Model-based Systems Engineering Mission Formulation and Implementation

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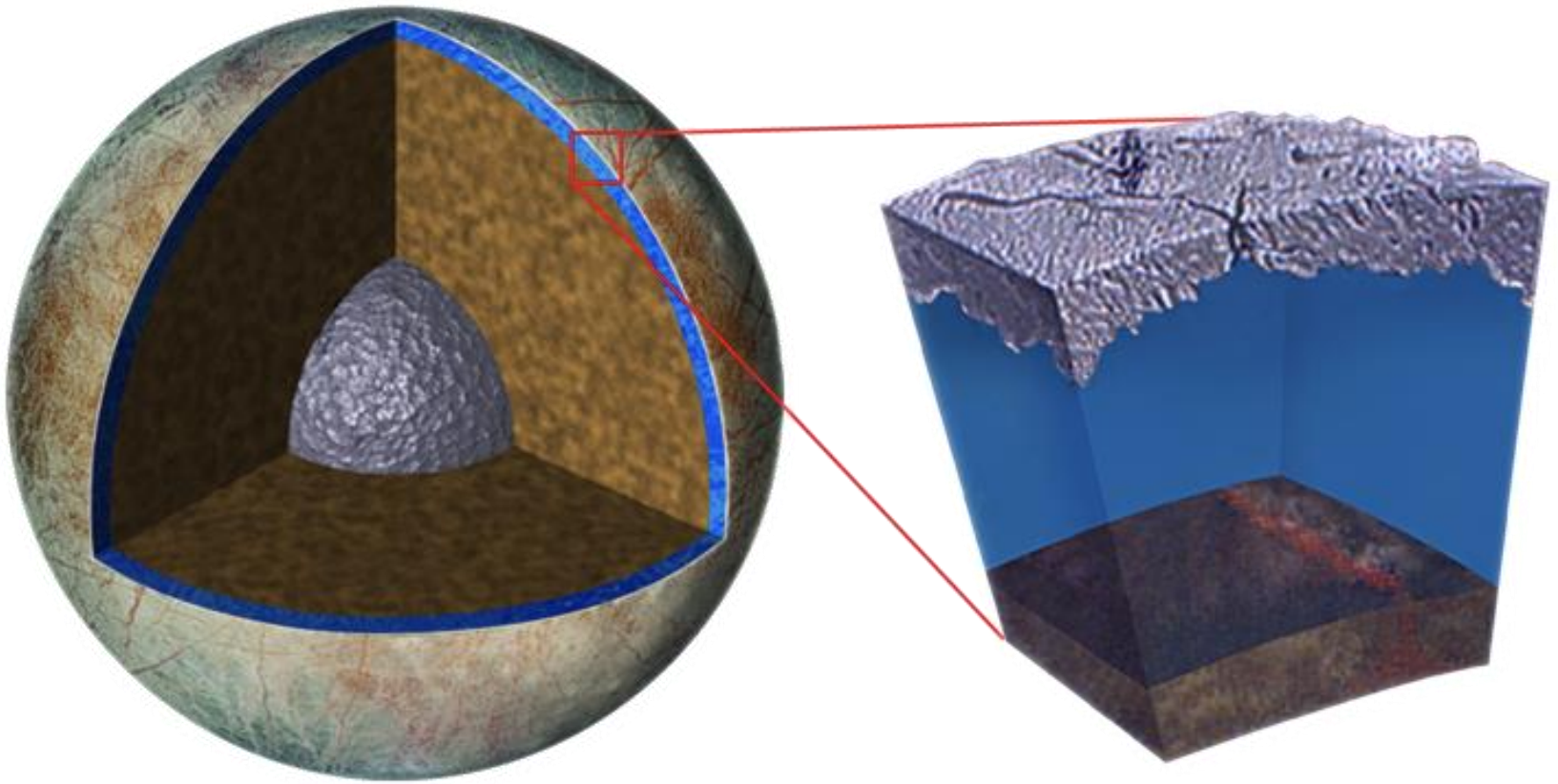
The Ocean That Beckons



"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

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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

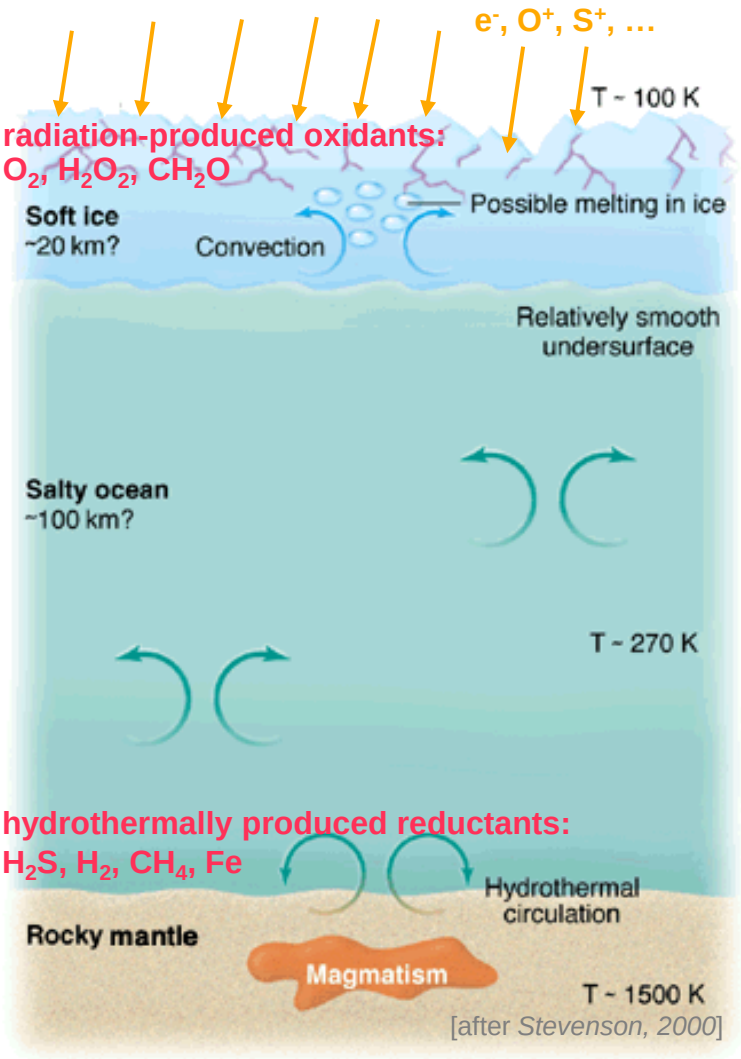
Chemistry:

- 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



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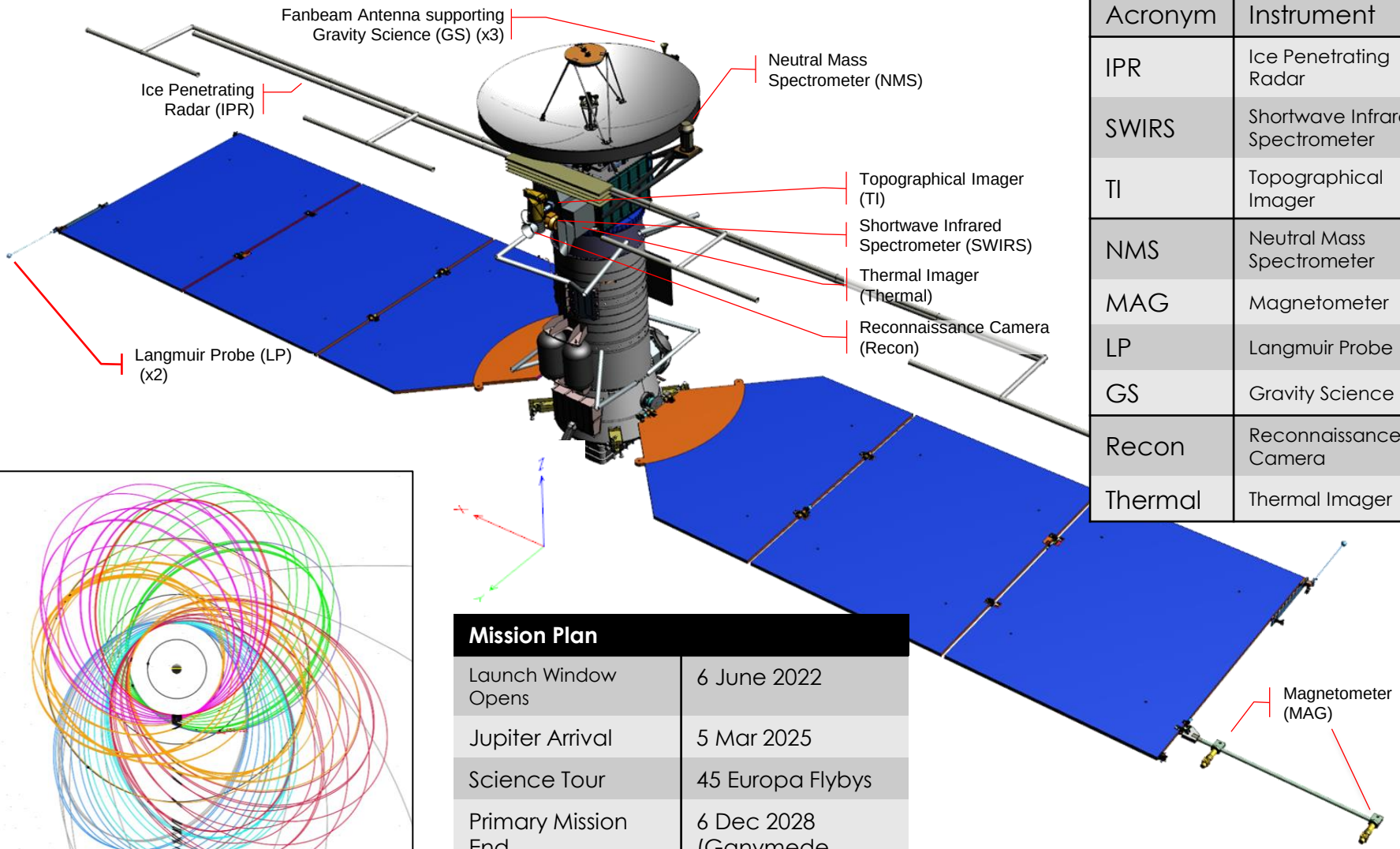
Europa Clipper Mission Concept Overview



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)

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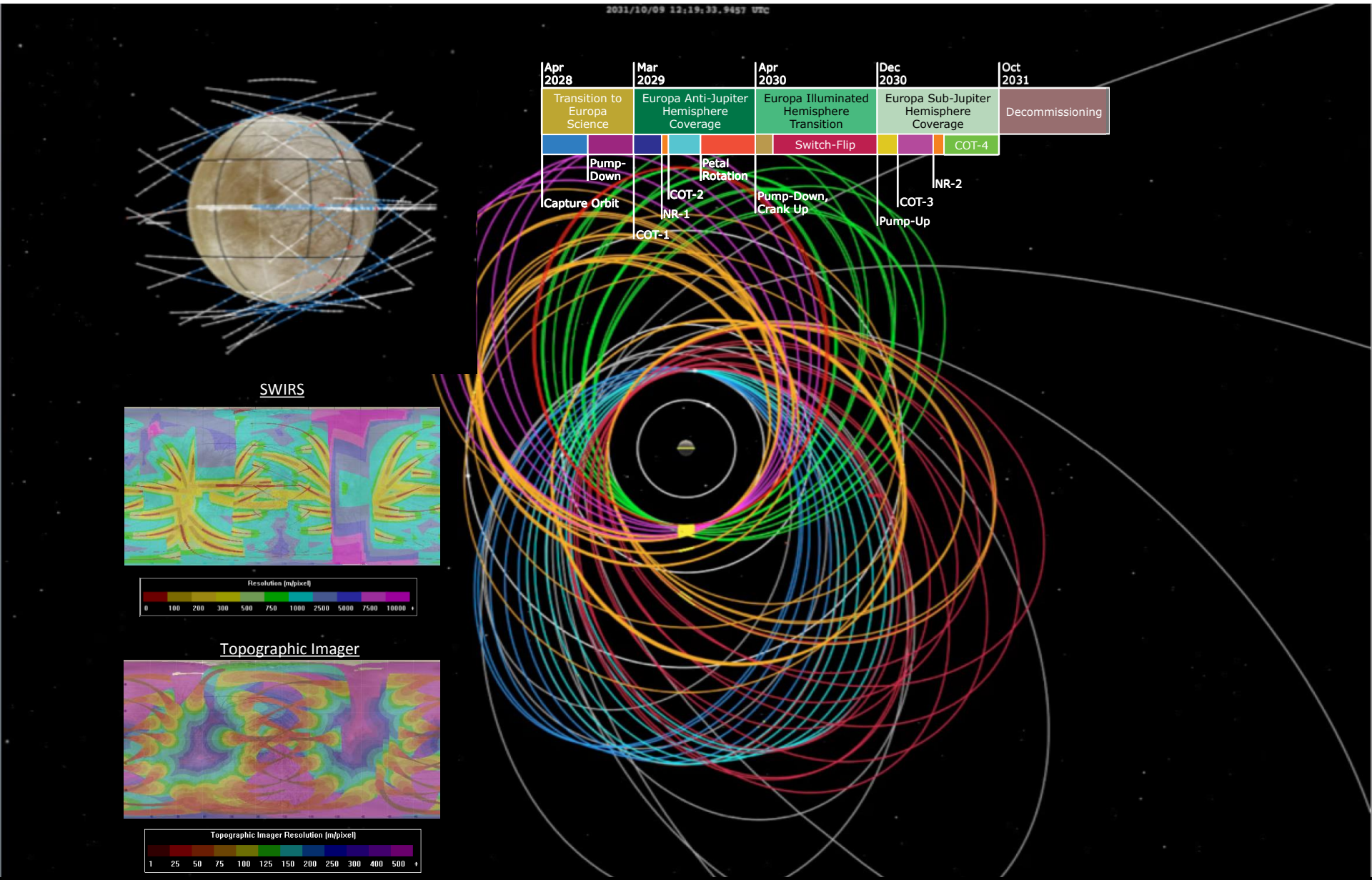
Europa Clipper Mission Design Concept



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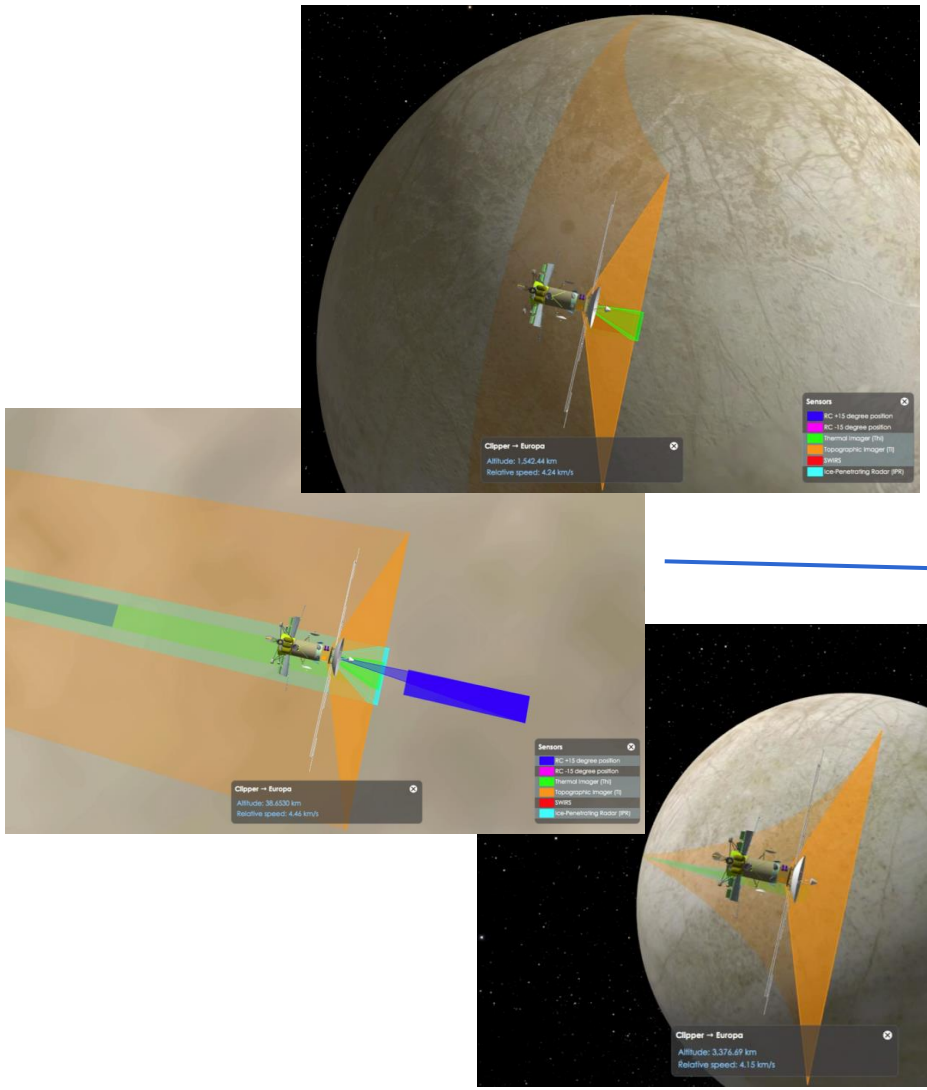
Europa Clipper Flyby Concept



25 km Europa Flyby

MAG and LP Observations Throughout
SWIRS Global Observation below 66,000 km
Start Thermal Imaging at 60,000 km
Start Gravity Science at 28,000 km
Start Topo Low-Res Imaging at 4,000 km
SWIRS High-Res Observation below 2,000 km
Start IPR, NMS, Topo Stereo at 1,000 km
Recon Stereo Imaging below 50 km
End IPR, NMS, Topo Stereo at 1,000 km
SWIRS High-Res Observation below 2,000 km
End Topo Low-Res Imaging at 4,000 km
End Gravity Science at 28,000 km
End Thermal Imaging at 60,000 km
SWIRS Global Observation below 66,000 km

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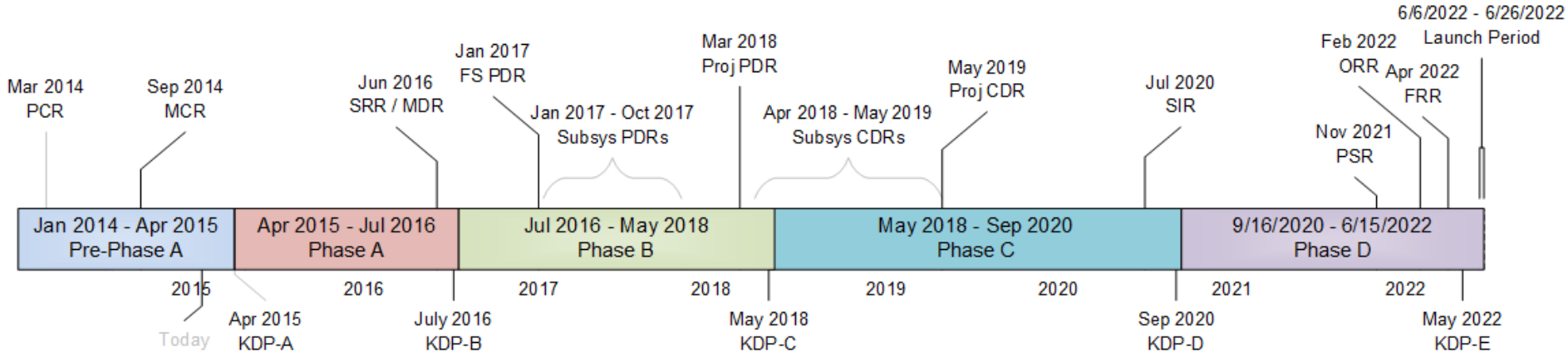
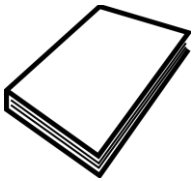
Europa Clipper Project Schedule

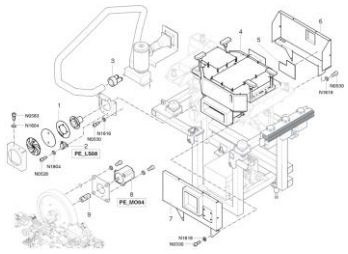
Europa Project Timeline – 2022 SLS Launch



Formulation | **Implementation**

We are here





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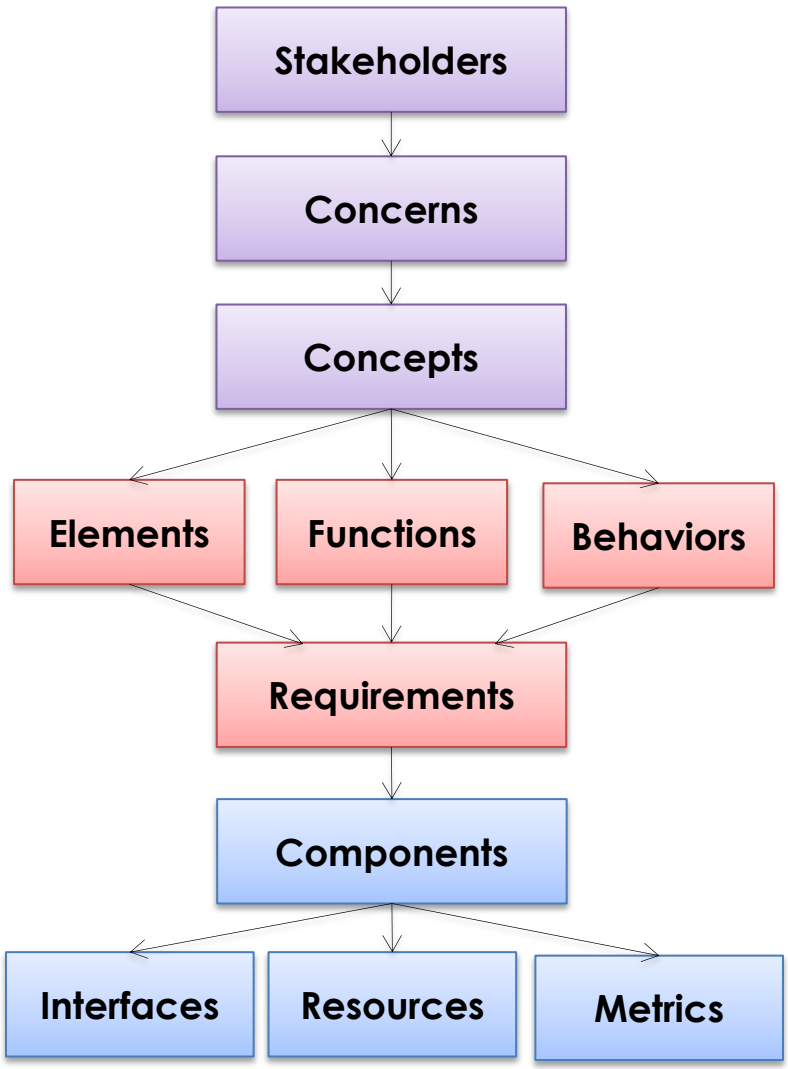
Model-Based System Engineering Approach



- 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

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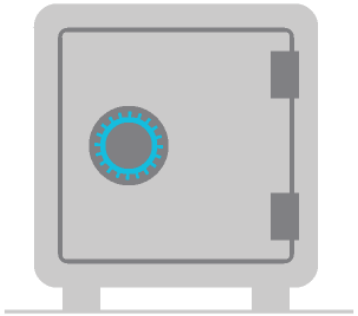
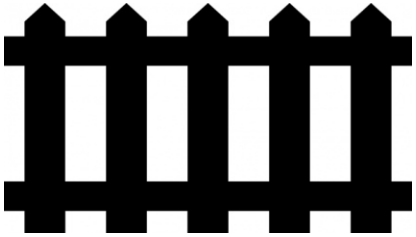
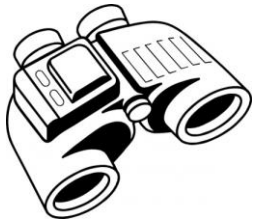
Modern Technical Information Management System

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







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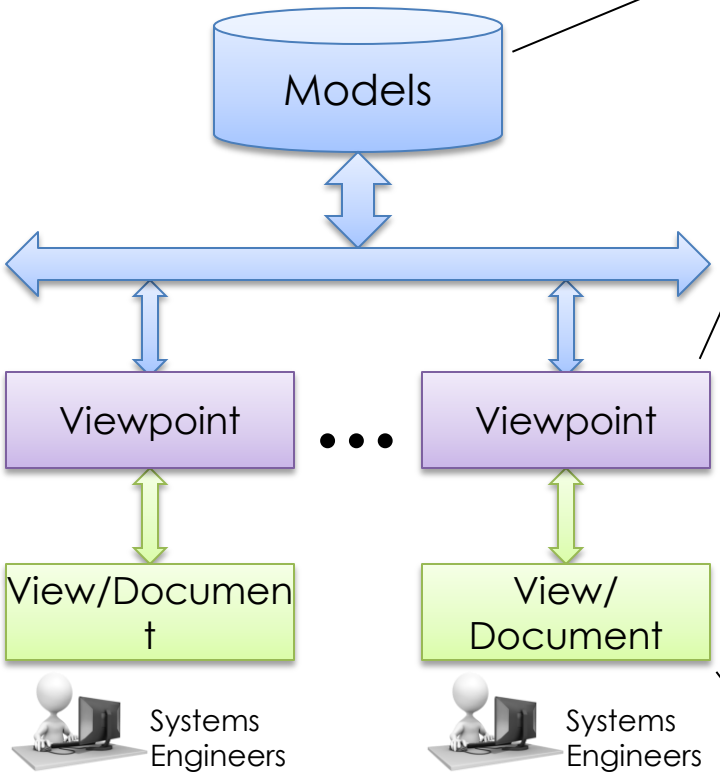
Modeling & Analysis Framework



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.

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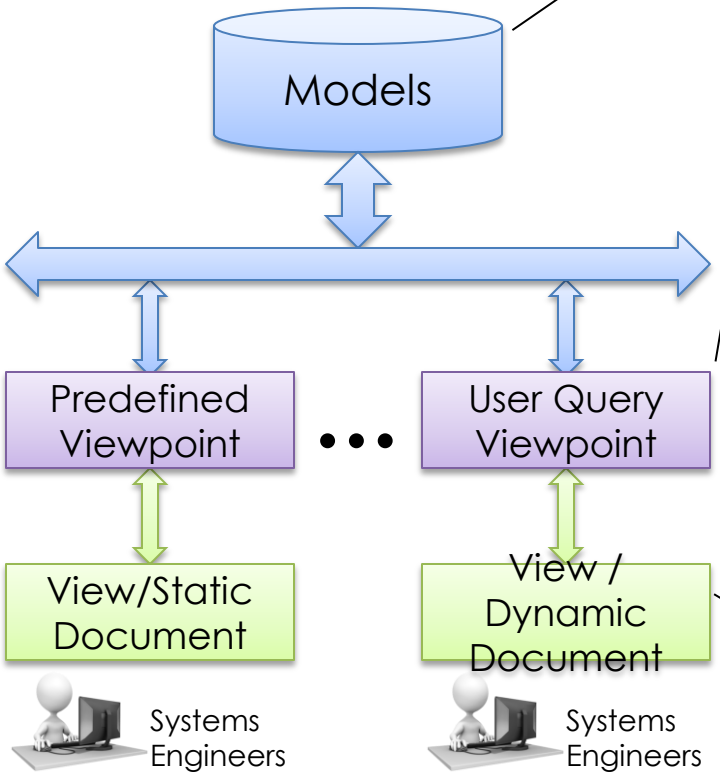
Modeling & Analysis Framework: MEL



Captures technical information using:

Alfresco + MagicDraw API + SysML + IMCE Ontology + **Architecture Framework**

Calculates and displays info by executing programs written using:

Alfresco + MagicDraw API + Java + Python + **DocGen**

Presents information in editable views:

Work Package	Component	Mass per Unit CBE (kg)	Mass per Unit Cont.	Mass per Unit MEV (kg)	Num of Units	Total Mass CBE (kg)	Total Mass Cont.	Total Mass 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
	...	...	...	...	...	...	...	...
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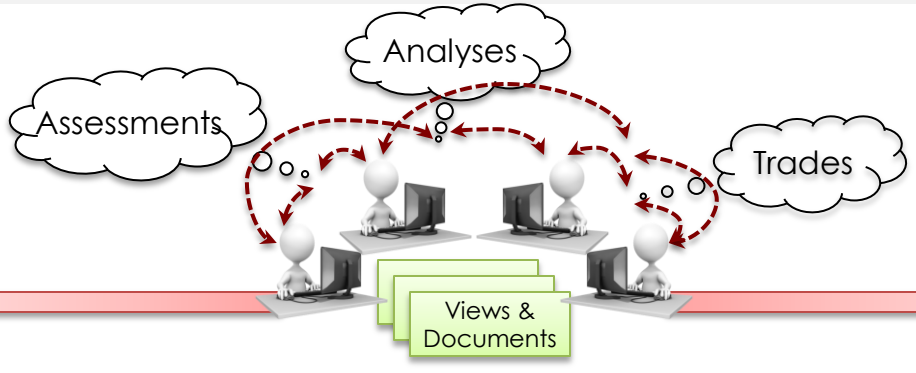
MBSE Enhancements to SE Processes



Request (ECR) Engineering Change

Engineering Impact Assessment

Impact Review and Change Approval

Implement Change

Revise, Review, Release Updated Documents

Traditional Change Control

Impact Assessment relies on engineering judgment; hard to trace dependencies

Impact Assessment performed by "dry running" in model producing complete updated system level analysis

Change approved with best effort knowledge of system level impact

Explicit deltas to baseline available at time of approval

True impact of change often not realized until implementation; most work occurs here

Implementation documentation is nearly automated.

Often great time lag in releasing updated documentation

Request (ECR) Engineering Change

Model Change in Isolated Branch

Preview & Review Updated Documents

Review and Approve Change

Merge Model Branch With Trunk & Release

MBSE Enhanced Change Control

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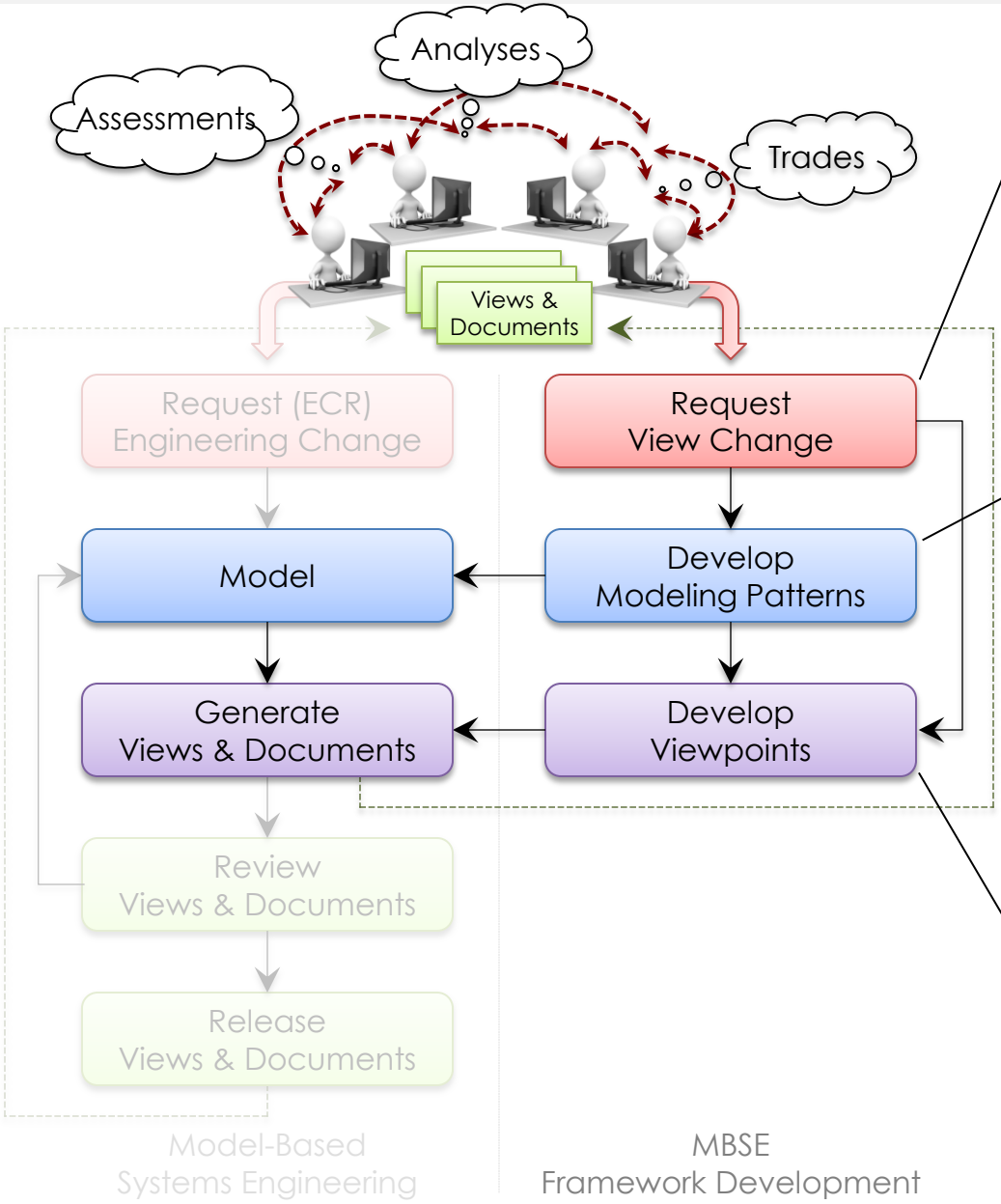
Modeling & Analysis Framework Development Process



- 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?

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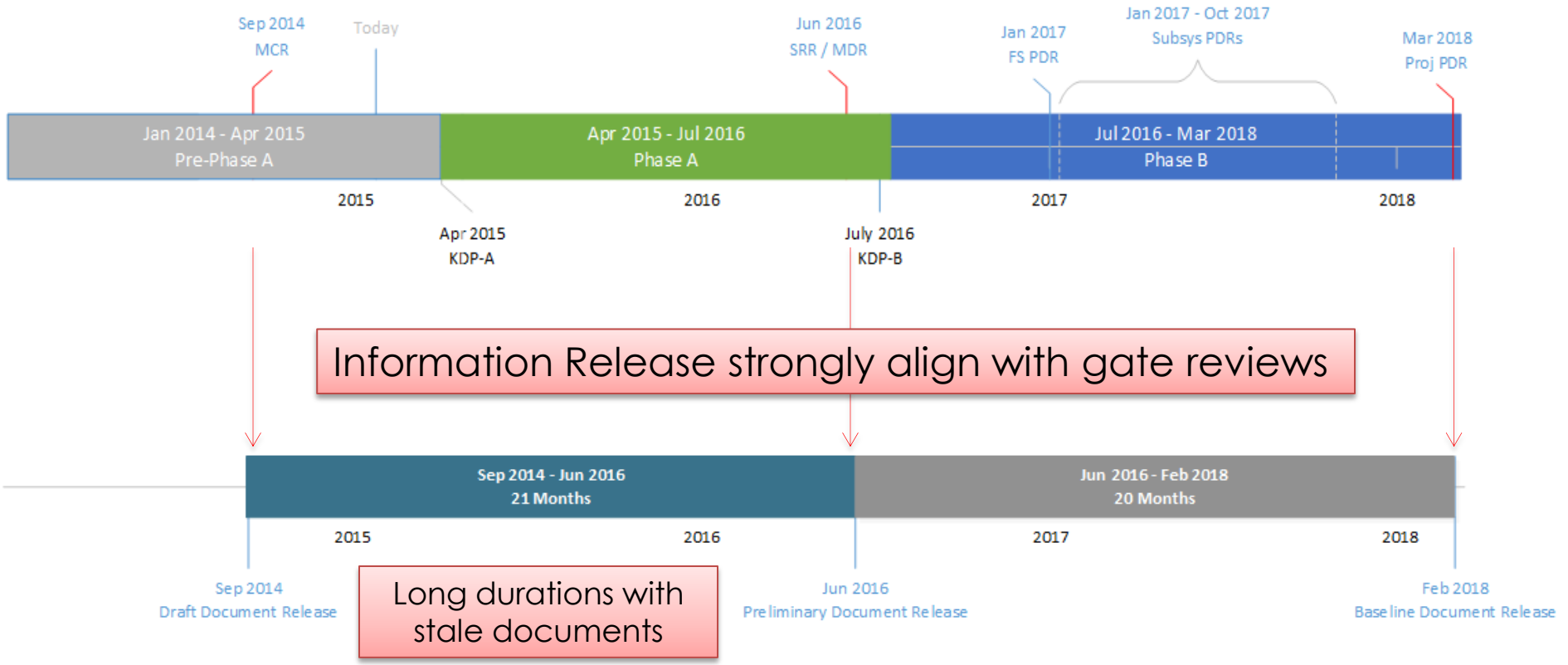
Typical Information Release Cadence

Project Timeline (typical):



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

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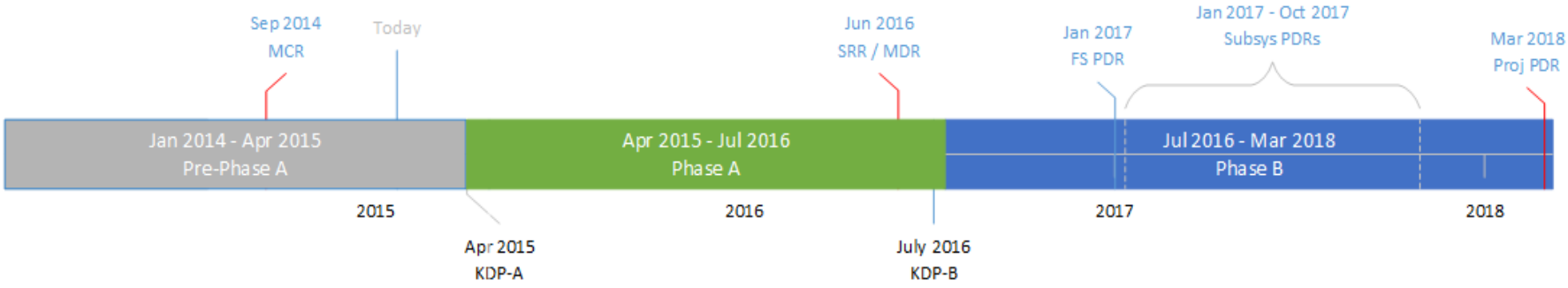
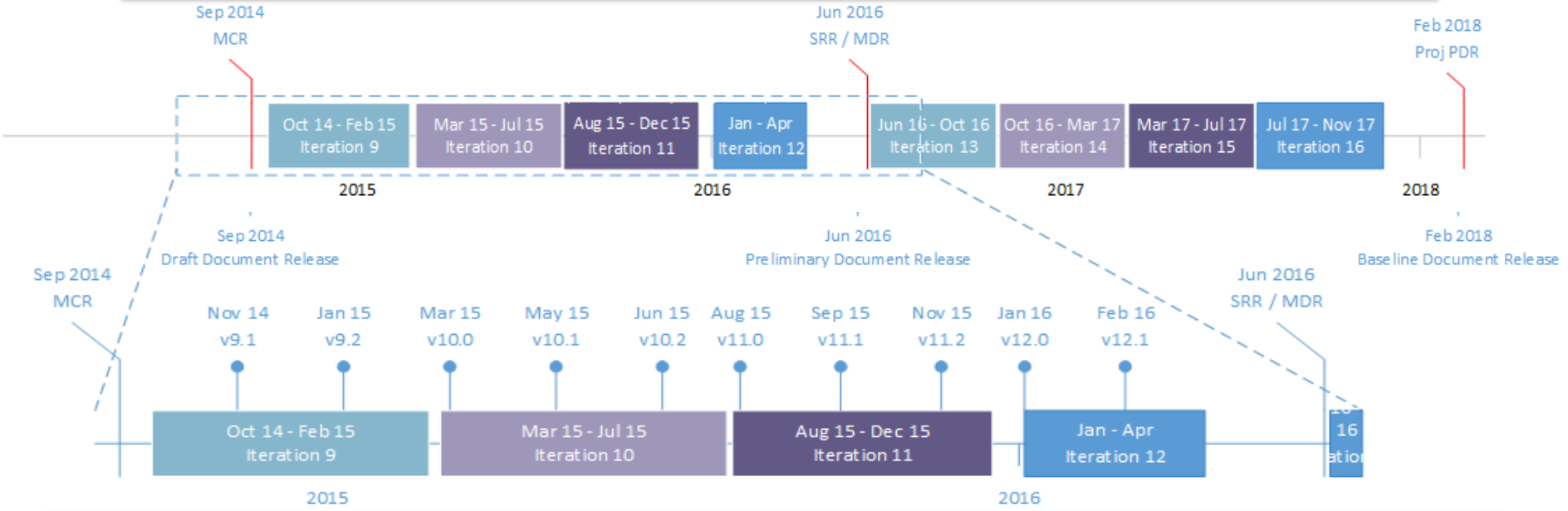
MBSE Enhanced Information Release Cadence

Project Timeline (typical):



Iterative approach sets regular release cadence; independent of review schedule



Increments set much shorter duration between change request and updated documentation

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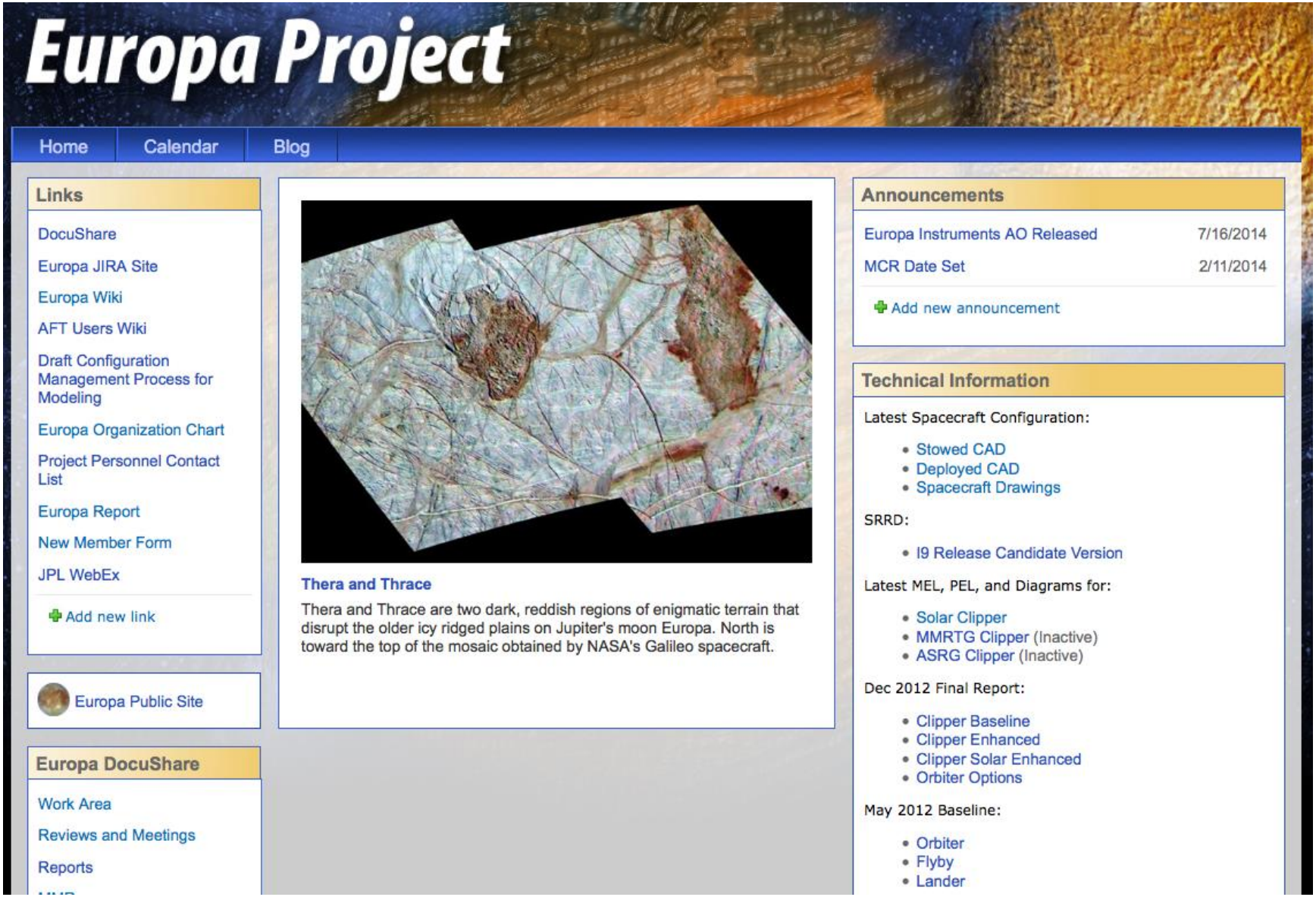
Project Portal



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Organization Charts

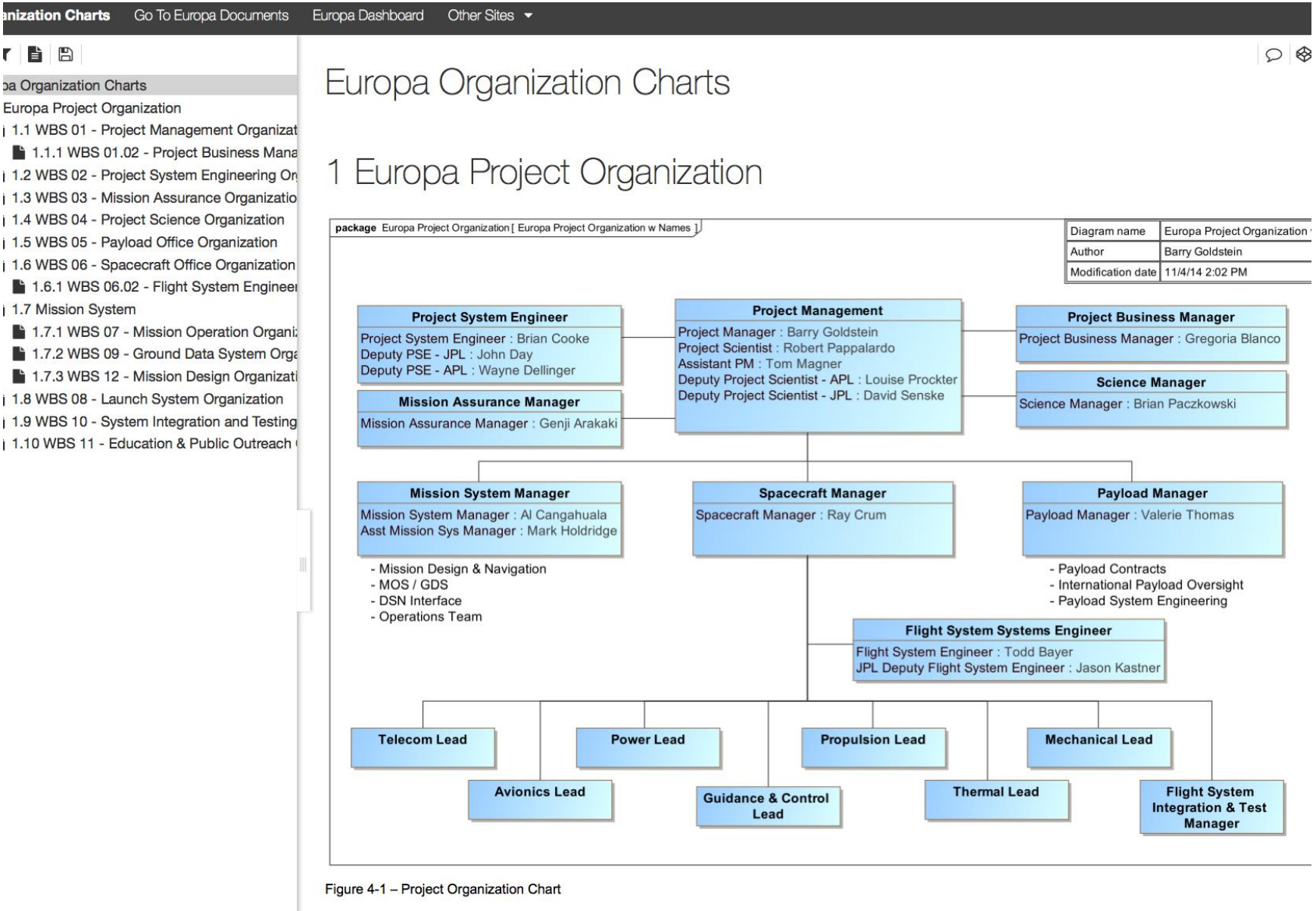

Figure 4-1 – Project Organization Chart

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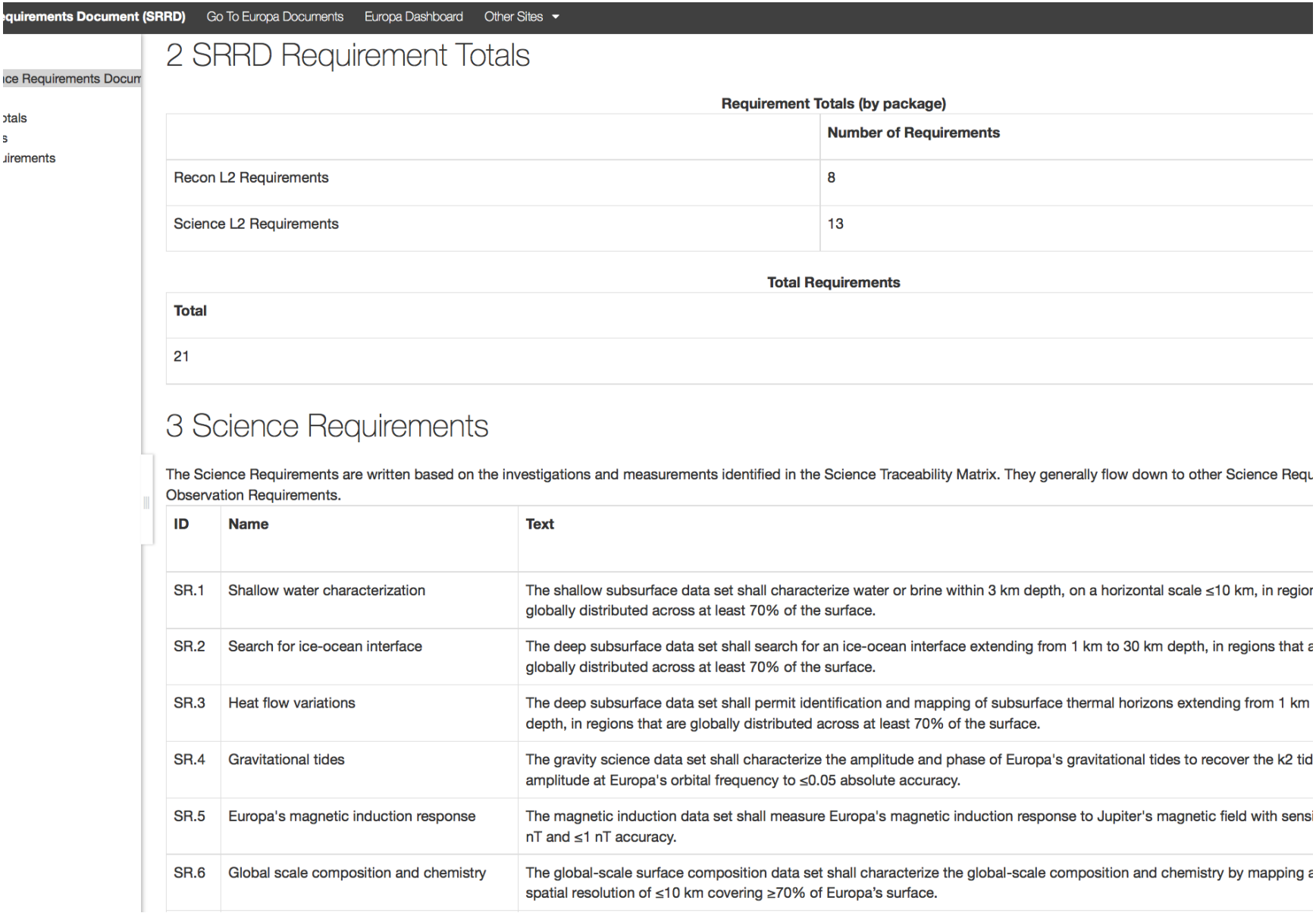
Requirements



quirements Document (SRRD) Go To Europa Documents Europa Dashboard Other Sites

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2 SRRD Requirement Totals

Requirement Totals (by package)

	Number of Requirements
Recon L2 Requirements	8
Science L2 Requirements	13

Total Requirements

Total
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 Requ
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 ≤10 km, in regior 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 a 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 tid amplitude at Europa's orbital frequency to ≤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 sensi nT and ≤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 ≤10 km covering ≥70% of Europa's surface.

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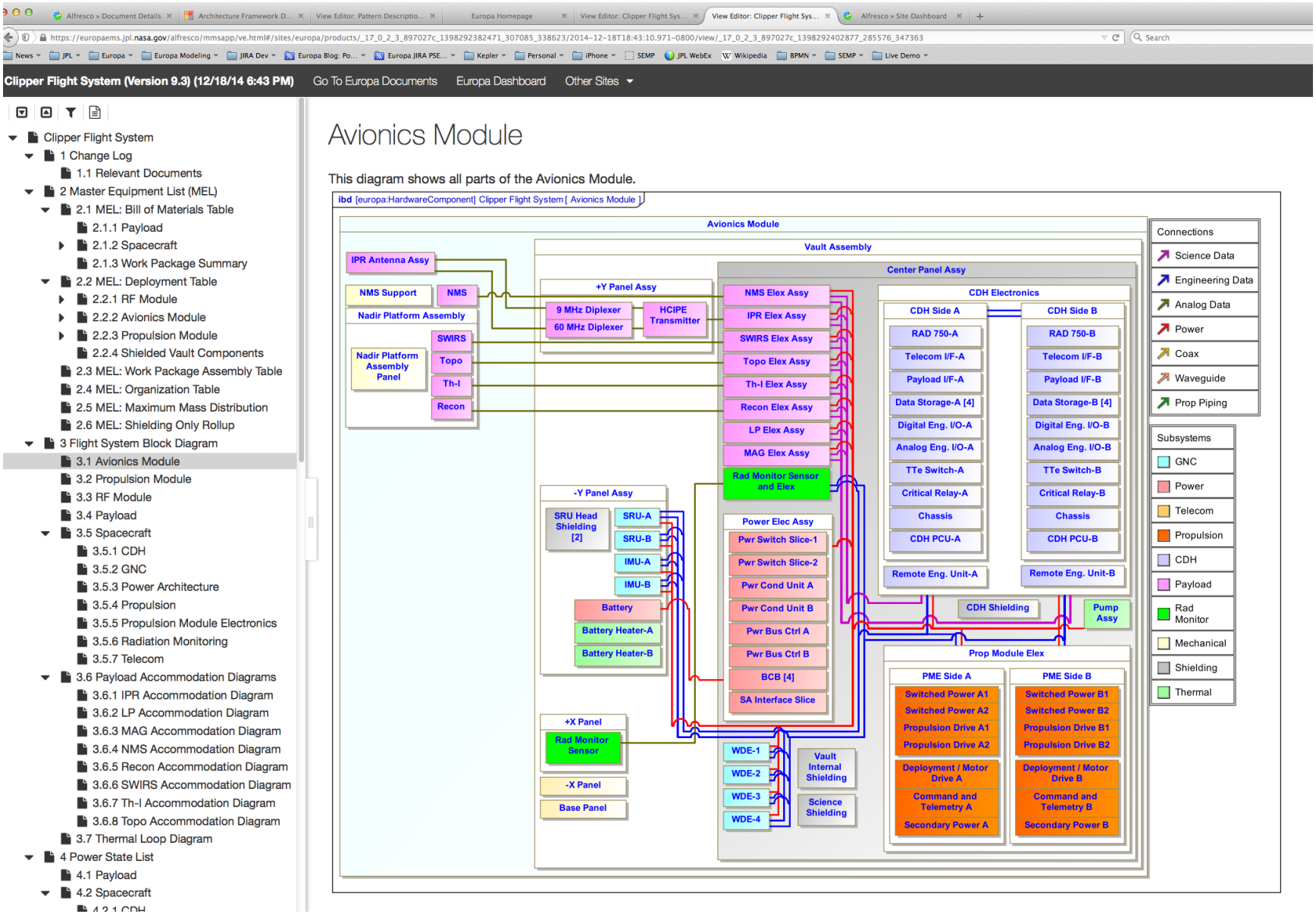
Block Diagrams



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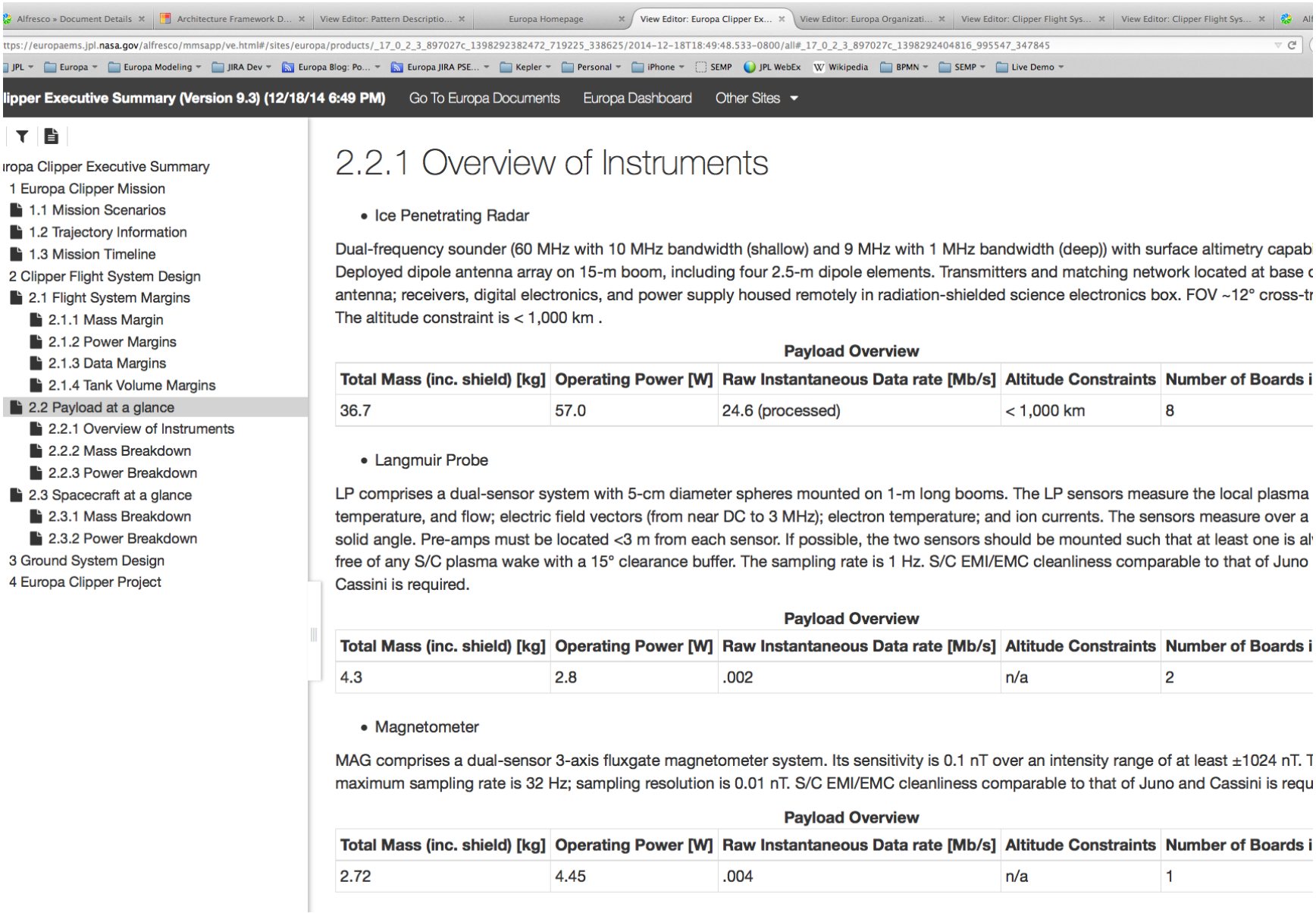
Instrument Overview



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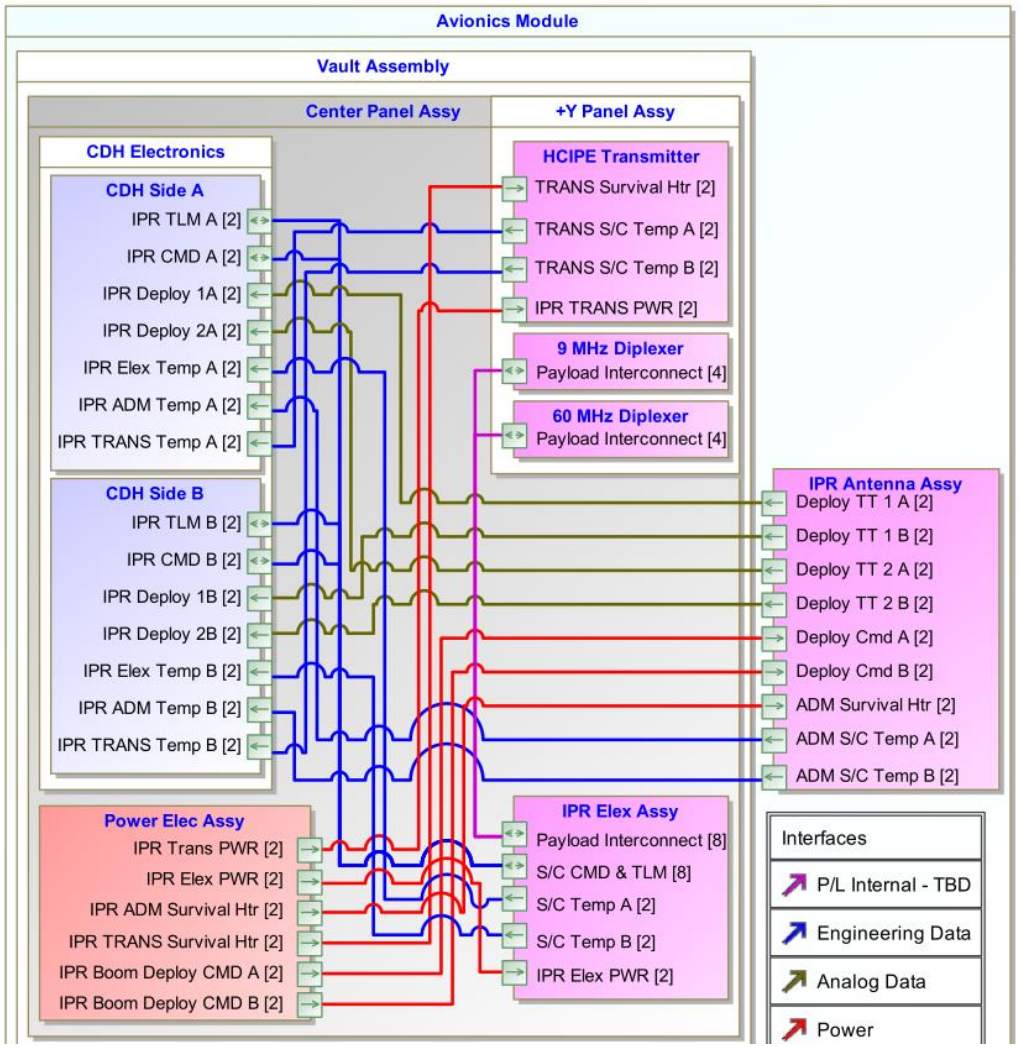
Instrument Accommodations

IPR Accommodation Diagram



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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_{mp}** - Current Density at maximum power
4. **V_{mp}** - Voltage at maximum power
5. **Converter Efficiency** - addresses additional loss between solar cell and panel interface slice
6. **$J_{mp}\_T_c$** - Temperature constant of J_{mp}
7. **$V_{mp}\_T_c$** - Temperature constant of V_{mp}
8. **I_{sc}** - Overall degradation factor for short circuit current
9. **V_{oc}** - Overall degradation factor for open circuit voltage

Solar Cell - Electrical Properties

Component	Type	Cell Efficiency	J_{mp} - Maximum Power Current Density [A/m^2]	V_{mp} - Maximum Power Voltage [V]	Converter Efficiency Fraction	Temperature Constants		Degradati
						$J_{mp}\_T_c$ [μA/cm^2/C]	$V_{mp}\_T_c$ [mV/C]	I_{sc} - Short Current
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 fo

Solar Cell - Assemble Group Loss Factors

Component	Type	Assemble Group					
		I_{sc}				V_{oc}	
		LAPSS Calibration	Coverglass	Mismatch	Production Variation	Assembly Loss	Blocking Dioc
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 and V_{oc}.

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

Component	Type	Environmental Group					Cell Loss Factors		Intensity (5
		Isc					I_{sc}	V_{oc}	I_{sc}
		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

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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

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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

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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

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