Early Formulation Model-Centric Engineering on NASA’s Europa Mission Concept Study

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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
- Compatible with SysML models through common ontology
- Complements CDF, RMA by improving capture of the “why”
- Inexpensive in-house development (Web-based OODB)
Mission and Flight System Descriptions
The authoritative statement of the Flight System composition

Mass & Power Reports are produced directly from the underlying model

3 Mission Alternatives Captured: Orbiter, Flyby, and Lander
Component Composition

RAD 750 1
- Mass Memory
- Spacewire Router

PCU 1
- Instrument Platform Gimbal Control-1
- Remote I/O-1

RAD 750 2
- Mass Memory
- Spacewire Router

PCU 2
- Instrument Platform Gimbal Control-2
- Remote I/O-2

Laser Altimeter PCU Card
- Laser Altimeter Card
- Magnetometer Card
- Mapping Camera Card
- Langmuir Probe Card 1
- Langmuir Probe Card 2

Spacewire
• Subsystems are seldom delivered as integrated components
• Better understood as aggregations of convenience, in this case delivery responsibility
• Work packages authorize other work packages
• Work packages supply products
- Applying values like mass to model elements can become unwieldy
- Characterization Blocks are used to keep things organized
- Durative events enable definition of properties at certain times (e.g., launch, EDL)
Analysis and Reporting
Equipment List and Mass Report

- Collects products from FS Composition, grouped multiple ways as needed:
  - By Work Package ("Bill of Materials")
  - By Physical Composition ("Deployment")
- 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)
  - Currently use a mix of QVT and Jython
- Enables completeness/correctness checks
- **Replaces Excel-based Master Equipment List**
- Mass Margin report still in Excel, but not for long
## Master Equipment Lists

Table 1.2. Bill of Materials Table of Flyby Flight System for WBS Flyby Flight System

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What Has Been Learned So Far
Lessons Learned (so far)

- Investment is crucial
- Unity of leadership is essential
- Early efforts draw from a limited pool of talent
- Synergistic work leverages learning
- Innovation is bottoms-up
- Team organization matters
- Everyone needs to be trained, but not to the same level
- Just Do It
- CM can start modestly
- Model only as much as necessary
- Models evolve
- First description then analysis
- Separate the model from the analysis
- Keep the focus on engineering products
- Real examples are powerful
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 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.
Talent Pool is Small During Early Efforts

- 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.
Synergistic work leverages learning

- With the limited pool of modeling talent available, we were tempted to ask for a full-time commitment.
- But we knew there were two other efforts where MBSE application was being tried and that these efforts would have a strong desire for the same personnel.
- We also believed that having the experts engaged in two or three modeling efforts would provide benefits that outweighed the lack of full time commitment.
- We have found this belief to be fully validated.
  - The learning that has been shared between the three efforts has been enormously beneficial for all,
  - and it has clearly accelerated the institutional infusion.
Innovation is bottoms-up

• We didn’t know what scripts or plugins or modeling patterns to develop before we started.
• We let the discovery of the need drive the solution.
• There was ‘top down’ innovation but not in the traditional sense of pre-ordained specifications: it consisted mainly of constant guidance during the modeling process to keep the effort focused on satisfying the end objectives.
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.
• …But not to the same depth
• Different levels of modeling familiarity are required, thus different levels of training

Everyone Needs to Be Trained…

Understand and express concepts using SysML standard notation

Collaborate and develop models with help from core team

Applies best practices, contributes to production models
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
Model Only As Much As Necessary

- Models are meant to be 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’.
Models Evolve

- The model needed in concept formulation is very different than the model needed in detailed design, or in operations.
- Models need to evolve and grow, and sometimes shrink.
- This should be the focus of model reuse along the project lifecycle.
- It also helps to answer the people who will suggest that building a detailed model of the last flown mission will help you formulate the next.
- It all goes back the principle of modeling for a purpose, and not more.
- KEY POINT: While the models may change, these changes can be evolutionary and cumulative as long as they are connected by a common set of ontologies and methodologies.
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.
Europa: Ingredients for Life?

Chemistry

Energy

Water

Habitability
Backup
Mission Domain

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

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

- Similar to mass report

### Table 1.5. Orbiter Flight System WBS-Based PEL

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<th>Number of Units</th>
<th>Power Timeline</th>
<th>Power State Prototype</th>
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<td>1.30</td>
<td>0.00</td>
<td>1.30</td>
</tr>
</tbody>
</table>
Data Balance

- Started with simple Excel model
- Moving into well-documented, reviewable Mathematica format
- Vision: products in FS Deployment will be exercised analytically through their data production and/or processing modes as driven by mission scenarios
• 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 60 sec sample,\(N_{\text{samples}}\), and number of samples used in the calculation, \(N_{o}\), given by \(\frac{1}{f_{\text{obs}}} \left( h + Re \right)^{1/2} \delta_{\text{doppler}}\). For the same number of samples the dependence on altitude is given by \(\left( \frac{h + Re}{\delta_{\text{doppler}}} \right)^{3/2}\) where \(h_0\) is a reference point, higher altitudes than \(h_0\) result in higher errors than at \(h_0\), lower altitudes have better errors than \(h_0\).

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 Kα-band coherent doppler measurement. Analysis of Asmar, et al indicates that Kα band has 10x better error in a 60 sec period than X-band.

Bruce Bills data are (duration, k2 error)

\[
\begin{align*}
\text{BruceBillsData} &= \{(4, 8.75 \times 10^{-4}), (8, 4.09 \times 10^{-4}), (12, 2.69 \times 10^{-4})
\}
\end{align*}
\]

\[
\begin{align*}
\text{BruceBillsData2} &= \{(46, 8.75 \times 10^{-4}), (92, 4.09 \times 10^{-4}), (138, 2.69 \times 10^{-4})
\}
\end{align*}
\]

Expressed in orbits this becomes

\[
\begin{align*}
\text{BruceBillsData2} &= \{(46, 8.75 \times 10^{-4}), (92, 4.09 \times 10^{-4}), (138, 2.69 \times 10^{-4})
\}
\end{align*}
\]

The data are fit to number of samples for the reference orbit and beta angle. The fit value for \(a\) is 1.076

\[
k2error[\beta, Re, h, \delta, t, a, Norb, o0, oKa] = \sqrt{\frac{5.603}{(Norb \times \text{Doppler samples}[\beta, Re, h, \delta, t])^a \left( \frac{h + Re}{100 + Re} \right)^{3/2} \left( \frac{o0}{oKa} \right)}}
\]

```math
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!