



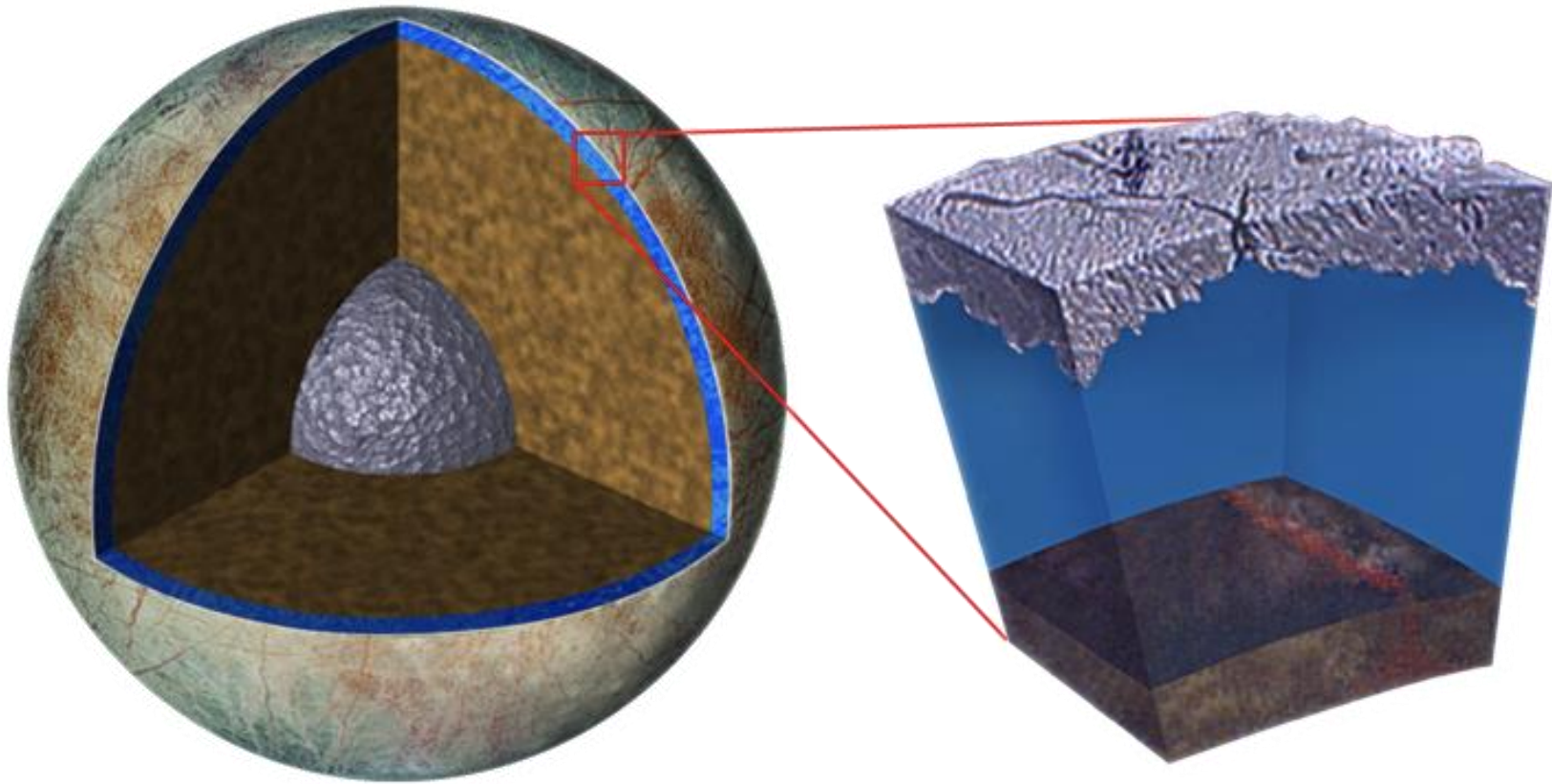
# Model-based Systems Engineering Mission Formulation and Implementation

Brian Cooke

Europa Clipper Pre-Project System Engineer  
Principal System Engineer

NASA – JPL / California Institute of Technology

# The Ocean That Beckons



*"Europa, with its probable vast subsurface ocean sandwiched between a potentially active silicate interior and a highly dynamic surface ice shell, offers **one of the most promising extraterrestrial habitable environments**, and a plausible model for habitable environments beyond our solar system"*

*"Visions and Voyages", 2011 Planetary Decadal Survey*

# 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

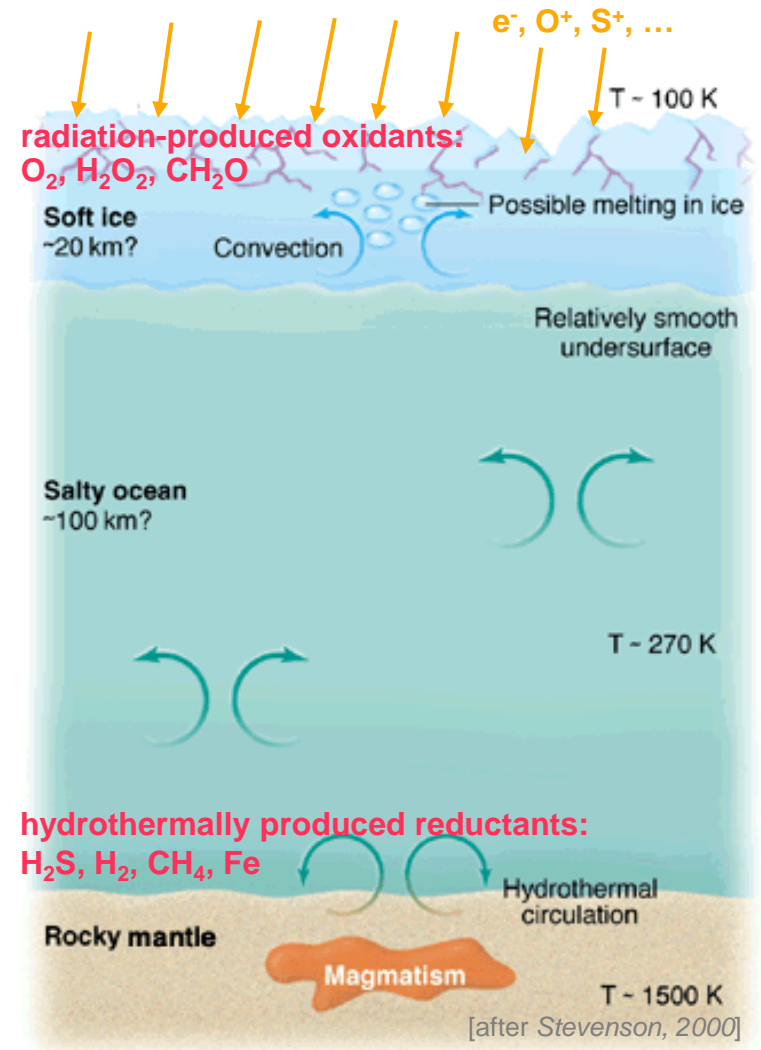
## Chemistry:

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

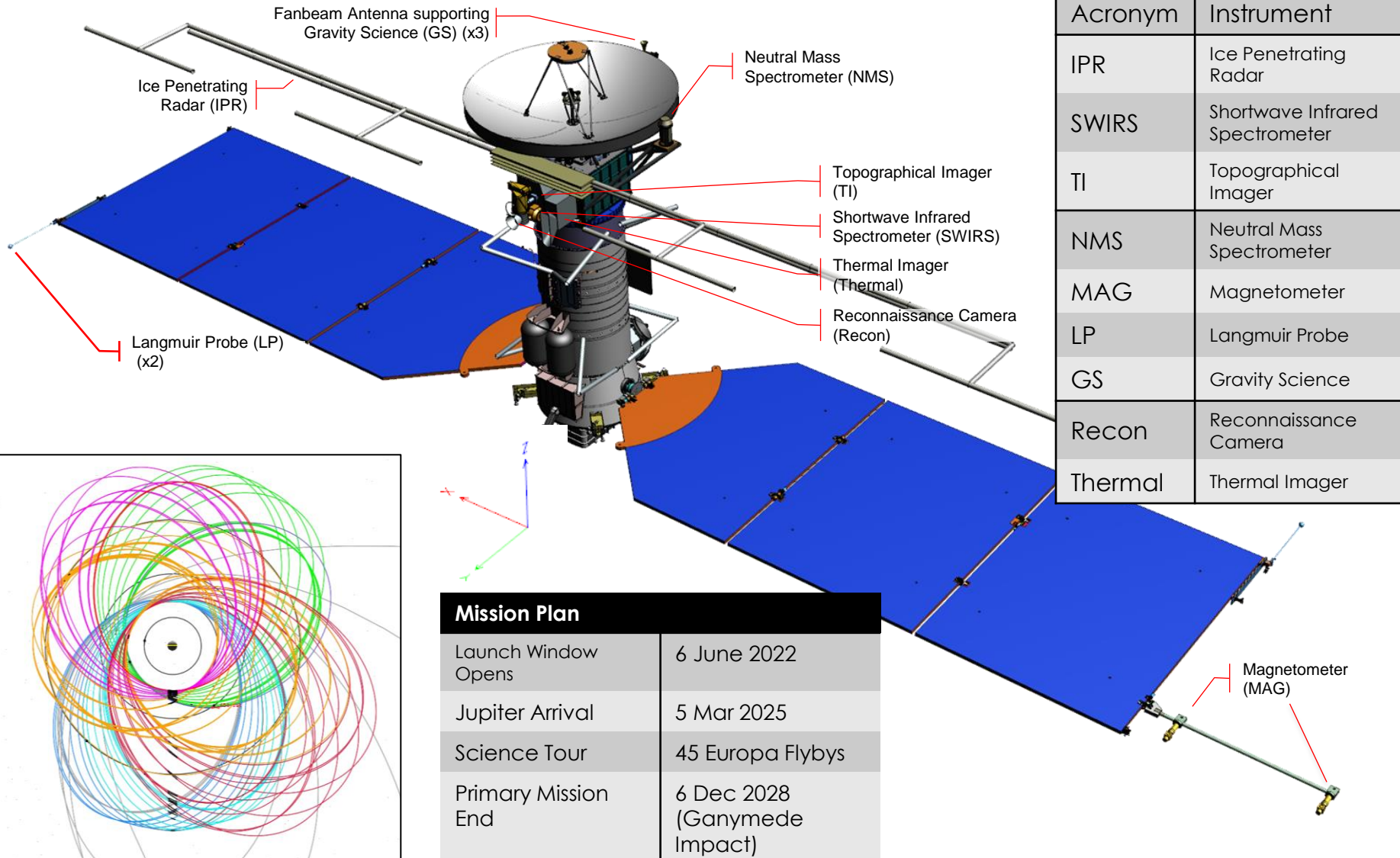
## Energy:

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

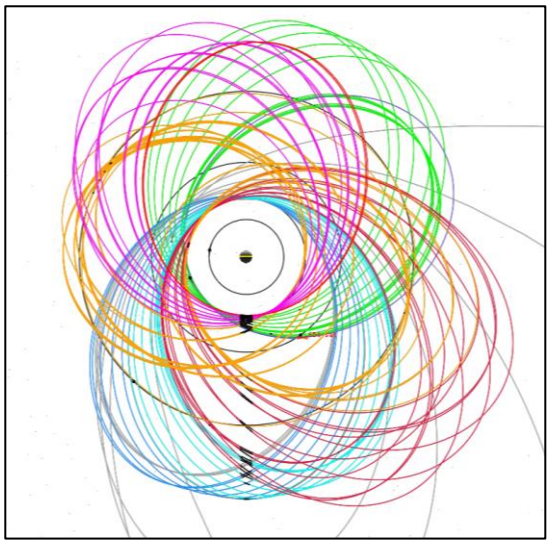
***The Europa Clipper would test habitability hypotheses***



# Europa Clipper Mission Concept Overview



Model Payload	
Acronym	Instrument
IPR	Ice Penetrating Radar
SWIRS	Shortwave Infrared Spectrometer
TI	Topographical Imager
NMS	Neutral Mass Spectrometer
MAG	Magnetometer
LP	Langmuir Probe
GS	Gravity Science
Recon	Reconnaissance Camera
Thermal	Thermal Imager



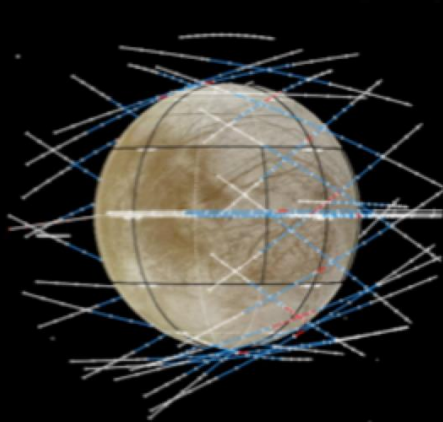
Mission Plan	
Launch Window Opens	6 June 2022
Jupiter Arrival	5 Mar 2025
Science Tour	45 Europa Flybys
Primary Mission End	6 Dec 2028 (Ganymede Impact)



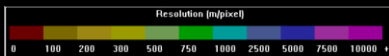
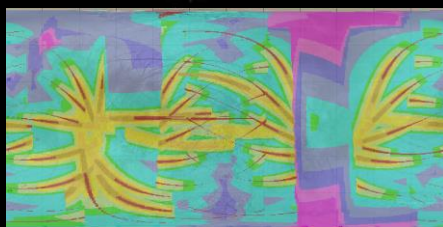
# Europa Clipper Mission Design Concept



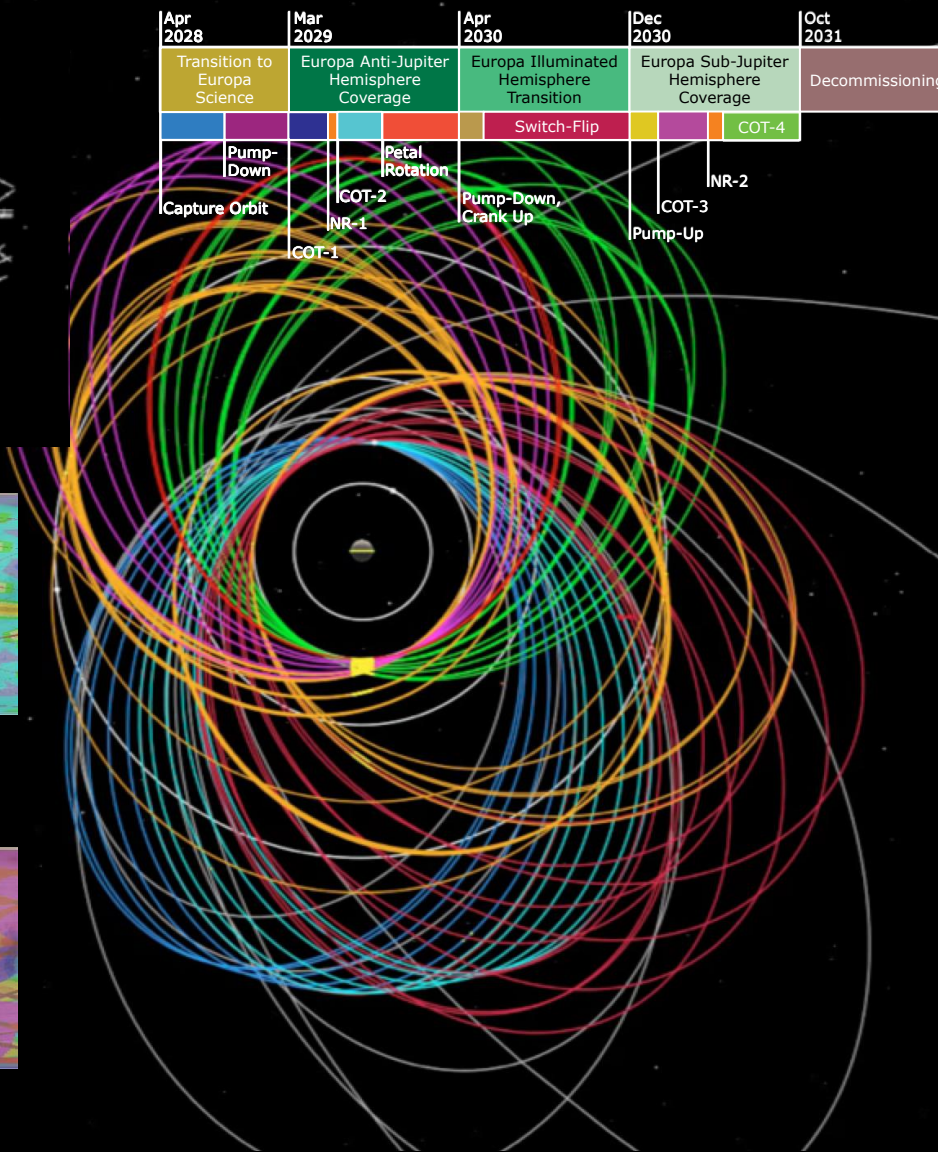
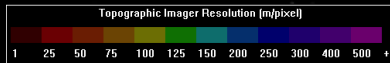
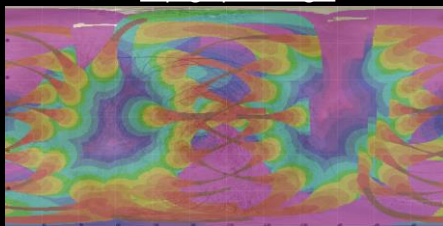
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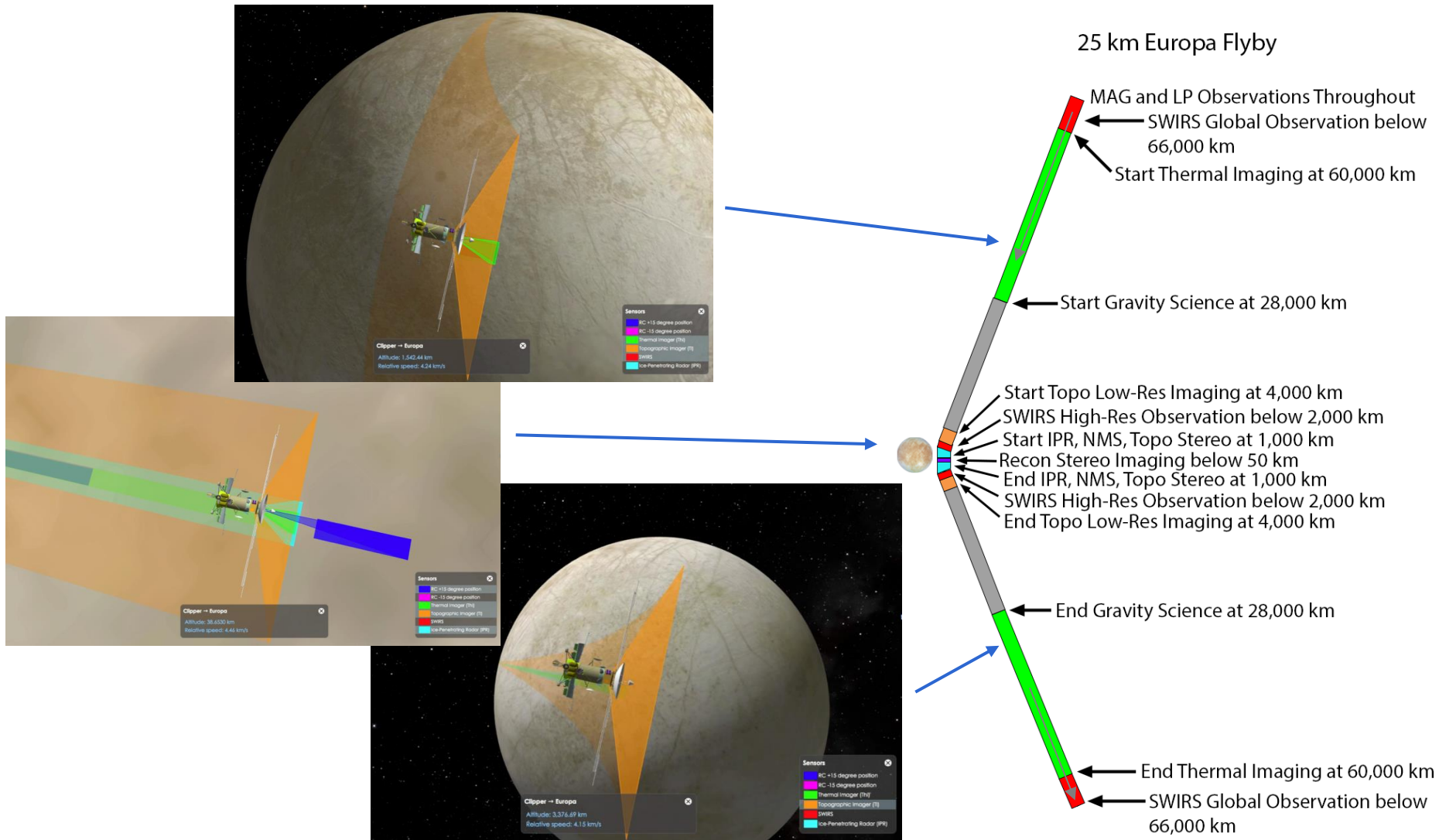
SWIRS



Topographic Imager



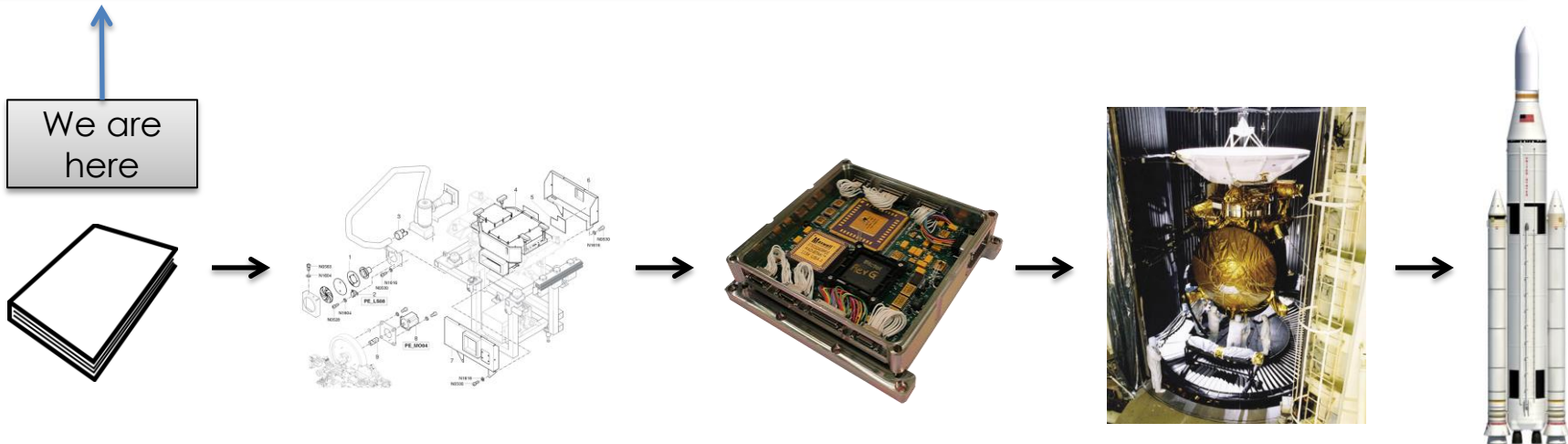
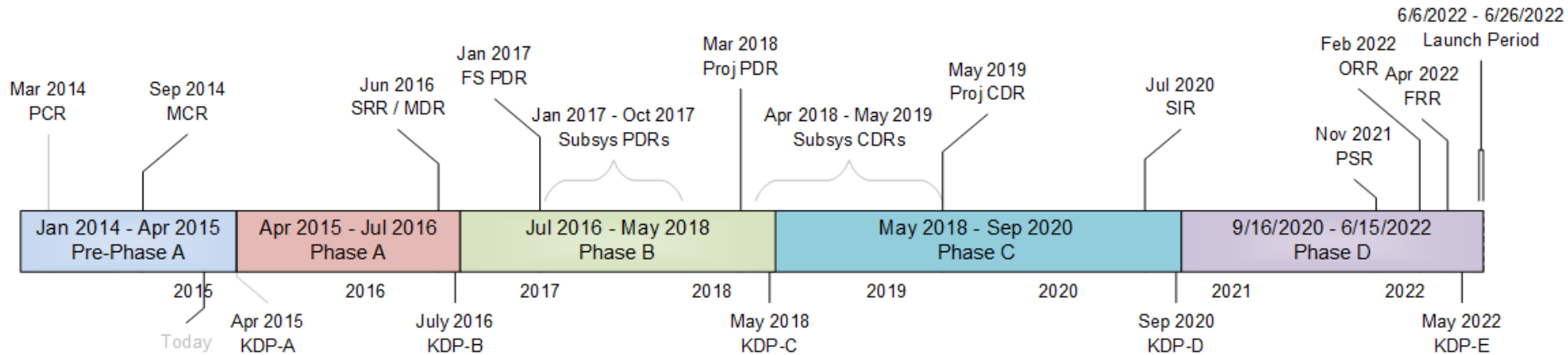
# Europa Clipper Flyby Concept



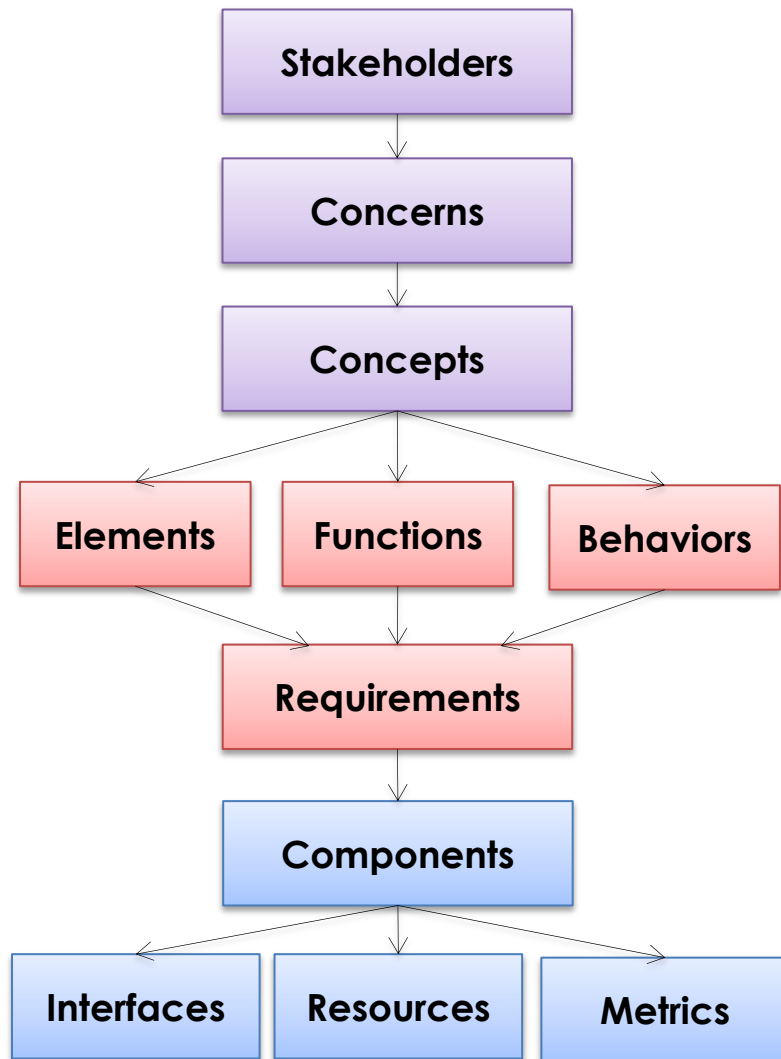
# Europa Clipper Project Schedule



## Europa Project Timeline – 2022 SLS Launch



# Model-Based System Engineering Approach



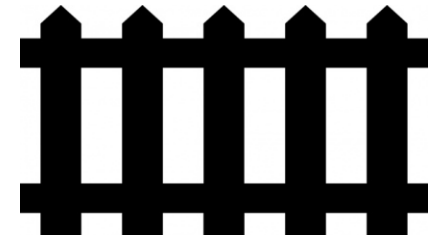
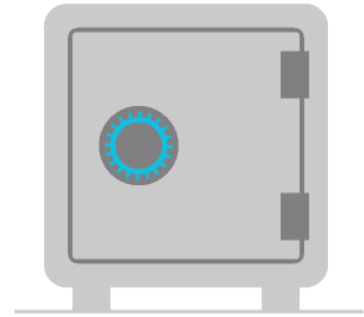
- Define formal semantics for technical information
- Construct patterns defining allowable element relationships and facilitating auditing and completeness checking
- Ensure consistency across all generated products through single-source-of-truth enforcement
- Make best use of modern information infrastructure to track details and calculate metrics; freeing engineers to consider design alternatives



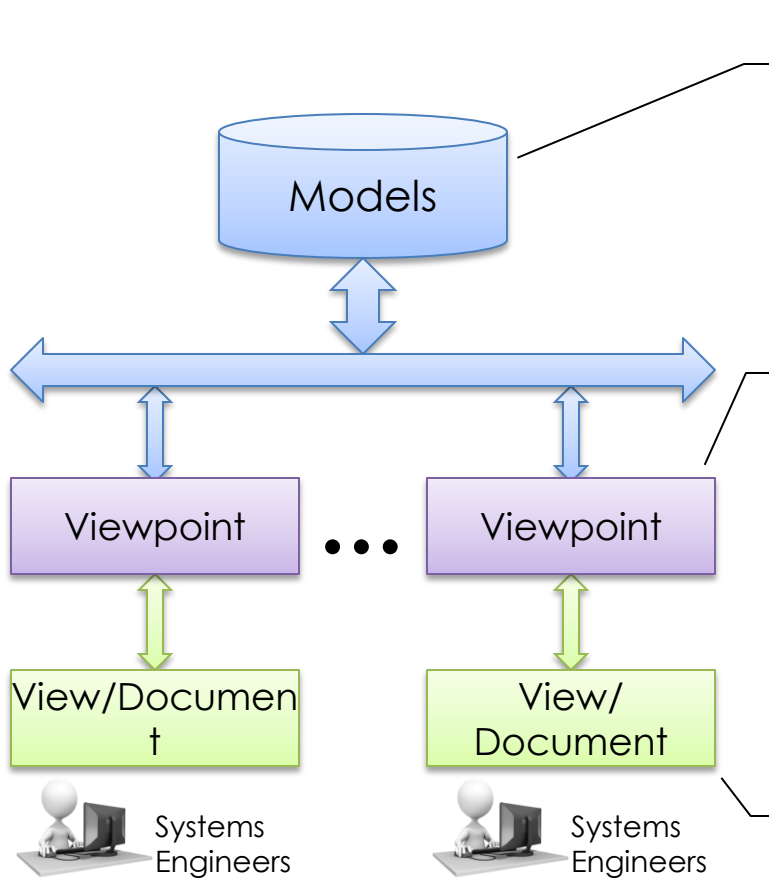
# Modern Technical Information Management System



1. Semantically Aware Information Repository
  - Automated version control
  - Layered user access control
  - Highly connected to other repository
2. Information Framework
  - Defines allowable information types and relationships
  - Explicitly excludes all else
3. Relationship Patterns
  - Defined acceptable patterns for describing information relationships and interactions
4. View / Comment / Edit Interface
  - Allowing easy, intuitive human interaction
  - Facilitating machine to machine information exchange



# Modeling & Analysis Framework

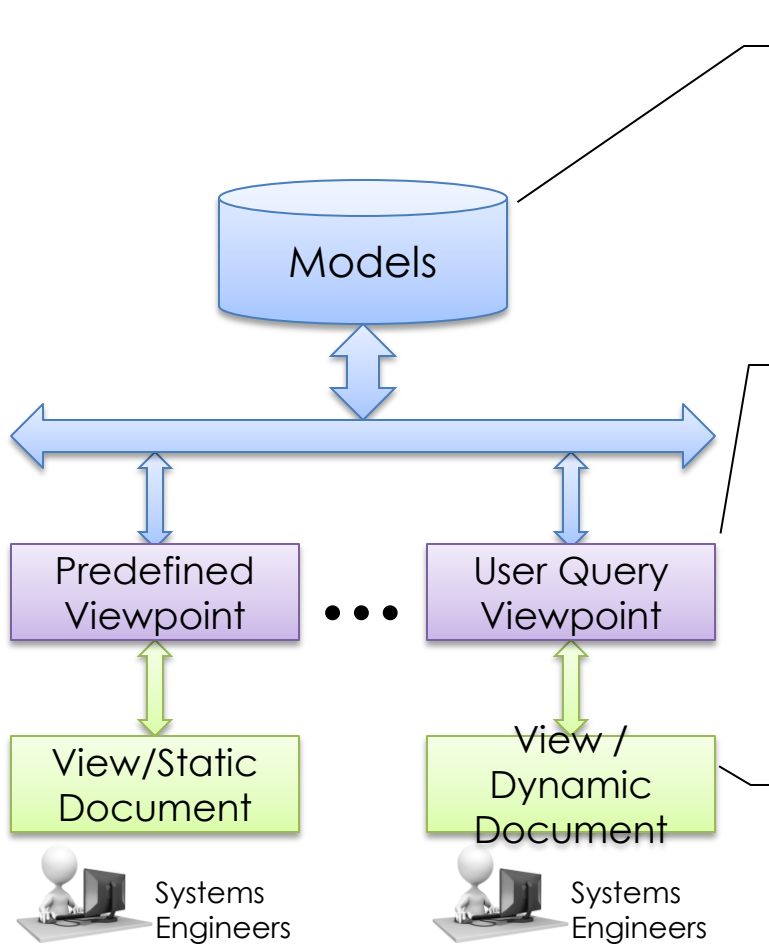


The **Single-Source-of-Truth** for all systems engineering information regarding the architecture, design and performance assessment of a system

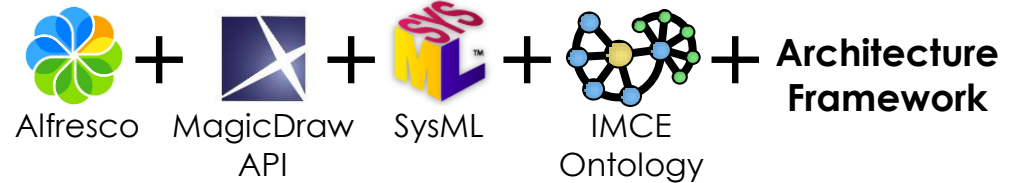
**Viewpoint** defines the subset of information of interest to address a particular topic. Combination of queries for static information and on-demand transformation or analysis

**View**, from the associated viewpoint, through which the systems engineers can view, assess, and judge the system architecture, design and performance. Provides a two way interface for editing and updating model data.

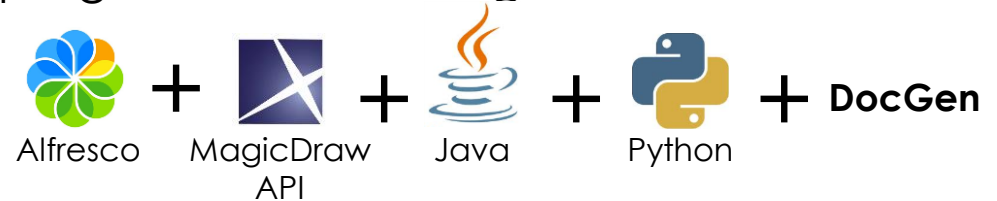
# Modeling & Analysis Framework: MEL



Captures technical information using:



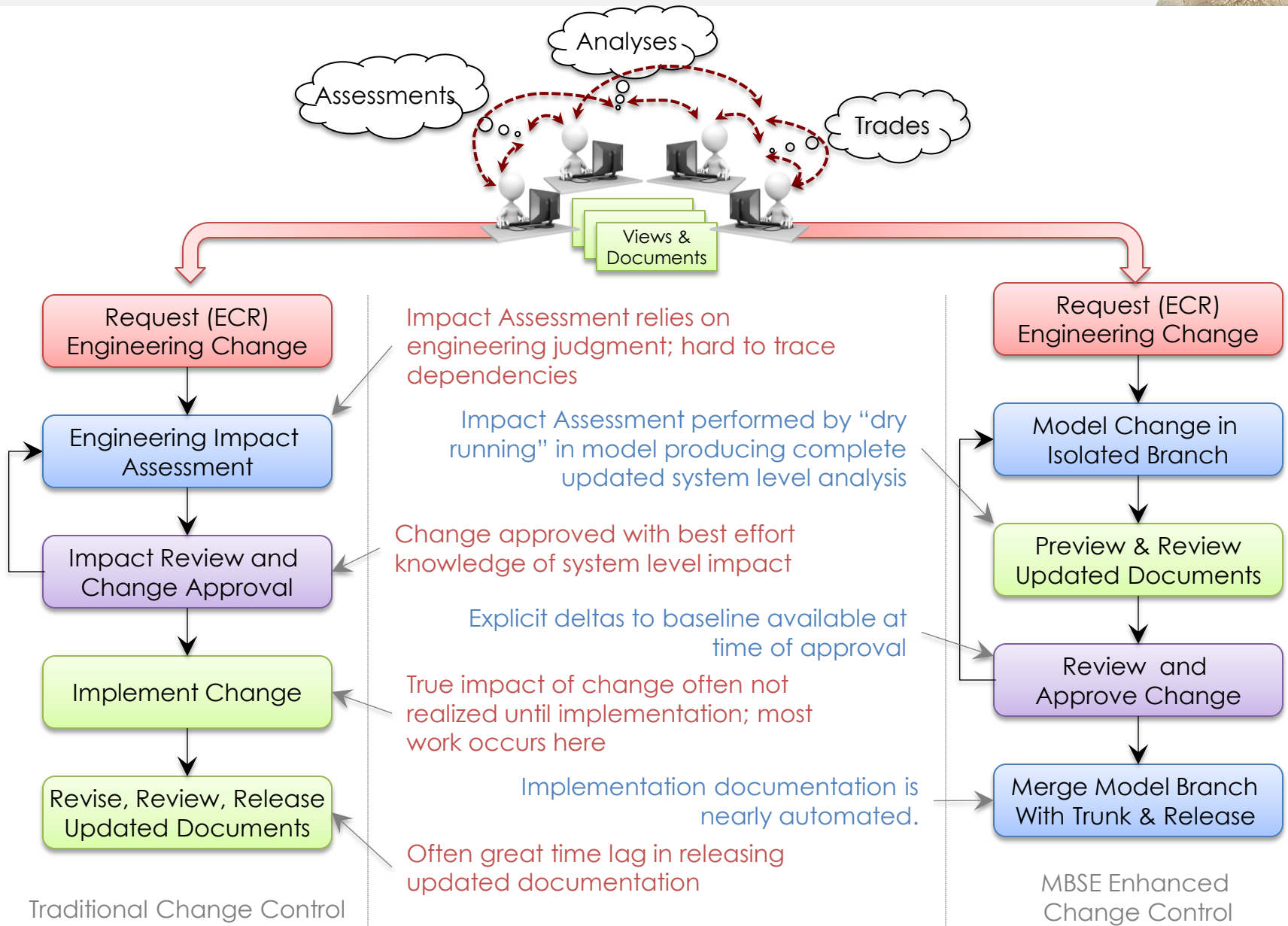
Calculates and displays info by executing programs written using:



Presents information in editable views:

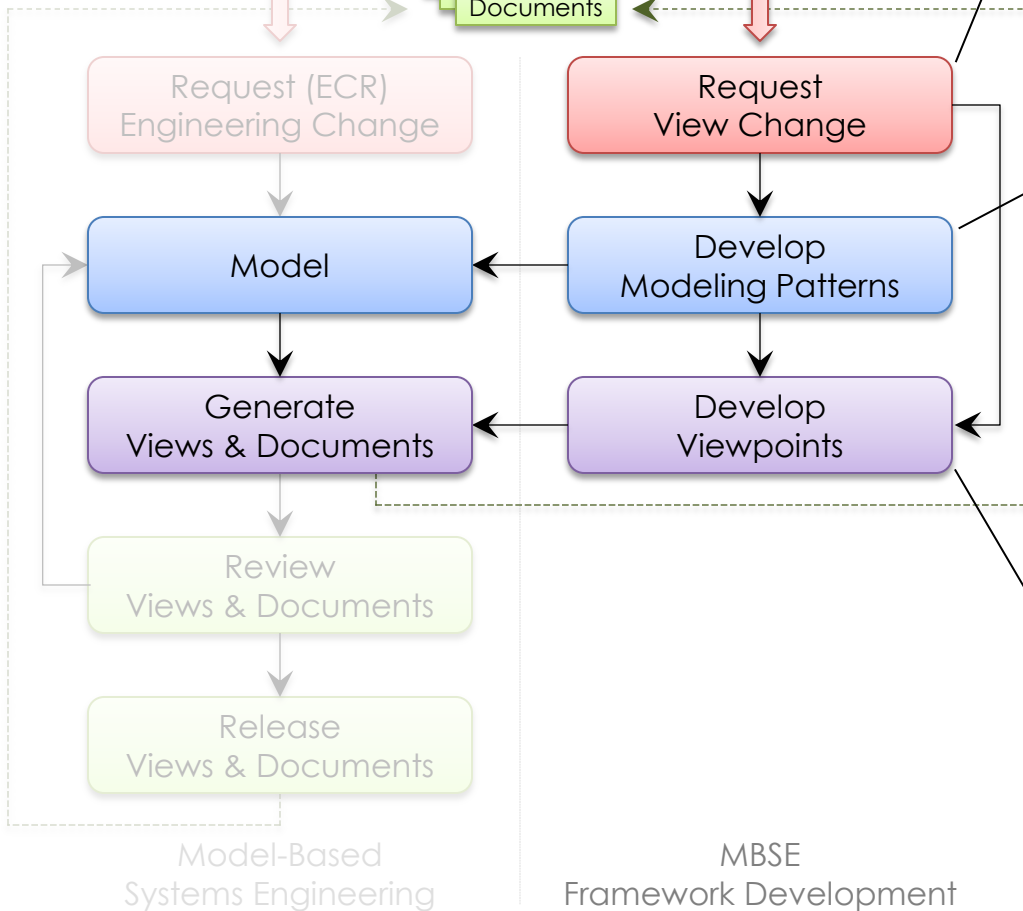
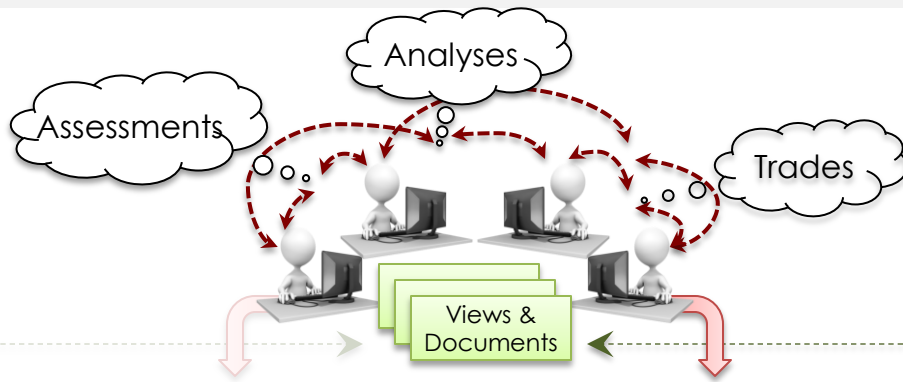
Work Package	Component	Mass per Unit			Num of Units	Total Mass		
		CBE (kg)	Cont.	MEV (kg)		CBE (kg)	Cont.	MEV (kg)
Europa Clipper Project						1763.5	0.28	2255.7
05 Payload						107.38	0.49	159.9
	IPR Antenna and Cable Assembly	12.2	0.50	18.3	1	12.2	0.50	18.3
	IPR HCIPE Transmitter Electronics	6.0	0.50	9.0	1	6.0	0.50	9.0
	...	...	...	...	...	...	...	...
06 Spacecraft						1656.1	0.27	2095.9
06.04 Power						470.4	0.17	548.0
	Battery Control Board	1.8	0.30	2.3	1	7.2	0.30	9.4
	Li-Ion Large Cell Battery	81.4	0.20	97.6	1	81.4	0.20	97.6
	...	...	...	...	...	...	...	...
06.05 CDH						18.0	0.30	23.4
	Analog Eng. I/O (LEU-A)	0.5	0.30	0.6	2	0.9	0.30	1.2
	Bulk Data Storage	0.5	0.30	0.6	8	3.7	0.30	4.8
	...	...	...	...	...	...	...	...
...						...	...	...
	...	...	...	...	...	...	...	...

# MBSE Enhancements to SE Processes





# Modeling & Analysis Framework Development Process

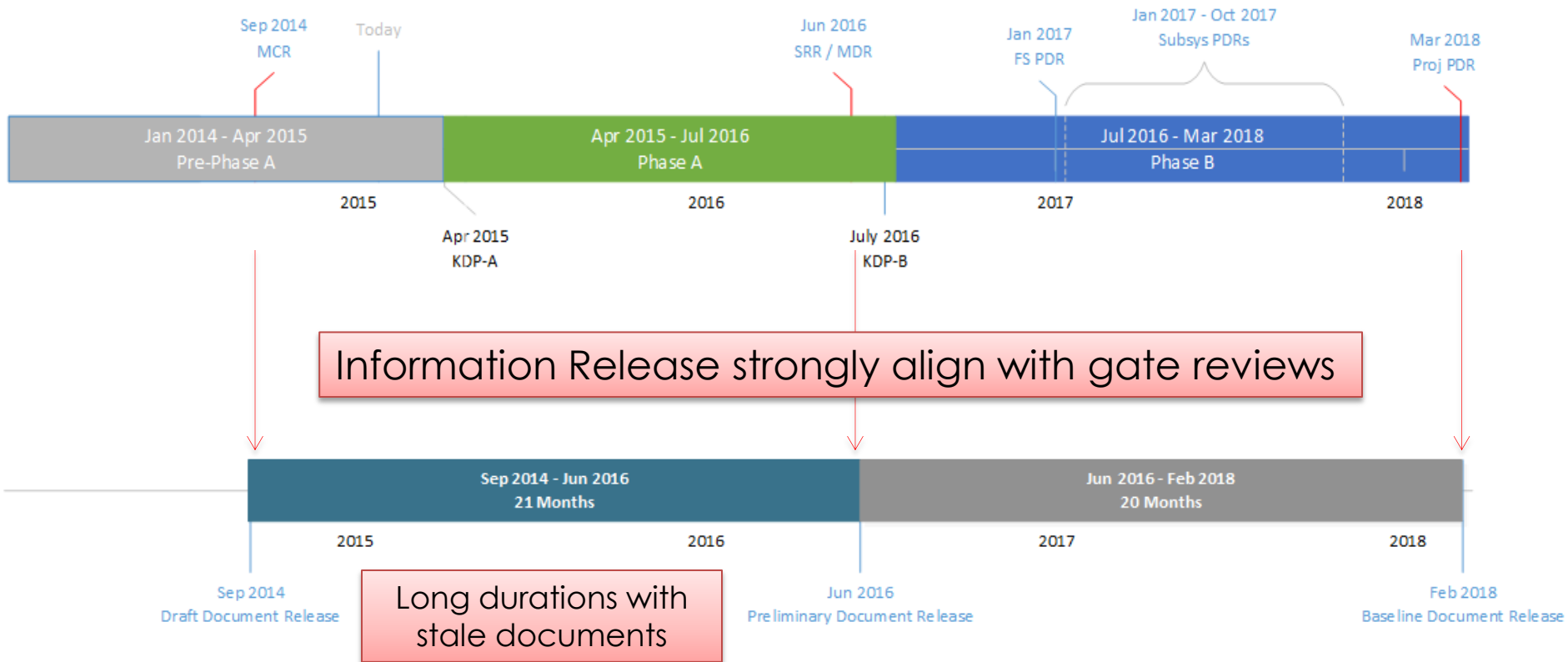


- What are the views, e.g. systems engineering products, that are required to effectively communicate, analyze and assess the system architecture and design?
- What kind of information is contained in the view?
- How should the information be organized? Considering, for example:
  - The evolution of the level of fidelity, completeness and maturity over the lifecycle of the project
  - The project's need to manage the authority and ownership of information
  - The collaborative engineering environment in which the information is created and updated concurrently
- What kind of information transformation or analysis is needed, if any?
- How can we verify the correctness of the generated view?

# Typical Information Release Cadence



Project Timeline (typical):

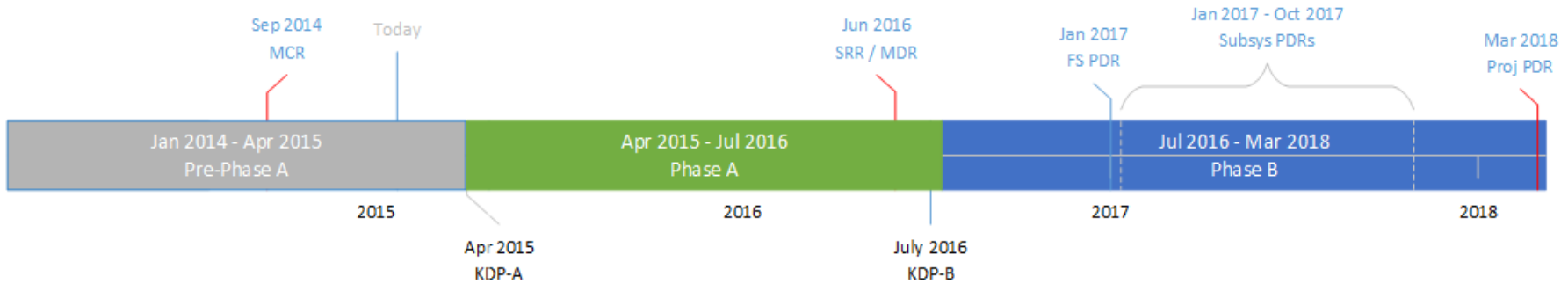


Project personnel relied upon to know what information is reliable and what is in the (long) process of being changed

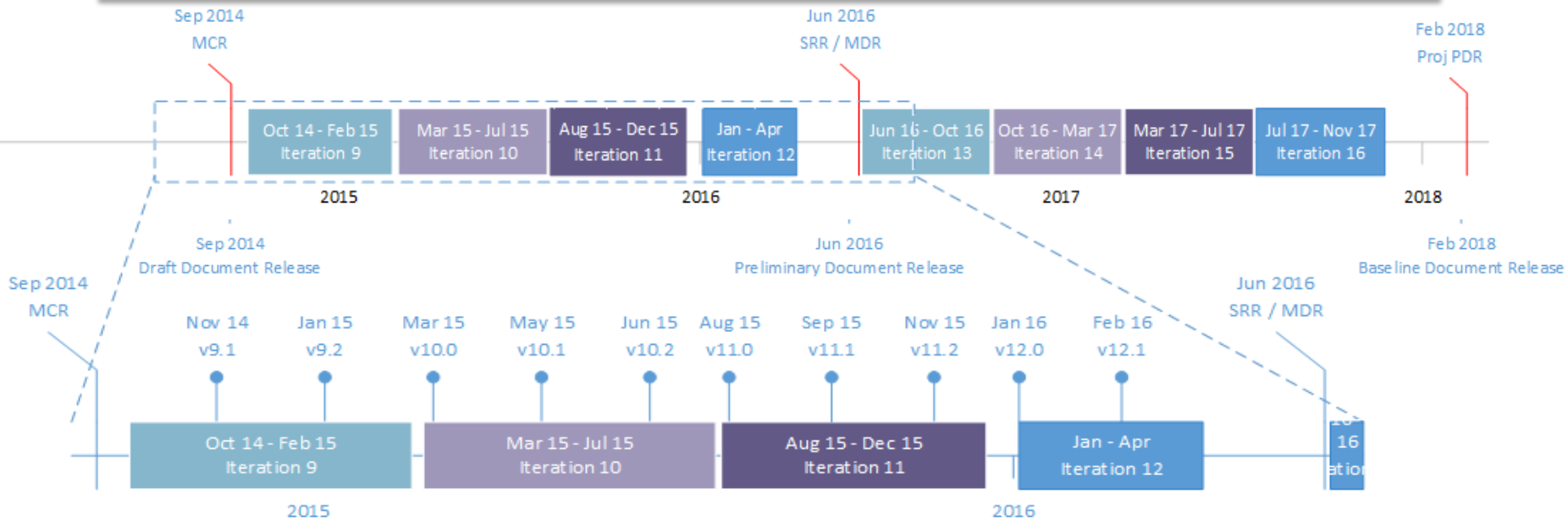
# MBSE Enhanced Information Release Cadence



## Project Timeline (typical):



Iterative approach sets regular release cadence; independent of review schedule



Increments set much shorter duration between change request and updated documentation



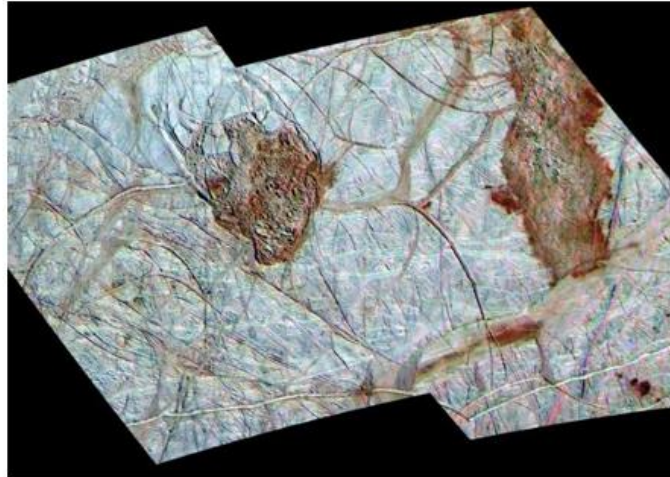
## Europa Project

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### Links

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#### Thera and Thrace

Thera and Thrace are two dark, reddish regions of enigmatic terrain that disrupt the older icy ridged plains on Jupiter's moon Europa. North is toward the top of the mosaic obtained by NASA's Galileo spacecraft.

### Announcements

Europa Instruments AO Released 7/16/2014

MCR Date Set 2/11/2014

[+ Add new announcement](#)

### Technical Information

#### Latest Spacecraft Configuration:

- Stowed CAD
- Deployed CAD
- Spacecraft Drawings

#### SRRD:

- I9 Release Candidate Version

#### Latest MEL, PEL, and Diagrams for:

- Solar Clipper
- MMRTG Clipper (Inactive)
- ASRG Clipper (Inactive)

#### Dec 2012 Final Report:

- Clipper Baseline
- Clipper Enhanced
- Clipper Solar Enhanced
- Orbiter Options

#### May 2012 Baseline:

- Orbiter
- Flyby
- Lander



# Organization Charts



Europa Organization Charts

Europa Project Organization

- 1.1 WBS 01 - Project Management Organization
  - 1.1.1 WBS 01.02 - Project Business Management
- 1.2 WBS 02 - Project System Engineering Organization
- 1.3 WBS 03 - Mission Assurance Organization
- 1.4 WBS 04 - Project Science Organization
- 1.5 WBS 05 - Payload Office Organization
- 1.6 WBS 06 - Spacecraft Office Organization
  - 1.6.1 WBS 06.02 - Flight System Engineering
- 1.7 Mission System
  - 1.7.1 WBS 07 - Mission Operation Organization
  - 1.7.2 WBS 09 - Ground Data System Organization
  - 1.7.3 WBS 12 - Mission Design Organization
- 1.8 WBS 08 - Launch System Organization
- 1.9 WBS 10 - System Integration and Testing
- 1.10 WBS 11 - Education & Public Outreach

## Europa Organization Charts

### 1 Europa Project Organization

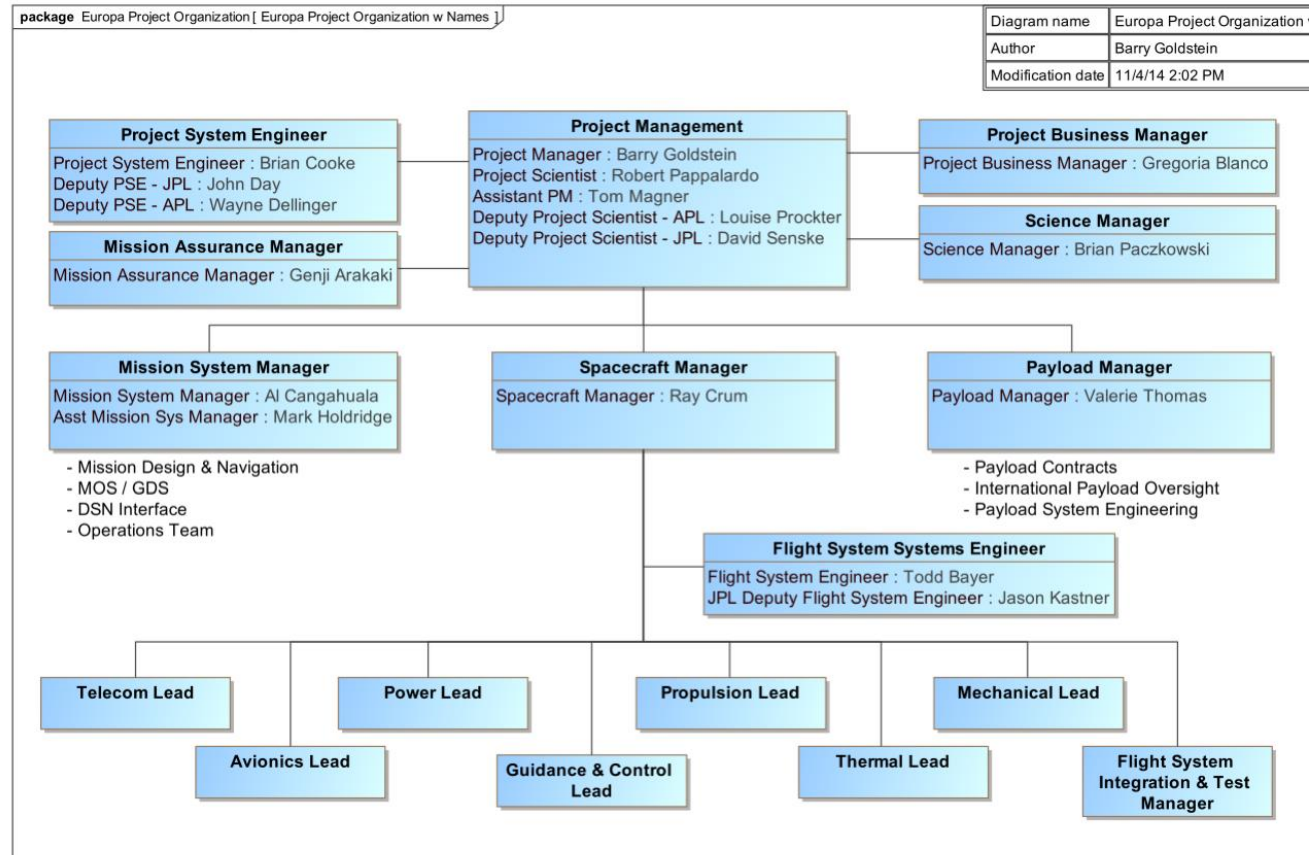


Figure 4-1 – Project Organization Chart

# Requirements



## 2 SRRD Requirement Totals

### Requirement Totals (by package)

	Number of Requirements
Recon L2 Requirements	8
Science L2 Requirements	13

### Total Requirements

<b>Total</b>
21

## 3 Science Requirements

The Science Requirements are written based on the investigations and measurements identified in the Science Traceability Matrix. They generally flow down to other Science Requirements, Observation Requirements.

ID	Name	Text
SR.1	Shallow water characterization	The shallow subsurface data set shall characterize water or brine within 3 km depth, on a horizontal scale $\leq 10$ km, in regions that are globally distributed across at least 70% of the surface.
SR.2	Search for ice-ocean interface	The deep subsurface data set shall search for an ice-ocean interface extending from 1 km to 30 km depth, in regions that are globally distributed across at least 70% of the surface.
SR.3	Heat flow variations	The deep subsurface data set shall permit identification and mapping of subsurface thermal horizons extending from 1 km depth, in regions that are globally distributed across at least 70% of the surface.
SR.4	Gravitational tides	The gravity science data set shall characterize the amplitude and phase of Europa's gravitational tides to recover the k2 tidal amplitude at Europa's orbital frequency to $\leq 0.05$ absolute accuracy.
SR.5	Europa's magnetic induction response	The magnetic induction data set shall measure Europa's magnetic induction response to Jupiter's magnetic field with sensitivity $\geq 1$ nT and $\leq 1$ nT accuracy.
SR.6	Global scale composition and chemistry	The global-scale surface composition data set shall characterize the global-scale composition and chemistry by mapping a spatial resolution of $\leq 10$ km covering $\geq 70\%$ of Europa's surface.

# Block Diagrams



Alfresco » Document Details Architecture Framework D... View Editor: Pattern Descriptio... Europa Homepage View Editor: Clipper Flight Sys... Alfresco » Site Dashboard

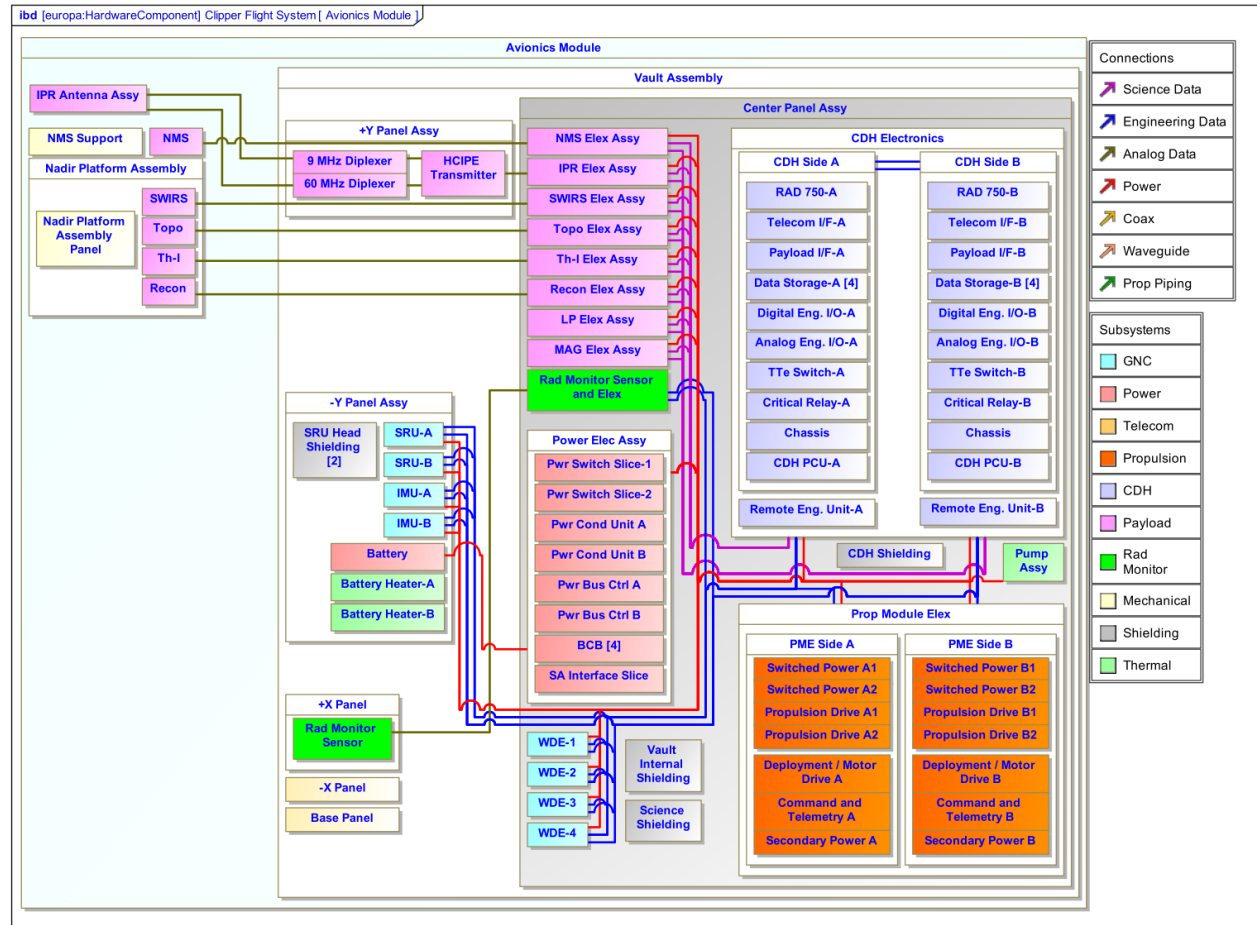
https://europa.nasa.gov/alfresco/mmsapp/ve.html#/sites/europa/products/\_17\_0\_2\_3\_897027c\_1398292382471\_307085\_338623/2014-12-18T18:43:10.971-0800/view/\_17\_0\_2\_3\_897027c\_1398292402877\_285576\_347363

Clipper Flight System (Version 9.3) (12/18/14 6:43 PM) Go To Europa Documents Europa Dashboard Other Sites

- Clipper Flight System
  - 1 Change Log
    - 1.1 Relevant Documents
  - 2 Master Equipment List (MEL)
    - 2.1 MEL: Bill of Materials Table
      - 2.1.1 Payload
      - 2.1.2 Spacecraft
      - 2.1.3 Work Package Summary
    - 2.2 MEL: Deployment Table
      - 2.2.1 RF Module
      - 2.2.2 Avionics Module
      - 2.2.3 Propulsion Module
      - 2.2.4 Shielded Vault Components
    - 2.3 MEL: Work Package Assembly Table
    - 2.4 MEL: Organization Table
    - 2.5 MEL: Maximum Mass Distribution
    - 2.6 MEL: Shielding Only Rollup
  - 3 Flight System Block Diagram
    - 3.1 Avionics Module
    - 3.2 Propulsion Module
    - 3.3 RF Module
    - 3.4 Payload
    - 3.5 Spacecraft
      - 3.5.1 CDH
      - 3.5.2 GNC
      - 3.5.3 Power Architecture
      - 3.5.4 Propulsion
      - 3.5.5 Propulsion Module Electronics
      - 3.5.6 Radiation Monitoring
      - 3.5.7 Telecom
    - 3.6 Payload Accommodation Diagrams
      - 3.6.1 IPR Accommodation Diagram
      - 3.6.2 LP Accommodation Diagram
      - 3.6.3 MAG Accommodation Diagram
      - 3.6.4 NMS Accommodation Diagram
      - 3.6.5 Recon Accommodation Diagram
      - 3.6.6 SWIRS Accommodation Diagram
      - 3.6.7 Th-I Accommodation Diagram
      - 3.6.8 Topo Accommodation Diagram
    - 3.7 Thermal Loop Diagram
  - 4 Power State List
    - 4.1 Payload
    - 4.2 Spacecraft
      - 4.2.1 CDH

## Avionics Module

This diagram shows all parts of the Avionics Module.



# Instrument Overview



Alfresco » Document Details x Architecture Framework D... x View Editor: Pattern Descriptio... x Europa Homepage x View Editor: Europa Clipper Ex... x View Editor: Europa Organizati... x View Editor: Clipper Flight Sys... x View Editor: Clipper Flight Sys... x All

https://europaems.jpl.nasa.gov/alfresco/mmsapp/ve.html#/sites/europa/products/\_17\_0\_2\_3\_897027c\_1398292382472\_719225\_338625/2014-12-18T18:49:48.533-0800/all#\_17\_0\_2\_3\_897027c\_1398292404816\_995547\_347845

JPL Europa Europa Modeling JIRA Dev Europa Blog: Po... Europa JIRA PSE... Kepler Personal iPhone SEMP JPL WebEx Wikipedia BPMN SEMP Live Demo

Clipper Executive Summary (Version 9.3) (12/18/14 6:49 PM) Go To Europa Documents Europa Dashboard Other Sites

- Europa Clipper Executive Summary
  - 1 Europa Clipper Mission
    - 1.1 Mission Scenarios
    - 1.2 Trajectory Information
    - 1.3 Mission Timeline
  - 2 Clipper Flight System Design
    - 2.1 Flight System Margins
      - 2.1.1 Mass Margin
      - 2.1.2 Power Margins
      - 2.1.3 Data Margins
      - 2.1.4 Tank Volume Margins
    - 2.2 Payload at a glance
      - 2.2.1 Overview of Instruments
      - 2.2.2 Mass Breakdown
      - 2.2.3 Power Breakdown
    - 2.3 Spacecraft at a glance
      - 2.3.1 Mass Breakdown
      - 2.3.2 Power Breakdown
  - 3 Ground System Design
  - 4 Europa Clipper Project

## 2.2.1 Overview of Instruments

- Ice Penetrating Radar

Dual-frequency sounder (60 MHz with 10 MHz bandwidth (shallow) and 9 MHz with 1 MHz bandwidth (deep)) with surface altimetry capability. Deployed dipole antenna array on 15-m boom, including four 2.5-m dipole elements. Transmitters and matching network located at base of antenna; receivers, digital electronics, and power supply housed remotely in radiation-shielded science electronics box. FOV ~12° cross-track. The altitude constraint is < 1,000 km.

### Payload Overview

Total Mass (inc. shield) [kg]	Operating Power [W]	Raw Instantaneous Data rate [Mb/s]	Altitude Constraints	Number of Boards
36.7	57.0	24.6 (processed)	< 1,000 km	8

- Langmuir Probe

LP comprises a dual-sensor system with 5-cm diameter spheres mounted on 1-m long booms. The LP sensors measure the local plasma temperature, and flow; electric field vectors (from near DC to 3 MHz); electron temperature; and ion currents. The sensors measure over a solid angle. Pre-amps must be located <3 m from each sensor. If possible, the two sensors should be mounted such that at least one is at free of any S/C plasma wake with a 15° clearance buffer. The sampling rate is 1 Hz. S/C EMI/EMC cleanliness comparable to that of Juno. Cassini is required.

### Payload Overview

Total Mass (inc. shield) [kg]	Operating Power [W]	Raw Instantaneous Data rate [Mb/s]	Altitude Constraints	Number of Boards
4.3	2.8	.002	n/a	2

- Magnetometer

MAG comprises a dual-sensor 3-axis fluxgate magnetometer system. Its sensitivity is 0.1 nT over an intensity range of at least ±1024 nT. T maximum sampling rate is 32 Hz; sampling resolution is 0.01 nT. S/C EMI/EMC cleanliness comparable to that of Juno and Cassini is required.

### Payload Overview

Total Mass (inc. shield) [kg]	Operating Power [W]	Raw Instantaneous Data rate [Mb/s]	Altitude Constraints	Number of Boards
2.72	4.45	.004	n/a	1

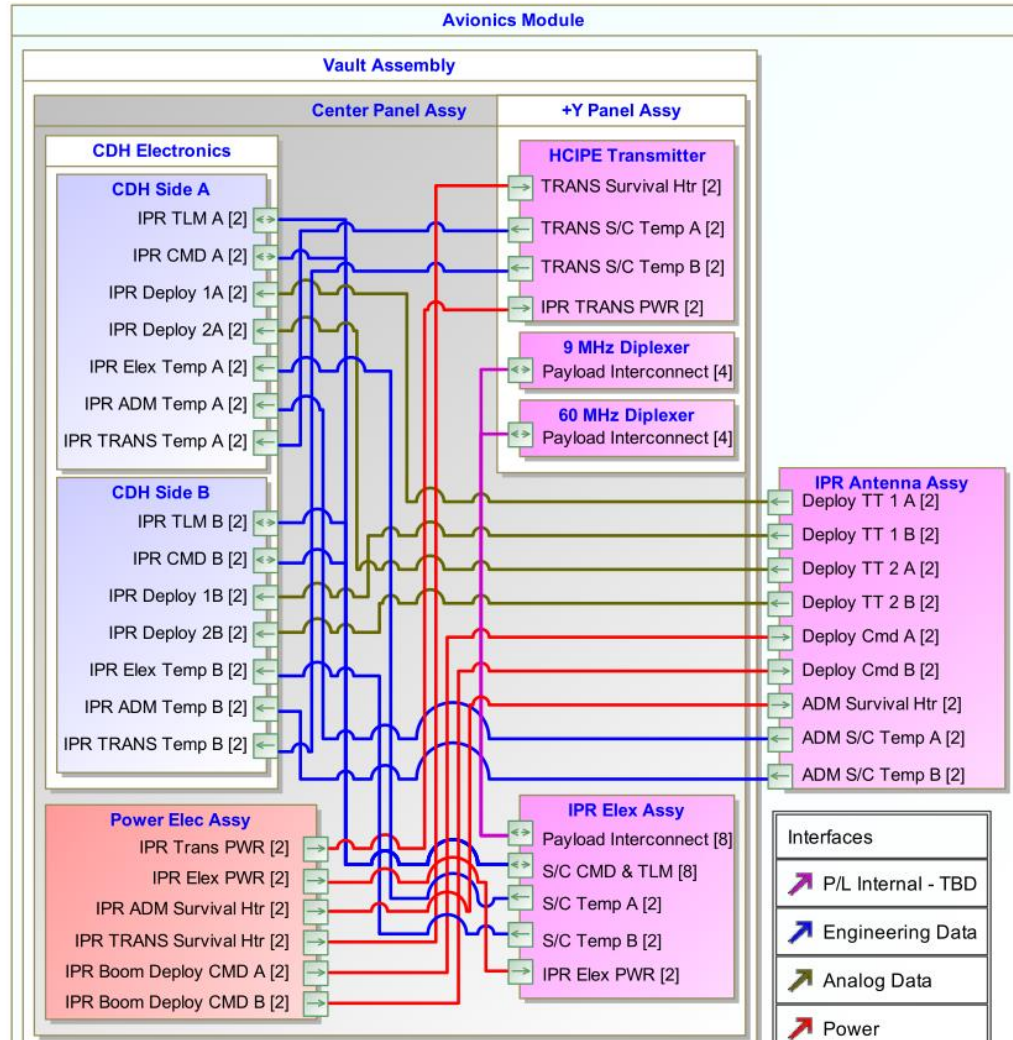


# Instrument Accommodations



- ▼ Subsystem View: Payload
  - 1 Summary
  - ▼ 2 Block Diagram
    - 2.1 IPR Accommodation Diagram
    - 2.2 LP Accommodation Diagram
    - 2.3 MAG Accommodation Diagram
    - 2.4 NMS Accommodation Diagram
    - 2.5 Recon Accommodation Diagram
    - 2.6 SWIRS Accommodation Diagram
    - 2.7 Th-I Accommodation Diagram
    - 2.8 Topo Accommodation Diagram
  - 3 Mass Equipment List (MEL)
  - 4 Power Equipment List (PEL)
  - 5 Subsystem Power Scenarios
  - 6 Thermal Equipment List (TEL)
  - ▼ 7 Card Margins
    - 7.1 List of Cards in Boxes
  - 8 Volume and Area

## IPR Accommodation Diagram



# Subsystem Views



## 11 Solar Cell Characterizations

The table below lists electrical attributes of the solar cells. These attributes are:

1. **Type** - solar cell type
2. **Cell Efficiency** - efficiency of the solar cell
3. **J<sub>mp</sub>** - Current Density at maximum power
4. **V<sub>mp</sub>** - Voltage at maximum power
5. **Converter Efficiency** - addresses additional loss between solar cell and panel interface slice
6. **J<sub>mp</sub>-T<sub>c</sub>** - Temperature constant of J<sub>mp</sub>
7. **V<sub>mp</sub>-T<sub>c</sub>** - Temperature constant of V<sub>mp</sub>
8. **I<sub>sc</sub>** - Overall degradation factor for short circuit current
9. **V<sub>oc</sub>** - Overall degradation factor for open circuit voltage

Solar Cell - Electrical Properties

Component	Type	Cell Efficiency	J <sub>mp</sub> - Maximum Power Current Density [A/m <sup>2</sup> ]	V <sub>mp</sub> - Maximum Power Voltage [V]	Converter Efficiency Fraction	Temperature Constants		Degradation
						J <sub>mp</sub> -T <sub>c</sub> [μA/cm <sup>2</sup> /C]	V <sub>mp</sub> -T <sub>c</sub> [mV/C]	
Solar Array Cell & Wiring	UTJ	0.28	163	2.35	0.9	2.6	-6.7	0.9

The table below lists the loss factors that are used to calculate the overall degradation factors of the solar cell. Specifically, this table shows the Assemble Group loss factors for

Solar Cell - Assemble Group Loss Factors

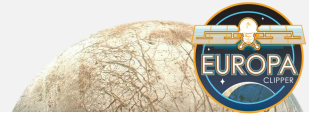
Component	Type	Assemble Group					
		I <sub>sc</sub>				V <sub>oc</sub>	
		LAPSS Calibration	Coverglass	Mismatch	Production Variation	Assembly Loss	Blocking Diode
Solar Array Cell & Wiring	UTJ	0.975	0.99	0.98	0.99	0.9957	0.8

The table below lists the loss factors that are used to calculate the overall degradation factors of the solar cell. Specifically, this table shows the Environmental Group, Cell, and V<sub>oc</sub>.

Solar Cell - Environmental Group, Cell, and Intensity Loss Factors

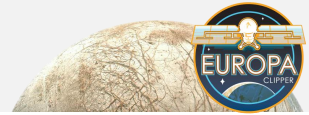
Component	Type	Environmental Group					Cell Loss Factors		Intensity (5)
		I <sub>sc</sub>					I <sub>sc</sub>	V <sub>oc</sub>	I <sub>sc</sub>
		Contamination	Thermal Cycling	Sun Angle (±10°)	UV	ITO			
Solar Array Cell & Wiring	UTJ	0.99	0.99	1.0	0.986	0.995	0.9	0.973	0.0331

# MBSE in Implementation



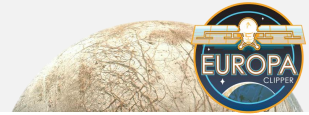
- System model used to enforce architecture
  - Explicitly understanding implementation changes vs mission concept changes
- Rapid assessment of system performance against requirements
- Margin visibility, management & disbursement
- Performance shortfall impact assessment
- Verification & validation planning, replanning & documentation
- Operations knowledge database

# Lessons Learned (so far...)



- Culture change is hard.
- Evolution not revolution
  - Make a link back to existing processes
- Confederation not integration
  - MBSE must embrace distributed ownership
- Model only what you need at the time
  - Incremental model upgrades
- Communication is the prime objective
  - All infrastructure must be supporting better communication as a top requirement

# Conclusion



- Europa Clipper has embraced MBSE as core to our formulation effort
- Product development and release efficiency improvement realized (and getting better)
- Some SE process improvement realized with much more to come
- Shift from document-based to model-based culture is slow but progressing

MBSE is ready to support flagship class mission formulation