National Aeronautics and Space Administration

Jet Propulsion Laboratory
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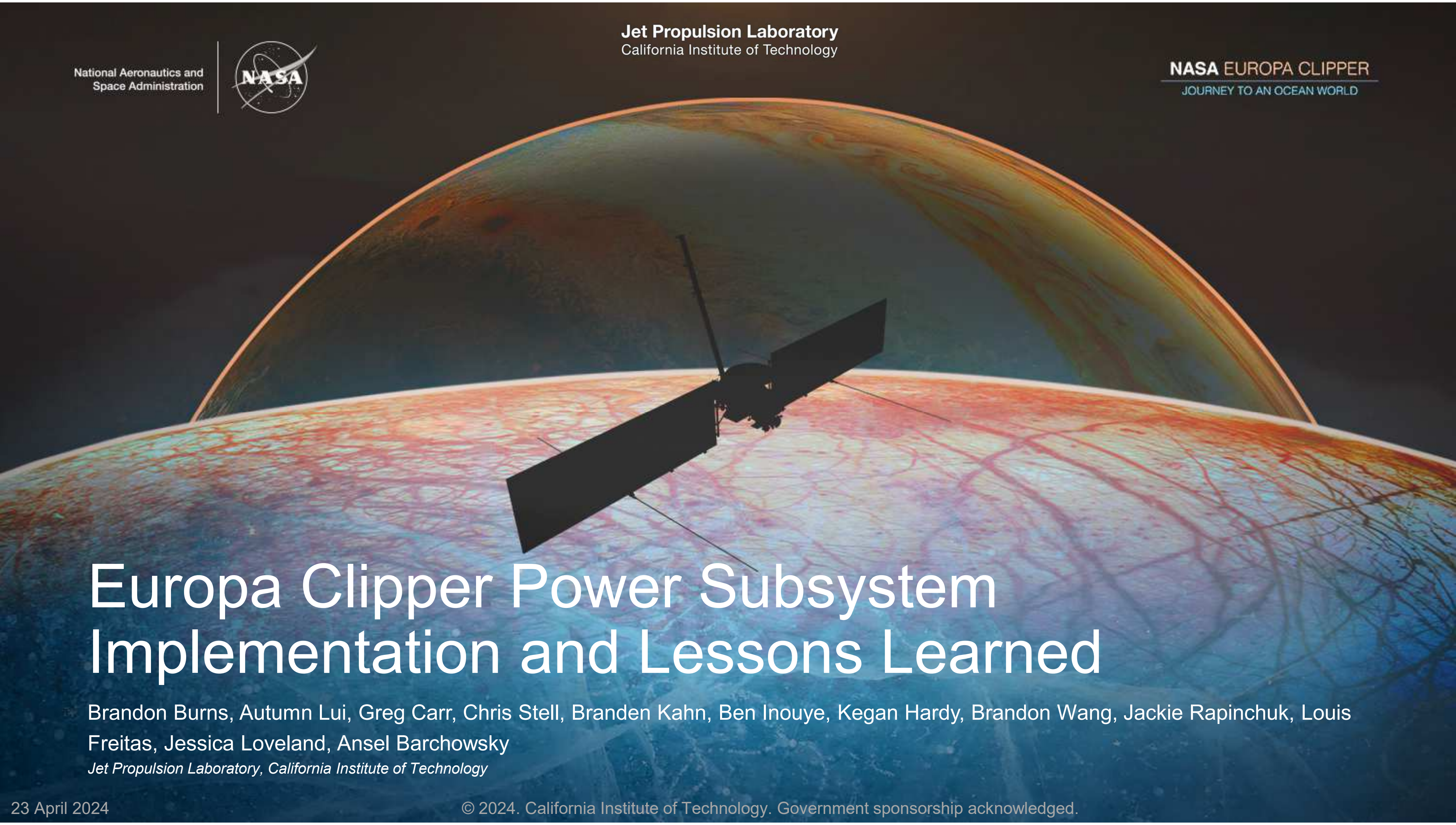
NASA EUROPA CLIPPER
JOURNEY TO AN OCEAN WORLD



Europa Clipper Power Subsystem Implementation and Lessons Learned

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23 April 2024

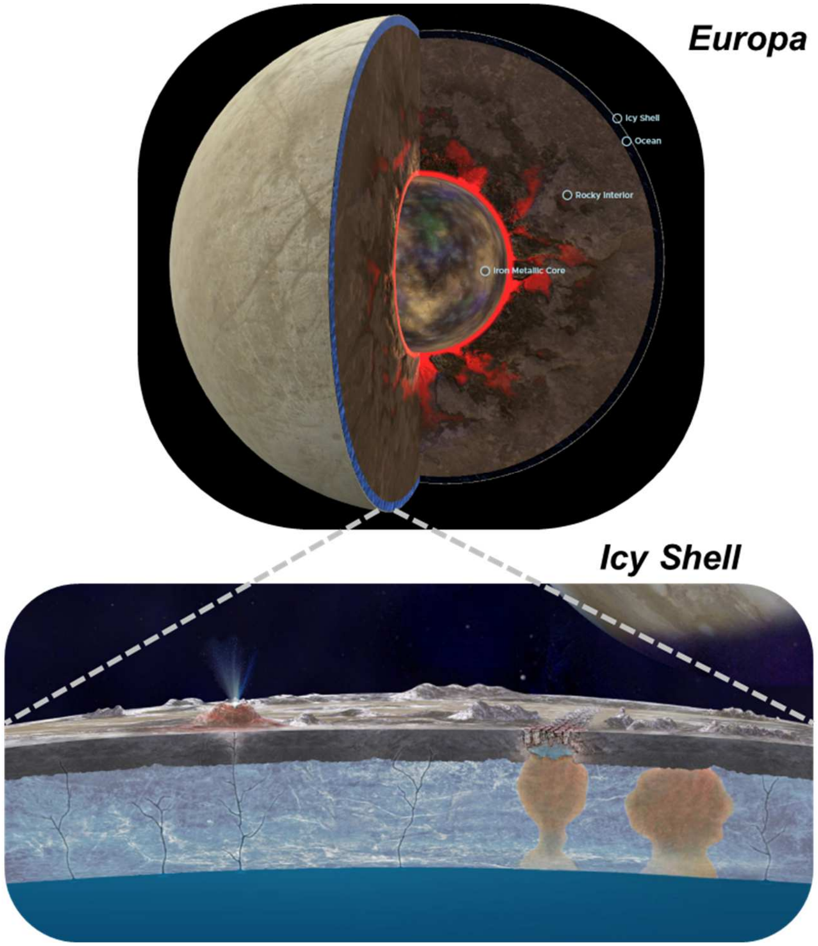
Agenda

- Scientific Objectives
- Mission Overview
- Requirements
- Subsystem Challenges
- Implementation & Verification
- Subsystem Status
- Lessons Learned
- Conclusions

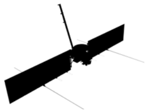
Scientific Goals & Objectives

Europa Clipper’s main ***science goal*** is to determine whether there are places below Europa’s surface that could support life.

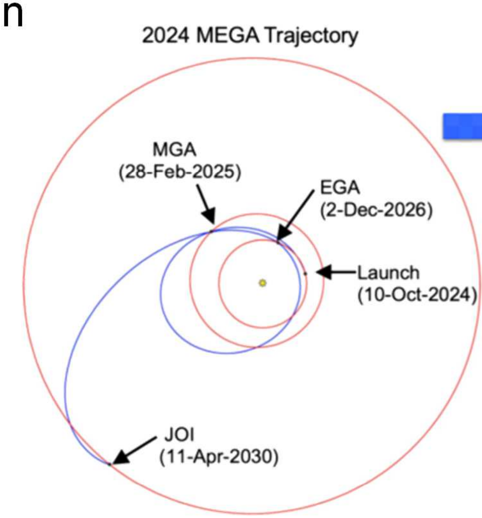
- **Icy Shell & Ocean**
    - Determine the thickness of Europa’s icy shell
    - Discover whether there’s liquid water within and beneath the shell
    - Estimate the size, salinity and other qualities of Europa's ocean
    - Study how the ocean interacts with the surface:
        - Does anything in the ocean rise up through the shell to the top?
        - Does any material from the surface work its way down into the ocean?
- **Composition**
    - Investigate the composition of Europa's ocean to determine if it has the ingredients to permit and sustain life
- **Geology**
    - Study how Europa’s surface features formed and locate any signs of recent activity such as sliding crust plates or plumes that are venting water into space



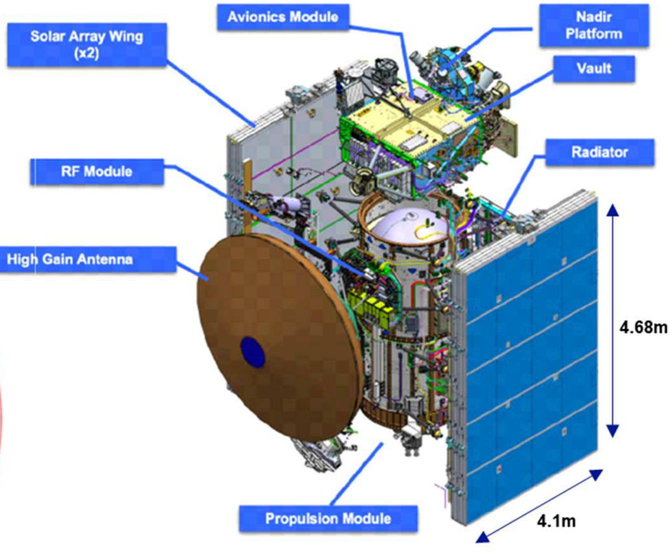
Mission Overview: Cruise & Arrival



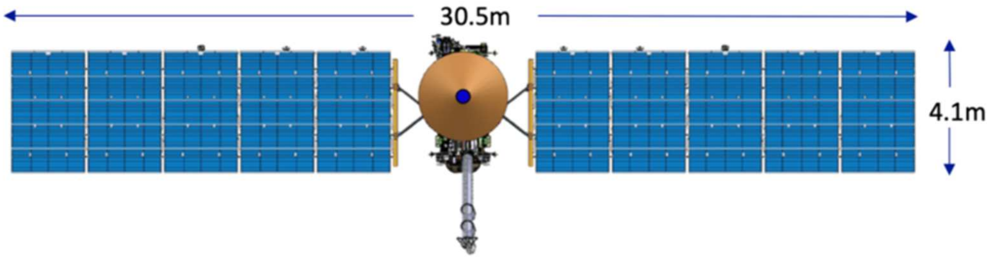
- Launch Date: 10 Oct. 2024
- Cruise Duration: 5.5 years
- Battery SOC: 60% to minimize degradation
- Inner Cruise (< 2AU)
  - Minimum sun distance: 0.82AU
  - Gravity assists at Mars & Earth
  - Solar array partially off-pointed to reduce temperature to ~100℃
  - Solar array operating voltage < 45V
  - Very high solar array short circuit current
- Outer Cruise (> 2AU)
  - Maximum sun distance 5.5AU
- Arrival Phase
  - Starts 3 months prior to JOI
  - Ends 8 hours after JOI perijove



2024 MEGA Trajectory



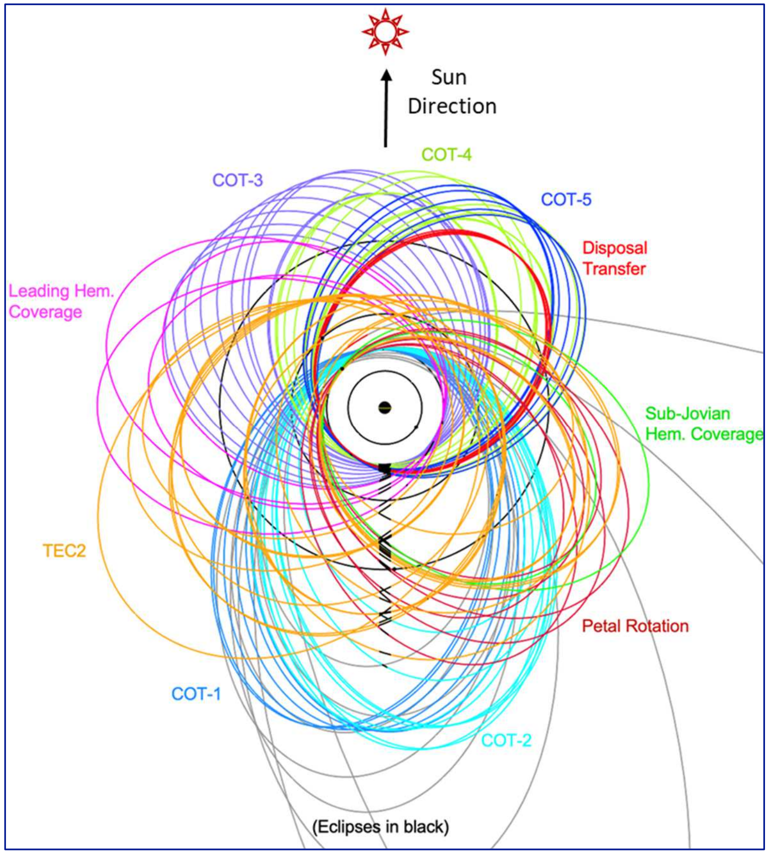
Europa Clipper Spacecraft



Mission Overview: Tour

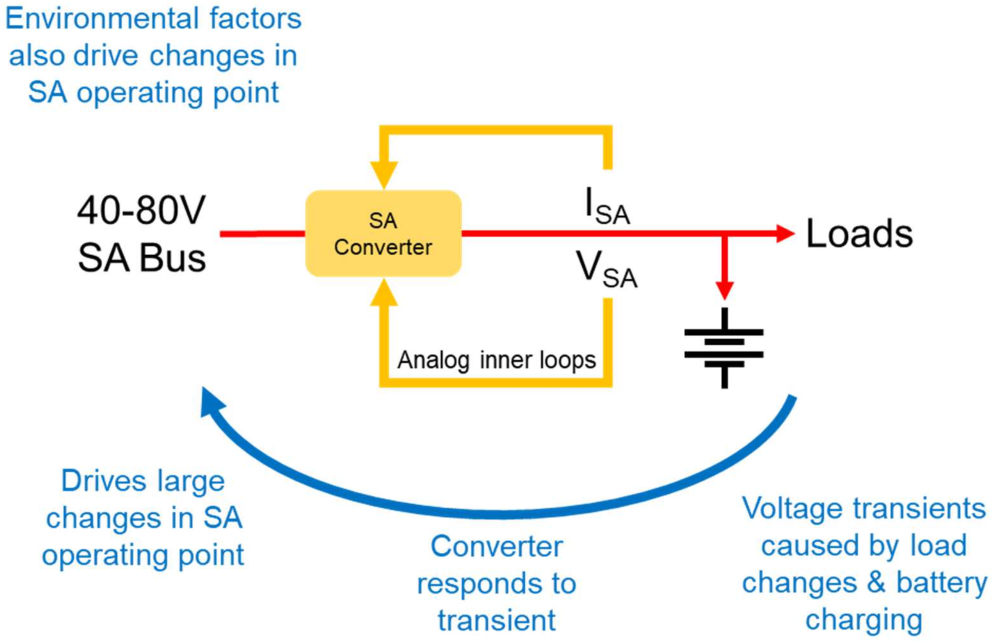
- Four Stages
  - Transition to Europa Campaign 1 (TEC1)
  - Europa Campaign 1 (EC1)
  - Transition to Europa Campaign 2 (TEC2)
  - Europa Campaign 2 (EC2)
- Transition stages shape the orbit in preparation for the campaigns
- Campaigns collect science for prime mission:
  - 49 flyby encounters, each lasting ~14 days
  - Most science during Flyby = closest approach +/- 2 days
  - Highly elliptical orbits
- Instruments:
  - Europa Imaging System (EIS)
  - Europa Thermal Emission Imaging System (E-THEMIS)
  - Europa Ultraviolet Spectrograph (Europa-UVS)
  - Mapping Imaging Spectrometer for Europa (MISE)
  - Europa Clipper Magnetometer (ECM)
  - Plasma Instrument for Magnetic Sounding (PIMS)
  - Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)
  - MAss Spectrometer for Planetary EXploration/Europa (MASPEX)
  - SUrface Dust Analyzer (SUDA)
  - Gravity/radio science

Tour Trajectory



Requirements: Stability & Dead Bus

- **Operational stability** –
  - Power subsystem is required to remain stable, based on phase and gain margin:
    - > 30˚ phase margin
    - > 6 db gain margin
  - Any point between 40-80V
    - Constant current side, constant voltage side, or near peak power point
  - Any viable mission IV curve, BOL to EOL
  - Remain stable in response to transitions:
    - Between the constant voltage and the constant current sides of an IV curve
    - Due to a changing IV curve
    - Due to changing load
  - In any operational mode or with operating on any control loop



Environmental factors also drive changes in SA operating point

40-80V SA Bus

SA Converter

I_{SA}

V_{SA}

Loads

Analog inner loops

Drives large changes in SA operating point

Converter responds to transient

Voltage transients caused by load changes & battery charging

- **Dead bus compliant** – Once solar power is restored, after a complete loss of power, the power subsystem must be capable of recovering its basic functionality and utilize the available solar energy to recover the spacecraft

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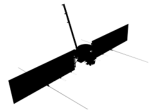
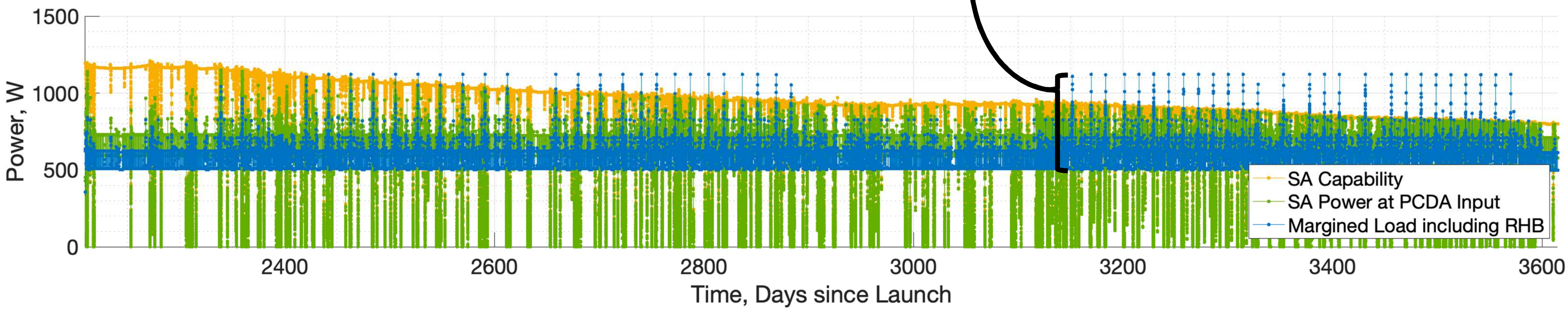
Requirements: Load Steps

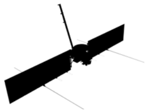


- **Maximum load step capability** –
  - Power subsystem is required to remain stable, and accommodate load transients
    - From system’s base load level to its peak load level
    - From peak level to its base load level

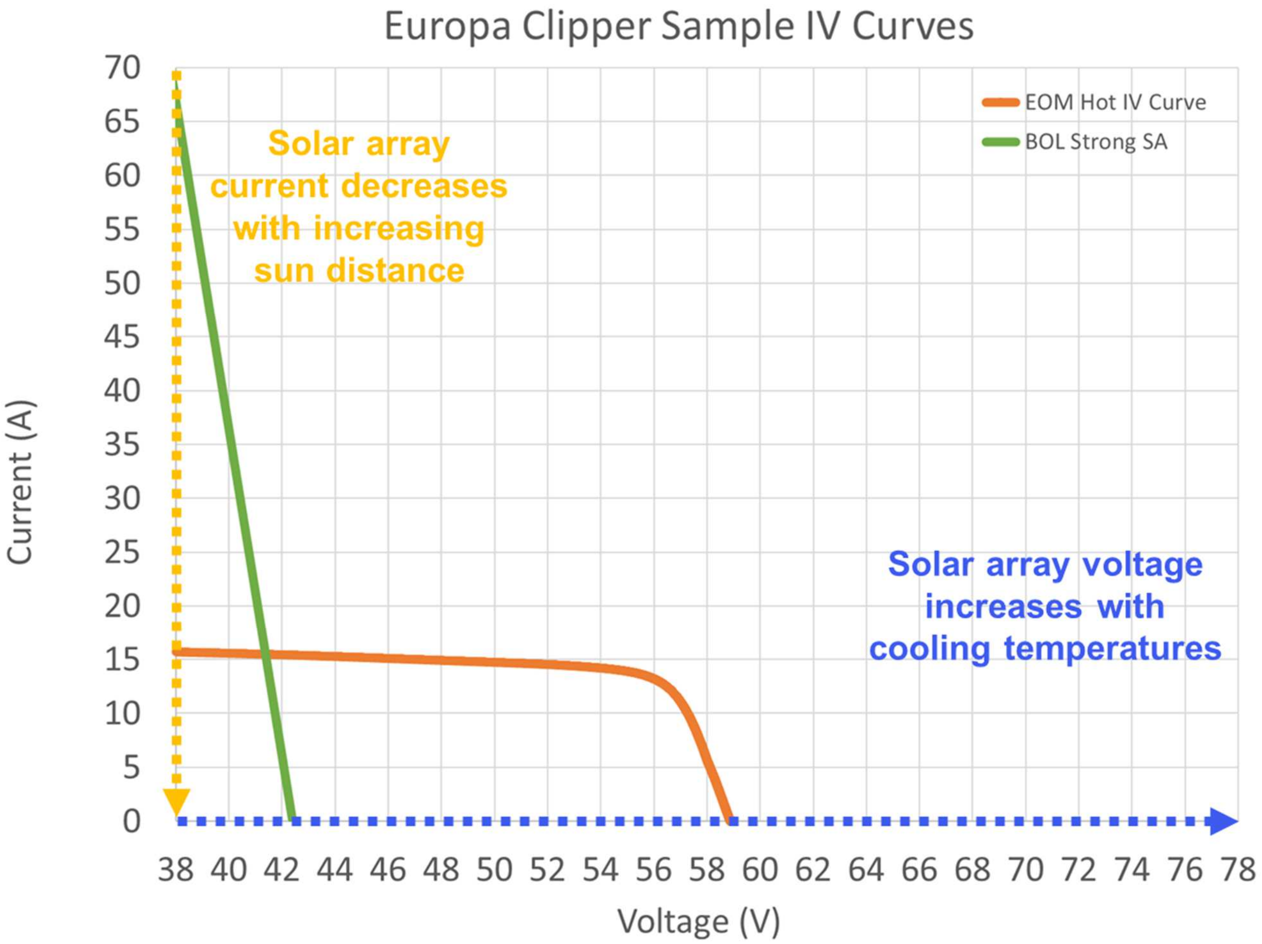


Spacecraft load can increase by ~75% during flyby, primarily to accommodate science collections at closest approach

Slow Changing Environmental Factors



Sun distance will be as low as 0.82AU in inner cruise and up to 5.5AU at Jupiter



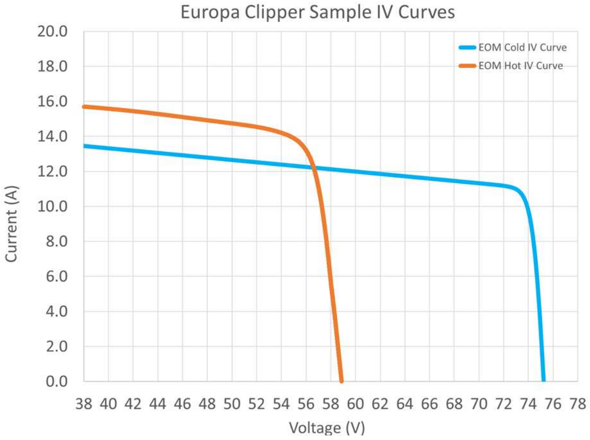
Typical total **mission fluences** of > 4E15 MeV e-/cm2 influenced:

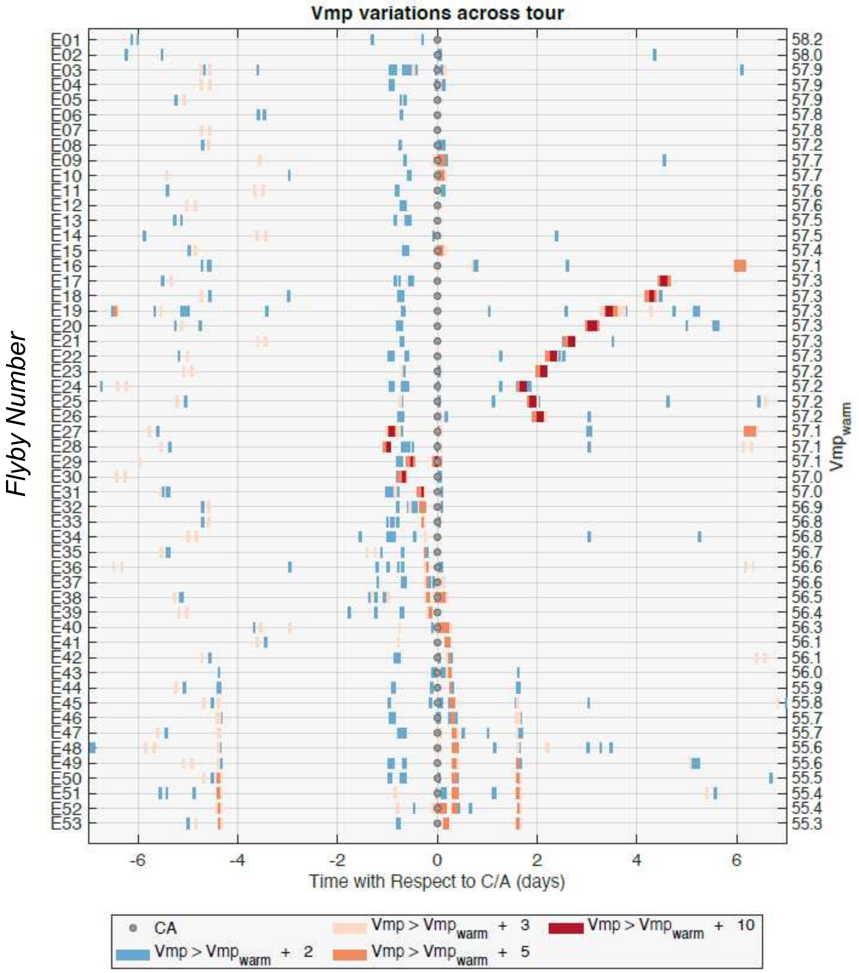
- Electronics design
- Part selection
- Chassis thickness
- ESD considerations
- Solar array degradation
- Highly elliptical orbits

Steady state **Solar array temperature** is predicted to be up to 100℃ in inner cruise and as cold as -135℃ at Jupiter

Fast Changing Environmental Factors

- During a single 14-day flyby the peak power point of the solar array can move by more than 10V
- Large changes in the IV curve driven by:
  - Eclipse drive a minimum solar array temperature of -240℃
  - SA off-pointing due to instrument calibrations
  - SA off-pointing due to nadir pointing at closest approach

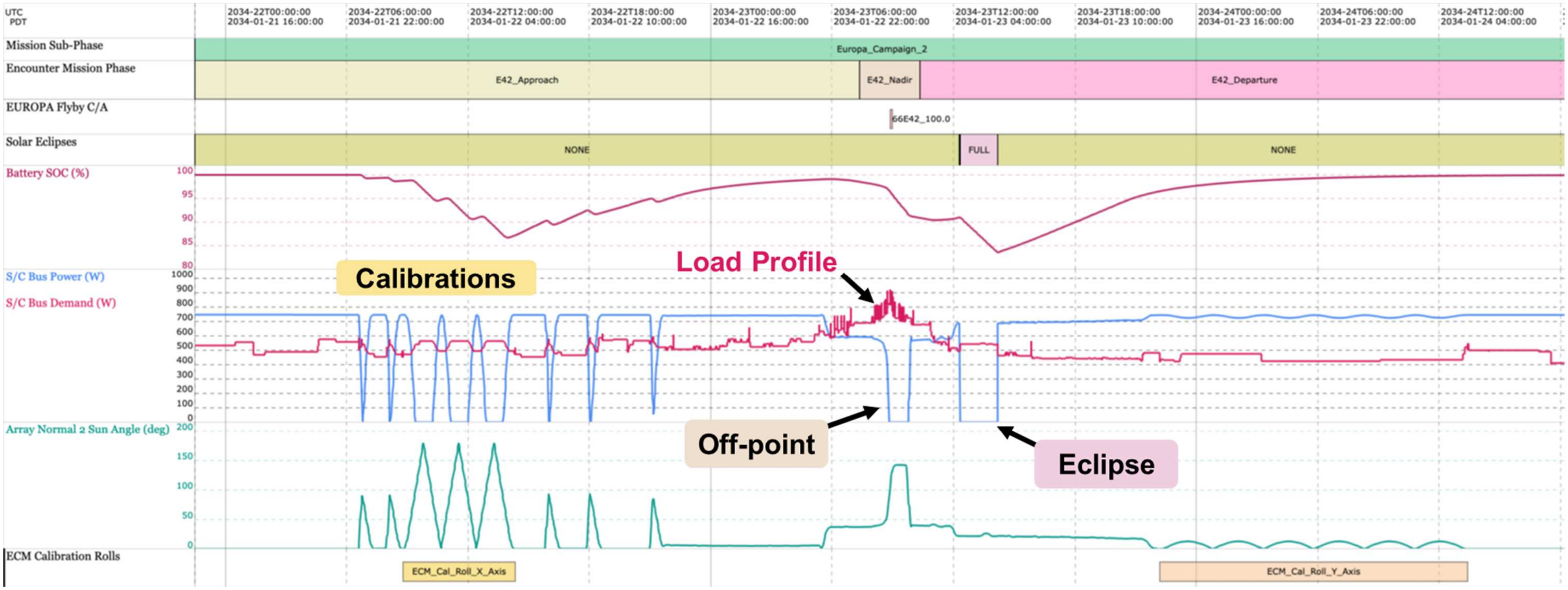




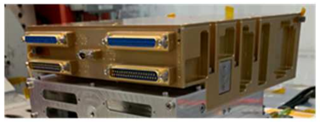
Mission Factors & Load Profile

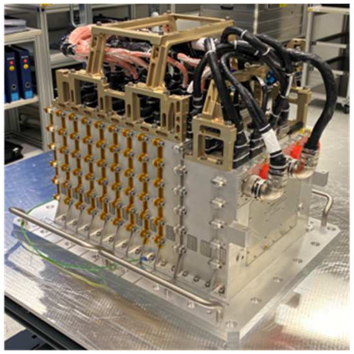
- During the most critical periods of the mission, the flybys, the spacecraft load will change quickly and can be nearly double the base load during cruise
- SA IV curve and desired operating point are moving independently and simultaneously

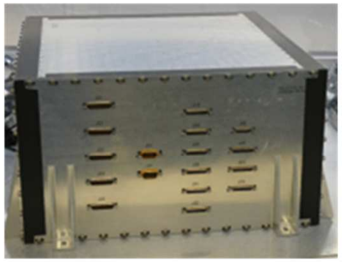
Typical Europa Flyby

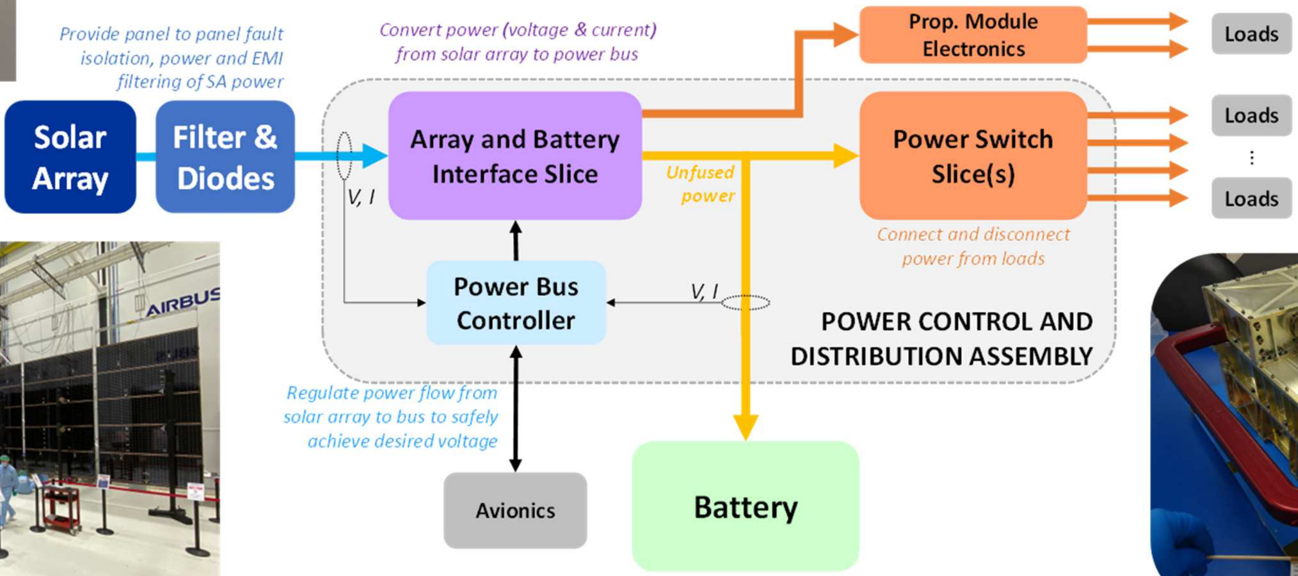


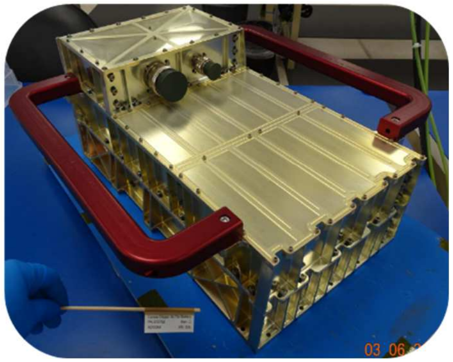
Power Subsystem Implementation



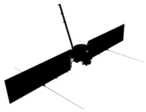




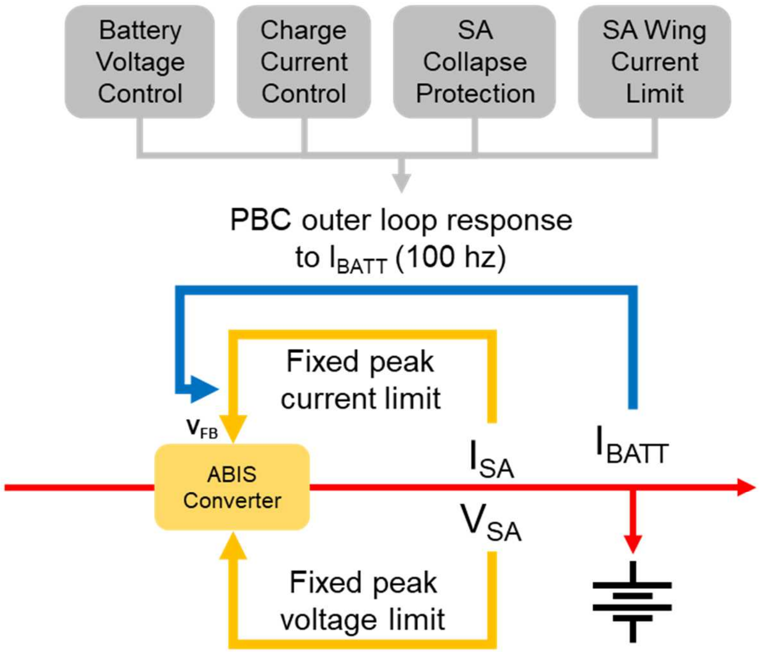




Initial Implementation



- Analog inner loop responds very quickly to load transients ► changing IV curve operating point
- PBC digital collapse prevention control loop was designed to prevent this response from causing an issue
- Test data revealed that the digital loop was not fast enough to prevent partial or full collapse of the array
- Resulted in instability near the peak power point and on constant current portion of the IV curve



Battery Voltage Control

Charge Current Control

SA Collapse Protection

SA Wing Current Limit

PBC outer loop response to I_{BATT} (100 hz)

Fixed peak current limit

V_{FB}

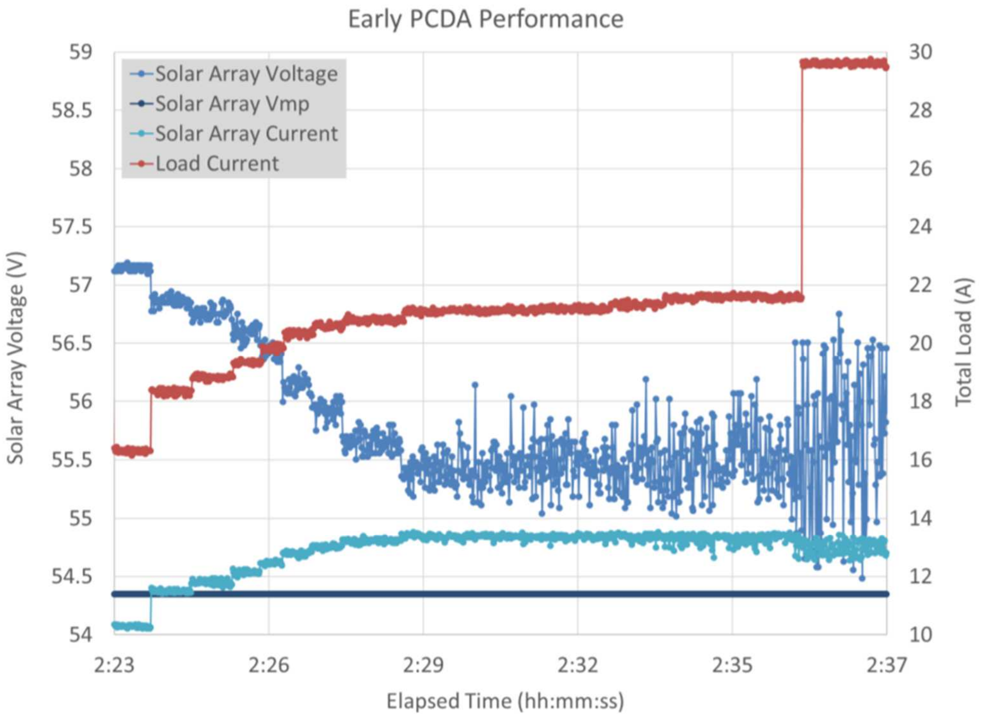
ABIS Converter

I_{SA}

I_{BATT}

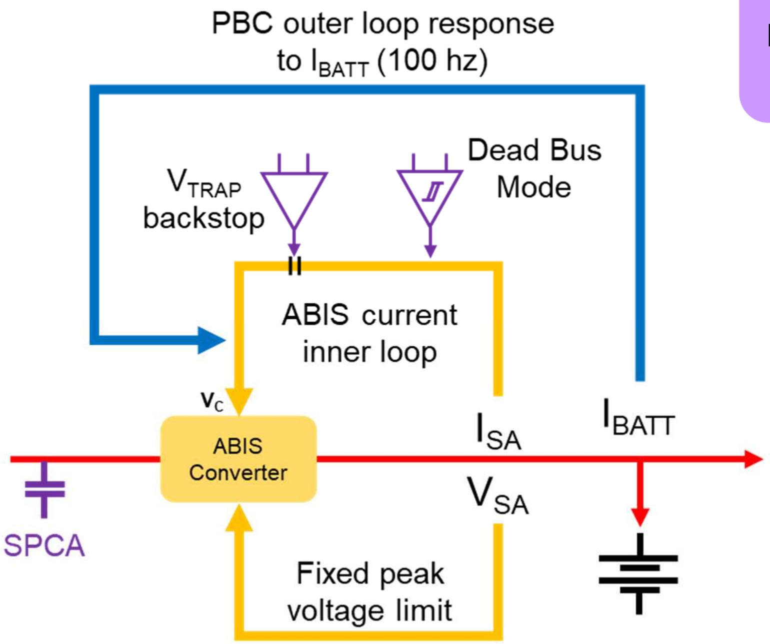
V_{SA}

Fixed peak voltage limit



Architecture Update

V_{TRAP}:
Provides analog back stop ensuring a minimum V_{SA}. Prevents array collapse. Protects ABIS buck converters.



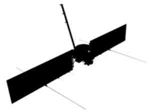
Dead Bus Mode:
Provides SA power, after complete loss of power, until PBC retakes control

Solar Power Capacitor Assembly:
Reduces source impedance as viewed by PCDA. Reduces ripple

Current Control:
PBC controlled current limit prevents local ABIS transient response from collapsing the array, allowing PBC to gracefully respond.

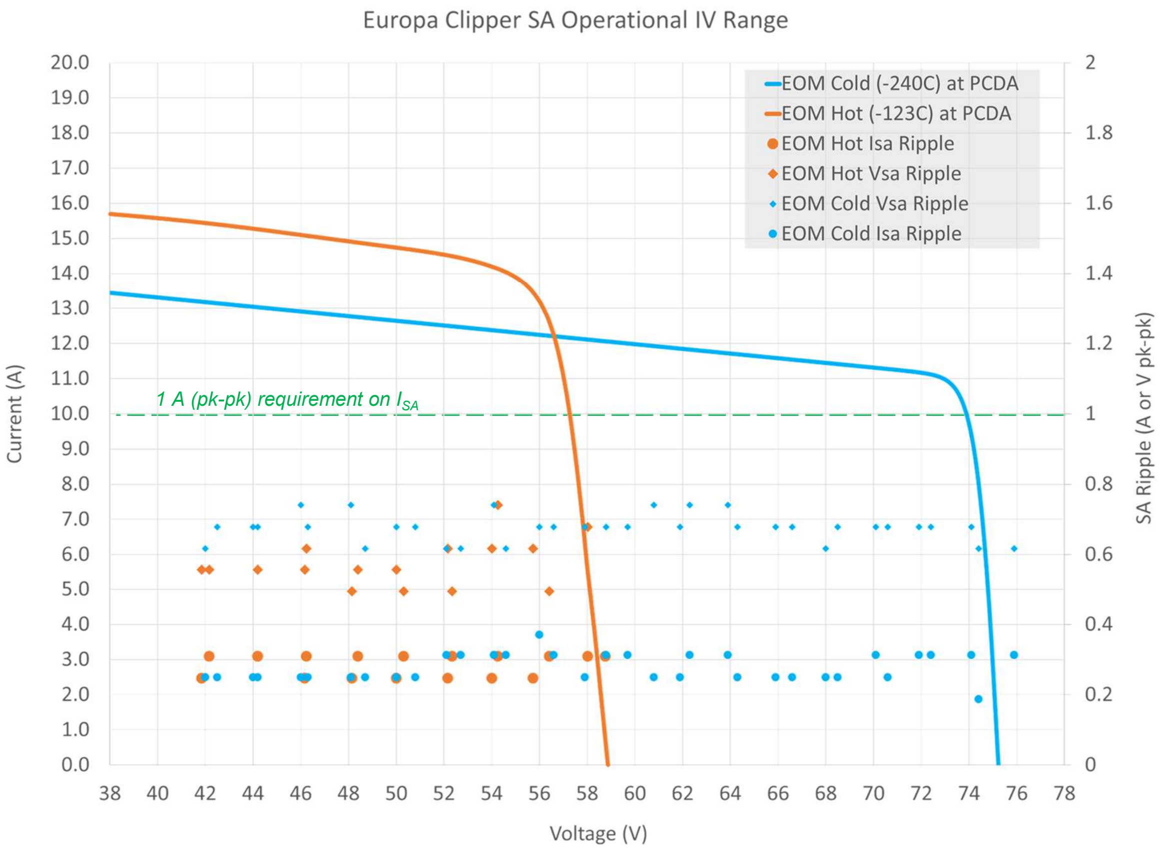
PBC controls ABIS current limit, over-rules any local converter response to voltage transients

Performance Summary



- HW is safe & providing power under all operational modes
- > 30˚ phase margin, > 6 db gain margin
- < 1 A I_{SA} ripple over full operational range
- Properly damped response to 25A step load
- No SA collapse ► V_{CPS} works as intended
- Dead bus compliant

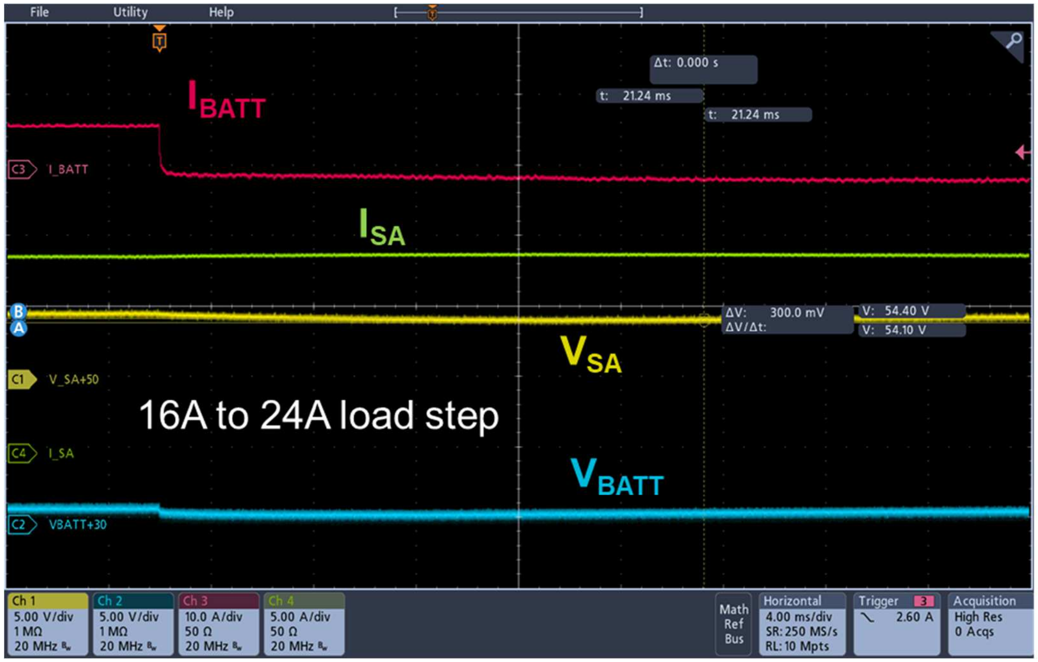
Default PIDs [Deadbus]		Tuned PIDs [Nominal Operations]	
Ripple (pk-pk)	Phase & Gain Margin	Ripple (pk-pk)	Phase & Gain Margin
V_{SA} < 0.63V I_{SA} < 0.31A	43° 21 dB	V_{SA} < 0.74 V I_{SA} < 0.37 A	60° 45 dB

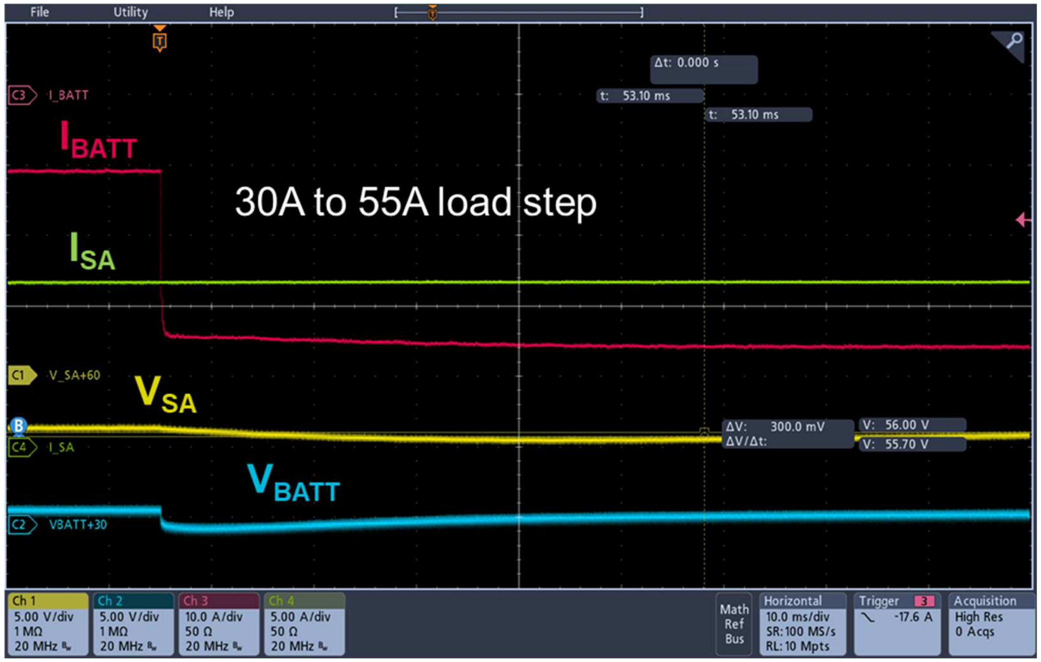


Response to Load Transients

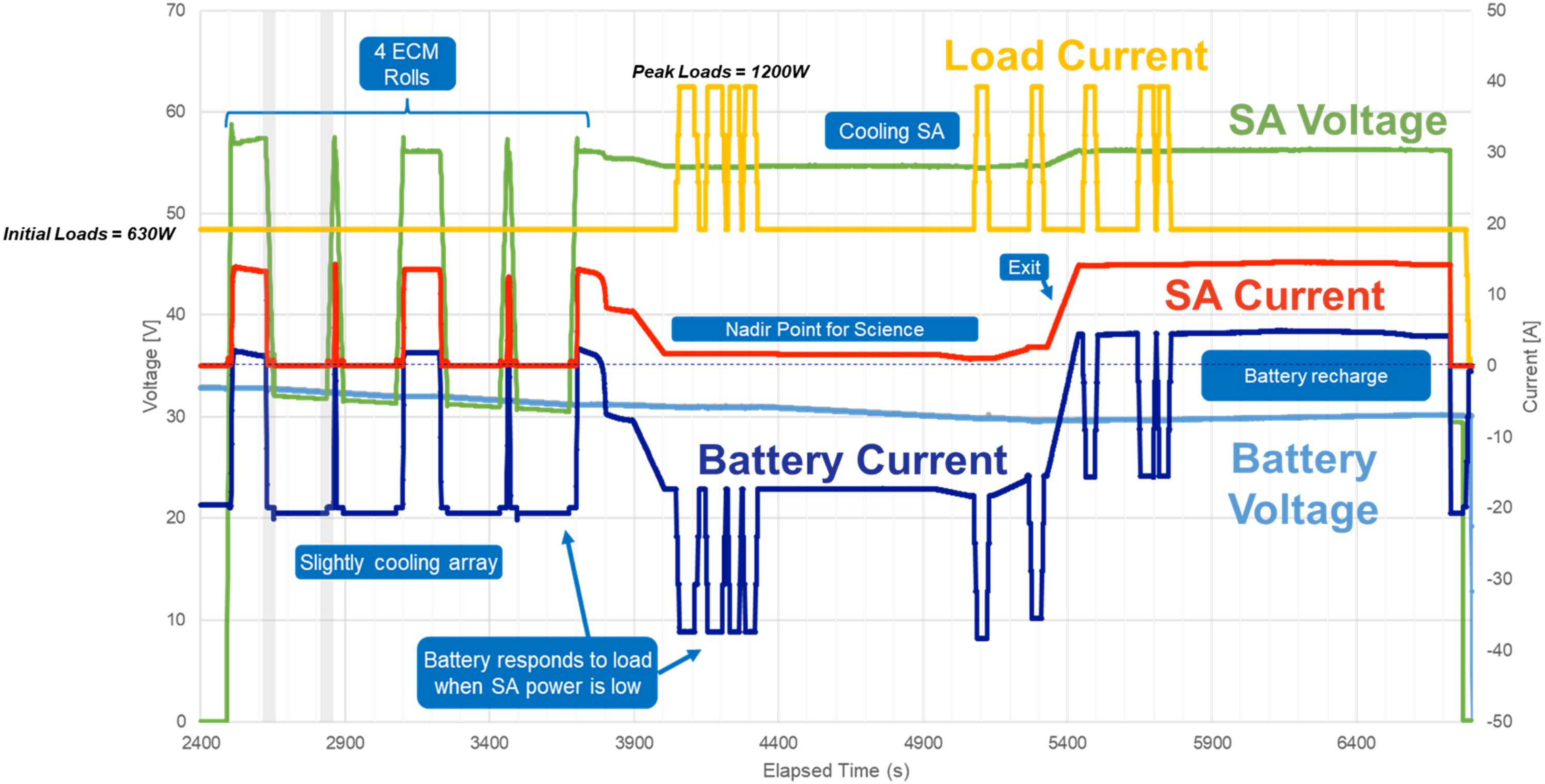
Load step from constant voltage to constant current portions of IV curve

Maximum amplitude load step


16A to 24A load step


30A to 55A load step

Mission Simulation Testing



4 ECM Rolls

Peak Loads = 1200W

Cooling SA

Initial Loads = 630W

Exit

Nadir Point for Science

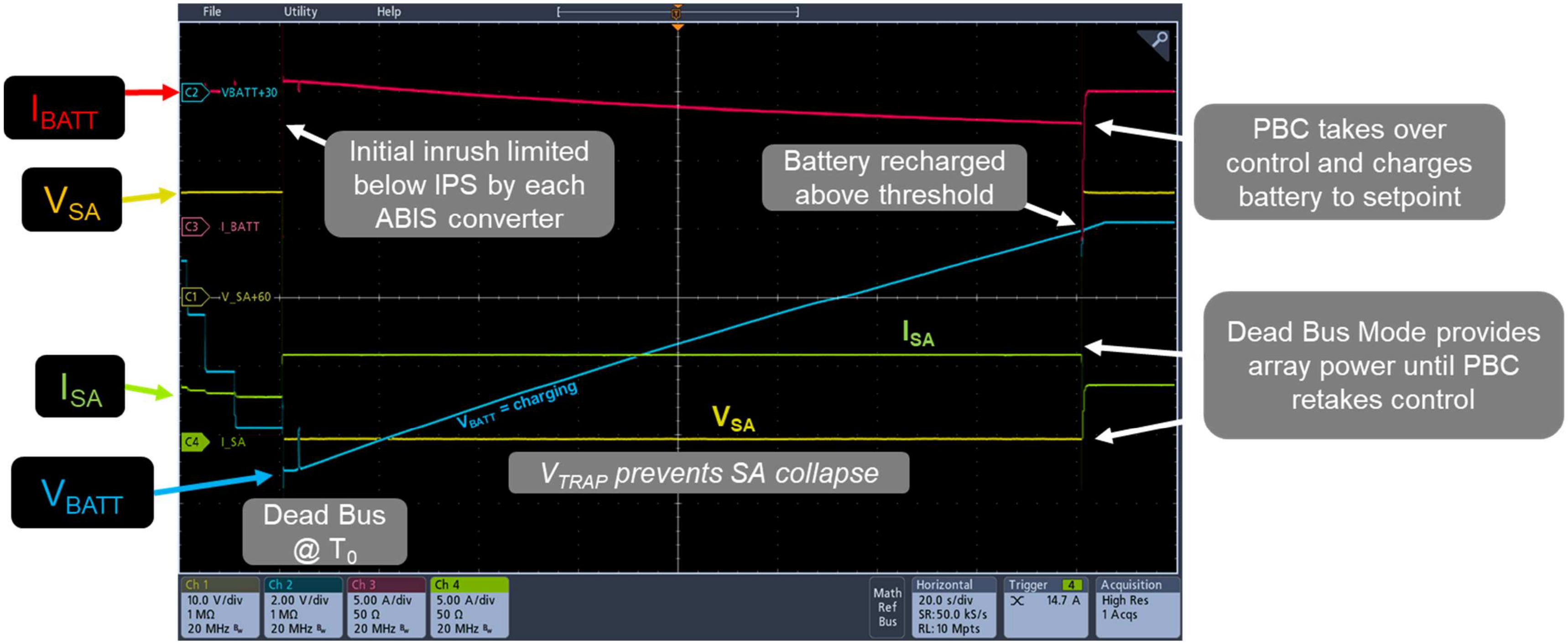
Battery recharge

Slightly cooling array

Battery responds to load when SA power is low

Dead Bus Recovery

- PCDA ensures controlled, graceful start up from dead bus condition, across any mission condition
- System transitions back to nominal control states



Initial inrush limited below IPS by each ABIS converter

Battery recharged above threshold

PBC takes over control and charges battery to setpoint

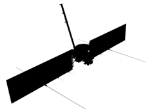
Dead Bus Mode provides array power until PBC retakes control

V_{TRAP} prevents SA collapse

Dead Bus @ T_0

Ch 1 10.0 V/div 1 MΩ 20 MHz
Ch 2 2.00 V/div 1 MΩ 20 MHz
Ch 3 5.00 A/div 50 Ω 20 MHz
Ch 4 5.00 A/div 50 Ω 20 MHz
Math Ref Bus
Horizontal 20.0 s/div SR:50.0 kS/s RL:10 Mpts
Trigger 4 14.7 A
Acquisition High Res 1 Acqs

Lessons Learned



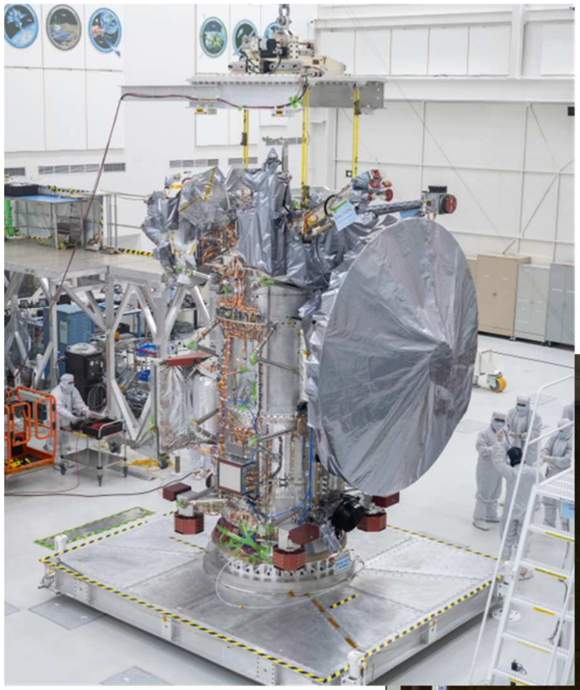
- A rigorous, top down, requirements definition process is needed early to shape the power architecture
- Requirements must be checked against a bottoms-up set of flight like mission test cases
- Engineers at the system level must understand how the mission design and operational modes drive the power subsystem design and breaking points
- It is equally important that the subsystem engineers have a deep understanding of how the spacecraft will be flown and tested on the ground
- Perform integrated (control loop, converters, flight software if required) testing as early as possible
- Perform flight like, mission test cases as early as possible to understand interdependencies of SA performance, battery performance, and load profiles on a power subsystem
- Continued emphasis on load management over the development of a project with an awareness of both system power/energy margins and also architectural breaking points
- Plan for the power subsystem team to be hardware rich

Conclusion

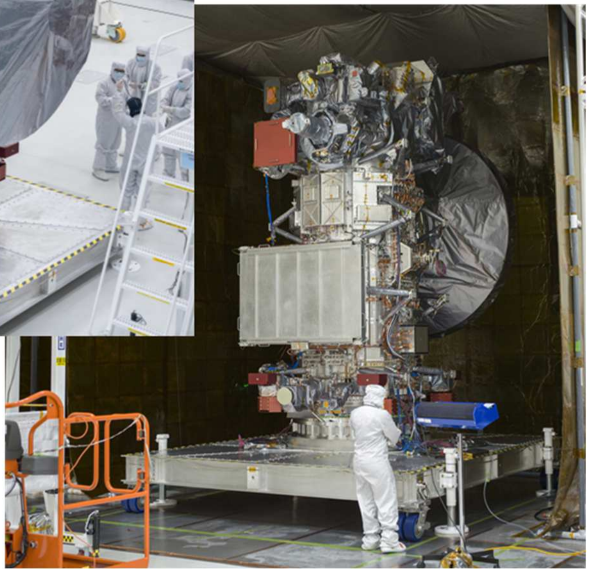
- Flight power subsystem design has passed functional and environmental testing and been verified to robustly satisfy all mission requirements
- Hardware complies to all requirements for stability, load transient tolerance, EMI/EMC, and supports dead bus recovery
- System has been analyzed to show margin across the challenging environmental and life conditions of the Europa Clipper mission.
- Power subsystem flight hardware installed on vehicle
- Spacecraft has completed all environmental tests

- Next steps:
  - Final checkouts at JPL
  - Shipment to Kennedy Space Center
  - Preparation for launch in October 2024

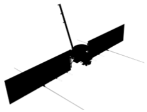
Spacecraft Status as of August 14, 2023



January 30, 2024



Acknowledgements & References



- The final implementation of the Europa Clipper power subsystem represents the work of countless teammates both at JPL as well as multiple institutions. We would like to thank our teammates from the Europa Clipper project, flight system, and instrument teams who helped to define and influence the final design. Many of these people are authors or mentioned in the papers referenced below.
- We'd like to specifically thank Jaber Abu-Qahouq, Charles Benson, Leo Bister, Steve Dawson, Tracy Drain, James Fischer, Mike Gross, Chris Ianello, Tejas Kularni, Sonny Orellana, Andres Rivera, Joel Schwartz, and Jeff Srinivasan.
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