Monte Carlo Simulation of a Triple Flyby Capture at Jupiter Using Paramat

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Overview

- Paramat
- A Triple Flyby Capture at Jupiter
- Preliminary Maneuver Error Modelling
- Navigation Requirements
  - Coarse Evaluation
  - Detailed Evaluation
- Combined Analysis
- Conclusions
Paramat
The Paramat Project

- **Parallel Mission Analysis Tool**
- Built on GMAT Numerical Engine
- SBIR Project in 2014
  - Prototype Threaded Application
  - Demonstrated Proof of Concept
  - Encountered Issues of Thread Safety and Code Maintainability
- Current Paramat Project
  - Rebuilt as MPI based Application
  - Uses GMAT R2015a Linux/Mac code base
Paramat Goals

- Run Multiple GMAT Simulations Simultaneously
- Collect and Display Run Data
- Simplify Multirun Analysis Problems
- Cross Platform Capabilities
  - Developed on Linux
  - Targeted for Linux, Windows and Mac
Paramat Process View
Paramat Parallel Run
A Triple Flyby Capture at Jupiter
Capture Trajectory

• Initial State
  - 4.5 days out
  - Maneuver to hit:

• Flyby 1: Callisto
  - Maneuver to hit:

• Flyby 2: Io

• Jupiter Periapse
  - Orbit Insertion Maneuver (JOI) targeted to hit:

• Flyby 3: Ganymede
Key Events

- **Initial State:**
  - 2 Feb 2025 21:19:19
  - $X = -4714128.923 \text{ km}$
  - $Y = 68943.330 \text{ km}$
  - $Z = -60914.940 \text{ km}$
  - $V_x = 9.078 \text{ km/s}$
  - $V_y = -1.970 \text{ km/s}$
  - $V_z = 0.060 \text{ km/s}$

- **Callisto:**
  - 6 Feb 2025 02:05:20
  - $B \cdot T = 2510 \text{ km}$
  - $B \cdot R = 0 \text{ km}$

- **Io:**
  - 7 Feb 2025 07:02:38
  - $B \cdot T = 2130$
  - $B \cdot R = 0$

- **JOI:**
  - 7 Feb 2025 11:29:26

- **Ganymede:**
  - 8 Feb 2025 3:54:36
  - $B \cdot T = -2900$
  - $B \cdot R = 0$
Maneuvers

• 3 Maneuvers:
  – At Start: 0.842 m/s
  – At Callisto: 11.985 m/s
  – JOI: 267.314 m/s
• Total: 280.14 m/s
• Without Flyby Assists: 768.96 m/s
Results

- Significant Delta-V Savings
- Acceptable Flyby Distances:
  - Callisto 55.5 km
  - Io 287.2 km
  - Ganymede 280.0 km

- Question: What are the Affects of Maneuver and Navigation Errors on the Trajectory?
Maneuver Error Modelling
Criteria for Evaluation

- Final Orbit Period \( \sim 200 \) Days
- Minimum Altitude at Callisto \( \sim 55 \) km
- Minimum Altitude at Io \( \sim 300 \) km
- Altitude at Jupiter \( > 2 \, R_j \)
- Avoid Impact at Ganymede
Maneuver Error Analysis

Script Configuration

- Maneuver Model:
  \[ dV = dV_{\text{nom}} \times \text{TSF} \]

- Burn 1: TSF = 0.999
  StDev 0.001

- Burn 2: TSF = 0.995
  StDev 0.005

- Burn 3: TSF = 0.995
  StDev 0.005

Paramat Configuration

- 19937-bit Mersenne twister pseudo-random generator
- Seeded from System Clock
- Gaussian Distribution
## Results

<table>
<thead>
<tr>
<th>Event</th>
<th>Altitude</th>
<th>SDev</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calisto</td>
<td>55.5 km</td>
<td>0.148</td>
<td>55.0</td>
<td>56.0</td>
</tr>
<tr>
<td>Io</td>
<td>287.3 km</td>
<td>2.169</td>
<td>279.6</td>
<td>295.0</td>
</tr>
<tr>
<td>Jupiter</td>
<td>2.232 RJ</td>
<td>0.0001</td>
<td>2.232</td>
<td>2.233</td>
</tr>
<tr>
<td>Ganymede</td>
<td>278.6 km</td>
<td>88.0</td>
<td>-9.1</td>
<td>606.5</td>
</tr>
<tr>
<td>Period</td>
<td>206.2 days</td>
<td>6.253</td>
<td>184.7</td>
<td>230.0</td>
</tr>
</tbody>
</table>

- 1 Impact at Ganymede out of 5000 iterations
- Paramat Run Time: 17 minutes 26 Sec
Navigation Requirements
Approach

- Goal: Determine Accuracy Needed for Position and Velocity
  - At Trajectory Start
  - For a Successful Capture
  - With No Intervening Estimation or Maneuver Targeting

- Two Steps
  - Course System Runs
  - Final Evaluation
Coarse Runs

- Find Acceptable Tolerances
- 7 Data Sets
- Criteria: Impacts at Ganymede

<table>
<thead>
<tr>
<th>dR</th>
<th>dV</th>
<th>Altitude</th>
<th>StDev</th>
<th>Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 m</td>
<td>5 mm/s</td>
<td>202.8 km</td>
<td>724.2</td>
<td>385</td>
</tr>
<tr>
<td>250 m</td>
<td>1 mm/s</td>
<td>224.8 km</td>
<td>179.8</td>
<td>108</td>
</tr>
<tr>
<td>100 m</td>
<td>5 mm/s</td>
<td>218.8 km</td>
<td>690.7</td>
<td>379</td>
</tr>
<tr>
<td>100 m</td>
<td>1 mm/s</td>
<td>219.7 km</td>
<td>133.4</td>
<td>56</td>
</tr>
<tr>
<td>50 m</td>
<td>5 mm/s</td>
<td>255.4 km</td>
<td>665.4</td>
<td>352</td>
</tr>
<tr>
<td>50 m</td>
<td>1 mm/s</td>
<td>214.5 km</td>
<td>137.4</td>
<td>56</td>
</tr>
<tr>
<td>50 m</td>
<td>0.5 mm/s</td>
<td>219.9 km</td>
<td>71.6</td>
<td>1</td>
</tr>
</tbody>
</table>

Paramat Notes

- 1000 Iteration Runs
- ~3.5 min/run
- Total run time < 30 min
Final Nav Evaluation

• Cases Evaluated:
  - \( dR = 50 \text{ m} \)
    \( dV = 0.5 \text{ mm/s} \)
  - \( dR = 50 \text{ m} \)
    \( dV = 0.25 \text{ mm/s} \)

• 5000 Iteration Runs
Results: Case 1

<table>
<thead>
<tr>
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<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calisto</td>
<td>55.7 km</td>
<td>0.144</td>
<td>55.1</td>
<td>56.2</td>
</tr>
<tr>
<td>Io</td>
<td>290.0 km</td>
<td>2.028</td>
<td>281.9</td>
<td>297.4</td>
</tr>
<tr>
<td>Jupiter</td>
<td>2.233 RJ</td>
<td>---</td>
<td>2.233</td>
<td>2.233</td>
</tr>
<tr>
<td>Ganymede</td>
<td>218.9 km</td>
<td>72.797</td>
<td>-44.4</td>
<td>510.4</td>
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<tr>
<td>Period</td>
<td>199.6 days</td>
<td>5.614</td>
<td>179.1</td>
<td>221.8</td>
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</tbody>
</table>

- 6 Impacts at Ganymede, 7 Additional Altitudes Below 25 km
- Provided Rational for Tighter dV Evaluation
# Results: Case 2

- 0 Impacts at Ganymede
- Lowest Alt. in 5000 Iterations: 73.1 km

<table>
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<th>Min</th>
<th>Max</th>
</tr>
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<tbody>
<tr>
<td>Calisto</td>
<td>55.7 km</td>
<td>0.084</td>
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<tr>
<td>Io</td>
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<td>1.184</td>
<td>286.1</td>
<td>294.1</td>
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<tr>
<td>Jupiter</td>
<td>2.233 RJ</td>
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<tr>
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<td>210.1</td>
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</table>
Combined Requirements
Maneuver + Navigation Run

- Combine Best Navigation Case with Maneuver TSF
- Apply No TSF at Initial Maneuver
  - Rationale: Treat as Included in State Estimation Post-burn
- 5000 Iteration Run

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>Initial State</td>
<td>50 m</td>
</tr>
<tr>
<td>Velocity</td>
<td>Initial State</td>
<td>0.25 mm/s</td>
</tr>
<tr>
<td>Callisto TSF</td>
<td>1.0</td>
<td>0.005</td>
</tr>
<tr>
<td>JOI TSF</td>
<td>1.0</td>
<td>0.005</td>
</tr>
</tbody>
</table>
## Results

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</tr>
<tr>
<td>Io</td>
<td>290.0 km</td>
<td>1.330</td>
<td>285.2</td>
<td>294.3</td>
</tr>
<tr>
<td>Jupiter</td>
<td>2.233 R(_\text{J})</td>
<td>8.0e-5</td>
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<tr>
<td>Ganymede</td>
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<td>63.346</td>
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<td>199.6 days</td>
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<td>213.4</td>
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</tbody>
</table>

- **1 Impact at Ganymede out of 5000 iterations**
- **3 Additional Cases Below 25 km**
Conclusions
Conclusions

• Preliminary Analysis:
  - Maneuver Modeling to 1% TSF
  - Tight Navigation Bounds (50 m, 0.25 mm/s)
• Estimation Between Maneuvers would Help, but Timing Makes this Difficult
  - 1 Day 9.5 Hr Between Callisto Maneuver and JOI
  - Includes Io Flyby
Notes on Paramat

- Large Scale Analysis Simplified
- Enables Fast Result Compilation
- Works on Multiple Platforms
- Status:
  - Currently in Early Development
  - Development Progress is Sporadic
Questions and Discussion