Europa Clipper: An Exploration of its Nascent Guidance Navigation & Control System

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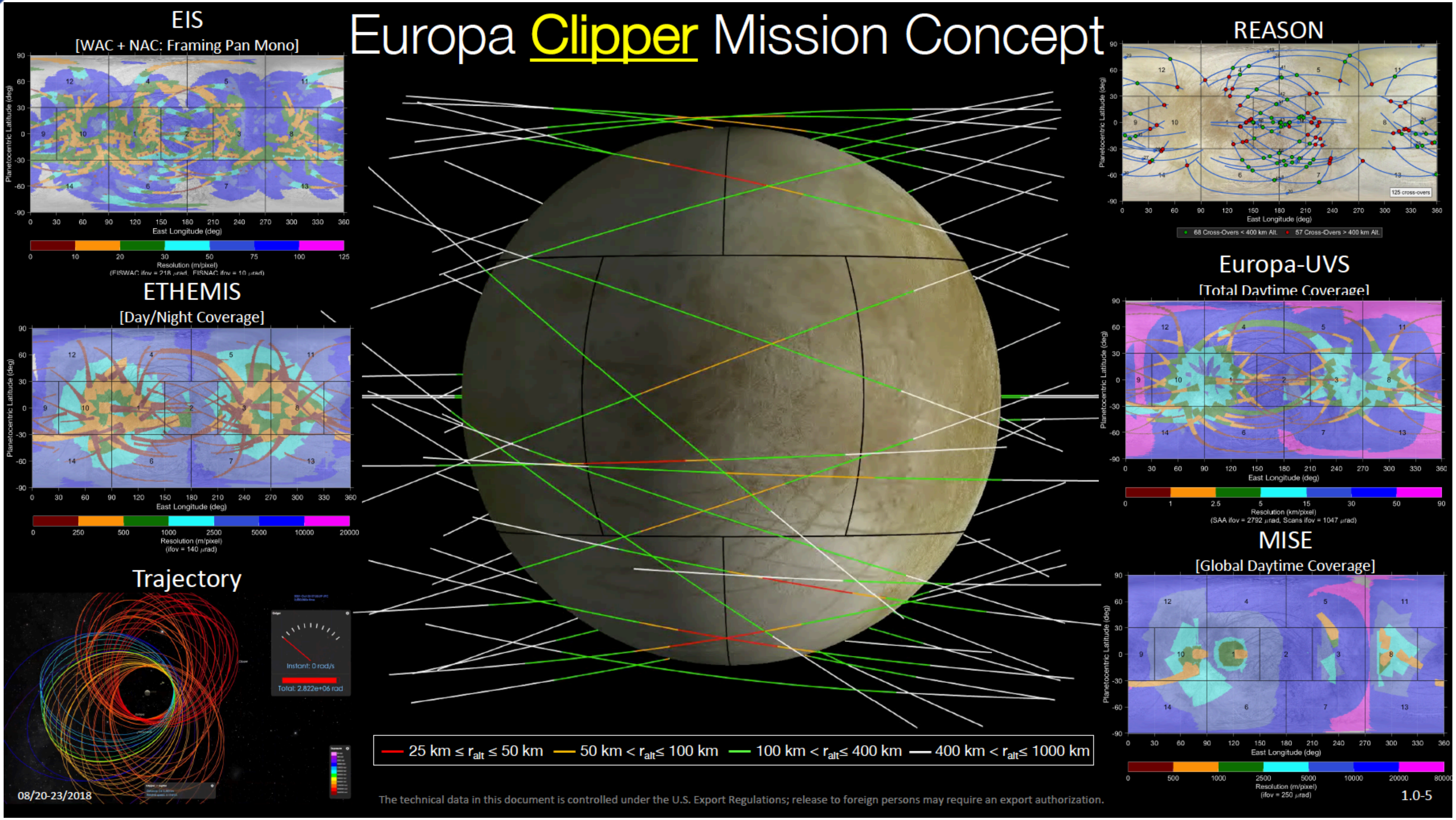
Europa Clipper Mission Concept
EIS
[WAC + NAC: Framing Pan Mono]
Resolution (m/pixel)
ETHEMIS
[Day/Night Coverage]
Resolution (m/pixel)
(ifov = 140 μrad)
Trajectory
08/20-23/2018
REASON
Europa-UVS
[Total Daytime Coverage]
Resolution (km/pixel)
MISE
[Global Daytime Coverage]
Resolution (m/pixel)
(ifov = 250 μrad)
Planetocentric Latitude (deg)
East Longitude (deg)
25 km ≤ r_alt ≤ 50 km
50 km < r_alt ≤ 100 km
100 km < r_alt ≤ 400 km
400 km < r_alt ≤ 1000 km
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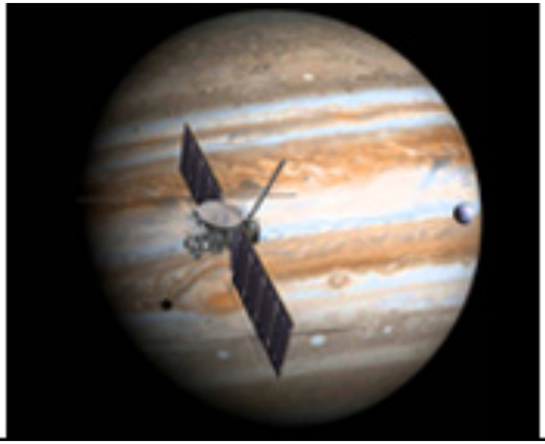
Mission Overview



Earliest Launch

***Period: 6/4/22 – 6/24/22 (SLS)**
***Period: 6/18/22 – 7/8/22 (EELV)**

*** - Dependent on Funding**

Cruise:

2.5 Years (SLS)
7.4 Years (EELV)

Jupiter Orbit Insertion

12/24/24 or 5/1/25 (SLS)
11/26/29 (EELV)

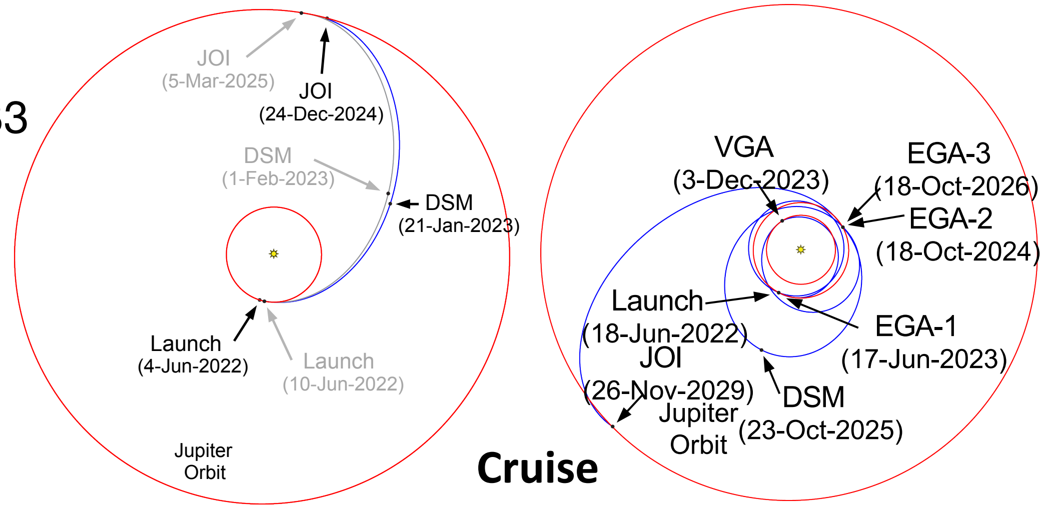
Jovian System Operations

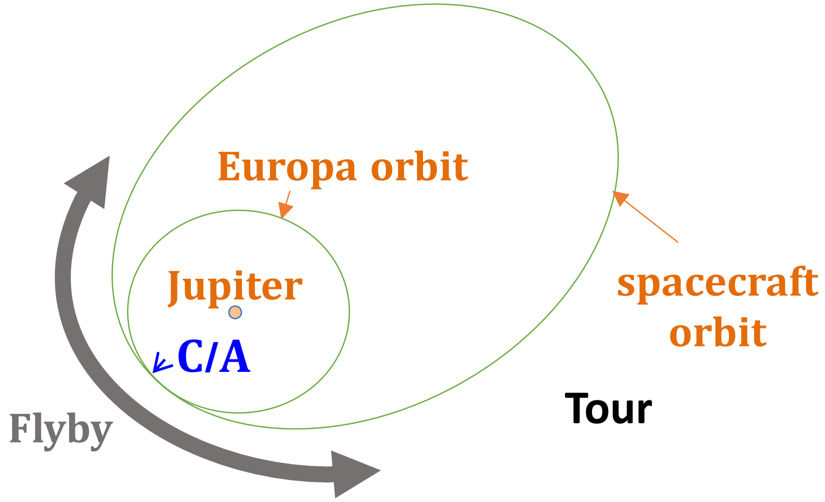
Transition to Europa Science: 12 months
Prime Europa Flyby Campaign: 36 months

- **Project Category 1**
  - LCC > $1B
- **Mission Risk Class A (Tailored)**
- **NPR 7120.5E Compliant**
- S/C design compatible with both SLS and EELV

The Europa Clipper Mission

- Mission
  - Prime: SLS Launch Jun/22, JOI Dec/24, EOM Sep/28
  - Secondary: Non-SLS Launch Jun/22, JOI Nov/2029, EOM Jun/33
  - Elliptical orbit about Jupiter with 46 flybys of Europa
- Phases
  - Launch
  - Interplanetary Cruise
    - Inner Cruise
    - Outer Cruise
  - Arrival
    - Jupiter Approach
    - Jupiter Orbit Capture
  - Tour
    - Transition to Europa Campaign 1
    - Europa Campaign 1
    - Transition to Europa Campaign 2
    - Europa Campaign 2
  - Disposal





Launch Vehicle Options

SLS Block 1	SLS Block 1B	Delta IV Heavy	Falcon Heavy	Atlas V 551
Direct	Direct	(E)VEEGA	(E)VEEGA	Not Compatible

SLS (Block 1 & 1B)

- Highest launch energy capability (by far)
- Enables significantly increased speed-of-access to outer planets (direct trajectory to Jupiter – **2.7 year time of flight)**
- Vehicle in development,
- Performance drives flight system mass limit
- **Block 1 compatible for Direct trajectory**
- **Block 1B Compatible for Direct trajectory**

Delta IV Heavy

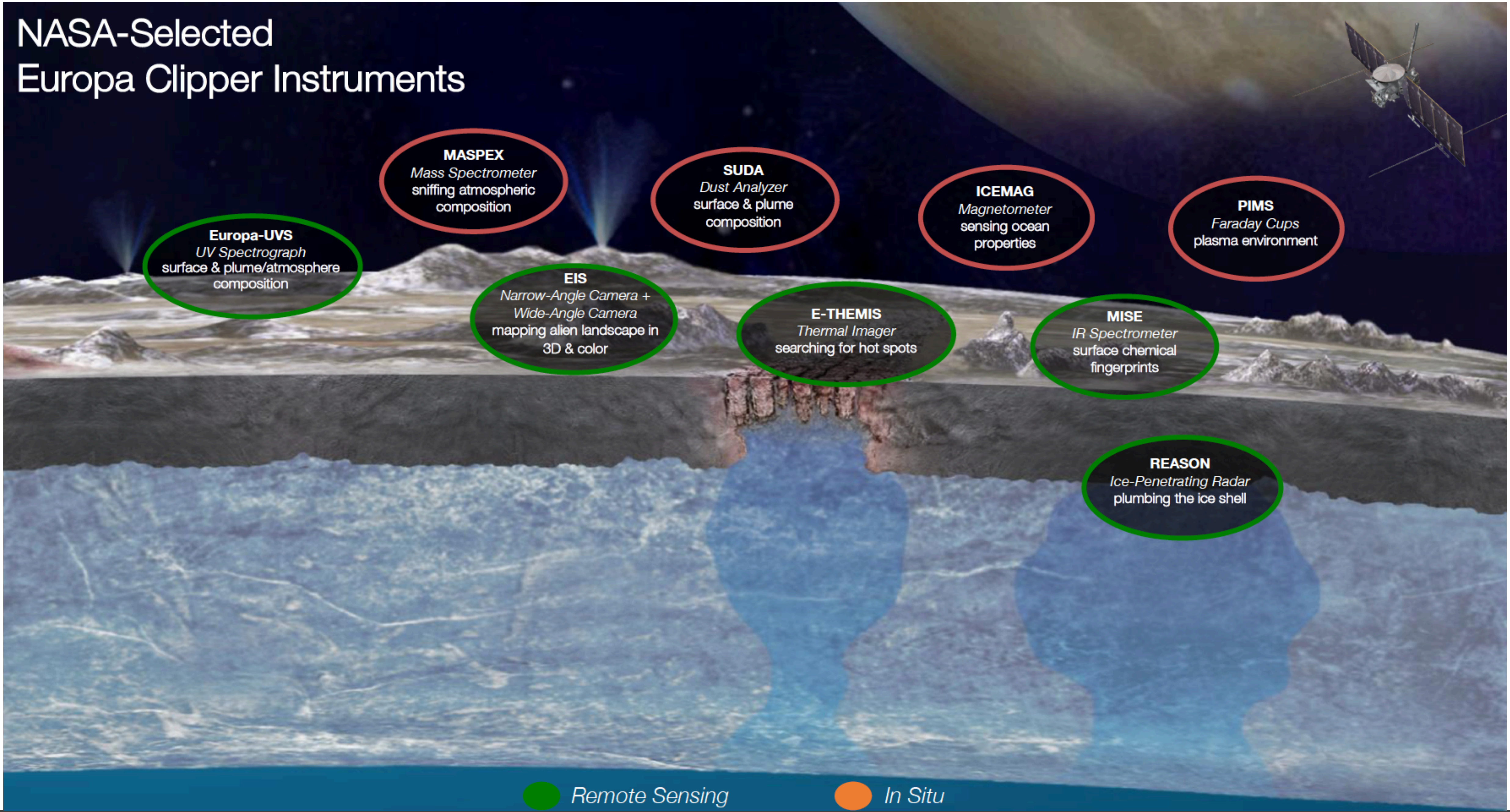
- Proven, high performance launch vehicle (7 of 8 successful launches)
- Supports (E)VEEGA with significantly margin
- **Compatible for (E)VEEGA trajectory**
- **Availability concerns after 2020**

Falcon Heavy

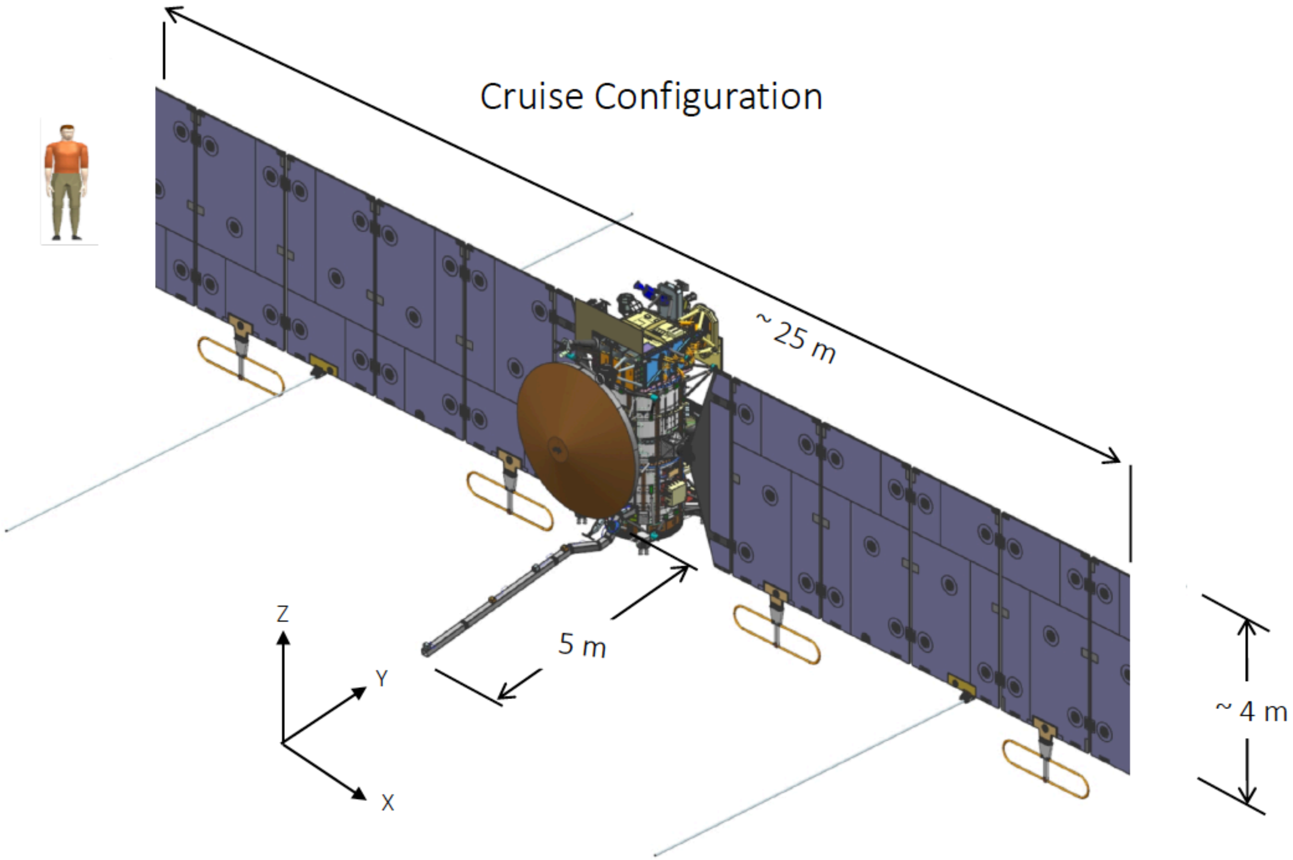
– Supports (E)VEEGA with significantly margin
– Limited launch environments data
– **Horizontal processing will require a waiver**

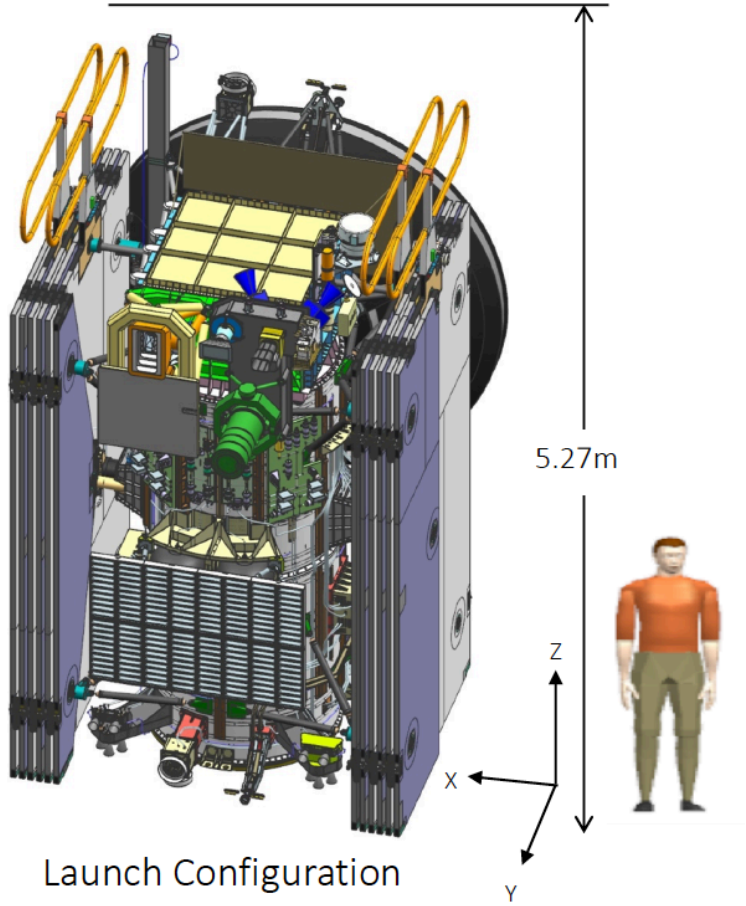
Atlas V 551

- **Not compatible with current or alternate mission plan**


NASA-Selected
Europa Clipper Instruments
MASPEX
Mass Spectrometer
sniffing atmospheric composition
SUDA
Dust Analyzer
surface & plume composition
ICEMAG
Magnetometer
sensing ocean properties
PIMS
Faraday Cups
plasma environment
Europa-UVS
UV Spectrograph
surface & plume/atmosphere composition
EIS
Narrow-Angle Camera + Wide-Angle Camera
mapping alien landscape in 3D & color
E-THEMIS
Thermal Imager
searching for hot spots
MISE
IR Spectrometer
surface chemical fingerprints
REASON
Ice-Penetrating Radar
plumbing the ice shell
Remote Sensing
In Situ

Flight System Configurations





Flight System = Spacecraft + Payload

Launch Configuration

Driving Environments

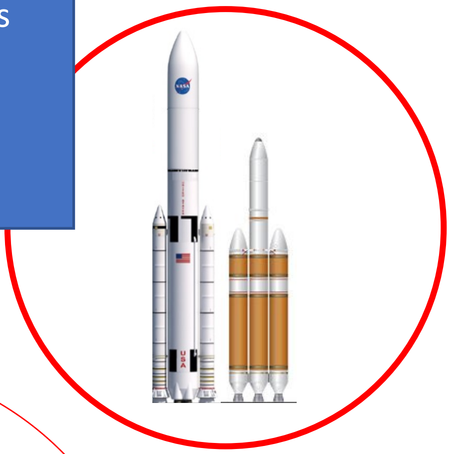
<u>Multiple Launch Vehicles</u>

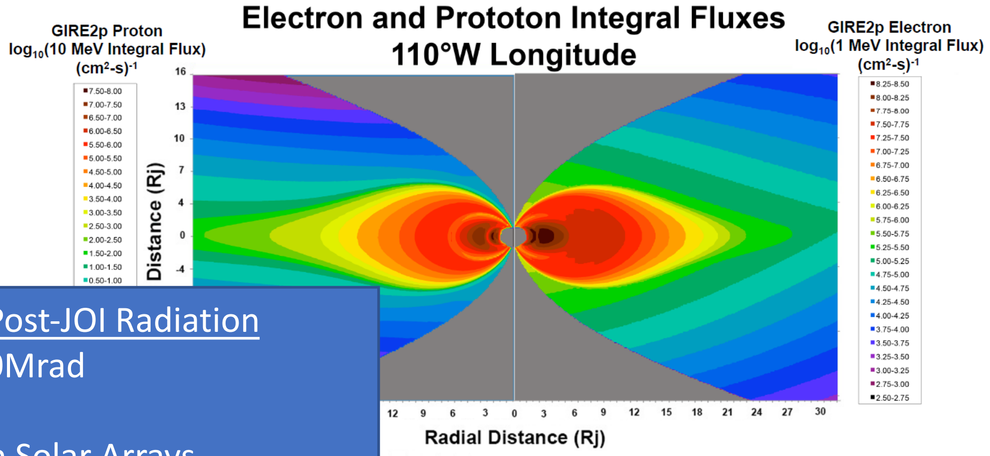
-Enveloping worst case (plus margin) for all potential LVs

-Dynamic

-Acoustic

-Shock



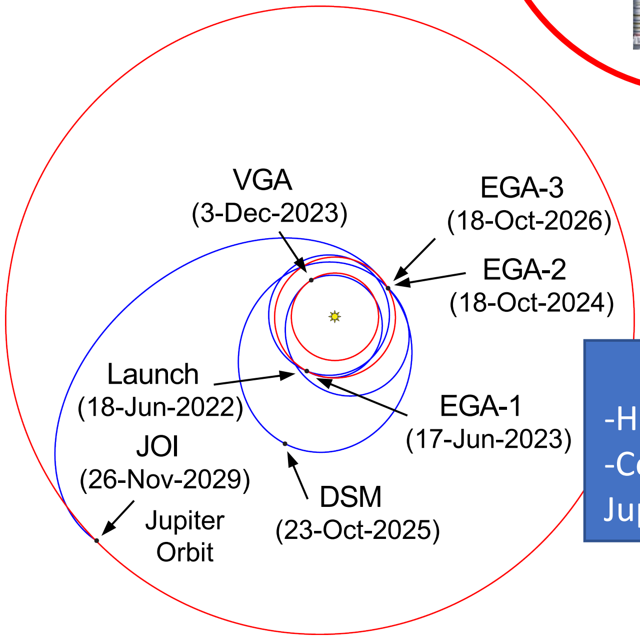


<u>Post-JOI Radiation</u>

-TID 3.0Mrad

-iESD

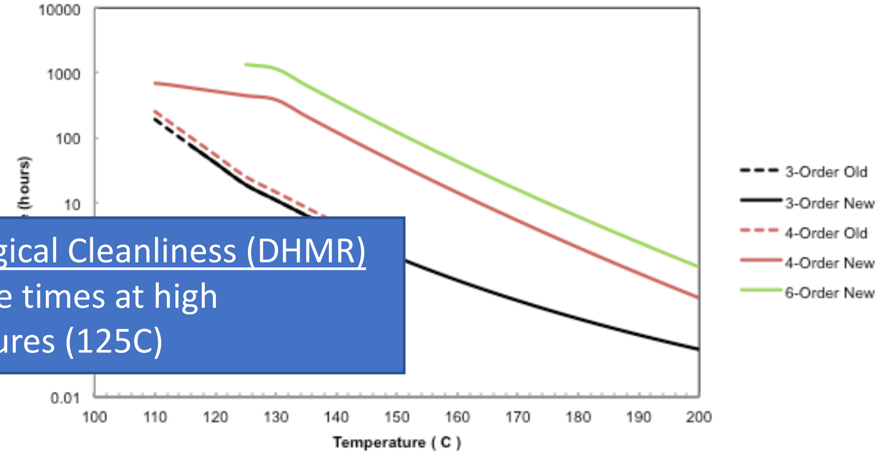
-Flux on Solar Arrays



<u>Thermal Extreme Environments</u>

-Hot extreme: .65AU during VGA

-Cold extreme: 9.2hr eclipse at Jupiter



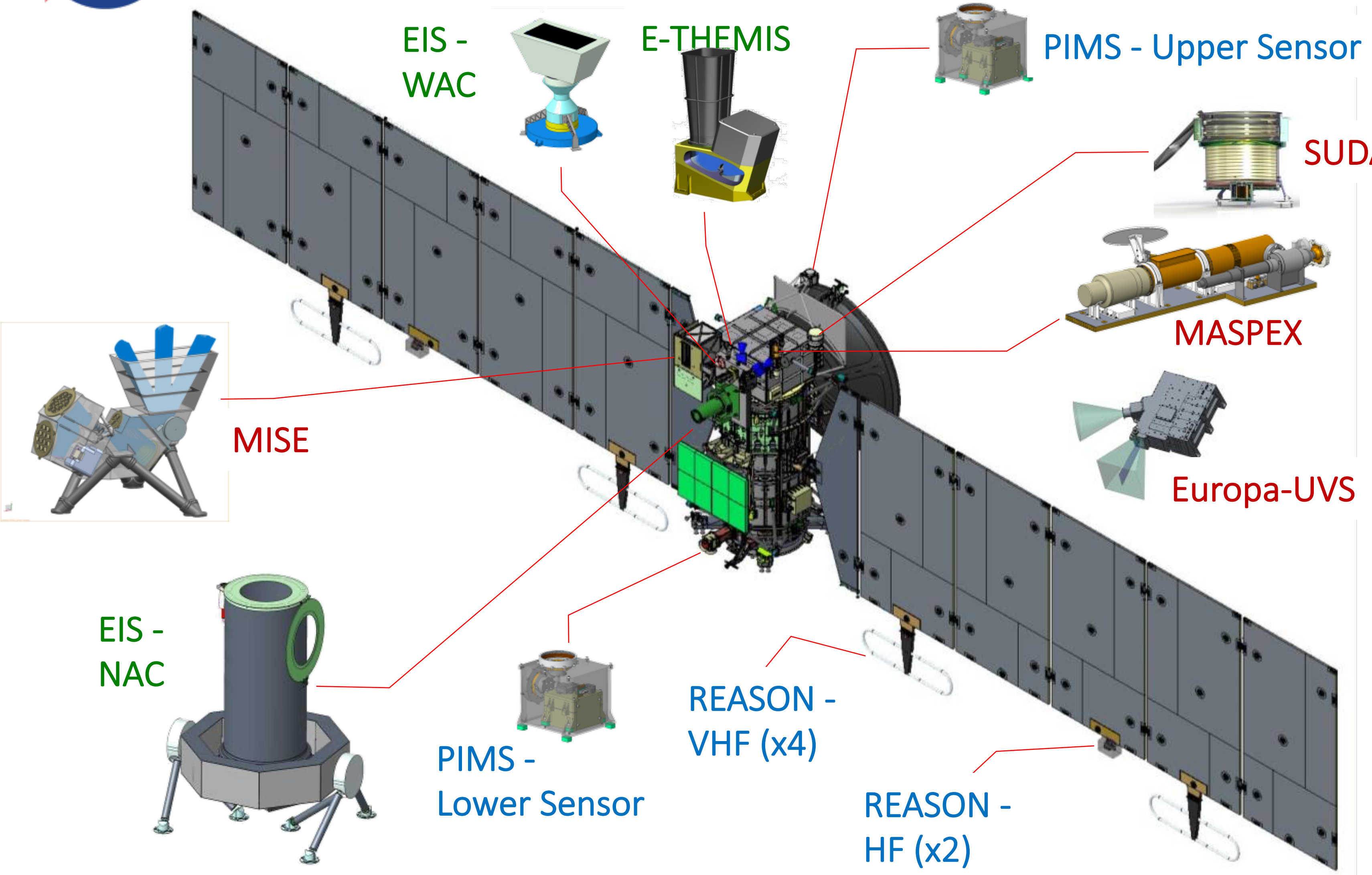
<u>PP Biological Cleanliness (DHMR)</u>

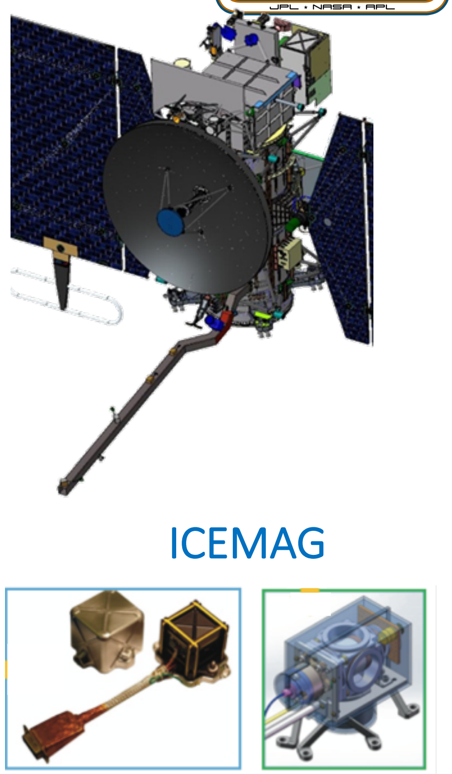
-Long bake times at high temperatures (125C)

The Europa Clipper Flight System Overview

- Payload:
  - 10 Instruments, including detectors for ultraviolet, visible, infrared, radio (HF, VHF)
- Power:
  - Solar arrays @ 650 W and batteries @ 339 Ah, end of mission
- Propulsion:
  - Bipropellant MMH/NTO/MON-3, with 1669 m/s capacity based on 2750 kg propellant mass
  - 24 x 25-N class engines (DST-13X)
- Avionics:
  - Computer: Rad750 CPU w/ 1 GB SDRAM, 1553, 422, SpaceWire
  - Remote Engineering Unit (REU): FPGA-based, provides I/O for reaction wheels, sun sensors, …
- Telecom:
  - X-band uplink & downlink, Ka-band downlink, both on 3-m HGA
  - MGA, 2x LGA, and 3x fan beam
- Thermal:
  - Active thermal fluid loop, heaters, MLI, radiator and louvers

The Europa Clipper Flight System (cont'd)
Spacecraft and Payload

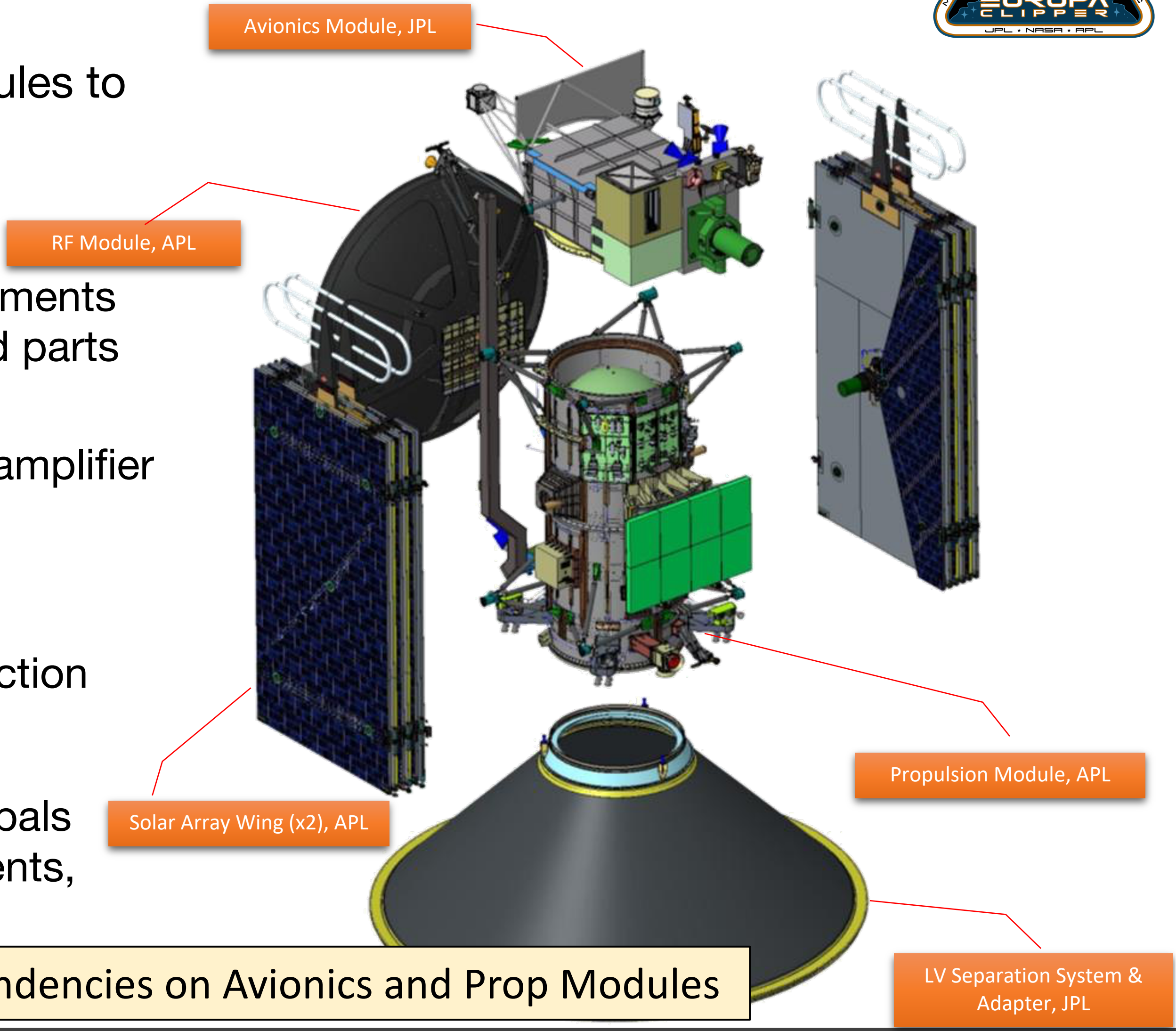




source: FP Peer Review

The Europa Flight System (cont'd) Spacecraft Modules

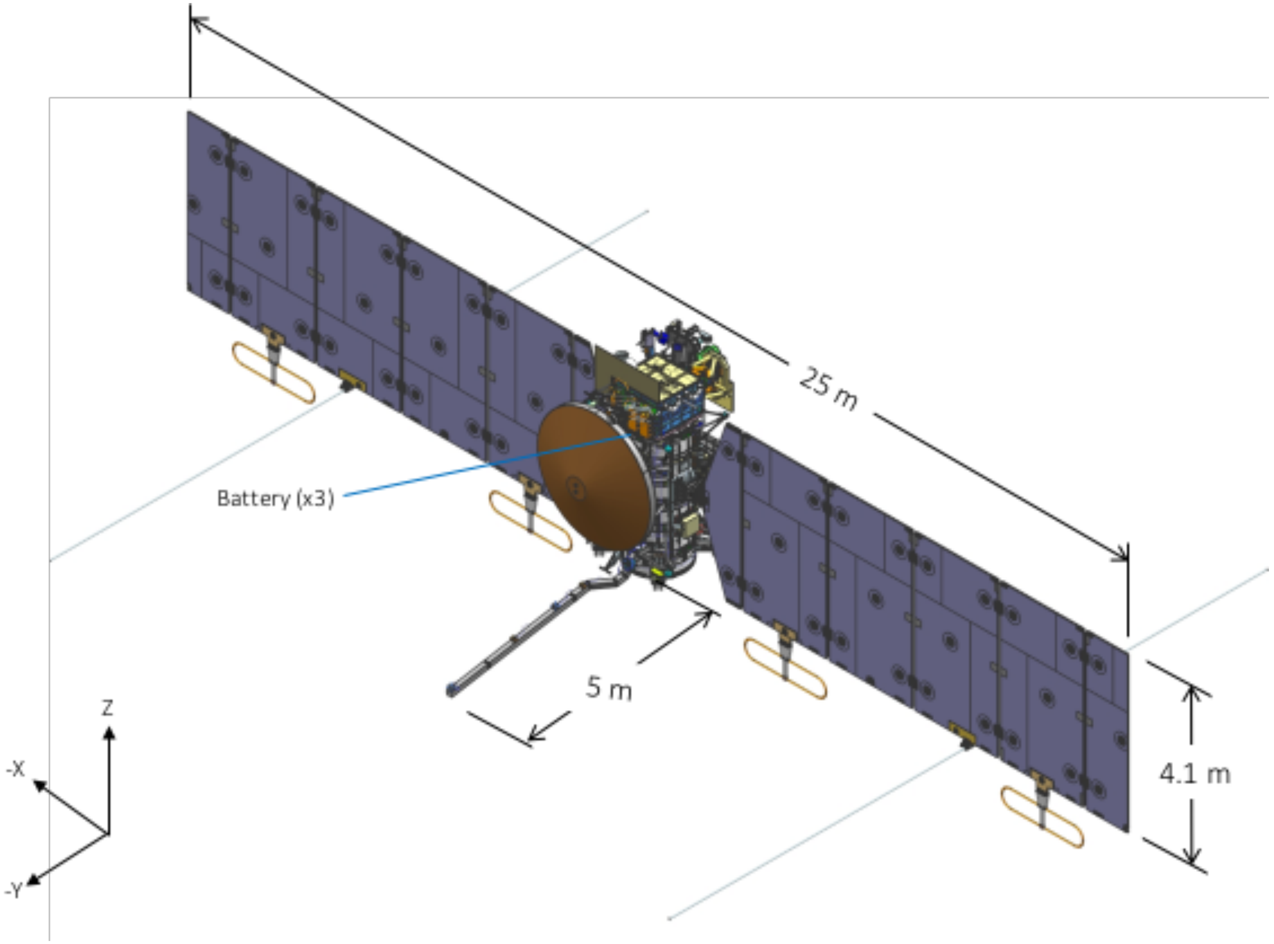
- Solar powered spacecraft broken into three distinct modules to define work packages between APL & JPL
- Avionics Module – JPL
  - Houses majority of S/C subsystem components
  - Includes the instrument nadir deck and majority of instruments
  - Not a distinct deliverable, an assembly of many delivered parts
- RF Module – APL
  - Consists of all telecommunication antennas, radios and amplifier assemblies
- Propulsion Module – APL/GSFC/MSFC
  - Accommodates entirety of Propulsion Subsystem
  - Contains dedicated power switching and telemetry collection capability
  - Serves as spacecraft primary structure and LV interface
  - Includes solar array wings, deployment devices and gimbals
  - Provides additional physical accommodation to instruments, subsystem components and assemblies



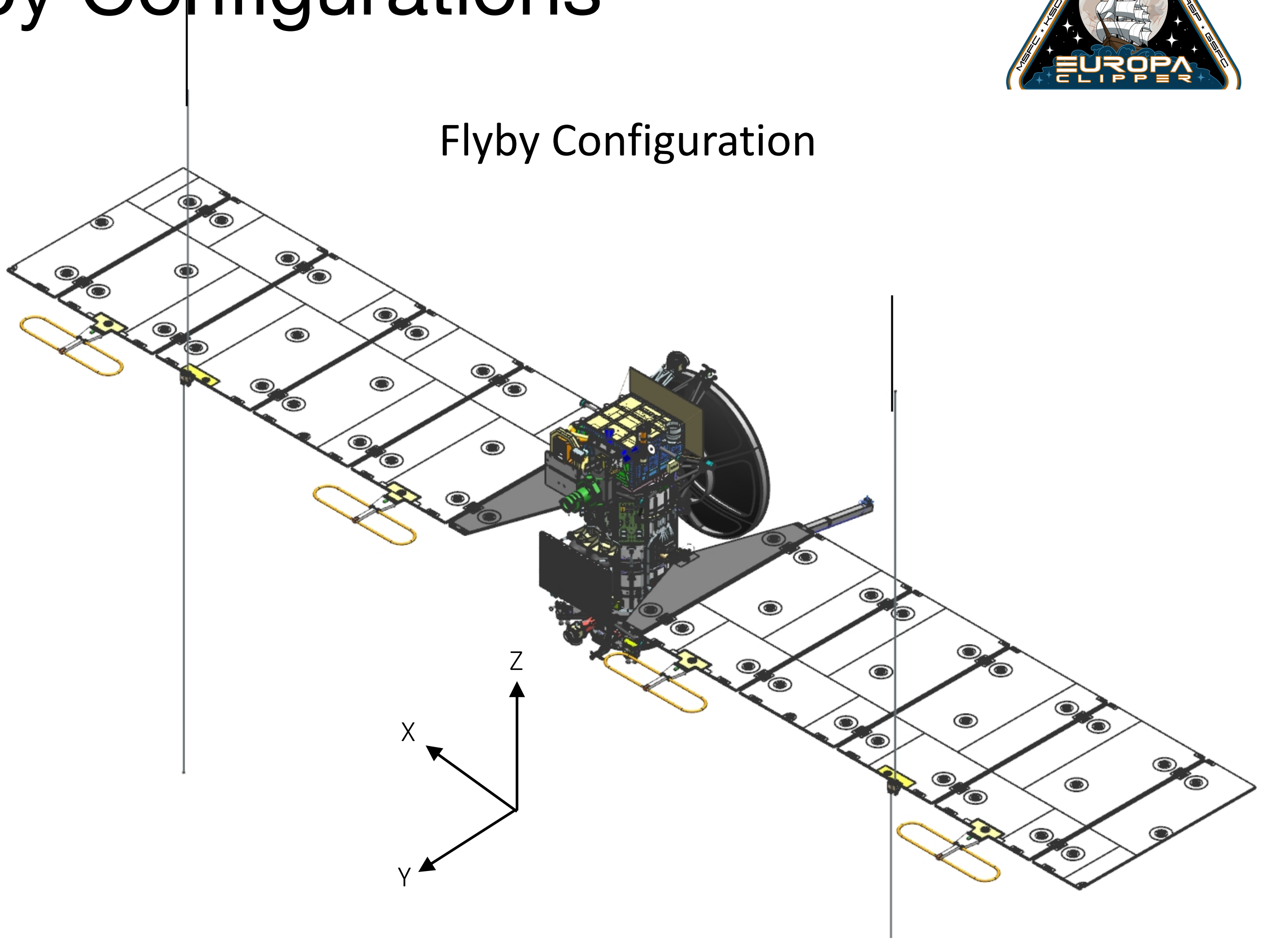
GN&C Subsystem spans most of the flight system w/ strong dependencies on Avionics and Prop Modules

The Europa Clipper Flight System (cont'd) Power and Flyby Configurations

Power Configuration



Flyby Configuration



A7 MOI (kg.m2), flyby, 5panel:
CBE: 7124, 38363, 35194
MEV: 8782, 46586, 42696

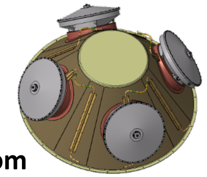
pic source:
J. St. Vaughn

GN&C Baseline Configuration

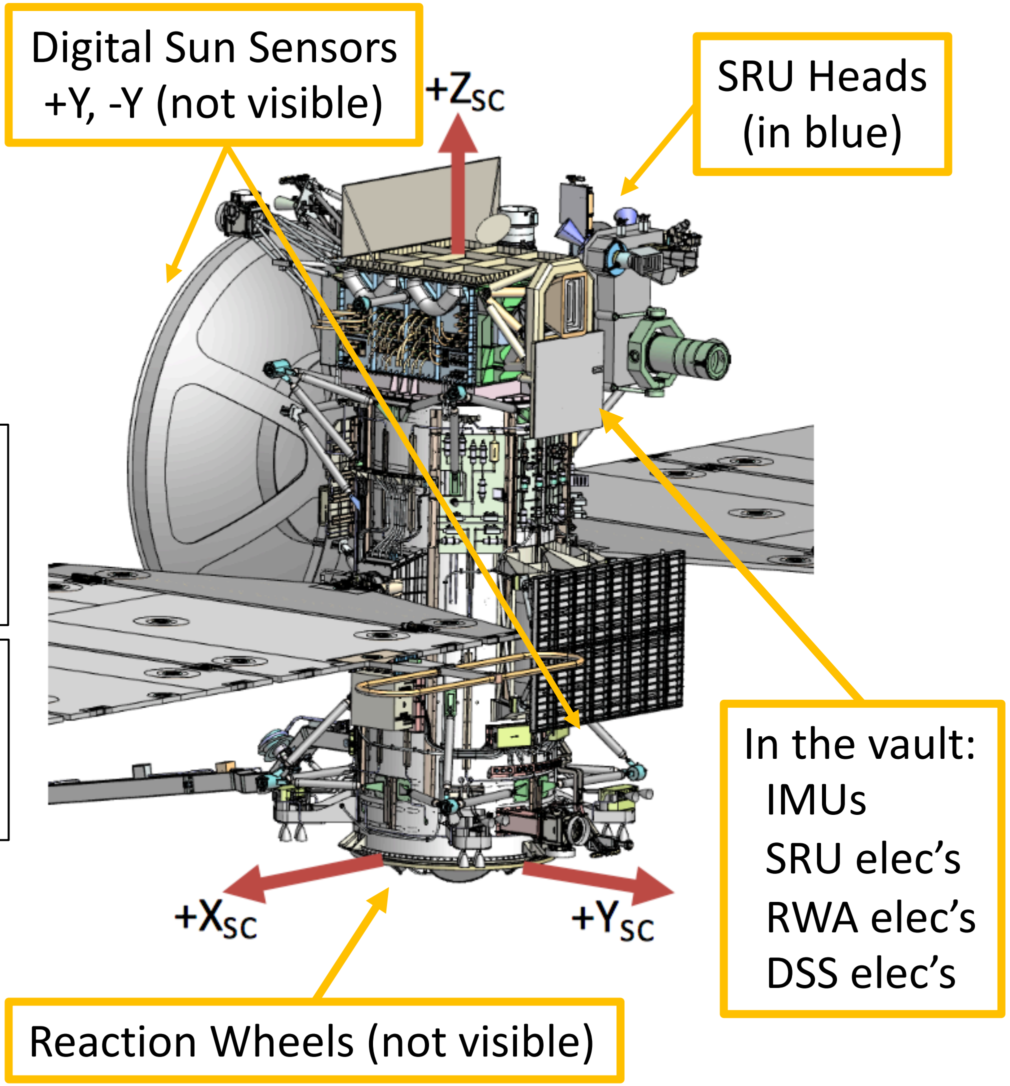
- Configuration, GN&C
  - 4 reaction wheels (RWAs), 3 operating
  - 2 SRU heads, 2 SRU elec's, 1 pair operating
  - 2 IMUs, 1 operating nominally, 2 during JOI
  - 4 digital sun sensor (DSS) 2-axis heads + elec box, 2 operating
  - 24 engines, 12 operating, all bi-prop
  - Control:
    - RCS and RWA based attitude control
    - Delta-V (along Z axis)
    - Up to 32 Hz sample rate
- Configuration ECRs in work:
  - SSIRU: add heater and 4th gyro for science
  - SSIRU: I/O to 422+1553, from 422 only
  - SRU I/O to 1553, from 422
  - RWA: I/O 422 vs analog (open)
  - RWA: to larger inertia rotor

Articulated bodies
2x solar array w/ stepper motor
2 axis gimbals on NAC
1 axis scan mirror on MISE

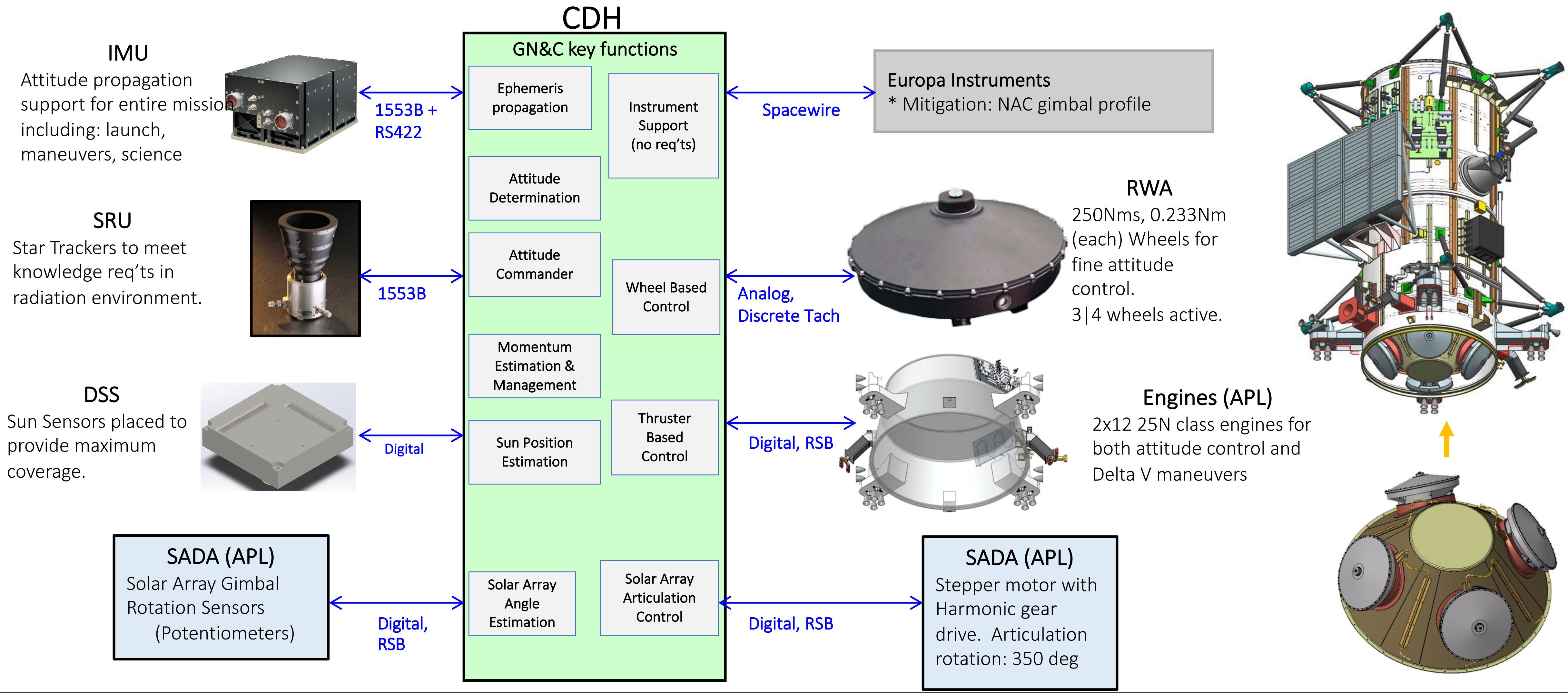
S/C Disturbance sources
cryocoolers, NAC gimbals, thermal pump, solar array drive
reaction wheels



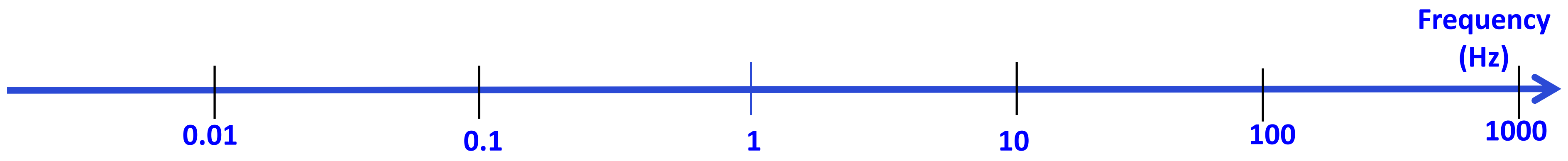
wheels viewed from S/C bottom



GN&C Top Level System Diagram



GN&C Viewed in the Frequency Domain

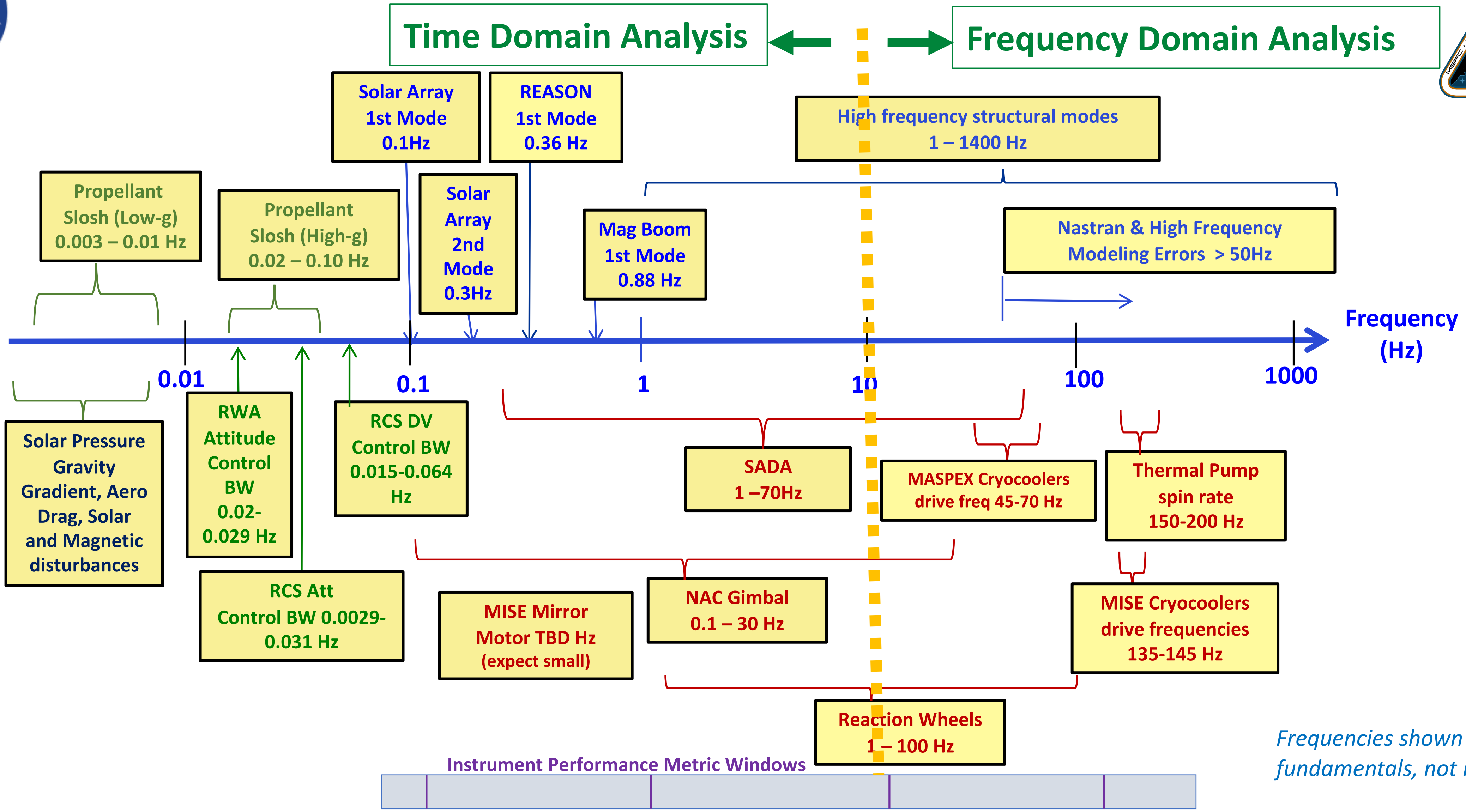


Range	Major Participants
DC to 0.01 Hz	solar pressure, magnetic fields, atmospheric drag, propellant slosh
0.01 to 0.1 Hz	crossover frequencies for RWA, RCS, delta-V control
0.1 to 1 Hz	HF antenna, solar array, mag boom
1 to 10 Hz	solar array drive dynamics, reaction wheel harmonics
10 to 100 Hz	core structure modes, reaction wheel harmonics
100 to 1000 Hz	cryocooler disturbances, thermal pump disturbances

Where possible, assessment is performed to A7 mass properties. Detailed Dynamics has been performed with A6 FEM.

Details of dynamics and control to be presented in more detail on Days 2 and 3.

Disturbances Affecting GN&C and Instrument Pointing



Frequencies shown are fundamentals, not harmonics

GN&C Top Level Functions

- Top Level Functions
  - Attitude and attitude rate estimation
  - RWA based attitude and attitude rate control
  - RCS based attitude and attitude rate control
  - Wheel speed control (for momentum management)
  - Delta-V control
  - Solar array control (open loop)
  - Target based pointing w/ on-board ephemeris service
  - Error monitors, as negotiated with System Fault Management

GNC Design Drivers:

1. Science Pointing,
2. Control Structure Interactions
3. RCS/DV design
4. Attitude estimation

- In general, GN&C operates with prime-only sensors and actuators. Some exceptions:
  - GN&C will have a hot IMU backup during JOI.
  - GN&C is required to operate with three or four reaction wheels.
  - GN&C is required to operate with measurements from one or two SRU heads.
  - GN&C is required to operate with measurements from two, three or four dual-axis sun sensor heads.

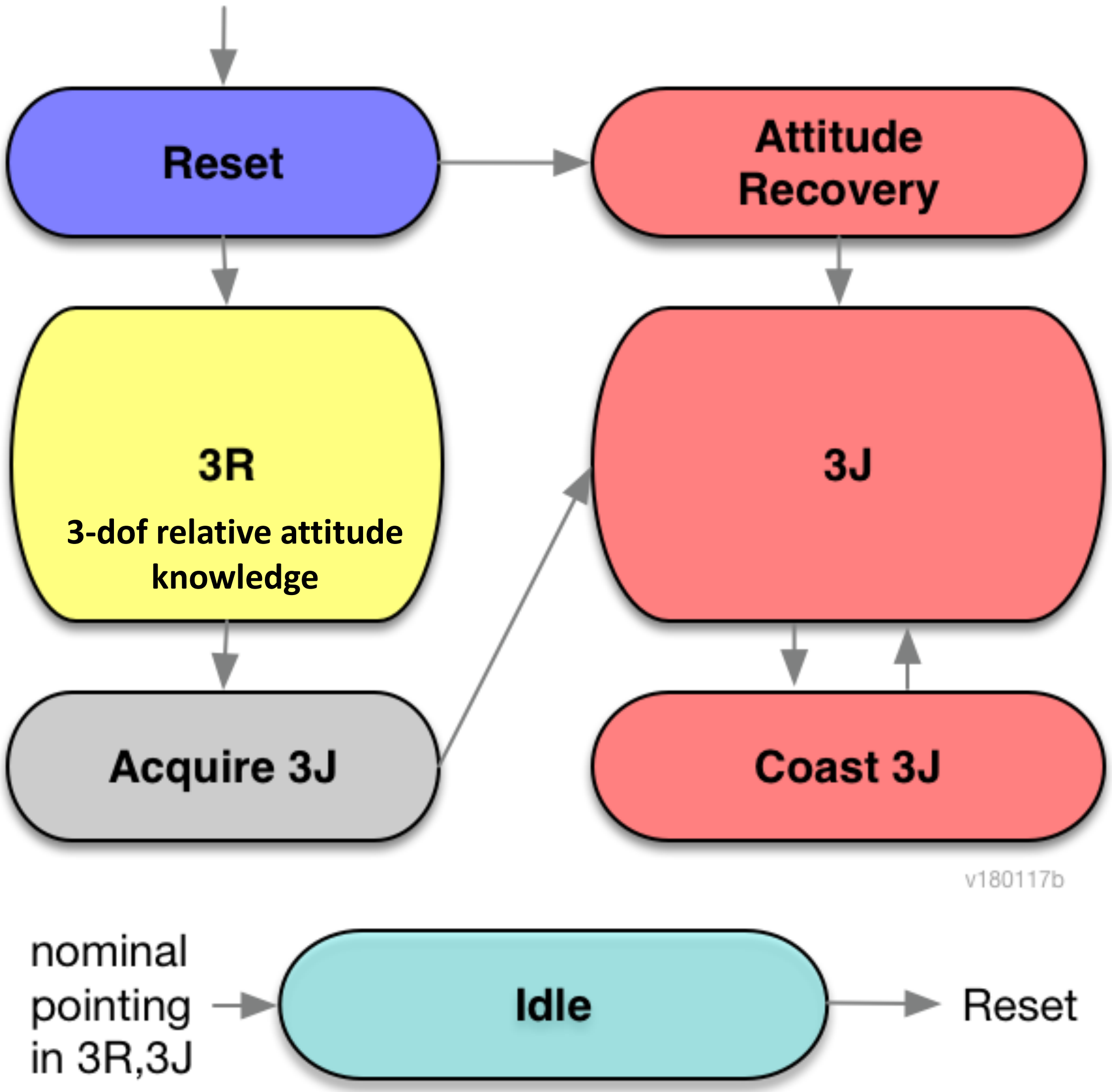
GN&C Subsystem Mode Diagram

Upon power-up or GN&C RESET, software goes to Reset.

3R is for recovery from complete loss of attitude knowledge.

Acquire 3J provides context for J2000 acquisition with the SRU.

In Idle, GN&C is open loop for operation in deployments.



Att. Rec. deals with "safe operational" scenarios (e.g., Flyby Recovery).

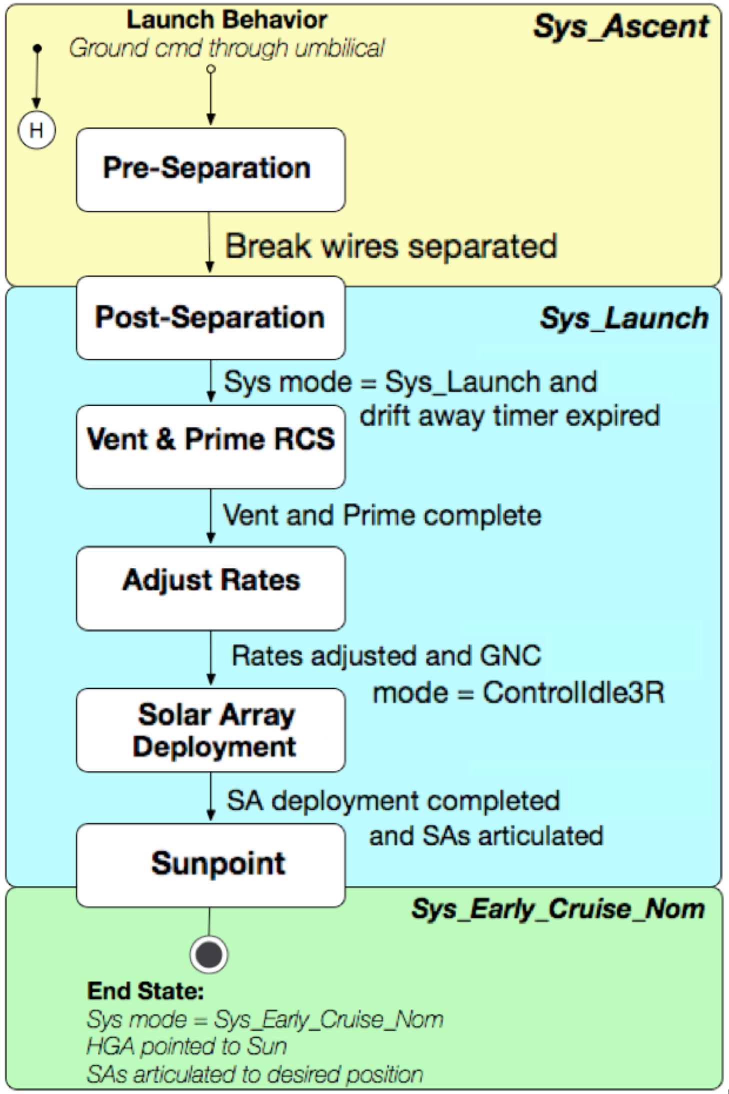
3J is for normal operations (pointing, delta-V, desats) with 3 DOF knowledge in J2000.

For dealing with short term loss of control.
A timeout results in RESET.

Details will be presented in Section D2-G tomorrow.

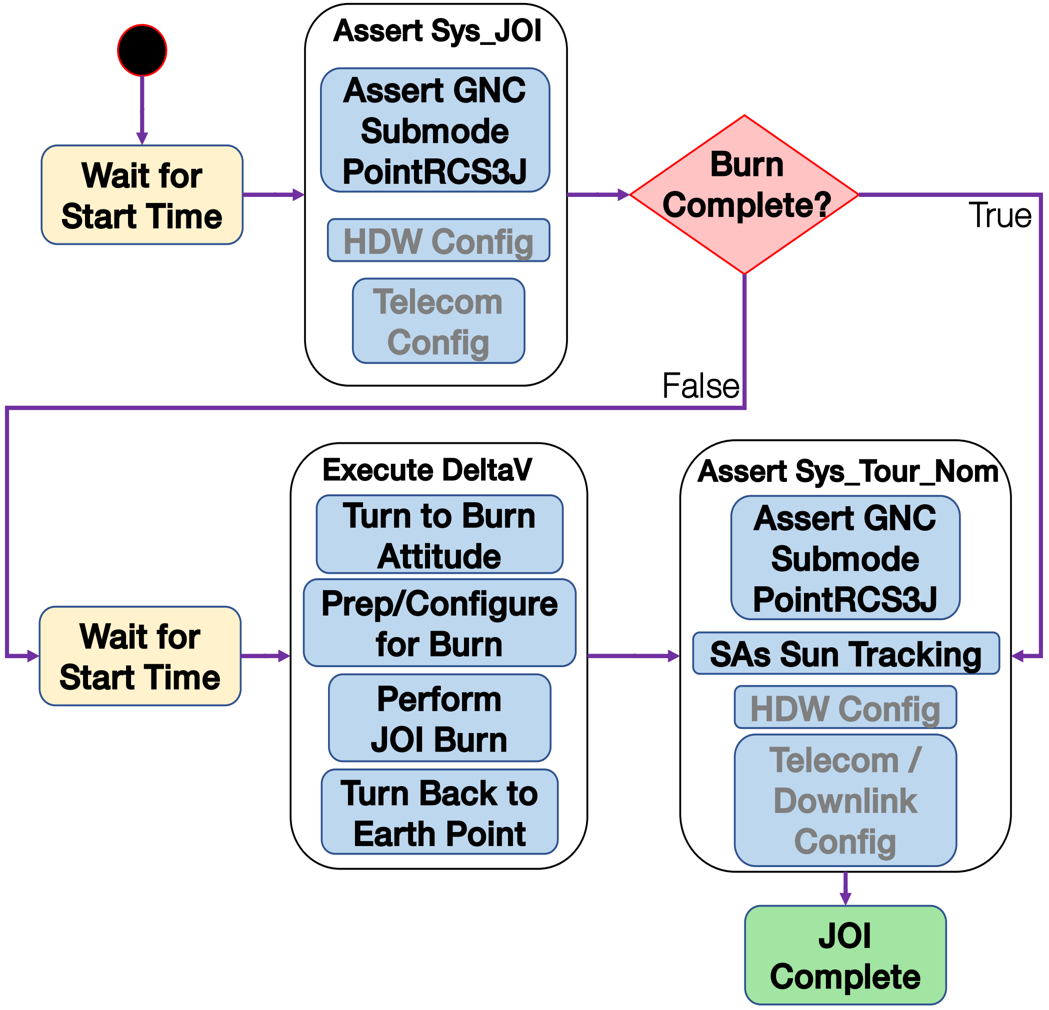
Launch Scenario

- Launch is one of the two mission Critical Events (JOI is the other)
- GN&C Responsibilities:
  - RCS Detumble to below 0.25 deg/s per-axis
    - Including from LV separation rate
  - GN&C Control Idle during SA Deploy (i.e. no RCS firing)
    - SA deployment nominally 11.5 minutes and required to be no more than 30 minutes (these are Mech requirements)
  - Point Arrays at Sun
    - Sun Search, Sun Point, clocking roll around –Y or inertially fixed
  - Maintain clocking rate, if required
- GN&C Hardware In-Use:
  - IMU – Detumble and 3R attitude/rate estimation
    - IMU powered off during ascent
  - Sun Sensor – If 3R attitude estimation used
  - SADA
- Notes:
  - Option: SA deploy may begin while SC has Z-axis rate imparted by LV (BBQ/rotisserie roll for thermal reasons)
  - No GN&C requirement for partial deployment (e.g. one wing out). Potentially pending.



Jupiter Orbit Insertion Scenario

- 300 km altitude G0 (Ganymede) flyby on 12/23/2024
  - ~14 hours before JOI start
  - No science activities
  - GN&C on RCS control holding a fixed Earth-pointed attitude
  - RWAs spun-down & powered off for entire scenario
- JOI Burn: 12/24/2024
  - ΔV: 860 m/s CBE (950 m/s MEV), Burn Duration MEV: 5.5-6 hours
  - SC-Jupiter Distance: 12 R_J at start of burn
    - Perijoves later in Tour go as low as 9.5 R_J
- JOI is a Critical Event
  - GN&C required to resume JOI if interruption occurs
  - Hot backup (thermally stable) IMU and possible SRU (If available)
- "Execute Delta-V" Behavior will restart if interrupted
  - If fault occurs:
    - Stop Burn, Resolve fault (swap HDW, reset, etc), Restart burn
  - JOI timeline has enough margin to accommodate interruption (up to 45 minutes) due to faults/safings/etc
  - ΔV accomplished (or ΔV to go) and estimated mass properties held in recovery data in case of CD&H reset
  - Behavior will repeat steps to prepare system for burn (e.g. latch valves state, array position, SC attitude, accel bias calibration)

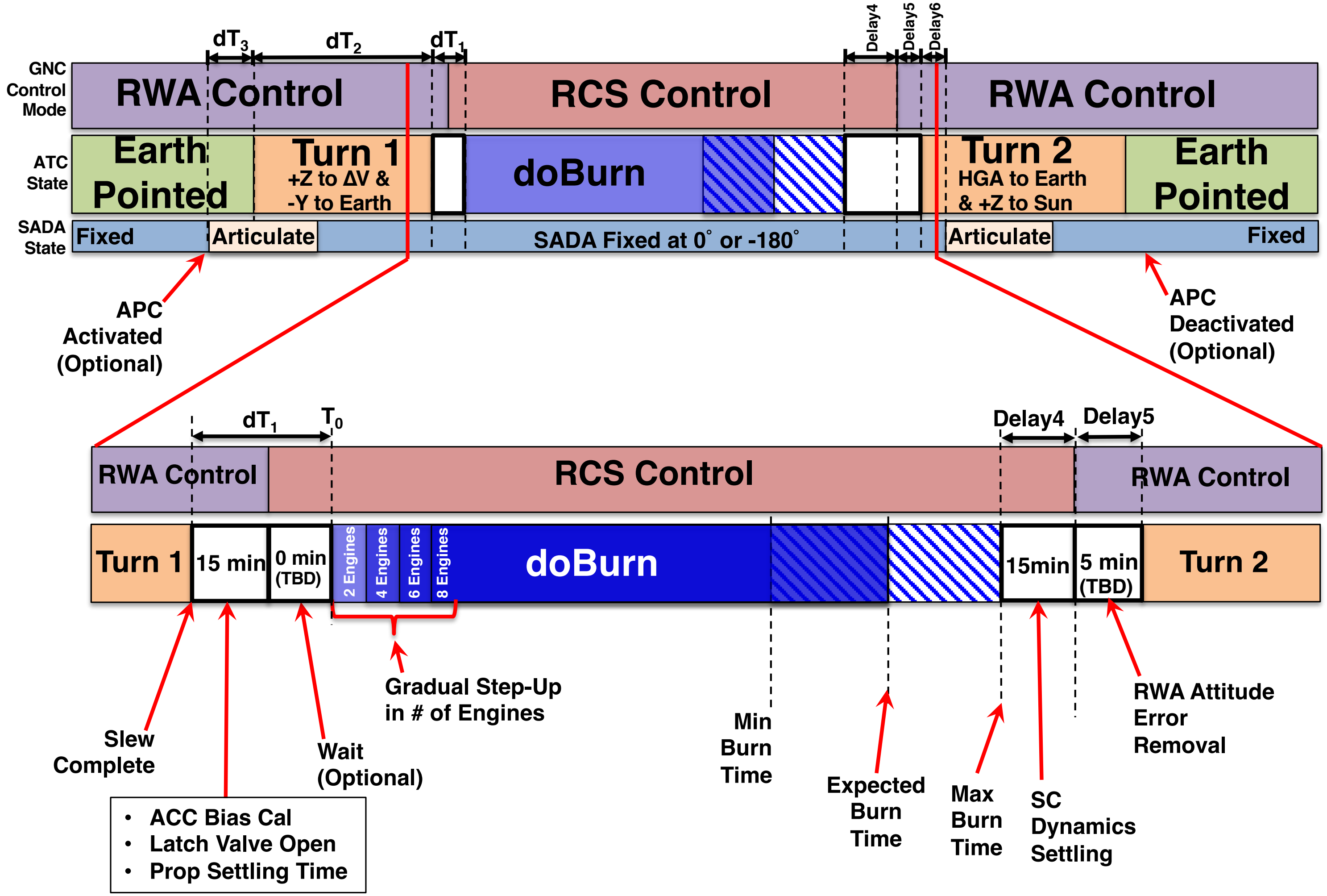


Maneuver (ΔV) Scenario

- Maneuver issued as single command
  - Maneuver activity event timing determined onboard
  - Autonomy needed for interrupted JOI and autonomous maneuver resumption
- Maneuver Command Arguments:
  - Burn ΔV Vector (direction and magnitude)
  - Burn Attitude (Primary & Secondary Pointing)
  - Burn Start Time (T_0)
  - Min & Max Burn Times
  - Final Target Attitude (primary & secondary)
  - Array Position for Burn (either 0° or -180°)
  - Delays: [dT1, dT2, dT3, Delay4, Delay5, Delay6]
  - Return to RWA: [Yes/No]
  - Enable APC: [Yes/No]
- Other Potential Arguments
  - Max # of RCS engines to use
  - RCS thrust parameters (force, rise, fall)
  - Timer Cutoff (instead of acc)? [Yes/No]
  - Turn rate/acceleration
  - SADA articulation rate/acceleration
  - SADA Park angle

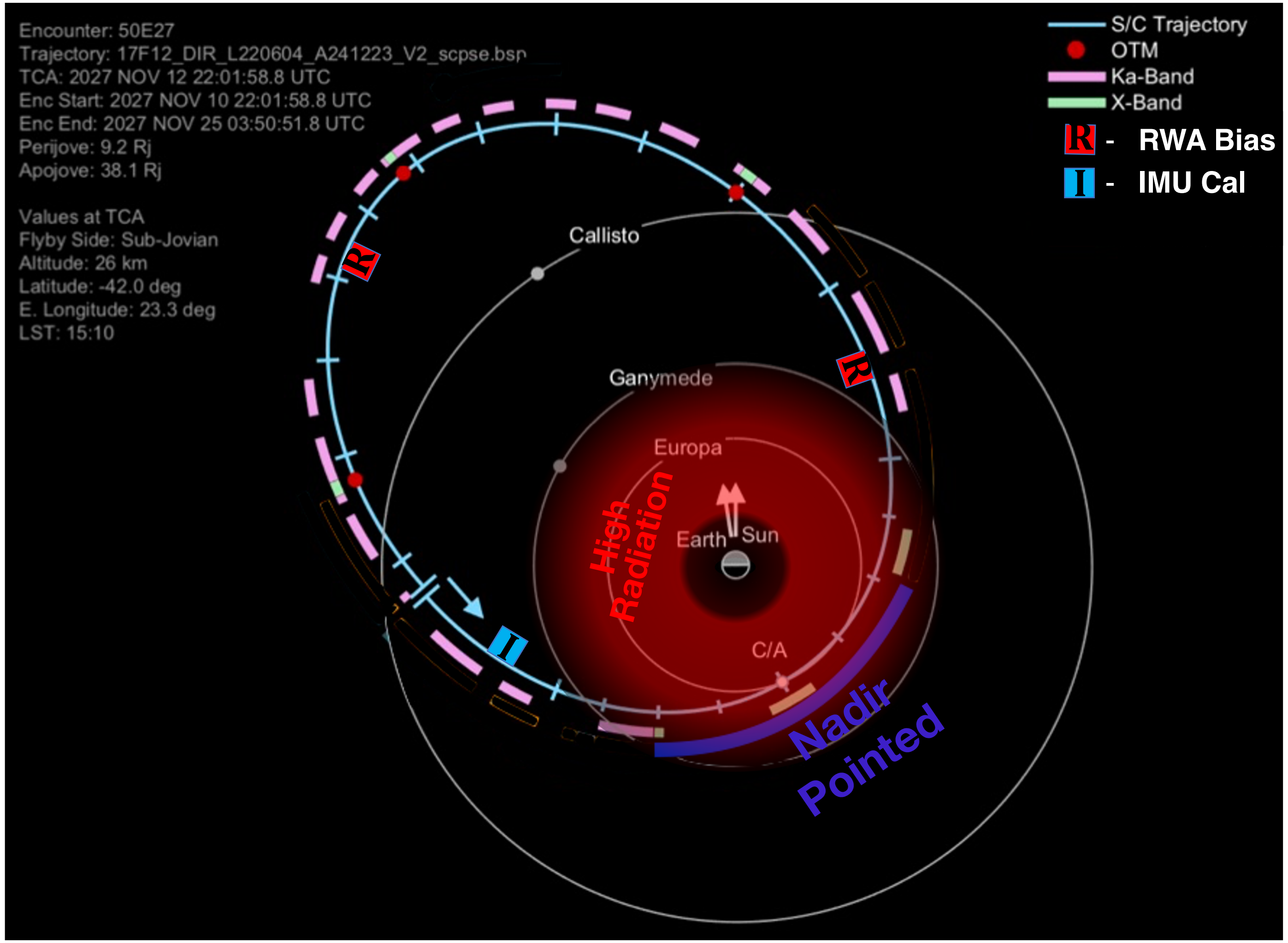
Europa Clipper Maneuver Timeline

Case: Initial Control Mode is RWA, 1 turn to burn attitude and 1 turn back to downlink attitude



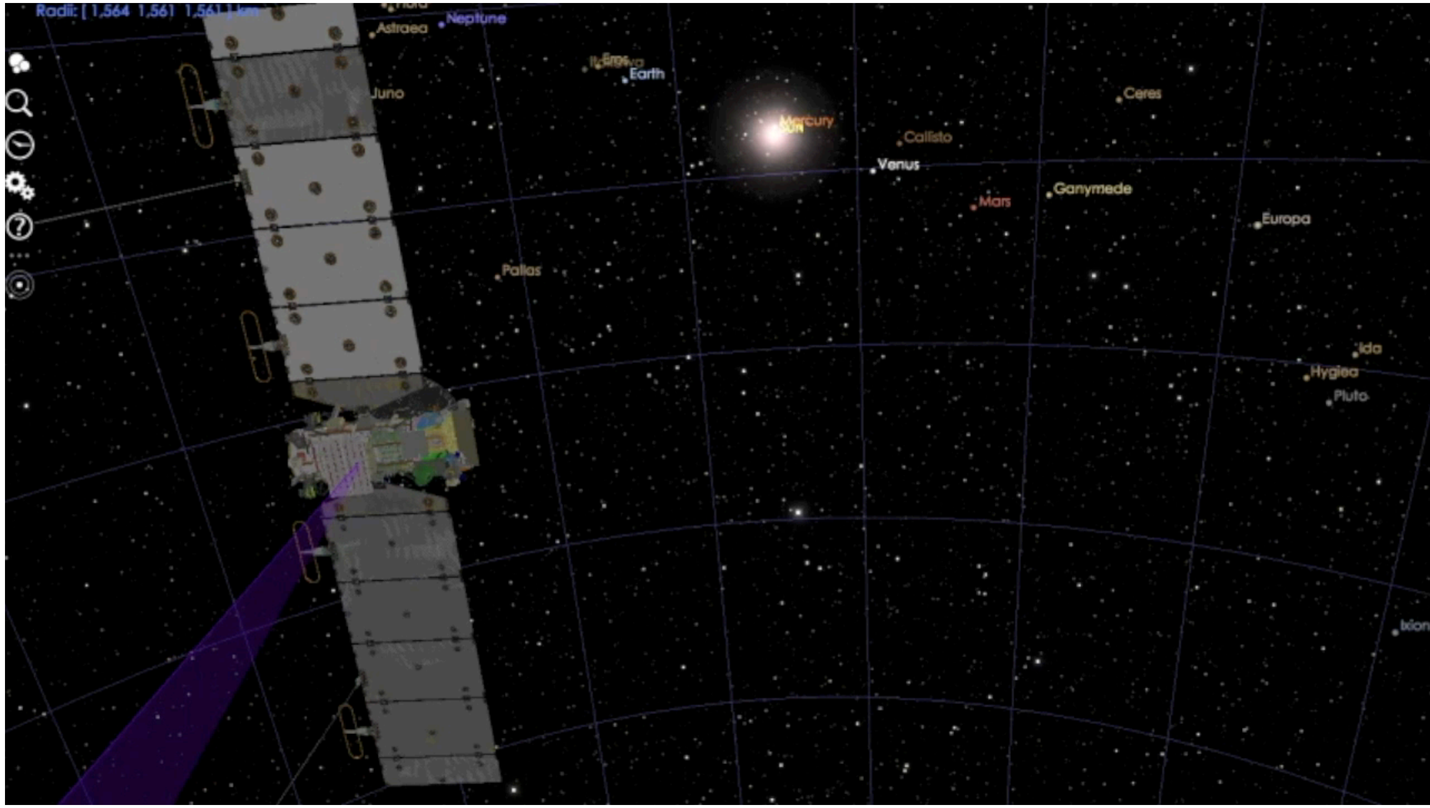
Jupiter Orbital Tour Scenario

- Flybys near perijove and data downlink for much of remainder of orbit
  - GN&C activities: RWA biases, IMU Cals
- 14 day orbit around Jupiter
  - Periapsis it/near Europa's orbital distance
  - Typically Europa flybys separated by 1 orbit (i.e. 14 days between flybys)
    - Shortest gap between Europa flybys: 10 days
- 3 OTMs per encounter period
  - C/A+3 days: Clean-up maneuver
  - Apojove: Targeting maneuver
  - C/A-3 days: Statistical approach maneuver
- Each flyby perijove dips into the "High Radiation Environment" (< 13 R_J)
- RWA biases occur:
  - Before flyby: Prior to DCO (data cutoff for OD) for approach maneuver
  - After flyby: Prior to DCO for the clean-up maneuver
  - As needed for long period (>21 days) without encounters or OTMs



Europa Flyby Scenario

- Nadir pointing for Europa Flybys have two parts:
  - Nadir Sun Optimal: +Y to Europa & +Z to Sun
    - Puts the Sun in the YZ plane so arrays can articulate to be exactly on sun while instruments are pointed at Europa
    - Used ±5-12 hours from Closest Approach
  - Nadir RAM Optimal: +Y to Europa & +X to inertially fixed vector
    - Puts +Z to RAM (SC velocity direction) at closest approach
    - Fixed 2ndary insures nadir tracking at ECA is purely an X axis rotation
    - Used within ±5 hours from Closest Approach
- Clipper is **<u>not</u>** a “nadir only” mission
  - Slews between Nadir SunOpt and RamOpt attitudes
  - EIS NAC mosaics (instrument gimbaling)
  - Numerous small X-axis Joint Scans
    - Optimized for UVS and E-Themis instruments, among others
  - Several small cross-track slews
  - 360 degree X-axis PIMS rolls



View Down +X-Axis Showing Solar Array Articulation

Field of View of UVS Airglow Port and EIS-NAC Base Pointing

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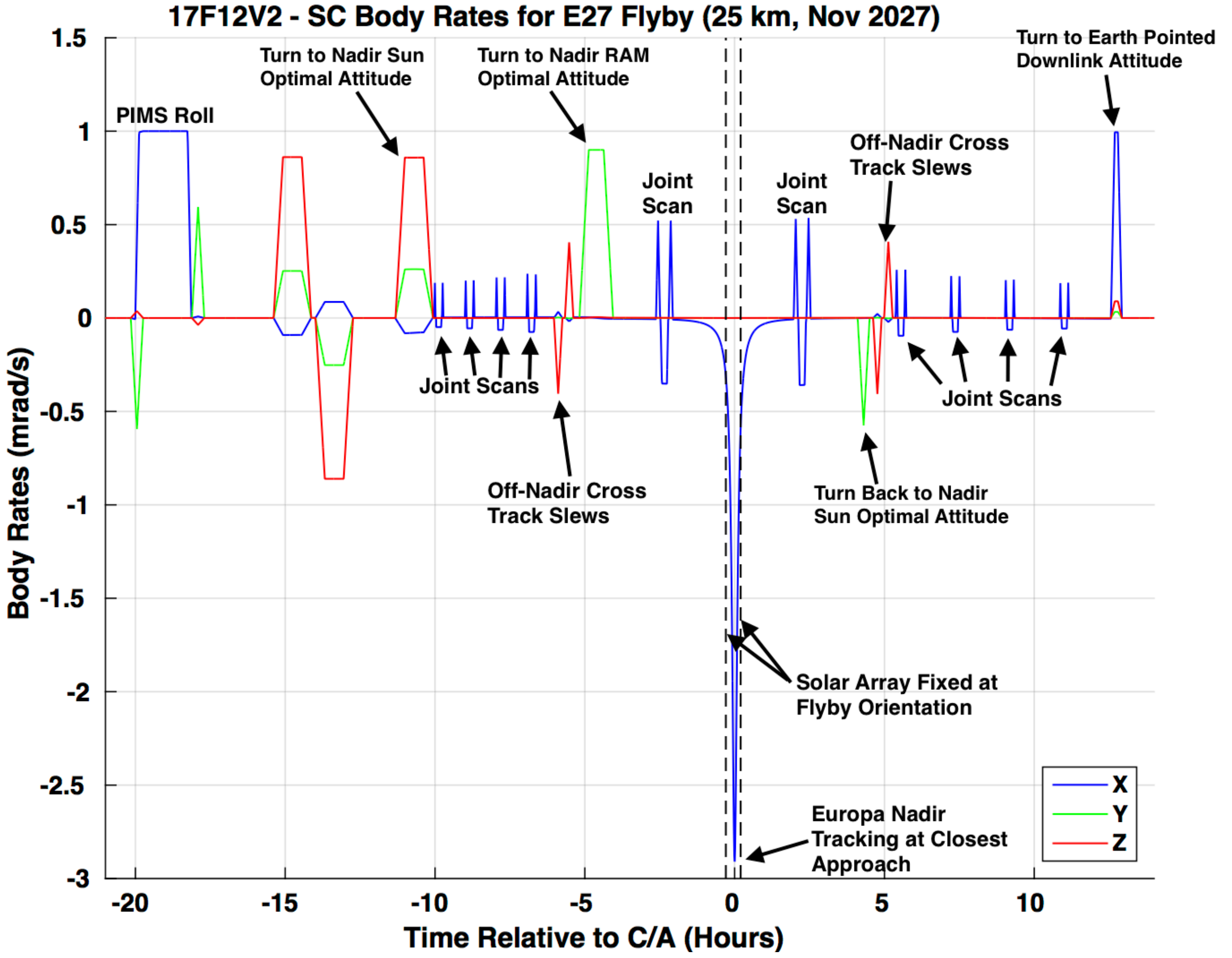
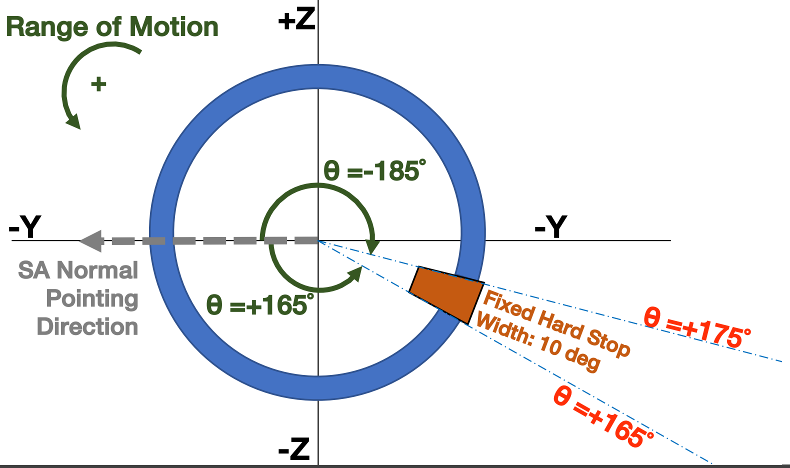
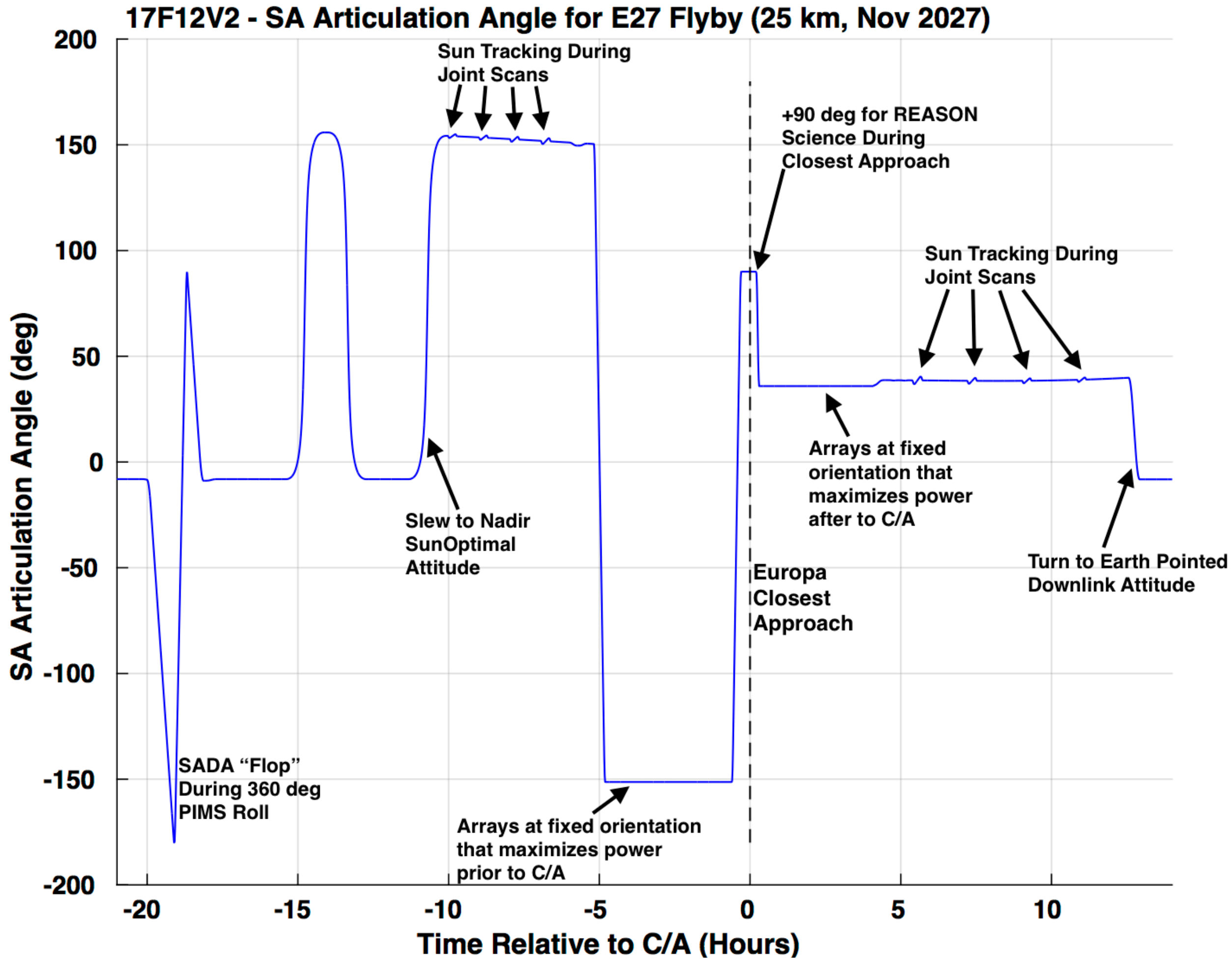


Solar Array Articulation Scenario

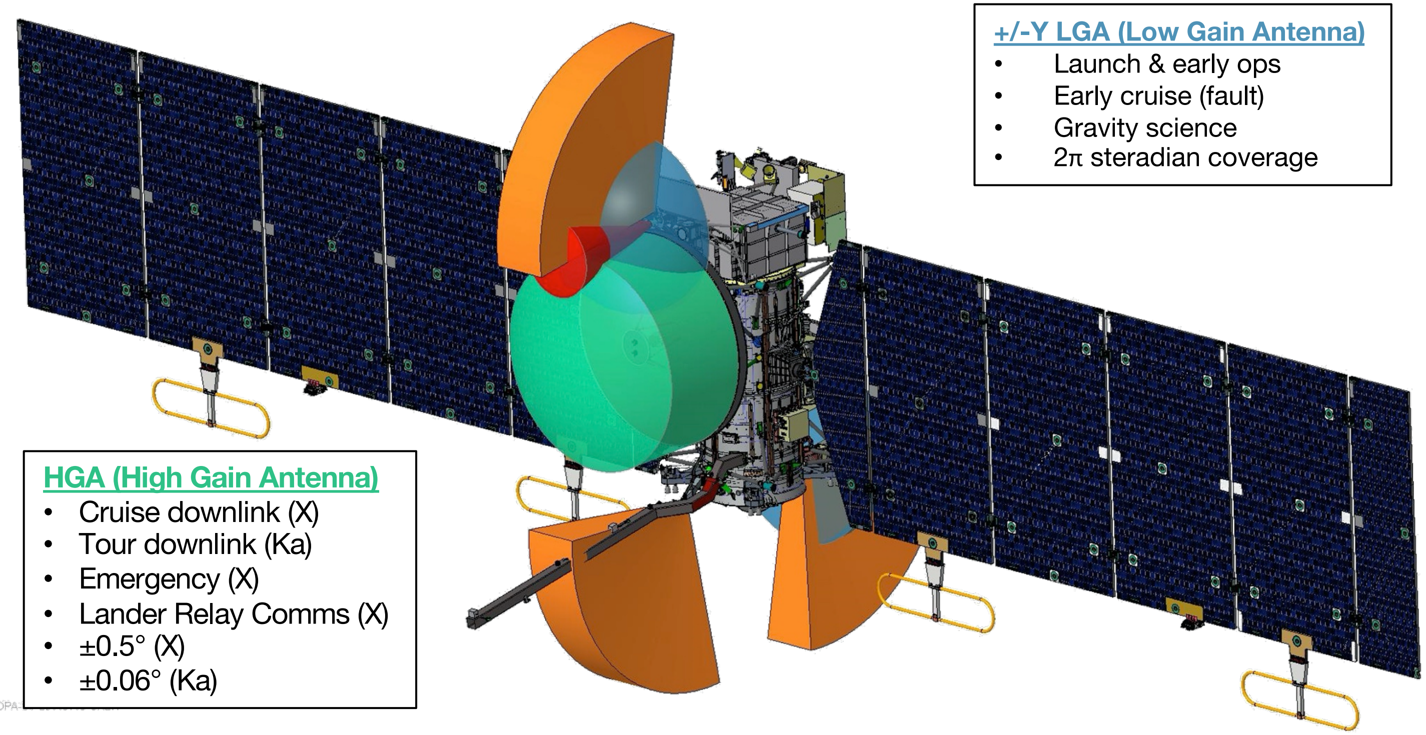
- SADA Range of motion: 350˚
- Settling time of ~6 minutes scheduled following articulations before pointing performance is assumed
- SADA Hard stop ~10 degrees wide (from +165 to +175)
  - SA Normal can be pointed to +Y, -Y, +Z, & -Z
- Sun Tracking (w-w/o X-axis offset)
  - Most common state (Cruise and Tour Orbital petal)
  - SADA de-energized automatically if array-to-Sun angle remains below threshold (3 deg)
- Body Fixed Position (w-w/o X-axis offset)
  - Fixed at +90˚ during Europa C/A
  - Index position for Maneuvers (-180˚) and Safe Mode (0˚), and REASON Science (+90˚)
  - For flybys, body fixed positions used before/after ECA to maximize power
- SADA "Flops" and Singularity handled autonomously by SA controller
  - Flop: Going from hard-stop to hard-stop (e.g. +165 to -185)
  - Singularity: Sun direction parallel to X-axis, so all articulation positions are 90˚ off





Downlink Scenario

- Numerous antenna on Clipper
  - Nearly 4π steradian coverage with LGAs
  - Generally possible for Doppler tracking and communication if Earth is in the YZ plane (Fan Beams)
  - High Rate data downlink uses KA-Band
    - X-Band to lesser extent
- SC attitude during HGA Downlink (3J):
  - Primary: [KA-Band Boresight] to EARTH
  - Secondary: ± Z to SUN
    - Puts Sun in YZ plane so arrays can articulate to point at it
- SC attitude during 3R Downlink:
  - Primary: -Y to SUN_3R (for MGA downlink)
    - Including X-axis offset angle
  - Secondary: Arbitrary
  - Rotate at constant rate around axis offset from -Y until ground commands a rotation stop
- Solar Arrays
  - Articulate to point at sun and then SADA motor is de-energized
  - Arrays repositioned only if SA Normal to Sun angle grows larger than parameterized threshold



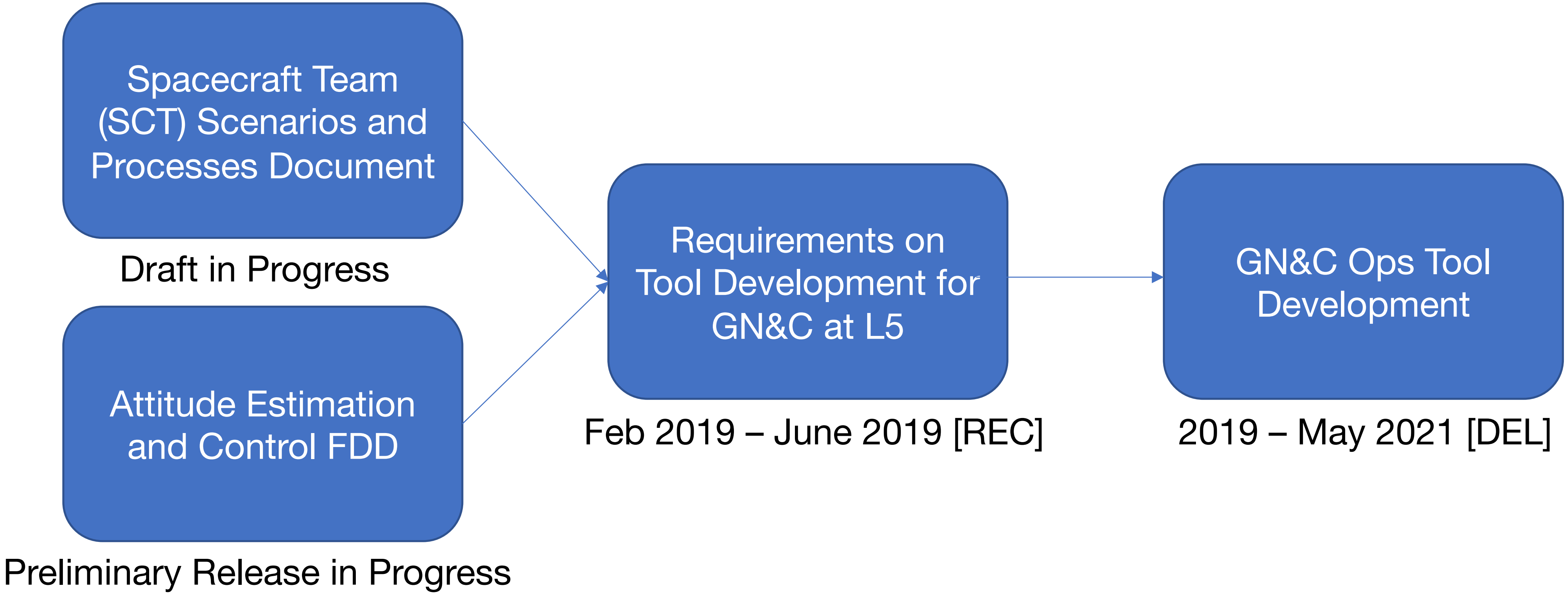
Europa Flyby Recovery Scenario

- This topic covered in detail Section D3-J
- <u>Scenario description</u>
  - FSW reset occurs while SC is Europa nadir tracking
  - GN&C RWA attitude control interrupted for 95 seconds, causing drift from target attitude and rate
  - GN&C required to return to the nadir pointed attitude and rate without typical safing response (e.g. no sun search, sun point, or rotisserie)
- Innovations for Europa Clipper Mission:
  - 3J attitude/rate state retained in memory across FSW reset
  - High-rate IMU data buffered during FSW interruption
    - Buffer processed by GN&C FSW after reset to recover 3J attitude estimate
  - New ATC rate/acceleration profiling logic more efficiently uses available RWA torque to speed recovery time
- Challenges
  - Recovery time severely limited by small available RWA torque and large system Y and Z axis inertia
  - Resets within C/A ±30 min are challenging due to large nadir tracking rates and accelerations
  - Reset that occurs during SA articulations are challenging because SA momentum is imparted to SC body
- GN&C Recovery Time Allocation:
  - For resets ≤30 min from C/A: 18.4 minutes (TBR)
  - For resets >30 min from C/A: 8.4 minutes (TBR)

Mission Operations’ Architecture Principles

- Small operations team
- “Close the loop”
  - Design in a way that includes an assessment of meeting intentions at all levels and stages of sequence development and execution
- Automate whenever possible
  - Allow for review and intervention by operators
- Plan for change
  - Design the system in such a way that re-planning an activity should be straightforward
- Data transparency
  - All operators should use the same model (one single centralized system)
  - All products should have operator-readable versions
- Invest in simplicity
- Ecosystem
  - Development will aim to be part of a cohesive system, not disconnected tools

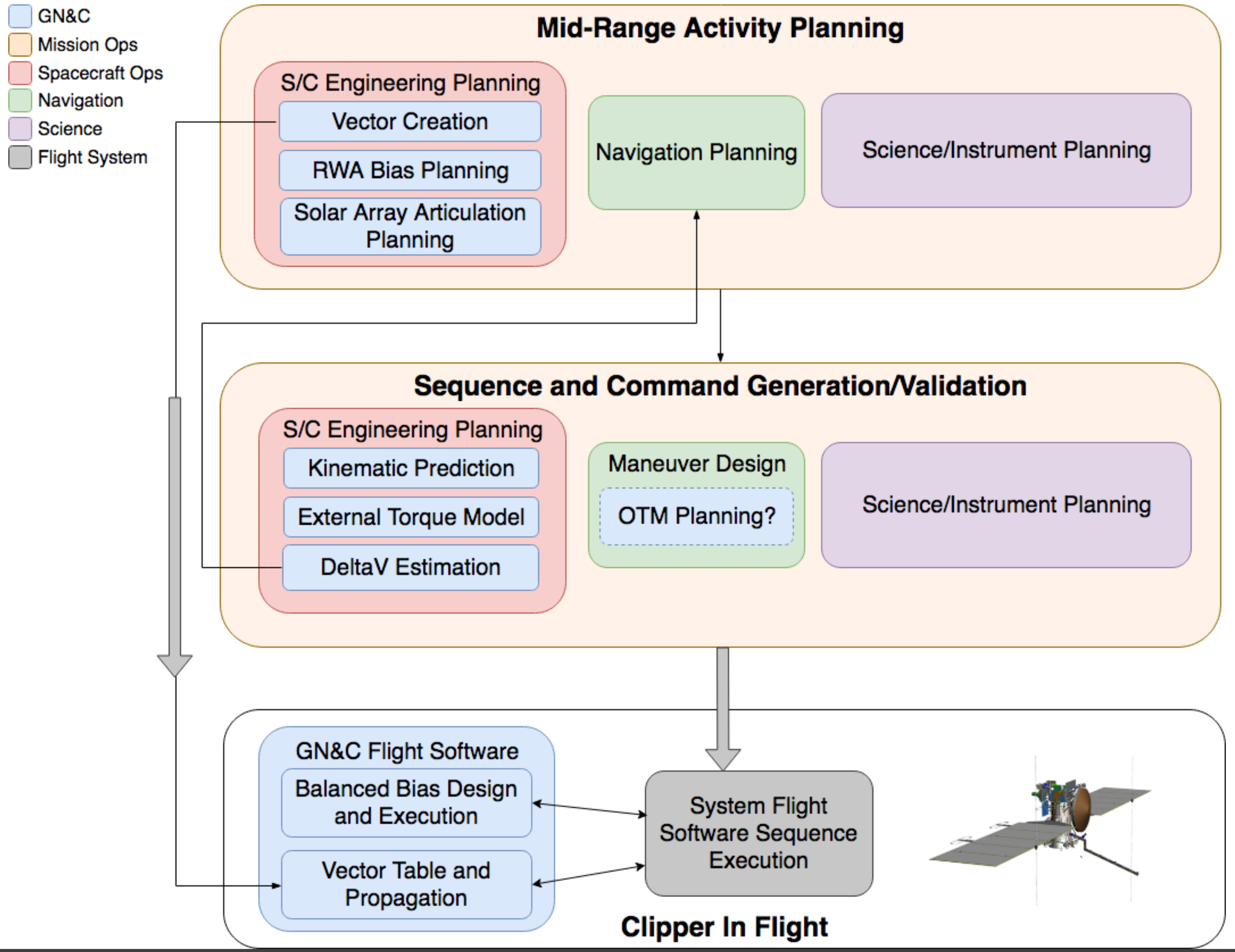
GN&C Operations' Development Flow



- GN&C subsystem is in communication with the Mission Operations Subsystem (MOS) regarding the contents of the SCT Scenarios and Processes Document

GN&C Role in Mission Ops Uplink Process

- GN&C system to deliver modules and scripts to be incorporated into system-wide tools, with small flight-ops team
- Vector creation is decoupled from sequence development and execution
- Balanced bias design and execution to happen onboard in flight
- System testing
  - WSTS (dynamic simulation)
  - System Testbed 1 (hardware closed loop)
  - System Testbed 2 (breadboards and simulations)
- OTM roles being worked with MOS



Questions?