A Quantitative Assessment of the Science Robustness of the Europa Clipper Mission

Kelli McCoy, Jet Propulsion Laboratory, California Institute of Technology

Dataworks, 2019
• Europa Clipper’s enabling strategy is to dip into Europa’s intense radiation, collect the bulk of its science data, and get out

• Due to the uncertainty in the radiation environment, disruptions to planned activity are expected
  • A robust Flight System and Mission Plan are required to return sufficient science data

A comprehensive suite of tools is needed to inform robustness conversations
Science Acquisition vs. Environment

24 hours

*Fieseler et al, 2002*
Assessment Tool Suite Overview

Nominal Scenario:
Objective: deterministically assess candidate tours against Measurement Requirements and L1 Science Objectives

- Measurement requirement organization by instrument
- ‘Checks’ whether requirements are met
- Meas RQ Assessment
- L1 Science Assessment
- Met=1; Not met=0
- Traces observations (from M-STAF) to L1 Science Objectives
- Observation schedule/ConOps

Robustness Scenario: Science PRA
Objective: probabilistically assess achievement of Measurement Requirements and L1 Science Objectives

- Fault/reliability Analysis
  - Sensitivity analysis, via DOE, is used to understand design recovery “needs”
- Fault timelines passed
- ‘Checks’ whether requirements are met (in Monte Carlo loop)
- Met with probability ‘y’
- Meas RQ Probabilistic Assessment
- L1 Science Probabilistic Assessment
- Met with probability ‘x’

M-STAF
VERITaS
APGen
P-STAF
Robustness Architecture Capability Examples

It’s known when (in tour) each L1 RQ is met. Use this to manage resources (e.g. power) in ops.

Given predicted disruptions, can the current system design meet L1 science RQs with high probability?

Does each instrument, s/c need the capability to recover during a flyby? If so, how quickly?

Is there a piece of hardware susceptible to radiation that could cause missed science? What fault rates can be tolerated?

Is a particular Measurement RQ or instrument critical to L1 achievement?

In the event of an anomaly, the tour can be replanned to target science needed for L1 baseline/threshold science completion.

If more observations/margin (of a particular type (margin) are needed in the tour to meet L1 science, mission plan or trajectory can be adjusted.

Tour duration required to achieve is L1 science known. This should inform system sizing (arrays, batteries, delta-V, etc).

Mission Related  Science Related  Flight System Related
Example Products Generated (Veritas/SSM)

Stellar Occultations: Map of Star-Atmosphere Pierce Points

Accumulation of Stellar Occs Throughout Mission
It is known when L2 and L1 requirements are met in the tour

Measurement RQ Margin
Low RQ margin (req’d vs achieved by traj/mission plan) typically means RQ is brittle
Faulted Timeline Examples

Example Timeline 1

Example Timeline 2

- FPGA fault
- RAD 750 fault
- Observation
- Closest Approach
- Undervoltage; safing
Model input/output

Input variables

• Transient and Ground-in-loop (GnL) fault rate for each of nine instruments and the spacecraft
  • For within the high radiation environment and outside
    • Fault rates are unknown, but bounded using historical fault rates from various JPL missions
  • Recovery time for GnL and transient faults for each of the nine instruments and the spacecraft
    • For within the flyby period (high science cadence) and outside the flyby period
      • Recovery time is varied within bounds of interest to establish a recovery requirement for the s/c and each instrument

Output variables

• Probability each Measurement RQ (L2 RQ) is achieved (~200 of these)
  • \( P[R_j = 1 | A] \), where \( R_j = 1 \) if the Measurement Requirement \( j \) is met and zero otherwise

• Probability each individual L1 Baseline RQ is achieved (9 of these)
  • \( P[L_i = 1 | A] \), where \( L_i = 1 \) if the L1 requirement \( i \) is met and zero otherwise, given input \( A \) and mapping, \( f: R \rightarrow L \)

• Probability set of L1 baseline science RQs is achieved
  • \( P[\bigcap_{i=1}^{9} L_i = 1 | A] \), probability of meeting the set of 9 L1 baseline Science Requirements

Performing a Design of Experiment in order to establish a response surface quick turnaround analysis
Performing a Design of Experiment in order to establish a response surface is key for quick turnaround analysis.
L1 Science Probabilistic Assessment

Calculate Being Met Probability and Met by Encounter up the Graph

P-STAF / M-STAF Graph Representation

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<table>
<thead>
<tr>
<th>L1 Req’t</th>
<th>Probability</th>
<th>Earliest Encounter</th>
<th>Latest Encounter</th>
<th>Latest Encounter if Met</th>
<th>Most Common Encounter</th>
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</thead>
<tbody>
<tr>
<td>RQ 1</td>
<td>70.00%</td>
<td>E40</td>
<td>N/M</td>
<td>E43</td>
<td>E40</td>
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<td>N/M</td>
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<td>RQ 5</td>
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<td>E32</td>
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Measurement Req’t Probability Earliest Encounter Latest Encounter Latest Encounter if Met Most Common Encounter

MsRQ 1 100.00% E25 E32 E32 E25
MsRQ 2 84.74% E39 N/M E45 E39
MsRQ 3 100.00% E35 E39 E39 E35
MsRQ 4 84.74% E39 N/M E45 E39

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Primary Trade

• Maximize the probability of collecting L1 Science (i.e. mission success)
  • This can be done via several strategies, each of which have penalties

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<th>Solution Proposed</th>
<th>Solution Space examples</th>
<th>Penalty</th>
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<td>Reduce likelihood of interruptions</td>
<td>• Additional shielding • Use parts less susceptible to radiation</td>
<td>• Adds mass; doesn’t mitigate workmanship escapes • Commercial parts may not be available; new flight hardware development</td>
</tr>
<tr>
<td>Speed up recovery time</td>
<td>• Hot swap compute elements • Recovery + feed forward hardware controller • Reduce ground in the loop recovery time • Ensure pointing (control/knowledge) can be regained quickly</td>
<td>• Adds mass, cost and power • Adds mass, cost and power • Additional ops staffing required (still ~1-2 hr light time round trip) • Adds power need</td>
</tr>
<tr>
<td>Increase number of observation Opportunities</td>
<td>• Extend tour duration (within current TID requirements) • Immediately replan lost flybys</td>
<td>• Adds operational cost; orbital mechanics may not allow a repeat exact missed science • Adds operational cost; will cause the rest of the tour to need to be replanned</td>
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<tr>
<td>Increase science margin</td>
<td>• Optimize scheduling of opportunities • Require less science</td>
<td>• Potentially greater power required • NASA HQ involvement; potentially retrieve less interesting science</td>
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• This modeling infrastructure enabled informed conversations and decisions to be made by management, as opposed defaulting to a worst-case expensive design

Pre-modeling Design Posture
• Considered AI solutions for quick recovery, using complex rules for science timeline restarts
• Required expensive feed forward controllers
• Excessive instrument measurement RQs (relative to L1 RQs)

Post-modeling Design Posture
• Lengthy recovery allowed for instruments and spacecraft (hours)
• Simple recovery solutions in play, like leaving instruments on (during a fault recovery) that don’t require pointing control
• Require a celestial mode to ensure attitude estimation can be obtained by using 1 IMU and 1 SRU during flyby
• Measurement RQ requests were scaled to appropriately track L1 RQs
• Ensure trajectory is flexible enough to target key missed science