

Improving Spacecraft Design and Operability for Europa Clipper through High-Fidelity, Mission-Level Modeling and Simulation

Eric Ferguson (presenter), Steve Wissler, Ben Bradley, Pierre Maldague, Jan Ludwinski, Chris Lawler



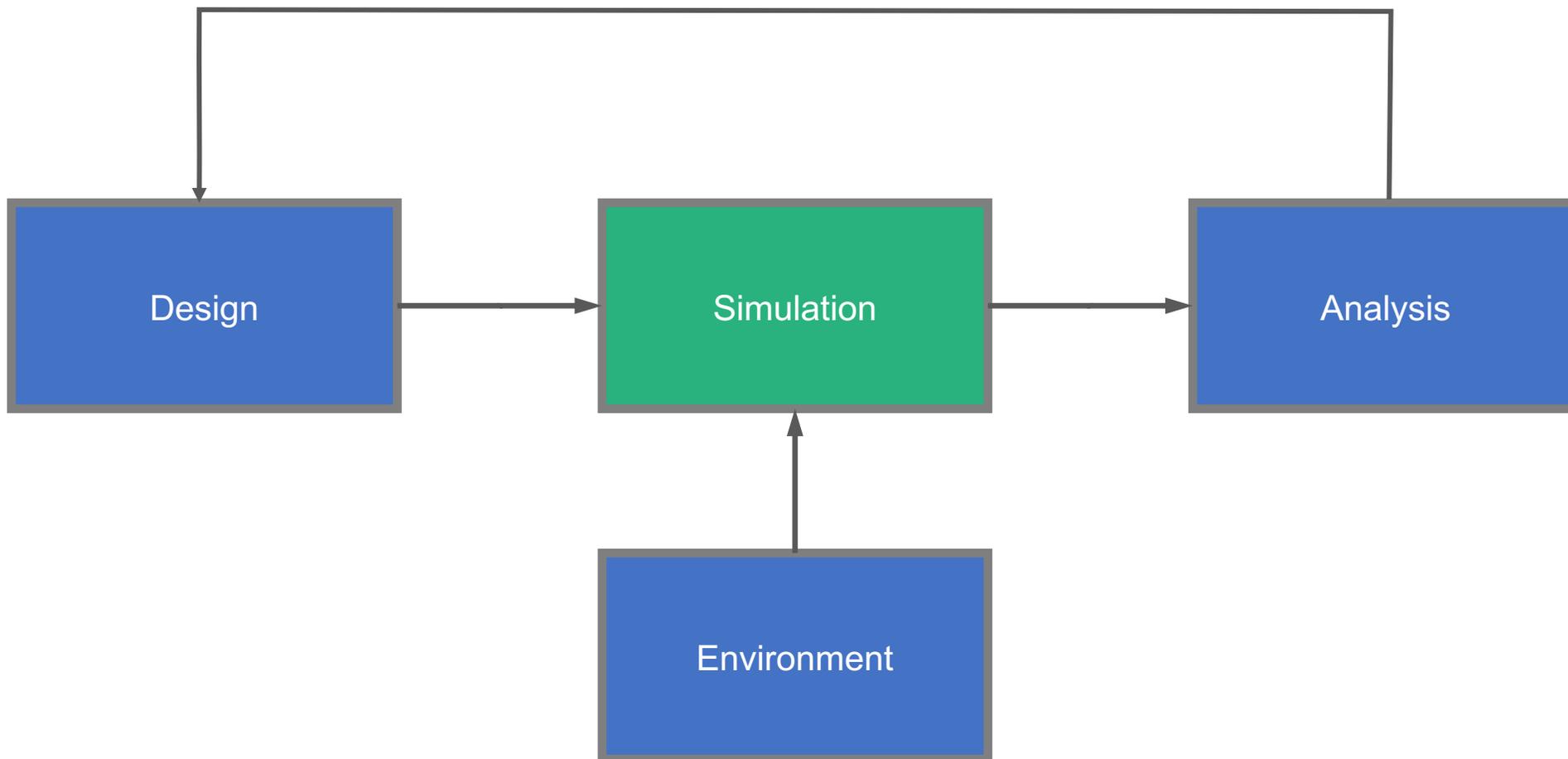
Jet Propulsion Laboratory
California Institute of Technology

May 29th 2018



I. Introduction

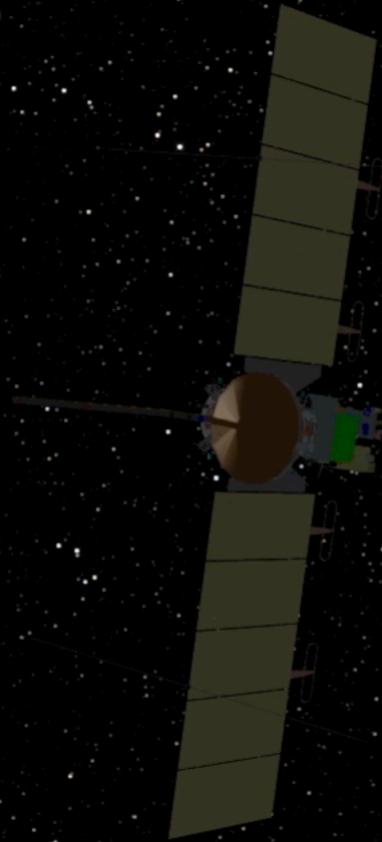
Power of High-Fidelity Mission Simulations



EUROPAM → Europa
Altitude: 79,432.1 km
Relative speed: 3.55 km/s

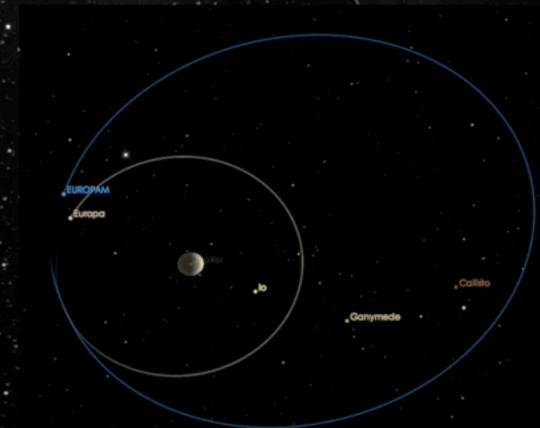
GNC: Nadir Sun-Optimized
ICEMAG: ORBITAL MODE
PIMS: SURVEY MODE

2028-Apr-09 21:40:42 UTC
1,200x time



Payload

	EISNAC
	EISWAC
	ETHEMIS
	ICEMAG
	MASPEX
	MISE
	PIMS
	REASON
	SUDA
	UVS

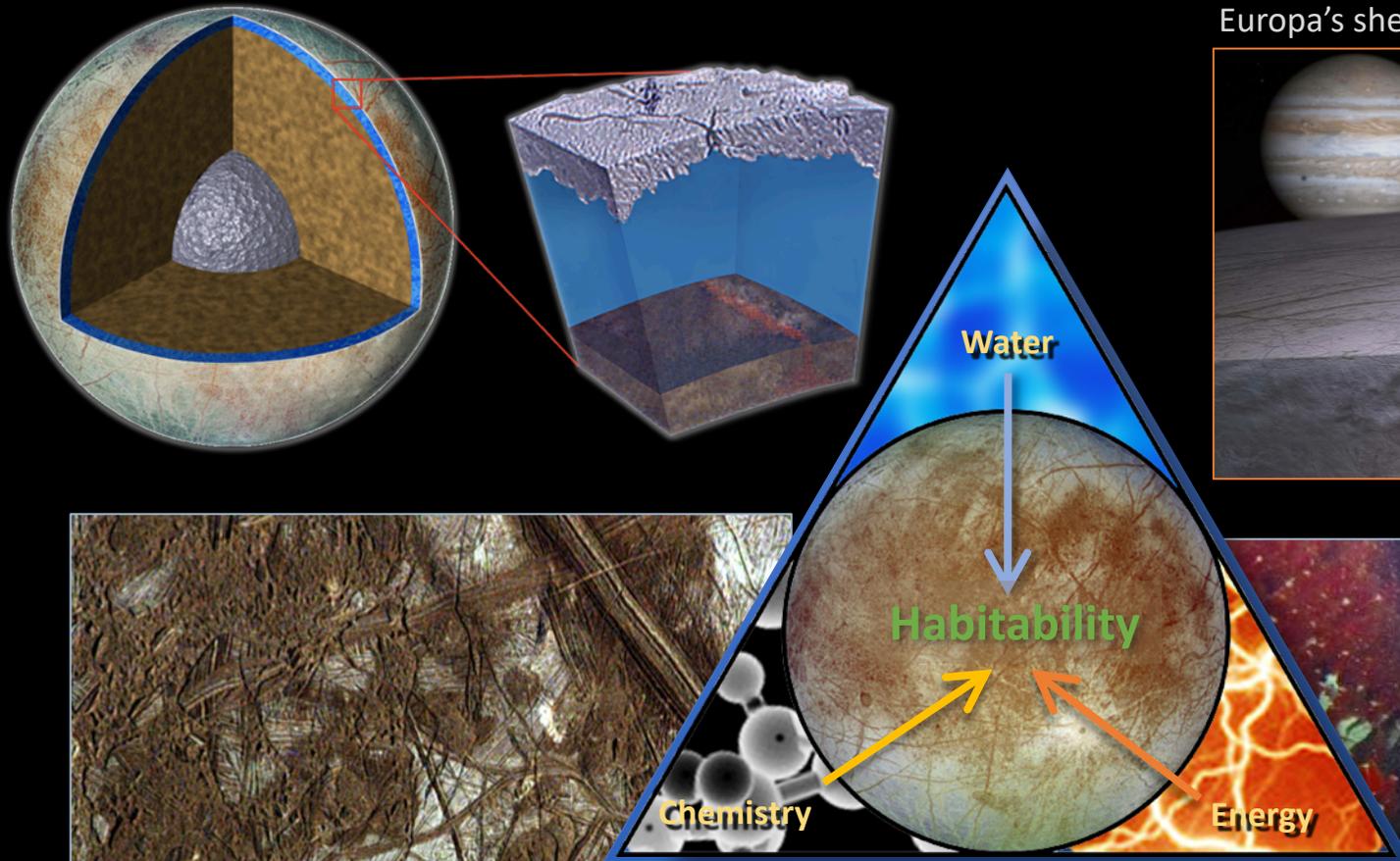
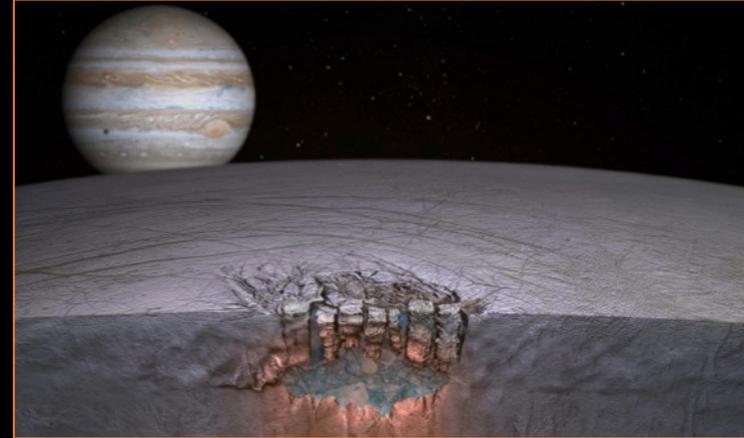


II. Europa Clipper Overview

Mission and Flight System Design

Ingredients for Life

Water: Are a global ocean and lakes hidden by Europa's shell of ice?

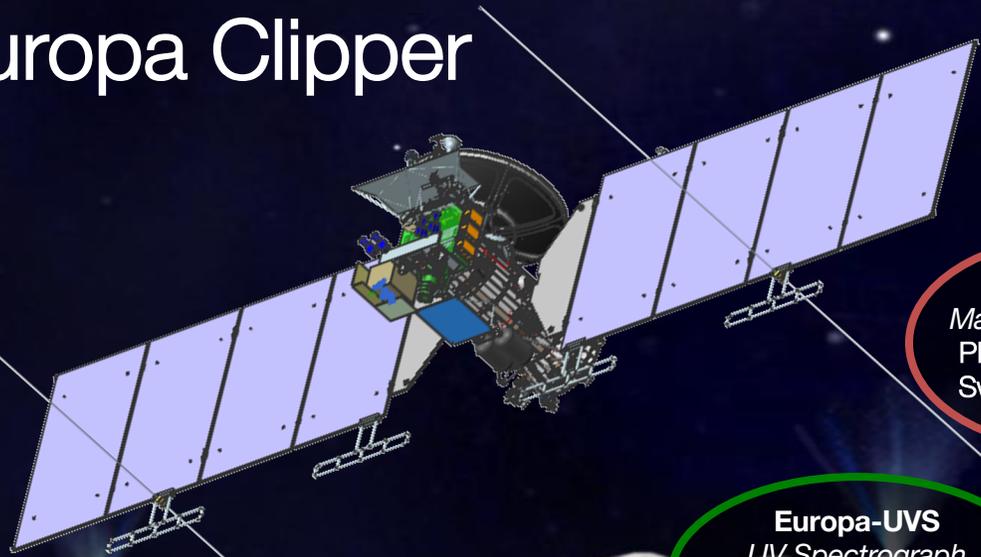


Chemistry: Do red surface deposits contain organics from below?



Energy: Are there hydrothermal vents and volcanoes within a global ocean?

Europa Clipper



MASPEX
Mass Spectrometer
PI: J. Hunter Waite
SwRI, San Antonio

SUDA
Dust Analyzer
PI: Sascha Kempf
Univ. Colorado,
Boulder

ICEMAG
Magnetometer
PI: Carol Raymond
JPL-Caltech

PIMS
Faraday Cups
PI: Joe Westlake
JHU-APL

Europa-UVS
UV Spectrograph
PI: Kurt Retherford
SwRI, San Antonio

EIS
Narrow-Angle Camera +
Wide-Angle Camera
PI: Zibi Turtle
JHU-APL

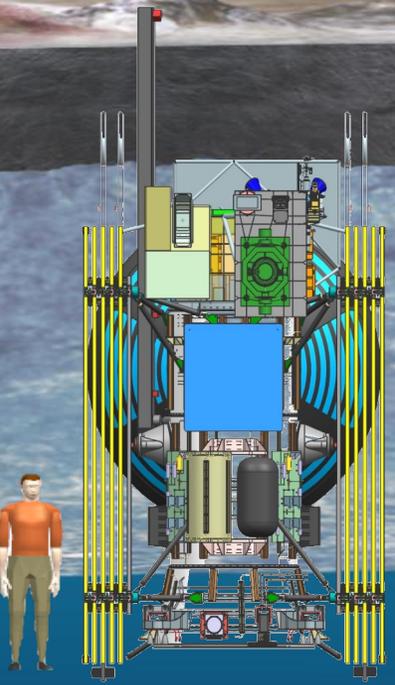
MISE
IR Spectrometer
PI: Diana Blaney
JPL-Caltech

E-THEMIS
Thermal Imager
PI: Phil Christensen
Arizona State Univ.

REASON
Ice-Penetrating Radar
PI: Don Blankenship
Univ. Texas Inst. Geophys.

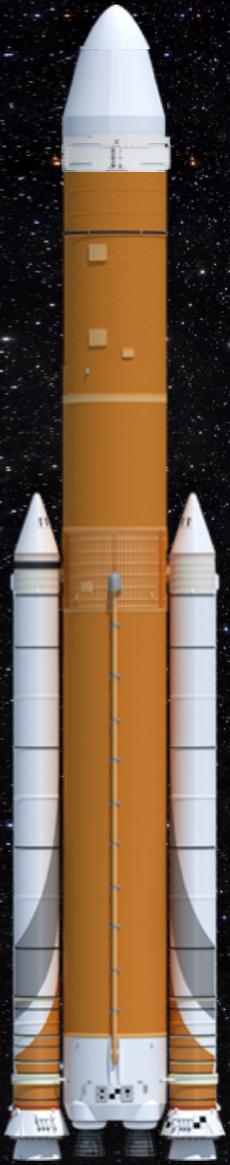
Gravity Science
Working Group

Radiation Science
Working Group
JHU-APL



● Remote Sensing

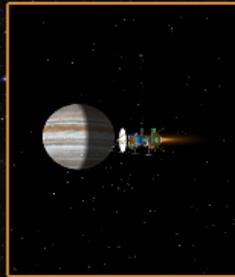
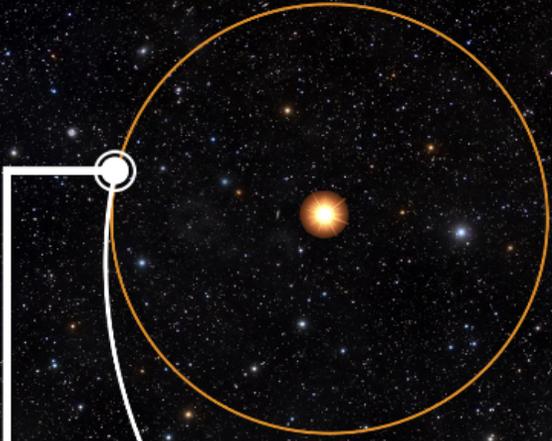
● In Situ



SLS Block 1B



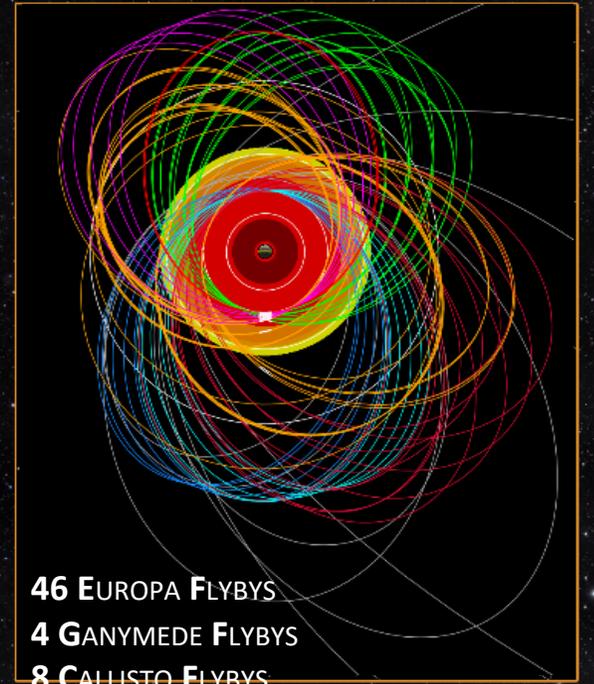
LAUNCH
JUNE 2022
CAPE CANAVERAL, FL
SLS



JUPITER ORBIT INSERTION
DEC 2024 OR MAY 2025

DEEP SPACE MANEUVER
JAN 2023 – MAR 2023

ORBITAL TOUR
MAY 2026 – Nov 2028



46 EUROPA FLYBYS
4 GANYMEDE FLYBYS
8 CALLISTO FLYBYS



Jupiter Tour

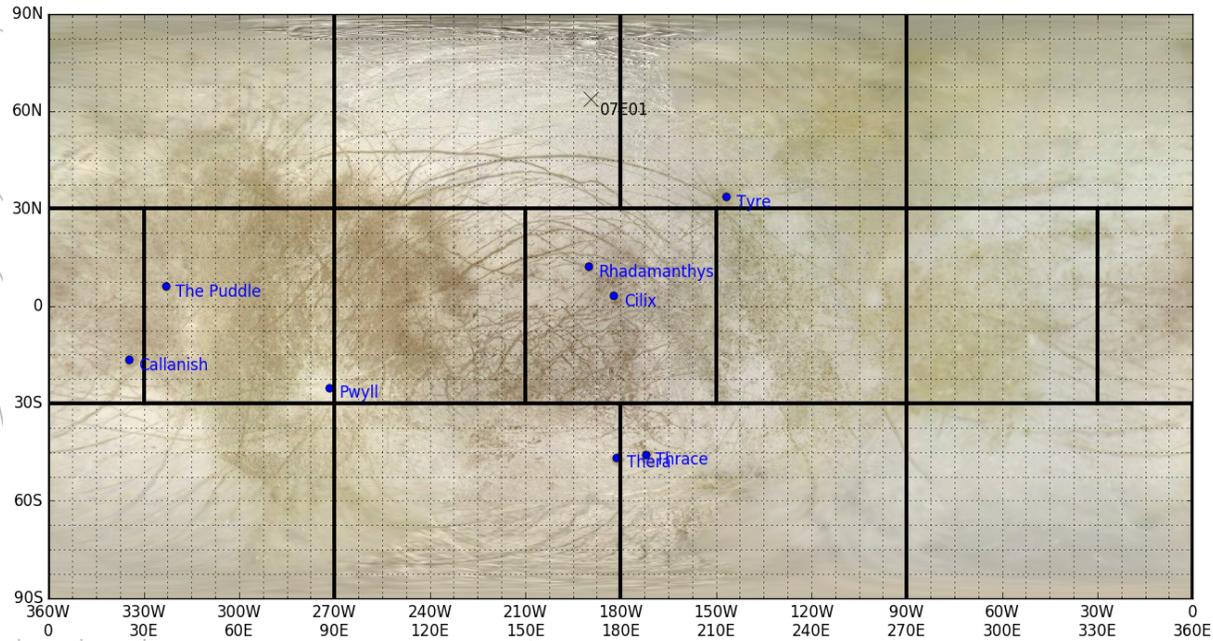
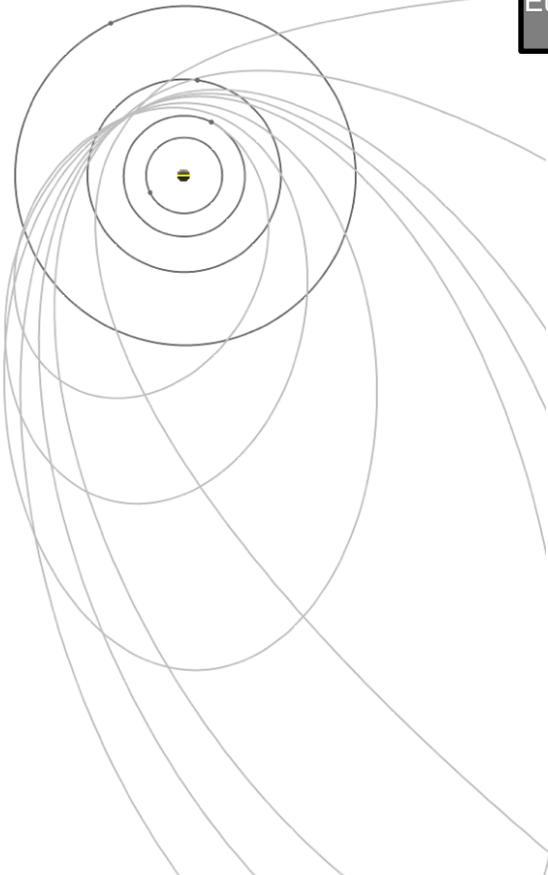
[Transition to Europa Campaign 1]



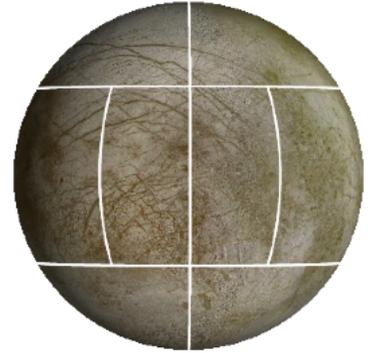
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Sun

Mission Phases

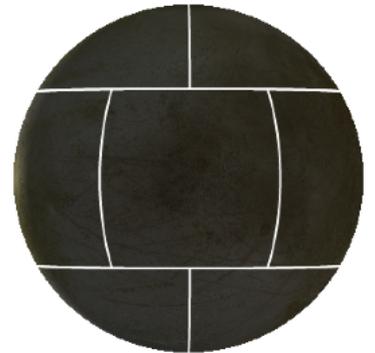
Dec 2024	May 2026	May 2027	Oct 2027	Aug 2028	Sep 2028
Transition to Europa Campaign 1	Europa Campaign 1	Transition to Europa Campaign 2	Europa Campaign 2		



Anti-Jupiter Hemisphere



Sub-Jupiter Hemisphere





Jupiter Tour

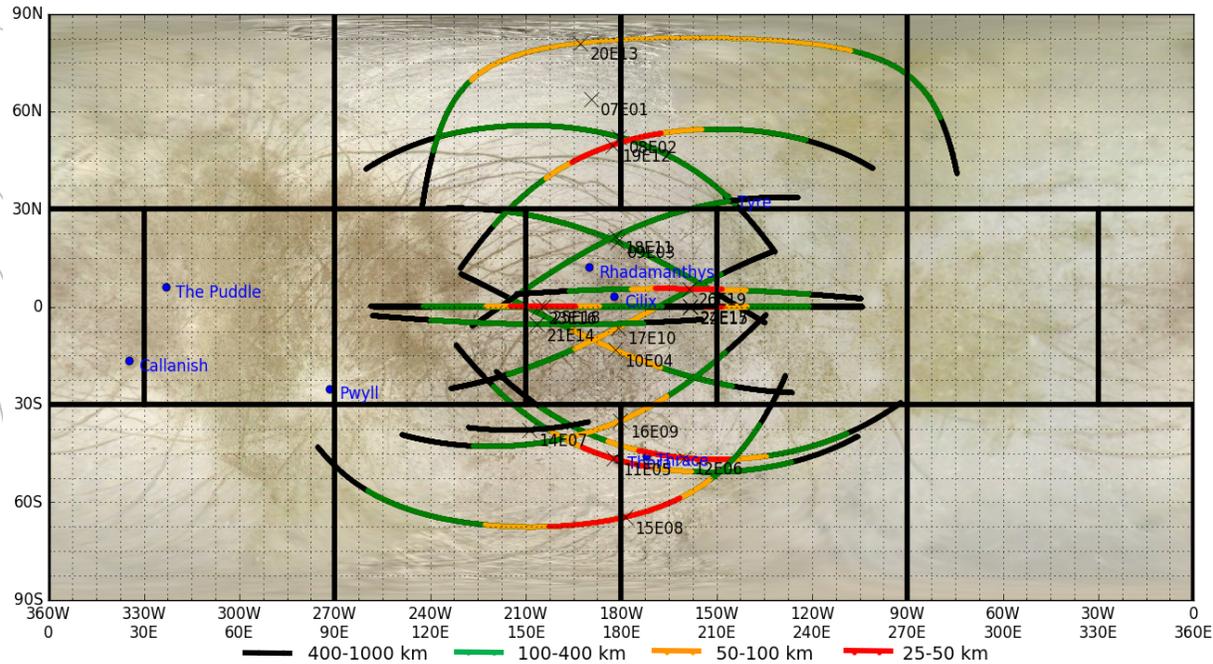
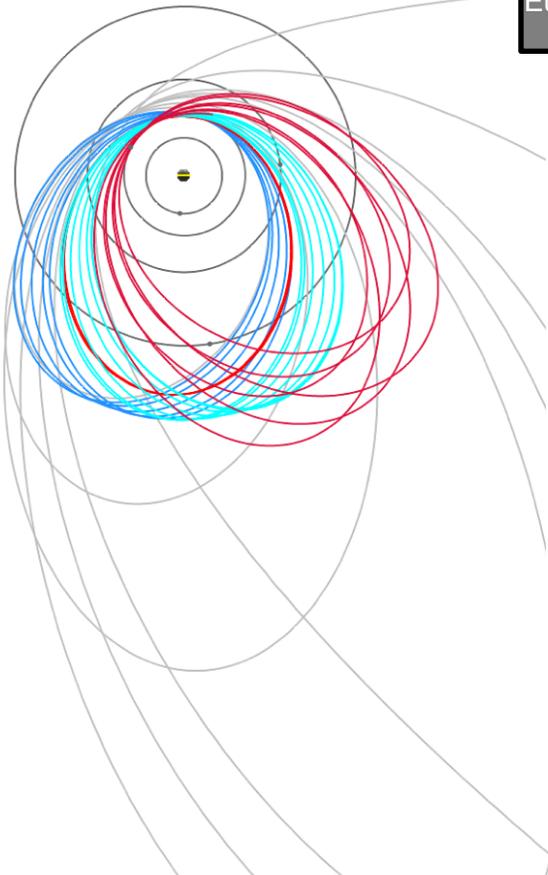
[Europa Campaign 1]



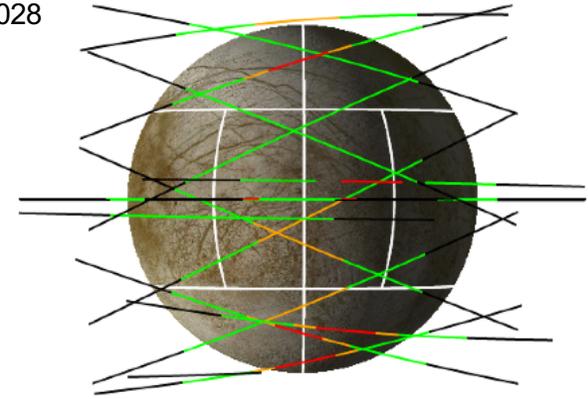
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Sun

Mission Phases

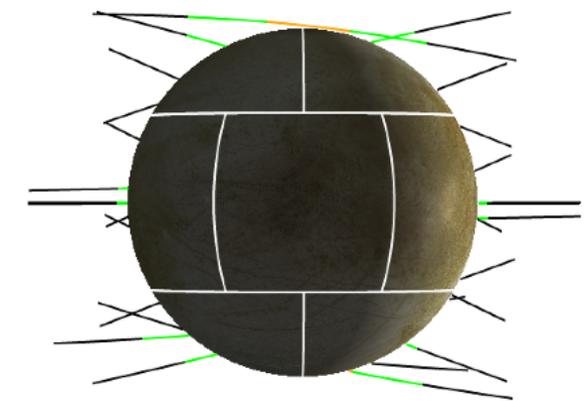
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Transition to Europa Campaign 1	Europa Campaign 1	Transition to Europa Campaign 2	Europa Campaign 2		



Anti-Jupiter Hemisphere



Sub-Jupiter Hemisphere



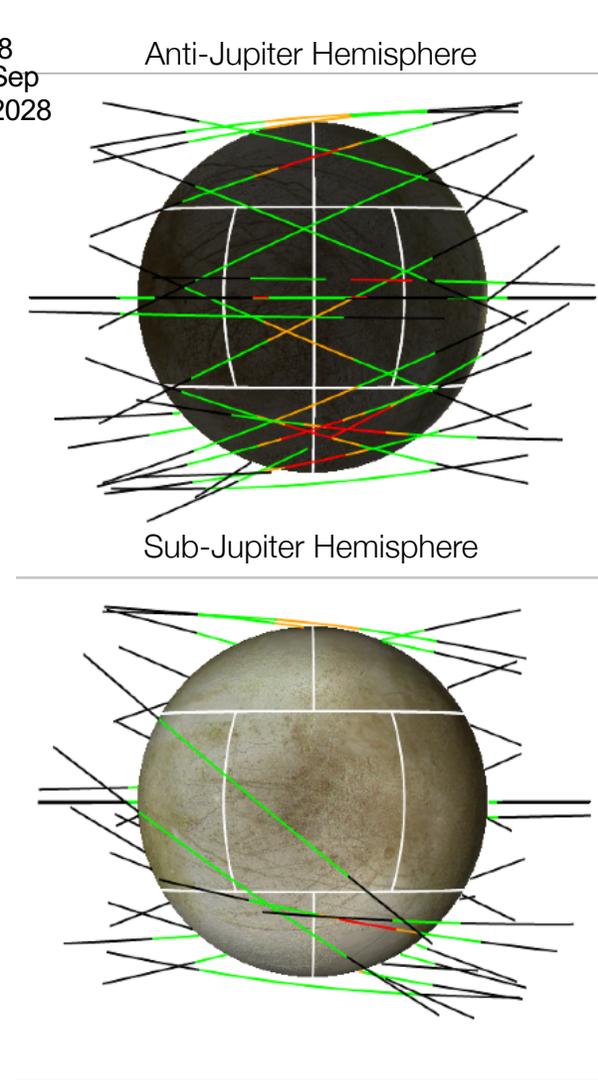
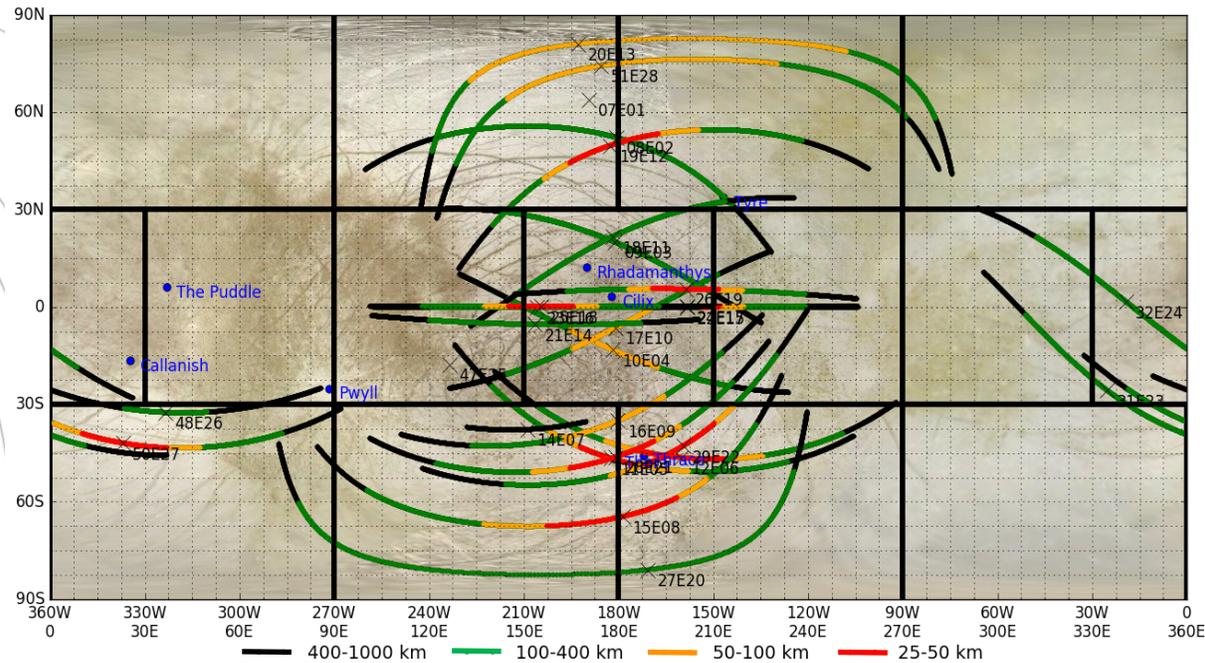
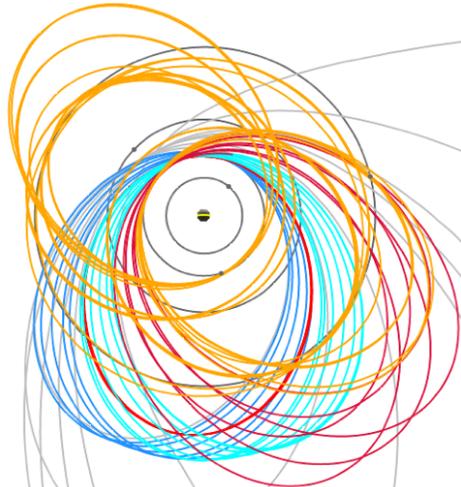


Jupiter Tour

[Transition to Europa Campaign 2]



↑
Sun



III. Simulation Framework and Heritage

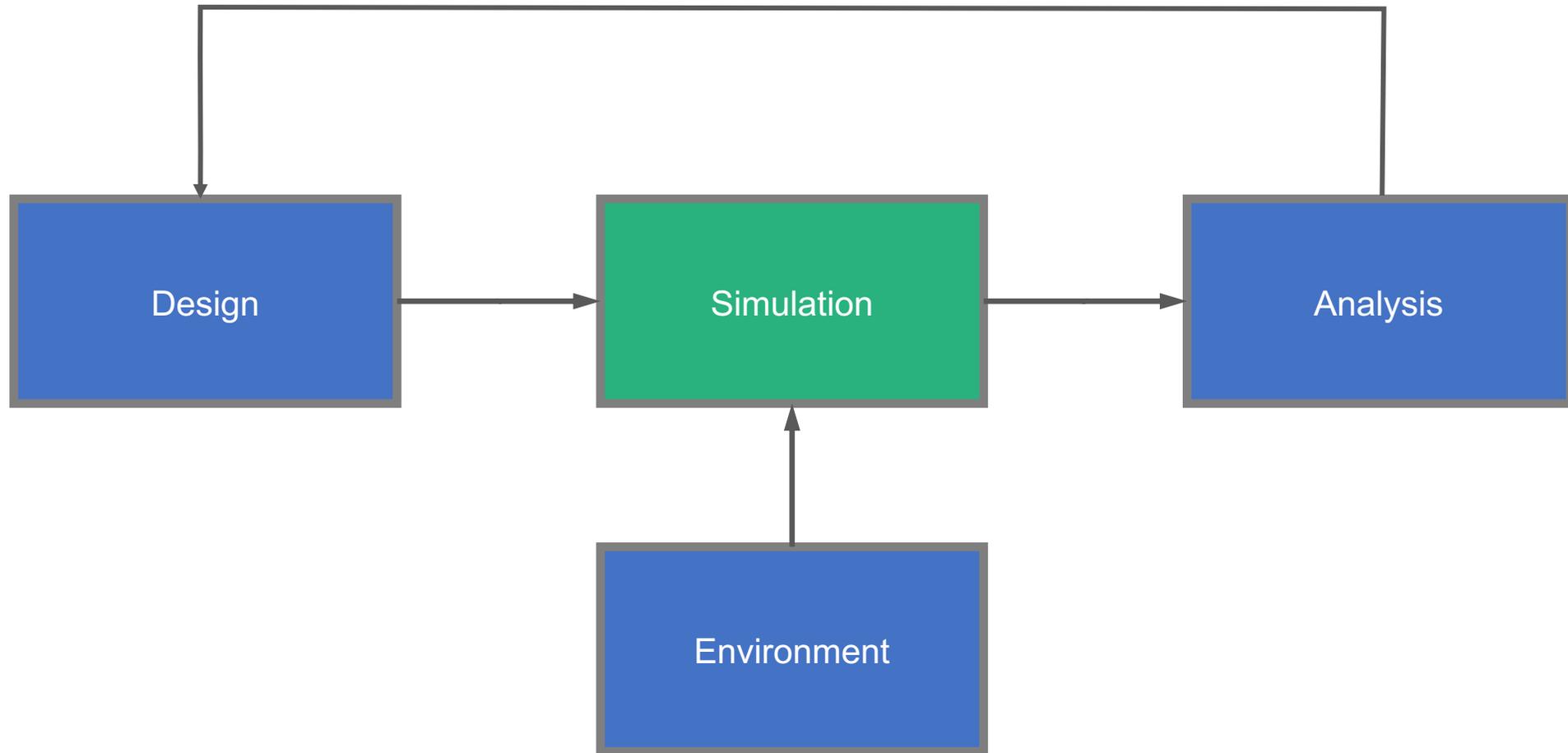
Activity Plan Generator (APGen)

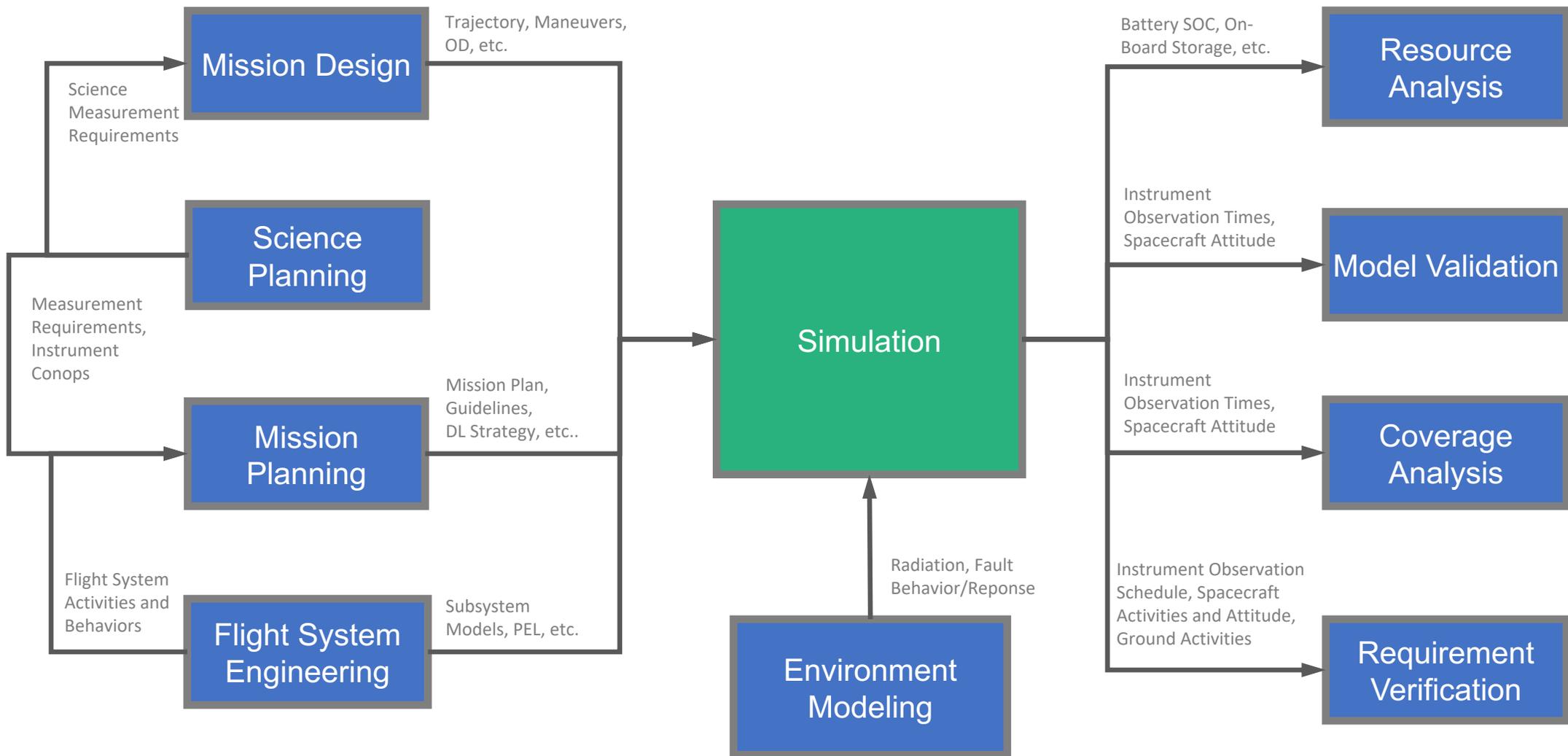
What is APGen (Activity Plan Generator)?

- Multi-Mission Modeling and Simulation Framework (“Core”)
 - Developed by NASA's Advanced Multi-Mission Operating System (AMMOS) organization
 - Originally developed to help mission planners create activity plans that did not oversubscribe critical resources
 - Key constructs are activities and resources
 - Discrete event simulator
 - Includes a scheduling engine
- Mission Heritage
 - Deep Impact / EPOXI, MSL Cruise, MRO, InSight
 - However, using APGen in early project lifecycles is new with Clipper
- Project Customization (“Adaptation”)
 - “Core” is programmed through non-standard, but highly effective domain-specific language (DSL)
 - *Build models of spacecraft and ground activities, subsystems, states, etc.*
 - *Schedule activities into a plan based on guidelines, constraints, and mission objectives*
 - *Simulate interaction between activities in a plan and their effect on spacecraft and ground resources*
 - “User-Defined Library” provides interface to external libraries and services (SPICE, MMPAT, etc.)

IV. Clipper Mission Simulations

APGen Adaptation of Clipper





Clipper Adaptation Models

Models

Heritage

Geometry (altitude, lighting angles, velocity, etc.)

Deep Impact (DI)

Ground Station (DSN, ESTRACK, NEN, etc.)

Mars Polar Lander, DI, Mars Odyssey, Mars Reconnaissance Orbiter, Mars Exploration Rovers (MER), Mars Science Laboratory (MSL), and InSight

Telecommunications (downlink rates, antenna patterns)

New to Europa Clipper

Data (data accumulation, deletion, and flow to ground)

Mars Polar Lander, DI, and Phoenix

Power (system-level model or interface to JPL's MMPAT)

*System-Level Model: New to Europa Clipper
MMPAT: MER, DI, MSL, Phoenix, InSight, and JUNO*

Guidance Navigation and Control (commander, rates, slew profiles, star tracker)

Deep Impact (DI)

Solar Arrays (hard stop, flops)

New to Europa Clipper

Radiation (solar array degradation, based on GIRE)

Galileo

Propulsion (engine cycling, fuel burned)

New to Europa Clipper

Payload (operating modes, power states and data production)

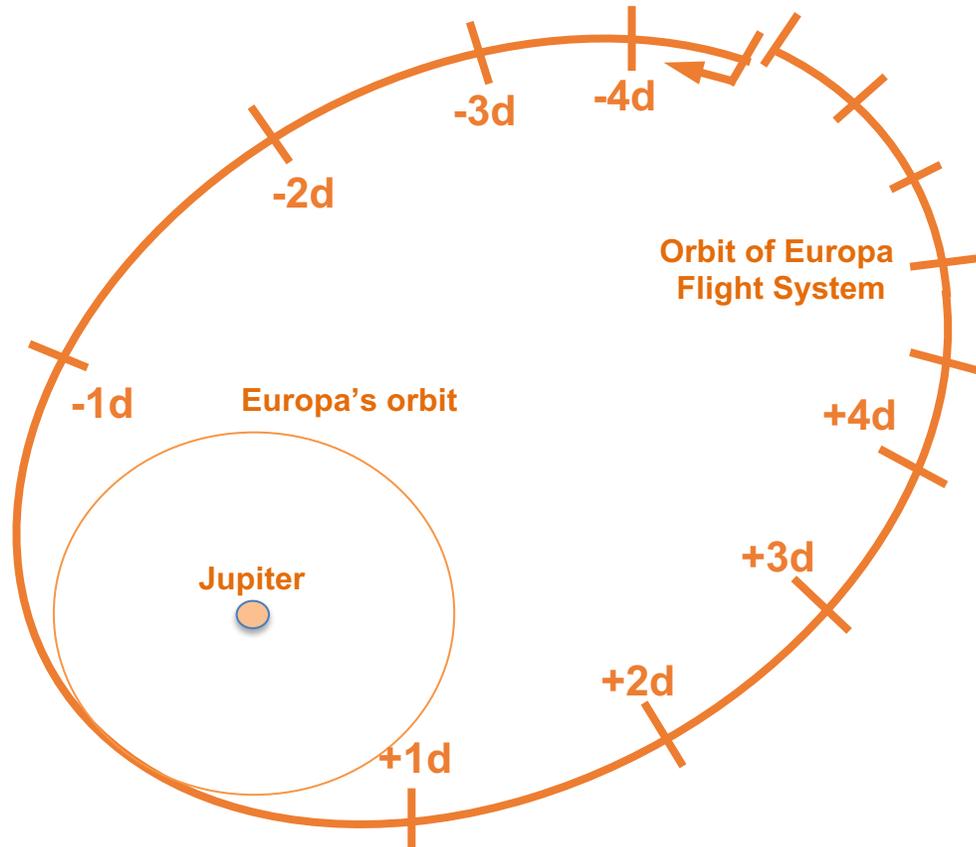
New to Europa Clipper

Mission Operations (uplink, ground processes, shift schedules)

Deep Impact (DI)

Activity Scheduling

Automated Schedulers
(layered as a function of priority / dependency)

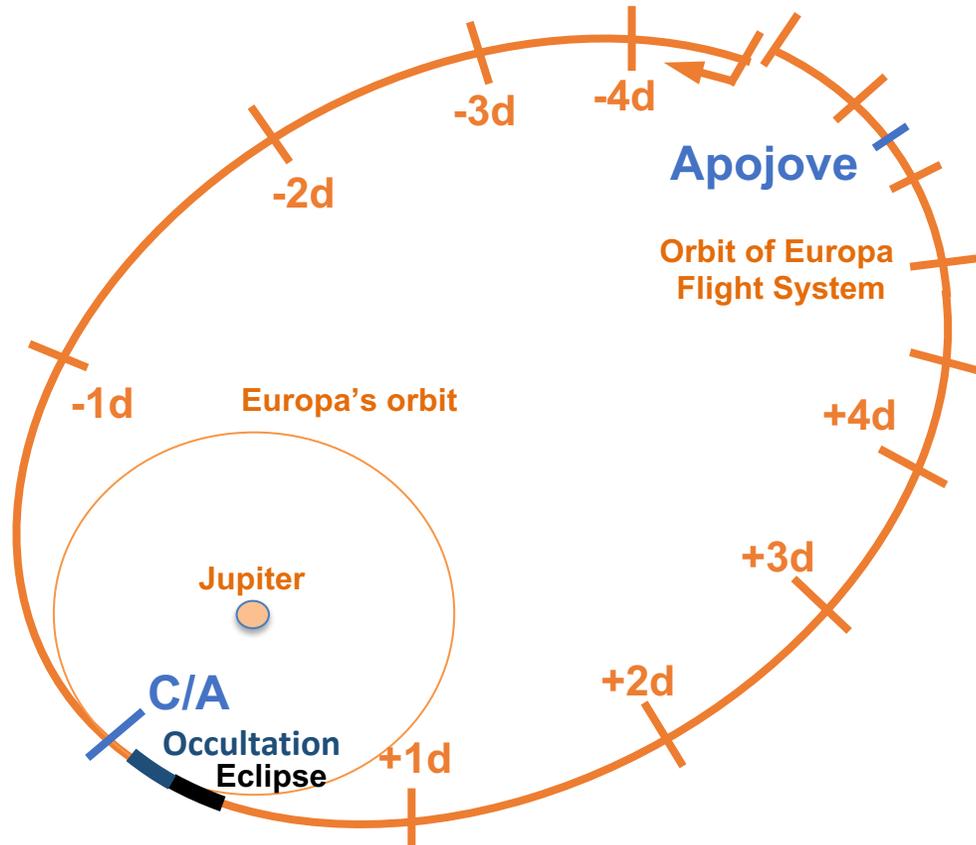


Activity Scheduling

Automated Schedulers

(layered as a function of priority / dependency)

- Ground Station View Periods
- Geometric Events (periapsis, apoapsis, eclipses, occultations, Transits)

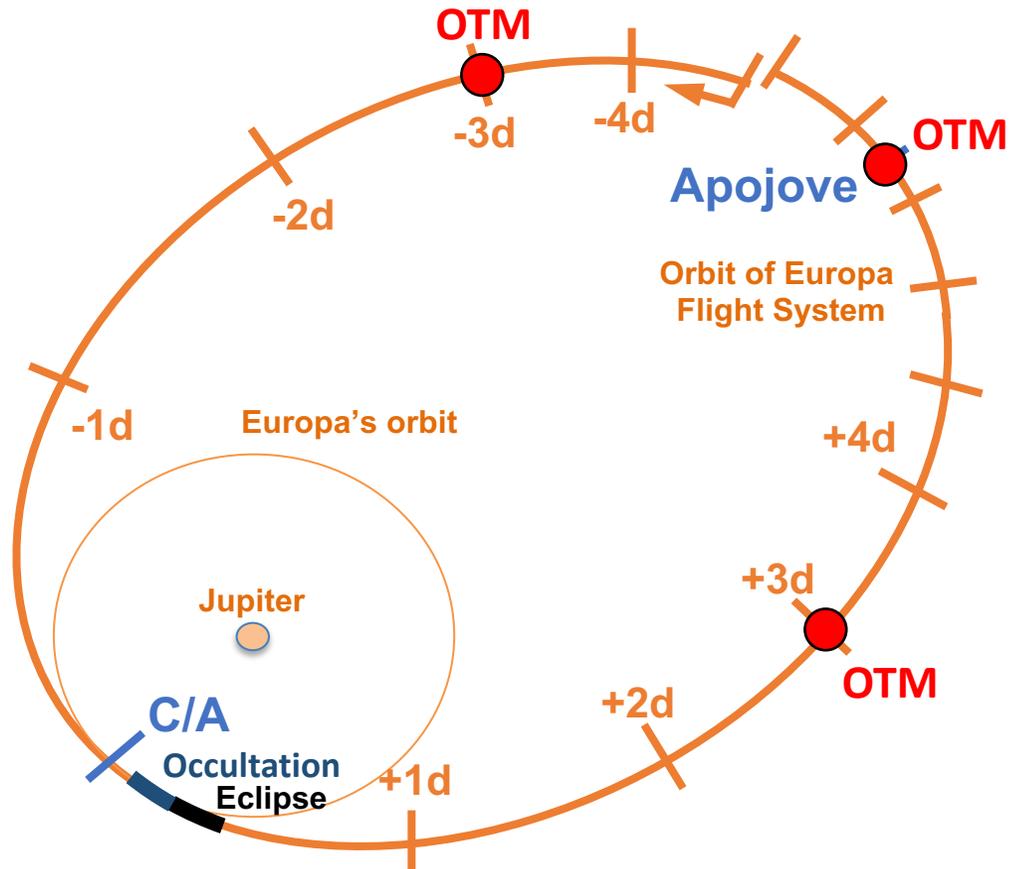


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- Maneuvers (TCMs and OTMs)

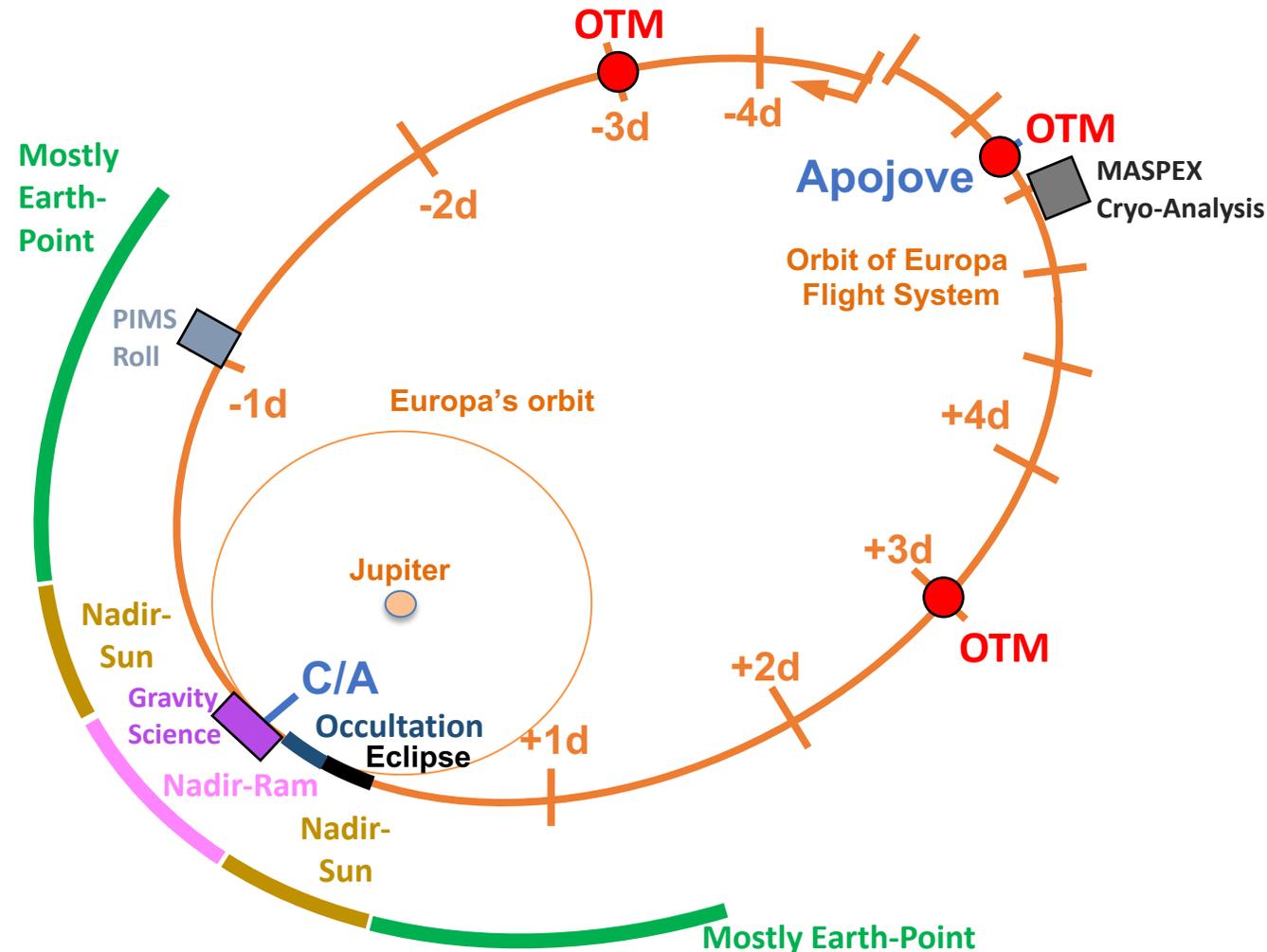


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- Maneuvers (TCMs and OTMs)
- Flyby Attitude Modes, Science, and Calibrations
- Gravity Science

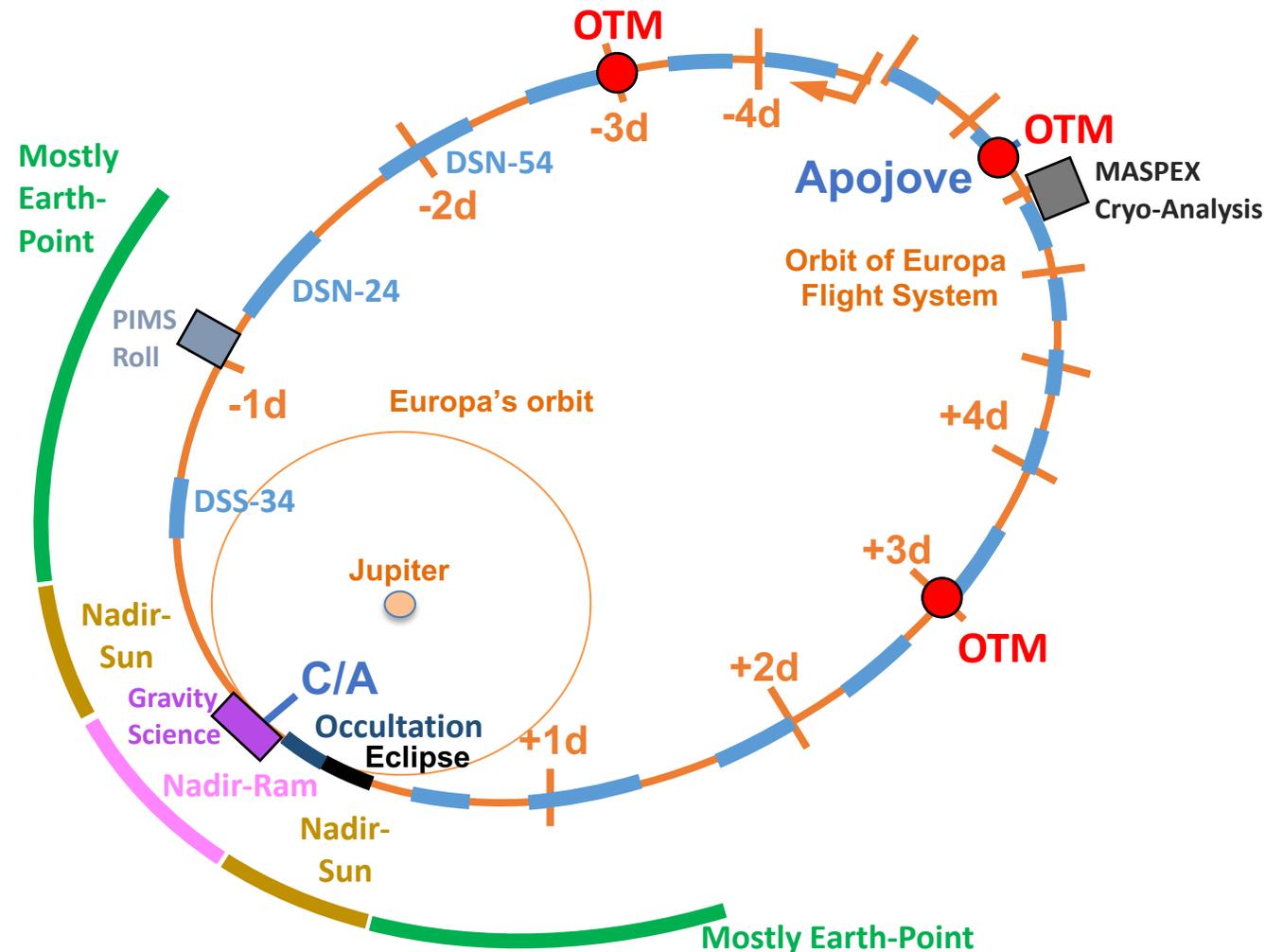


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- Gravity Science
- Ground Station Allocations

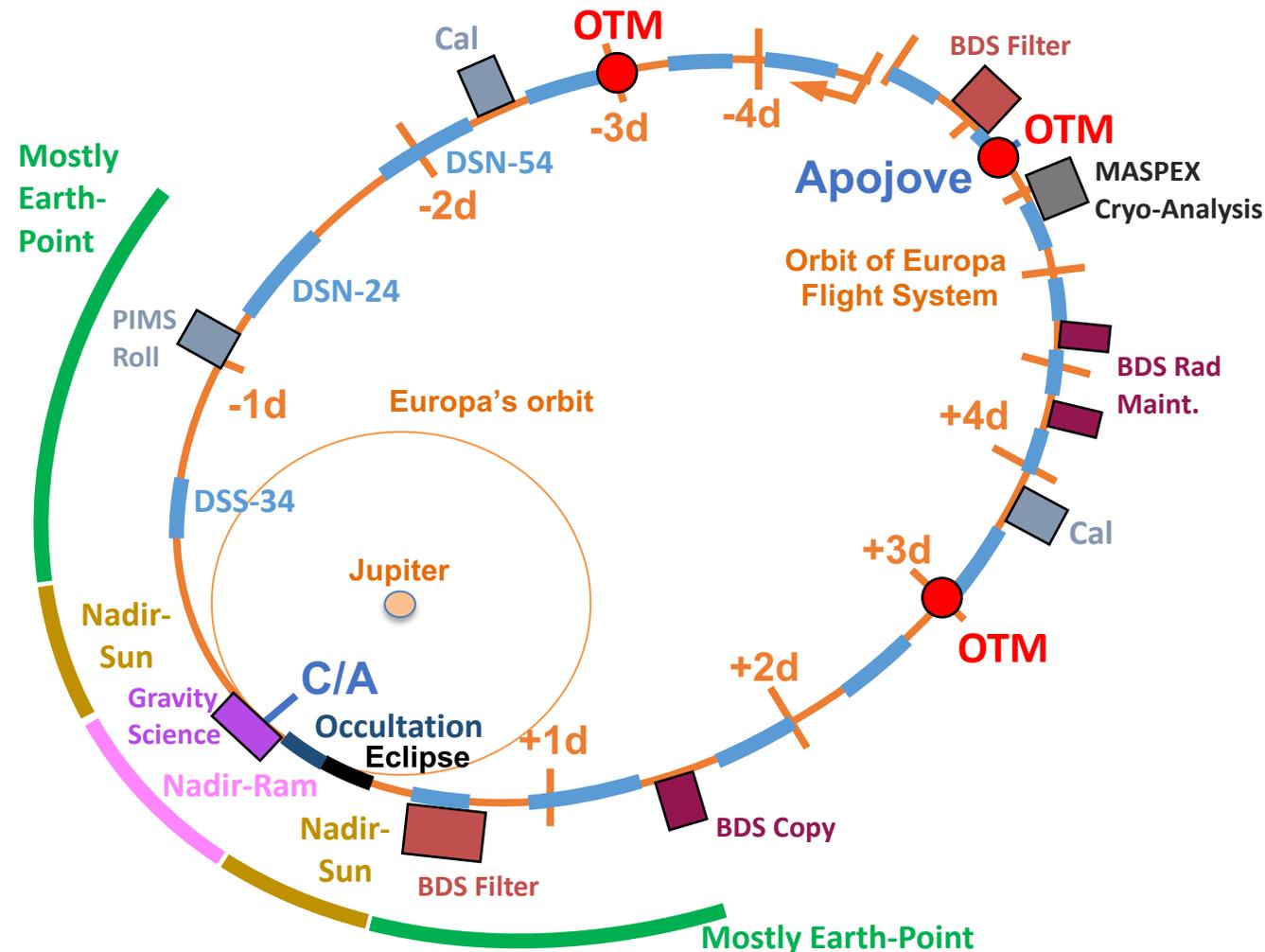


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- Gravity Science
- Ground Station Allocations
- Avionics Maintenance (filter, copy, radiation maintenance)
- Instrument and Subsystem Calibrations and Maintenance (outside flyby period)

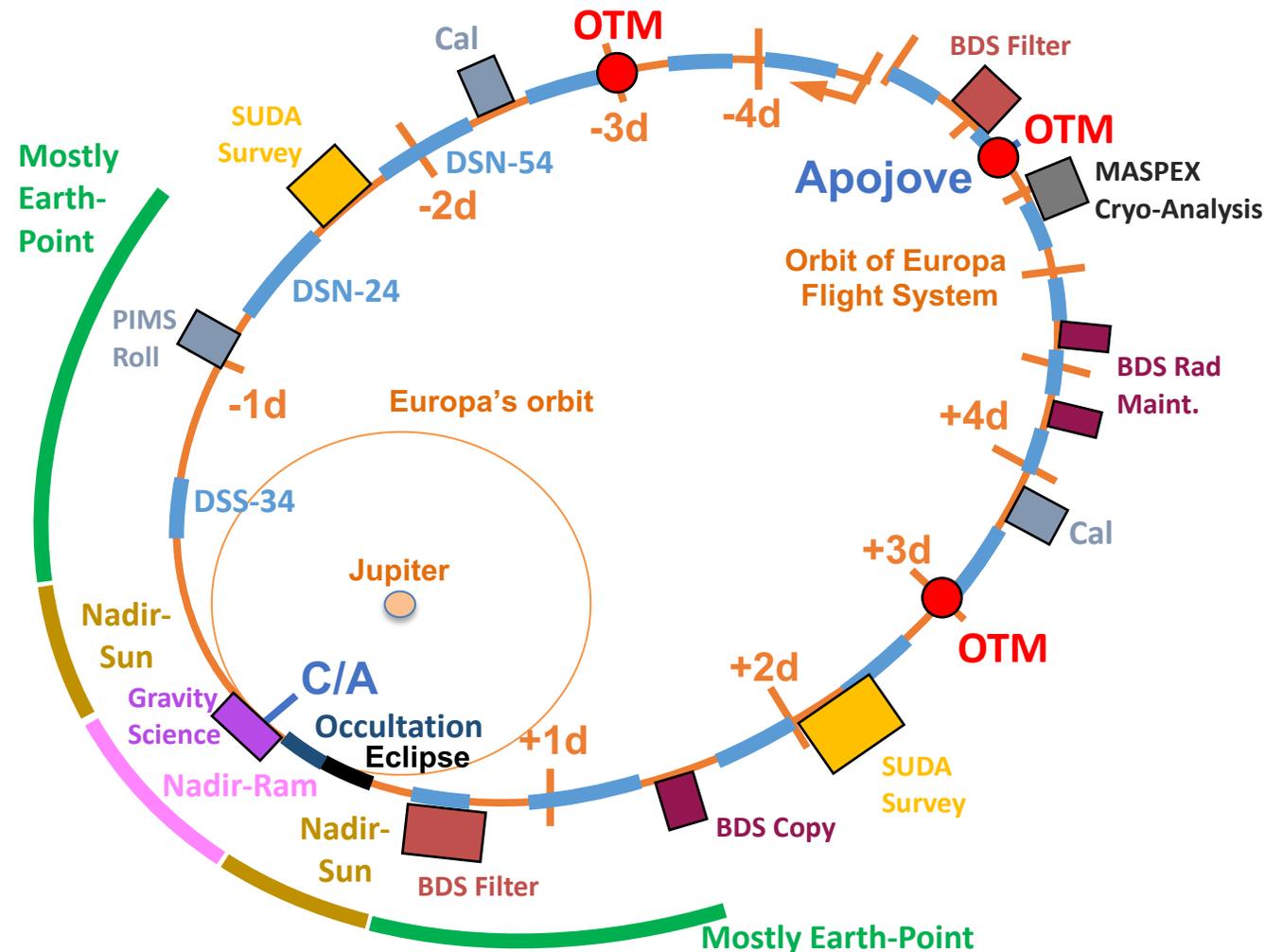


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- Flyby Attitude Modes, Science, and Calibrations
- Gravity Science
- Ground Station Allocations
- Avionics Maintenance (filter, copy, radiation maintenance)
- Instrument and Subsystem Calibrations and Maintenance (outside flyby period)
- SUDA Surveys
- Downlinks



Final Simulation Run

- Once all activities have been “built up”, a final simulation run is performed
- Activities trigger models that change the value of resources
- Every change is recorded, stored, and ultimately provided as an output once the simulation run completes.

End-To-End Clipper Simulation Metrics (covering 6 years)

Number of Scheduled Activities: 165,000+

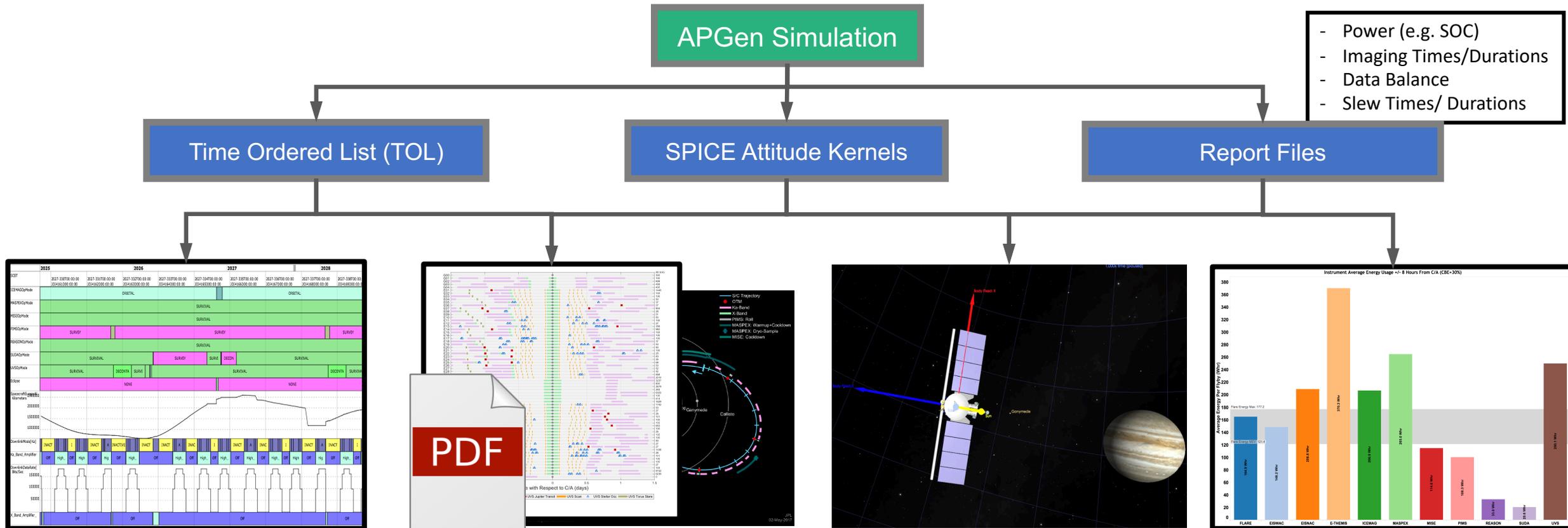
Run Time: (~8000x real-time)

- Activity Scheduling: 24 hours
- Final Simulation Run: 6-8 hours

Max RAM usage: ~40 GB

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Simulation Output and Visualization



RAVEN

- Interactive, web-based activity and resource timeline visualizer
- Customize layouts, zoom in/out, share views via URL

PDF Simulation Reports

- Detailed metrics on critical system resources (e.g. power, data, DSN)
- Plots showing spacecraft activities per encounter

Cosmographia

- Interactive 3D visualizer of planetary bodies, spacecraft trajectories, orientations, and observations
- Scriptable, build videos, SPICE-based

Tableau Workbooks

- Interactive data visualizations great for cross-comparing sims
- Filter data, perform statistics, build beautiful charts in seconds

V. Applications of Mission Simulations During Project Formulation

Extensive Scope of APGen Simulations on Clipper

- Mission Planning
- Project Trade Studies
- Energy / Data Allocations
 - Qaida, B., et al., "A Statistical Approach to Payload Energy Management for NASA's Europa Clipper Mission," IEEE Aerospace Conference, Big Sky, MT, 3-10 Mar. 2018.
- Hardware Design
- Hardware Test Plan Development
- Operability Analysis
 - Signorelli, J., Bindschadler, D. L., Schimmels, K. A., and Huh S. M., "Operability Engineering for the Europa Clipper Mission: Formulation Phase Results and Lessons," AIAA 15th International Conference on Space Operations (SpaceOps), Marseille, France, 2018.
- Requirement Verification
 - Buffington, B., et al., "Evolution of Trajectory Design Requirements on NASA's Planned Europa Clipper Mission," 68th International Astronautical Congress (IAC), IAC-17-C1.7.8, Adelaide, Australia, 25-29 Sep. 2017.
- Fault Sensitivity Analysis
 - McCoy, K., et al., "Assessing the Science Robustness of the Europa Clipper Mission: Science Sensitivity Model," IEEE Aerospace Conference, Big Sky, MT, 3-10 Mar. 2018.
- Europa Lander Concept
 - Lawler, C. R., Wissler, S. S., Kulkarni, T., Ferguson E. W., and Maldague P. F., "Europa Lander Concept: High fidelity system modeling informing flight system and concept of operations years before launch," AIAA 15th International Conference on Space Operations (SpaceOps), Marseille, France, 2018 (to be published).

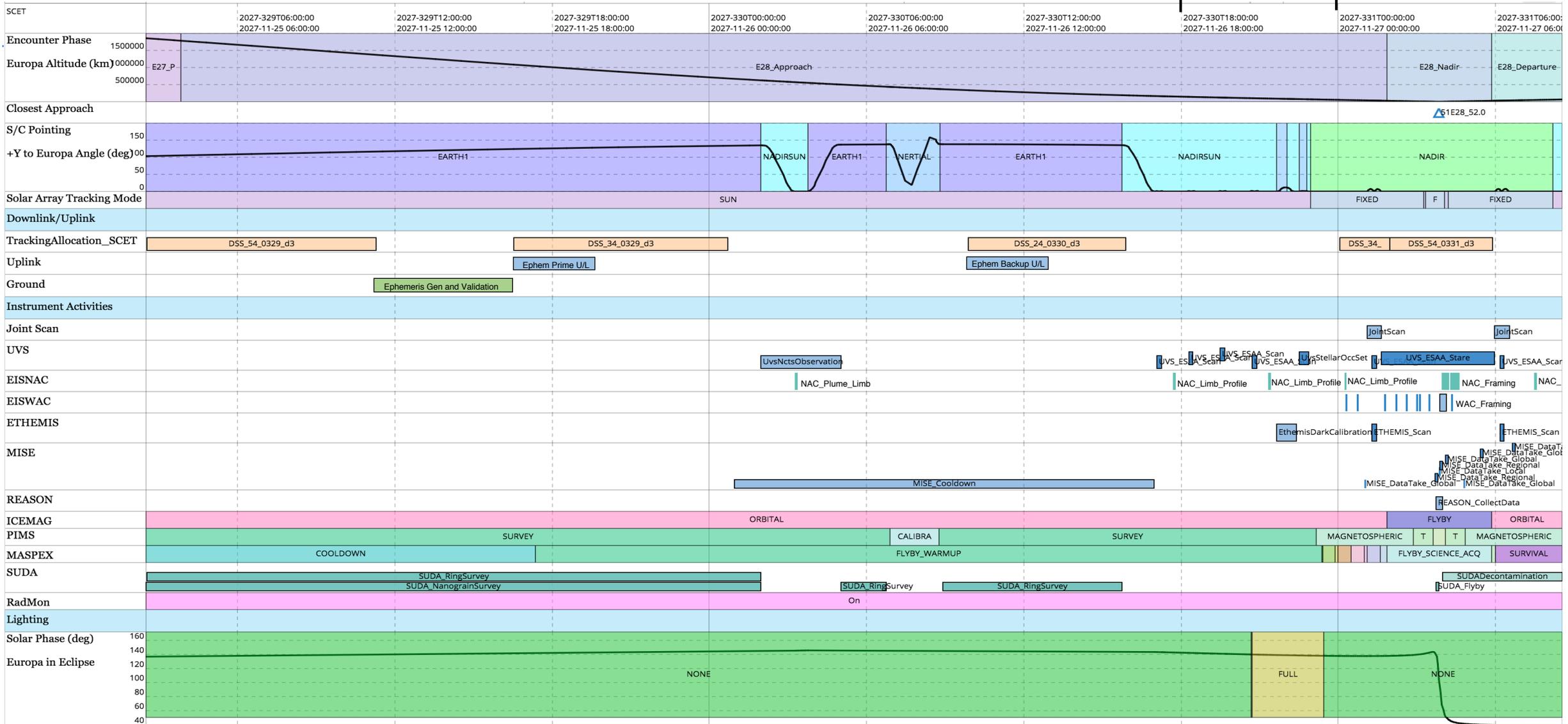
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Mission Planning

Approach: C/A - 2 days to C/A + 5 hr

6 hr

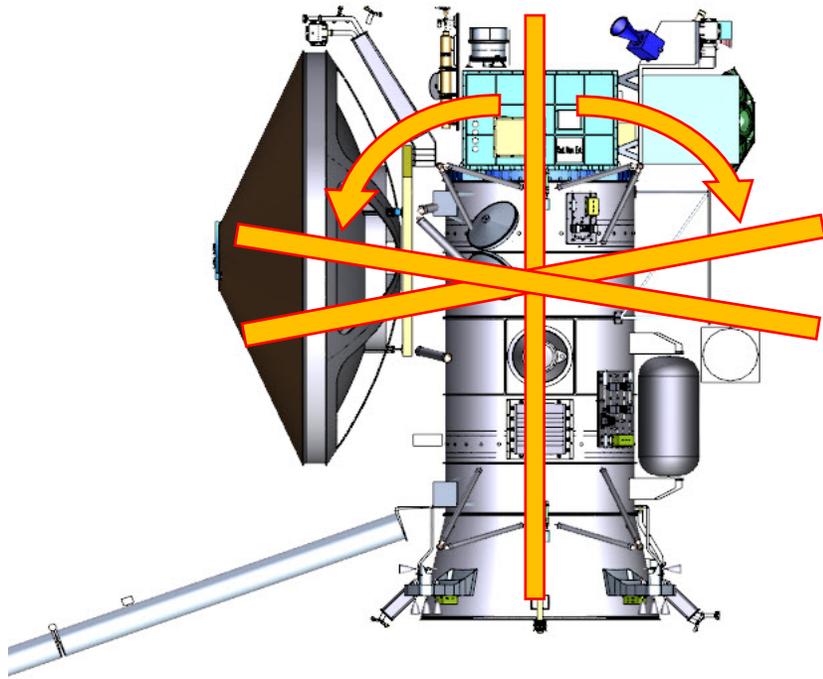


Trade Studies

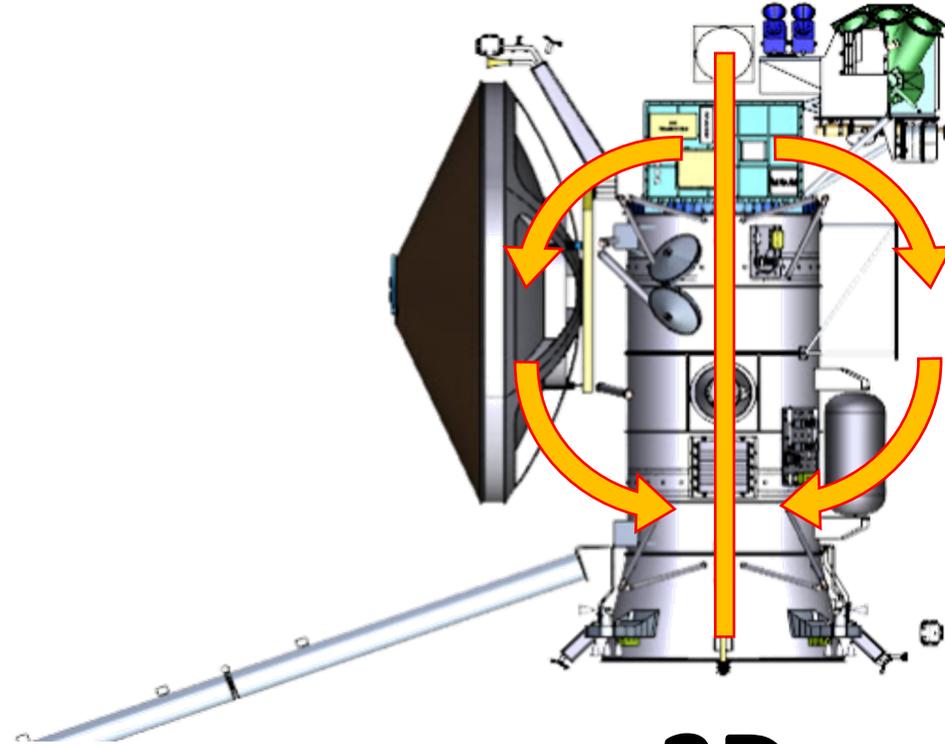
+/-76°

VS

+/-180°



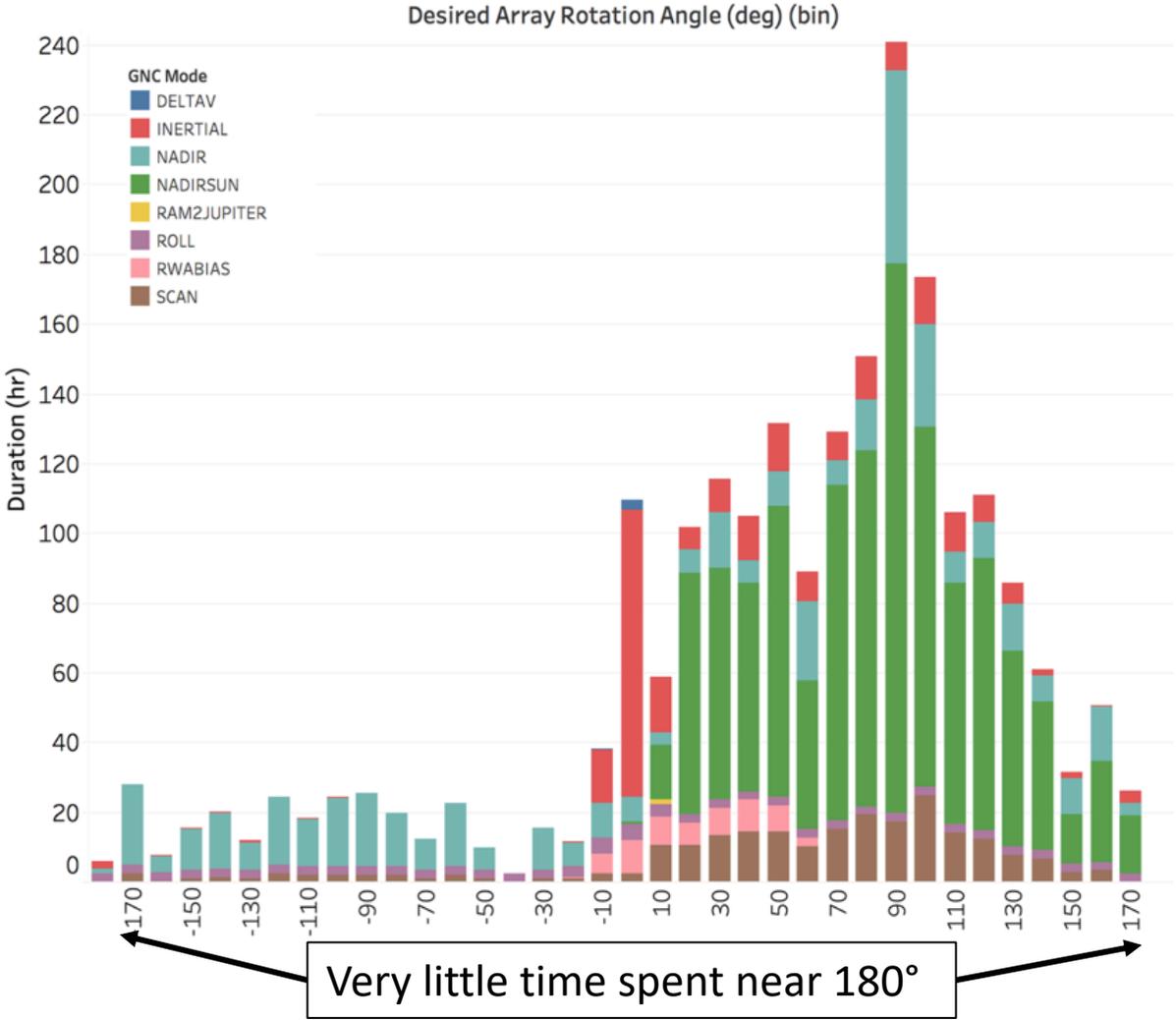
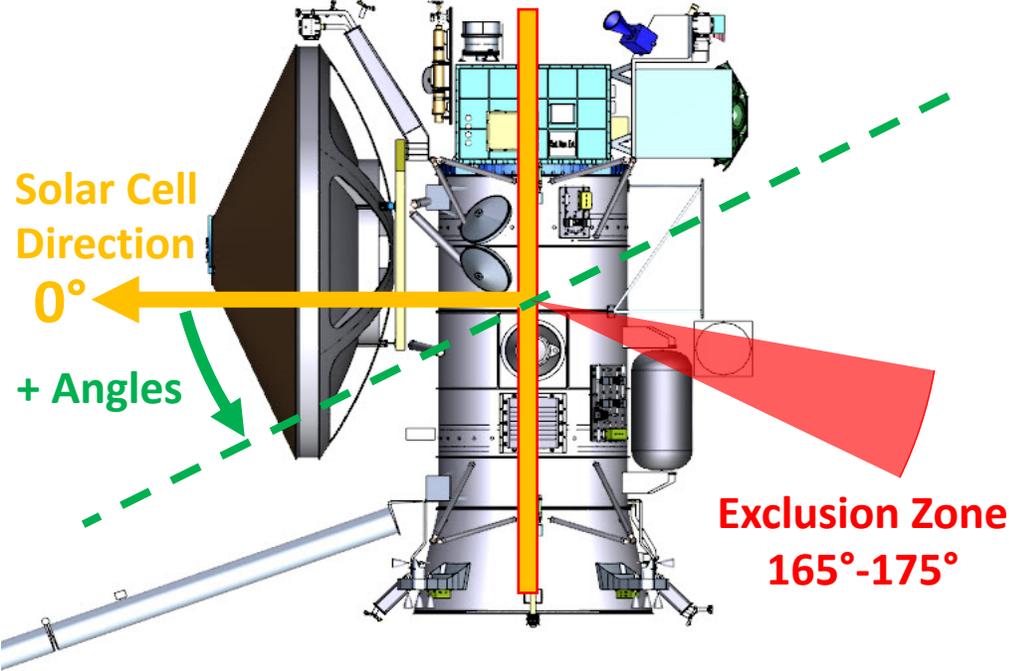
2C



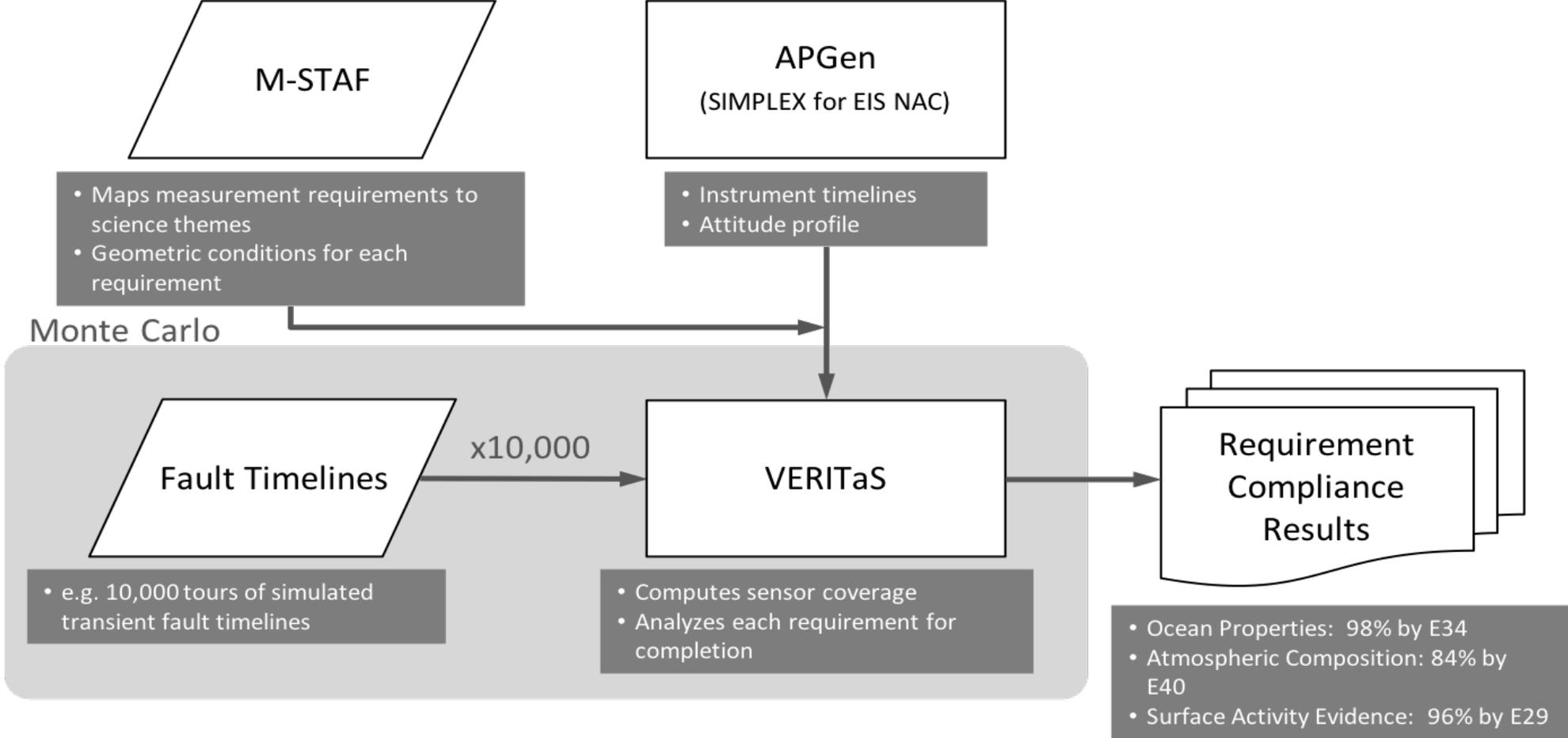
2D

Solar Array Range of Motion

Hardware Design

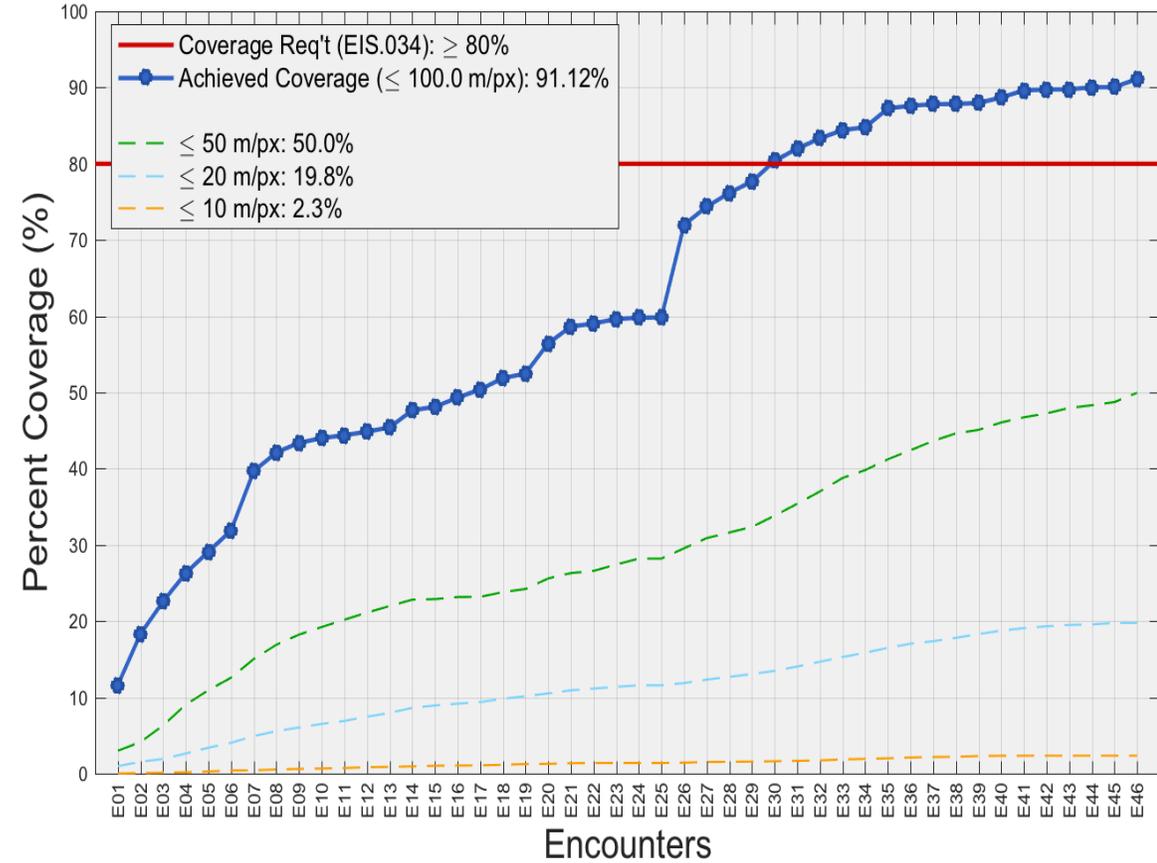
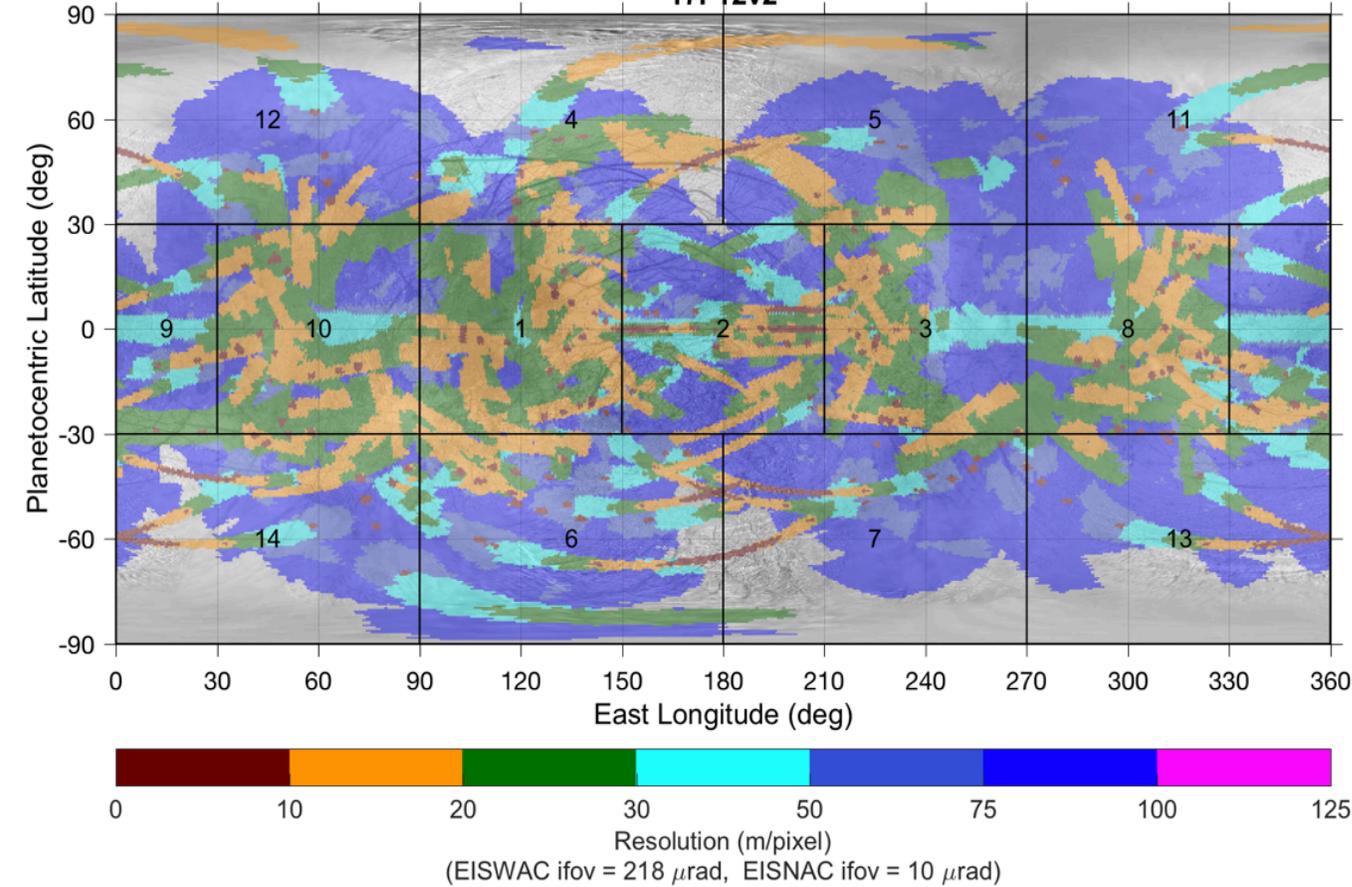


Requirement Verification



VERITaS (Verification of Europa Requirements Integrating Tour and Science)

EISWAC+EISNAC Framing-Pan-Mono Total Coverage
17F12v2



VERITaS

(Verification of Europa Requirements Integrating Tour and Science)

VI. Improving Future Mission Simulations

Simulation Performance

Core

- Identify as much information as possible at “compile time”
- Efficiently parse the adaptation and thoroughly analyze its content before execution.

3.4x run-time performance improvement based on initial tests

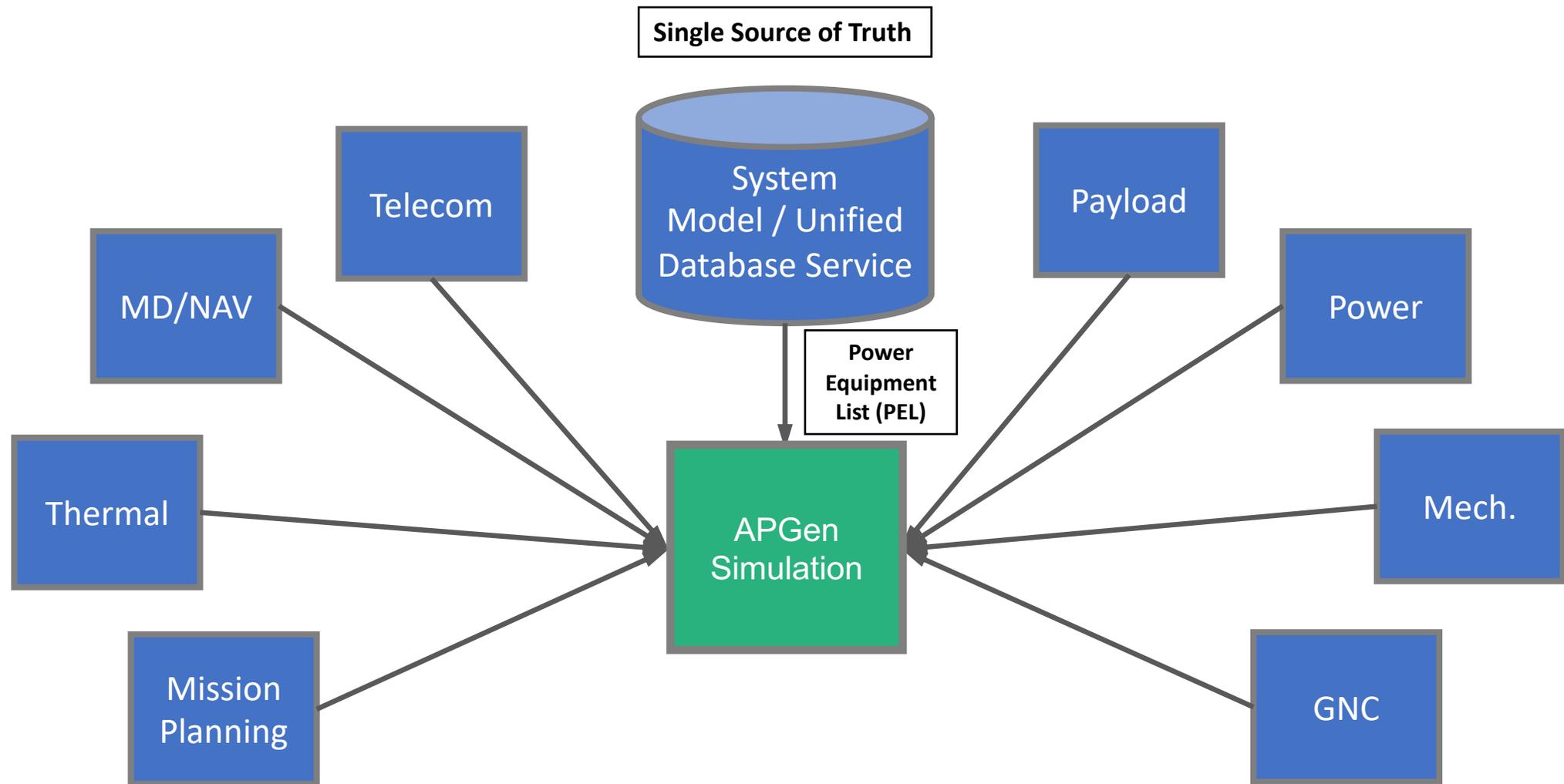
Adaptation

- Only compute resource calculations when necessary
- Resource profile can be saved off and read back into APGen during subsequent activity scheduling or simulation runs
- Switches are available within adaptation to turn subsystem models on/off contingent on whether resources within those models need to be calculated

2x reduction in total run-time thus far

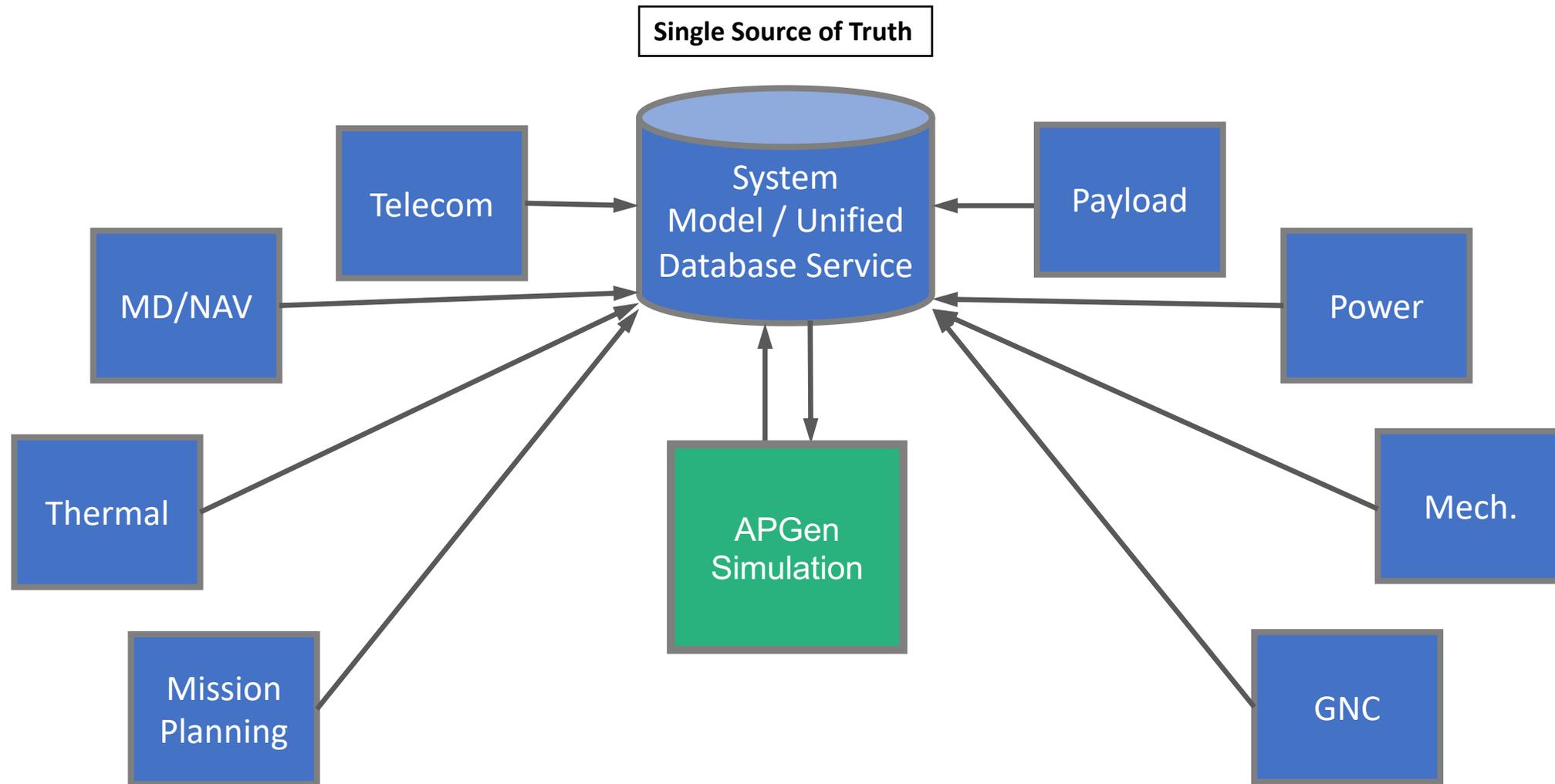
Transformation of System Knowledge into Simulation Inputs

[Current]

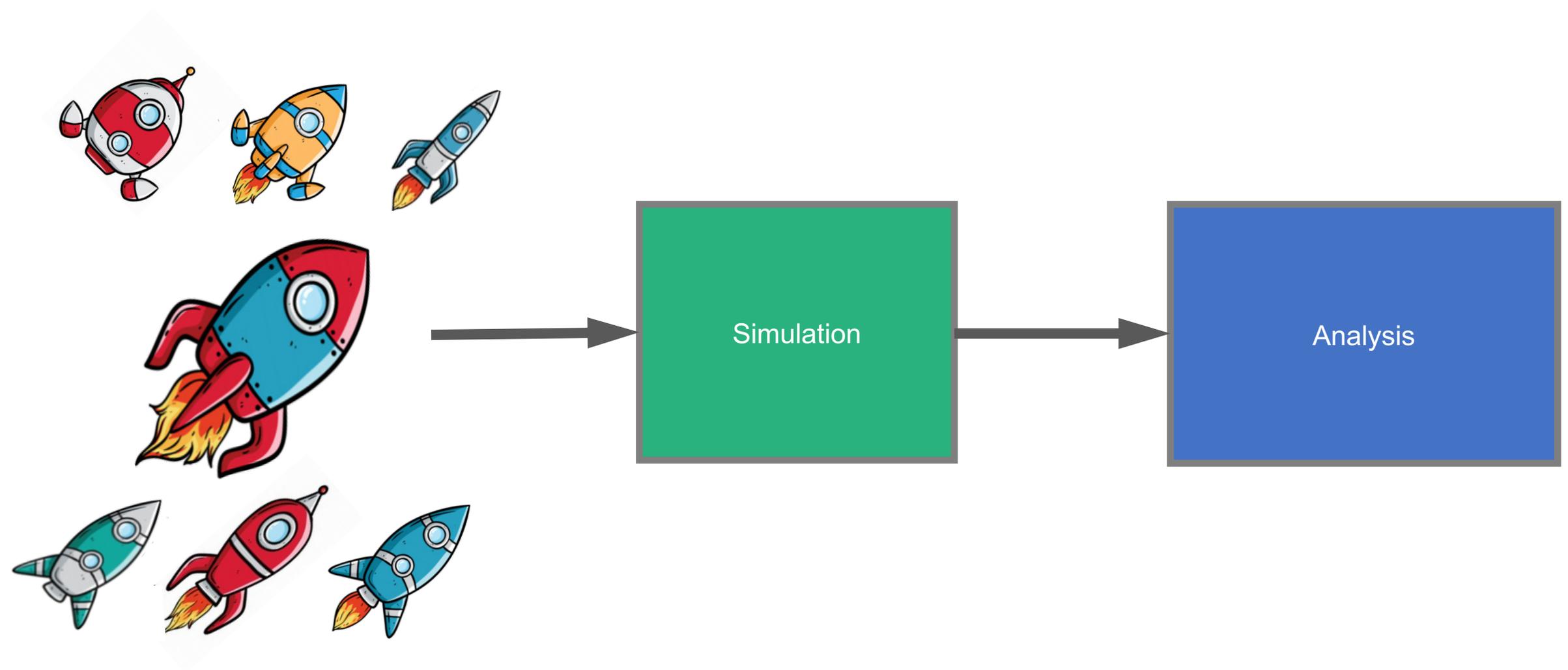


Transformation of System Knowledge into Simulation Inputs

[Ideal]



Parameterization and Automation



VII. Simulations in Operations

Phase E?

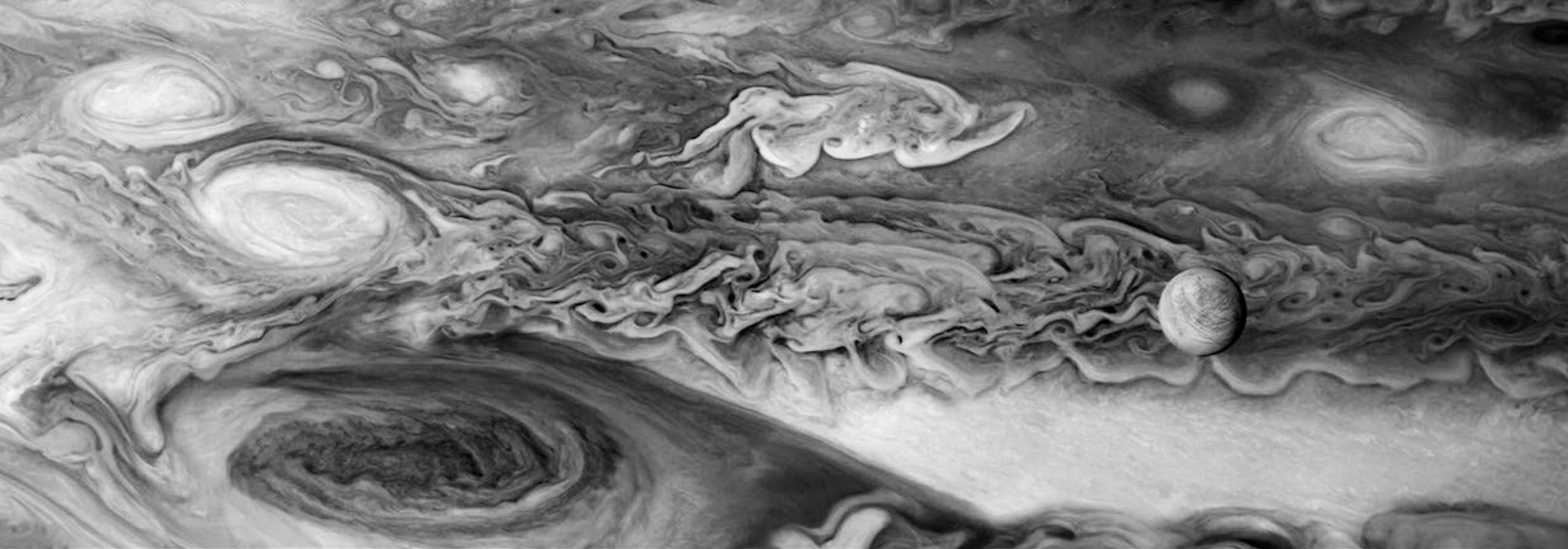
Phase B

Phase A

Pre-Phase A



EVOLUTION of Europa Simulation to Operations?



Improving Spacecraft Design and Operability for Europa Clipper through High-Fidelity, Mission-Level Modeling and Simulation

Eric Ferguson (presenter), Steve Wissler, Ben Bradley, Pierre Maldague, Jan Ludwinski, Chris Lawler



Jet Propulsion Laboratory
California Institute of Technology

May 29th 2018

EUROPA
CLIPPER

Backup

Setup/Run Process

As a user, running a simulation is a two step process:



Sets up simulation environment based on user configuration and builds scheduling/simulation scripts.

Configuration parameters include:

- Time Range
- Trajectory
- Global Overrides
- Pointer to User Defined Library
- Pointer to Adaptation Code
- Simulation Name

A few different run options are available:

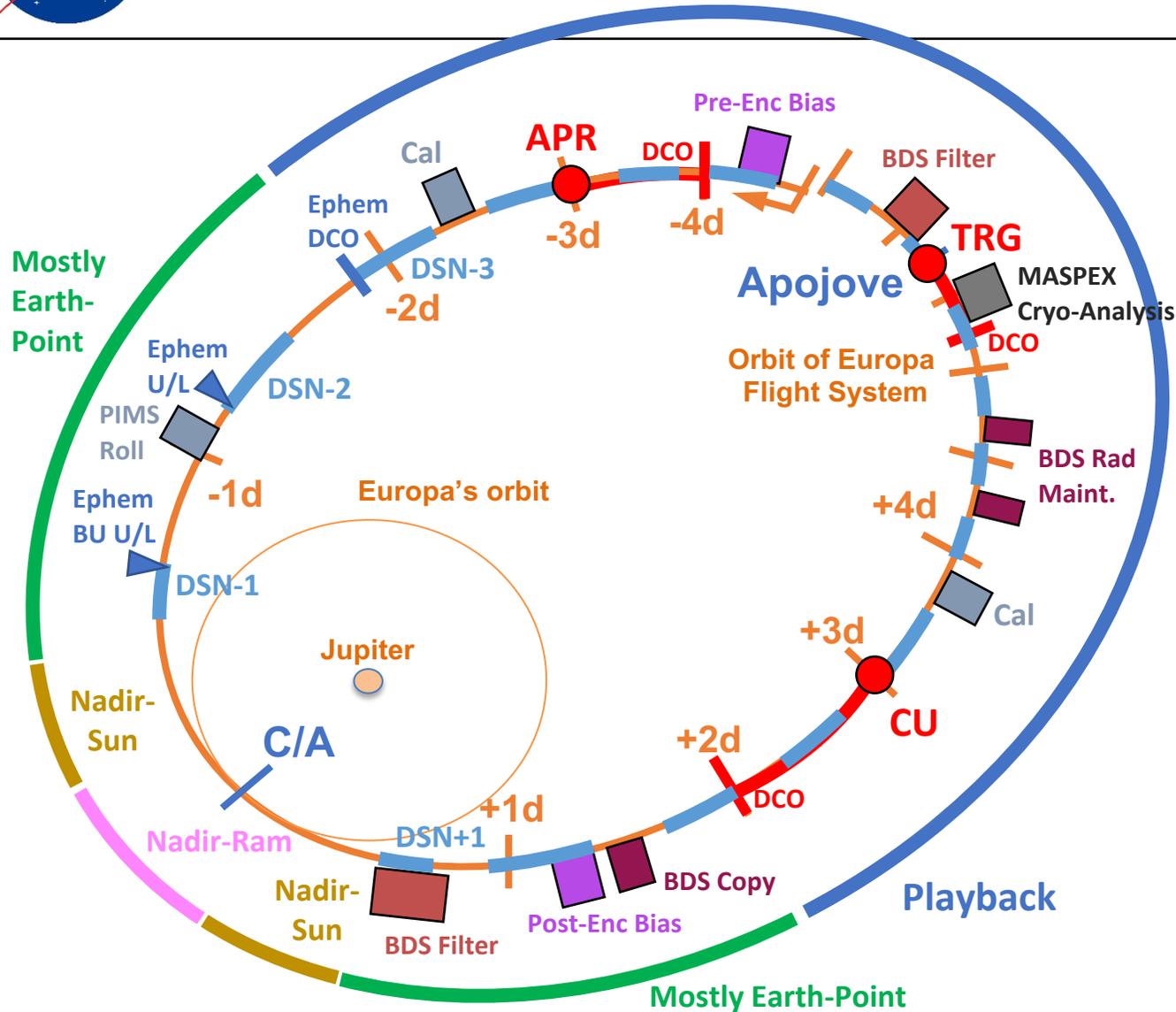
1. Run single/multiple schedulers
2. Run the simulation script – loads in all saved off activities built by previous scheduling runs and models them. ***Produces a TOL file at completion***
3. Run All – this runs all schedulers in order and then runs the simulation script.

```
1. gen_europasim_cfg -n
   plan-name -begin btime -end
   etime
2. europasim plan-name.cfg
3. concurrent_executor
   executors/plan-
   name_apf_build_executor
4. concurrent_executor
   executors/plan-
   name_simulation_executor
```

Setup/Run Commands

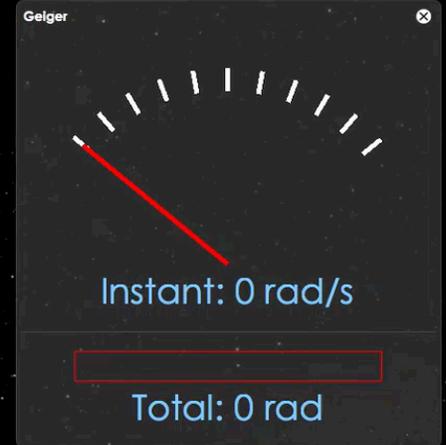


Encounter Overview



Altitude Time from C/A	Description (Attitude / Solar Array Motion)
1M – 165k km (-1.5d to -12h)	Mostly Earthpoint SA Sun Tracking
Re-Orient	3-axis turn
165k – 60k km (-12h to -4.5h)	Mostly Nadir Sun-Optimized SA Sun Tracking
Re-Orient	Twist about S/C +Y only
60k km – C/A – 60K km (-4.5h to TCA to +4.5h)	Nadir-Ram SA Moved Once Per-Side of C/A @~5K
Re-Orient	Twist about S/C +Y only
60k - 165k km (+4.5h to +12h)	Mostly Nadir Sun-Optimized SA Sun Tracking
Re-Orient	3-axis turn
165k - 1M km (+12h to +1.5d)	Mostly Earthpoint SA Sun Tracking

2028-Feb-01 00:39:19 UTC
2,000,000x time



Callisto
Jupiter
Ganymede

Clipper → Jupiter
Distance: 37,976,900 km
Relative speed: 6.11 km/s

