# Is MBSE Helping?

## *Measuring Value on NASA's Europa Clipper Mission*

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*JANNAF 12th Modeling and Simulation Meeting*
*24 May 2018*


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# Topics

- Background and Context
- The Five System Engineering Challenges
- Introduction to Europa Clipper
- Europa MBSE Scorecard
- Conclusions and Future Work


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# Background and Context

- JPL's Integrated Model Centric Engineering Initiative (IMCE)
  - 2009: IMCE Initiative established
  - First IMCE workshop focused on ConOps.
  - Key action: determine what problems MBSE is intended to address
  - Action answered by white paper "Articulating the Need"
    - Based on review of lessons learned from recent JPL missions.
    - **Introduced the "Five System Engineering Challenges"** (later included in INCOSE Vision 2025)
  - 2012: Augmented white paper to describe explicitly how MBSE could help address SE Challenges
    - **This is the basis for a practical method for measuring value added by MBSE**
- Europa Clipper
  - 2010: Europa mission study team, during early formulation phase, partnered with IMCE to attempt a concerted adoption of MBSE.
  - 2011: Study team delivered first modeling results (Mass List) on Europa Mission
  - 2014: Europa Clipper Pre-Project Team began Phase A after a highly successful MCR
  - 2017: Europa Clipper Project Team began Phase B after a highly successful SRR/MDR
  - **This is a good point on the project to apply the value measurement technique**


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# Five System Engineering Challenges

1. Mission complexity is growing faster than our ability to manage it
   …increasing mission risk from inadequate specification & incomplete verification

2. System design emerges from the pieces, not from an architecture
   …resulting in systems which are brittle, difficult to test, and complex and expensive to operate.

3. Knowledge and investment are lost at project lifecycle phase boundaries
   …increasing development cost and risk of late discovery of design problems.

4. Knowledge and investment are lost between projects
   …increasing cost and risk; damping the potential for true product lines

5. Technical and programmatic sides of projects are poorly coupled
   …hampering effective project decision-making; increasing development risk.


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# Intro to the Europa Clipper Mission

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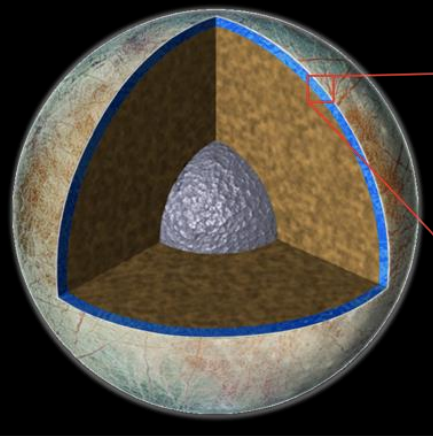
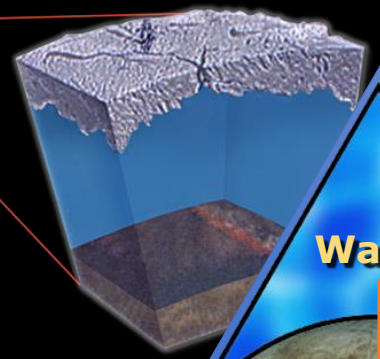
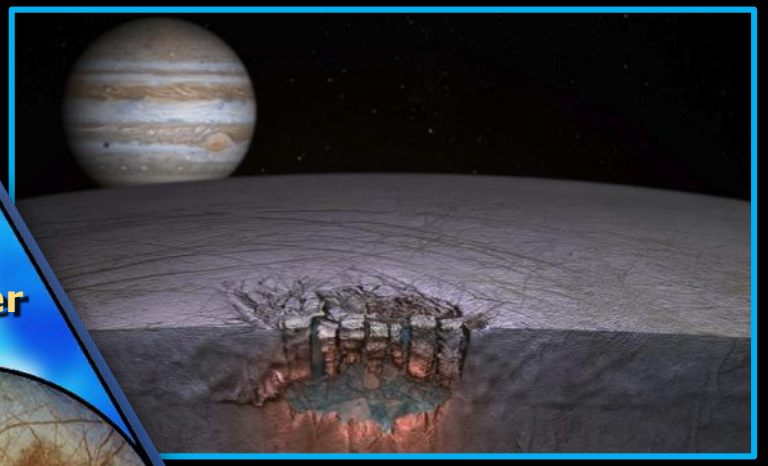
# Why Investigate Europa?

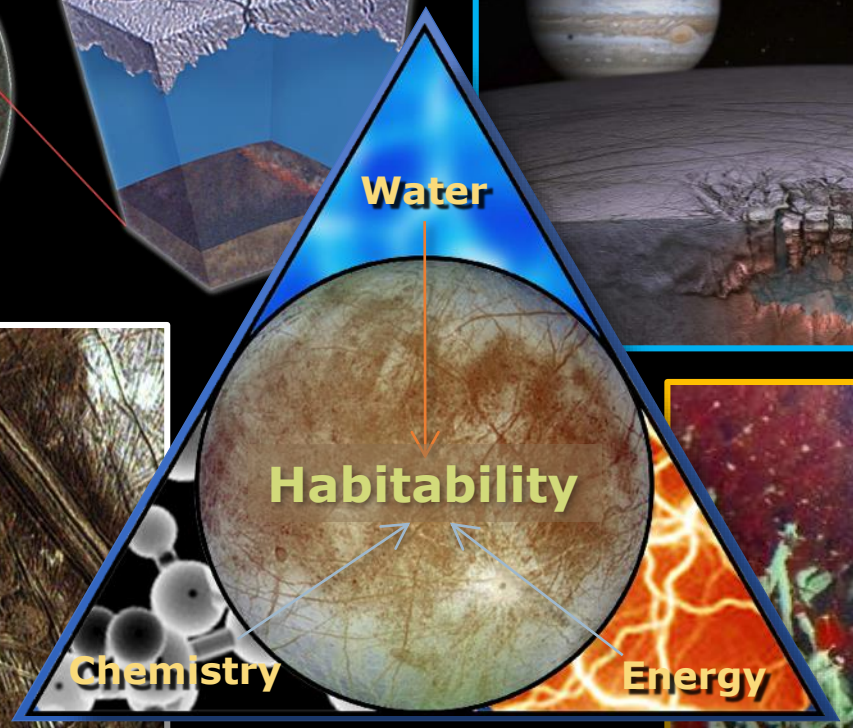
## The Search for Life

**Water:** Are a global ocean and lakes of water hidden below the ice?









**Chemistry:** Do red surface deposits tell of habitability below?

**Energy:** Can chemical disequilibrium provide energy for life?

# Europa: Ingredients for Life?

## Water:

- Probable saltwater ocean, indicated by surface geology and magnetic field
- Possible lakes within the ice shell, produced by local melting

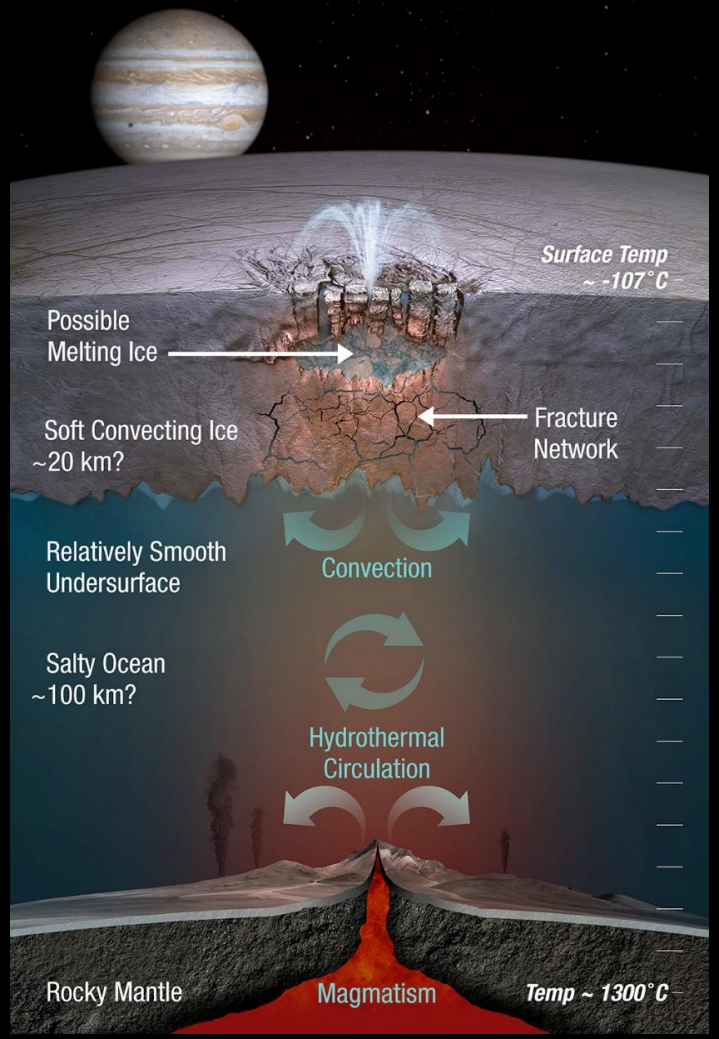
## Chemistry:

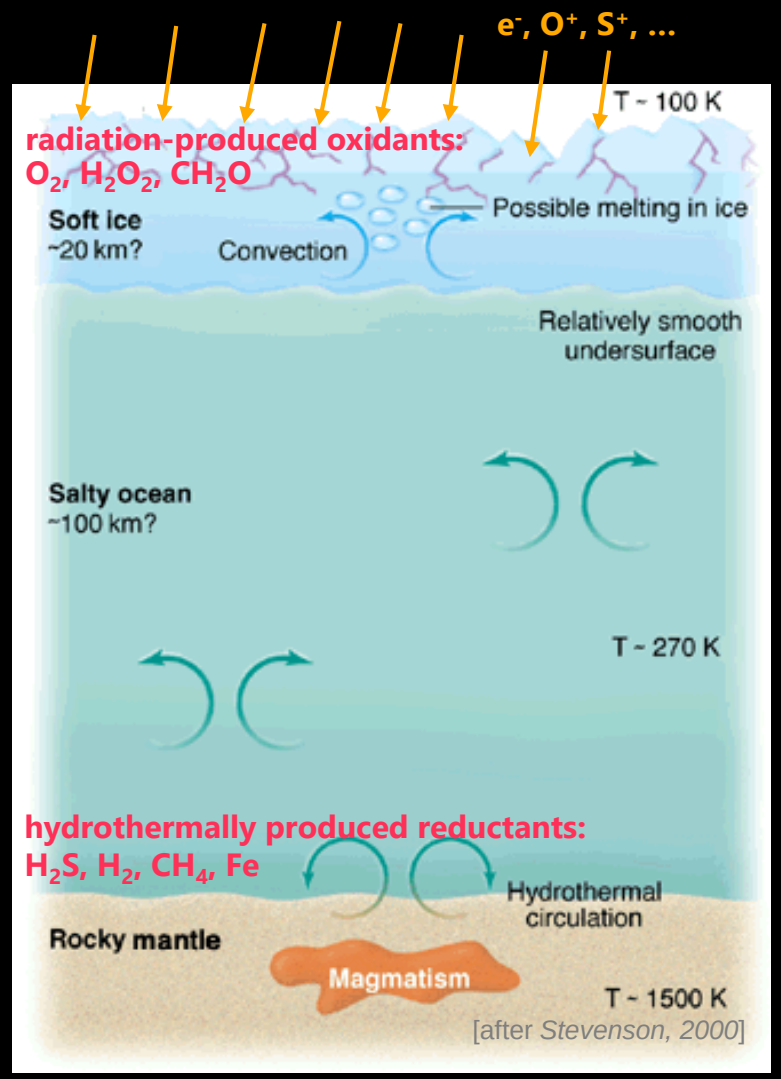
- Ocean in direct contact with mantle rock, promoting chemical leaching
- Dark red surface materials contain salts, probably from the ocean

## Energy:

- Chemical energy could sustain life
  - Surface irradiation creates oxidants
  - Mantle tidal heating could create reductants
- Geological activity would “stir the pot”

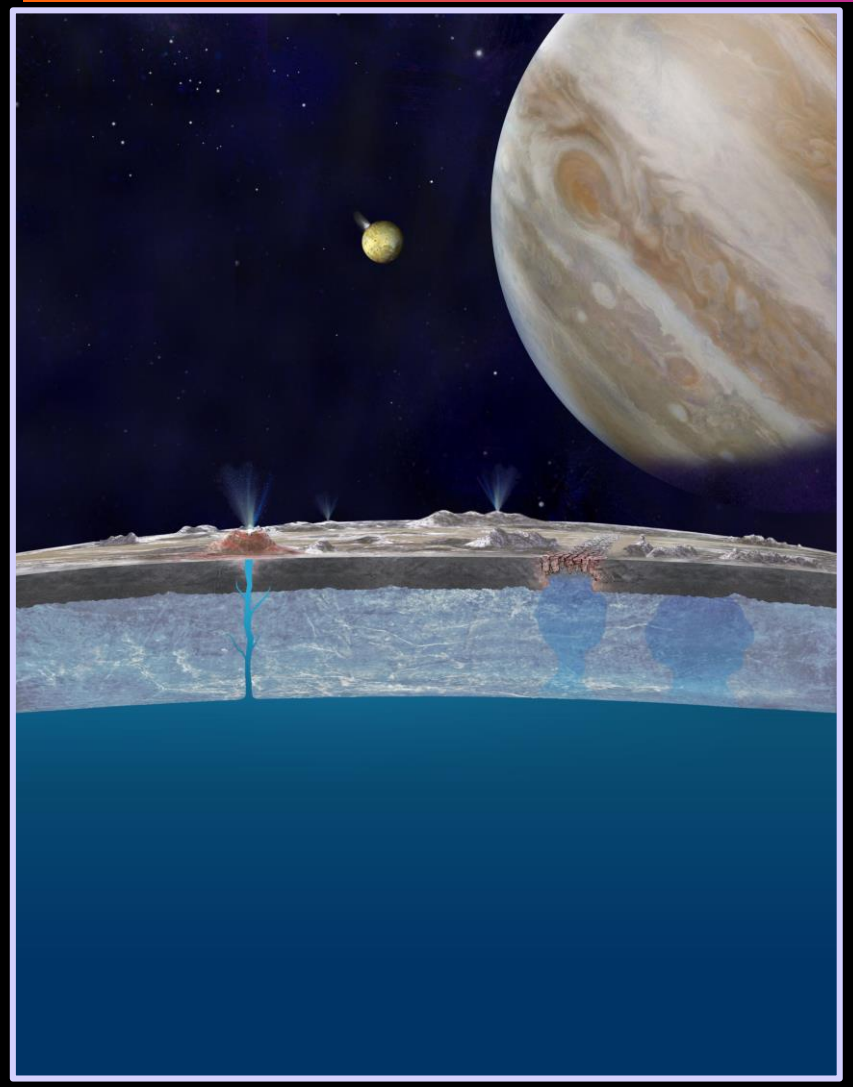
***The planned Europa mission would test habitability hypotheses***



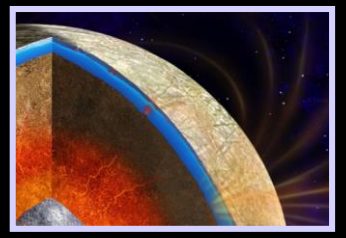

[after *Stevenson, 2000*]

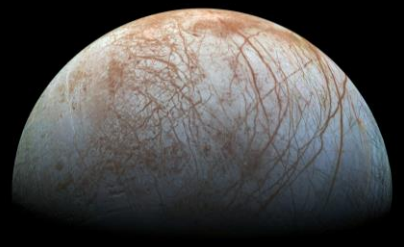
# What are we looking at?



- In Situ investigations:
  - Detect and analyze composition of Europa's thin atmosphere
  - Detect and analyze particles originating on Europa's surface
  - Measure magnetic fields
  - Measure density, flow, and energy of ions and electrons

- Remote Sensing investigations
  - Look below the surface (*ice shell and ocean sounding*)
  - Image the surface
  - Locate and characterize plumes
  - Analyze composition of surface (*organics, acid hydrates, salts*)
  - Search for thermal anomalies (*plumes, venting, resurfacing*)
  - Assess possible landing sites (*for potential future mission*)





# The Europa Clipper Instruments

## Payload specifically designed to assess habitability

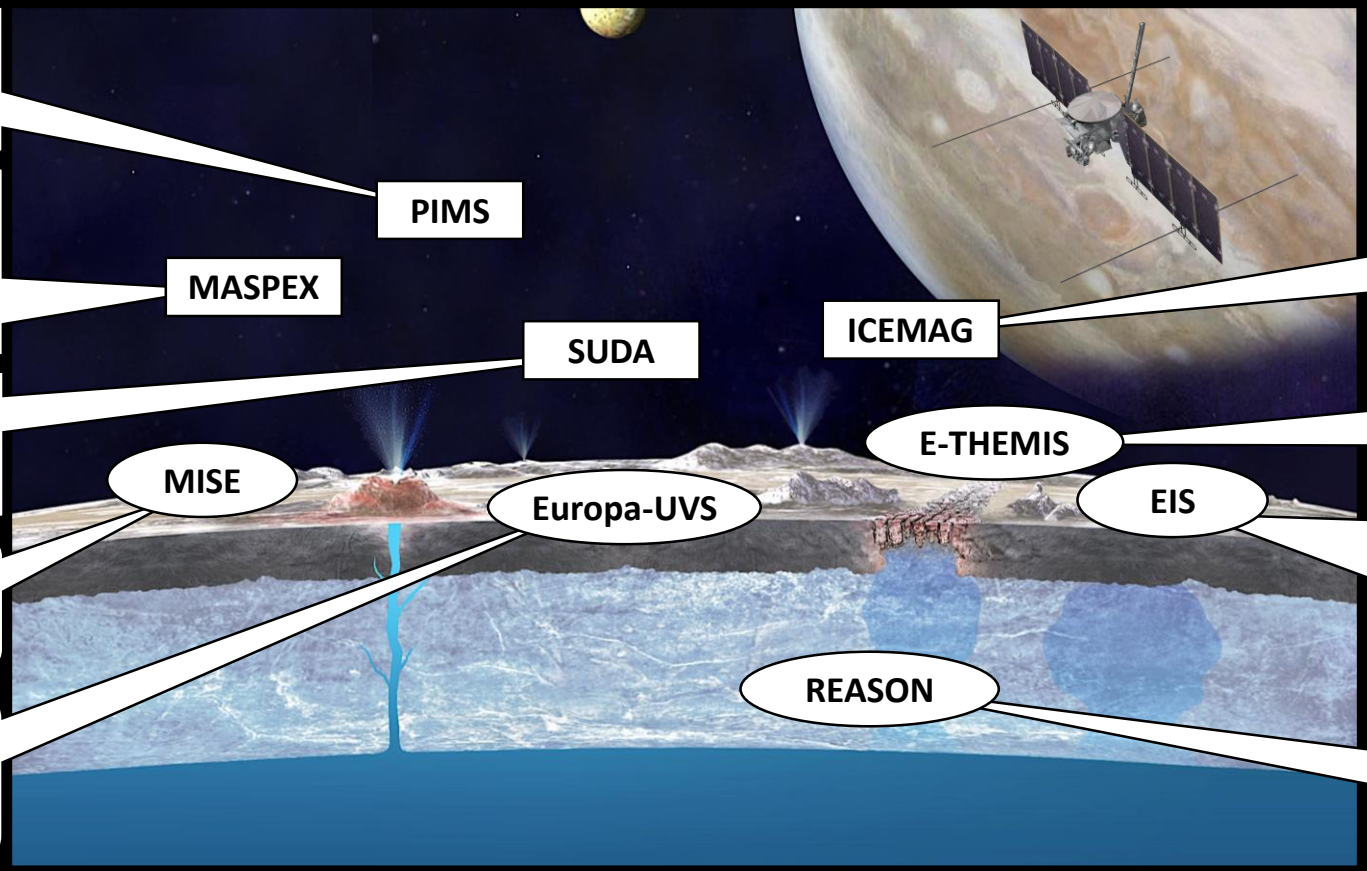
**PIMS**
*Faraday Cups*
plasma environment

**MASPEX**
*Mass Spectrometer*
sniffing atmospheric composition

**SUDA**
*Dust Analyzer*
surface & plume composition

**MISE**
*IR Spectrometer*
surface chemical fingerprints

**Europa-UVS**
*UV Spectrograph*
surface & plume/atmosphere composition




**In Situ**

**Remote Sensing**

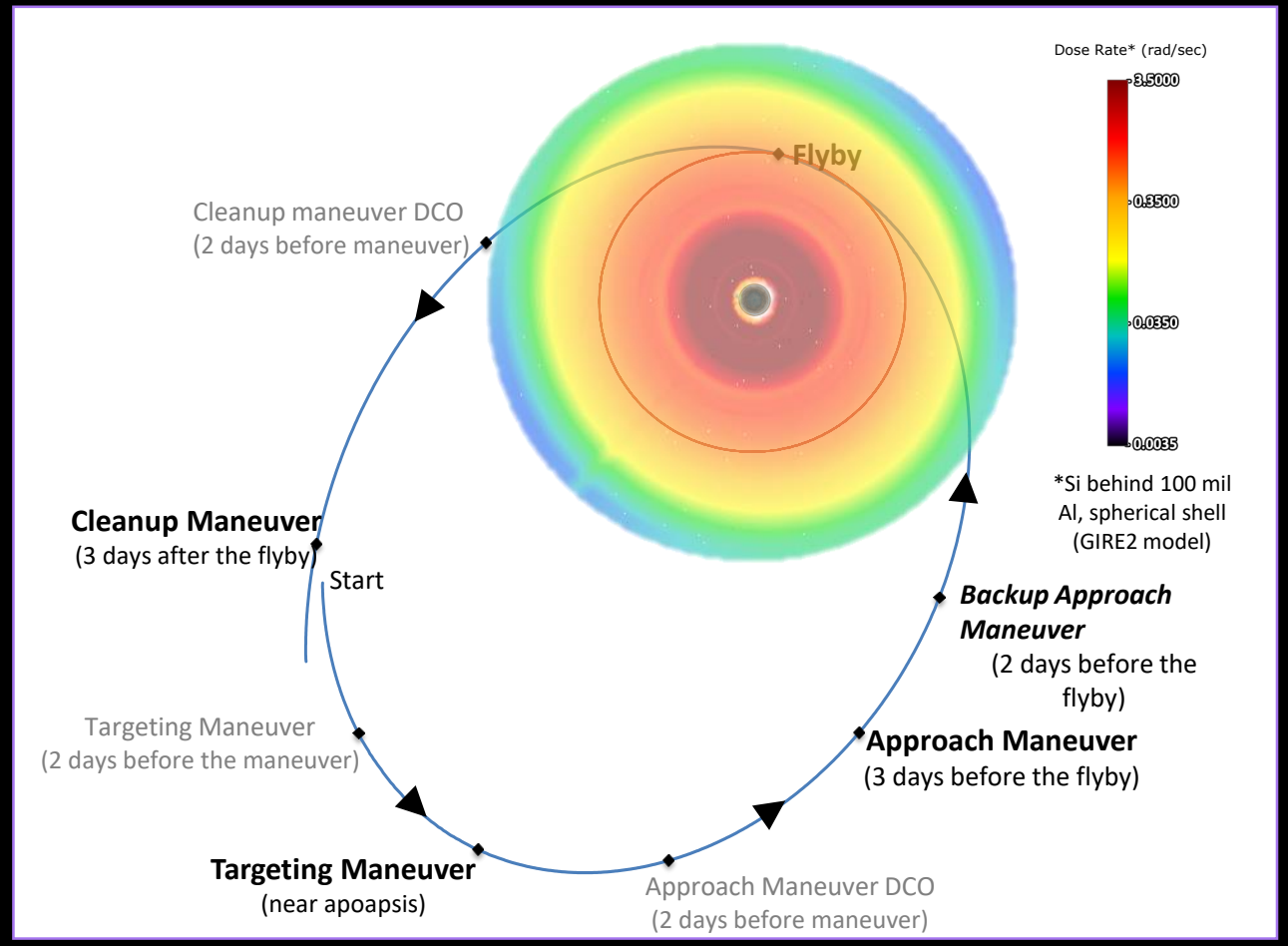
**ICEMAG**
*Magnetometer*
**sensing ocean properties**

**E-THEMIS**
*Thermal Imager*
**searching for hot spots**

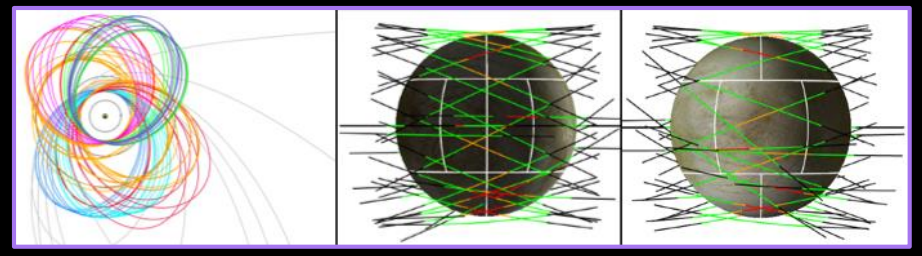
**EIS**
*Narrow-Angle Camera + Wide-Angle Camera*
**mapping alien landscape in 3D & color**

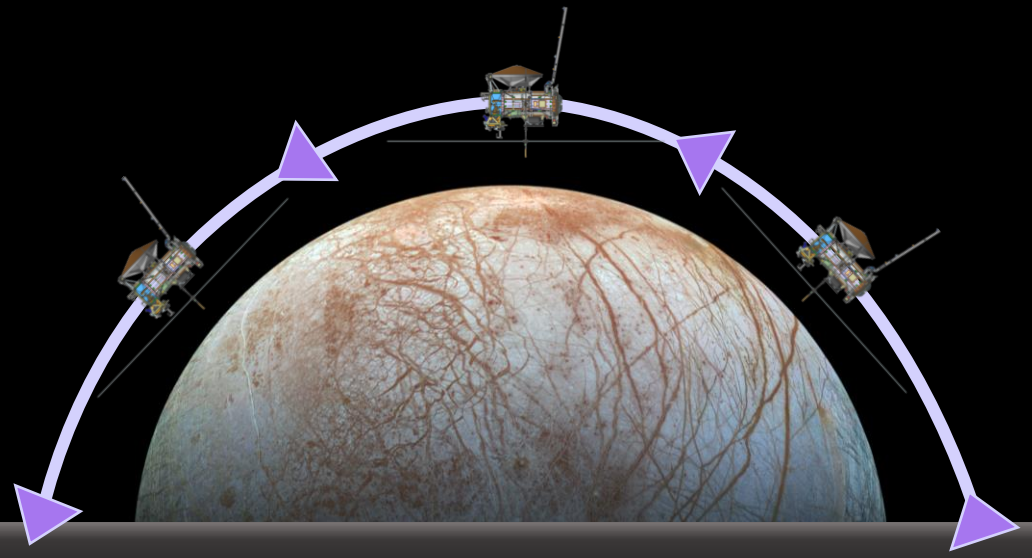
**REASON**
*Ice-Penetrating Radar*
**plumbing the ice shell**

# Challenge: Radiation

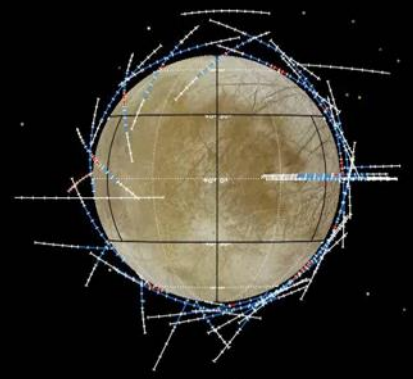


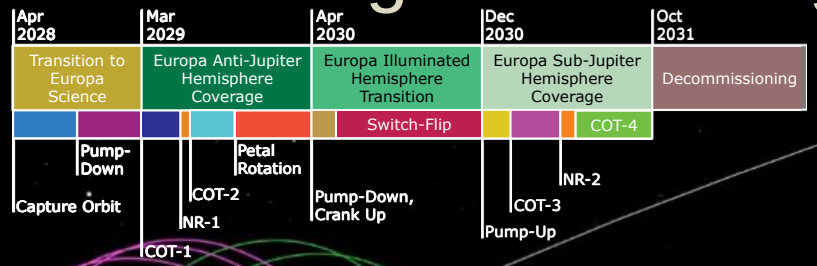

Strategy 1: Radiation-tolerant parts
Strategy 2: Vault (shields electronics)
Strategy 3: Flyby trajectory design
(*minimize time in intense radiation*)

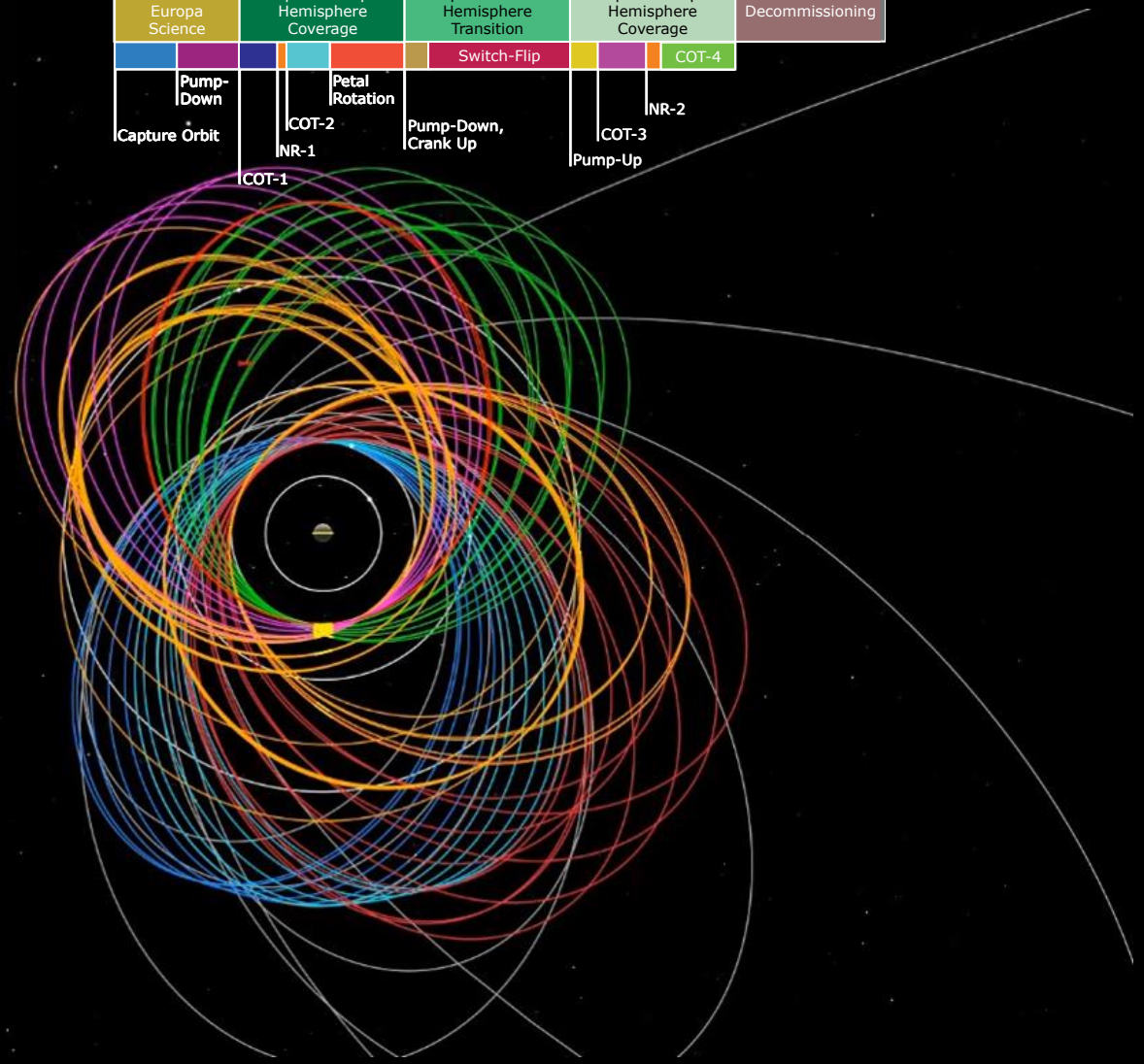




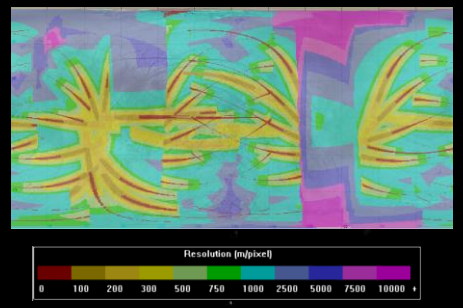
# Innovative Mission Design is Enabling



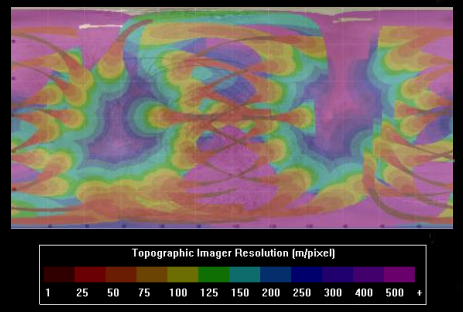


SWIRS




Topographic Imager





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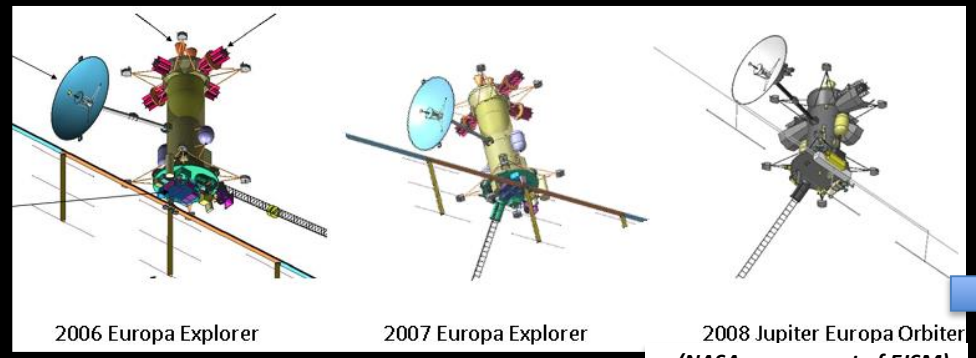
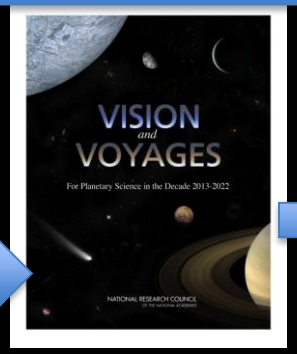
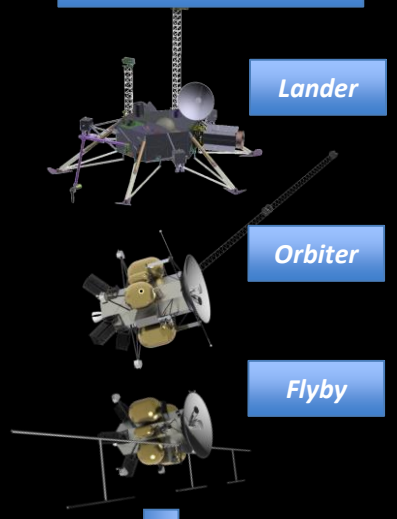
# The long road to the current concept




Decadal Survey 2011

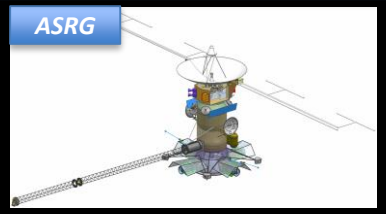


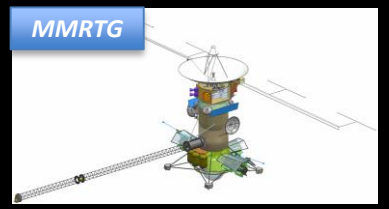

Mission Studies 2011

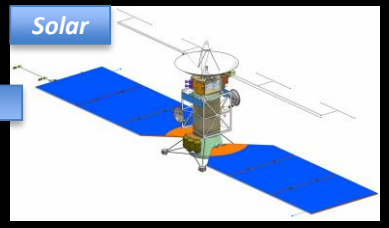


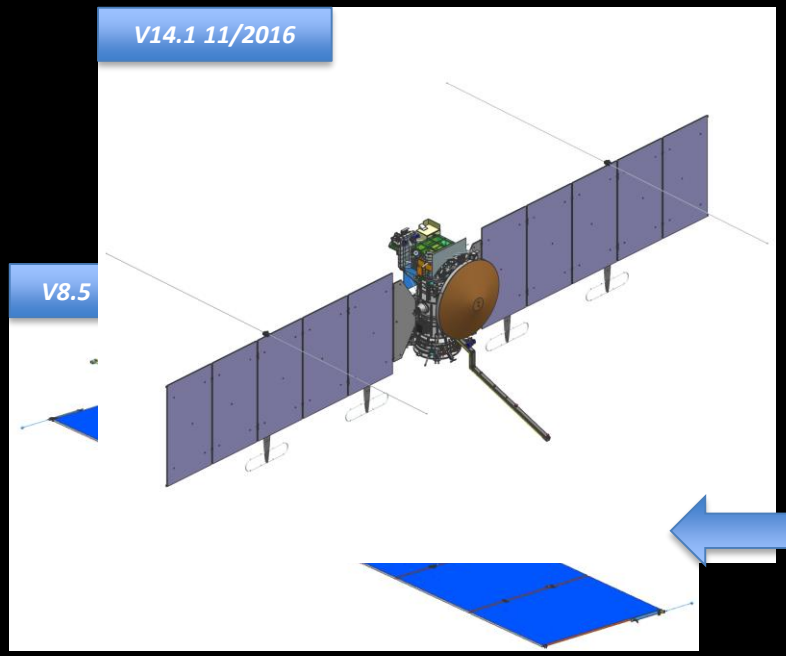
Europa Clipper (Flyby)
2012

Power Source Trades
2013 and 2014





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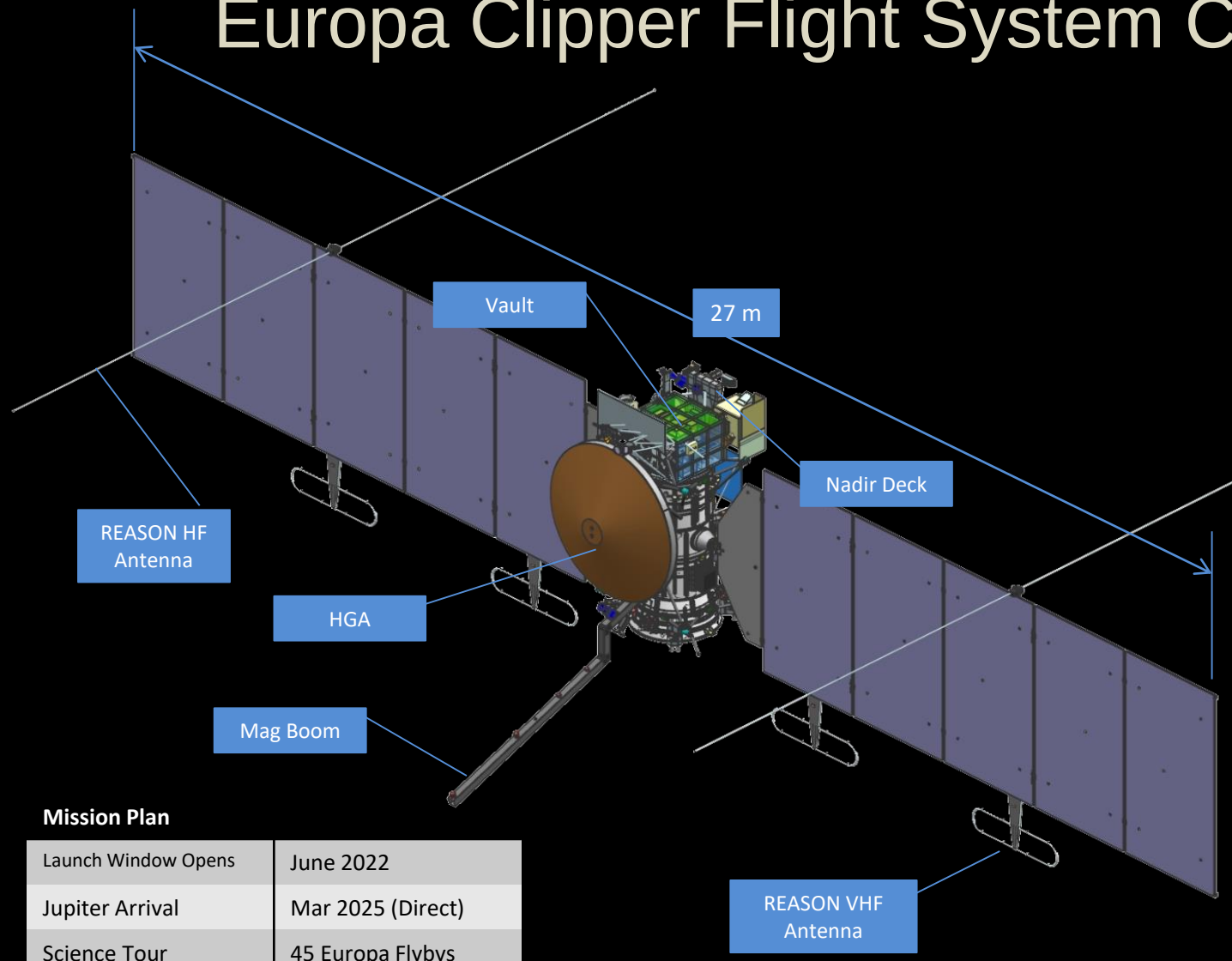
# Europa Clipper Flight System Concept




**Selected Science Payload**

| Acronym | Instrument |
|---|---|
| REASON | Ice Penetrating Radar |
| EIS NAC/WAC | Topographical and Reconnaissance Imager |
| MISE | Shortwave Infrared Spectrometer |
| E-THEMIS | Thermal Imager |
| ICEMAG | Magnetometer |
| MASPEX | Neutral Mass Spectrometer |
| PIMS | Plasma Probe |
| SUDA | Dust Analyzer |
| GS | Gravity Science |

**Mission Plan**

| | |
|---|---|
| Launch Window Opens | June 2022 |
| Jupiter Arrival | Mar 2025 (Direct) |
| Science Tour | 45 Europa Flybys |
| Primary Mission End | Dec 2028 (Ganymede Impact) |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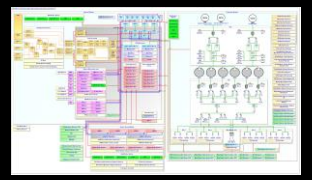
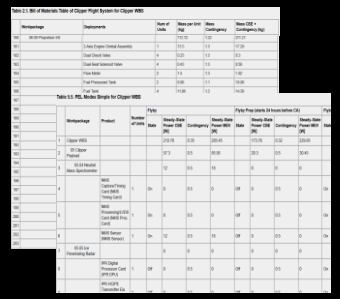
# Europa System Model Framework

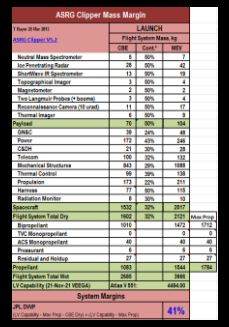
**SysML Models**
System, Programmatic, etc.

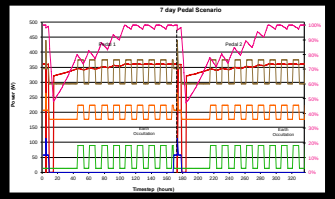
magicdraw

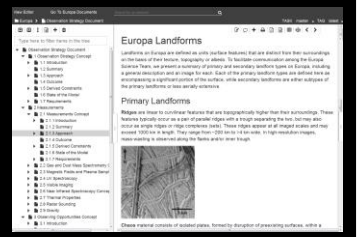
| Block Diagram Viewpoints | Mass/Power/Data Equipment List Viewpoints | Mass Margin Viewpoints | Power Scenario Viewpoints | Concept Viewpoints | Requirement Viewpoints | … |
|---|---|---|---|---|---|---|
| Block Diagram | MEL/PEL/DEL Tables | Mass Margin Analysis & Report | Power/Energy Margin Analysis | Conceptual Descriptions | Requirement Documents | |







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# MBSE Scorecard for the planned Europa Mission


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# Scorecard: Challenge 1

## Challenge 1: Growing Risk from Unmanaged Complexity

**Mission complexity is growing faster than our ability to manage it, increasing mission risk from inadequate specification & incomplete verification**

| Specific Issues | Envisioned Mitigations 2012 | Europa Clipper Actual 2016 |
|---|---|---|
| System behavior is often an emergent property discovered during system test | Enhanced understanding of system behavior and reasoning about engineering completeness | FDDs with rigorous behavior diagrams allowed discovery of missing functions and requirements |
| Design errors are introduced through miscommunication and go undetected until system test or even operations | Improved communication and reduced confusion using 'Single Source Of Truth' (SSOT) information | System Model has saved time, prevented errors, minimized drudge work |
| System properties are generated infrequently and at significant cost | Automatically generated human-interpretable documentation provides frequent and authoritative snapshots of system properties | Machine generated documentation provides monthly snapshots:<br>- System Model releases (MEL, PEL, block diagrams, system margins, etc)<br>- Concept Descriptions<br>- Requirements Documents<br>- Functional Description Documents |
| Design description comes together only infrequently, when preparing for major reviews | Design reviews consist largely of model inspection and validation | Informal working level reviews often use model directly (MEL, PEL, '- Block Diagrams, Modes, Scenarios, Requirements, Concepts, FDDs)<br><br>MCR, and SRR/MDR were still hand-crafted powerpoint slide decks that tell a story BUT<br>- more content came directly from system model, and<br>- there were no major surprises in the review prep |

| Key: | Good |
|---|---|
| | Partial |
| | Future Phase |


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# Scorecard: Challenge 2



## Challenge 2: System Design Emerges from the Pieces

**System design emerges from the pieces, rather than from an architected solution, resulting in systems which are brittle, difficult to test, and complex and expensive to operate.**

| Specific Issues | Envisioned Mitigations 2012 | Europa Clipper Actual 2016 |
|---|---|---|
| Architectural principles are seldom articulated or used in design | Having a better way to talk about our systems at an architectural level enables us to do a better architecting job: better separation of concerns; less unnecessary coupling; more coherence of function | - Explicit articulation and separation of concerns<br>- Thorough, linked, living rationale for requirements<br>- Multiple constraints explicitly reconciled<br>- Analyses explicitly included in requirements flow<br>- Requirements explicitly associated with components |
| System designs are spread across multiple disconnected artifacts | Design discussions between subsystems and with systems use common, authoritative representations | - SSOT for mass, power, composition, suppliers, interfaces, requirements.<br>- System Model enables engineers to work and think at a higher level.<br>- System Modeling is a viable part of SE career path |
| Domain physics-based models are not connected to each other or to a system model | -Integrated models enable early validation of requirements completeness, operability, performance<br>- Integration with physics-based models enables more complete design space exploration | - Integration of high fidelity power model, sequencing planner, system model enabled full mission energy modeling (more examples to come!)<br>- System Model provides stable, repeatable inputs<br>- Better validation of System Model due to wide availability and use. |
| Insufficient consideration of V&V during requirements development | System model captures and encourages early V&V planning | A start: Requirements, components, functions explicitly associated.<br>Phase B: integrate V&V events into system model |
| Actual science merit of a given point solution is not known until late | Architecture trades in formulation are informed by quantitative comparisons of science return | - Science coverage of proposed Jovian tours (SIMPLEX)<br>- Science data return with radiation upsets<br>- Gravity science modeling |
| Desired system behaviors are poorly articulated, resulting in software whose behavior must be 'discovered' | System Behavior is specified rather than discovered:<br>- SE and SW collaborate on behavior models which are executable/analyzable to discover logic flaws very early<br>- FSW directly implements behavior models | A start.<br>- FDDs with explicit behavior diagrams<br>- Power, Data Sims use scenarios in System Model<br>- Phase B: make executable/autocodeable using SysML |
| | Proposed design changes are expressed, analyzed, and considered by change boards in the system model directly | A start. System model impacts reported at Change Board, but model branch/merge is still being perfected |

| Key: | |
|---|---|
| | Good |
| | Partial |
| | Future Phase |


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# Scorecard: Challenge 3

## Challenge 3: Investments Lost at Phase Boundaries

**Knowledge and investment are lost at project lifecycle phase boundaries, resulting in increased development cost and risk of delayed discovery of design problems.**

| Specific Issues | Envisioned Mitigations 2012 | Europa Clipper Actual 2016 |
|---|---|---|
| Formulation models are abandoned and new ones created when Implementation phase begins | System models evolve and mature from formulation through operations<br>Rapid Mission Architecting and TeamX will eventually draw from the same line-developed model libraries as the implementation team | - System Model has been used and evolved from Pre-Phase A through Phase A and into Phase B.<br>- Identical automated analyses have been applied to all configurations and versions, providing continuous history of concept evolution. |
| CM of existing models is lacking, impeding continued use | Configuration management of the system design is rigorous, for the first time | - Successfully configuration managed the mission concept Pre-Phase A and Phase A.<br>- This coupled with the iterative approach have allowed a concept to evolve in a controlled way.<br>- Build up to major gate reviews is no longer the only time the baseline comes together. No major suprises at either gate review prep. |
| Essential attributes of design are not captured consistently in readily accessible manner:<br>- Architectural principles<br>- Trade study assumptions and rationale<br>- System Design | Rich capture of design information is enabled: structure, behavior, requirements, and parametrics connected in a unified model | A start. Structure, behavior, requirements, delivery responsibility are linked. More linkage is possible |
| Training takes longer than necessary<br>- Affects staffing arc during phases A-D<br>- Affects team turnover as projects moves into operations | - Model repositories enable quicker, more effective and less expensive training<br>- They also enable ongoing independent study and exploration | - Vastly improved access to information for new team members. Rich system model allows self-study and exploration. |

| Key: | |
|---|---|
| | Good |
| | Partial |
| | Future Phase |


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# Scorecard: Challenge 4

## Challenge 4: Insufficient Re-use of System Designs

**Knowledge and investment are lost between projects, increasing cost and risk, and damping the potential for true product lines.**

| Specific Issues | Envisioned Mitigations 2012 | Europa Clipper Actual 2016 |
|---|---|---|
| System architectures and designs are not well-captured. Re-using them on subsequent projects is difficult and seldom happens -- except where the project team itself is 'inherited' by the next project | - Architecture and detailed designs are captured in a formalized and repeatable system model<br>- Once the architecture is captured, it is possible to consider reusing all or part of it | Within Clipper,<br>- Enabled 5 major architectural variants to be analyzed in parallel in Pre Phase A.<br>- Enabled 3 full mission studies in the time it usually takes for 1 or 2 |
| | | Between projects:<br>- Capabilities have been adapted for use in other projects with little additional effort (Clipper NRE is paying off): M2020, ARRM, others<br>- Mission architectures have not yet been shared between projects. TBD in subsequent projects. |
| Too much of the system development "way of doing business" is custom<br>-tools (some)<br>-models (more)<br>-processes(much more) | - Increased reuse System Engineering Line Organizations join Subsystem Line Organizations in curating libraries of CM'd and reusable models, tools and processes. | - Line organizations have adopted and standardized mass and power models and tooling<br>- Line and Clipper are collaborating on additional standardized models - behavior, electrical interfaces, etc. |

| Key: | |
|---|---|
| | Good |
| | Partial |
| | Future Phase |


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# Scorecard: Challenge 5

## Challenge 5: Poor Technical - Programmatic Coupling

**Technical and programmatic sides of projects are not well-coupled, hampering effective project decision-making and increasing development risk.**

| Specific Issues | Envisioned Mitigations 2012 | Europa Clipper Actual 2016 |
|---|---|---|
| Cost, schedule, scope, investment, risk implications of a given set of requirements, science objectives, components, functions is very difficult to determine. | Behavioral, physical, cost and risk models are integrated allowing for an integrated fully-informed approach to system optimization | A start: System Model used as input to Phase A cost models for multiple architecture variants, allowing more reliable and comparable cost model results. |
| Trade studies seldom fully incorporate programmatic considerations. Existing tools do not support such a view. | Risk and resource implications of trade study options will be better understood | A start: Model enables better trade choices: identical automated analyses are applied to all configurations and versions, providing more consistent, controllable generation of system metrics and normalization of risk assessment. |

| Key: | |
|---|---|
| | Good |
| | Partial |
| | Future Phase |


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# Future Work: Some improvements will first be apparent in future mission phases



## Challenge 1: Growing Risk from Unmanaged Complexity

| Specific Issues | Envisioned Mitigations 2012 | Europa Clipper Actual 2016 |
|---|---|---|
| System test must cover full set of possible behaviors | System test activities focus on model validation and correlation | TBD in Phase D |
| - Mission Ops teams must work around unresolved development issues<br>- Significant in-flight anomalies can occur; some are mission-threatening | Fewer surprises and workarounds in operations. | TBD in Phase D/E |

## Challenge 2: System Design Emerges from the Pieces

| Specific Issues | Envisioned Mitigations 2012 | Europa Clipper Actual 2016 |
|---|---|---|
| | Kludges are less necessary and their impact more fully understood | A start. More reliable margins -> fewer resource "hunts" -> less future regret from hasty decisions. TBD in Phase B/C/D |
| Where they exist, principles are abandoned to solve pressing technical problems | Architectural principles are explicit and enforceable in the design | A start. Explicit association of requirements with system components is first step to enabling performance assessment against requirements. |
| Desired system behaviors are poorly articulated, resulting in software whose behavior must be 'discovered' | Missions arrive at the launch pad with more of their architecture intact, reducing operations cost and risk | TBD in Phase B/C/D |
| Control parameters for a function are scattered across the system | Integrated model at parameter level enables synoptic view and minimizes chance of missed interactions | TBD in Phase C/D |

## Challenge 4: Insufficient Re-use of System Designs

| Specific Issues | Envisioned Mitigations 2012 | Europa Clipper Actual 2016 |
|---|---|---|
| Heritage reviews narrowly focus on full re-use of components | Well-architected systems have less tightly coupled parts, enabling more reuse | TBD in subsequent projects |
| The current institutional guidance (e.g., JPL Design Principles), while providing important and useful heuristics and lessons learned, is not sufficient to enable architecture re-use. | Good architecture capture enables sharing of architecture and design principles between projects | TBD in subsequent projects |


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# Conclusion

- This work has:
  1) Proposed a set of core problems which systems engineering faces.
  2) Proposed ways in which these problems can be mitigated by use of MBSE. This is used as a yardstick against which to measure attempted applications of MBSE
  3) Assessed the current state of Europa Clipper against this yardstick.
- This method should also be applicable to other organizations outside of JPL.
  - The five systems engineering challenges appear to be generally applicable and adaptable
  - The method is generic
- Europa has shown compelling benefits so far, yet there is more work, and much more promise, in the years ahead
- Final observation: Before embarking on Europa MBSE, it was extremely valuable to consider what problems could be solved and to envision what the end state might look like.
  - This guided the initial applications of MBSE and contributed significantly to their success.


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# Further Information

***For this work***
***the joint Europa/JPL Integrated Model Centric Engineering Teams***
***were awarded***
***the NASA SE Excellence Award***
***in 2013***

https://nen.nasa.gov/web/se/announcements/-/announcements/detail/2070

**Recent papers on Europa MBSE**


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