

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

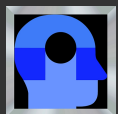
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Overview

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



Paramat



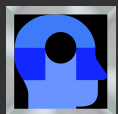
The Paramat Project

- **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

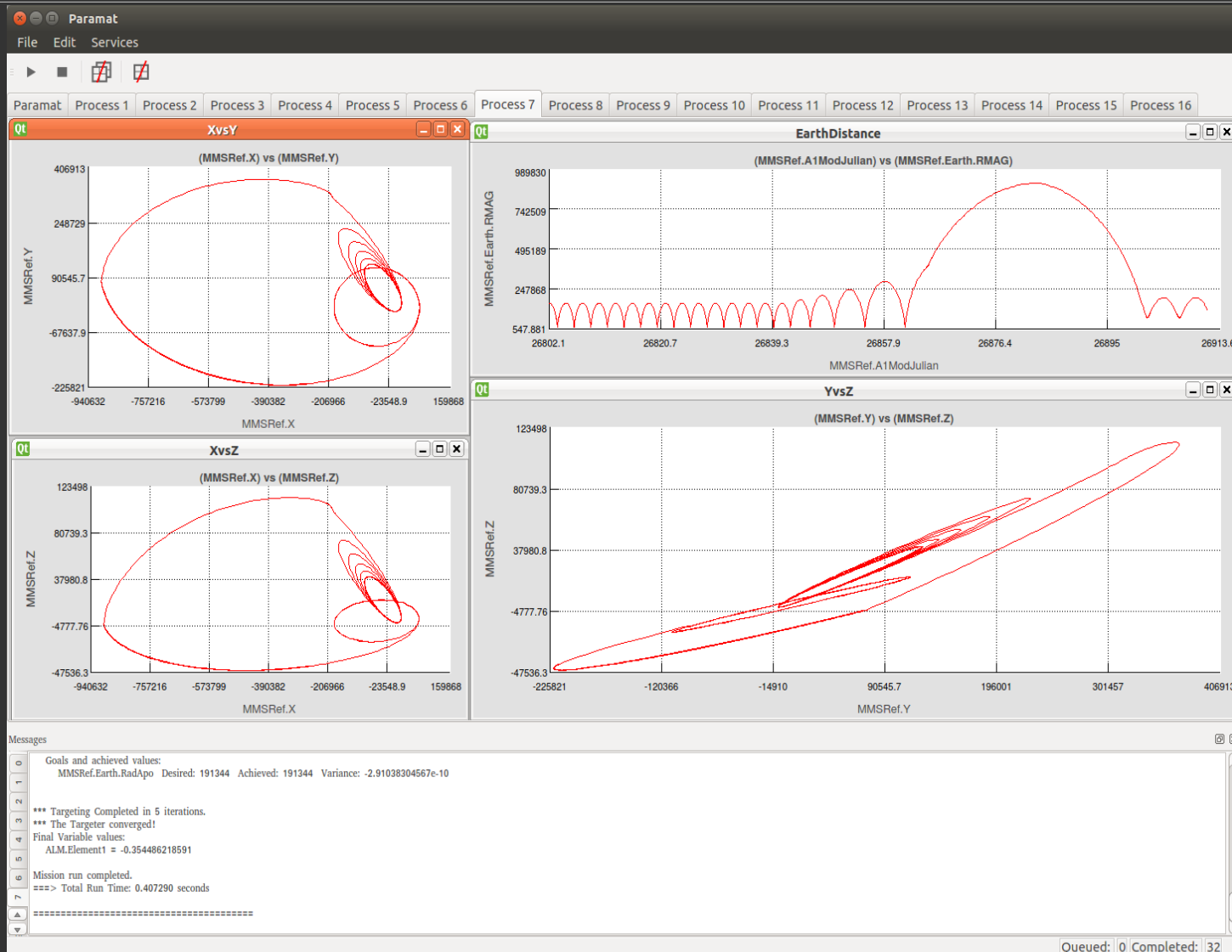


Paramat Goals

- 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

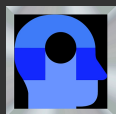
The screenshot displays the Paramat software interface during a parallel run. The main window is titled "Paramat" and features a menu bar (File, Edit, Services) and a toolbar. Below the toolbar is a process list showing 16 processes (Process 1 to Process 16). The "Setup" panel on the left includes a "On Process:" dropdown set to "0", a radio button for "Everywhere", a script path "/home/djc/ParamatMPI/ParamatMPI/MyScripts/CATT_Baseline.script", and a "Iterations:" field set to "8000". There are buttons for "Build Script Queue...", "Save Run Data", "Clear Run Data", and "Graphics Off".

The "Results" window displays a list of numerical data points, likely representing simulation results for various parameters. The data points are listed in a single column, with values ranging from approximately 0.2687383234346268 to 0.2687385188500446.

Three scatter plots are shown, each representing a different parameter space:

- AtGanymede:** A scatter plot showing a dense distribution of red data points. The x-axis ranges from -2980.8 to -2689.77, and the y-axis ranges from -5.61613 to 3.96576.
- AtIto:** A scatter plot showing a dense distribution of red data points. The x-axis ranges from 2124.37 to 2132.4, and the y-axis ranges from -5.09911 to 3.29054.
- AtCallisto:** A scatter plot showing a dense distribution of red data points. The x-axis ranges from 2509.61 to 2510.23, and the y-axis ranges from -0.236813 to 0.363331.

The "Messages" window at the bottom shows the status of multiple GMAT MPI clients, indicating that the run is completed. The status bar at the bottom right shows "Queued: 2444 Completed: 5540".

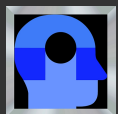
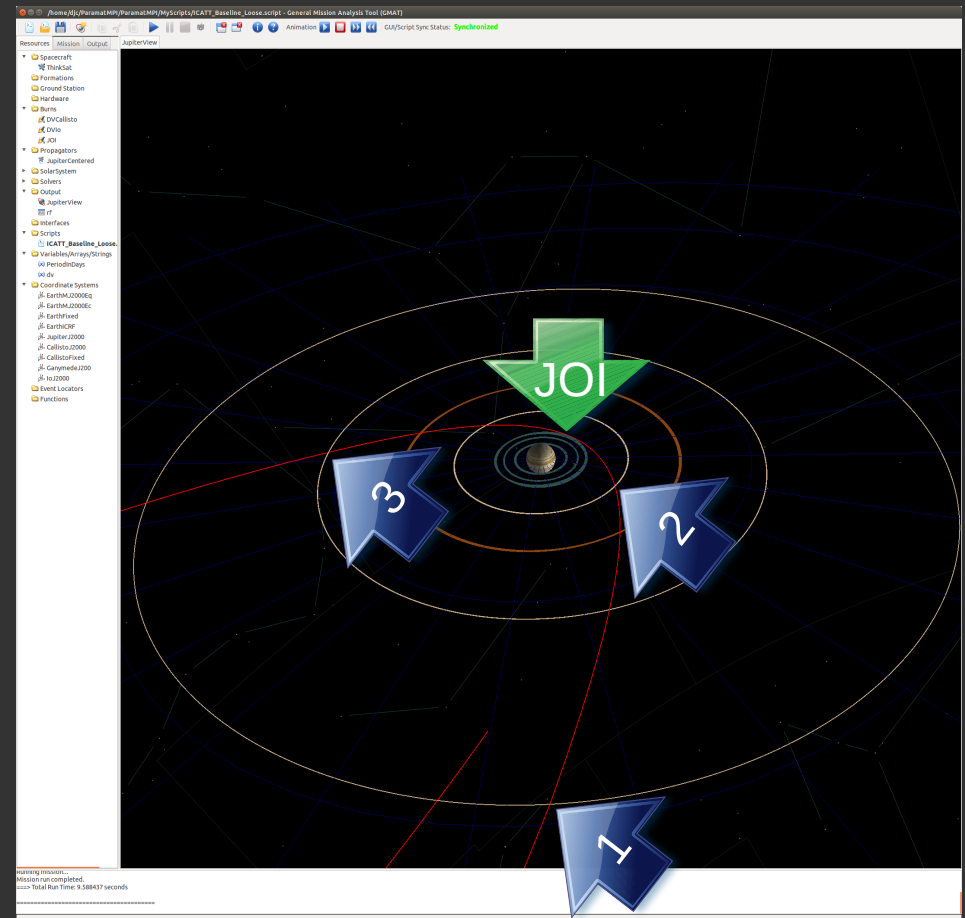


A Triple Flyby Capture at Jupiter



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

$X = -4714128.923$ km

$Y = 68943.330$ km

$Z = -60914.940$ km

$V_x = 9.078$ km/s

$V_y = -1.970$ km/s

$V_z = 0.060$ km/s

- **Callisto:** 6 Feb 2025 02:05:20

$B \cdot T = 2510$ km

$B \cdot R = 0$ km

- **Io:** 7 Feb 2025 07:02:38

$B \cdot T = 2130$

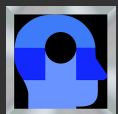
$B \cdot R = 0$

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

- **Ganymede:** 8 Feb 2025 3:54:36

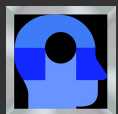
$B \cdot T = -2900$

$B \cdot R = 0$



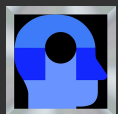
Maneuvers

- 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 ~ 200 Days
- Minimum Altitude at Callisto ~ 55 km
- Minimum Altitude at Io ~ 300 km
- Altitude at Jupiter $> 2 R_J$
- Avoid Impact at Ganymede



Maneuver Error Analysis

Script Configuration

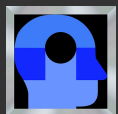
- Maneuver Model:

$$dV = dV_{\text{nom}} * \text{TSF}$$

- Burn 1: TSF = 0.999
StDev 0.001
- Burn 2: TSF = 0.995
StDev 0.005
- Burn 3: TSF = 0.995
StDev 0.005

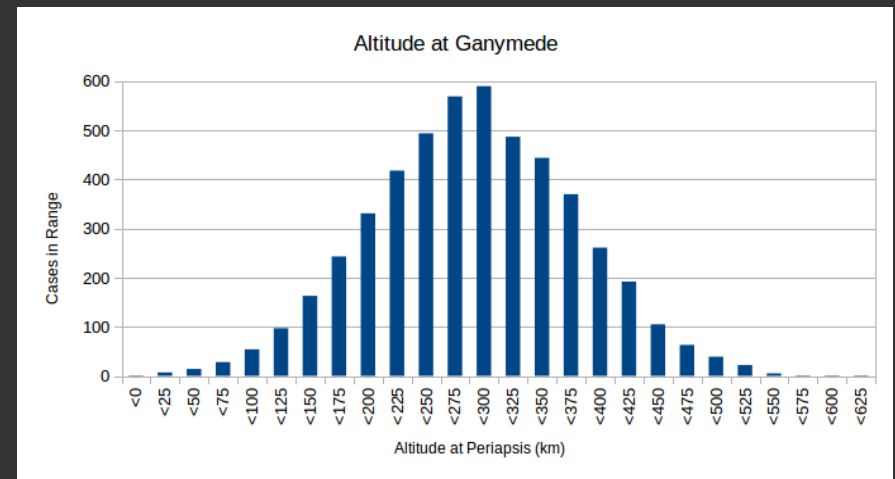
Paramat Configuration

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

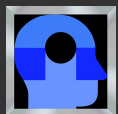


Results

Event	Altitude	SDev	Min	Max
Calisto	55.5 km	0.148	55.0	56.0
Io	287.3 km	2.169	279.6	295.0
Jupiter	2.232 RJ	0.0001	2.232	2.233
Ganymede	278.6 km	88.0	-9.1	606.5
Period	206.2 days	6.253	184.7	230.0



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

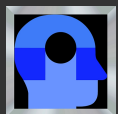


Navigation Requirements



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



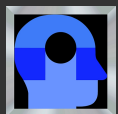
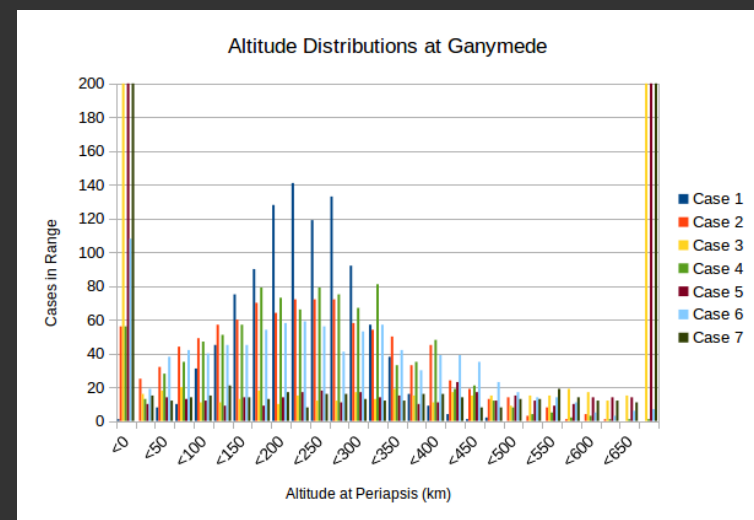
Coarse Runs

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

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

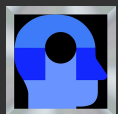
Paramat Notes

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



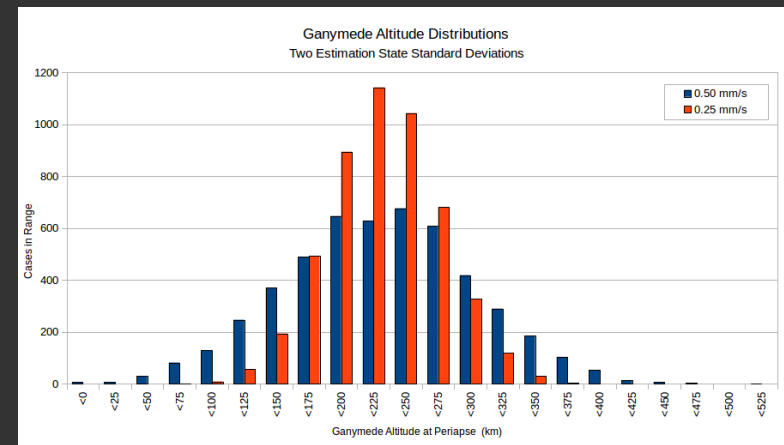
Final Nav Evaluation

- Cases Evaluated:
 - $dR = 50$ m
 $dV = 0.5$ mm/s
 - $dR = 50$ m
 $dV = 0.25$ mm/s
- 5000 Iteration Runs



Results: Case 1

Event	Altitude	SDev	Min	Max
Calisto	55.7 km	0.144	55.1	56.2
Io	290.0 km	2.028	281.9	297.4
Jupiter	2.233 RJ	---	2.233	2.233
Ganymede	218.9 km	72.797	-44.4	510.4
Period	199.6 days	5.614	179.1	221.8

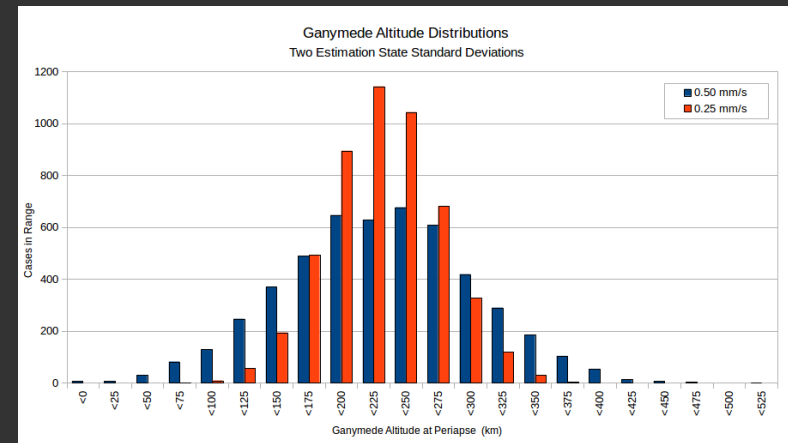


- 6 Impacts at Ganymede, 7 Additional Altitudes Below 25 km
- Provided Rational for Tighter dV Evaluation

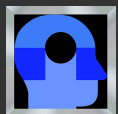


Results: Case 2

Event	Altitude	SDev	Min	Max
Calisto	55.7 km	0.084	55.4	56.0
Io	290.0 km	1.184	286.1	294.1
Jupiter	2.233 RJ	6.9e-5	2.233	2.233
Ganymede	218.9 km	42.466	73.1	355.7
Period	199.6 days	3.275	188.3	210.1



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



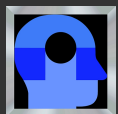
Combined Requirements



Maneuver + Navigation Run

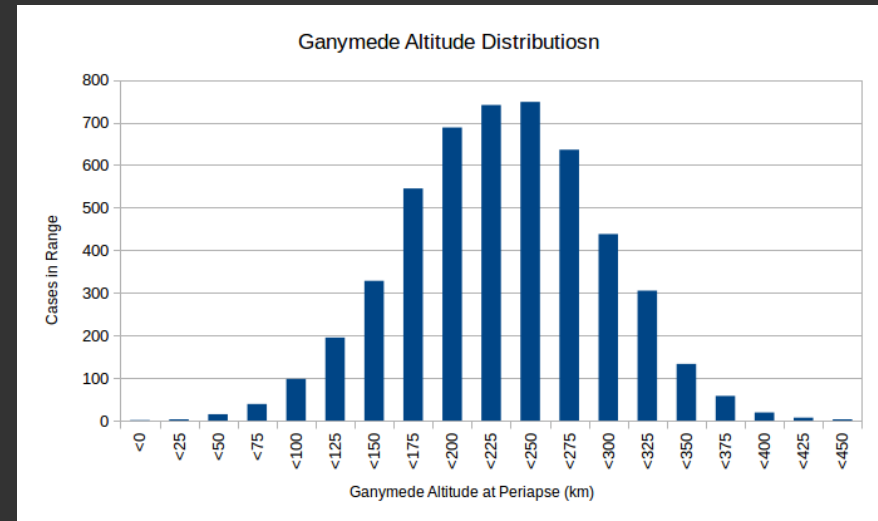
- Combine Best Navigation Case with Maneuver TSF
- Apply No TSF at Initial Maneuver
 - Rationale: Treat as Included in State Estimation Post-burn
- 5000 Iteration Run

Component	Value	StDev
Position	Initial State	50 m
Velocity	Initial State	0.25 mm/s
Callisto TSF	1.0	0.005
JOI TSF	1.0	0.005

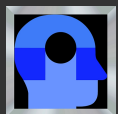


Results

Event	Altitude	SDev	Min	Max
Calisto	55.7 km	0.084	55.4	56.0
Io	290.0 km	1.330	285.2	294.3
Jupiter	2.233 R_J	8.0e-5	2.233	2.233
Ganymede	219.4 km	63.346	-5.8	443.0
Period	199.6 days	3.978	185.5	213.4



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

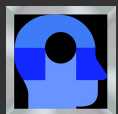


Conclusions



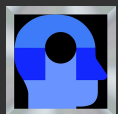
Conclusions

- 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

