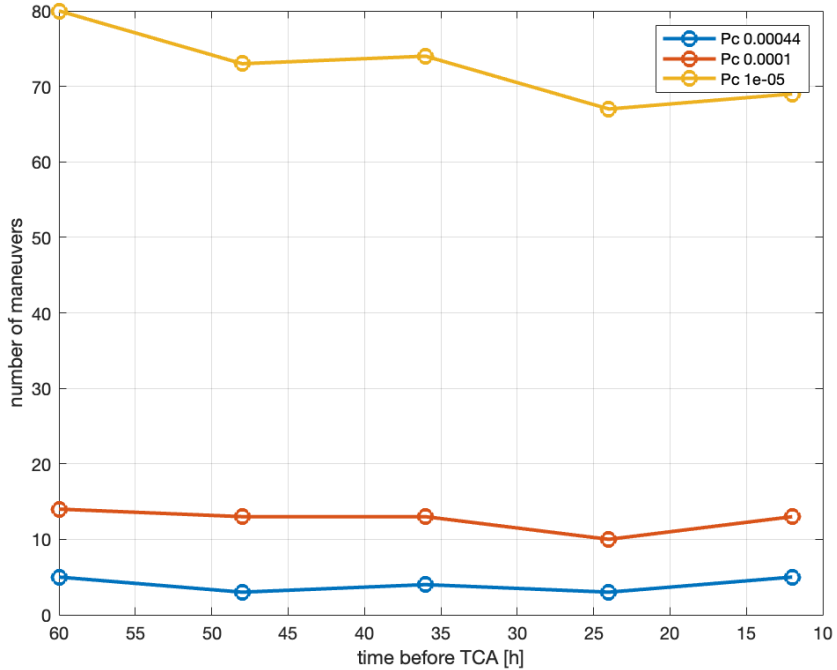


AQUA Dataset 1 (2015)

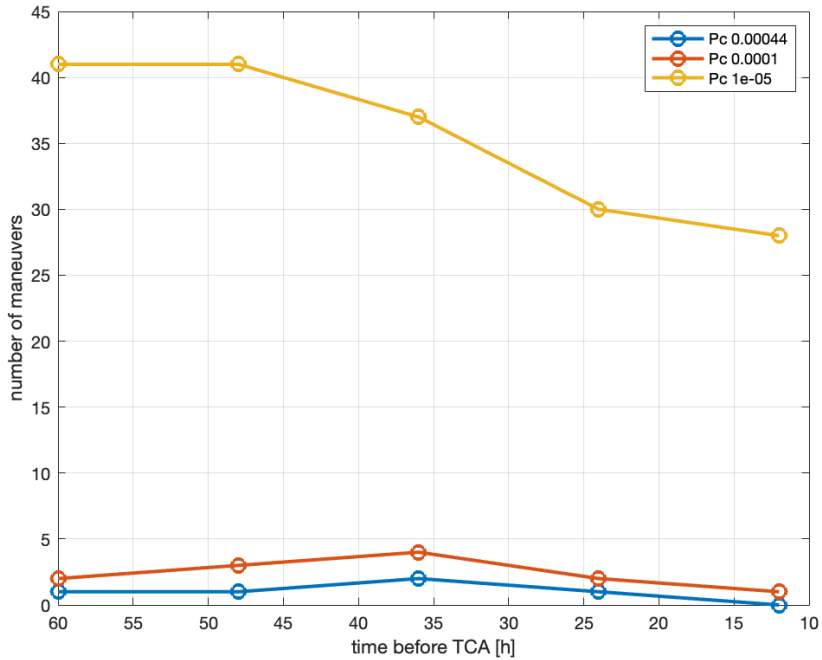


AQUA Dataset 2 (2023)

Policy Study: Common Pc and Time of Maneuver Threshold



TERRA Dataset 1 (2015)



TERRA Dataset 2 (2023)

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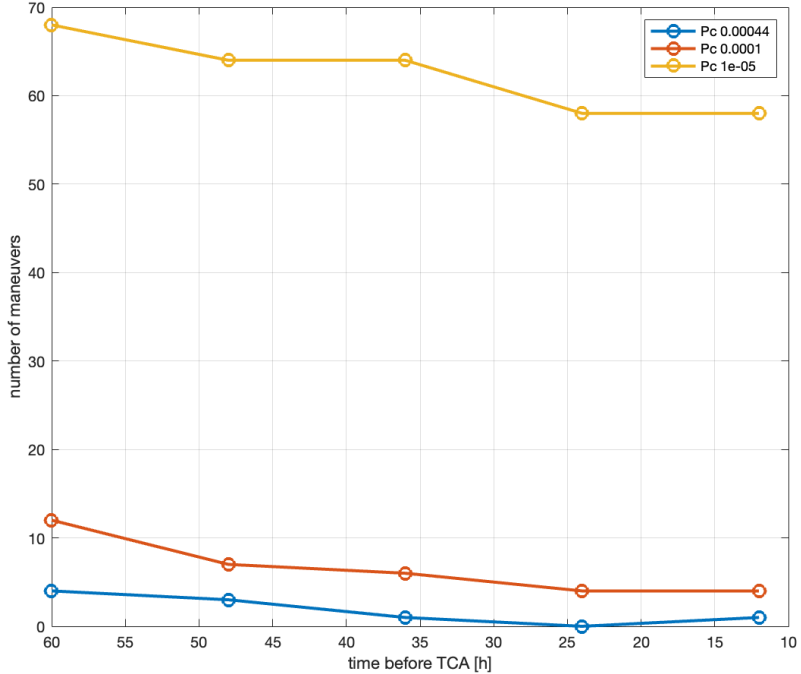
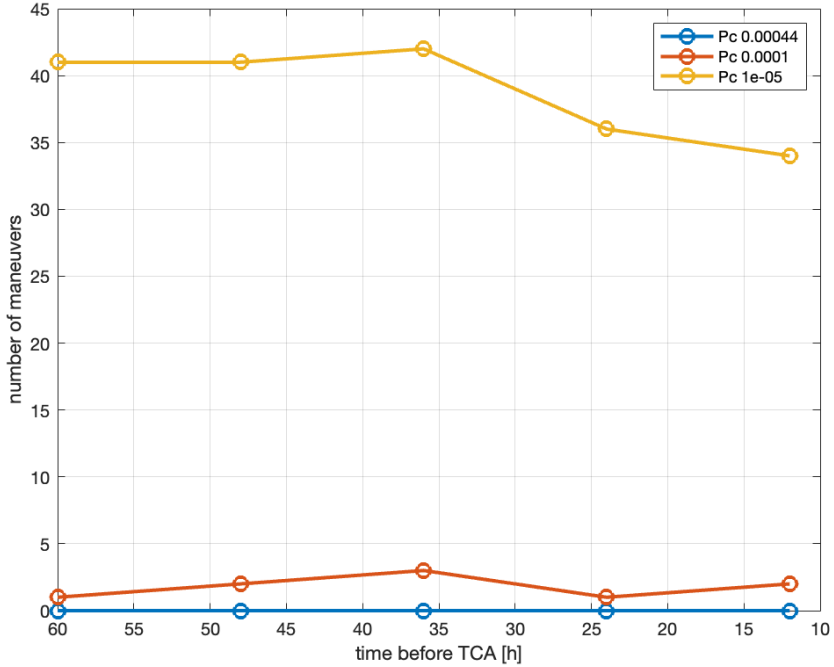
Policy Study: Common Pc and Time of Maneuver Threshold



Landsat 7 Dataset 1 (2015)



ICESat-2 Dataset 2 (2023)

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Policy Study: Common Pc and Time of Maneuver Threshold

Main Findings:

- Results suggest that **the influence of the Pc threshold is significantly higher than the influence of the time of maneuver threshold** on the resulting number of maneuvers
- The influence of the time of maneuver seems to be higher in dataset 2: better orbit determination could provide smaller covariance matrices closer to TCA

Next step:

- Use a more diverse set of CDMs to understand how different orbital parameters and different detection capabilities influence the results

Policy Study: Ordinal Ranking based Maneuver Decision

Spacecraft name	Av. nb of primary maneuver	Av. nb of secondary maneuver	Primary maneuvers %
Terra	0.4	6.6	7 %
Aqua	0	15.6	0 %
ICEYE-X14	9.28	1	91 %

Ordinal Ranking Based Decision

Spacecraft name	Av. nb of primary maneuver	Av. nb of secondary maneuver	Primary maneuvers %
Terra	0	7	0 %
Aqua	0	15.6	0 %
ICEYE-X14	7.8	3	72.4 %

NORAD ID Based Decision

Policy Study: Socioeconomic Factor Sensitivity Analysis

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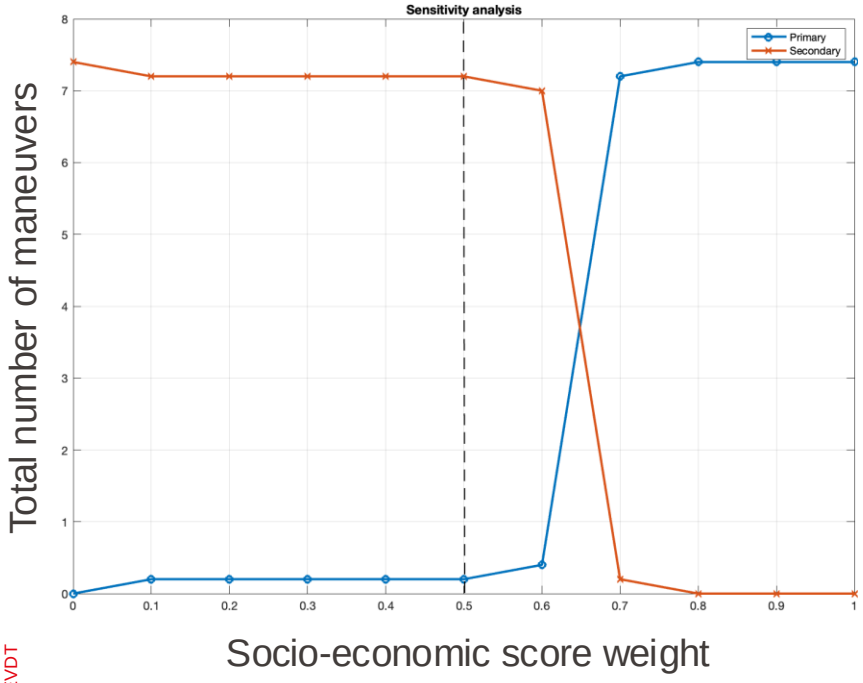
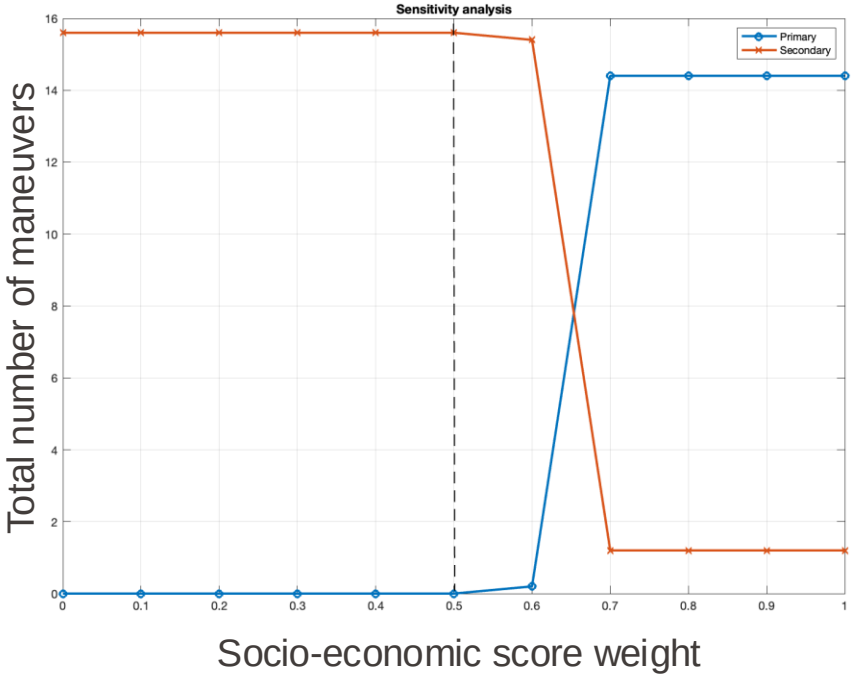
TERRA Sensitivity Analysis

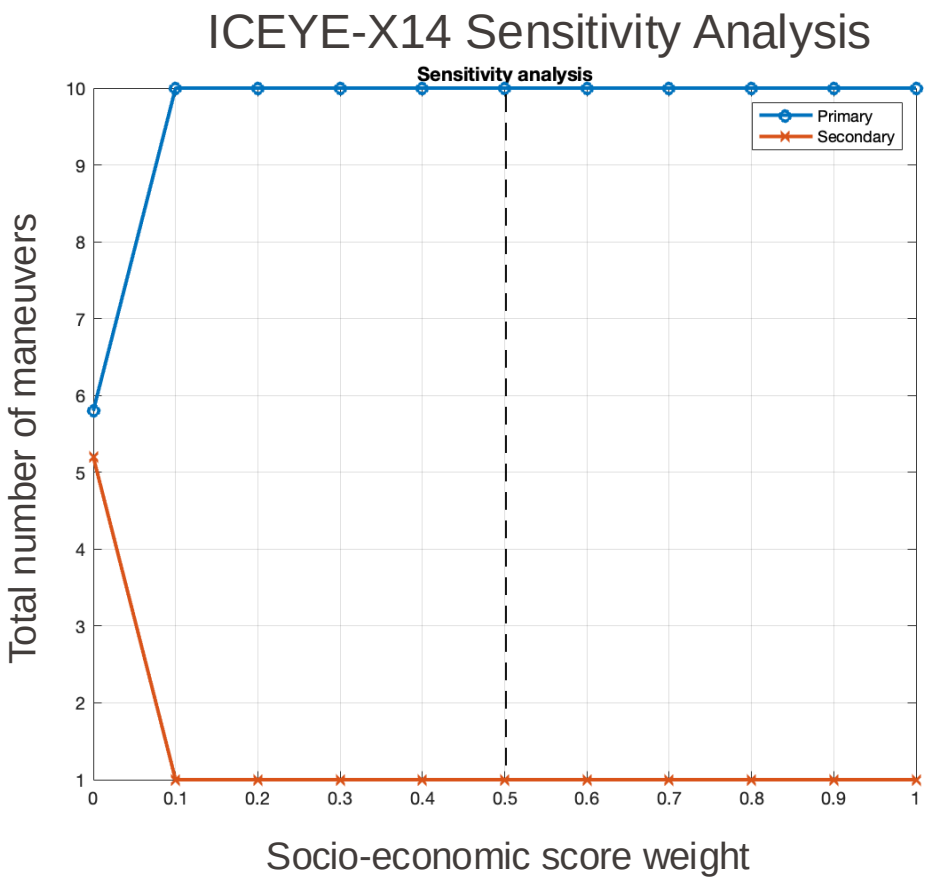


AQUA Sensitivity Analysis



$$S_{tot} = \gamma \cdot S_{sse} + (1 - \gamma) \cdot S_c$$

Policy Study: Socioeconomic Factor Sensitivity Analysis



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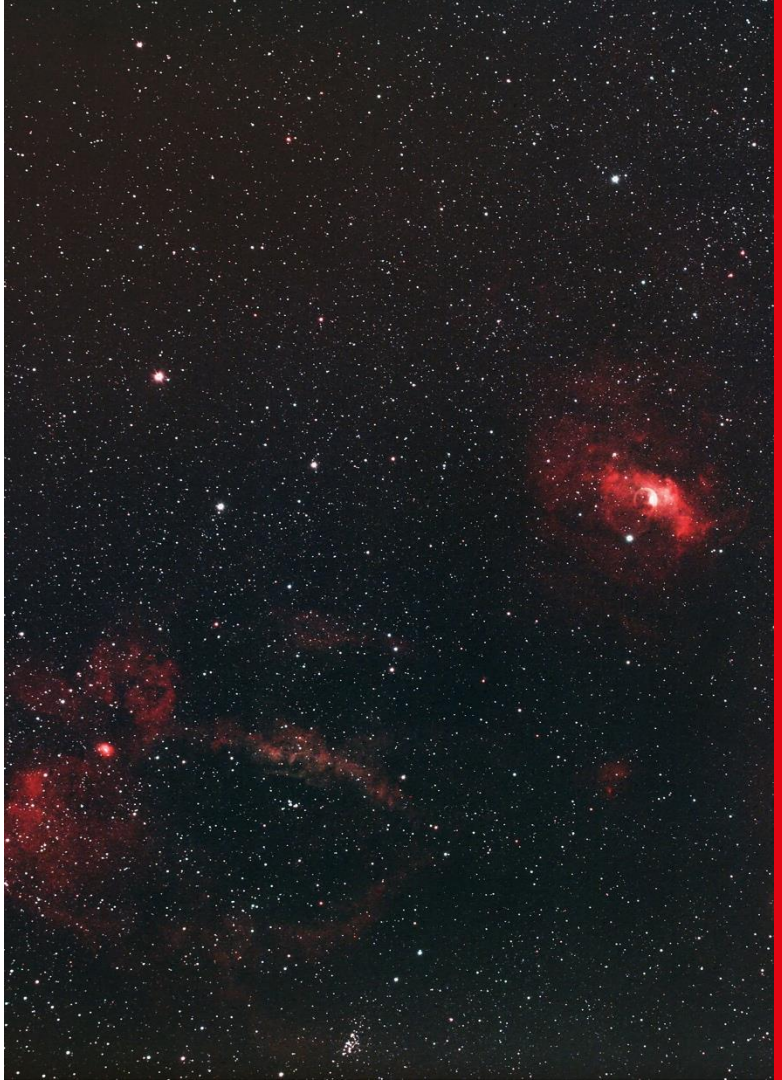
Policy Study: Socioeconomic Factor Sensitivity Analysis

Main Findings:

- With **low and balanced socio-economic score weighting**, TERRA & AQUA will not take maneuver initiative: very high cost score
- With **high socio-economic score weighting**, high cost score has less influence, remaining lifetime reduce their total score: TERRA & AQUA take maneuver initiative
- ICEYE-X14 will take maneuver initiative most of the time as it has low socio-economic score and low cost score
- Overall, a 50/50 split is a reasonable weighting



Conclusion

1. Outcome Summary

2. Limitations & Future Work

Outcome Summary

COLA EVDT 2.0 Main Improvements:

- **CDM mode**: directly read & study CDMs, Orbit Determination quality check
- **TLE mode**: ordinal ranking based decision model & sensitivity analysis, simplified Pc vs HBR, SWTS

Simulation Outcome:

- Common Pc threshold has significantly more influence on number of maneuvers than time of maneuver
- Simulations on TERRA, AQUA & ICEYE-X14 confirm assumptions on who would maneuver most of the time
- Socio-economic weighting sensitivity analysis suggests that a 50/50 split between socio-economic score and cost score is reasonable

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Limitations & Future Work

Limitations:

- Use of J_2 propagator & TLEs which are not accurate enough for real conjunction assessment
- Ordinal based ranking: accurate information not always readily available (price, operational status, maneuverability)
- Currently assume that active secondary payloads are maneuverable

  → acceptable for capability demonstration

Future Work:

- Pc and time of maneuver threshold study on a more diverse set of CDMs
- Study other potential space policies
- Use SSR as socio-economic valuation method

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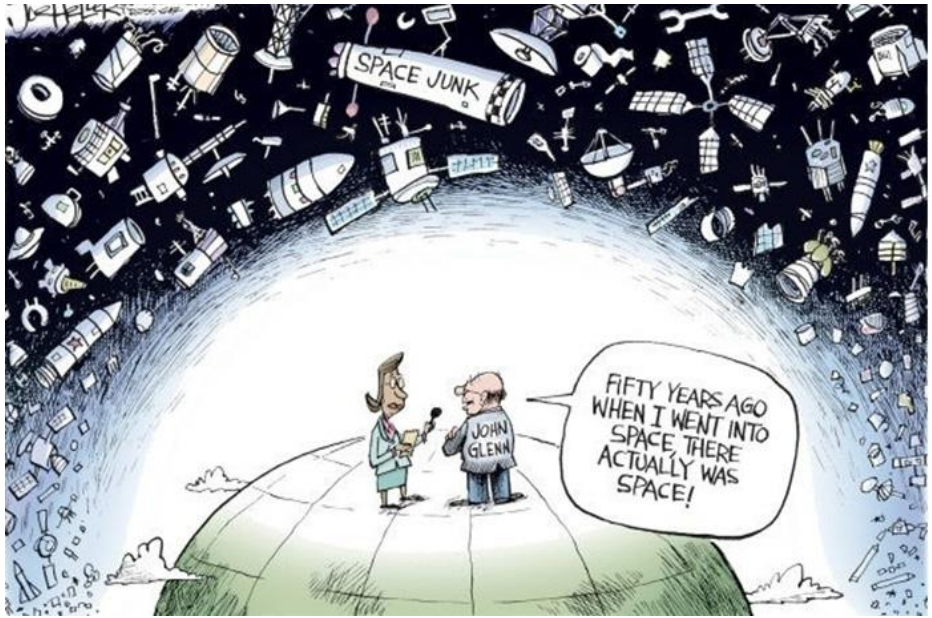
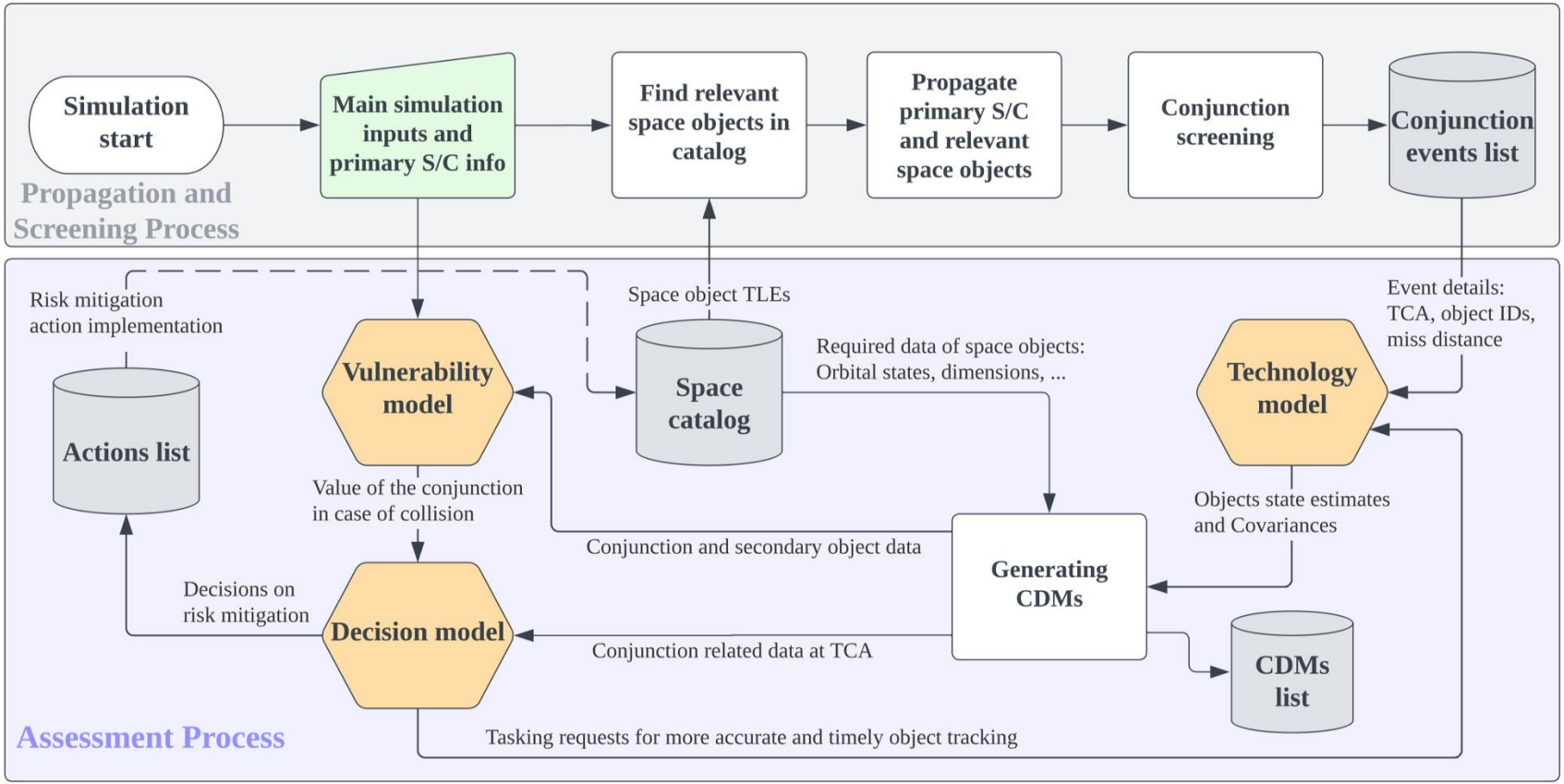


Fig.: John Glenn cartoon

COLA-EVDT 1.0



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