National Aeronautics and Space Administration

Europa Mission Concept Studies

Early Formulation MBSE and Lessons Learned

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Topics

- Background and Approach
- What Has Been Produced So Far
- What Has Been Learned So Far

Background and Approach

Early Formulation is a Fluid Time

- The proposed Jupiter Europa Orbiter and Jupiter Ganymede Orbiter missions were formulated using current state-of-the-art MBSE facilities:
  - JPL's TeamX, Rapid Mission Architecting
  - ESA's Concurrent Design Facility
  - APL's ACE Concurrent Engineering Facility
- When JEO became an official "pre-project" in Sep 2010, we had already
  - developed a strong partnership with JPL's Integrated Model Centric Engineering (IMCE) initiative;
  - decided to apply Architecting and SysML-based MBSE from the beginning
  - begun laying these foundations to support work in Phase A…
- Release of Planetary Science Decadal Survey and FY12 President's Budget in March 2011 changed the landscape:
  - JEO reverted to being a pre-phase A study.
- A conscious choice was made to continue application of MBSE on the Europa Study, refocused for early formulation
- *This presentation describes the approach, results, and lessons.*

Europa Modeling Approach, Refocused

- Objective: Support study team in formulating affordable mission concepts.
- Focus: October 2011 report/briefing to Outer Planets Advisory Group
  - And now the Study Report due to NASA in May 2012
- Significant infrastructure was in place due to previous investments by JEO Pre-Project and especially by IMCE. This was enabling.
- To keep the cost commensurate with a small study budget, we have been focused and pragmatic.
- We support a modeling 'ecosystem', containing a mix of SysML, Excel, Mathematica, Simulink, in-house web service tools, etc.
- A core modeling team exists, but they are also integrated into the study team by assigning them key deliverables, not just models
  - ~3FTEs (6 people) working since May 2011
  - Mostly from Systems Engineering organization
  - NOT a parallel effort – as they are stood up, the models become the authoritative engineering artifact.

What Has Been Produced So Far

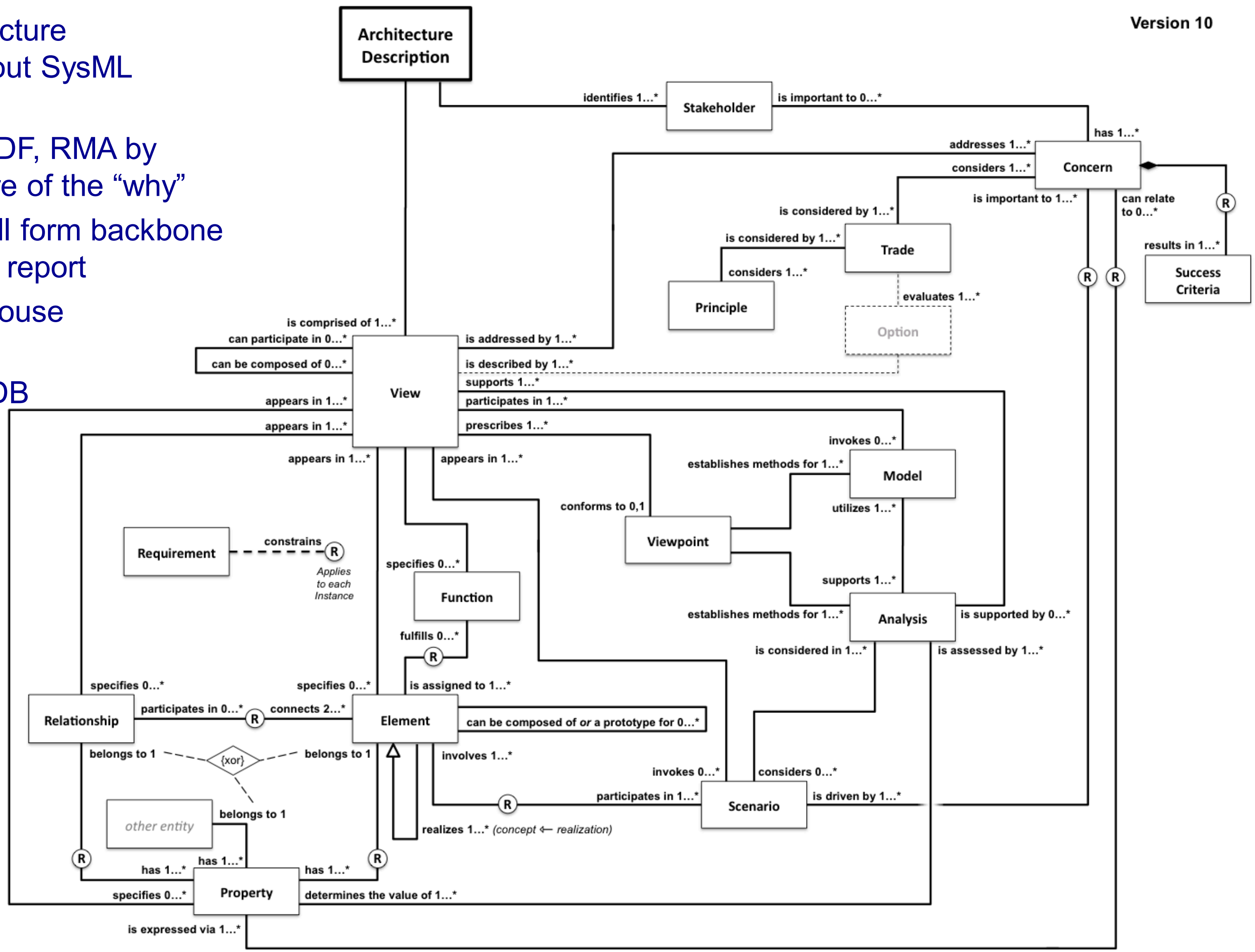
Europa Modeling Examples

- Architecture Description
  - Metamodel
  - Stakeholders and Concerns, Views and Viewpoints, Scenarios, etc.
- Flight System Description
  - Flight System Product Deployment Breakdown (System Block Diagram)
  - Work Breakdown (Subsystem Definition)
- Analysis and Reporting
  - Master Equipment List and Mass Margin Report
  - Power Margin/Energy Balance
  - Data Balance
  - Science Margin
  - Integration with Cost Models: NICM, PRICE-H, SEER, CATE
  - Radiated Equipment Lifetime and Margin (RELM)

Architecture Description

Architecture Framework Tool (AFT)

- Captures architecture information without SysML learning curve
- Complements CDF, RMA by improving capture of the “why”
- Report output will form backbone of concept study report
- Inexpensive in-house development
- Web-based OODB



Mission and Flight System Descriptions

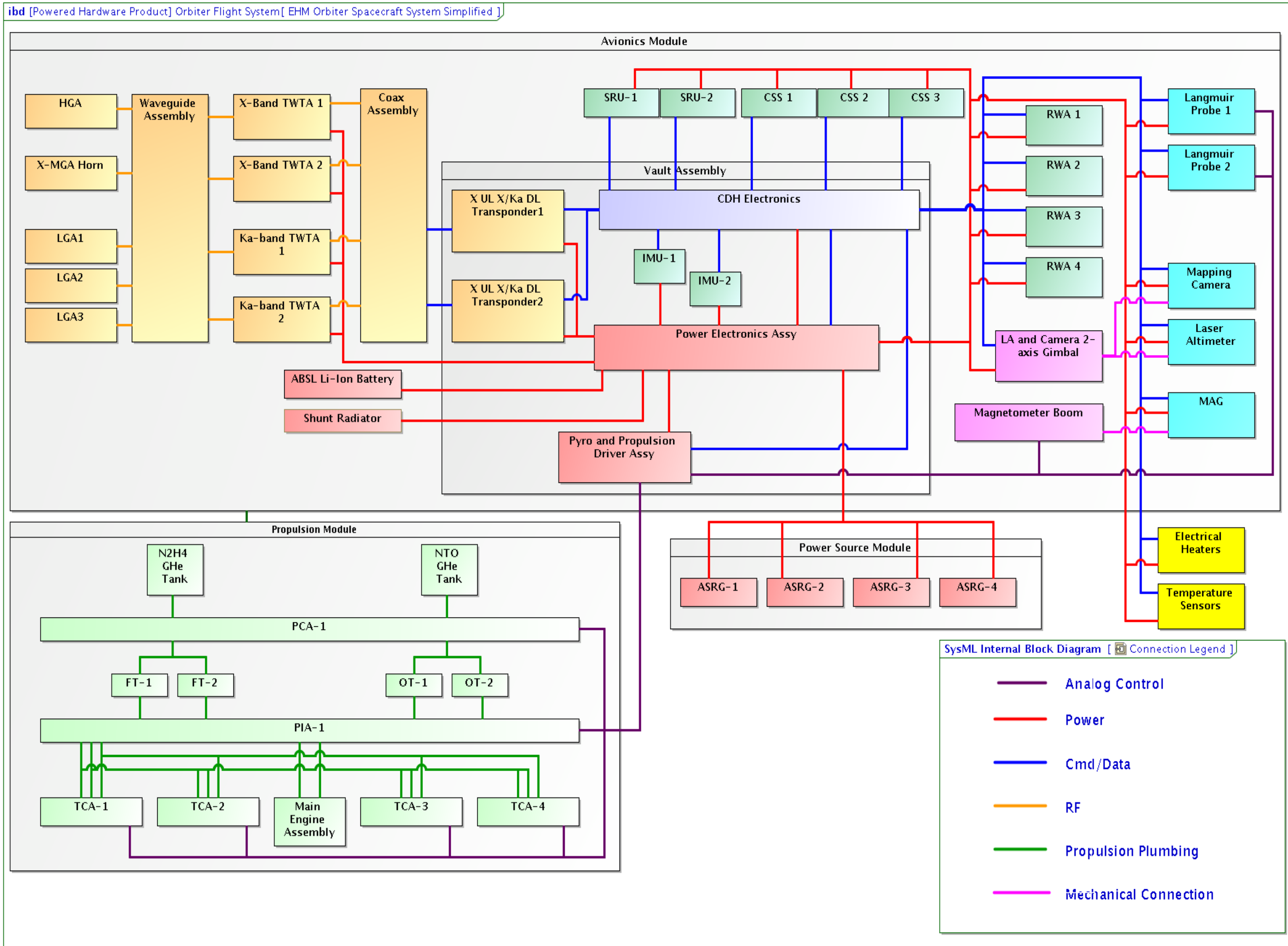
Flight System Block Diagram

Deployment: a specific arrangement of parts from the product list.

The authoritative statement of the Flight System decomposition

The Mass and Power Reports are produced directly from the model underlying this diagram

Orbiter, Flyby, and Lander



Subsystem Definition

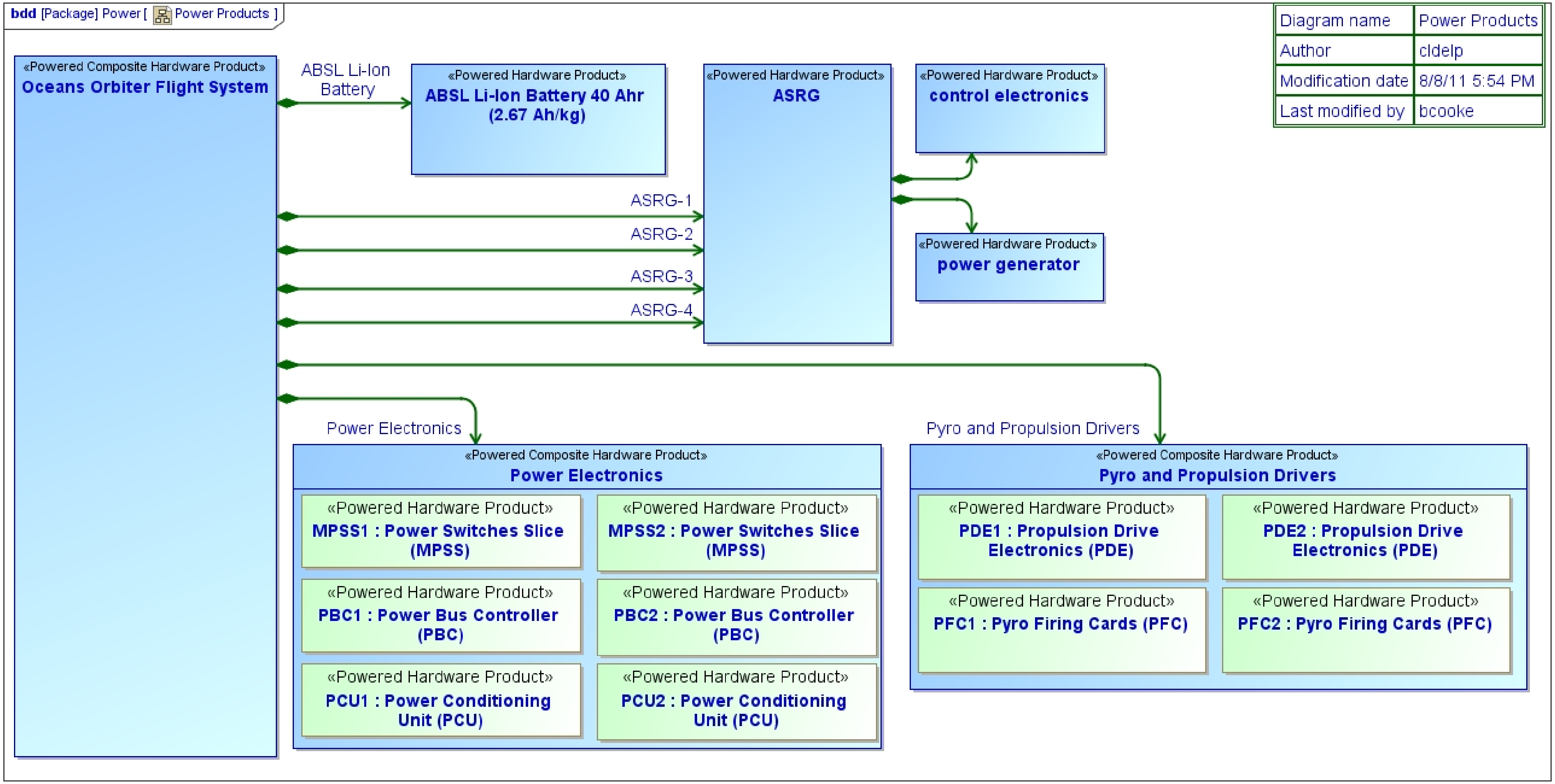


Diagram name	Power Products
Author	cldelp
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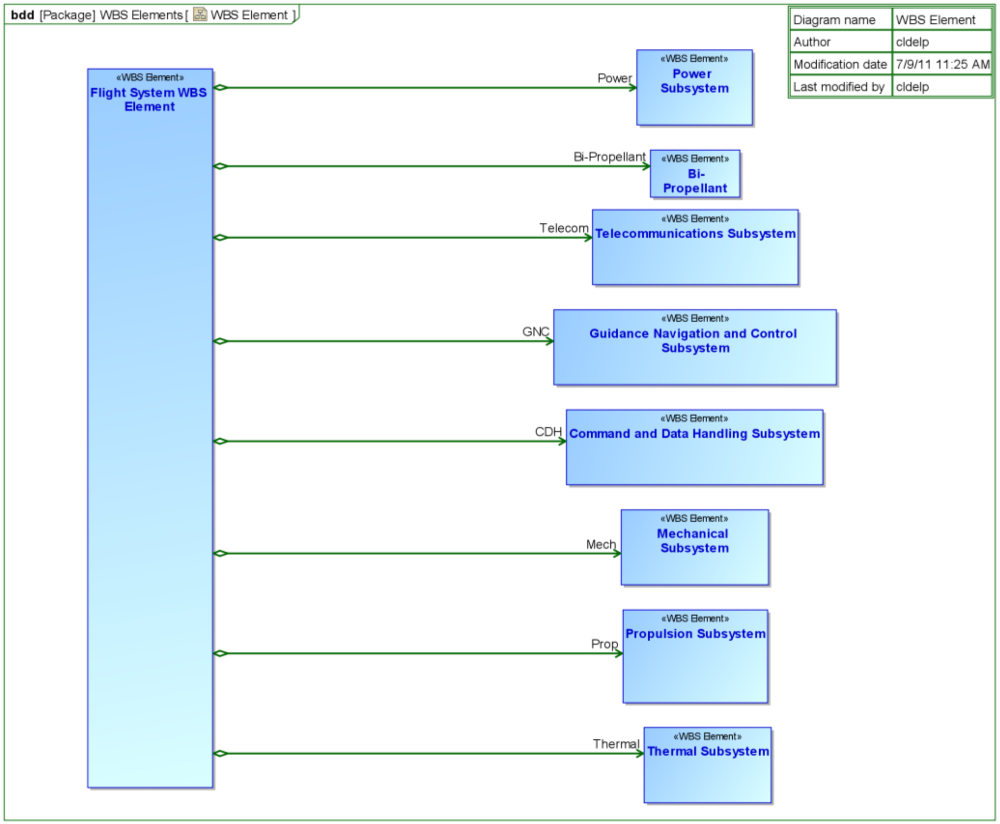
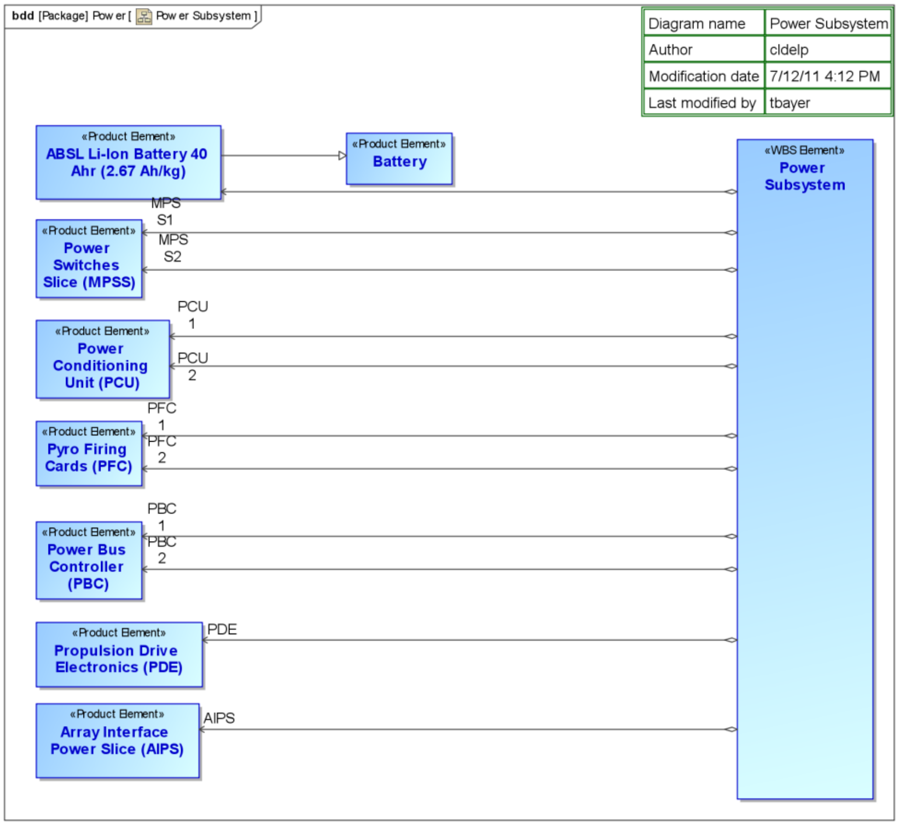
Last modified by	bcooke

Work Breakdown

- Subsystems are seldom delivered as integrated components
- Better understood as aggregations of convenience, in this case delivery responsibility





Analysis and Reporting

Equipment List and Mass Report

- Collects products from FS Deployment, grouped multiple ways as needed:
  - By Work Package (“subsystem”)
  - By Physical Composition (“assembly”)
- Produced directly from the model
- Took several tries with tooling:
  - Tried and “broke” Paramagic and Cameo Simulation Toolkit
  - Then we went to QVT which was the long term solution anyway (Query/View/Transformation language)
- Enables completeness/correctness checks
- Replaces Excel-based Equipment List
  - Analysis against margin remains in Excel for now

Table 1.2. Orbiter Flight System WBS-Based MEL

	Number of Units	Launch Mass		
		Mass State		
		Mass Current Best Estimate	Mass Contingency	Mass CBE_+_Contingency
00 Orbiter Flight System	1	1344.89	1.32	1772.64
05 Orbiter Payload	1	20.21	1.50	30.32
LA	1	10.15	1.50	15.23
LA	1	7.95	1.50	11.93
LA Sensor	1	3.25	1.50	4.88
LA Sensor Shielding	1	4.70	1.50	7.05
LA Card	1	0.90	1.50	1.35
LA PCU Card	1	1.30	1.50	1.95
LP	1	2.74	1.50	4.11
LP Card-1	1	0.90	1.50	1.35
LP Card-2	1	0.90	1.50	1.35
LP-1	1	0.47	1.50	0.70
LP Sensor	1	0.47	1.50	0.70
LP Sensor Shielding	1	0.00	1.50	0.00
LP-2	1	0.47	1.50	0.70
LP Sensor	1	0.47	1.50	0.70
LP Sensor Shielding	1	0.00	1.50	0.00
MAG	1	3.32	1.50	4.98
MAG	1	2.42	1.50	3.63
MAG Sensor	1	2.42	1.50	3.63
MAG Sensor Shielding	1	0.00	1.50	0.00
MAG Card	1	0.90	1.50	1.35
Mapping Camera	1	4.00	1.50	6.00
Mapping Camera	1	3.10	1.50	4.65
Sensor	1	1.60	1.50	2.40
Sensor Shielding	1	1.50	1.50	2.25
Mapping Camera Card	1	0.90	1.50	1.35
06 Orbiter Spacecraft	1	1324.68	1.32	1742.32

Power Consumption

- Similar to mass report

Table 1.5. Orbiter Flight System WBS-Based PEL

	Number of Units	Power Timeline					
		Power Off		Power On		Power Standby	
		Power State Prototype		Power State Prototype		Power State Prototype	
		Power Contingency	Power Current Best Estimate	Power Contingency	Power Current Best Estimate	Power Contingency	Power Current Best Estimate
00 Orbiter Flight System	1	1.30	0.00	1.30	0.00	1.30	0.00
05 Orbiter Payload	1	n/a	n/a	n/a	n/a	n/a	n/a
LA	1	n/a	n/a	n/a	n/a	n/a	n/a
LA	1	1.30	0.00	1.30	15	1.30	0.00
LA Sensor	1	1.30	0.00	1.30	0.00	1.30	0.00
LA Sensor Shielding	1	n/a	n/a	n/a	n/a	n/a	n/a
LA Card	1	1.30	0.00	1.30	0.00	1.30	0.00
LA PCU Card	1	1.30	0.00	1.30	0.00	1.30	0.00
LP	1	n/a	n/a	n/a	n/a	n/a	n/a
LP Card-1	1	1.30	0.00	1.30	0.00	1.30	0.00
LP Card-2	1	1.30	0.00	1.30	0.00	1.30	0.00
LP-1	1	1.30	0.00	1.30	1.15	1.30	0.00
LP Sensor	1	1.30	0.00	1.30	0.00	1.30	0.00
LP Sensor Shielding	1	n/a	n/a	n/a	n/a	n/a	n/a
LP-2	1	1.30	0.00	1.30	1.15	1.30	0.00
LP Sensor	1	1.30	0.00	1.30	0.00	1.30	0.00
LP Sensor Shielding	1	n/a	n/a	n/a	n/a	n/a	n/a
MAG	1	n/a	n/a	n/a	n/a	n/a	n/a
MAG	1	1.30	0.00	1.30	4	1.30	0.00
MAG Sensor	1	1.30	0.00	1.30	0.00	1.30	0.00
MAG Sensor Shielding	1	n/a	n/a	n/a	n/a	n/a	n/a
MAG Card	1	1.30	0.00	1.30	0.00	1.30	0.00
Mapping Camera	1	n/a	n/a	n/a	n/a	n/a	n/a
Mapping Camera	1	1.30	0.00	1.30	6.00	1.30	0.00
Sensor	1	1.30	0.00	1.30	0.00	1.30	0.00
Sensor Shielding	1	n/a	n/a	n/a	n/a	n/a	n/a
Mapping Camera Card	1	1.30	0.00	1.30	0.00	1.30	0.00

What Has Been Learned So Far

Investment is Crucial

- Europa had the benefit of several years of investment by IMCE, and of most of a year investment by JEO:
  - A SysML tool was selected and deployed at JPL (MagicDraw)
  - A JEO/Europa collaborative modeling environment was established
  - MagicDraw customization was done enough to be useful
  - Architecture Framework Tool was mature
  - SysML/MagicDraw training had been given to the Europa team

Unity of Leadership is Essential

- In the first infusions, management support for the effort must to be clear and consistent.
  - They must be willing to pay the startup costs and to give time for the effort to pay dividends.

- And… the engineering leadership must be reasonably unified in their willingness to work together to figure out how to do this.

The Best Way to Start Modeling…

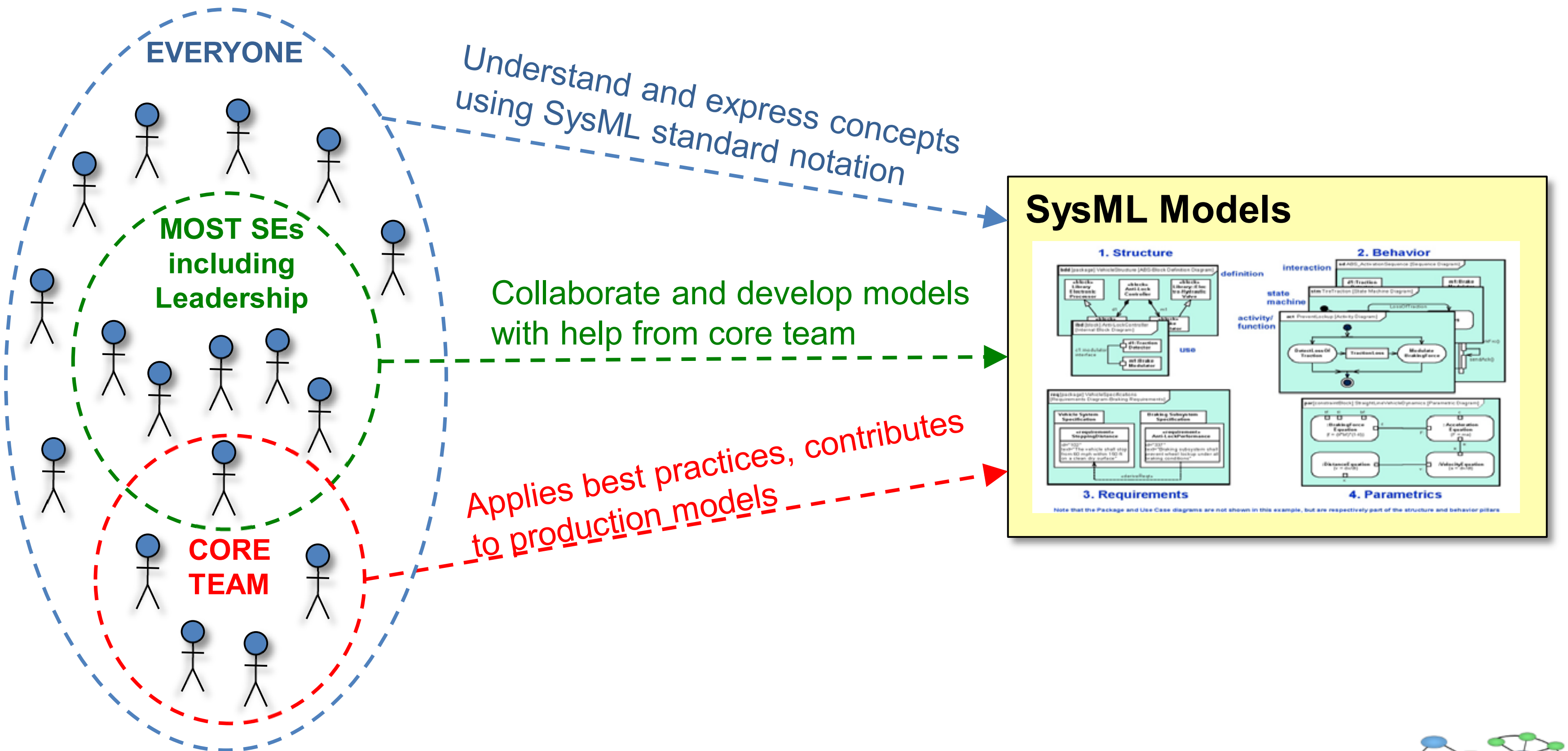
- …Is to hire people who already know how to do it
- The first infusions will not have the benefit of an engineering pool with ubiquitous modeling skills.
- We found the best way to get started was simply to hire as many of the existing cadre of skilled MBSE practitioners as we could afford.

Team Organization Matters

- Before JEO, most JPL pilots had been small scale and grass-roots.
  - The lead (or only) SE tended to become the primary modeler, primary custodian of the single source of authoritative information, and most expert SysML user.
- JEO, as a fledgling flagship project and as the first full, top-down infusion of MBSE at JPL, had to figure out a different way.
  - IMCE ConOps helped
- Our approach: a three-tiered pattern involving a small set of core modelers within a larger set of modeling-savvy systems engineers, within a larger set of all project personnel.
- The experienced systems engineers provided guidance to keep the modeling focused on providing useful information
  - As well as mentoring of the core modelers who tended to be more junior
- Frequent (daily) interactions were key to getting useful products
  - We were pathfinding so we had to stay very closely in touch
- We avoided fencing the core modelers off from the rest of the project
  - We assigned them actual engineering tasks and deliverables rather than just modeling tasks.

Everyone Needs to Be Trained…

- …But not to the same depth
- Different levels of modeling familiarity are required, thus different levels of training



Just Do It

- The best way to figure out how to apply MBSE is to do it for real.
- “Shadow Pilots” would not have been as helpful, and are problematic:
  - Resources are seldom adequate to do the job right once, let alone twice
  - A useful comparison requires good metrics, but they don’t exist (big effort)
  - The pressure to deliver real engineering products forces discovery and resolution of problems not likely encountered in a shadow
  - It's asking the wrong question. We believe the move to MBSE is not a question of "whether" but a question of "when" and "how“
  - Finally, we think the question is its own self evident answer:
    - Does capturing our designs in an expressive and rigorous language via an integrated, durable, analyzable model give us better engineering products? Does that help avoid risk and cost downstream?
- So how does a project control infusion cost and risk without this comparative knowledge?
  - Do it by carefully scoping the infusion
  - Start small, but always start on a real product.

CM Can Also Start Small

- Initial exploration in the IMCE Concept of Operations was helpful
- Set up the model to support collaboration
  - Modules and packages structured with collaboration in mind.
  - Emphasized single owner packages in topically-defined modules
- Set model access permissions loosely for now
  - Full team has read access
  - Core modeling team plus key systems engineering leads have write access
  - Assigned responsibility for a package and everyone else on honor system not to write into this model without coordinating with the “owner”
  - Agility more important than tight control
- Lightweight Versioning is sufficient
  - Teamwork tracks changes to model elements
  - DocWeb reports capture snapshot of full model and resource reports
  - Reviewed and baselined versions are tagged as such in DocWeb
- Quality Control is developing as needed
  - Scripts doing some rudimentary model validation
  - A hand calculation is used before report release as final correctness check

Models are Meant to be Abstractions

- So make sure they're useful abstractions:
- Model only as far as you need to answer the question.
- A model *does not* have to describe everything and in all details.
- Nor does it have to fill in the full space between conceptual and realizational
  - Europa captured high level concepts, and racked up mass from a specific 'instance'.

First Description, Then Analysis

- Capture and description are *powerful*, and *far-reaching*, first steps. Just describing something in a formal modeling language like SysML immediately improves communications and understanding
- Don't underestimate the value of this.
- Don't underestimate the difficulty of building meaningful analyses.
  - Take that one slow; don't overpromise.
  - For the mass margin report, even our modest ambitions were a bit of a stretch the first time.
    - Took about 2 w-months to get working model + report
  - But the second and third times went many times faster.
    - We produced models of two additional concepts + mass report
    - Each took only 0.5 w-month
    - Significant refactorings now take just a few days

Separate Models from Analyses

- For our mass analysis we have achieved a high degree of separation of the model from the analysis, and as a result we are able to run exactly the same mass analysis script on all three of our mission option models.
  - The more the model can be a self-contained, internally self-consistent and intuitive description of the concept, the more informative it will be.
  - The more the analysis can be separated from the model, the more reusable it will be.
- Corollary: Align the model with the concept, not with the analysis.
  - We initially found ourselves adopting modeling patterns which made the analysis scripts easier.
  - But we soon found ourselves forced to model in more and more non-intuitive ways. (drifting back into the Excel trap)
  - Therefore we discovered, and adopted, the principle that the model should be kept intuitive and aligned with the concept.
  - The extra work required for smarter analysis tools is well worth it.

Keep the Focus on Engineering Products

- Tie expectations to project deliverables, not merely modeling solutions
- This may need to be constantly reinforced

Real Examples are Powerful

- Trying to describe what MBSE looks and feels like has proven difficult
- Actual examples have proven much more effective at conveying understanding and building support
  - The mass model and margin report was the thing that helped the light go on for several skeptical but open-minded stakeholders.
- Also, mass model and margin report were immediately recognized as higher fidelity work than traditional method. Since parametric cost estimates are based heavily on mass, this is a crucial parameter to estimate accurately
- Finally, projects are where the 'just do it' happens, working on actual products - that's where the applications are really worked out, and that is what feeds back into IMCE for others to use. These first examples discover useful patterns which can be fed back into IMCE for capture and provision to the next users.

Conclusion

Conclusion

- Modeling tools and techniques developed for the proposed JEO Flagship Mission are proving useful for the smaller Europa Study
- We expect this will improve the May 2012 Study Report, in turn enhancing the chance of an eventual new start
- Any detailed follow-on study will be significantly strengthened by the architecture and design concept capture enabled by MBSE
- The Europa example should enable other teams to adopt MBSE sooner rather than later

The current state of the art in early formulation modeling can be extended using architecting frameworks, SysML, and symbolic math tools:

- To produce *better formulation products*
- To begin to *bridge the information divide* between early formulation and project start.

Backup

Mission Domain

- Top Level View, Front Door to lower level views
- Expresses unique two-element concept for Europa

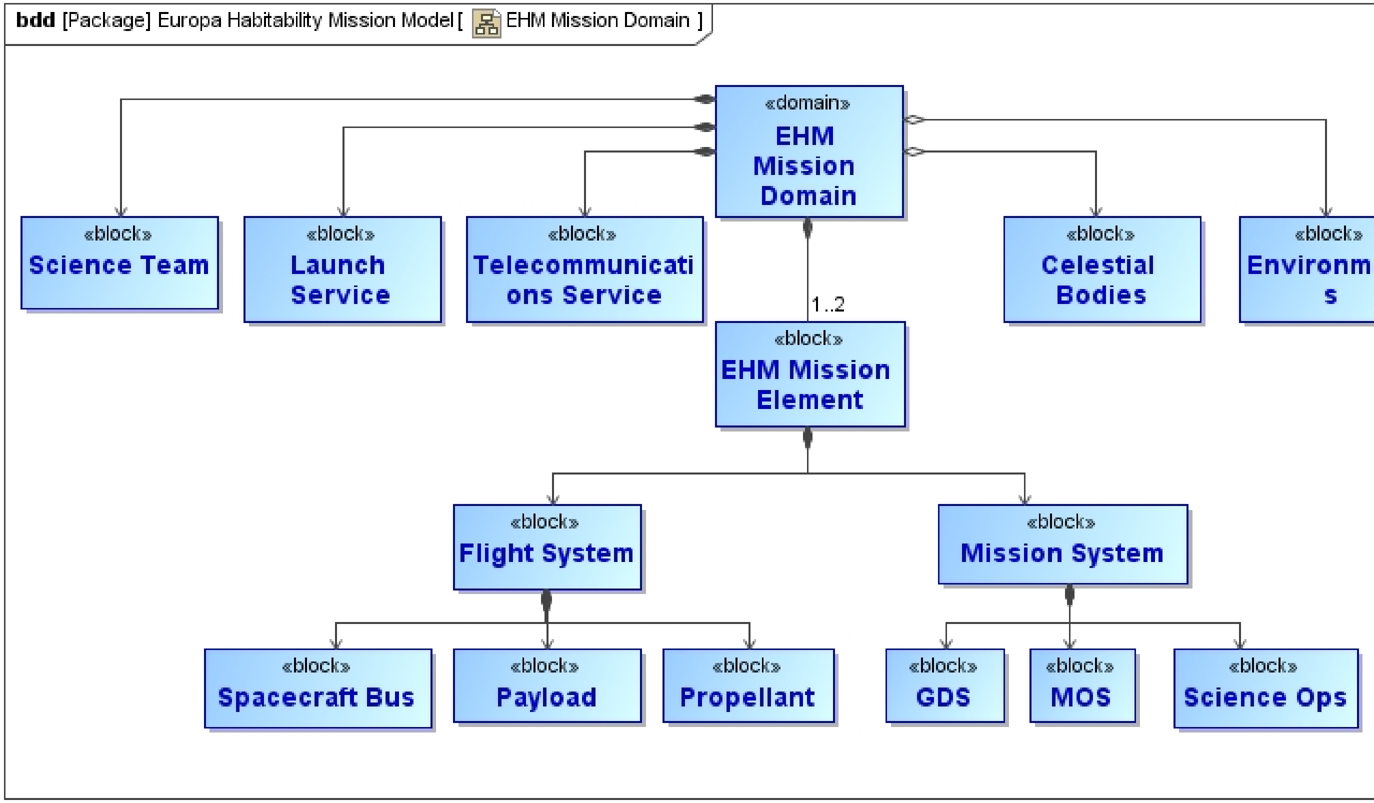
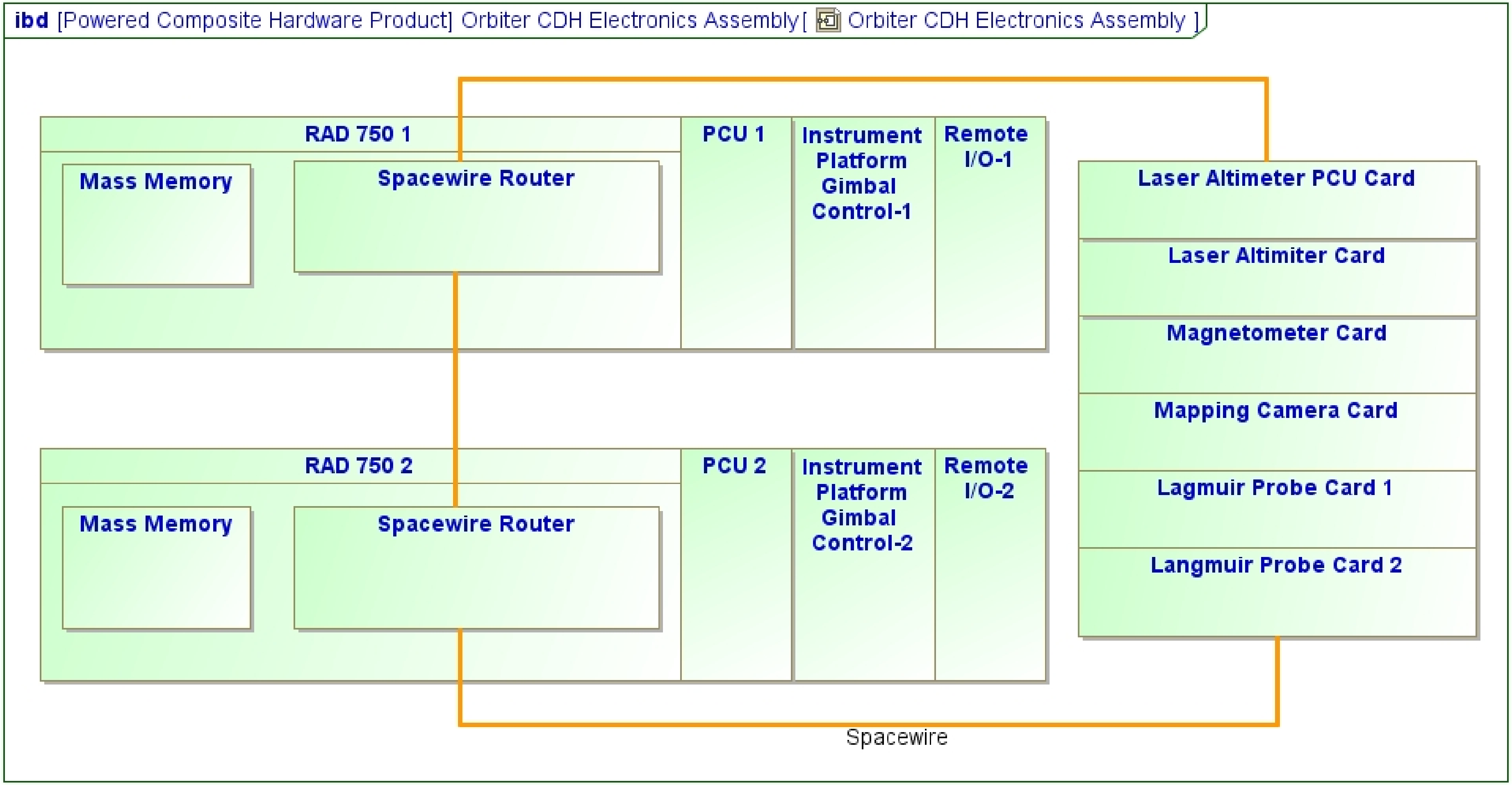


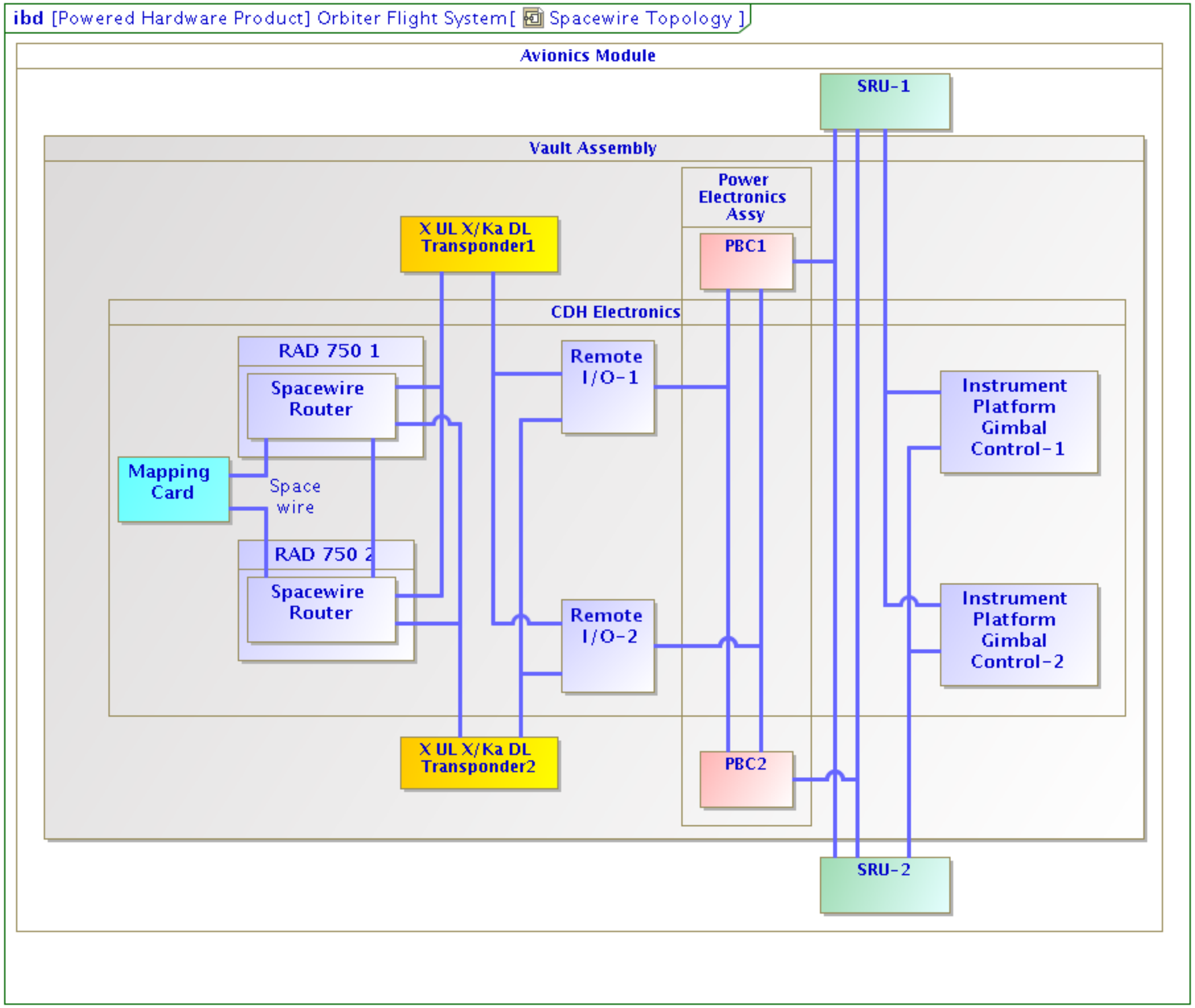
Diagram name	EHM Mission Domain
Author	tbayer
Modification date	7/7/11 5:07 PM
Last modified by	tbayer

Component Deployment (a.k.a. Box Diagram)



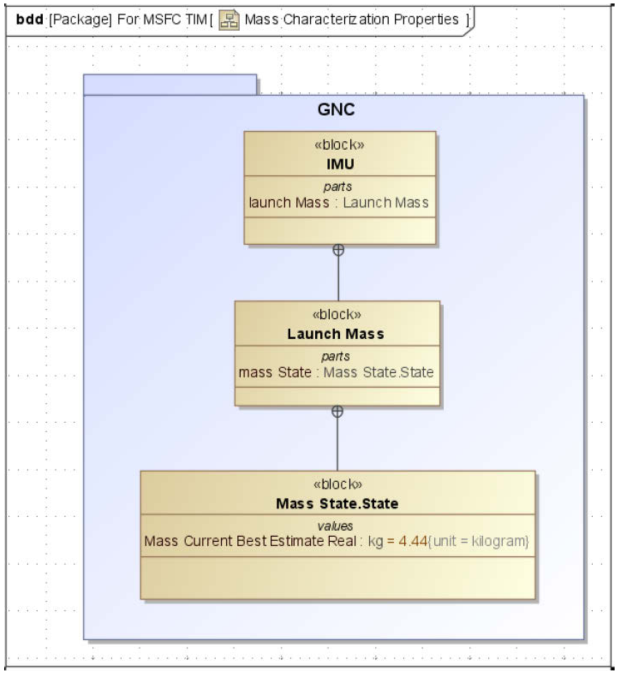
Special Views

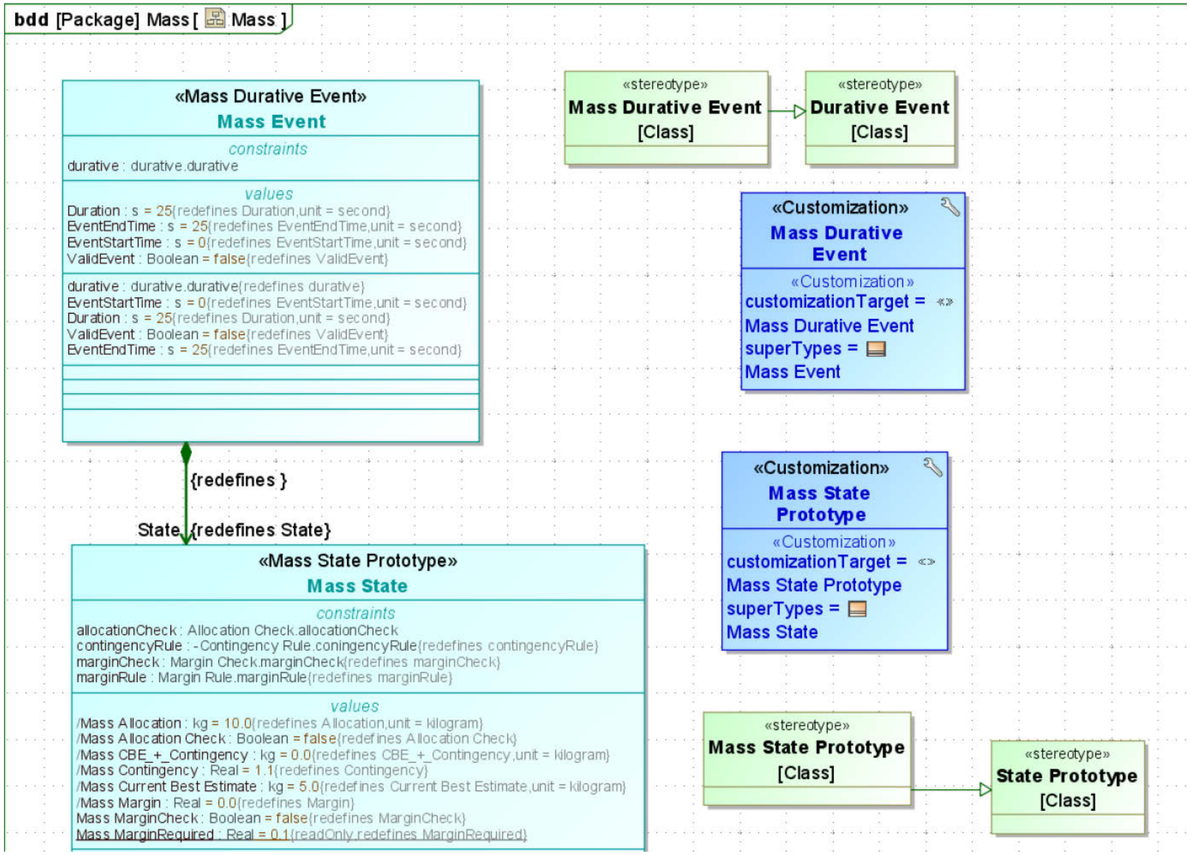
- Many special-purpose views can be created, all using the same modeling elements



Characterization Blocks

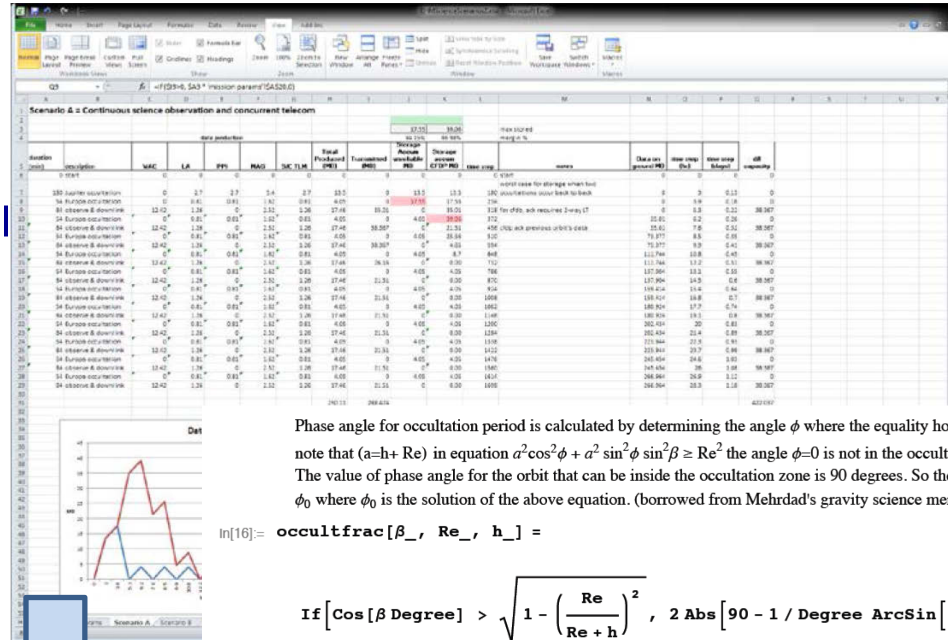
- Applying values like mass to model elements can become unwieldy
- Characterization Blocks are used to keep things organized





Data Balance

- Started with simple Excel model
- Moving into well-documented, reviewabl Mathematica format
- Vision: products in FS Deployment will be exercised analytically through their data production and/or processing modes as driven by mission scenarios



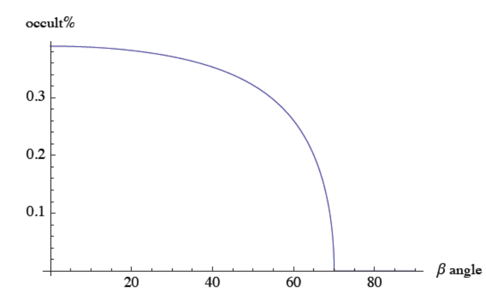
Phase angle for occultation period is calculated by determining the angle ϕ where the equality holds, to find which range defines occultation note that (a=h+ Re) in equation $a^2\cos^2\phi + a^2 \sin^2\phi \sin^2\beta \geq Re^2$ the angle ϕ=0 is not in the occultation zone because a is always greater than Re. The value of phase angle for the orbit that can be inside the occultation zone is 90 degrees. So the occultation range for the angle ϕ is twice 90-ϕ_0 where ϕ_0 is the solution of the above equation. (borrowed from Mehrdad's gravity science merit model).

```
In[16]:= occultfrac[β_, Re_, h_] =
  If[Cos[β Degree] > Sqrt[1 - (Re/(Re + h))^2], 2 Abs[90 - 1/Degree ArcSin[Sqrt[1 - (Re/(Re+h))^2]/Cos[β Degree]]], 0]/360;

In[17]:=

In[18]:= Plot[occultfrac[β, R/Meter, altitude/Meter], {β, 0, 90},
  AxesLabel → {"β angle", "occult%"}, PlotRegion → {{.05, .95}, {.05, .95}}]
```

Out[18]=



Science Margin

- Approach is to develop the model one science objective at a time
- First develop a Mathematica description of the science and the related engineering parameters (show the Gravitational Tides whitepaper)
- Then develop SysML description to house the parameters
- Then integrate and run analyses

- Conceptual model for the gravity science k2 measurement accuracy is as follows, based on simple analysis from Bruce Bills. The errors on the second order harmonic terms have a simple dependence on the altitude h and doppler measurement accuracy for a nominal 60sec sample, $\sigma^0_{\text{Doppler}}$ and number of samples used in the calculation, Ns, given by $\frac{1}{f(\text{Ns})}(h+\text{Re})^{3/2}\sigma^0_{\text{Doppler}}$. For the same number of samples the dependence on altitude is given by $\left(\frac{h+\text{Re}}{\text{h0}+\text{Re}}\right)^{3/2}$ where h0 is a reference point; higher altitudes than h0 result in higher errors than at h0, lower altitutdes have better errors than h0.
- Bruce bills has provided a data set based on his simulations that show the improvement on k2 error as a function of duration of observation for a Ka-band coherent doppler measurement. Analysis of Asmar, et al indicates that Ka band has 10x better error in a 60 sec period than X-band.
- Bruce Bills data are (duration, k2 error)

```
BruceBillsData = {{4, 8.75 × 10^-4}, {8, 4.09 × 10^-4}, {12, 2.69 × 10^-4}}

{{4, 0.000875}, {8, 0.000409}, {12, 0.000269}}
```

- Expressed in orbits this becomes

```
BruceBillsData2 = {{46, 8.75 × 10^-4}, {92, 4.09 × 10^-4}, {138, 2.69 × 10^-4}}

{{46, 0.000875}, {92, 0.000409}, {138, 0.000269}}
```

- The data are fit to number of samples for the reference orbit and beta angle. the fit value for α is 1.076

```
k2error[β_, Re_, h_, δ_, τ_, α_, Norb_, σ0_, σKa_] =
```

$$\frac{5.603}{(\text{Norb} * \text{Dopplersamples}[\beta, \text{Re}, \text{h}, \delta, \tau])\text{^}\alpha}\left(\frac{\text{h}+\text{Re}}{100+\text{Re}}\right)^{3/2}\left(\frac{\sigma0}{\sigma\text{Ka}}\right);$$

```
k2errlist =
  Table[{Norb, k2error[5, 1565, 100, 60, 60, 1.076, Norb, .01, .01]}, {Norb, 1, 160, 1}];

BruceBillsData2
```

Cost Models

- Integration with Cost Models: NICM, PRICE-H, SEER, CATE
  - NICM brought internally as a design aid (can get early results within the model)
- Now building the project internal cost model
- We started developing reports containing required inputs for independent cost models.
  - Then found that our costing engineer was directly using the Docweb report!