Lumos

GSAW 2021

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Acknowledgements

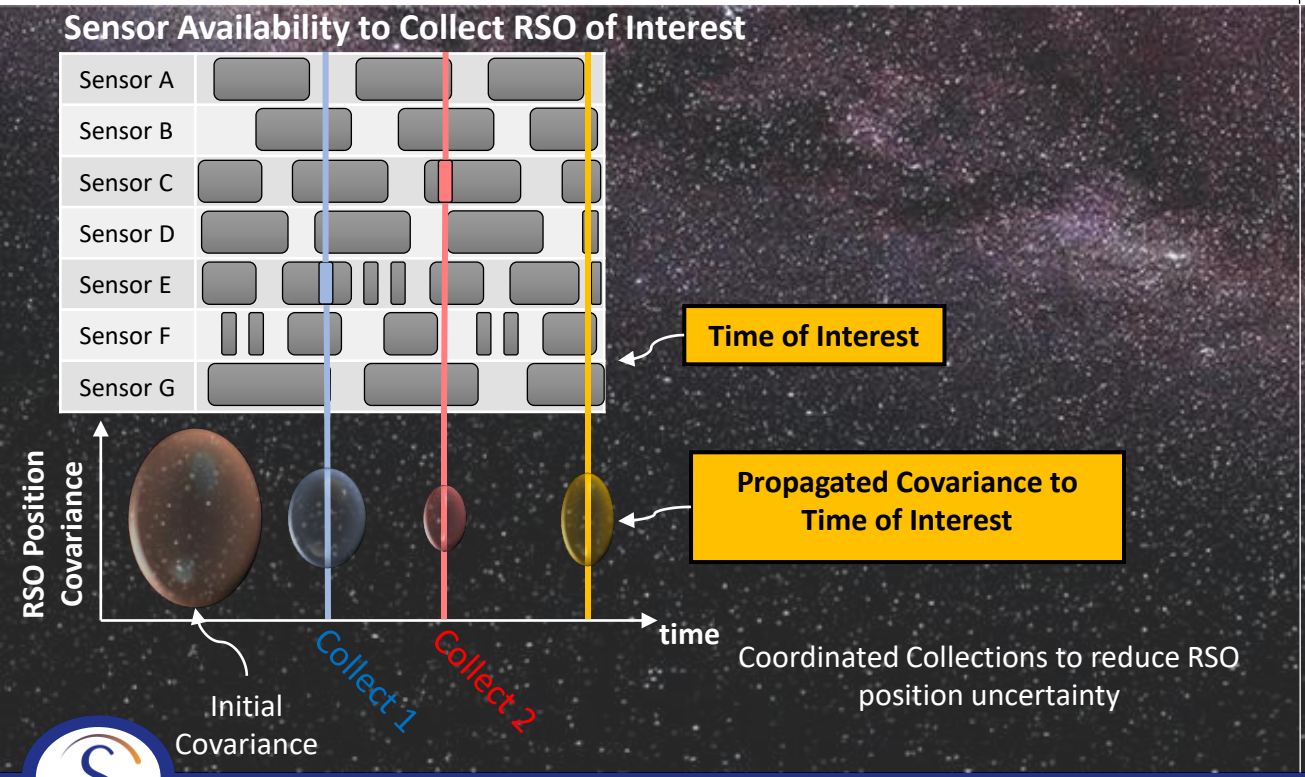
- Emily Gerber
- Bill Delude
- Dr. Wes Faber
- Taylor Nave
- Dr. Thomas Kelecy
- Brian Bontempo
- Ben Avicolli

Lumos Summary

Collection Recommender

Need: *1 SOPS requires the ability to plan coordinated collections across space surveillance sensors to arm decision makers with the high-quality SDA information*

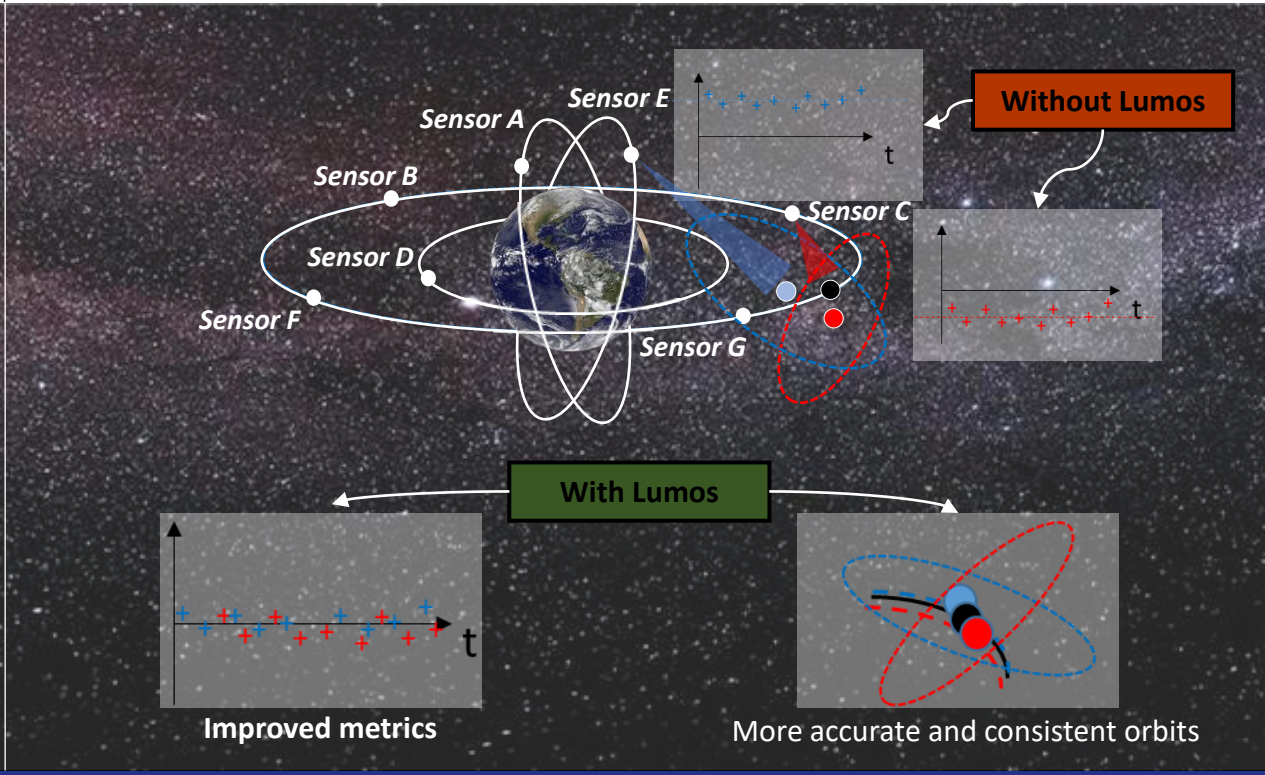
Solution: Lumos Collection Recommender employs reinforcement learning to optimize strategies for sensor tasking



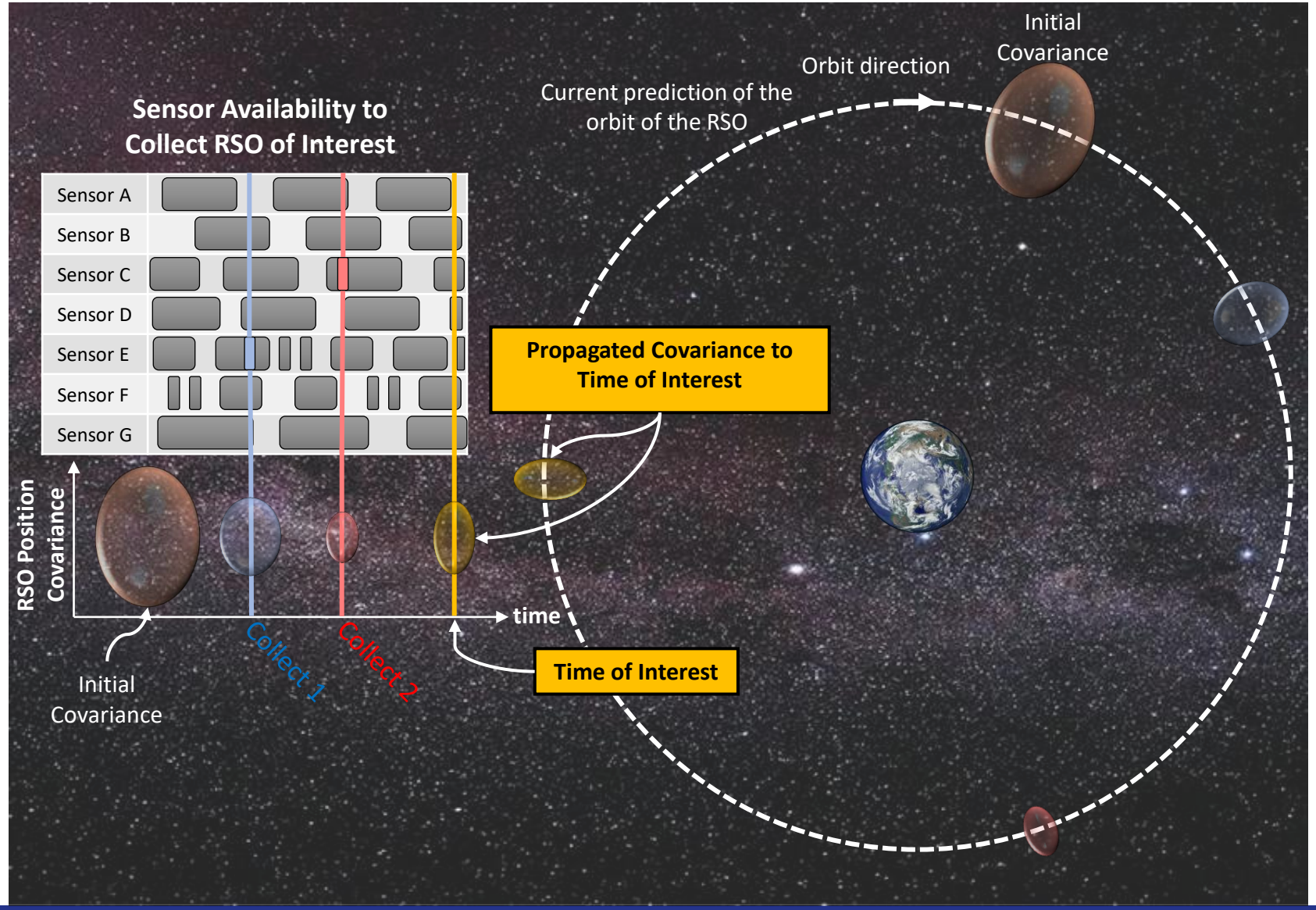
Anomaly Detector

Need: *1 SOPS requires the ability to provide consistent, accurate, and timely Space Domain Awareness (SDA) observation data*

Solution: Lumos consolidates information from the multiple systems to improve data quality assessment through a multi-state bias estimation process



Lumos Collection Recommender



Collection Recommender Problem Statement

- The goal of Lumos Collection Recommender is to determine ***Sensor Configurations***, $A(t)$, that:
  - Minimizes the amount of ***Effort***, a metric that is a function of number of sensors required, number of observations from each system, and time/duration the systems are operating
  - Minimizes **user defined measurement of RSO covariance** at a desired time, T, subject to inequality constraints provided by the user

- When given the **Initial Covariance**, $\chi(t_0)$, we will find the optimal sensor configuration that maximizes our underlying objective function based on **Information Gain**:

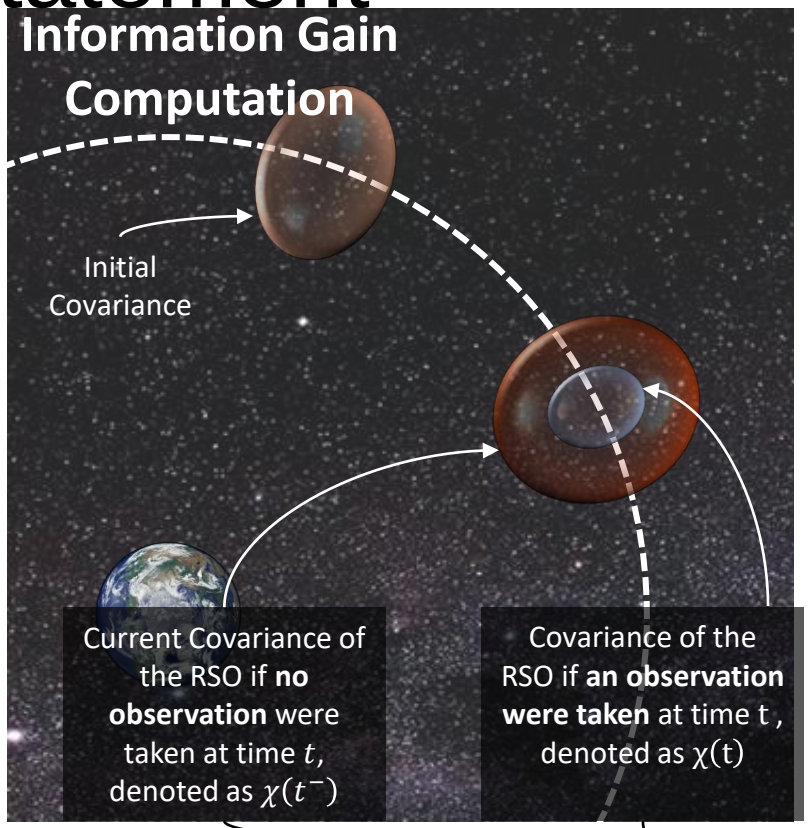
$$A^*(t_f) \approx \underset{A(t)}{\operatorname{argmax}} J(\chi(t), A(t), T)$$

  - Such that:

$$g(\chi(T)) \leq R_T$$

  - where $g(\chi(t))$ is a measurement of the covariance at time t
  - **Objective function is non-convex**!

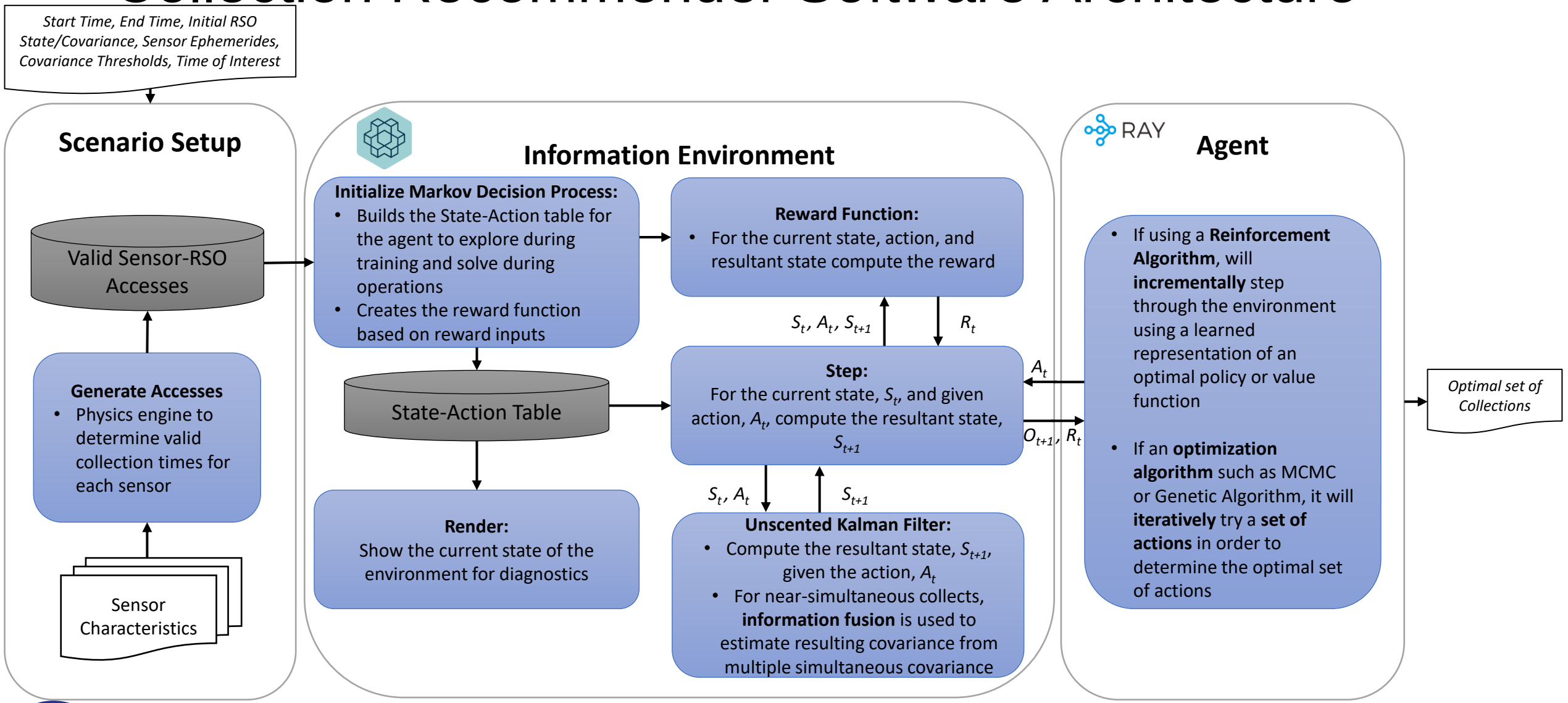
- Computation of Information Gain is shown in the diagram to the right



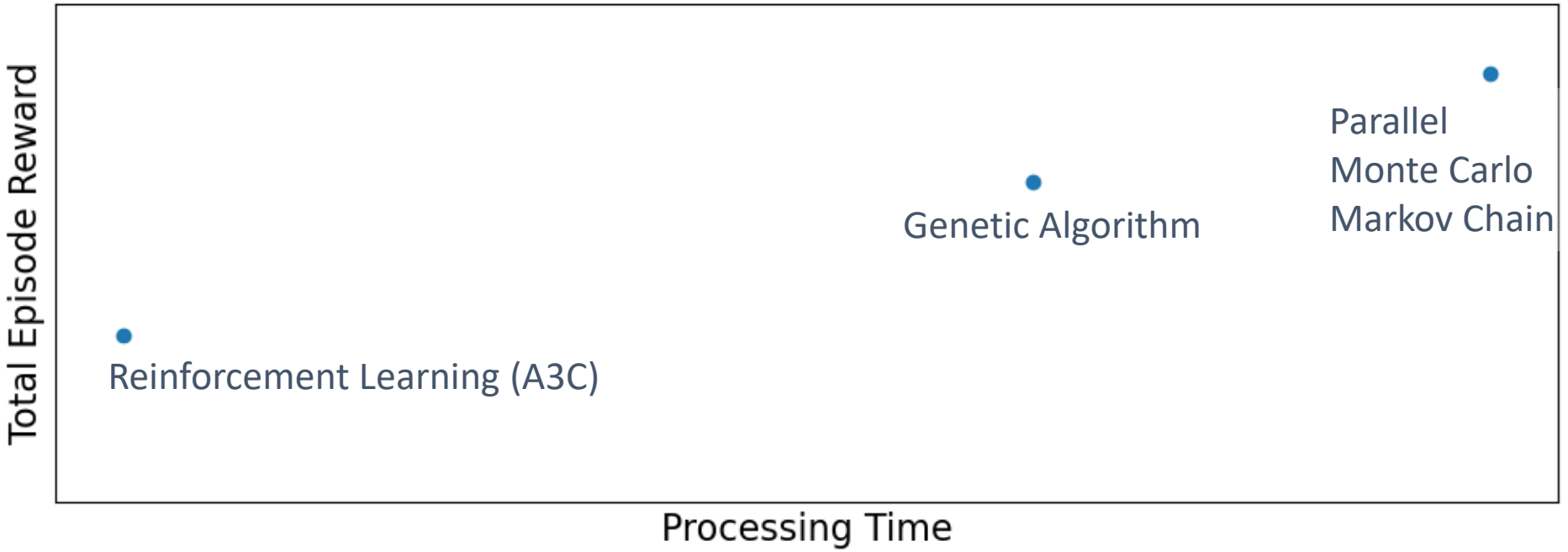
$$\Delta I(\chi(t_0), A(t)) = \left(g(\quad) - g(\quad)\right)$$

$$\Delta I(\chi(t_0), A(t)) = \left(g(\chi(t^-)) - g(\chi(t))\right)$$

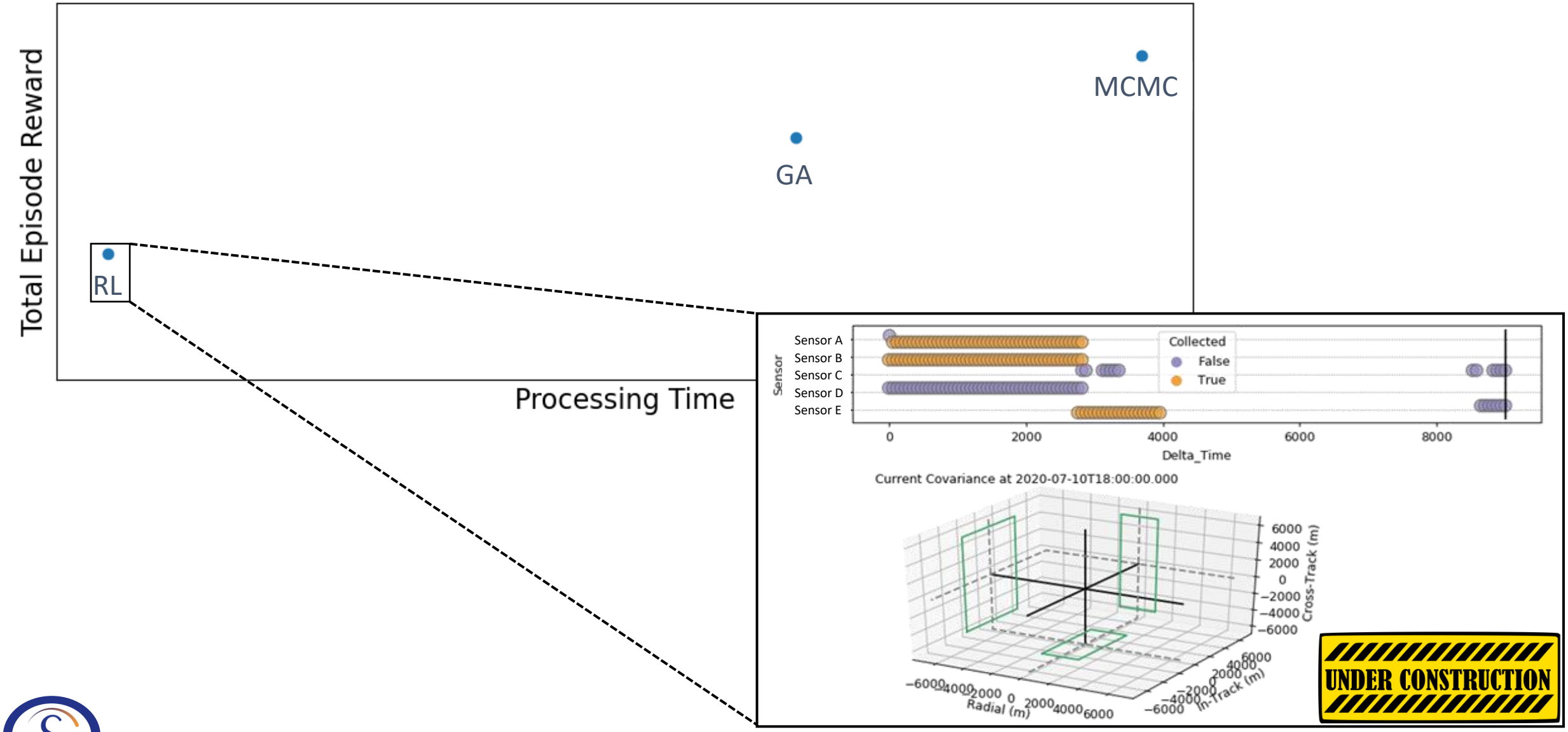
Collection Recommender Software Architecture



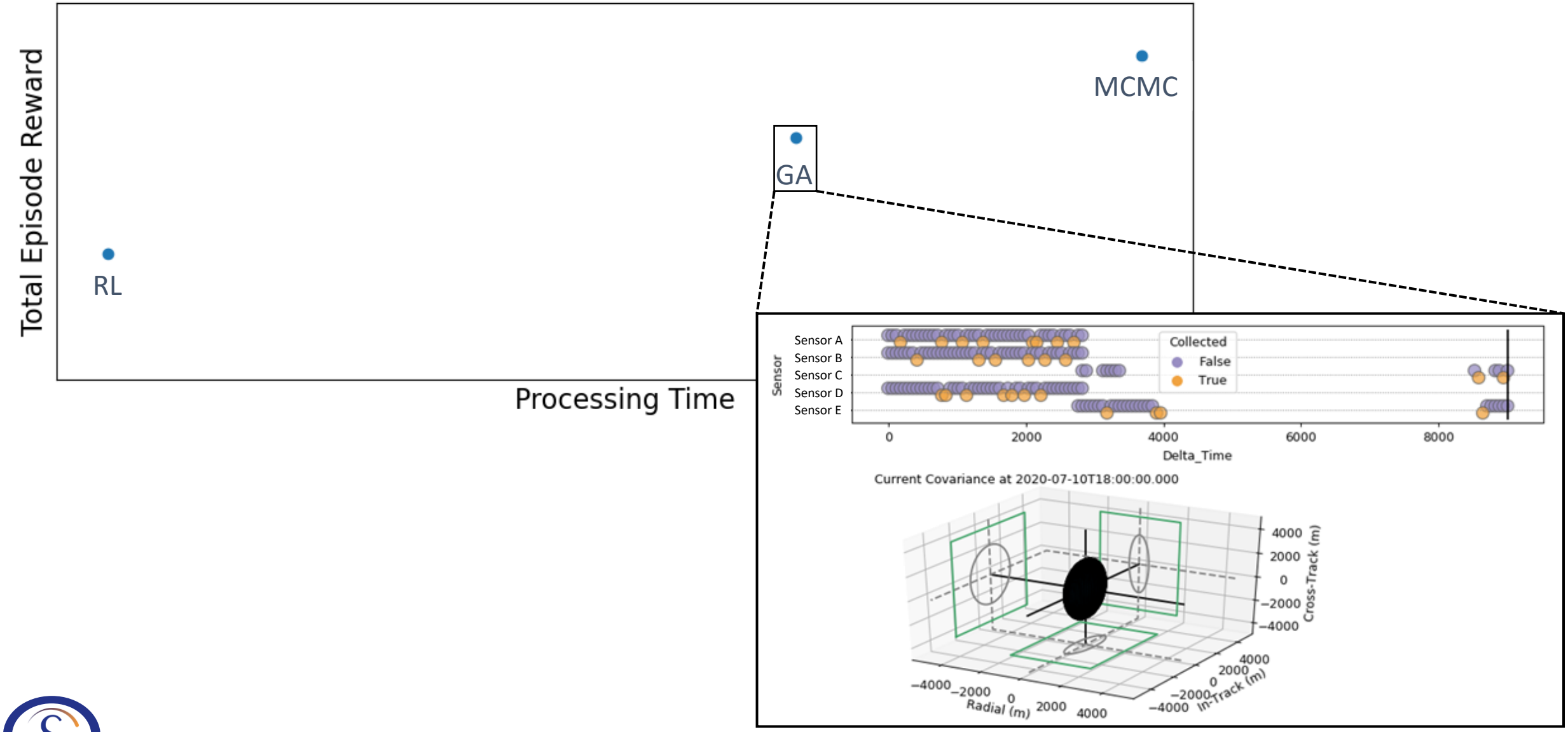
Collection Recommender Optimization Results



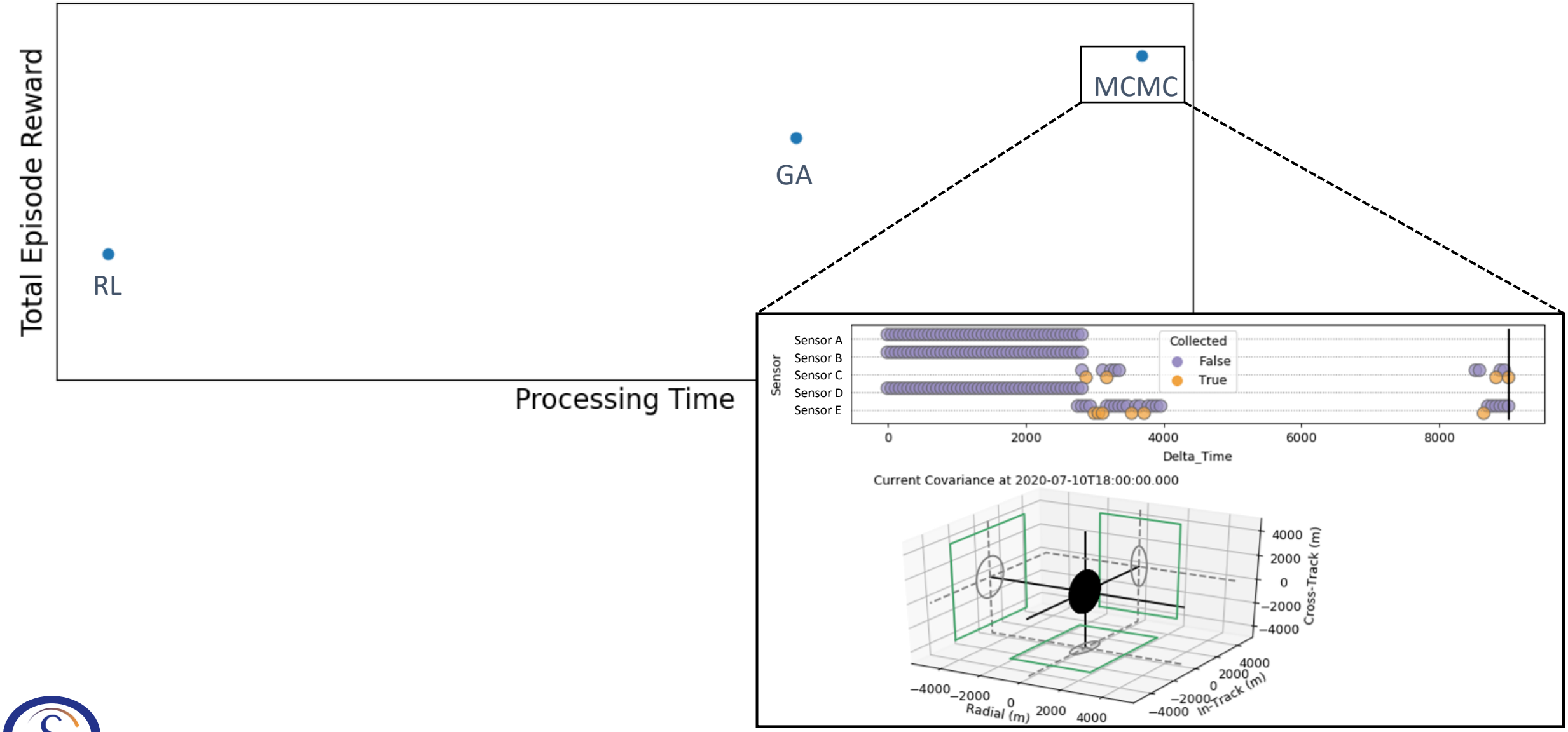
Collection Recommender Optimization Results: RL



Collection Recommender Optimization Results: GA



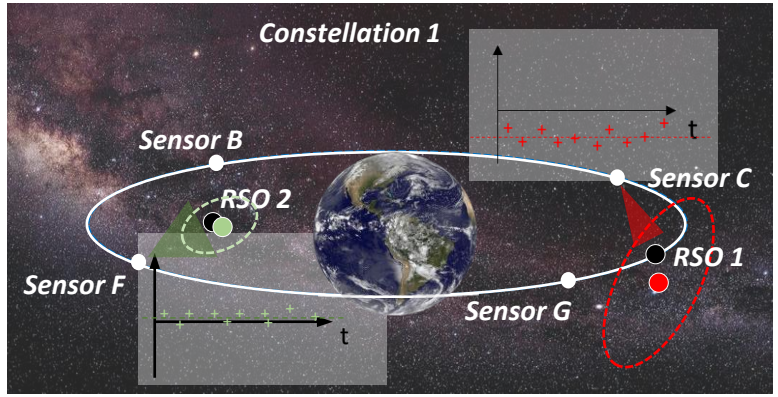
Collection Recommender Optimization Results: MCMC

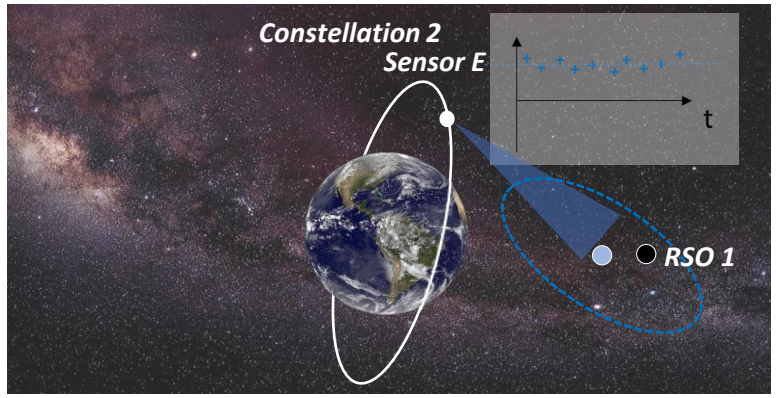


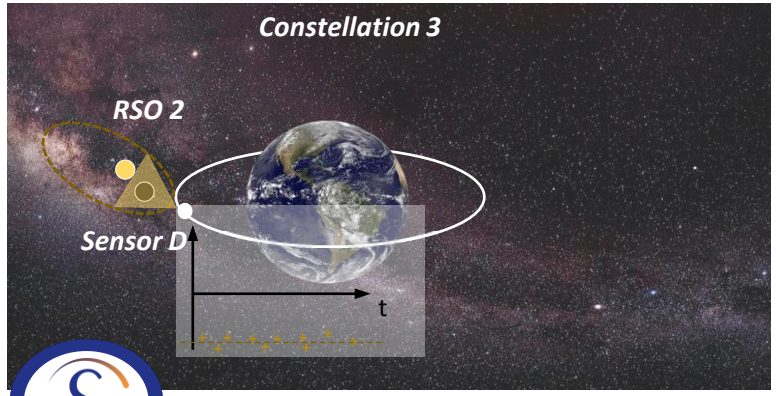
Agent Strengths vs. Weaknesses

	Reinforcement Learning	Genetic Algorithm	Parallel-MCMC
Strengths	• Fast! Only needs to run through the environment one time. Offers a **responsive solution towards a real-time solution**	• Offers the ability to present an operator with a diverse set of solutions	• If sufficient iterations are executed, will converge to a global maxima • Fewest hyperparameters
Weaknesses	• Large number of hyperparameters to tune, and more complex to train a solution that generalizes 	• Potential to converge to a local maximum • Large number of hyperparameters to try to tune results and avoid local maximum • **Iterative** process—Runs through the environment multiple times to evaluate each generation • **Realization of optimization is dependent on collects resulting in successful tracks**	• **Incrementally steps** through the environment, and at each step **iteratively** explores a part of the environment based on Horizon Depth • Runtime grows significantly as number of potential collects increases • **Realization of optimization is dependent on collects resulting in successful tracks**

Lumos Anomaly Detector

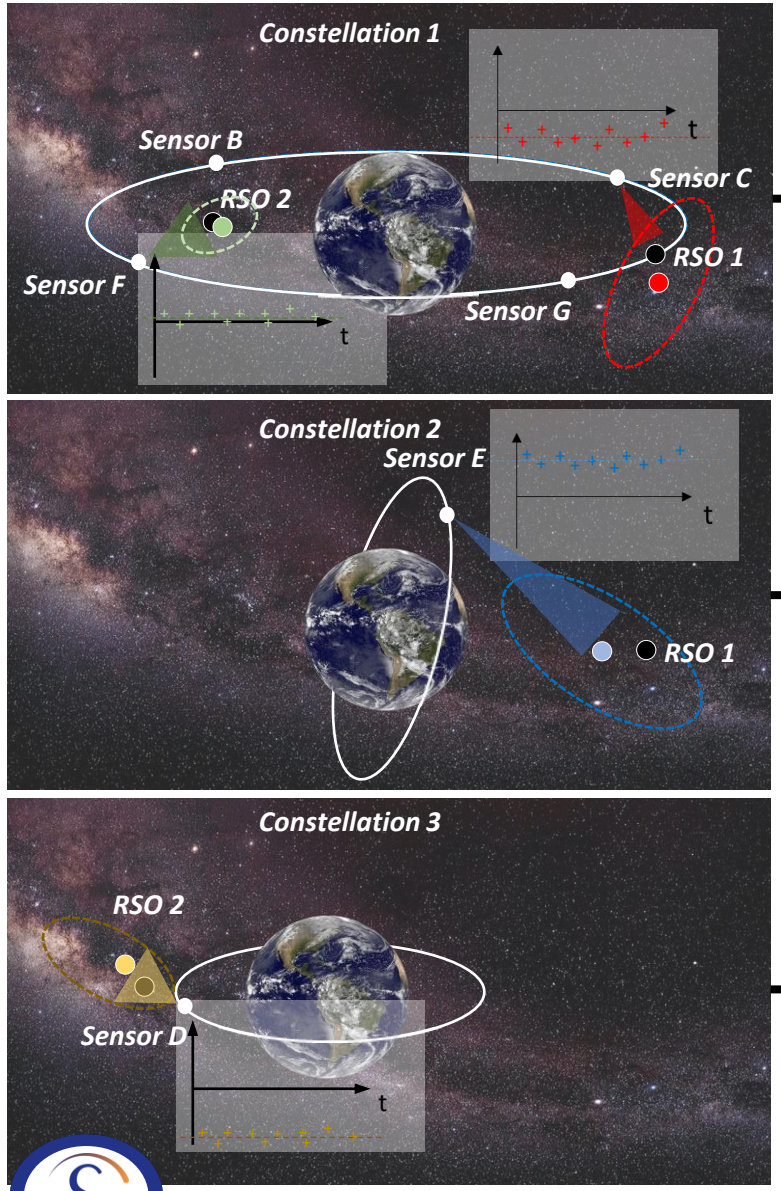






- Each satellite/sensor constellation in the 1 SOPS constellation was built independently
  - Observations are used to maintain accurate orbital knowledge of a large catalog of RSOs for their end-users, not to cross-validate measurements from other sensors
- When a single sensor is used to estimate an RSO state, resultant estimated state may be biased due to sensor errors
  - Analysts today manually detect when a sensor may be generating biased observation data
- Comparing observations of RSOs from multiple sensors can detect anomalous observations due to:
  - Sensor errors such as:
    - Sensor timing bias errors
    - Out-of-date data used to compute sensor ephemerides
  - Unmodeled orbit maneuvers of RSOs

Lumos Anomaly Detector



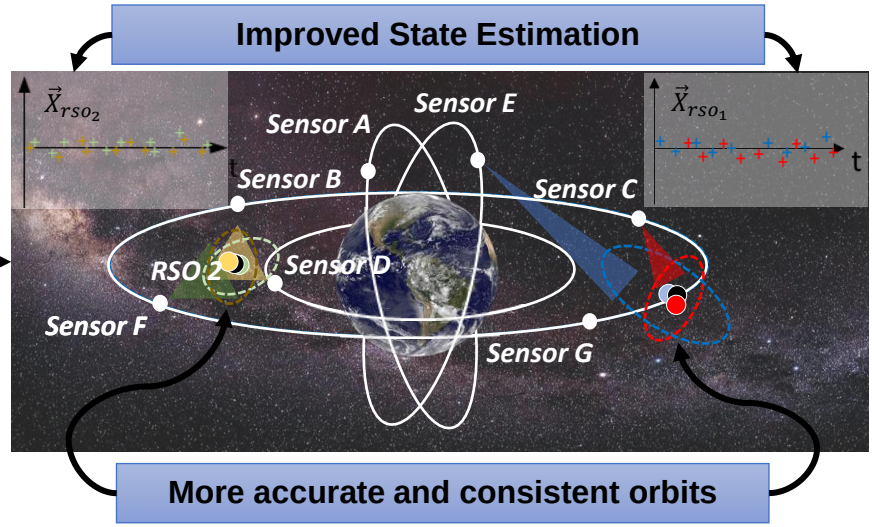
Observations

Lumos USKF

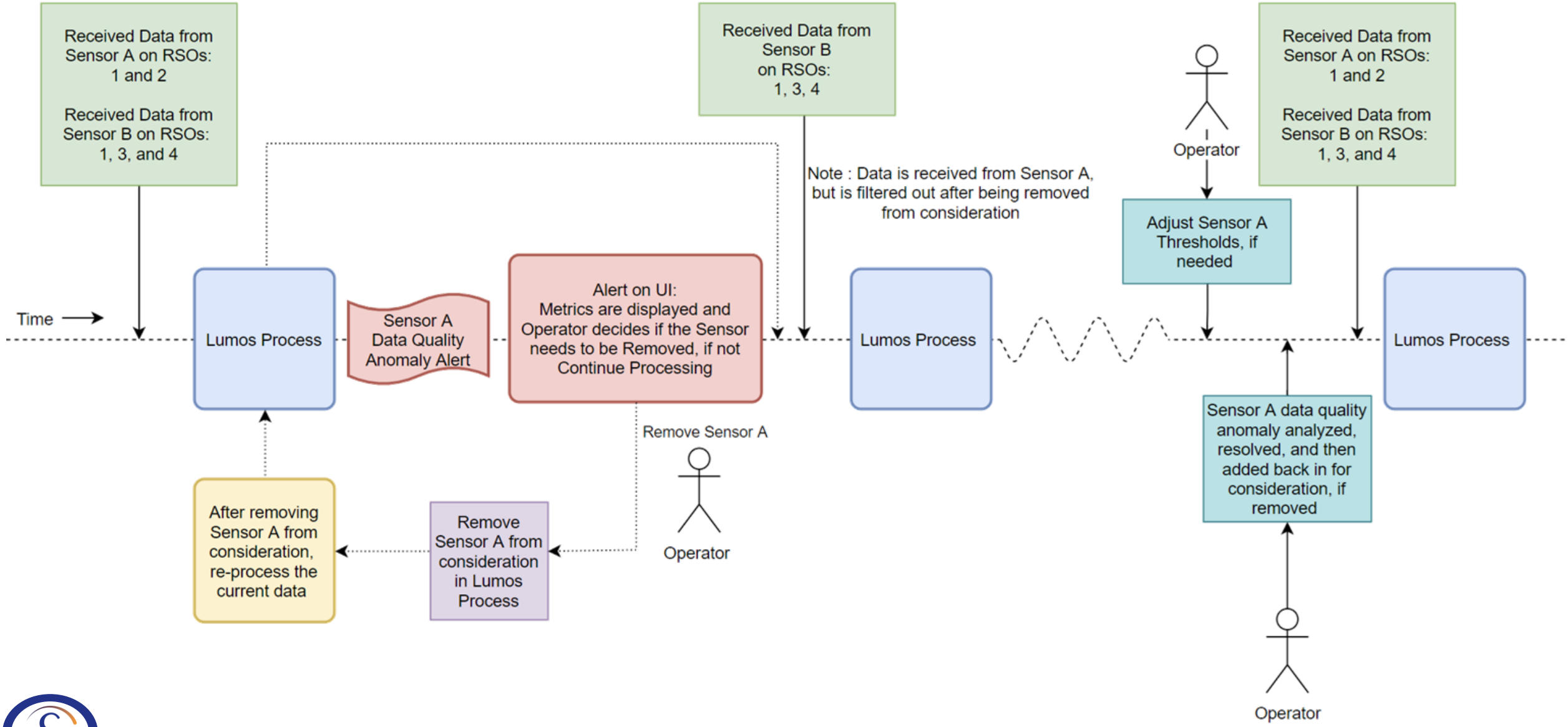
Estimated State

$$\vec{X} = \begin{bmatrix} \vec{X}_{rso_1} \\ \vec{X}_{rso_2} \\ \delta_{t_A} \\ \delta_{t_B} \\ \vdots \\ \delta_{t_G} \end{bmatrix}$$

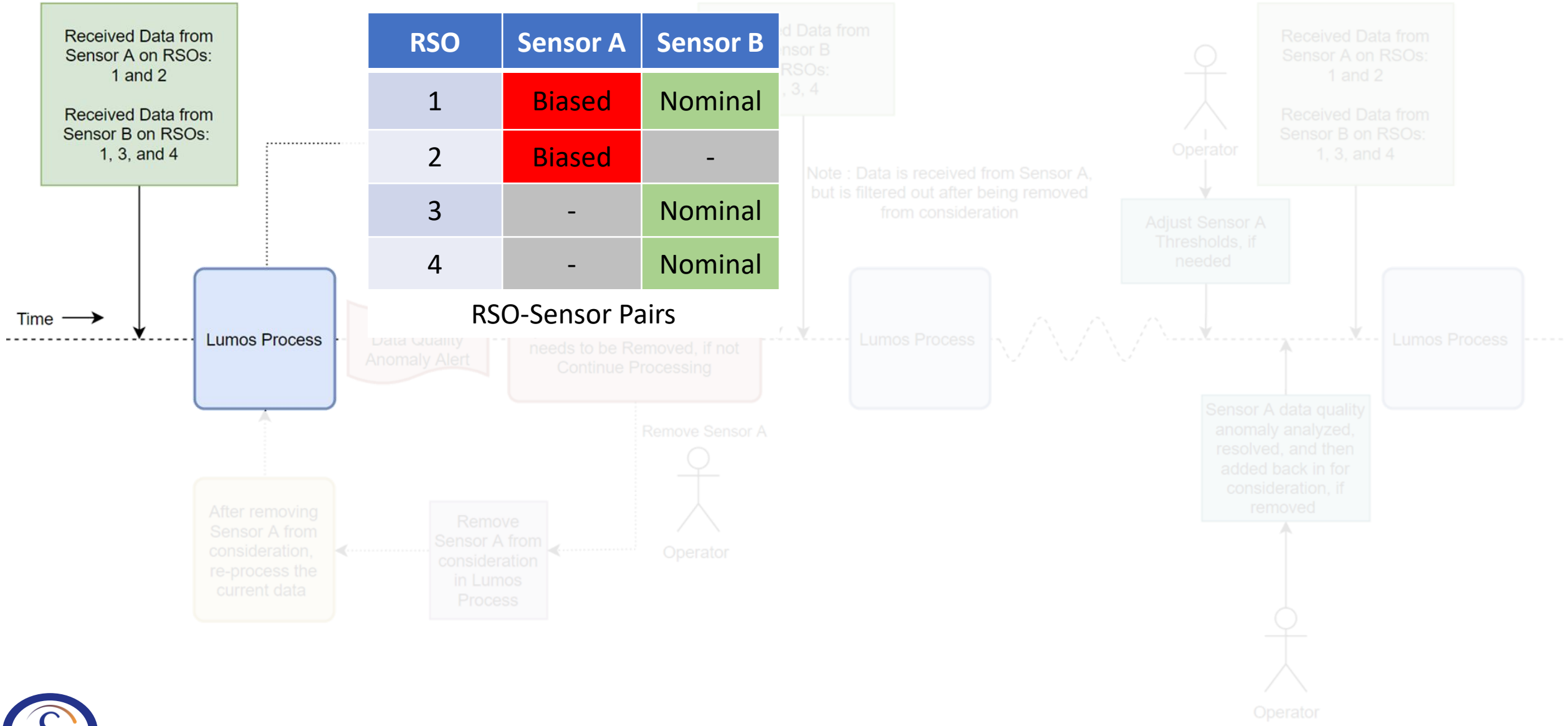
- Lumos's Anomaly Detector fuses observations of well-known / well-behaved RSOs from various space-based EO SDA constellations to monitor for sensor anomalies
  - Uses a multi-state Unscented Schmidt Kalman Filter to estimate:
    - Sensor timing bias
    - State(s) of RSO(s): $\vec{X}_{rso}$



Anomaly Detector Walkthrough



Anomaly Detector Walkthrough



RSO	Sensor A	Sensor B
1	Biased	Nominal
2	Biased	-
3	-	Nominal
4	-	Nominal

RSO-Sensor Pairs

Anomaly Detector Walkthrough

Received Data from Sensor A on RSOs: 1 and 2

Received Data from Sensor B on RSOs: 1, 3, and 4

Time

Lumos Process

Sensor A Data Quality Anomaly Alert

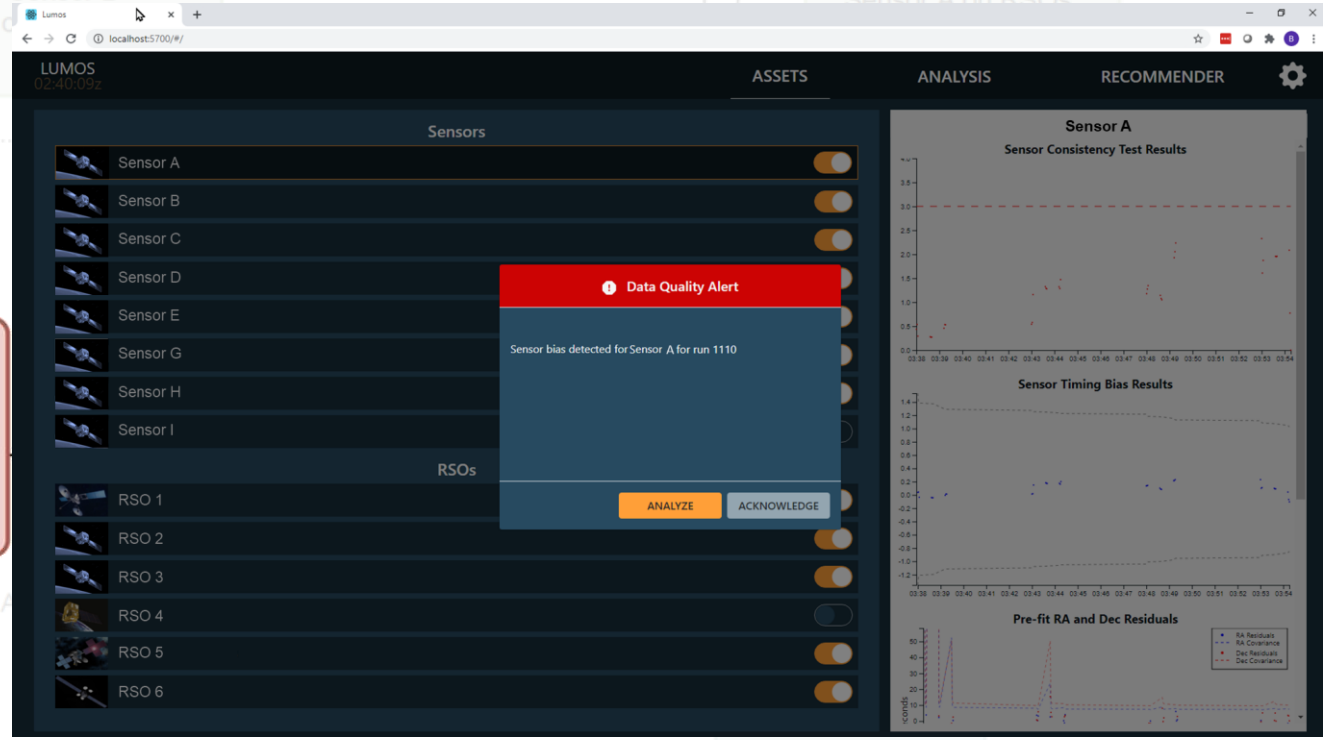
Alert on UI: Metrics are displayed and Operator decides if the Sensor needs to be Removed, if not Continue Processing

Remove Sensor A

Operator

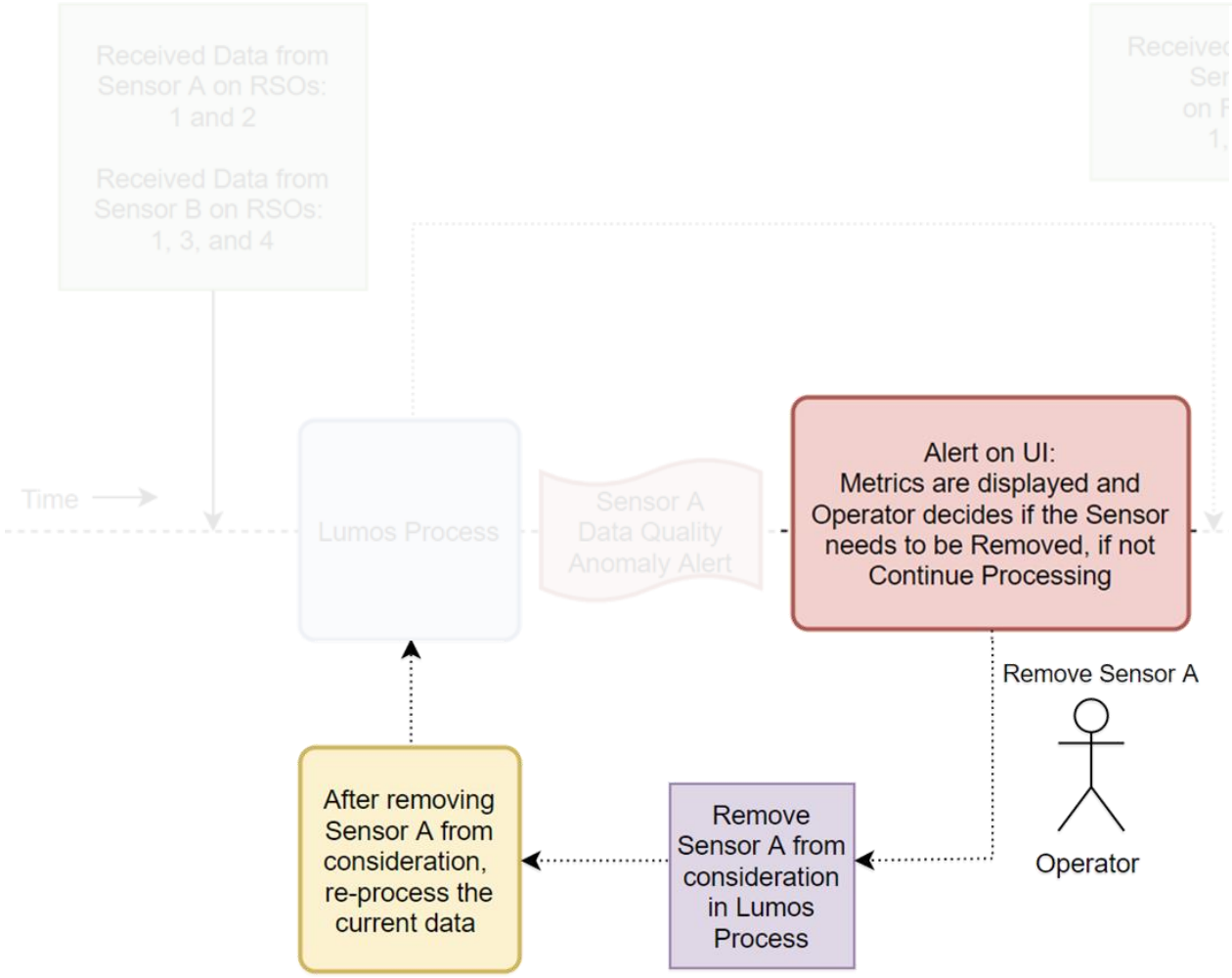
Remove Sensor A from consideration in Lumos Process

After removing Sensor A from consideration, re-process the current data

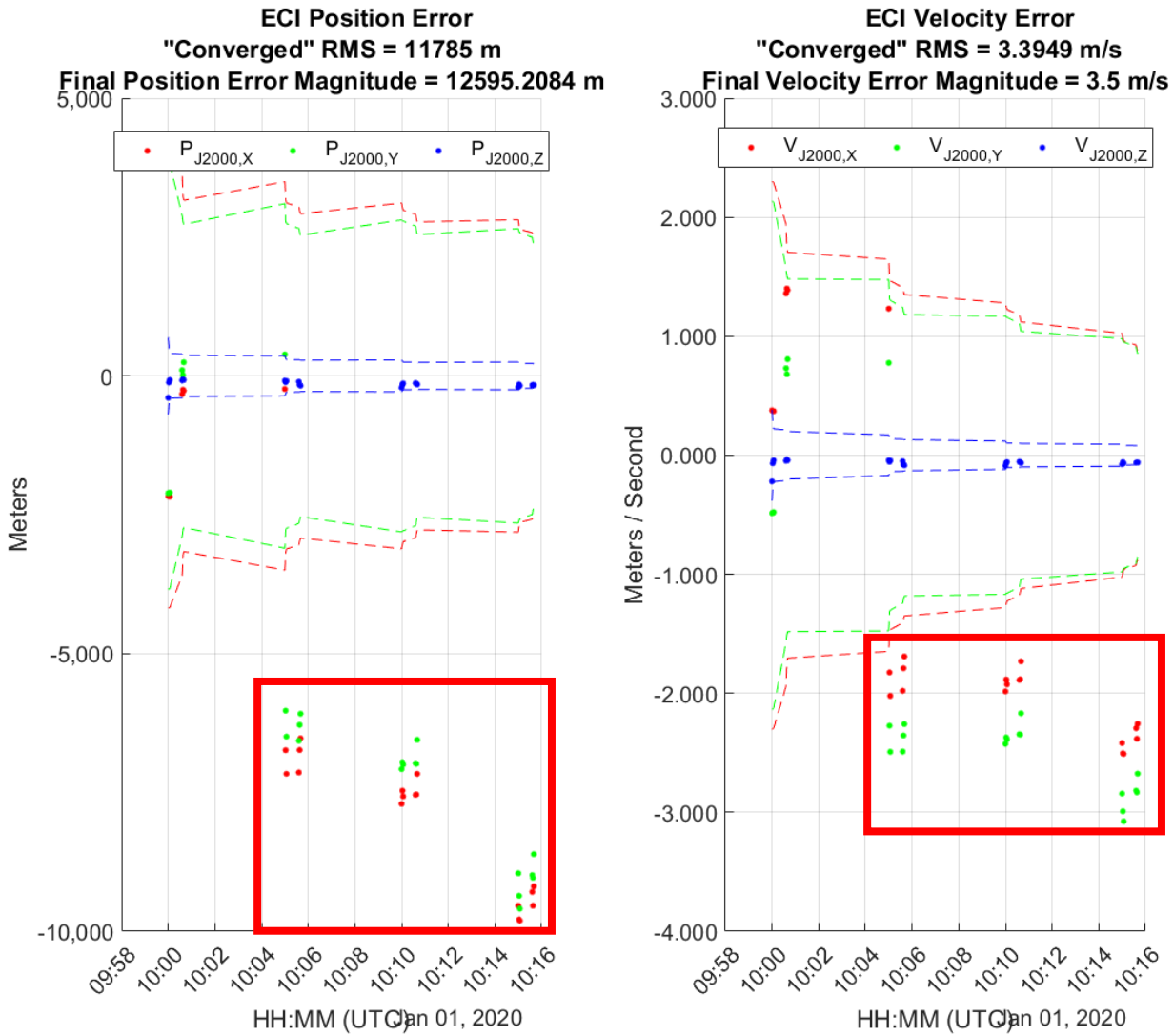


Operator

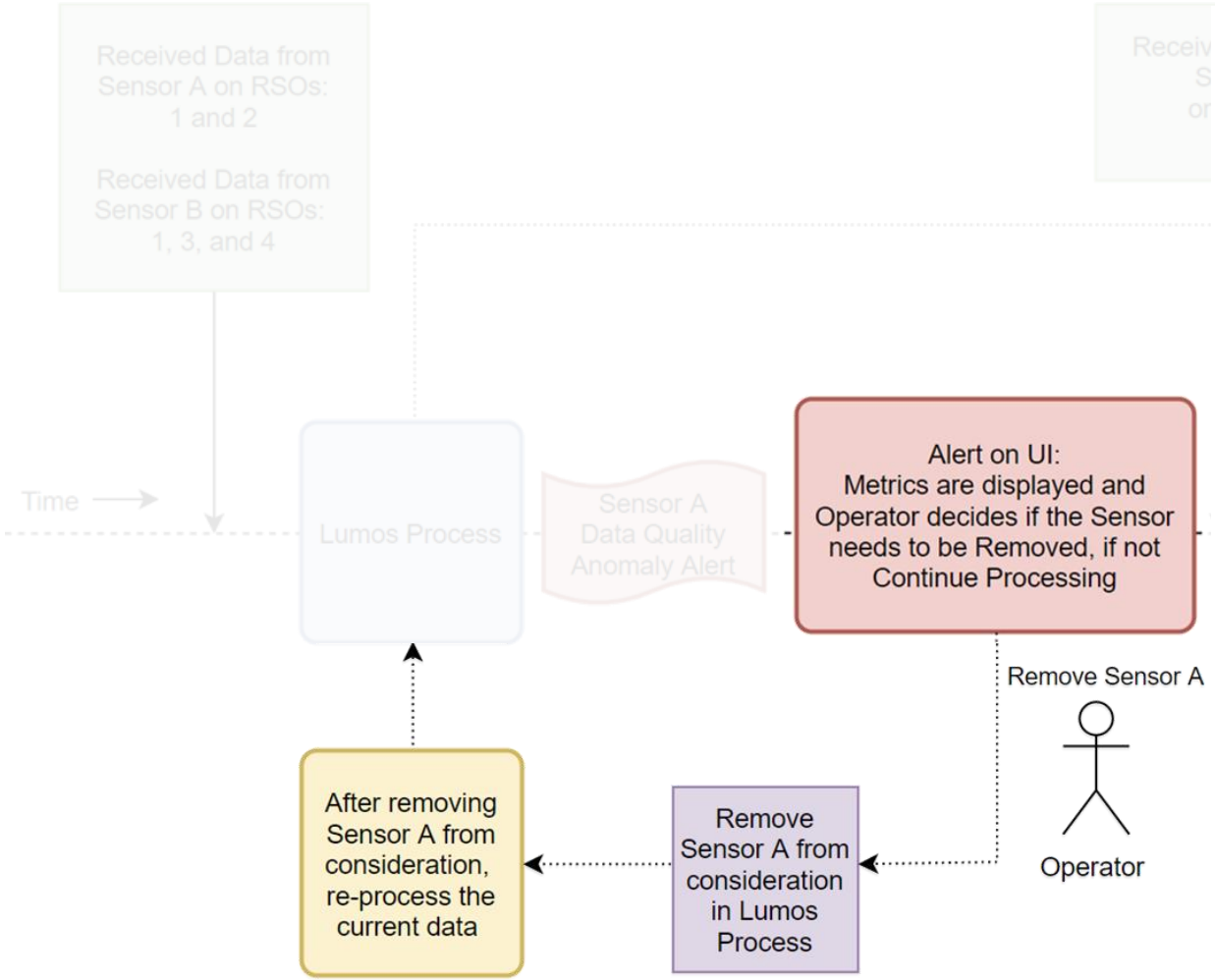
Anomaly Detector Walkthrough



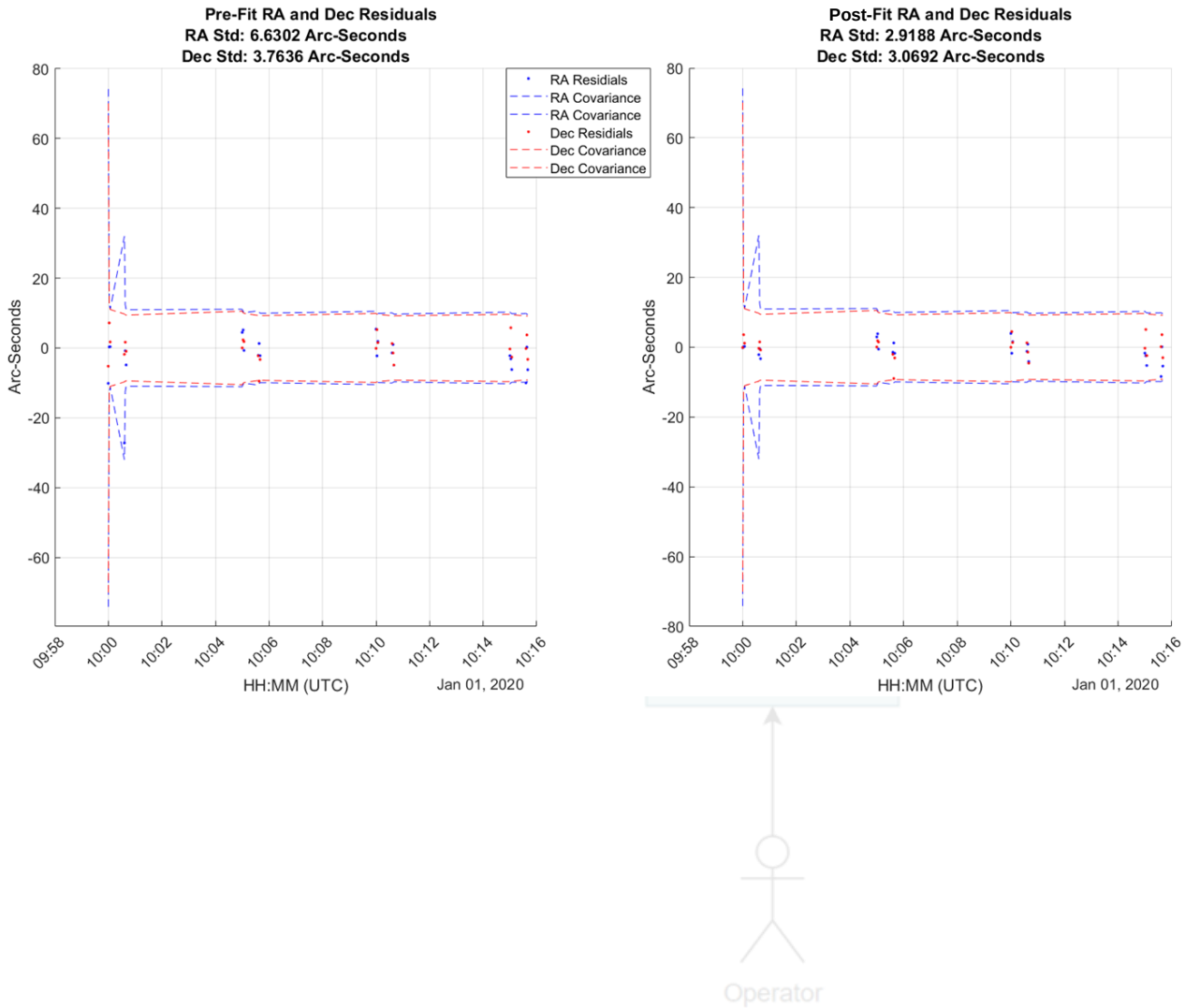
RSO 1 Diagnostic Plots



Anomaly Detector Walkthrough



RSO 1 Diagnostic Plots



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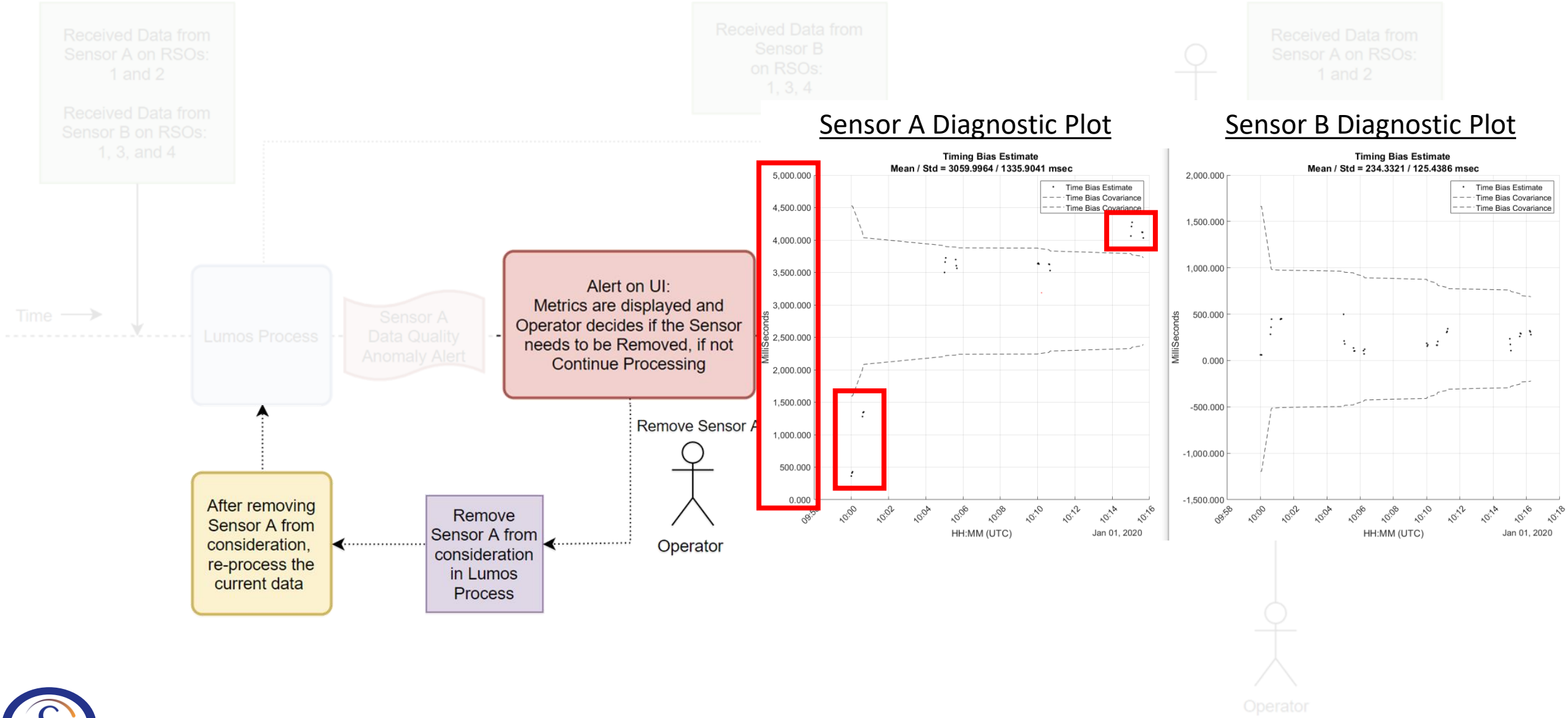

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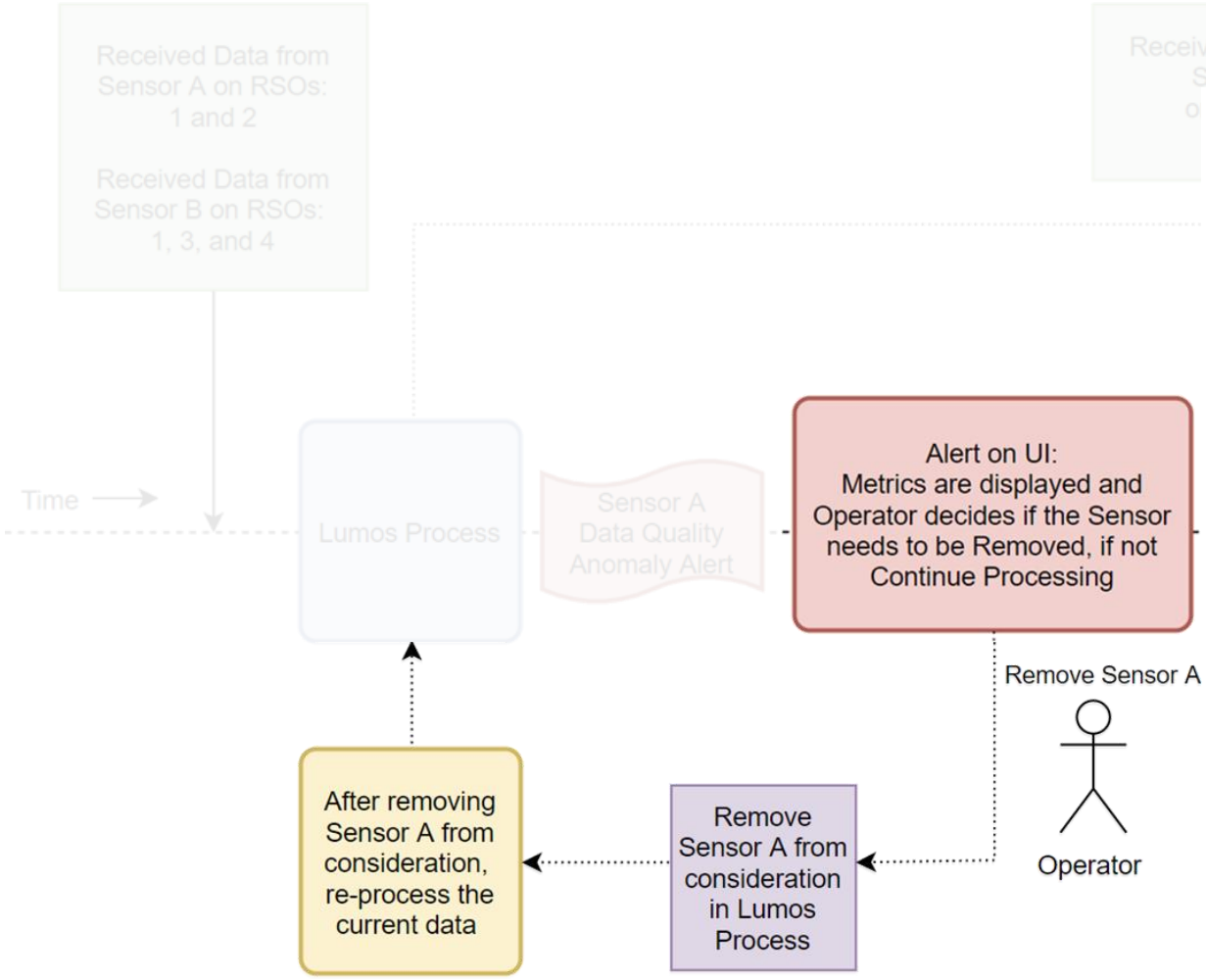
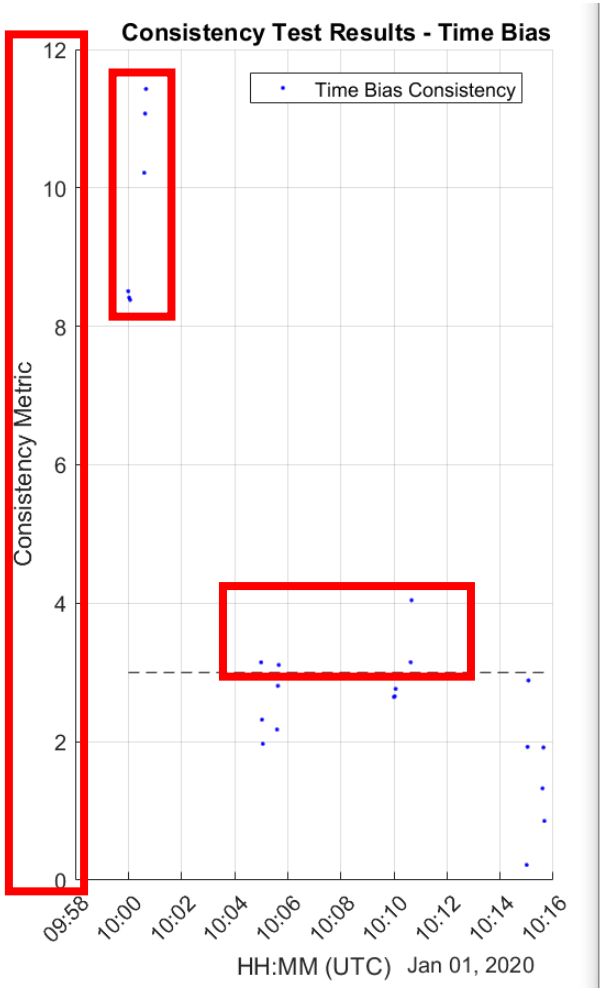
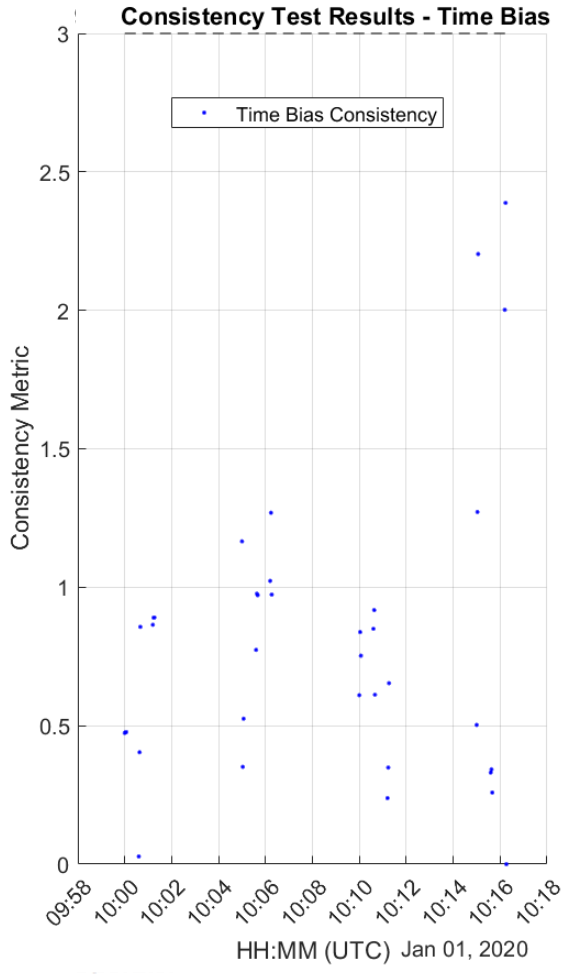


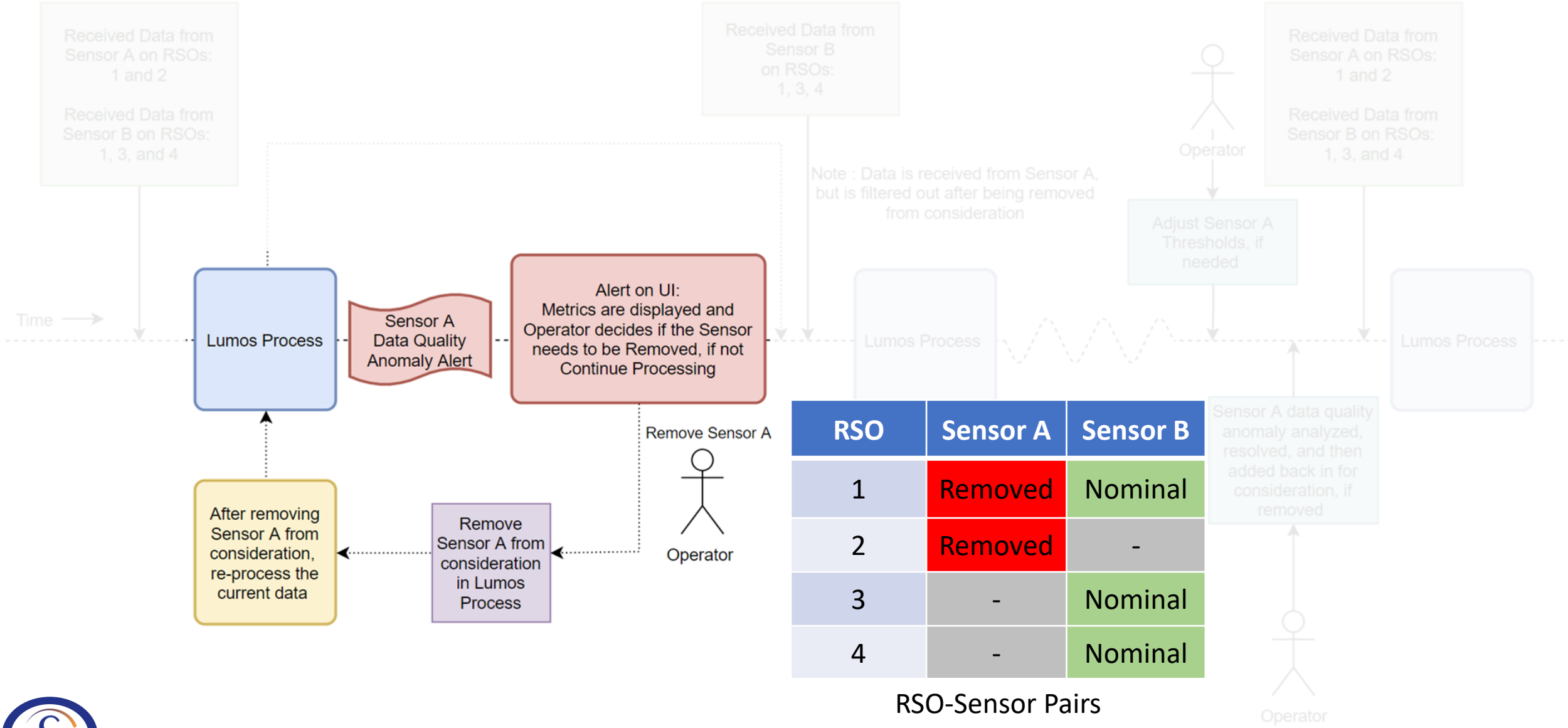
Sensor A Diagnostic Plot



Sensor B Diagnostic Plot



Anomaly Detector Walkthrough



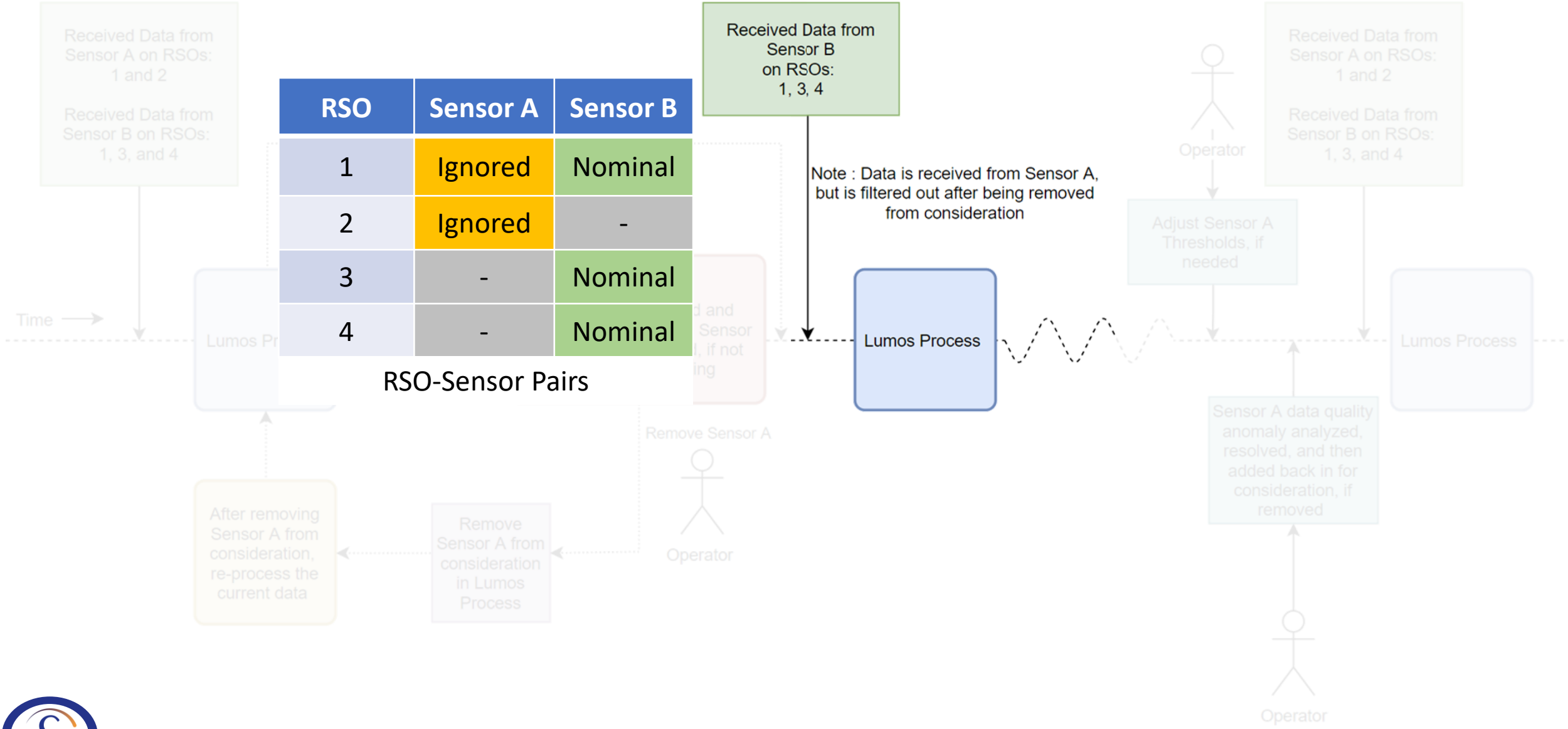
RSO	Sensor A	Sensor B
1	Removed	Nominal
2	Removed	-
3	-	Nominal
4	-	Nominal

RSO-Sensor Pairs

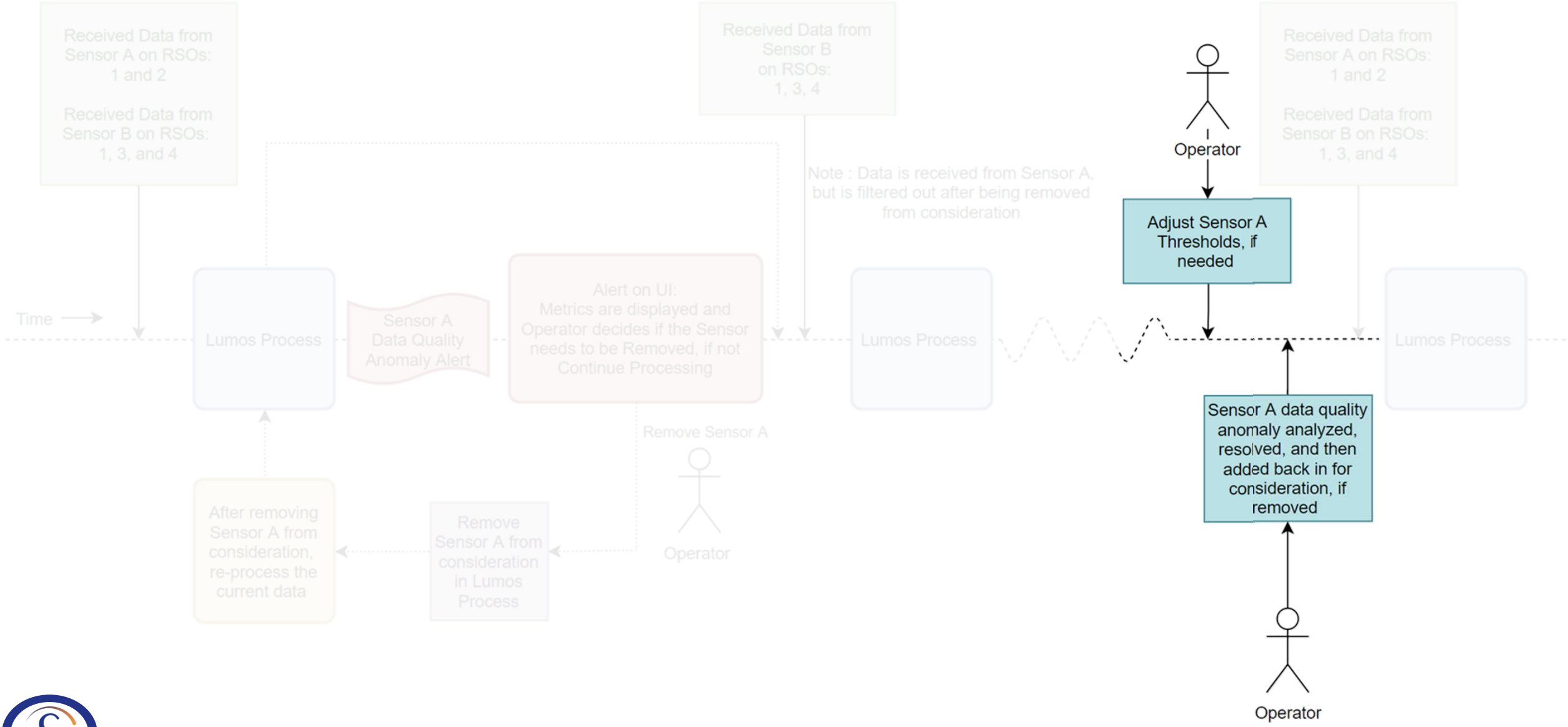
Anomaly Detector Walkthrough

RSO	Sensor A	Sensor B
1	Ignored	Nominal
2	Ignored	-
3	-	Nominal
4	-	Nominal

RSO-Sensor Pairs



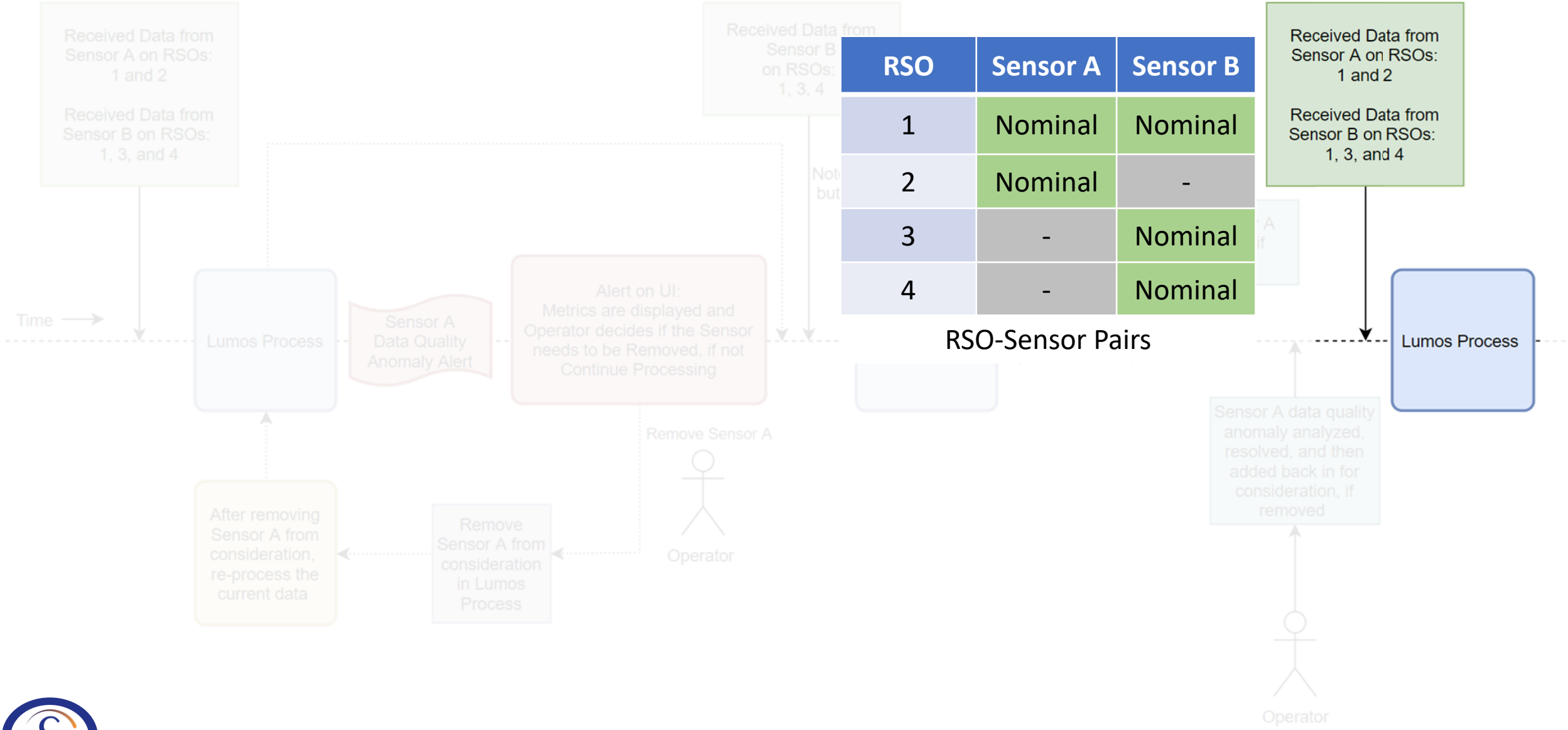
Anomaly Detector Walkthrough



Anomaly Detector Walkthrough

RSO	Sensor A	Sensor B
1	Nominal	Nominal
2	Nominal	-
3	-	Nominal
4	-	Nominal

RSO-Sensor Pairs



Lumos Anomaly Detector Summary

- Lumos will provide 1 SOPS operators **automated processes** enabled by advanced techniques to:
    - Schedule co-collections of RSOs of interest to maintain accurate orbit knowledge
    - Monitor sensors for anomalous data to ensure the accuracy of their computed orbital states
  - These capabilities are currently manual processes and will free up 1 SOPS operators to focus on other areas

- Future Work:
  - Incorporating the output from Lumos into operational workflows
  - Continued research to train a Reinforcement Learning agent to better solve the environment for the Lumos Collection Recommender
  - Extend Lumos capabilities to other sensor systems (e.g. add mount angle state to Anomaly Detector for ground-based sensors)
  - Model and incorporate other systematic biases into the Lumos Anomaly Detector
  - Conjunction assessment management for large constellations (e.g. Starlink)—consolidated states and covariances