Design and Analysis of Experiments for Europa Clipper’s Science Sensitivity Model

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Outline

- Introduction
- The Europa Clipper mission
- Data acquisition
- Factors affecting data acquisition
- Mission requirements
- The experiment
- Experiment design
- Experiment analysis
- Conclusions
Goals:

- Design, implement, and analyze a simulation experiment to quantify the probability of mission success as a function of instrument fault and autonomous recovery rates.

- Mission success = meeting the set of “Level 1” Baseline requirements with probability at least .95.

- Provide a tool to allow scientists and engineers to study how changes in both requirements and hardware performance affect mission and Level 1 requirement success probability.
The Europa Clipper spacecraft will carry nine science instruments—thus there are ten “systems”:

<table>
<thead>
<tr>
<th>System</th>
<th>Code</th>
<th>System</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft</td>
<td>Sc</td>
<td>Instrument 5</td>
<td>I5</td>
</tr>
<tr>
<td>Instrument 1</td>
<td>I1</td>
<td>Instrument 6</td>
<td>I6</td>
</tr>
<tr>
<td>Instrument 2</td>
<td>I2</td>
<td>Instrument 7</td>
<td>I7</td>
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<tr>
<td>Instrument 3</td>
<td>I3</td>
<td>Instrument 8</td>
<td>I8</td>
</tr>
<tr>
<td>Instrument 4</td>
<td>I4</td>
<td>Instrument 9</td>
<td>I9</td>
</tr>
</tbody>
</table>
Each system’s transient fault behavior is modeled by two different exponential distributions, depending on orbital conditions.

Each system’s recovery time (after a fault) is modeled by a (shifted) beta distribution “outside” the flyby region, and as a constant “within” the flyby region (see next slides).
Europa Clipper Mission

Europa’s orbit: ∼3.5 days

High radiation zone: fault rates are higher

Closest approach -3 days
Closest approach +2 days
Closest approach +10 hrs
Closest approach -10 hrs
Europa Clipper Mission

Europa’s orbit: \(\sim 3.5 \) days

Europa Clipper’s orbit: \(\sim 14 \) days; nominal mission is 46 orbits
**Europa Clipper Mission**

Europa Clipper’s orbit: ~14 days; nominal mission is 46 orbits

Jupiter

Closest approach -3 days

Closest approach -10 hrs

Closest approach +10 hrs

Closest approach +2 days

High radiation zone: fault rates are higher

Low-radiation zone: fault rates are lower

Most important science data acquired in high-radiation zone
Europa Clipper Mission

Europa’s orbit: ~3.5 days

Europa Clipper’s orbit: ~14 days; nominal mission is 46 orbits

Closest approach
-3 days

Closest approach
-10 hrs

Closest approach
+10 hrs

Closest approach
+2 days

“Outside” portion of orbit: recovery can be slower

Most important science data acquired in high-radiation zone
Europa Clipper Mission

Europa's orbit: \(\sim 3.5\) days

Europa Clipper's orbit: \(\sim 14\) days; nominal mission is 46 orbits

Closest approach
-3 days

Closest approach
+2 days

“Outside” portion of orbit: recovery can be slower

“Within” portion of orbit: recovery must be faster

Most important science data acquired in high-radiation zone
Each system will be in either an active or inactive state at every time point during the 46-orbit "tour".

Let $X_i(t)$ be the state of system $i$, $i = 0, 1, 2, \ldots, 9$, at (continuous) time $t$, $t \in (0, T)$, where $T$ is the number of seconds in the 46-day tour ($i = 0$ for the spacecraft).

If system $i$ is active at time $t$, then $X_i(t) = 1$. Otherwise $X_i(t) = 0$.

If the spacecraft goes down ($X_0(t) = 0$), all other systems go down.

Ability to acquire high-value science data will depend on the complex super-positiion of the ten systems’ states during the period from -10 to +10 hours of closest approach. (Caveat: two instruments do take data throughout the whole orbit, and these are also critical for science.)
Data Acquisition

\[ \text{Sc} \quad I_1 \quad I_2 \quad I_3 \quad I_4 \quad I_5 \quad I_6 \quad I_7 \quad I_8 \quad I_9 \]

\[ t = 0 \quad t = T \]

Diagram showing time intervals for Sc, I1 to I9.
Factors affecting data acquisition

High-value data acquisition/high-radiation periods

Each instrument takes complete, partial, or no data during the critical periods.
Factors affecting data acquisition

“within” periods

Sc
I1
I2
I3
I4
I5
I6
I7
I8
I9
Factors affecting data acquisition

Different fault rates and recovery times apply (for each system) depending on whether EC is in the red, orange, or green period.
Mission requirements

- Each instrument takes complete, partial, or no data during the critical periods.

- Each instrument has a set of instrument-specific requirements that are either met or not met depending on the degree to which data are acquired during the critical periods.

- A tree-structured graph shows how instrument-level requirements are progressively aggregated up through intermediate science objectives through to Level 1 requirements.
The experiment

- Determine maximum allowable fault rates and recovery times such that the set of Level 1 Baseline requirements have success probabilities that exceed .95.

- Use Monte Carlo to simulate 1000 tours, each with faults generated by exponential distributions with specified parameters, and recovery times generated as described earlier.

- These parameters are factors in the experiment.

- Responses are the probabilities of success for the Level 1 requirements after aggregating over the ensemble of 1000 tours.

- Build a response surface that relates factor levels to responses.
The experiment

\[ Y_{jk} = 1 \text{ if timeline } j \text{ passes req. } k, \]
\[ Y_{jk} = 0 \text{ otherwise.} \]

\[ Y_1 = (Y_{11}, Y_{12}, \ldots, Y_{1,91})' \]
\[ Y_2 = (Y_{21}, Y_{22}, \ldots, Y_{2,91})' \]
\[ Y_{1000} = (Y_{1000,1}, Y_{1000,2}, \ldots, Y_{1000,91})' \]
Suppose \( \mathbf{p} \) is the 91-dimensional vector of probabilities,

\[
\mathbf{p} = \frac{1}{1000} \sum_{n=1}^{1000} \mathbf{x}_n = (p_1, p_2, \ldots, p_{91})',
\]

where \( p_k \) is the probability of passing the \( k \)th (basic/“level 2”/leaf) requirement.
**Experiment design**

<table>
<thead>
<tr>
<th>System</th>
<th>Factors</th>
<th>System</th>
<th>Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft</td>
<td>ScTH-F, ScTL-F, ScT-WR</td>
<td>Instrument 5</td>
<td>I5TH-F, I5TL-F, I5T-WR</td>
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<tr>
<td>Instrument 1</td>
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<td>I6TH-F, I6TL-F, I6T-WR</td>
</tr>
</tbody>
</table>

T = “transient” fault (the only kind here). H/L = high/low radiation. F = fault rate, R = recovery time. W = “within”.

All other factor combinations are fixed, and treated deterministically.

Not all factors applicable to all Level 1 requirements.
experiment design

- 30 factors (10 systems, three factors each). Experiment run for two levels for each factor (a high value and a low value).

- \(\sim 9\) Baseline Level 1 requirements.

- Definitive Screening Design (Jones and Nachtsheim, (2011). *Journal of Quality Technology*, Vol 43, No. 1.) created in JMP 14 Pro. Requires only a relatively small number of runs (\(\sim 2 \times \) (number of factors)).

- We had sufficient computational power to augment the DSD with additional space-filling runs. Total number of runs = 577.

- Design space = 577 points in a 30-dimensional space. Responses = 577 probabilities for each Level 1 req.
## Experiment Design

<table>
<thead>
<tr>
<th>Design</th>
<th>Model</th>
<th>Evaluate Design</th>
<th>Original Data Table</th>
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- ScTH-F
- ScTL-F
- ScT-WR
- ITH-F
- ITL-F
- ITR-WR
- ITH-F
- ITL-F
- iTR-WR
- iTH-F
- iTL-F
- iTR-WR
- iTH-F
- iTL-F
- iTR-WR

### Rows
- All rows: 577
- Selected: 0
- Excluded: 0
- Hidden: 0
- Labelled: 0

### Data Table

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### Notes
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### Values
- ScTH-F: 0.25 to 0.000000235
- ScTL-F: 0.000000235 to 0.25
- ScT-WR: 60 to 8640
- ITH-F: 0.075 to 0.000000257
- ITL-F: 0.075 to 0.000000257
- ITR-WR: 60 to 8640
- ITH-F: 0.075 to 0.000000257
- ITL-F: 0.075 to 0.000000257
- ITR-WR: 60 to 8640
- iTH-F: 0.075 to 0.000000257
- iTL-F: 0.075 to 0.000000257
- iTR-WR: 60 to 8640
- All values are decimal.
Fit full response surfaces and main effects only models.
Conclusions

- Tom Youmans to discuss substantive conclusions (next talk).

- The Europa Clipper requirements model and experiment provides a quantitative way to relate science outcomes to design choices in building instrument and spacecraft systems.

- The Monte Carlo simulation experiment allows us to interrogate these relationships, which are too complex to understand analytically.

- The experimental design is crucial to making the Monte Carlo-based strategy feasible: it ensures that the limited number of conditions under which the experiment can be run, is as informative as possible.

- Personal reflection: JMP is a great tool, but I wish it was programmable!
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