Optimization of the Juice Ganymede phase scheduling with genetic algorithms

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Solar System Exploration

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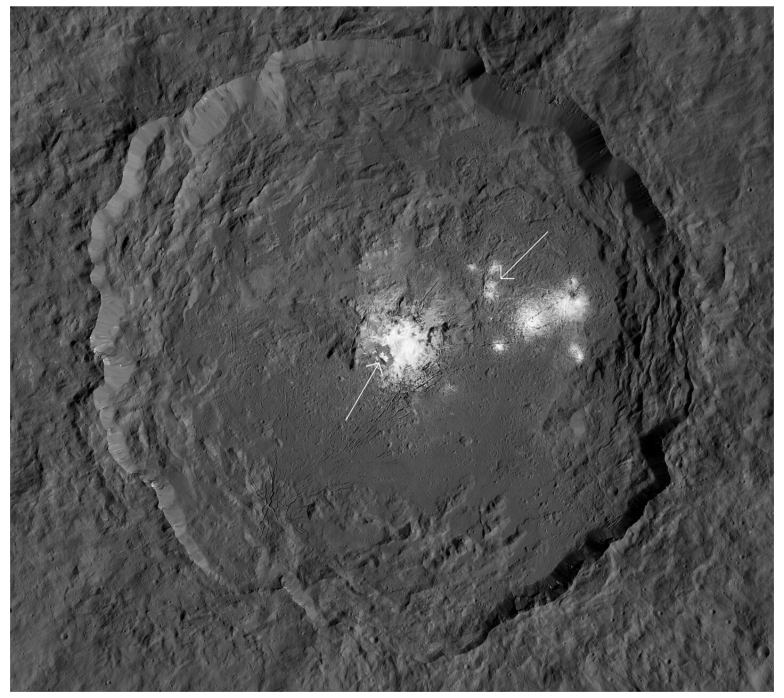
Solar System robotic missions explore objects in space to elicit key information that will ultimately aid answering the great questions on the origins and evolution of the Solar System as well as of life

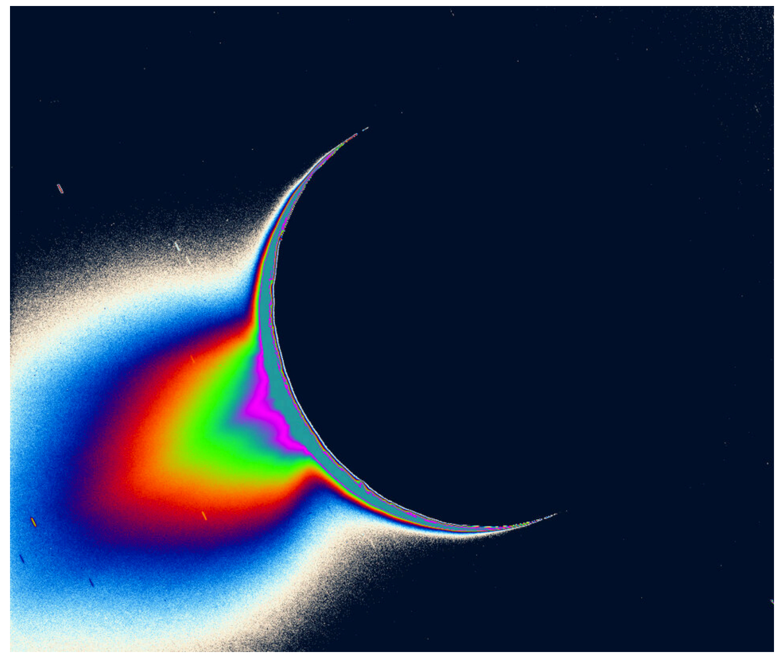
- Key information ↔ Scientific data from the instruments
- Such an ambitious goal demands an equally challenging endeavor from the scientific and engineering perspectives
- Science & Mission Operations Teams ensure that the spacecraft (and its instruments) will be able to **fulfill the scientific objectives of the mission,** whilst concurrently guaranteeing the spacecraft performance and safety, ensuring a **good management of the available resources**

Science & Mission Operations

Science Planning involves an early construction of an Observation Plan; nevertheless, when in operations these observations might require a re-planning in observation of unexpected opportunities. There is a need for a rapid re-planning capacity. Examples:

- DAWN observations were re-planned after the discovery of bright spots in Ceres [1]
- CASSINI trajectory was updated after the Enceladus plume observations [2]
- Rosetta trajectory and science operations planning system was updated following the safe-mode due to the comet high activity [3]





[1] Llopis, M., Polanskey, C. A., Lawler, C. R. & Ortega, C. (2019, July). The planning software behind the bright spots on ceres: The challenges and successes of science opportunity analyzer. In *2019 IEEE International Conference on Space Mission Challenges for Information Technology (SMC-IT)* (pp. 1-8). IEEE
[2] https://www.space.com/38559-how-cassini-discovered-enceladus-plumes.html
[3] Marc Costa, Miguel Pérez, Miguel Almeida, et al "Rosetta: rapid science operations for a dynamic comet," AIAA 2016-2538. *SpaceOps 2016 Conference*. May 2016.

Objectives

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- Complex and inter-divisional task, need to account for a wide spectrum of variables
- Automated mission planning and scheduling for Planetary Exploration Missions
- Optimize the observation plan according to a set of scientific queries while guaranteeing operation feasibility
- Agile multi-mission software that generates a reliable skeleton science plan in a timely manner
- Mission design, mid and long-term planning, mission operations (event of failures, new science opportunities, etc.)

Problem Formulation

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- Instrument onboard a spacecraft, tasked with a series of observations of the target surface.
- 2D-framing instrument traversing systematically various observable features.
- **When is it best to execute each observation, according to the scientific objectives?**

Our ultimate objective is to devise a timeline of the instrument's activity plan $\boldsymbol{o}$ that maximizes the scientific return of the mission $\boldsymbol{S}$, while ensuring compliance with a set of constraints $\boldsymbol{C}$:

$$\max_{\boldsymbol{o}} \{\boldsymbol{S}(\boldsymbol{o})\} \text{ subject to } \boldsymbol{C}.$$

The **Observation Planning Tool for Instrument and Mission Analysis (OPTIMA)** is a Planning and Scheduling (P&S) software prototype that assesses and optimizes the scientific return of a Planetary-Exploration mission

OPTIMA upper-level flow

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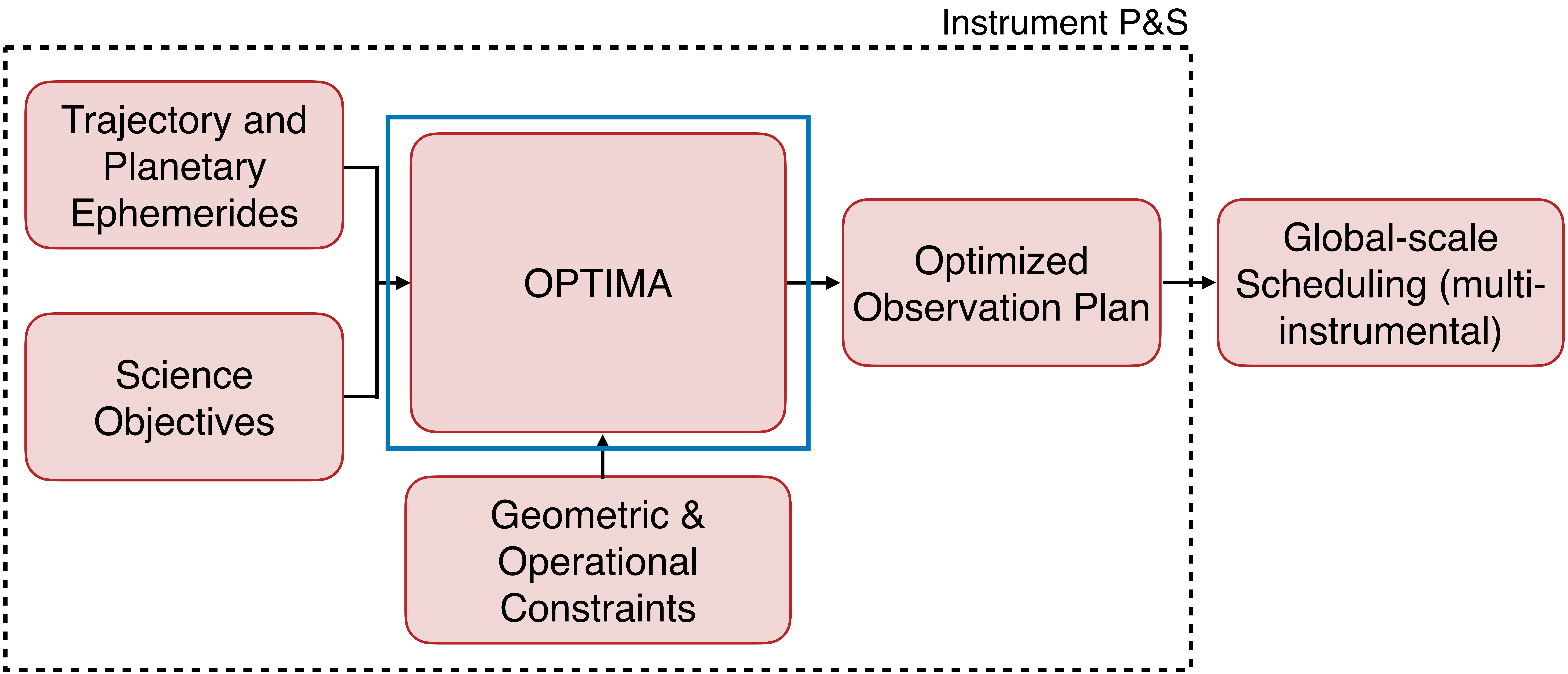
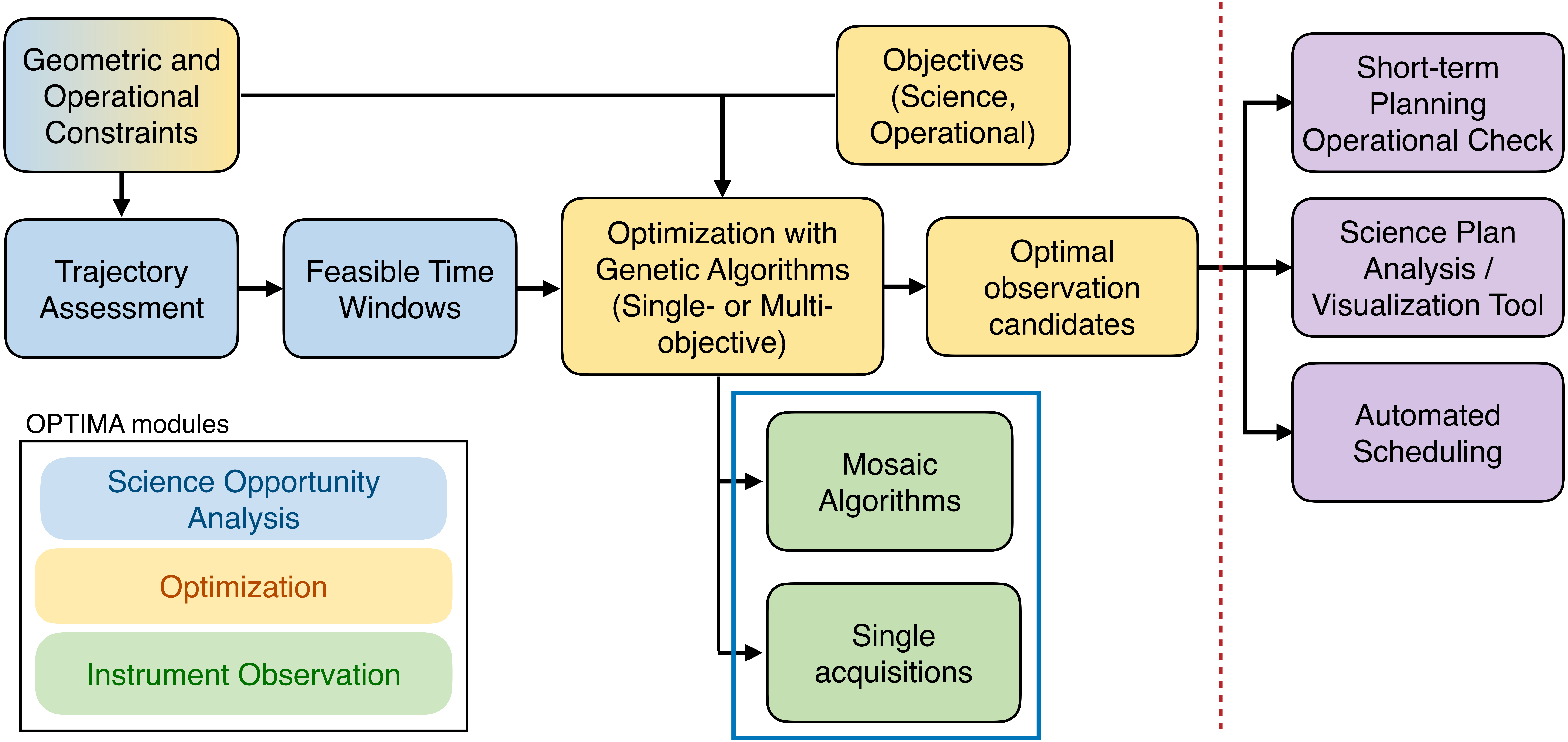


OPTIMA lower-level flow



Phase I: Science Opportunity Analysis

- Given the initial set of available time intervals, we aim to find the time windows where the instrument acquisitions are feasible according to a set of science requirements
- These segments are also known as **science opportunity windows**.

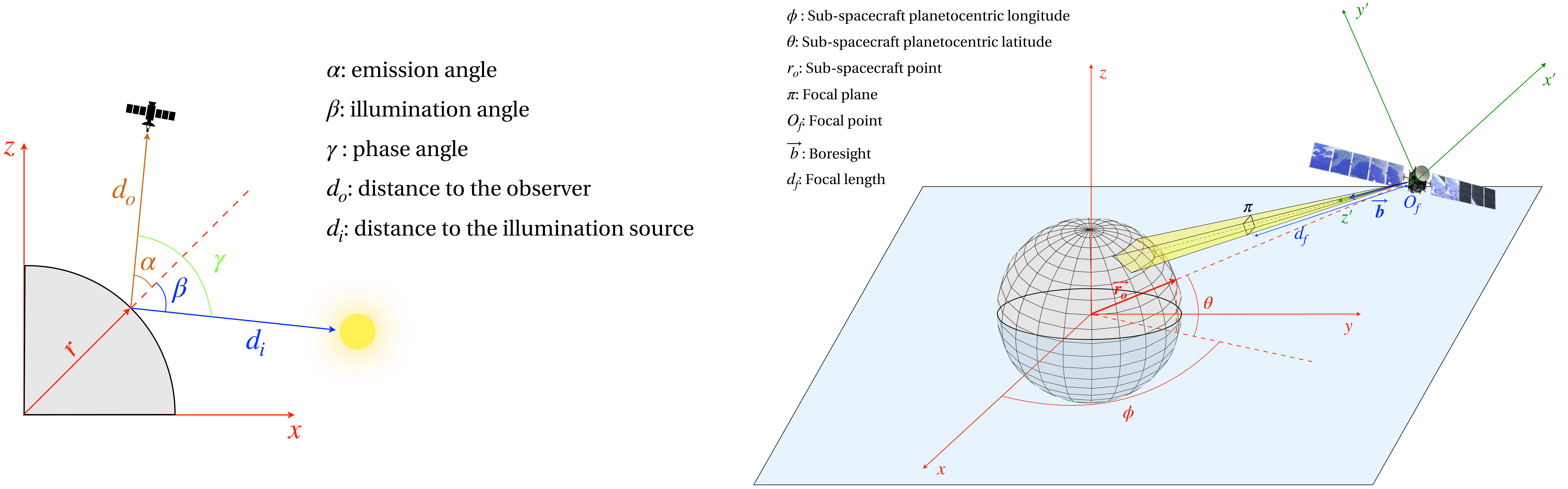


Figure 2. On the left, set of parameters that define the observation geometry of an observer with respect to its target. On the right, observation and acquisition geometries of a 2D-frame instrument onboard a spacecraft projecting its FOV onto the surface of its target. The spacecraft represented is Dawn, its image is provided courtesy of NASA

Phase II: Optimization

- Thus far, we have assessed the set of static constraints and obtained the science opportunity windows
- Now, we want to optimize the observation plan $\boldsymbol{O}$ while adhering to the set of dynamic constraints
- Due to the complexity of the problem, robust heuristics: **Genetic Algorithms**
- Family of evolutionary algorithms: optimization meta-heuristics that essentially mimic natural selection
- Purely driven by quality, solutions that lie outside of the scope of "intuitive" thinking

Case Study 1

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- JUICE orbit phase around Ganymede GCO500
- Instrument: JANUS (camera)
- Time period: August 1st to 30th, 2035
- Primary objective: build an observation plan that intends to maximize as well as uniformize (memory allocation) the specific coverage of each observable target (ROI), considering memory constraints and downlink windows

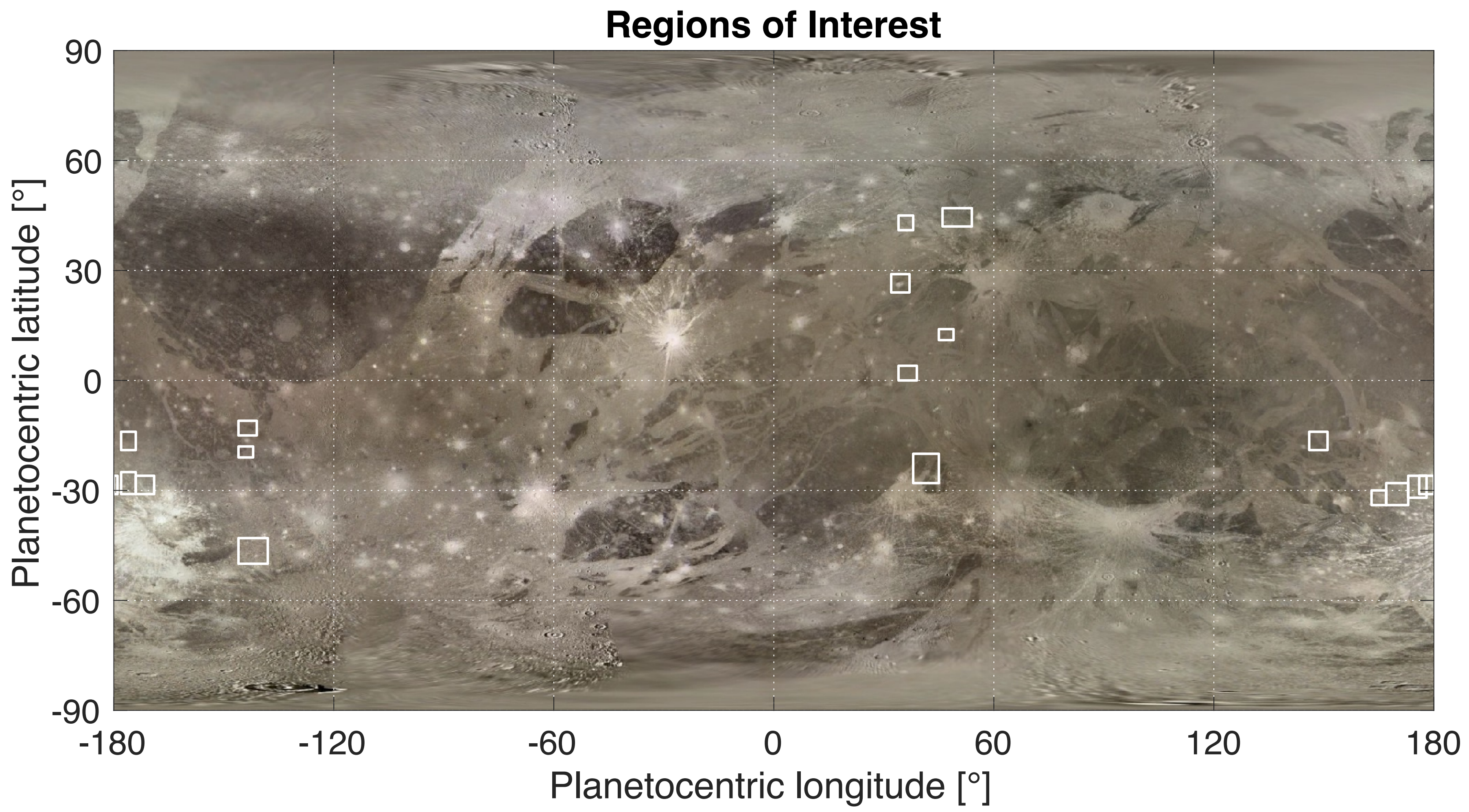


Figure 3. Set of observable targets (ROIs) on Ganymede's surface (potential cryovolcanic areas [1])

Constraint definition

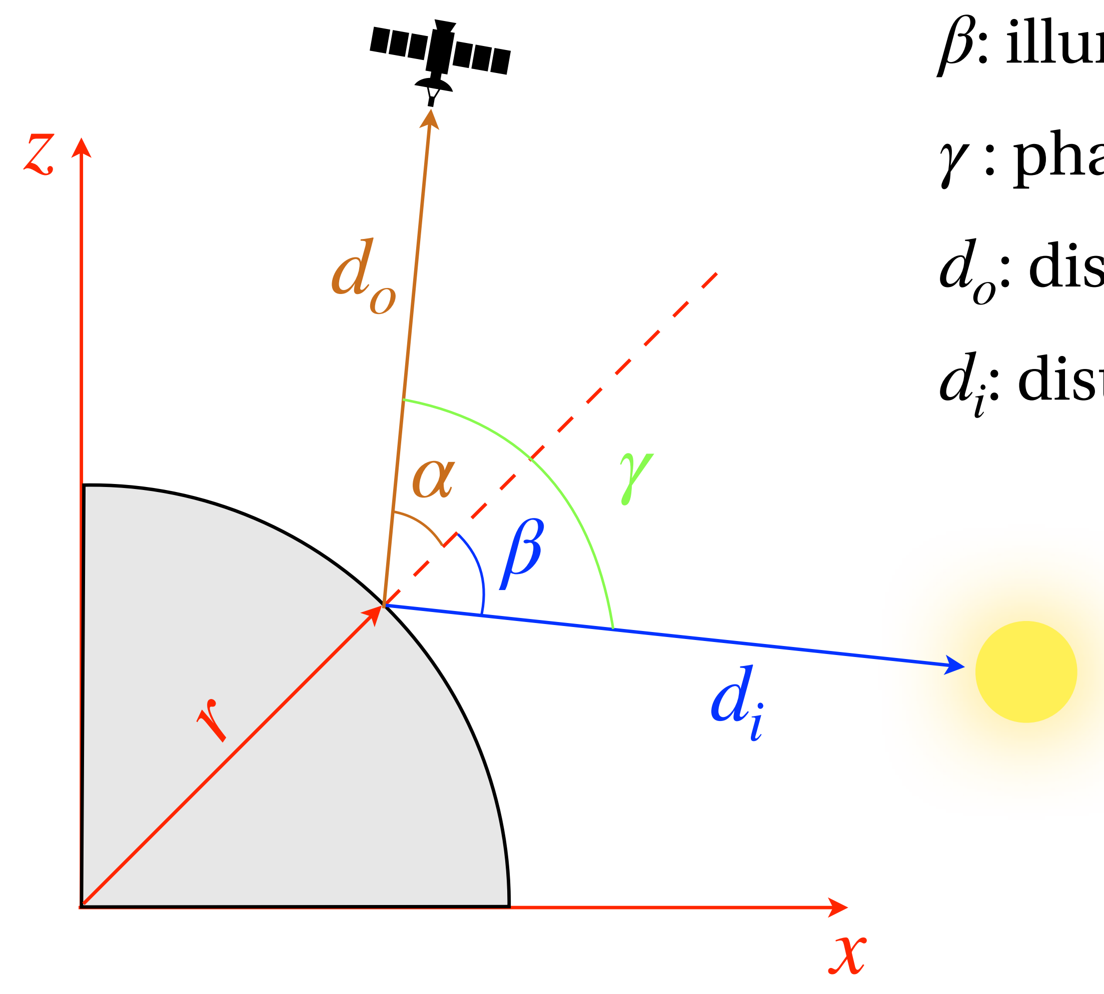
Geometric constraints

Illumination conditions are mandatory in all the observable targets

- Illumination: $20° \leq \beta \leq 90°$

Operational constraints

- Nadir pointing (this implies $\alpha = 0°$)
- Fixed cadence of the acquisitions $t_{obs} = 30s$
- 40% memory allocation for JANUS: 200 Gb
- Average memory release per downlink window: 1.4 Gb
- Fixed data volume per acquisition 1.2 Gb
- Fixed downlink windows



α: emission angle

β: illumination angle

γ : phase angle

d_o: distance to the observer

d_i: distance to the illumination source

Segmentation

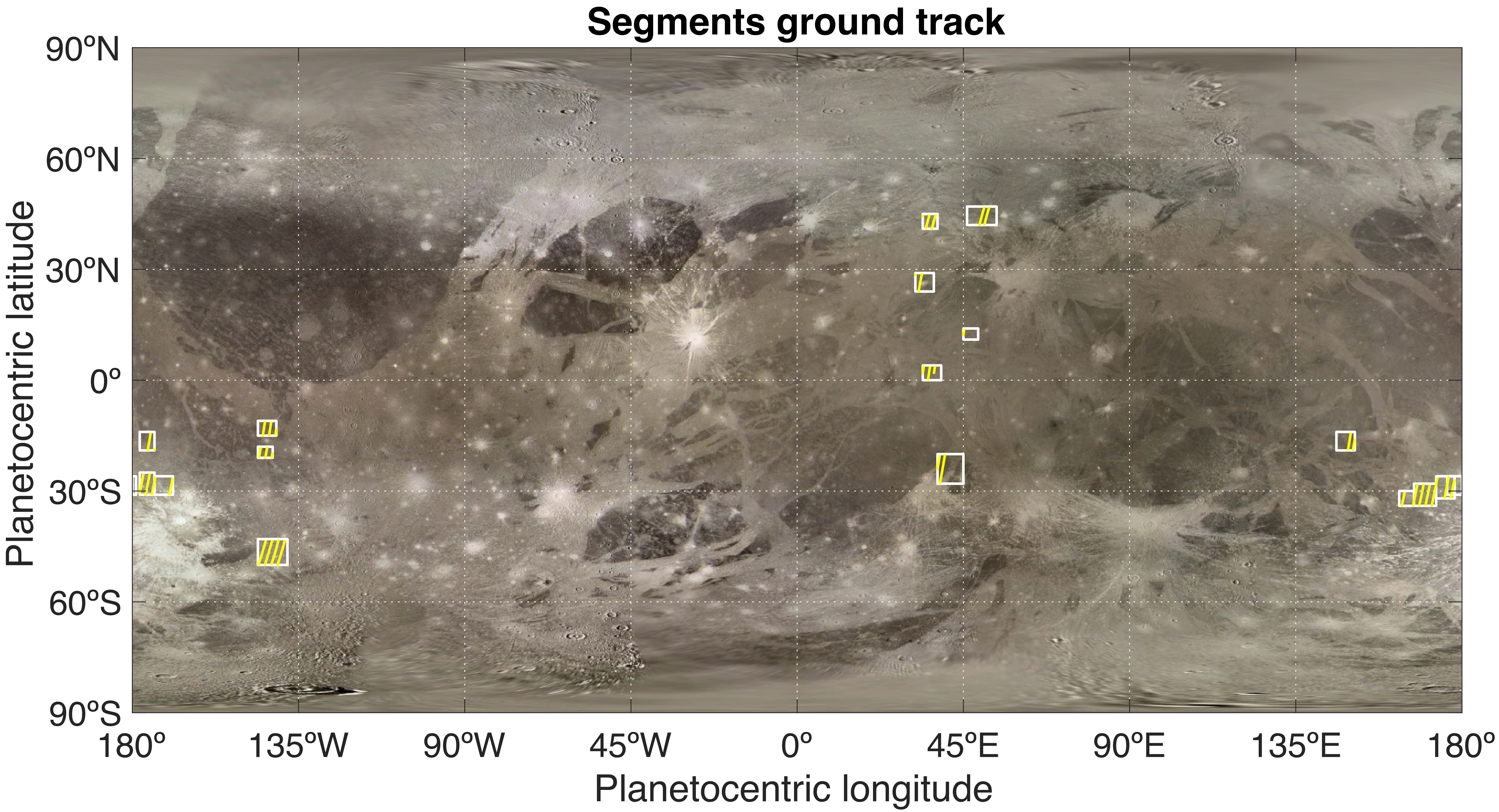


Figure 4. Ground track of the possible observation segments

Fitness and Quality

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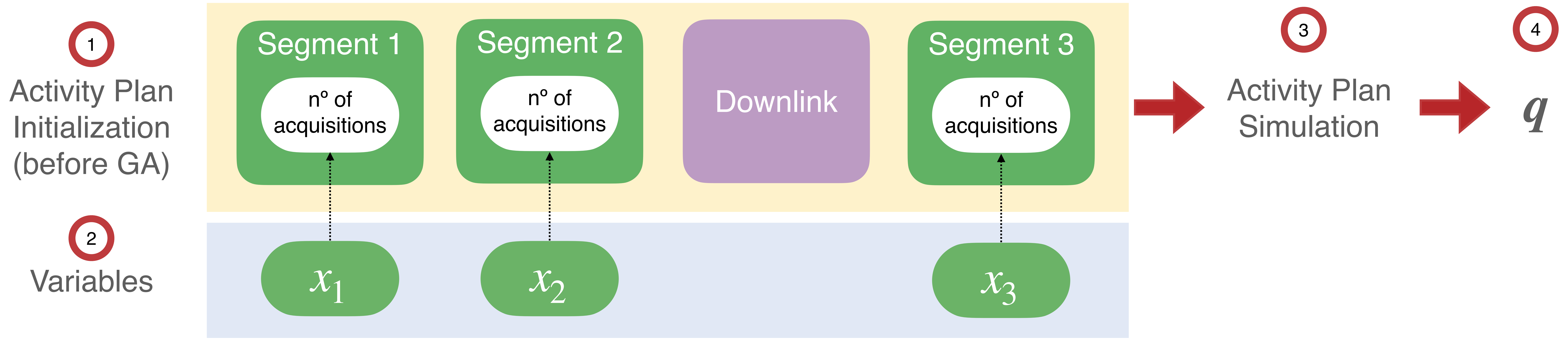
Objective	Variables	Constraints
Maximize specific coverage	Allocation of acquisitions per segment	Memory

- The quality of an individual $\boldsymbol{q} = \{q(x_1), q(x_2), \ldots, q(x_N)\}$, where q is the allocation of acquisitions for each ROI
- Each evaluation of quality implies a simulation of the activity plan in order to check memory constraints



Fitness and Quality

Objective	Variables	Constraints
Maximize specific coverage	Allocation of acquisitions per segment	Memory

- The objective is to maximize the specific coverage, aiming to:
  - Maximize coverage on the ROIs
  - Promote uniform allocation of acquisitions across segments (since we have limited memory)
- In the fitness function, these objectives may be reflected by:
  - Maximize the mean of the quality set $\mu(\boldsymbol{q})$, addressing comprehensive coverage
  - Minimize the standard deviation of the quality set $s(\boldsymbol{q})$, ensuring equitable allocation
- Thus,

$$f = \frac{\mu(\boldsymbol{q})}{2} + \frac{1}{2s(\boldsymbol{q})},$$

Algorithm set-up

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> Fitness:

$$f = -\left(\frac{\mu(\boldsymbol{q})}{2} + \frac{1}{2s(\boldsymbol{q})}\right)$$

> Parent selection (roulette wheel):

$$p_i^n = \frac{r_i^n}{\sum_{j=1}^{N_b} r_j^n}, \quad r_i^n = \frac{\max(f^n) - f_i^n}{\max(f^n) - \min(f^n)}$$

> Recombination (arithmetic):

$$x_{\text{off}} = x_i + \frac{f_i}{f_i + f_j} \cdot (x_j - x_i)$$

> Mutation:

$$\sigma' = \sigma \cdot e^{\tau \cdot N(0,1)}, \tau = N^{-1/2}$$

$$\boldsymbol{x}^p_{\text{mut}} = \boldsymbol{x}^p_{\text{off}} + \sigma' \cdot N(0,1),\ p = R(1,N)$$

Glossary	
d	Distance
f	Fitness value
p	Probability
x	Individual
R	Random variable
N	Number of segments

Total population	500
Fitness goal	0
Number of generations	10
Number of elite individuals	50
Number of breeders	100
Number of mutants	50
Number of offspring (excluding mutants)	375
Number of newcomers (random)	25

Summary of configuration parameters of the genetic algorithm

Results

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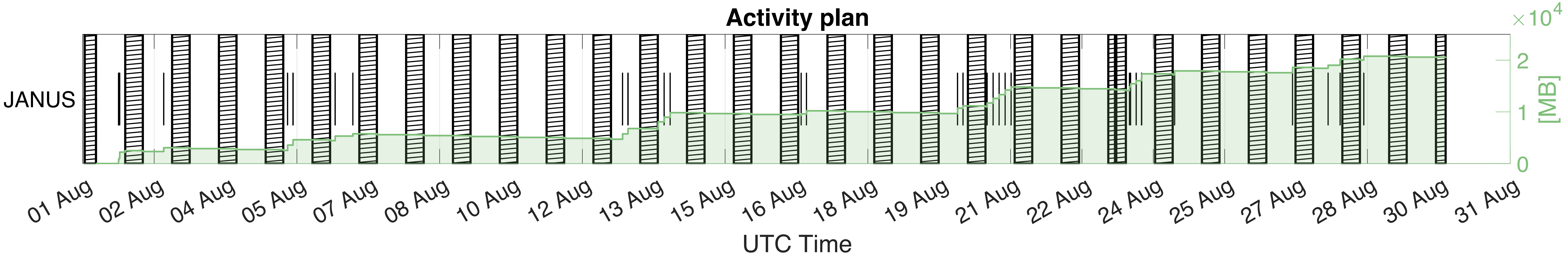
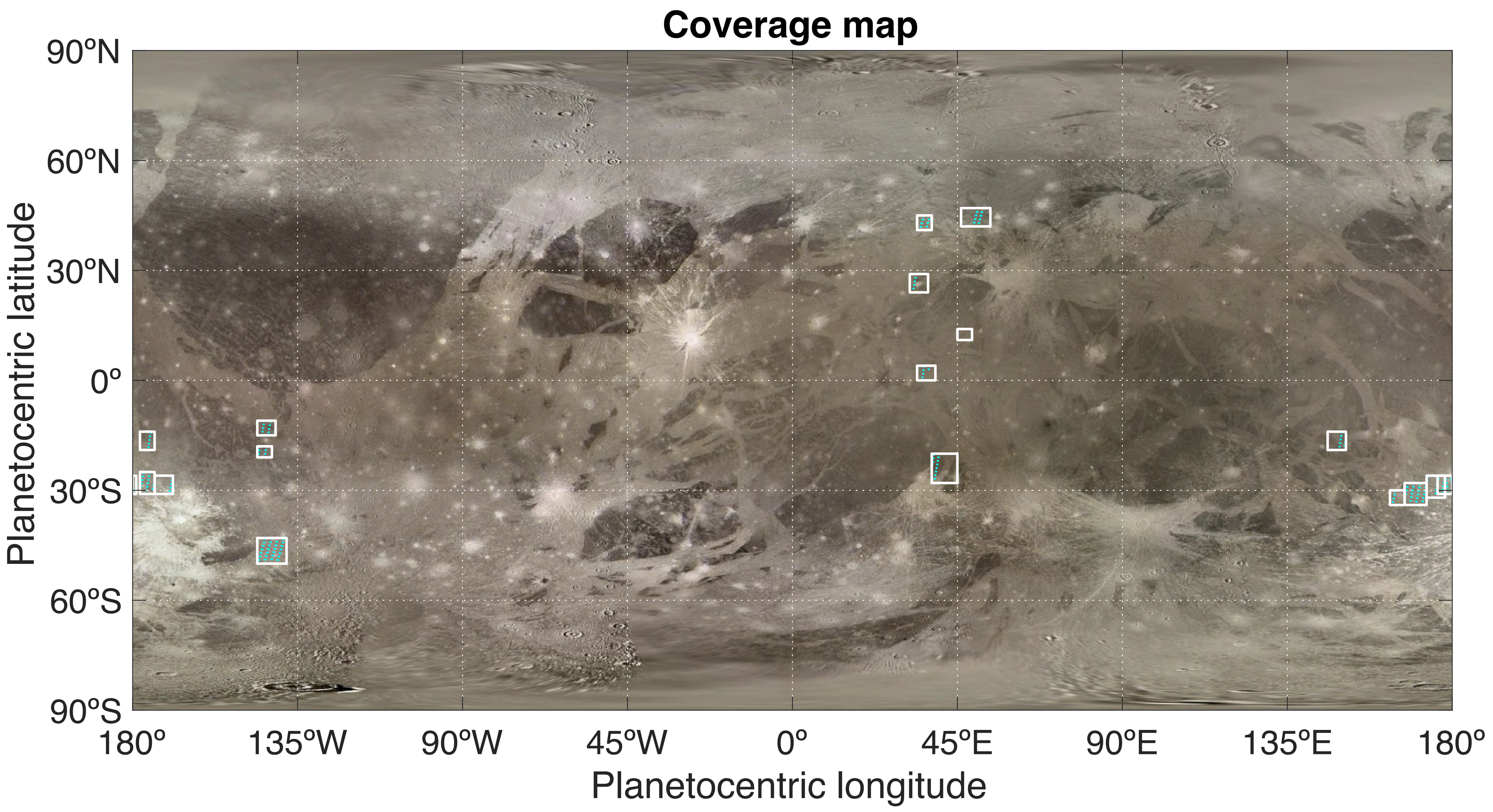
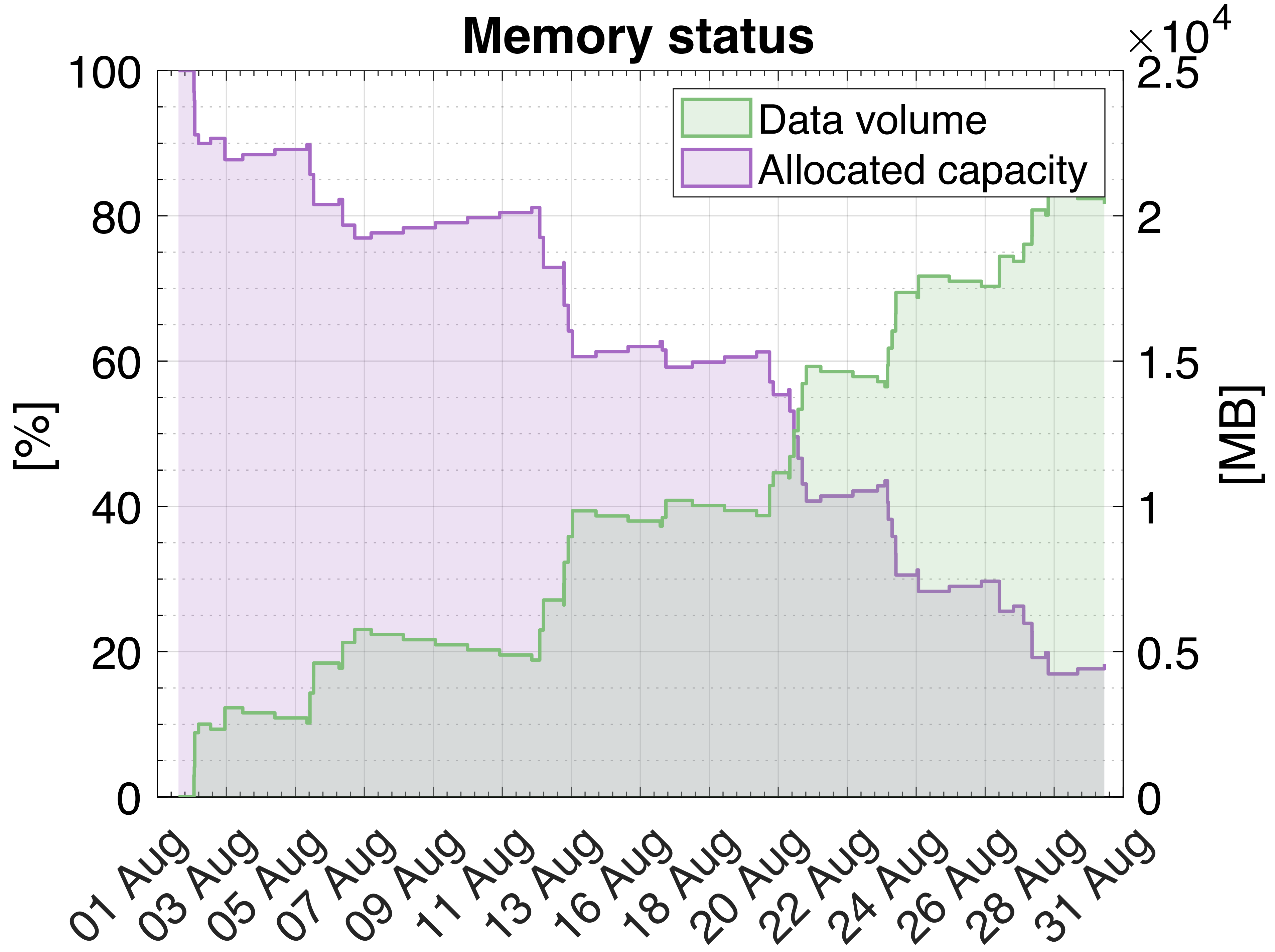






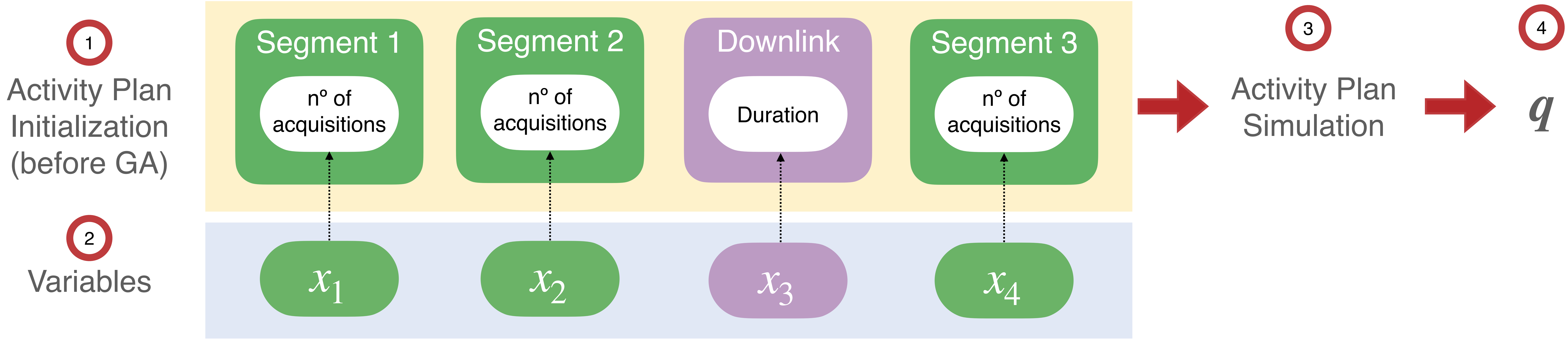
Case Study 2

- Same problem context as Case Study 1
- Primary objective: build an observation plan that intends to maximize as well as uniformize (memory allocation) the specific coverage of each observable target (ROI), considering memory constraints and downlink windows
- Variables: acquisition allocations (memory) and downlink windows compressibility (20% can be reduced by half)
- Same group of regions of interest as in previous case
- Problem constraints: same as Case Study 1 (without fixed downlinks)

Fitness and Quality

Objective	Variables	Constraints
Maximize specific coverage	Allocation of acquisitions per segment Downlink window compressibility	Memory

- Since we have the same objective as in the previous case, fitness function does not change, nor does quality
- As in Case Study 2, downlink windows are “built” during the activity plan simulation



Results

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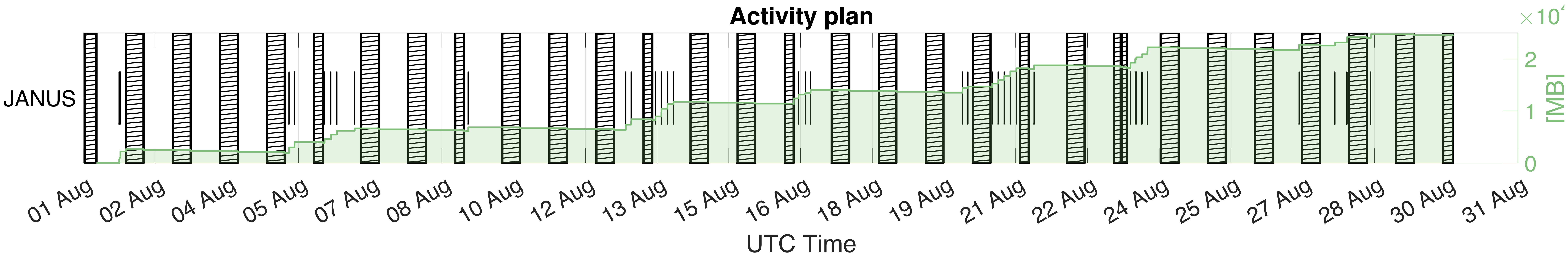

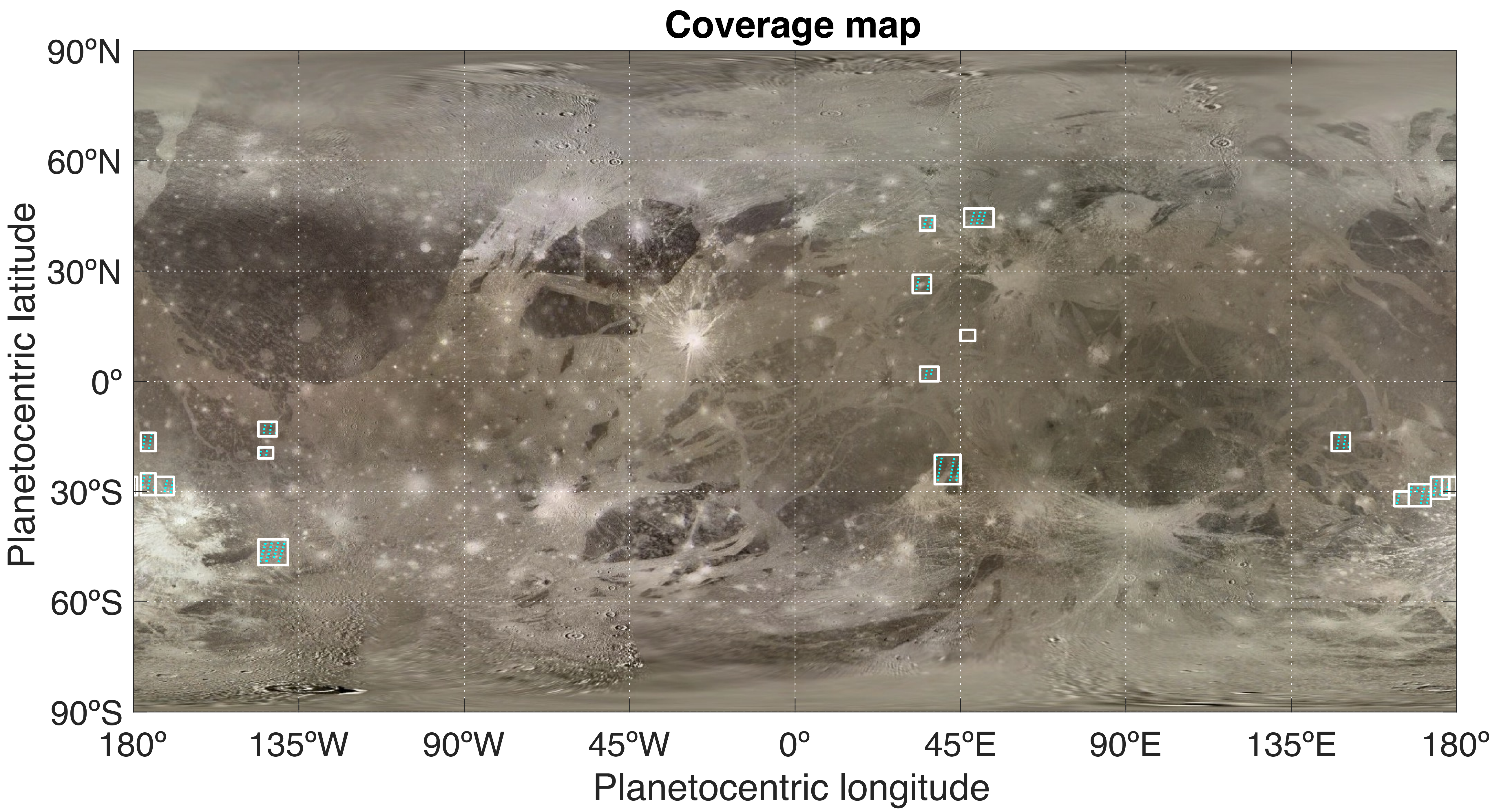

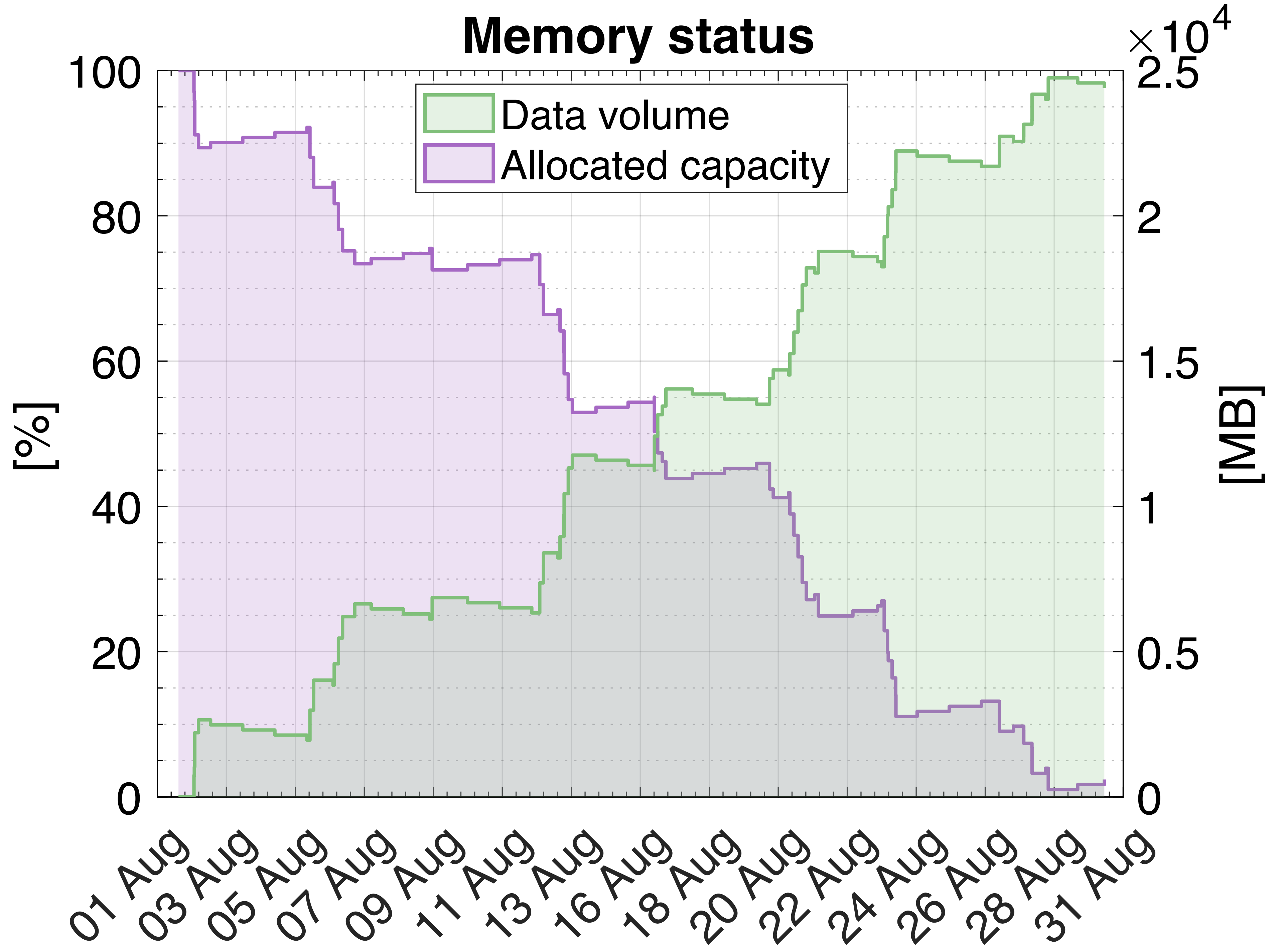

Results

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Region of interest	Coverage Fixed DL [%]	Coverage Compress. DL [%]	Difference [%]
JUICE_ROI_GAN_2_0_01	1,81	3,84	2,03
JUICE_ROI_GAN_2_0_02	3,84	5,34	1,5
JUICE_ROI_GAN_2_0_03	14,13	17,87	3,74
JUICE_ROI_GAN_2_0_04	5,86	4,85	-1,01
JUICE_ROI_GAN_2_0_05	5,97	5,76	-0,21
JUICE_ROI_GAN_2_0_07	5,17	4,79	-0,38
JUICE_ROI_GAN_2_0_08	2,14	3,95	1,81
JUICE_ROI_GAN_2_0_09	2,90	2,81	-0,09
JUICE_ROI_GAN_2_0_10	2,42	3,66	1,24
JUICE_ROI_GAN_2_0_11	2,53	4,18	1,65
JUICE_ROI_GAN_2_0_12	2,70	3,09	0,39
JUICE_ROI_GAN_2_0_13	0,95	0,95	0
JUICE_ROI_GAN_2_0_14	4,82	4,82	0
JUICE_ROI_GAN_2_0_15	3,73	3,73	0
JUICE_ROI_GAN_2_0_16	4,54	4,03	-0,51
JUICE_ROI_GAN_2_0_17	1,55	3,10	1,55
JUICE_ROI_GAN_2_0_18	2,04	3,99	1,95
Global coverage: 0,038%			

Table 2. Coverage results

Conclusions

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- +13,7% increase on specific coverage
- Negligible increase on global coverage
- After 31 downlink windows, the memory has depleted to almost 0% of its capacity
- The enhanced specific coverage results directly from the 20% memory availability retained from the previous scenario (Case study 1)
- The problem is highly constrained by memory restrictions
- Once memory is depleted, downlinks are not able to compensate (1.4Gb release vs. 1.2Gb/acquisition)
- In more complex scenarios, memory fills up very soon, leaving small room for improvement from downlink configurations

Conclusions

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- What we can do…
  - During the first transitional period (memory availability), we can analyze impact of different variables and optimize them for enhanced coverage
  - Enforce constraints for improved problem-solving
- What we can not do…
  - Once memory is depleted (majority of the time), the problem becomes overconstrained
  - In this state, we are unable to perform any further optimization