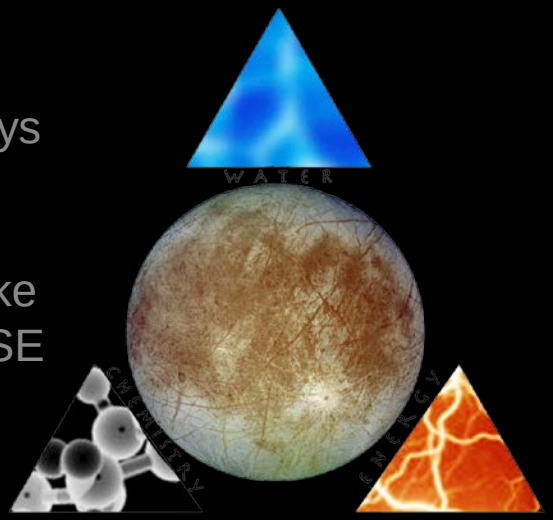
Model-Based System Engineering on NASA's Planned Europa Mission

For the Airbus R&T Days
18 November 2016

Todd Bayer/Brian Cooke
Europa Clipper FSE/PSE



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Topics

- Introduction to the planned Europa mission
- MBSE Application to Europa Clipper Formulation
- What we've learned from the experience... so far

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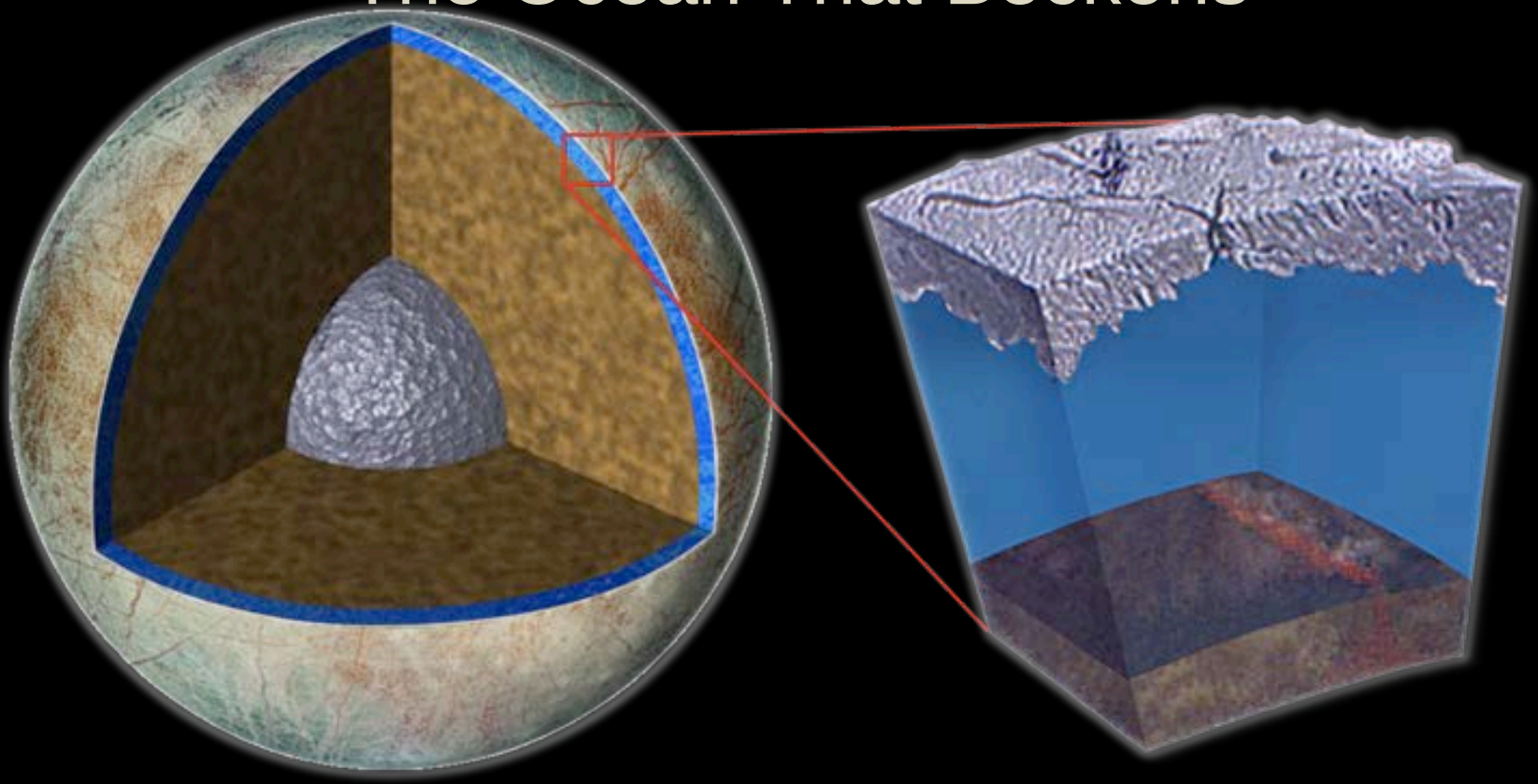
The Ocean That Beckons



"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"*

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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

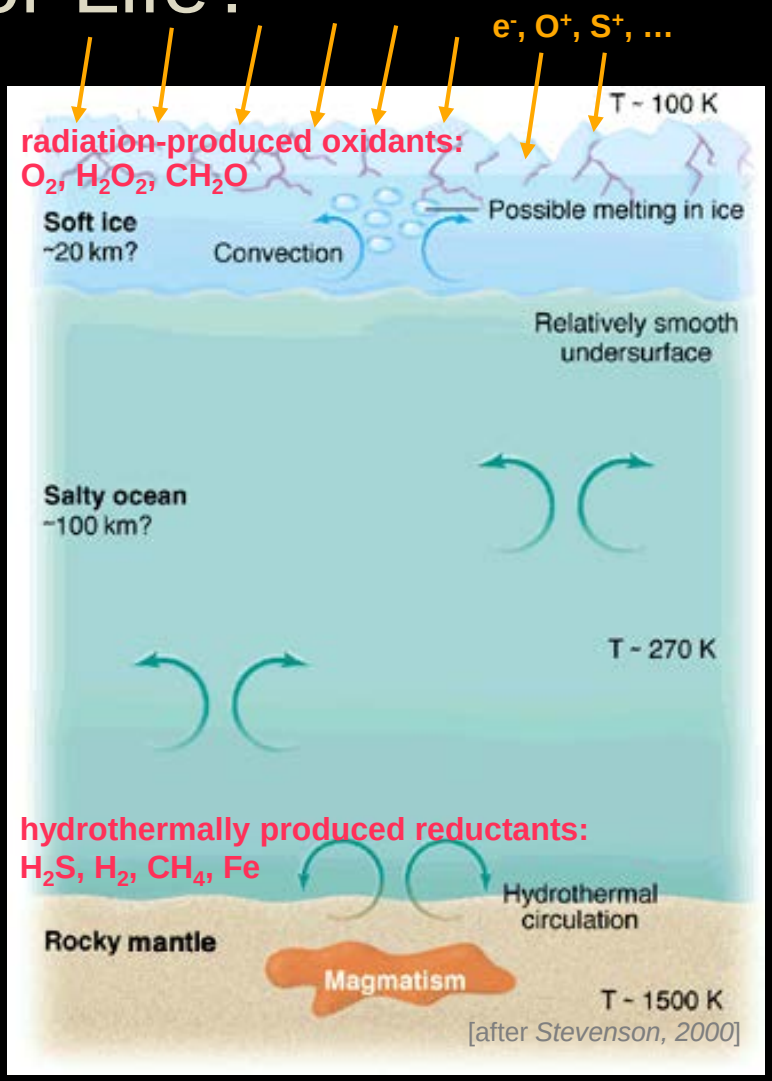
Chemistry:

- 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 planned Europa mission would test habitability hypotheses



[after *Stevenson, 2000*]

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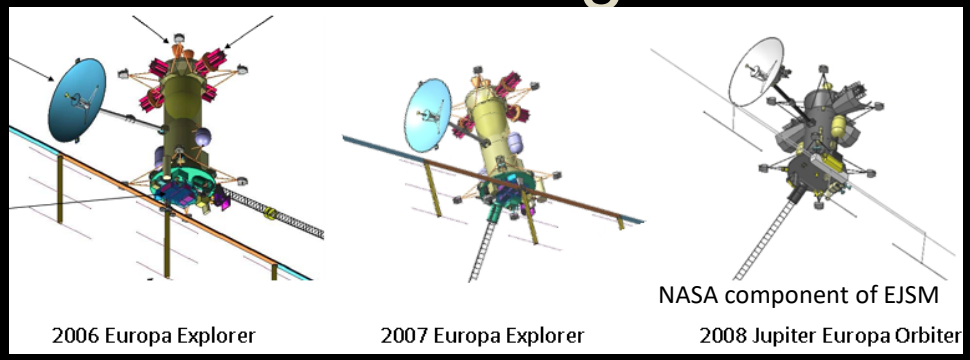
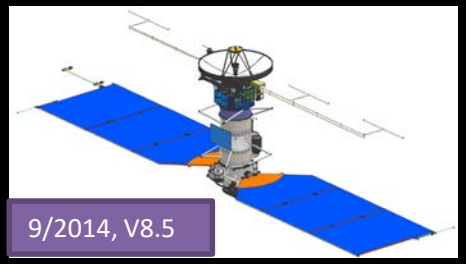
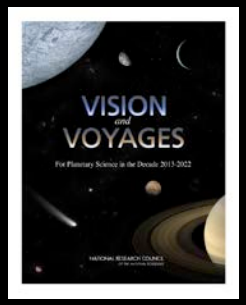
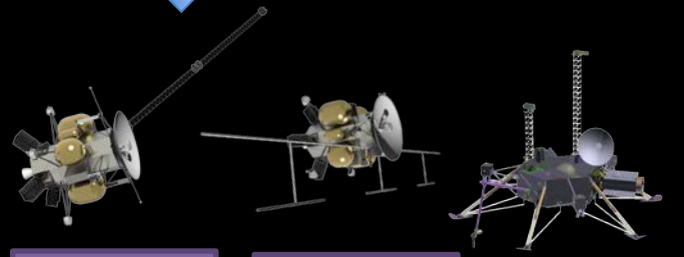
The long road to the current concept







Mission Studies 2011



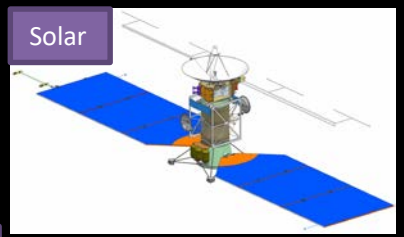
Orbiter

Flyby

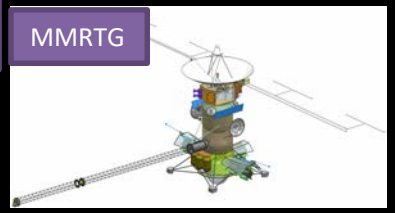
Lander

Europa Clipper (Flyby) 2012

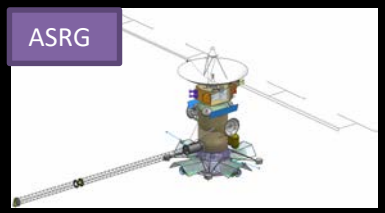
Power Source Trades 2013 and 2014



Solar



MMRTG



ASRG

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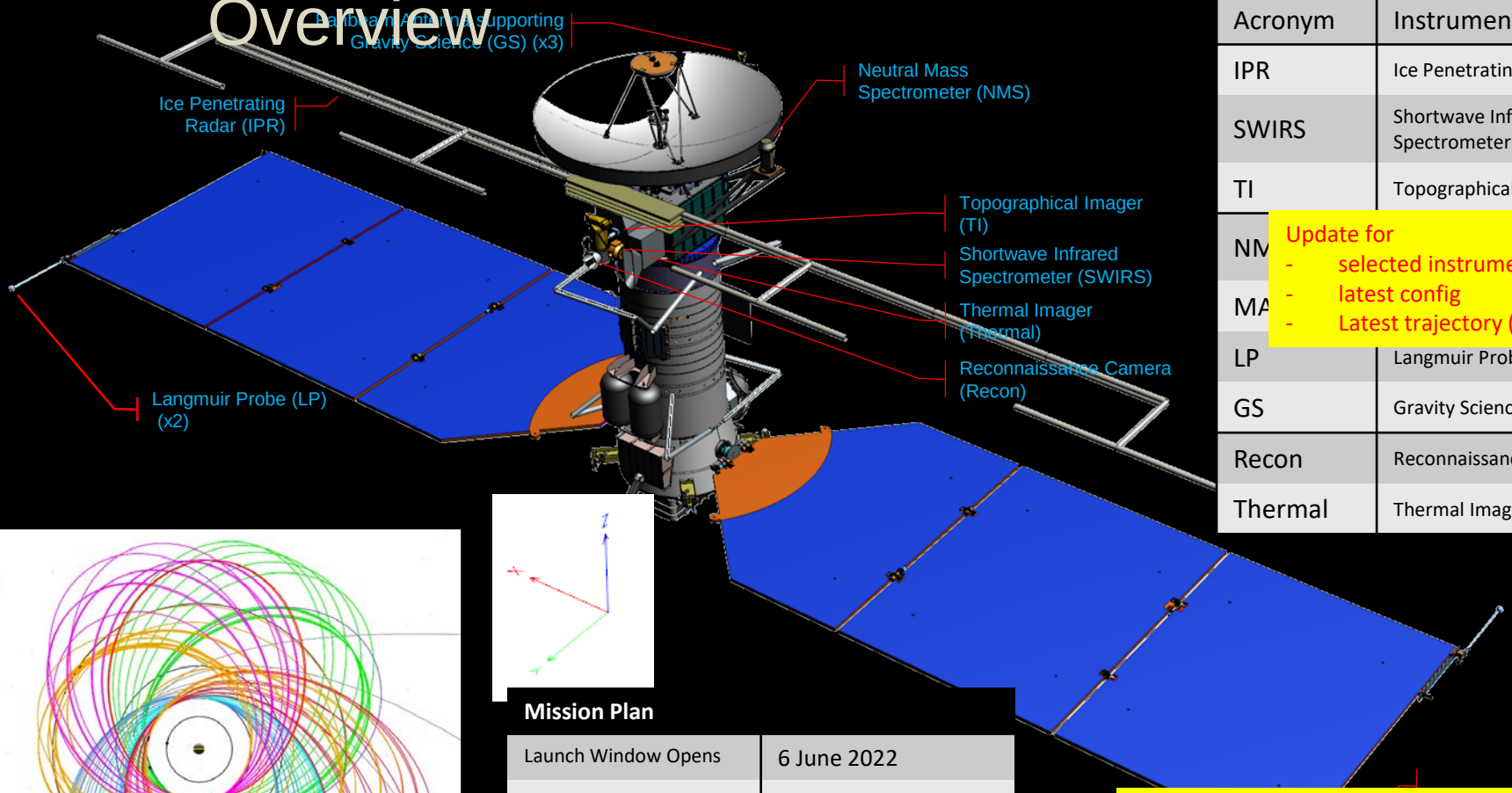
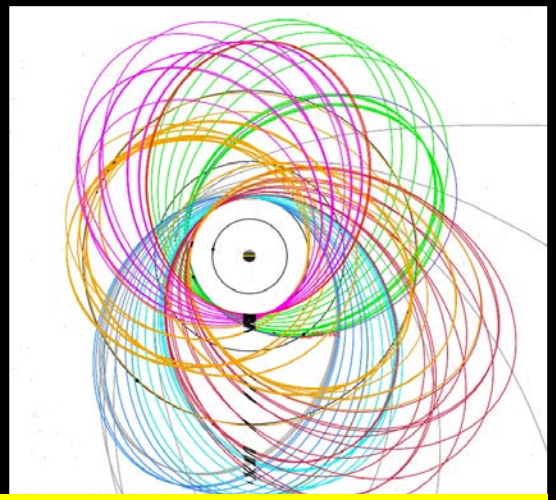
Europa Clipper Mission Concept Overview



Model Payload

Acronym	Instrument
IPR	Ice Penetrating Radar
SWIRS	Shortwave Infrared Spectrometer
TI	Topographical Imager
NM	
MA	
LP	Langmuir Probe
GS	Gravity Science
Recon	Reconnaissance Camera
Thermal	Thermal Imager

Update for
- selected instruments
- latest config
- Latest trajectory (or not)



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)

Fix art so graphics backgrounds match slide background

Intro to project. Few people will know what Europa is, few have experience in deep space

- Make it clear how deeply we've gone in pre and phase A compared to what most people in the audience are used to (their pre-phase A/phase A is more conceptual)

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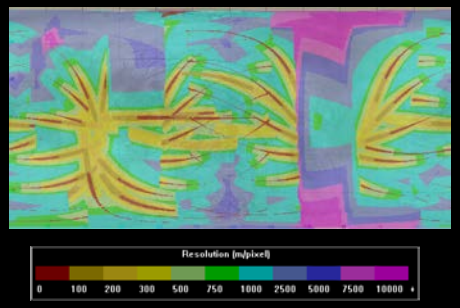
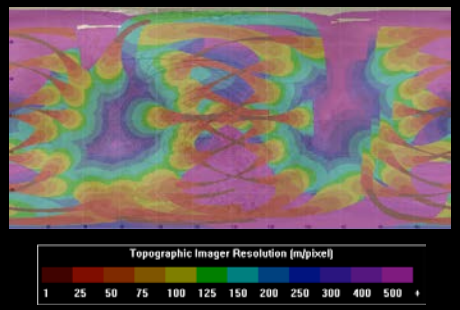
Innovative Mission Design is Enabling

Stripped out videos to fit in email

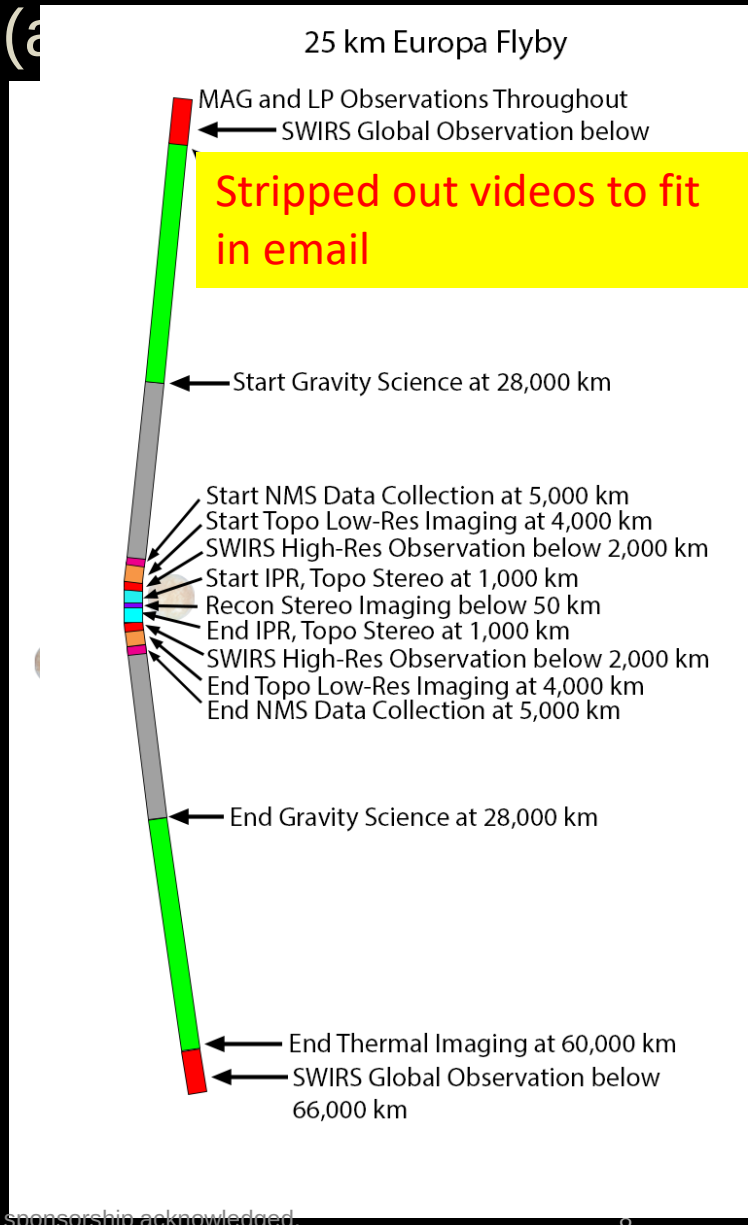
SWIRS



Topographic Imager



Europa Flyby's Are Repetitive (a



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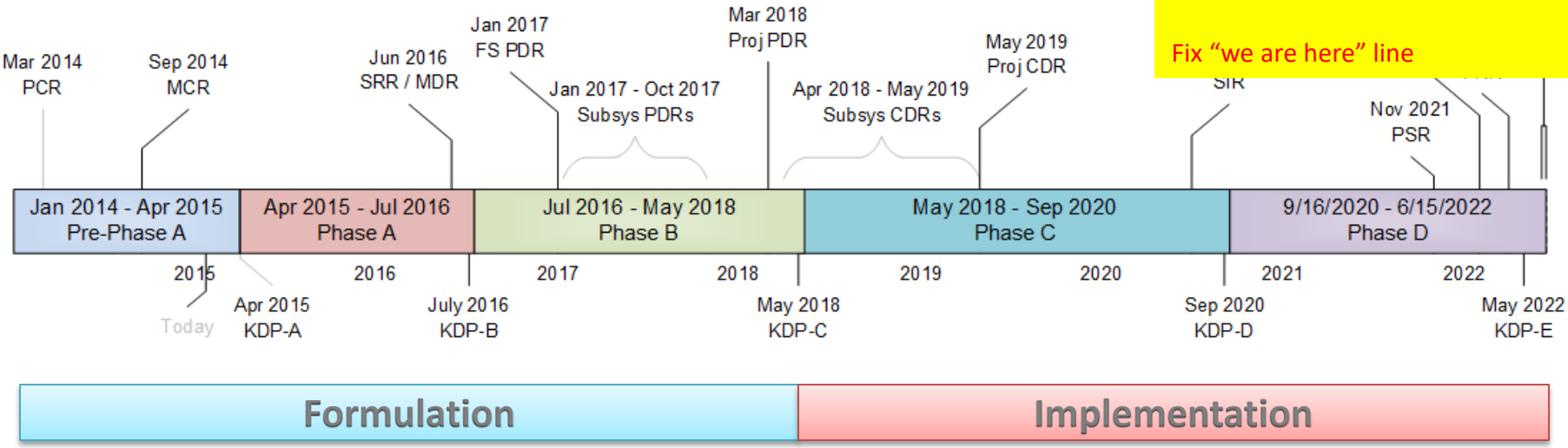
Europa Clipper Project Schedule

Europa Project Timeline – 2022 SLS Launch

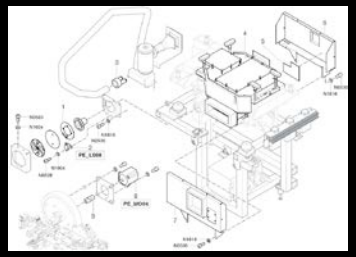
Fix art so graphics backgrounds match slide background

Fix “we are here” line



Formulation | **Implementation**

We are here



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Systems Engineering Challenges During Formulation Phase

- Managing multiple architectural alternatives
- Making the correct choices in system trades
- Reliably determining whether design concepts “close” on key technical resources
- Ensuring correctness and consistency of multiple, disconnected engineering reports
- Managing design changes before a full design exists
- Developing a coherent, complete and concise requirement set from L1 (Sponsor) to L4 (Subsystems)

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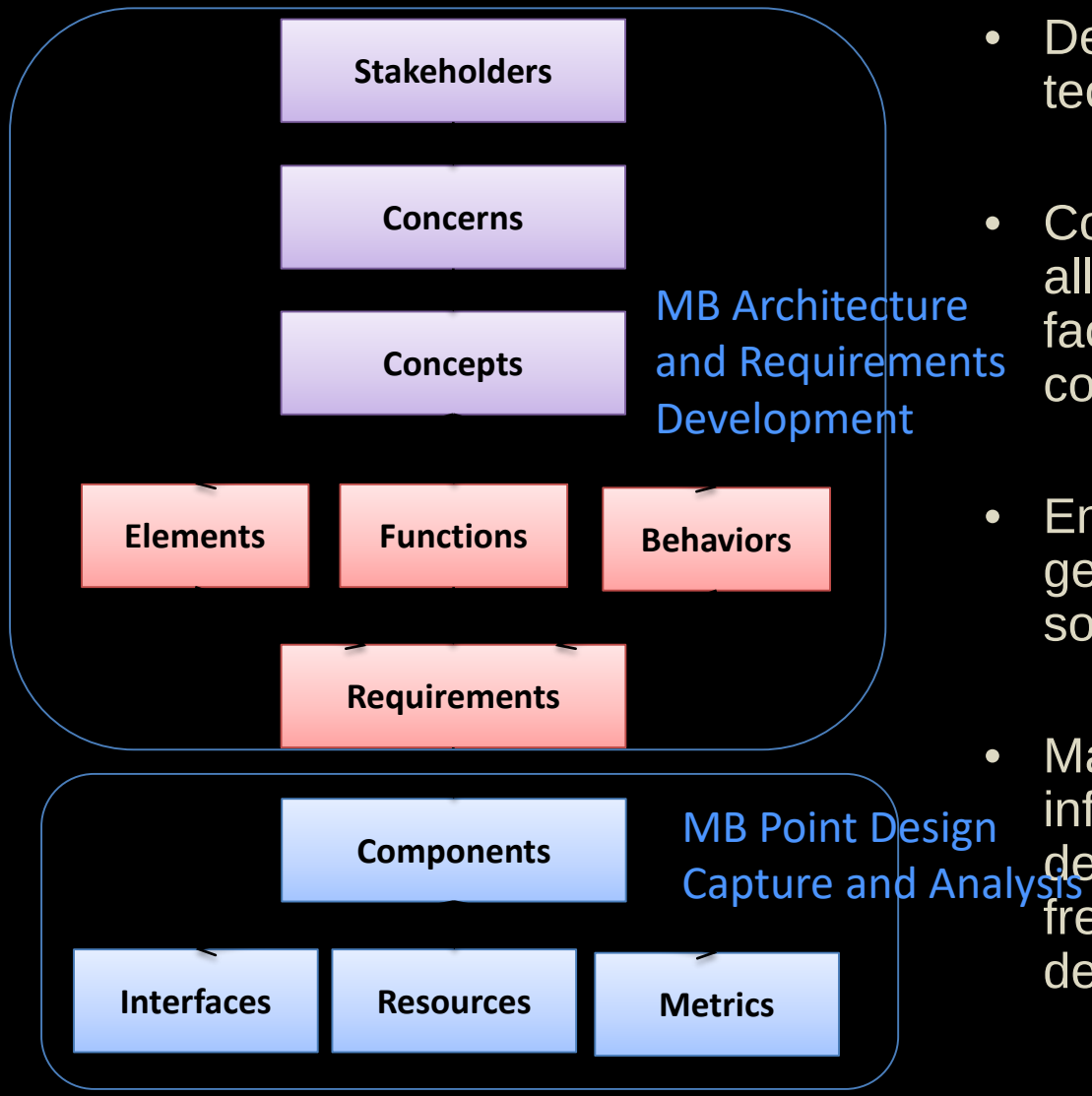
Model-Based System Engineering Approach



- 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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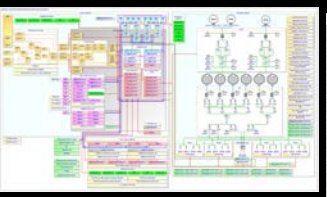
Europa System Model Framework

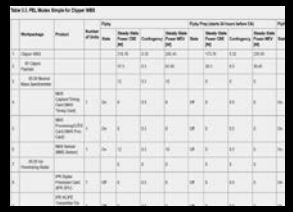
Update to include requirements, concepts.

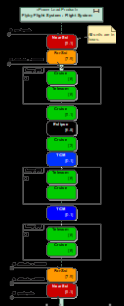
SysML Models
System, Programmatic, etc.

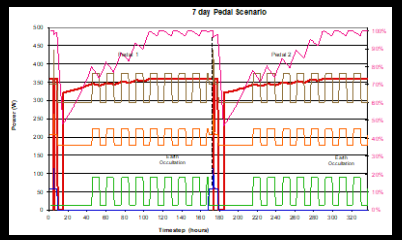
magicdraw

Block Diagram Viewpoints	Mass Equipment List Viewpoints	Mass Margin Viewpoints	Power Equipment List Viewpoints	Power Scenario Viewpoints	Data Margin Viewpoints
Block Diagram	MEL Table	Mass Margin Analysis & Report	PEL Table	Power Margin Analysis	Data Margin Analysis &Report
DocWeb	DocWeb	Office Excel	DocWeb	DocWeb	Wolfram Mathematica









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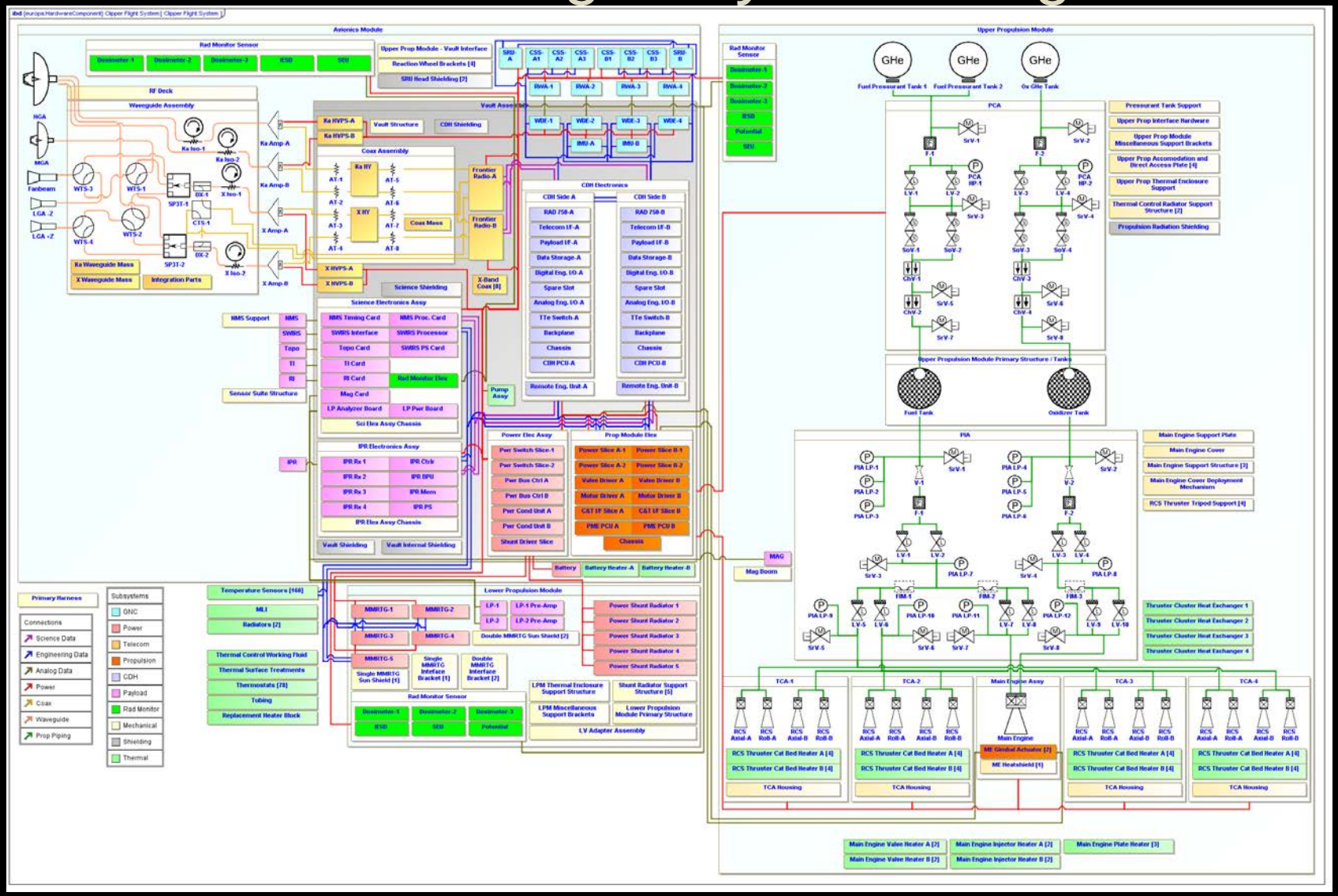
More Meaningful System Diagrams



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Automated Mass Accounting

Table 2.14. Deployment Table of Clipper Flight System

	Deployment
1	Clipper Flight Syster
2	Multi-layer Insulatic
3	Radiators
4	Temperature sens
5	Thermostats
6	Thermal Surface T
7	Thermal Control W
8	Tubing
9	Replacement Hea
10	Primary Harness
11	Avionics Module
12	Neutral Mass Sp
13	NMS Sensor
14	NMS Detecto
15	Ice Penetrating
16	IPR Antenna a
17	IPR HCIPE Tr
18	IPR Shielding
19	Short Wave IR S
20	SWIRS Sens
21	SWIRS Shiel

Table 2.1. Bill of Materials Table of Clipper Flight System for Clipper WBS

	Workpackage	Deployments	Num of Units	Mass CBE per Unit (kg)	Total Mass CBE (kg)	Mass Contingency	Mass MEV per Unit (kg)	Total Mass MEV (kg)
1	Clipper WBS			1439.91	1439.91	0.27	1835.26	1835.26
2	05 Clipper Payload			69.94	69.94	0.5	104.91	104.91
3	05.04 Neutral Mass Spectrometer			4.74	4.74	0.5	7.11	7.11
4		NMS Capture/Timing Card	1	0.9	0.90	0.5	1.35	1.35
5		NMS Processing/LVPS Card	1	0.9	0.90	0.5	1.35	1.35
6		NMS Sensor	1	2.94	2.94	0.5	4.41	4.41
7	05.05 Ice Penetrating Radar			28.2	28.2	0.5	42.3	42.3
8		IPR Antenna and Cable Assembly	1	12.2	12.20	0.5	18.3	18.30
9		IPR Digital Processor Card	1	1	1.00	0.5	1.5	1.50
10		IPR HCIPE Transmitter Elx	1	8	8.00	0.5	12	12.00
11		IPR Power Supply Card	1	1	1.00	0.5	1.5	1.50
12		IPR Receiver Board	4	1	4.00	0.5	1.5	6.00
13		IPR System Controller Card	1	1	1.00	0.5	1.5	1.50
14		IPR Waveform Memory Card	1	1	1.00	0.5	1.5	1.50
15	05.06 Short Wave Infrared Spectrometer			12.9	12.9	0.5	19.35	19.35
16		SWIRS Interface Card	1	0.9	0.90	0.5	1.35	1.35
17		SWIRS Pixel Processor Card	1	0.9	0.90	0.5	1.35	1.35
18		SWIRS Power Supply Card	1	1	1.00	0.5	1.5	1.50
19		SWIRS Sensor	1	10.1	10.10	0.5	15.15	15.15
20	05.07 Topographic Imager			2.5	2.5	0.5	3.75	3.75
21		TI Detector + Flex	1	0.35	0.35	0.5	0.52	0.53

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Integrated Power/Energy Analysis

System Model:
- Equipment List
- Demand vs Mode
- Scenario Definitions

Subsystem Power Models
- Power Source Models
- Battery Models
- Load Profile Simulation

Integrated Power/Energy Analysis

Update power to show the real integrated analysis?

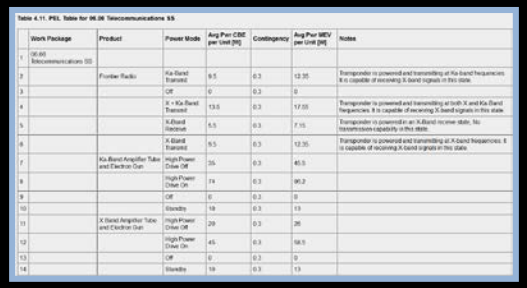
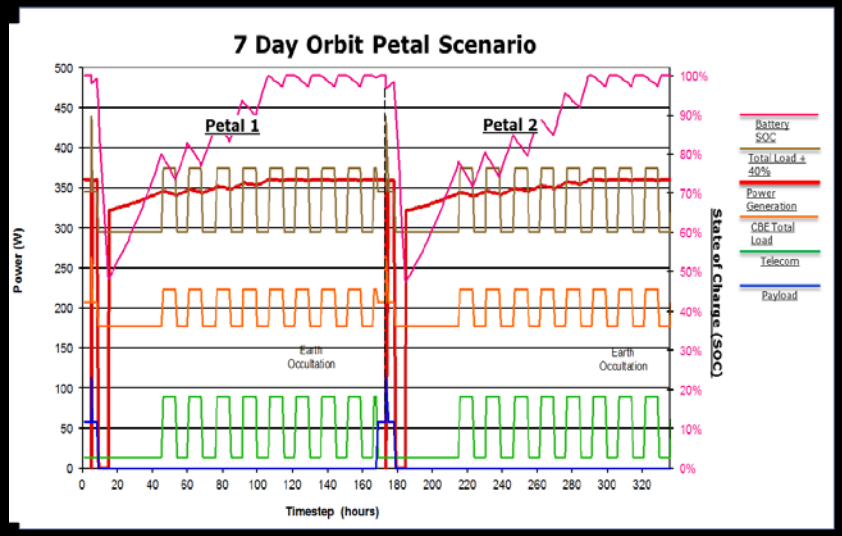
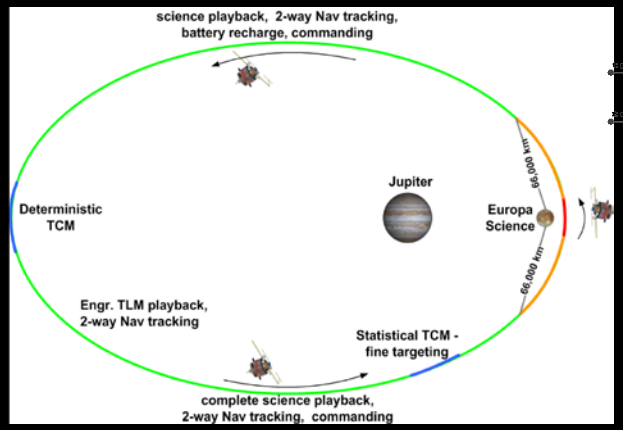


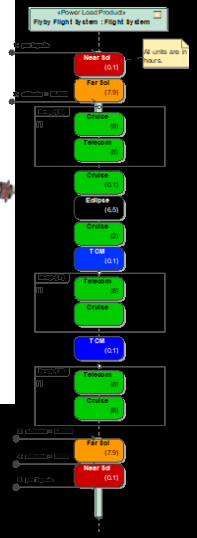
Table 4.11. PEL Table for 06.06 Telecommunications SS

	Work Package	Product	Power Mode	Avg Pwr CBE per Unit [W]	Contingency	Avg Pwr MEV per Unit [W]	Notes
1	06.06 Telecommunications SS						
2		Frontier Radio	Ka-Band Transmit	9.5	0.3	12.35	Transponder is powered and transmitting at Ka-band frequencies. It is capable of receiving X-band signals in this state.
3			Off	0	0.3	0	
4			X + Ka-Band Transmit	13.5	0.3	17.55	Transponder is powered and transmitting at both X and Ka-Band frequencies. It is capable of receiving X-band signals in this state.
5			X-Band Receive	5.5	0.3	7.15	Transponder is powered in an X-Band receive state. No transmission capability in this state.
6			X-Band Transmit	9.5	0.3	12.35	Transponder is powered and transmitting at X-band frequencies. It is capable of receiving X-band signals in this state.
7		Ka-Band Amplifier Tube and Electron Gun	High Power Drive Off	35	0.3	45.5	
8			High Power Drive On	74	0.3	96.2	
9			Off	0	0.3	0	
10			Standby	10	0.3	13	
11		X-Band Amplifier Tube and Electron Gun	High Power Drive Off	20	0.3	26	
12			High Power Drive On	45	0.3	58.5	
13			Off	0	0.3	0	
14			Standby	10	0.3	13	

Power Profile Analysis







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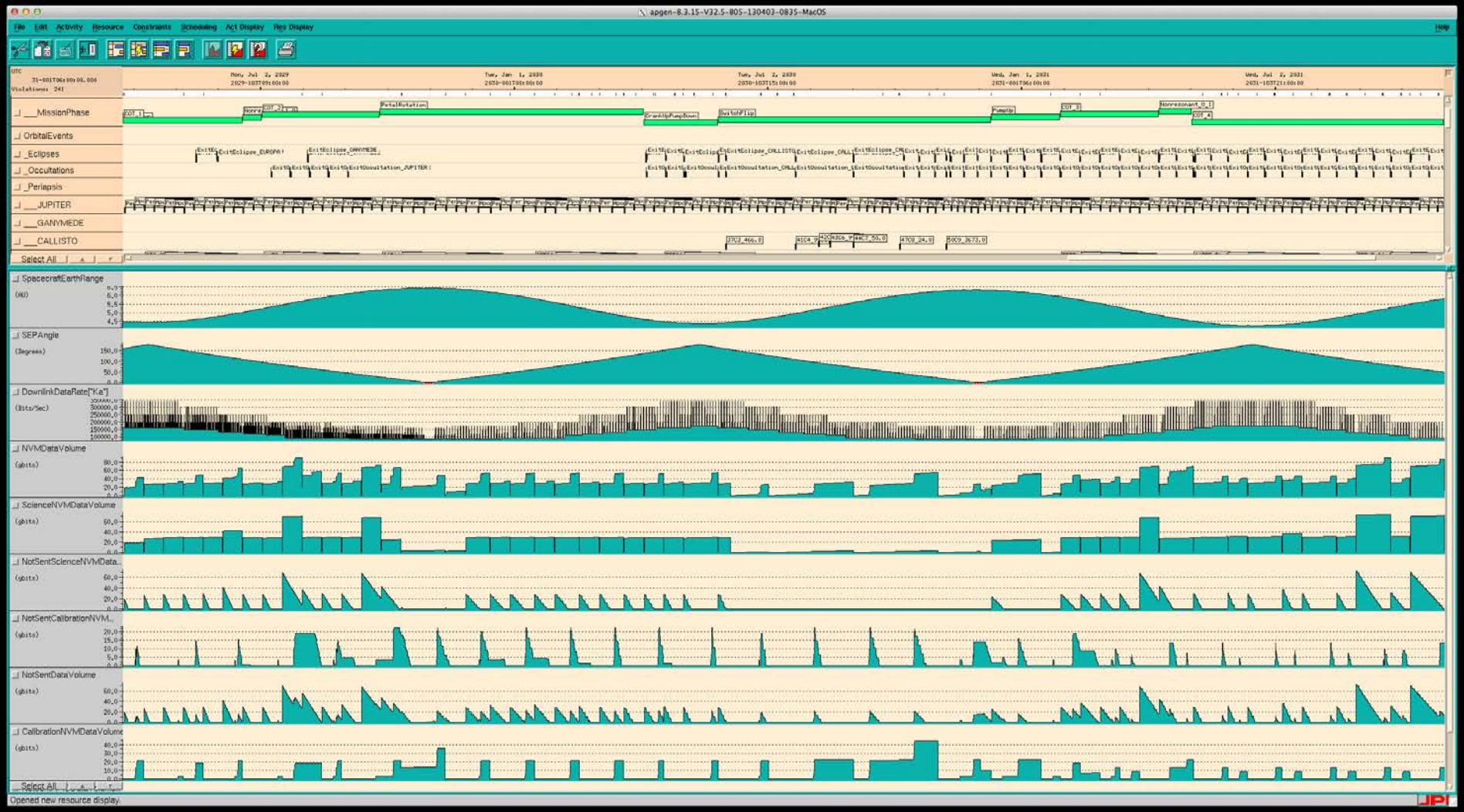
Integrated Data Throughput Analysis



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Additional New Product Types

Just quickly flash these and move on

Table 6.3. Thermal Loop Heat Information

	Items on the thermal loop
1	Total thermal power on loop without heater
2	CDH Electronics (CDH Electronics)
3	Flow Meter (FIM-1)
4	Flow Meter (FIM-2)
5	Flow Meter (FIM-3)
6	Frontier Radio (Frontier Radio-A)
7	Frontier Radio (Frontier Radio-B)
8	Inertia Measuremen Unit (IMU) (IMU-A)
9	Inertia Measuremen Unit (IMU) (IMU-B)
10	IPR Remote Electronics Assembly (IPR

Instrument Resources Table

Edit Save Cancel Last saved/exported by dcoren at 2013-10-21T17:48:15.810-07:00

Instrument Resources Spreadsheet

Instrument	Total Mass (inc. shield) [kg]	Shielding Mass [kg]	Operating Power [W]	Standby Power [W]	Survival Power [W]	Energy per encounter [W-hr]	Volume [cm]	Data Collection Interval	Field of View	Observing Geometry	Mounting	Pointing	Raw Instantaneous Data rate [Mb/s]	Data Volume	S/C Data Storage Volume	Data Interface	Number of Boards
Ice Penetrating Radar	33.2	5.0	55.0	13.0	5.0	22/flyby	15-m wide dipole antenna with 4 2.5-m dipole prongs, 15x20x30 electronics box	16 min/flyby	~12 deg swath width	Nadir viewing	Plane of antenna perpendicular to S/C Z axis	Control: 1° Stability: 208 µrad/s Knowledge: 1°	24.5	23.5 Gb/flyby	23.5	SpaceWire	8
Langmuir Probes	2.98		2.3	1.0	1.0	55/day	Two 5-cm diameter sphere sensors	Continuous	4pi ster	One sensor always free of S/C wake	Two 5-cm diameter spheres mounted on 1-m long booms	Control: 5°, absolute knowledge: 1°	.002	1.2 Gb/orbit	.9	SpaceWire	2
Magnetometer	1.62	0.0	2.8	1.2	0.0	96/day	6x6x6 per sensor	Continuous	N/A	N/A	Two sensors on 10-m boom (6.5 m out & 10 m out)	Control: 5° Absolute knowledge: 0.1° when near Europa; else 1°	.004	1 Gb/orbit	1.8	SpaceWire	1
Neutral Mass Spectometer	6.78	2.04	15.0	6.0	2.0	3/flyby	15 diam x 33	16 min/flyby	2pi ster	Aligned with Velocity vector	Viewing in the ram direction	Control: 1° Absolute knowledge: 1°	.003	1 Mb/flyby	.001	Mil-Std-1553	2
Reconnaissance Imager	13.1	2.0	20.0	14.0	4.0	170/flyby	60x15x15	2 min/flyby	92 mrad cross-track x 10 µrad along track	under 50 km range, 60-80 deg angle of incidence	View nadir ±15°; detector line perpendicular to ground track; radiator view to dark space	Control: 9 mrad Stability: 50 µrad/s Jitter @ ≥50 Hz: <4 µrad peak-to-peak Relative knowledge: 10 µrad over any 4s period Absolute knowledge: 0.9 mrad Agility: repoint flip mirror 15° and settle in <1s	1991	26.5 Gb/flyby	26.5	SpaceWire	1
Short-wave Infrared Spectrometer	18.8	5.9	19.14	11.5	3.0	100/flyby	30x20x15	14.5 min/flyby	72 mrad cross-track x 150 µrad along track; ±45 deg along track mirror scan from nadir	prefer under 45 deg angle of incidence	View nadir ±45° along track; detector line perpendicular to ground track; radiator view to dark space	Control: 7 mrad Stability: 25 µrad/s Relative knowledge: 150 µrad over any 60s period Absolute knowledge: 0.7 mrad	2.4 (hi-res, 4.5 min), 1.6 (lo-res, 10 min)	.53 Gb/flyby	.53	SpaceWire	3
Thermal Instrument	7.18	1.28	11.0	3.0	3.0	92/flyby	35x20x20	8.4 hr/flybyd	100 mrad cross-track x 2.5 mrad along track	Nadir viewing	Boresighted with IPR and topo imager; view nadir	Control: 10 mrad Stability: 0.65 mrad/s Absolute knowledge: 2.5 mrad	.07	.23 Gb/flyby	.23	Mil-Std-1553	1
Topographic Imager	4.0	1.5	5.86	2.2	1.2	5/flyby	10x10x15	52 min/flyby	58 deg cross-track x 250 µrad along track	Nadir viewing, 20-80 deg phase	Nadir line boresighted with IPR and thermal imager; detector lines perpendicular to ground track; radiator view to dark space	Control: 100 mrad Stability: 7 mrad/s Relative knowledge: 250 µrad over any 60s period Absolute knowledge: 10 mrad	.71	4.79 Gb/flyby	.5	SpaceWire	1

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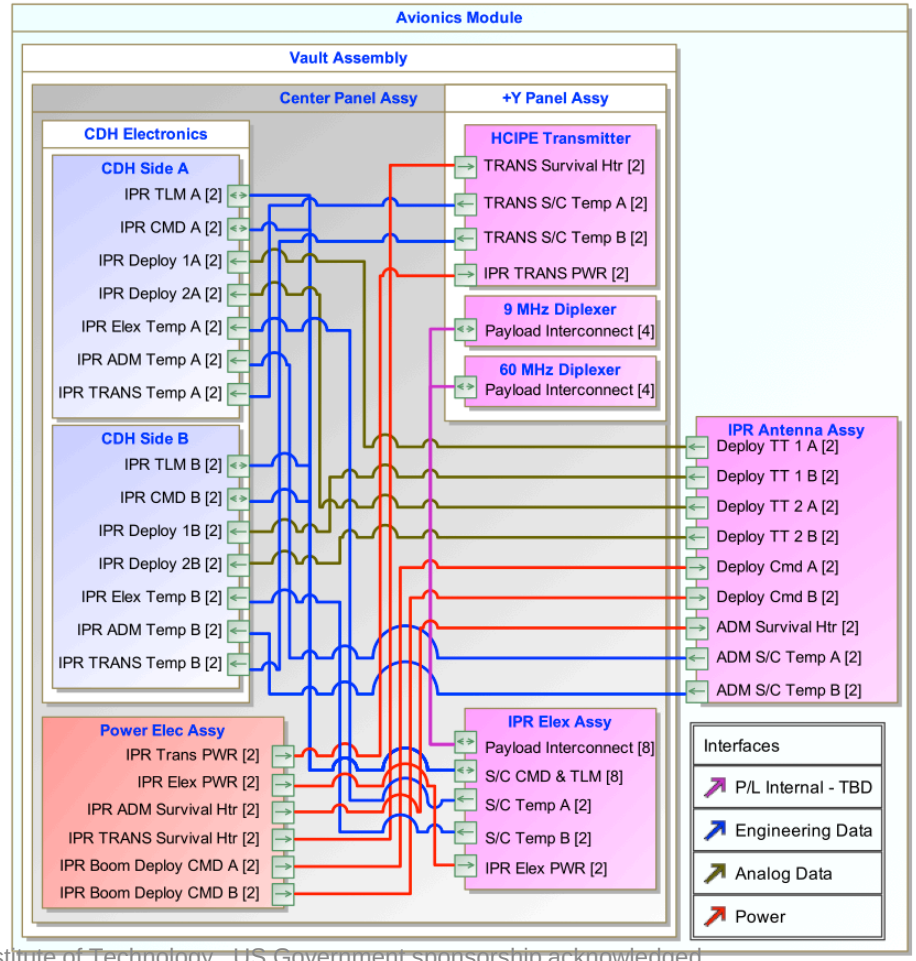
Instrument Accommodations

Just quickly flash these and move on

Subsystem View: Payload (Version 9.3) (12/18/14 10:52 AM) Go To Europa Documents Europa Dashboard Other Sites

- 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



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Subsystem Views

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Subsystem View: Power (Version 9.2) (Latest Baselined Documents - 06 Flight System) (Latest Baselined Flight System Design) (11/25/14 2:11 PM) Go To Europa Documents Europa Dashboard Other Sites

Subsystem View: Power
- 1 Summary
- 2 Block 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
- 9 Solar Wing Characterizations
- 10 Solar Panel Characterizations
- 11 Solar Cell Characterizations

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		Degradation Factors	
						$J_{mp_}T_c$ [μA/cm^2/C]	$V_{mp_}T_c$ [mV/C]	I_{sc} - Short Circuit Current	V_{oc} - Open Circuit Voltage
Solar Array Cell & Wiring	UTJ	0.28	163	2.35	0.9	2.6	-6.7	0.9	0.882

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 both I_{sc} and V_{oc}.

Solar Cell - Assemble Group Loss Factors

Component	Type	Assemble Group						
		I_{sc}				V_{oc}		
		LAPSS Calibration	Coverglass	Mismatch	Production Variation	Assembly Loss	Blocking Diode	Wiring Harness
Solar Array Cell & Wiring	UTJ	0.975	0.99	0.98	0.99	0.9957	0.8	0.025

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 Intensity loss factors for both I_{sc} and V_{oc}.

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

Component	Type	Environmental Group					Cell Loss Factors		Intensity (5.5AU) Loss Factors	
		Isc					I_{sc}	V_{oc}	I_{sc}	V_{oc}
		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	0.857

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Organization Charts

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Europa Organization Charts | Go To Europa Documents | Europa Dashboard | Other Sites

- Europa Organization Charts
  - 1 Europa Project Organization
    - 1.1 WBS 01 - Project Management Organizat
      - 1.1.1 WBS 01.02 - Project Business Mana
    - 1.2 WBS 02 - Project System Engineering Or
    - 1.3 WBS 03 - Mission Assurance Organizatio
    - 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 Engineer
    - 1.7 Mission System
      - 1.7.1 WBS 07 - Mission Operation Organi
      - 1.7.2 WBS 09 - Ground Data System Orga
      - 1.7.3 WBS 12 - Mission Design Organizati
    - 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

package Europa Project Organization [Europa Project Organization w Names]

Diagram name	Europa Project Organization w Names
Author	Barry Goldstein
Modification date	11/4/14 2:02 PM

Project System Engineer
Project System Engineer : Brian Cooke
Deputy PSE - JPL : John Day
Deputy PSE - APL : Wayne Dellinger

Mission Assurance Manager
Mission Assurance Manager : Genji Arakaki

Project Management
Project Manager : Barry Goldstein
Project Scientist : Robert Pappalardo
Assistant PM : Tom Magner
Deputy Project Scientist - APL : Louise Prockter
Deputy Project Scientist - JPL : David Senske

Project Business Manager
Project Business Manager : Gregoria Blanco

Science Manager
Science Manager : Brian Paczkowski

Mission System Manager
Mission System Manager : Al Cangahuala
Asst Mission Sys Manager : Mark Holdridge

- Mission Design & Navigation
- MOS / GDS
- DSN Interface
- Operations Team

Spacecraft Manager
Spacecraft Manager : Ray Crum

Payload Manager
Payload Manager : Valerie Thomas

- Payload Contracts
- International Payload Oversight
- Payload System Engineering

Flight System Systems Engineer
Flight System Engineer : Todd Bayer
JPL Deputy Flight System Engineer : Jason Kastner

Telecom Lead

Power Lead

Propulsion Lead

Mechanical Lead

Avionics Lead

Guidance & Control Lead

Thermal Lead

Flight System Integration & Test Manager

Figure 4-1 – Project Organization Chart

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Requirements

Add a L3 example

Science and Reconnaissance Requirements Document (SRRD) | Go To Europa Documents | Europa Dashboard | Other Sites

Science and Reconnaissance Requirements Docum
1 Introduction
2 SRRD Requirement Totals
3 Science Requirements
4 Reconnaissance Requirements
5 SRRD Analyses

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 Requirements or Science Observation Requirements.

ID	Name	Text	Notes (not rationale)
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 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 to 30 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 ≤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 ≤0.1 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 at a spatial resolution of ≤10 km covering ≥70% of Europa's surface.	

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Configuration-Managed, Web-Based Reporting

Update – use the latest solar model.

Europa Project

Home | Calend

Links

- DocuShare
- Europa JIRA Site
- Europa Wiki
- AFT Users Wiki
- Draft Configuration Management Process fo Modeling
- Europa Organization Ch
- Project Personnel Conta List
- Europa Report
- New Member Form
- JPL WebEx
- Add new link

Europa Public Site

Europa DocuShare

- Work Area
- Reviews and Meetings
- Reports

DocWeb Clipper MMRTG

Clipper MMRTG Nov. 19, 2013, 2:22 p.m. PDF

The technical data in this document is controlled under the U.S. Export Regulations, release to foreign persons may require an export authorization.

Clipper MMRTG

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    4.2.4. Power
    4.2.5. Propulsion

Table 1.1. Change log

Version	Release Date	Changes
7.2	11/22/2013	This version incorporates the following Model Change Requests (MCRs): • EMOD-423 (Add Propellant & Pressurant Tank Capacity in MEL Notes Field) • EMOD-428 (Update MMRTG Battery Capacity & Mass) • EMOD-445 (Implement ECR 539 Prop Module Electronics Change in MMRTG Clipper Model) • EMOD-450 (Connector from SRU to CDH is wrong, not carrying science data) This version also incorporates the following items that were not associated with a JIRA: • [TBD] The following are known issues with this version: • In the Telecom block diagrams, some attenuators are connected directly to other attenuators. This seems incorrect.
7.1	11/13/2013	This version incorporates the following Model Change Requests (MCRs): • EMOD-337 (Need Legends for line & block colors on all Flight System Block Diagrams) ○ Subtask: EMOD-341 (Add Legends to DocWeb Figures) • EMOD-351 (Add New Power Mode Scenario to MMRTG Model) • EMOD-406 (Remove Gravity Science Antennas from MMRTG Model) • EMOD-407 (Replace SDST with Frontier Radio in MMRTG Model) • EMOD-415 (Update MMRTG Telecom Workpackage per ECR-534) • EMOD-427 (Update Flyby 6 Mode Scenario Text) • EMOD-434 (CDH subsystem MEL, PEL, and Block Diagram updates as per ECR-527) • EMOD-447 (IPR component name change) • EMOD-449 (Change to Change Log format) This version also incorporates the following items that were not associated with a JIRA: • An error in the Inner Cruise mode scenarios was corrected: the Magnetometer and Langmuir Probes were incorrectly set to be on. This resulted in a 4.5W savings in all Inner Cruise mode scenarios. The following are known issues with this version:

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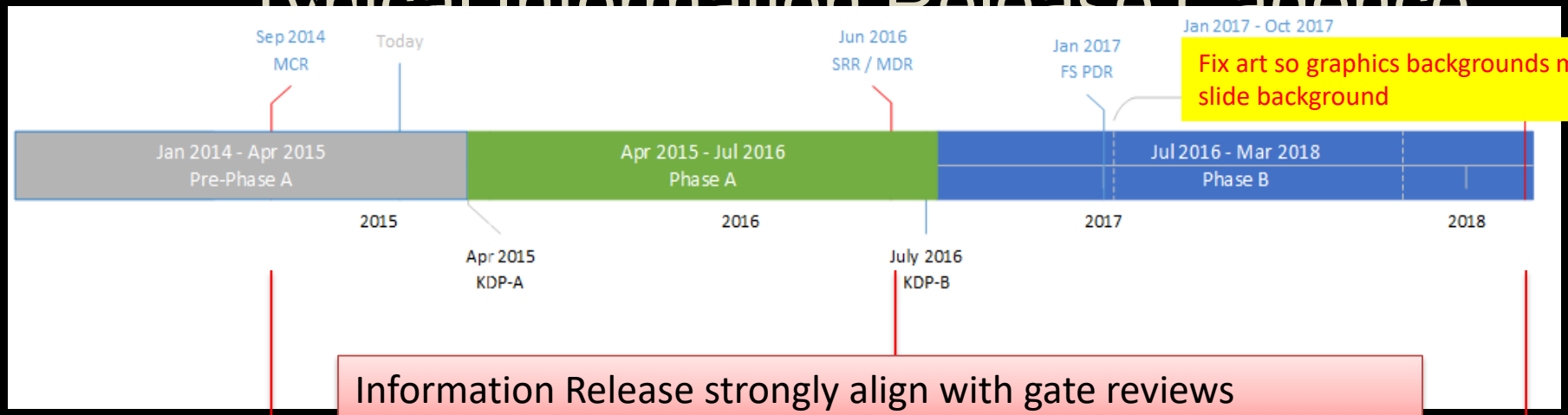
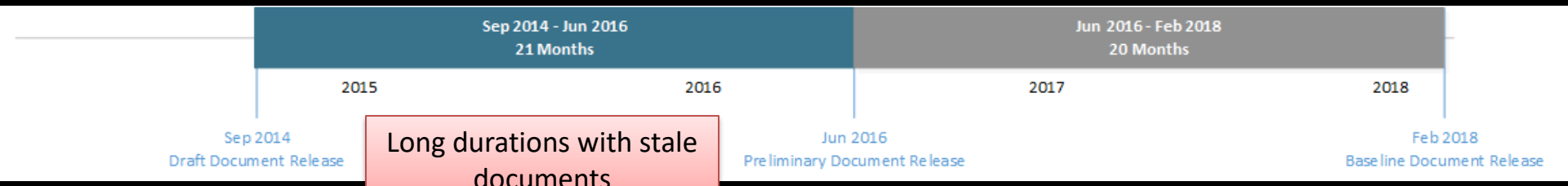
Typical Information Release Cadence



Fix art so graphics backgrounds match slide background

Information Release strongly align with gate reviews



Long durations with stale documents

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

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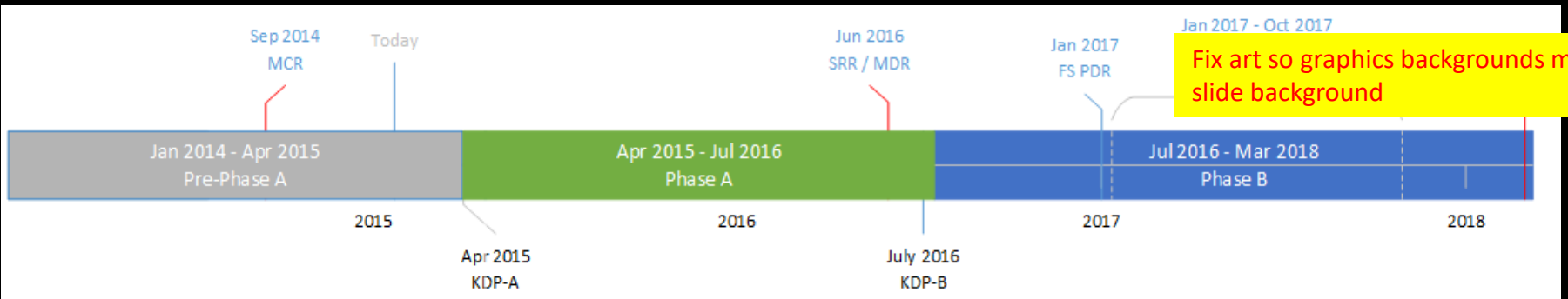
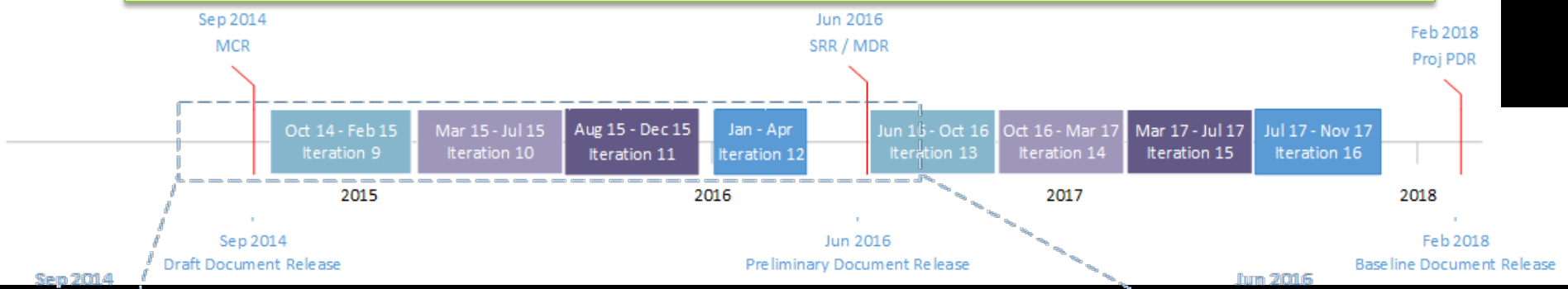
MBSE Enhanced Information Release



Fix art so graphics backgrounds match slide background

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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Benefits Seen:
MB Point Design Capture and Analysis:

- More efficient and accurate technical communication
- Greater re-use of system designs
- Better control over evolution of system designs
- More consistent system metrics
- More efficient generation of project documentation
- Better bridge from universities to project best practices

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Benefits seen: *Architecture & Requirements*

- Deriving requirements from fundamental concepts has
  - promoted more disciplined thinking, more complete coverage, better early integration with science and operations needs, and better rationale
  - Enabled explicit incorporation of analyses as part of requirements flowdown
  - Enabled explicit association of requirements with system components
- Other benefits seen so far
  - Improved understanding of impacts on mission concept of implementation changes
  - Improving ability for rapid assessment of system performance against requirements, and assessment of impacts from performance shortfalls
  - Improved visibility, management and disbursement of system margin
- Verification & validation planning, replanning & documentation

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Issues and Lessons
1 of 2

- Architecting/Requirements effort has been more difficult than Point Design Capture, and is not yet complete
  - Entailed concurrent methodology, tooling, process, and training development
  - Methodology mostly complete but difficult to grok
    - Process methodology lags the end-state data model (missing practitioner guidance)
    - Methodology requires significant re-training of how engineers think
  - Significant in-house tooling development only partly successful
    - Significant performance issues with scaling
    - Lacks support for process of mapping resulting requirements into traditional requirements documents
    - Lacks support for process of deriving requirements from concepts/constraints
  - It is most mature at L2 (Project).
    - L3 (Spacecraft, Ground System) have adopted hybrid approach between new approach and traditional to meet project needs
    - L4 (Subsystems) remains traditional (per original groundrule)
  - Offramps and adjustments were necessary along the way

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Issues and Lessons
2 of 2

- Selected lessons *
  - Culture change doesn't happen overnight, and it may not look like one expects
  - It's not just a new software tool
  - Scope is critically important to get – and keep - right
  - In order to stay relevant, models must evolve as the project moves through its lifecycle

* more in the referenced papers

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Conclusion

- Europa team has embraced MBSE as core to our formulation effort
- The shift from document-based to model-based culture is slow but progressing
- Not everything has worked out as expected, but
- Carefully scoped applications have shown compelling benefits
- A fuller assessment will be possible when formulation has finished (PDR in October 2018)
  - Much work remains, and many challenges lie ahead
  - The path ahead is becoming clearer. MBSE is on that path.

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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

- Update on the Model Based Systems Engineering on the Europa Mission Concept Study, IEEE Aerospace Conference Proceedings, 2013, Todd Bayer, Seung Chung, Bjorn Cole, Brian Cooke, Frank Dekens, Chris Delp, Ivair Gontijo, Dave Wagner.
- Model Based Systems Engineering On The Europa Mission Concept Study, IEEE Aerospace Conference Proceedings, 2012, T. J. Bayer, S. Chung, B. Cole, B. Cooke, F. Dekens, C. Delp, I. Gontijo, K. Lewis, M. Moshir, R. Rasmussen, D. Wagner,
- Model-Based Systems Engineering Approach to Managing Mass Margin, in Proceedings of the 5th International Workshop on Systems & Concurrent Engineering for Space Applications (SECESA), Lisbon, Portugal, 2012, Seung H. Chung, Todd J. Bayer, Bjorn Cole, Brian Cooke, Frank Dekens, Christopher Delp, Doris Lam.
- Early Formulation Model-centric Engineering On Nasa's Europa Mission Concept Study, Proceedings of 22nd Annual International Symposium (IS2012), Rome, Italy, 2012, T. J. Bayer, S. Chung, B. Cole, B. Cook, F. Dekens, C. Delp, I. Gontijo, K. Lewis, M. Moshir, R. Rasmussen, and D. Wagner.
- Update – Concept of Operations for Integrated Model-Centric Engineering at JPL, IEEE Aerospace Conference Proceedings, 2011, T. Bayer, M. Bennett, C. Delp, D. Dvorak, J. S. Jenkins, S. Mandutianu.
- An Operations Concept for Integrated Model-Centric Engineering at JPL, IEEE Aerospace Conference Proceedings, 2010, T. Bayer, L. Cooney, C. Delp, C. Dutenhoffer, R. Gostelow, M. Ingham, J. S. Jenkins, B. Smith.

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Backup

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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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Key Lessons Learned from Point Design Capture papers

- Investment is crucial
- Unity of leadership is essential
- Early efforts draw from a limited pool of talent
- Team organization matters
- Everyone needs to be trained, but not to the same level
- Just Do It
- CM can start modestly
- Models are meant to be abstractions
- First description then analysis
- Separate the model from the analysis
- Keep the focus on engineering products
- Real examples are powerful
- Synergistic work leverages learning
- Innovation is a bottoms-up process
- Models evolve along the project lifecycle
- Automated web-based model reports are critical
- Outside expertise accelerates learning
- Peer pressure pays

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Instrument Overview

Europa 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 in vault
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 density, temperature, and flow; electric field vectors (from near DC to 3 MHz); electron temperature; and ion currents. The sensors measure over a 4π sr 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 always 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 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 in vault
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. The 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 in vault
2.72	4.45	.004	n/a	1

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