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COordinated PLAnner Algorithms

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“This project has received funding from the Horizon 2020 research and innovation programme under grant agreements No 952852. The content of this presentation reflects only the view of the SST Cooperation and the European Commission, and the Research Executive Agency are not responsible for any use that may be made of the information it contains”

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Motivation

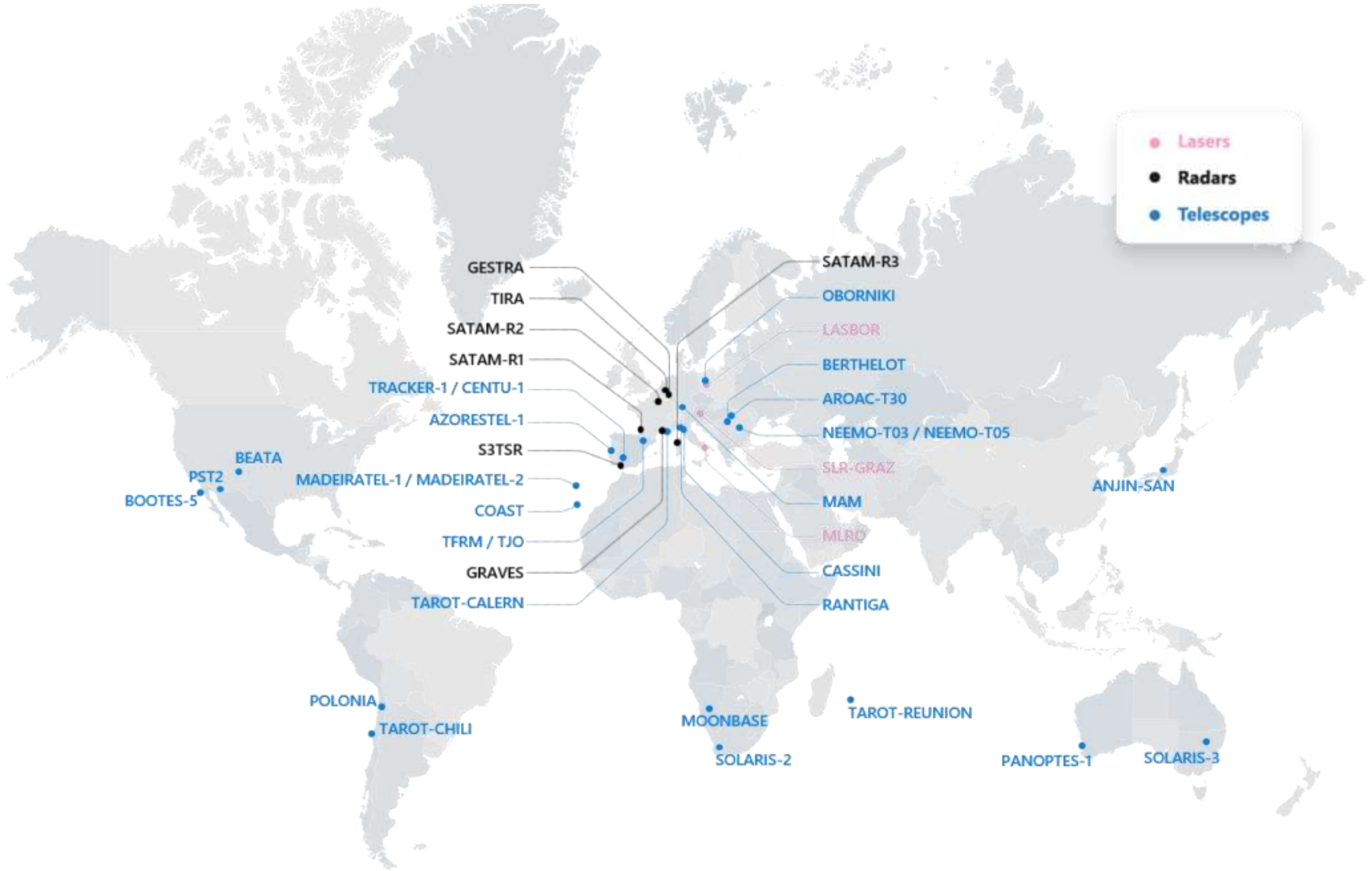
- The “Decision of the European Parliament and the Council Establishing a Space Surveillance and Tracking Support Framework” was adopted on April 16, 2014. It established the European Space Surveillance and Tracking (EU SST) Support Framework at European level, which evolved into a fully-fledged component of the European Union Space Programme adopted on 28 April 2021.

- EU SST contributes to the global burden sharing of ensuring the sustainable and guaranteed access to and use of space for all. Its primary objective is the provision of space-safety services, namely, to protect spacecraft from the risk of collision, to monitor uncontrolled re-entries, and to survey the in-orbit fragmentation of space objects.

- An **SST system relies**, in a first approach, **on its SST network of sensors in order to produce all the SST products downstream**.

- **CDTI**, as part of the **EUSST Consortium**, is developing a COordinated PLAnner (**COPLA**) for EU SST network of sensors. The objective of **COPLA** is to coordinate all the EU SST sensors in order to contribute and improve the SST services.

Motivation



EU SST Sensor Network (October 2021). Image taken from https://www.eusst.eu/about-us/

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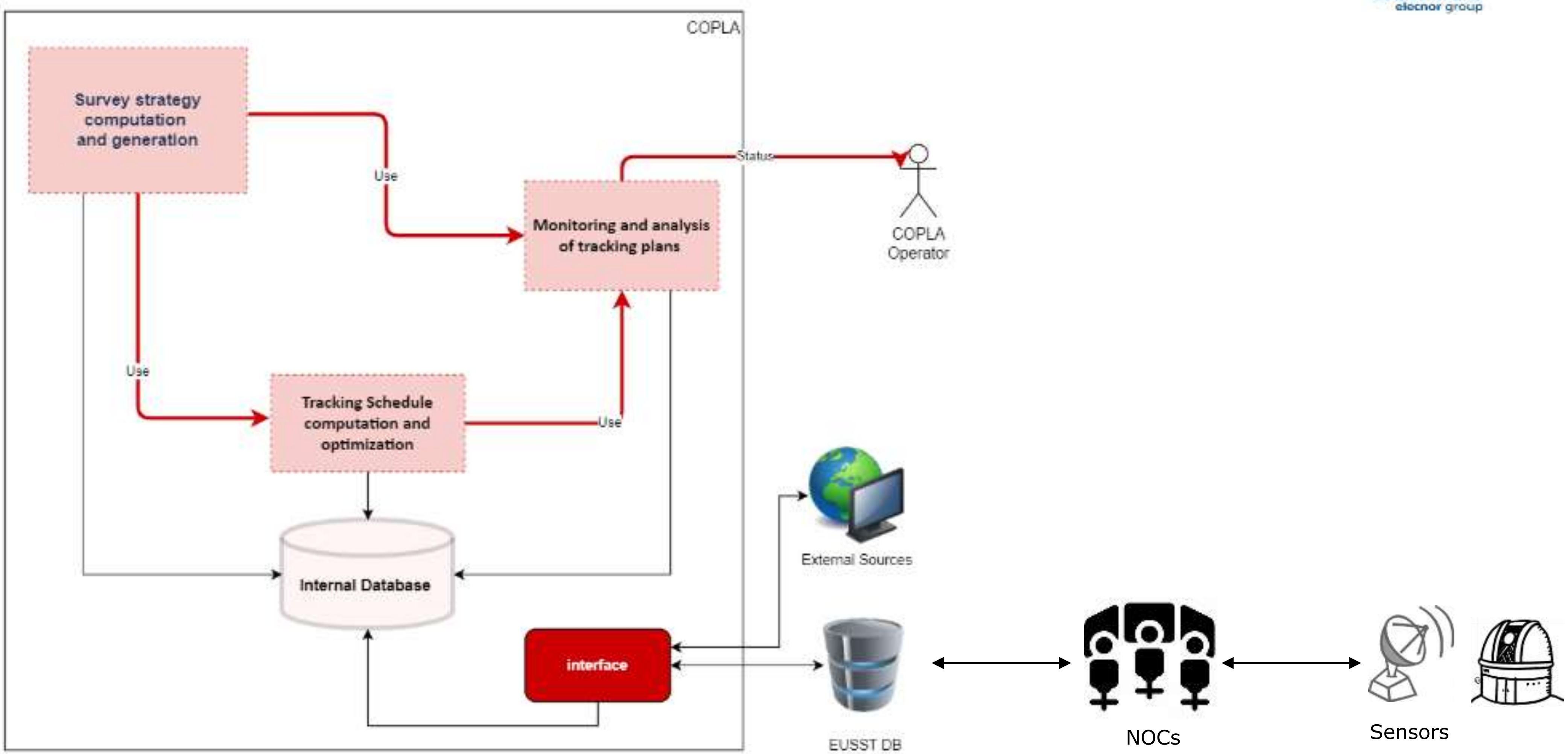
COPLA



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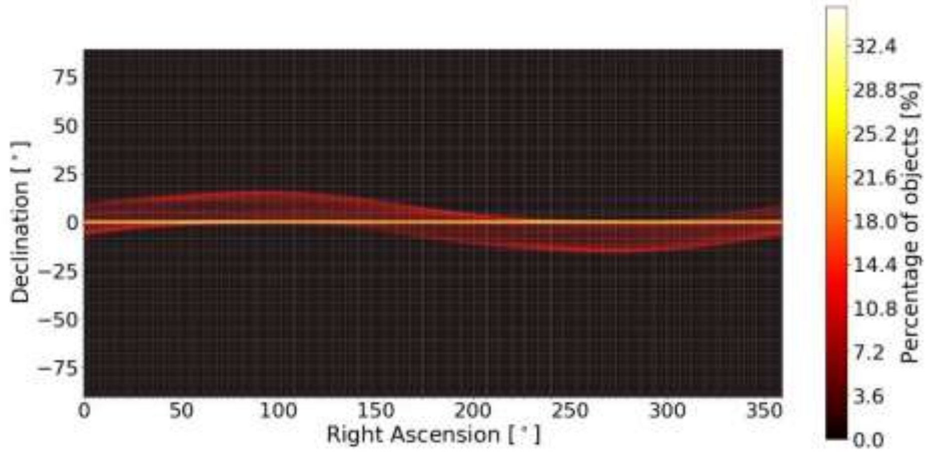
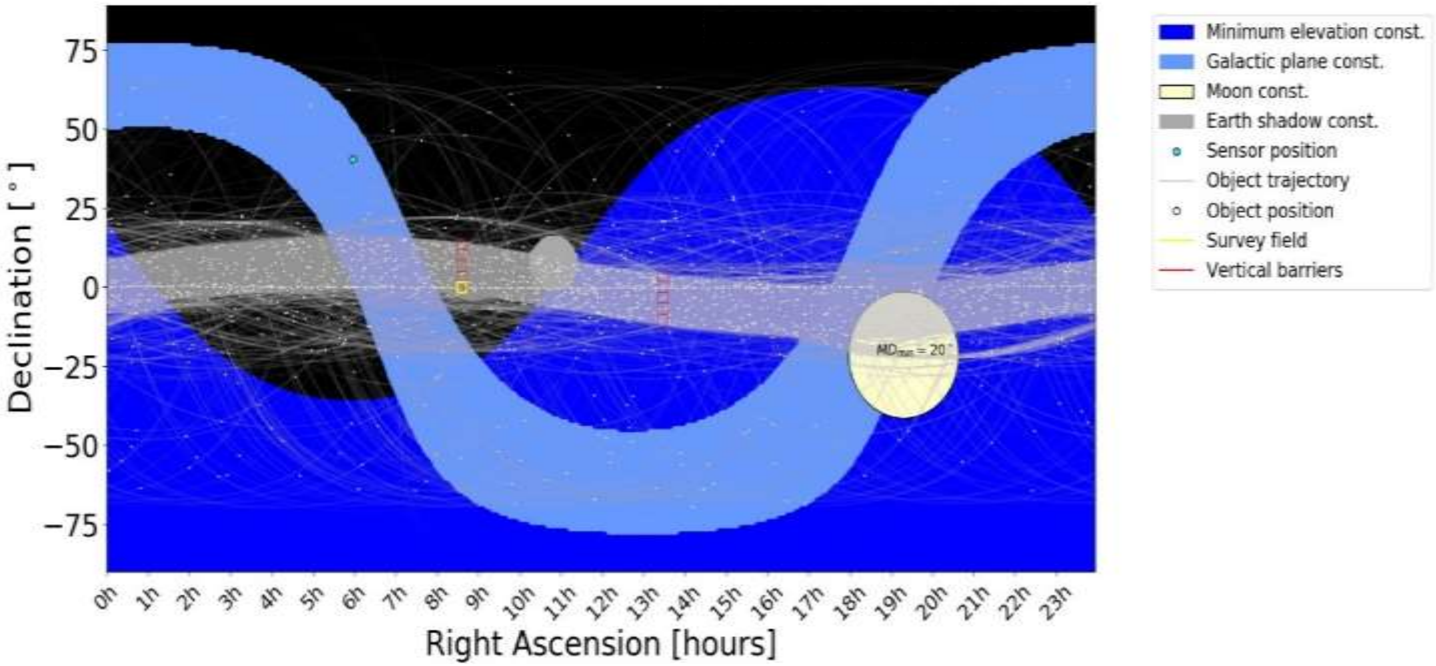
Survey chain

Survey strategy





"Brightness balanced effective survey time" [seconds]

$$F(\alpha_j, \delta_j) = \sum_{i=1}^{N_b} \sum_{j=1}^{N_e} Z_{i,j} \Delta t_{i,j}$$

Brightness component from the phase condition

Survey time component from the sky constraints

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Survey chain

Survey visibilities

Survey strategy

- **Observability constraints** → Sky constraints
- **Detectability constraints**
  - Maximum angular velocity
  - Minimum apparent magnitude

Field of view constraint

Fixed pointing

- **Observability constraint** → Minimum elevation
- **Detectability constraints**
  - Maximum angular velocity
  - Radar equation → minimum RCS

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Survey chain

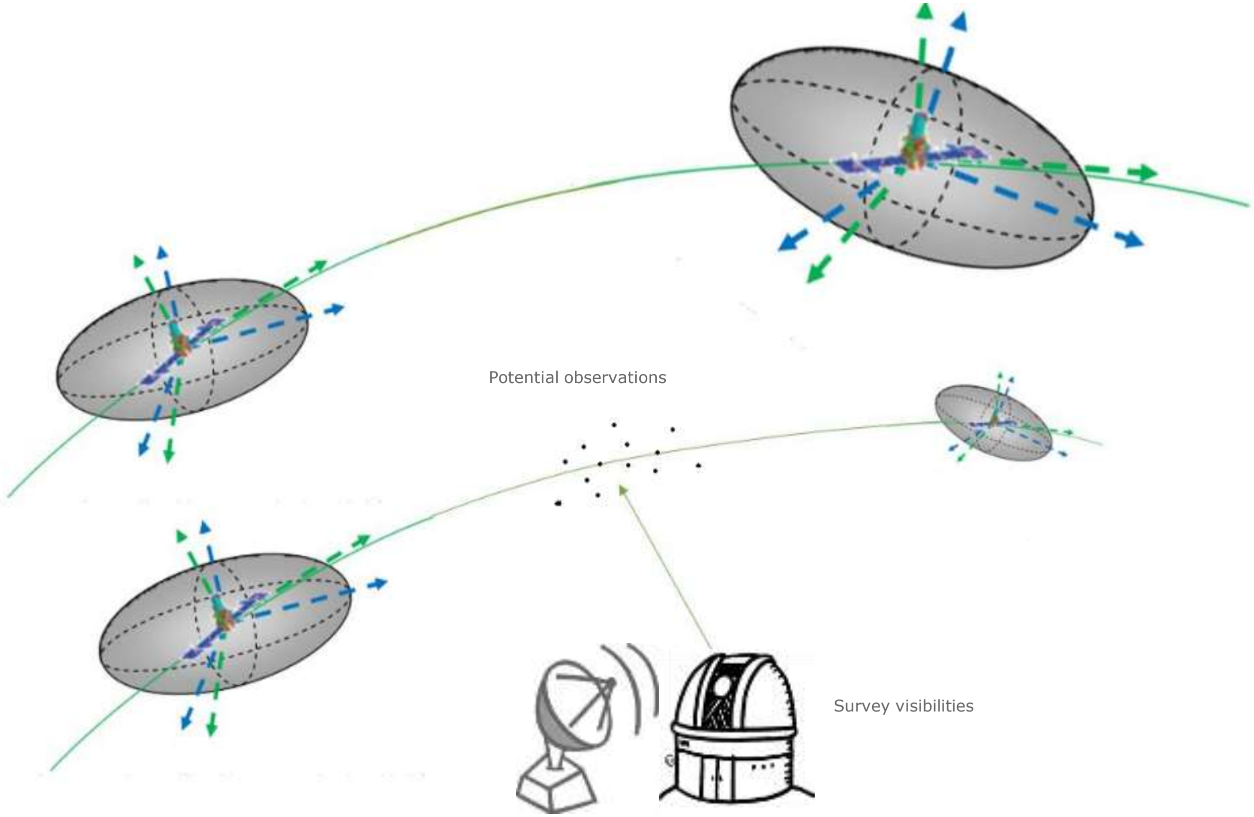
Survey accuracy gain

Propagation of the object's covariance from reference epoch to final epoch

Covariance improvement due to a set of measurements per slot at the final epoch

$$\hat{P}_f^{-1} = \left(\Phi_{t_f,t_0} P_0 \Phi_{t_f,t_0}^T\right)^{-1} + \sum_{i=1}^{n} H_i^T W H_i$$

Updated covariance at the final epoch of a survey campaign



- W: weights of the components of the measurement
- H: partial derivatives of the measurements and transition matrix

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Tracking chain

Object characterization

Usual objects:

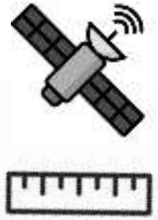
Priority multiplier:

- Type of event
- Risk level
- Object Status
- Orbital regime

Accuracy factor

Size factor

$$Priority = f_{pm} f_{acc} f_s = f_{pm} \frac{1}{2}\left(\frac{C}{W_c C} + \frac{t_{last\ obs}}{W_{last\ obs} t_{last\ obs}}\right)\left(\frac{A}{W_A A}\right)$$



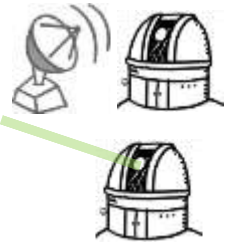
EU SST tasking request objects:

$$Priority = f_{pm} f_{TR}$$

Tracking chain

Tracking opportunities

Slot computation (availability)

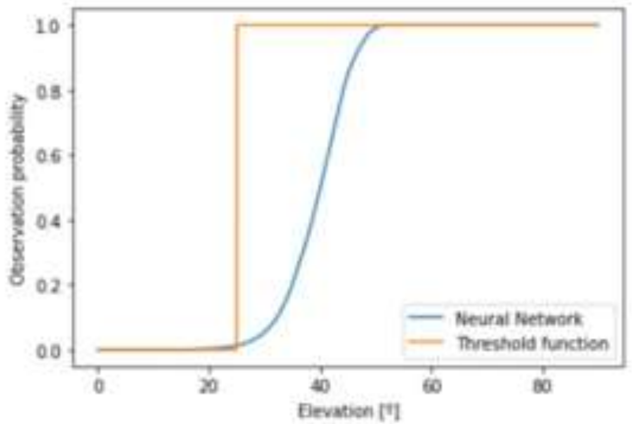


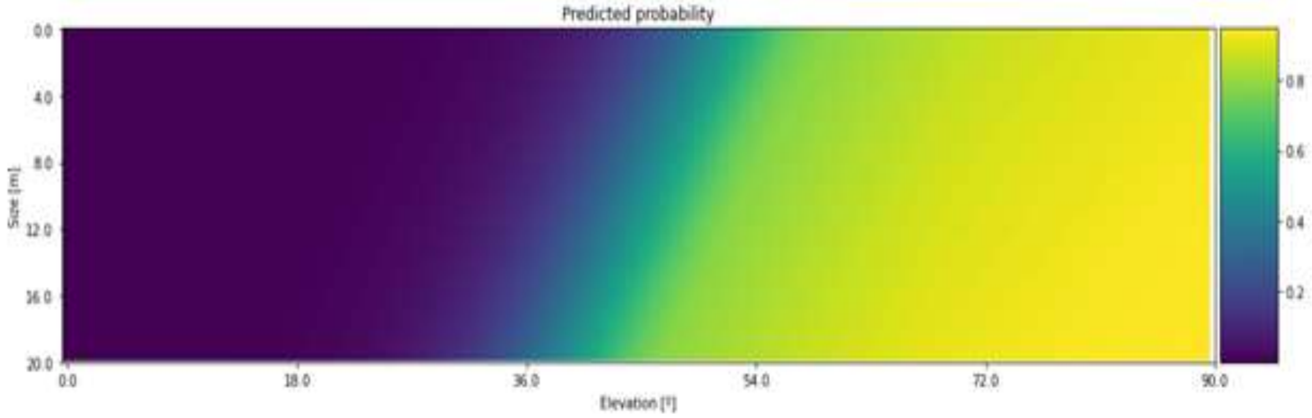
Filtered opportunities:

- Sky constraints
- Allow relaxation by configuration

Observation probability, FoM1 (sensor-object):

- Machine learning algorithms trained with historic/simulated data
- Allow to model cross effects and complex(rigid) constraints





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Tracking chain

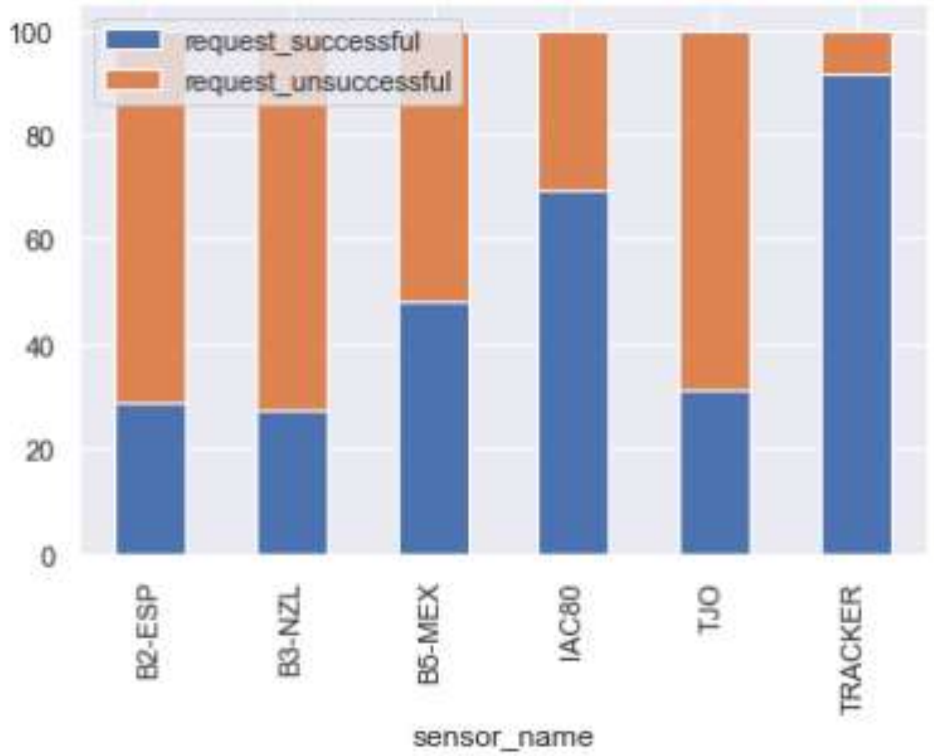
Sensor performance weight

Sensor performance indicator, FoM2 , two approaches:

- Statistics model
- Machine learning algorithm model

Based on:

- Previous performance of the sensor in past requests of the same object
- Orbit information of the object
- Physical features of the sensor
- Agreements on the use of the sensor



Tracking chain

Tracking plan optimization. Problem definition

Constrained satisfaction problem ➔ evaluation of the object for each sensor-slot couple

- Hard constraint (**feasibility**): minimum required observation time for a sensor
- Soft constraints (**optimization**):
  - Quality of observations and object: feedback from survey, accuracy gain, observation probability and sensor weight
  - Movement of the sensor

$$minimize \sum_{j=0}^{obj} F_{obj} \cdot \frac{1}{Acc_T} \cdot w_1 + \sum_{s=1}^{sens} \sum_{m=0}^{mov} \alpha_m \cdot w_s$$

$$Acc_T = Trace(\hat{P}_{fS}^{-1}) + Trace\left(\sum_{i=1}^{m} H_i^T W H_i\right) \cdot F_{obs} \cdot F_{sw}$$

Tracking chain

Tracking plan optimization. Solver optimization process (OptaPlanner)

Construction Heuristic (CH): initializes the planning fulfilling hard constraint:

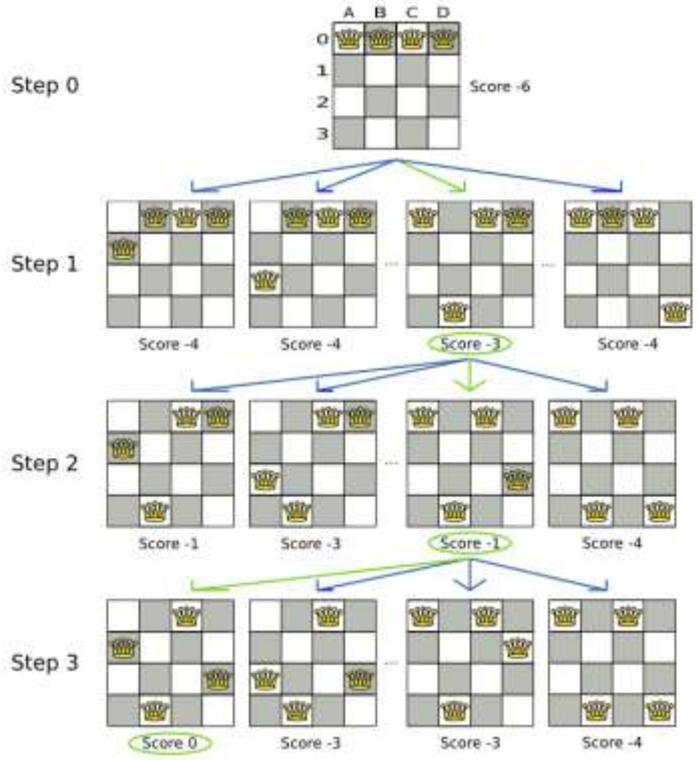
- Random initialization
- Criteria-based initialization (object priority)

Local Search (LS): evolves initial solution based on the score and search algorithm:

- Suitable for real time problems
- Suitable for complex problems

Termination criteria:

- Maximum allowed time ➔ depends on the resources
- Minimum improvement between steps ➔ always get a “good” solution but in uncontrolled time
- Number of steps ➔ always get a “good” solution in controlled time



Conclusions

- Important need of **feedback** of the **tracking** chain with the results of the **survey** chain
- **Object characterization** is required in order to narrow down the problem and optimize it based on SST services
- **Machine learning algorithms** will provide a great improvement to capture and quantify complex behaviors of the sensor and object

→ **Optimization of the complete sensor network will allow to extract the maximum benefits for SST services**

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THANK YOU VERY MUCH !

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Annex

$$\underset{\alpha_j,\,\delta_j}{\text{maximize}} \sum_{i}^{N_b} \sum_{j}^{N} \frac{1}{2}\left[1+\cos(\theta_{i,j})\right]\Delta t_{i,j}$$

$$\text{subject to} \begin{cases} \mathrm{el_j} > \mathrm{el_{min}} \\ \mathrm{SZD_j} > \mathrm{SZD_{min}} \\ \mathrm{GDP_j} < \mathrm{GDP_{max}} \\ \mathrm{MD_j} > \mathrm{MD_{min,NM}} \text{ if } (\alpha, \delta) \in \text{New Moon} \\ \mathrm{MD_j} > \mathrm{MD_{min,FM}} \text{ if } (\alpha, \delta) \in \text{Full Moon} \\ \beta_j > \mathrm{VA_{Sun,j}} + \mathrm{VA_{Earth,j}} \end{cases}$$

$$\alpha_{\mathrm{shift,i}} = \mathrm{t_{barrier,i}} \mathrm{n_{GEO}}$$

$$\alpha_{corr} = \mathrm{t_{stripe}} \mathrm{n_{GEO}} - FoV + \gamma_r$$

Annex

$$m = m_0 - 2.5\log_{10}\left(\frac{\frac{2}{3\pi^2} F_S \frac{\pi d_s^2}{4R^2} a(\sin\theta + (\pi - \theta)\cos\theta)}{F_0}\right) < \ m_{lim}$$

$$RCS_{\mathrm{obj}} > \ \mathrm{RCS}_{\mathrm{min}} = \frac{RCS_{ref}\,\rho_{obj}^4}{\rho_{ref}^4}$$

$$Conical\ FoV: \bar{x}_{point} \cdot \bar{x}_{object} \leq \frac{FoV}{2}$$

$$Pyramidal\ FoV: \begin{cases} a = \bar{x}_{object} \cdot (\bar{x}_{point_{+x,+y}} \times \bar{x}_{point_{+x,-y}}) \\ b = \bar{x}_{object} \cdot (\bar{x}_{point_{+x,-y}} \times \bar{x}_{point_{-x,-y}}) \\ c = \bar{x}_{object} \cdot (\bar{x}_{point_{-x,-y}} \times \bar{x}_{point_{-x,+y}}) \\ d = \bar{x}_{object} \cdot (\bar{x}_{point_{-x,+y}} \times \bar{x}_{point_{+x,+y}}) \end{cases} satisfying \begin{cases} a, b, c, d \geq 0 \\ a, b, c, d \leq 0 \end{cases}$$

Annex

$$H_i = \frac{\partial \bar{z}_i}{\partial \bar{x}_f} = \frac{\partial \bar{z}_i}{\partial \bar{x}_i}\frac{\partial \bar{x}_i}{\partial \bar{x}_f} = G_i \Phi_{t_i, t_f}$$

$$W = diag(\sigma_{\beta}^{-2}, \sigma_{\varepsilon}^{-2}, \ldots, \sigma_{\dot{\rho}}^{-2})$$