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

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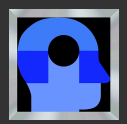
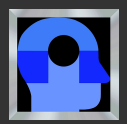
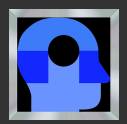


Overview

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

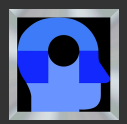


Paramat



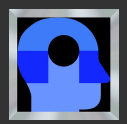
The Paramat Project

- **Para**llel **M**ission **A**nalysis **T**ool
- 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

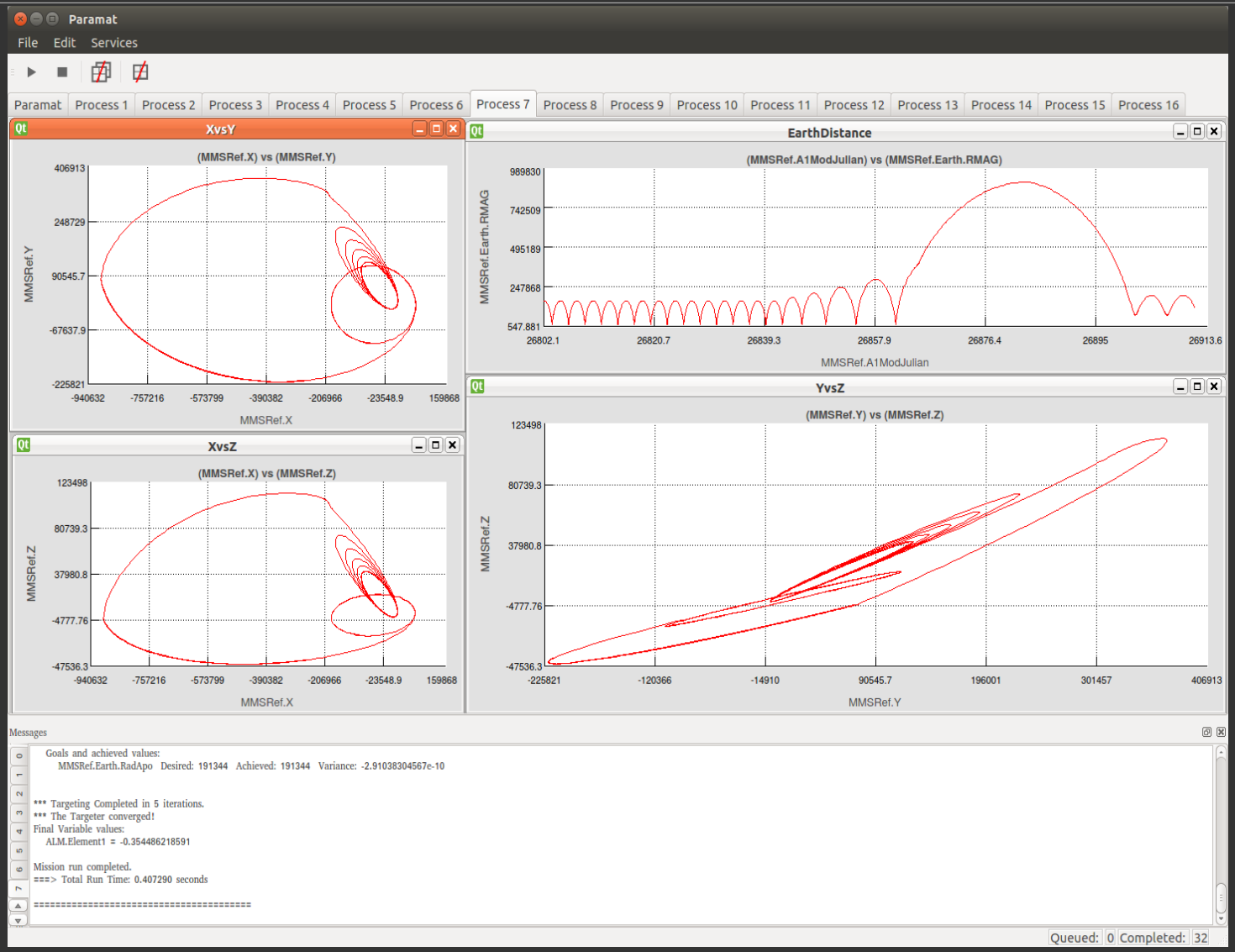


Paramat Goals

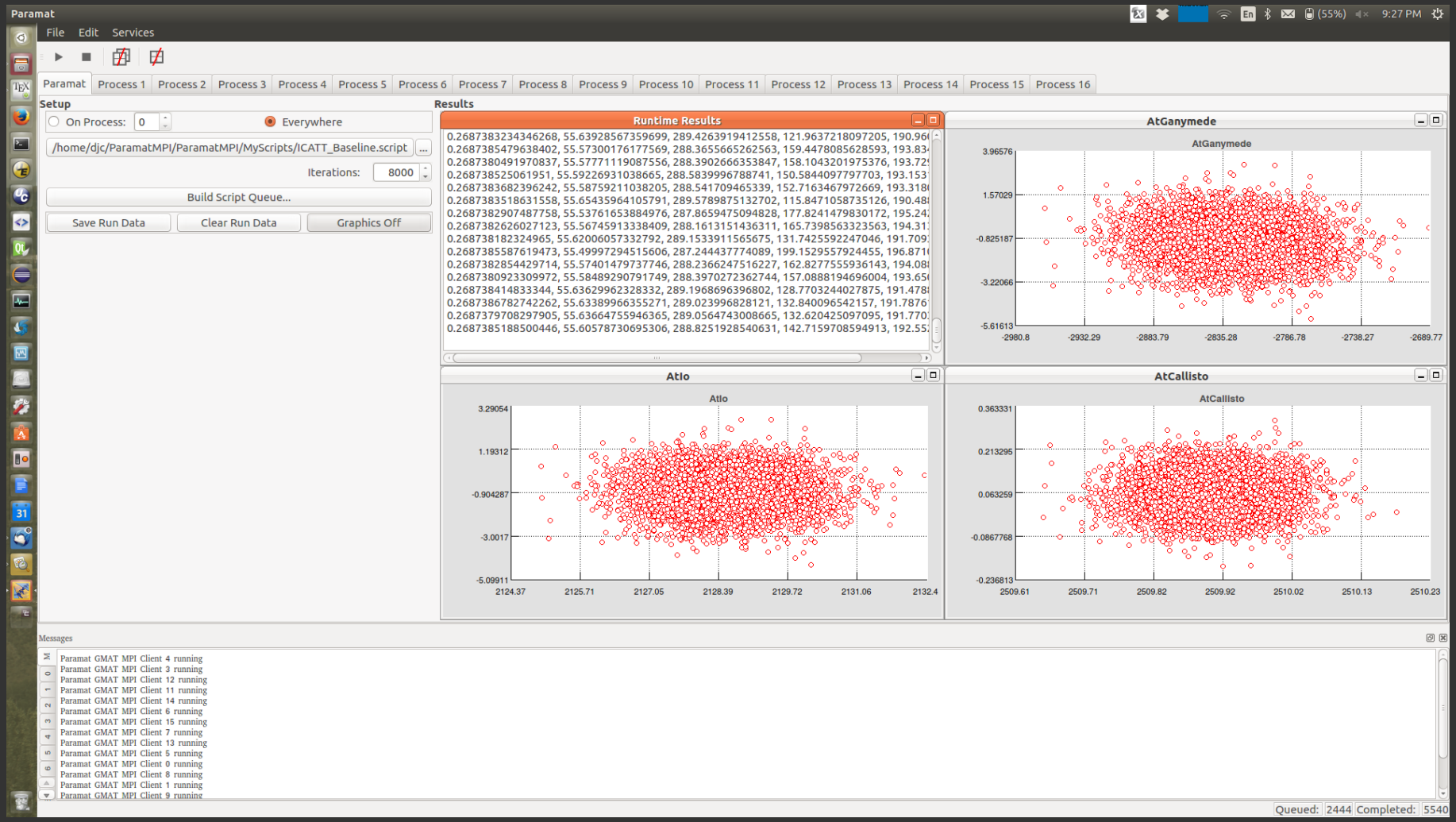
- Run Multiple GMAT Simulations Simultaneously
- Collect and Display Run Data
- Simplify Multirun Analysis Problems
- Cross Platform Capabilities
  - Developed on Linux
  - Targeted for Linux, Windows and Mac



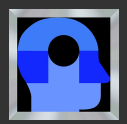
Paramat Process View



Paramat Parallel Run

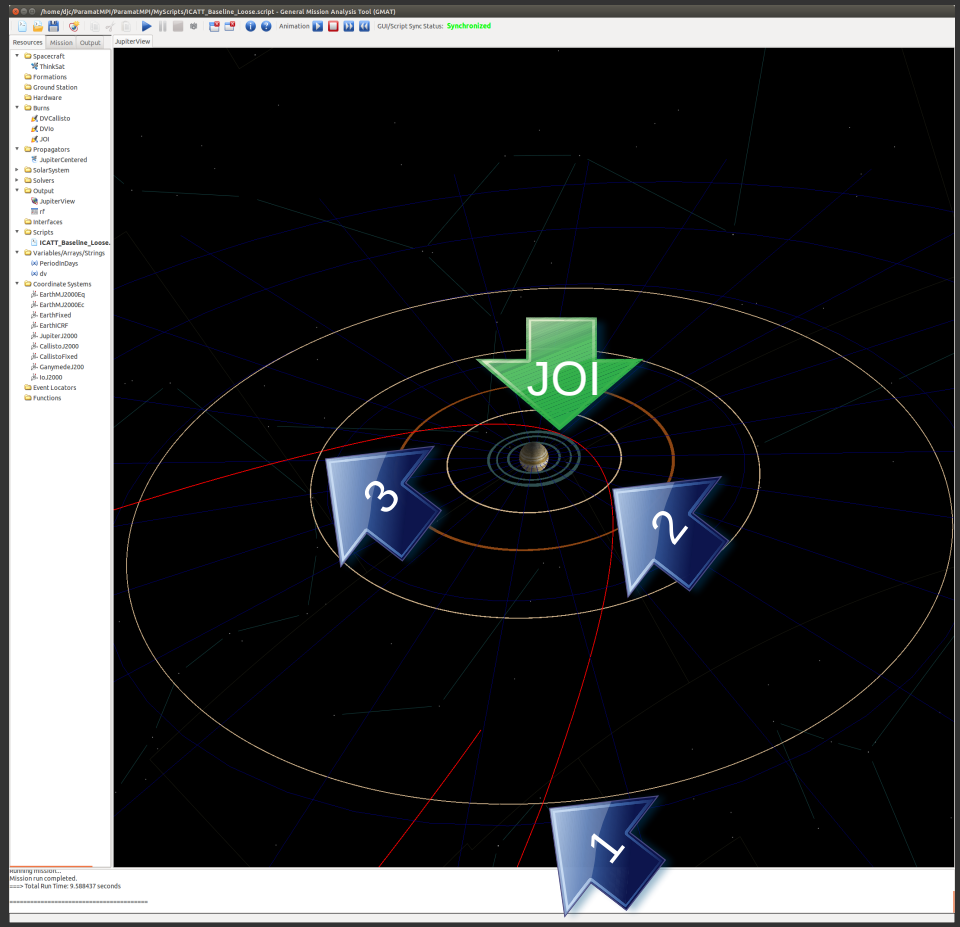


A Triple Flyby Capture at Jupiter



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 km

  Y = 68943.330 km

  Z = -60914.940 km

  Vx = 9.078 km/s

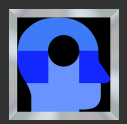
  Vy = -1.970 km/s

  Vz = 0.060 km/s

- **Callisto**: 6 Feb 2025 02:05:20
  B • T = 2510 km
  B • R = 0 km
- **Io**: 7 Feb 2025 07:02:38
  B • T = 2130
  B • R = 0
- **JOI**: 7 Feb 2025 11:29:26
- **Ganymede**: 8 Feb 2025 3:54:36
  B • T = -2900
  B • R = 0

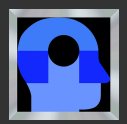
Maneuvers

- 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

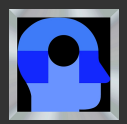


Results

- 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?

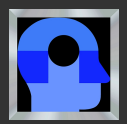


Maneuver Error Modelling



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

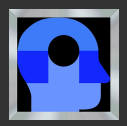
- Maneuver Model:

  $dV = dV_{nom} * TSF$

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

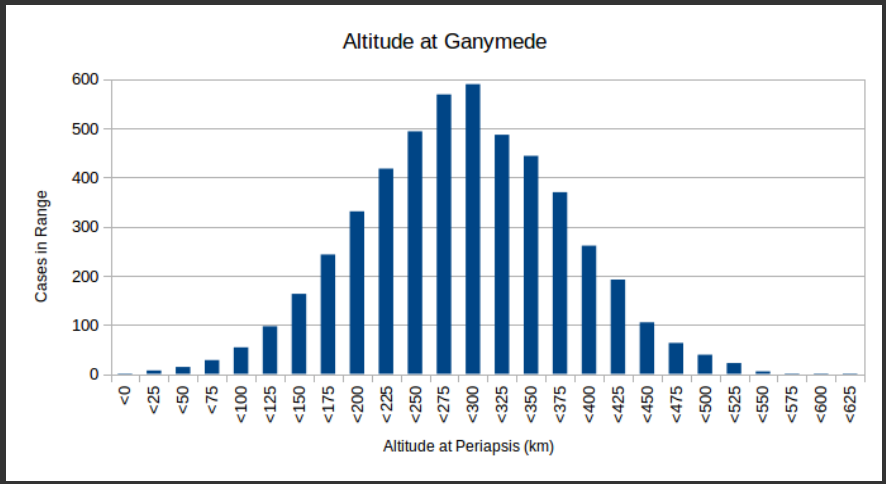
Paramat Configuration

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



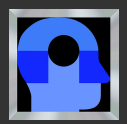
Results

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



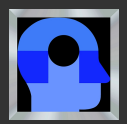
- 1 Impact at Ganymede out of 5000 iterations
- Paramat Run Time: 17 minutes 26 Sec

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



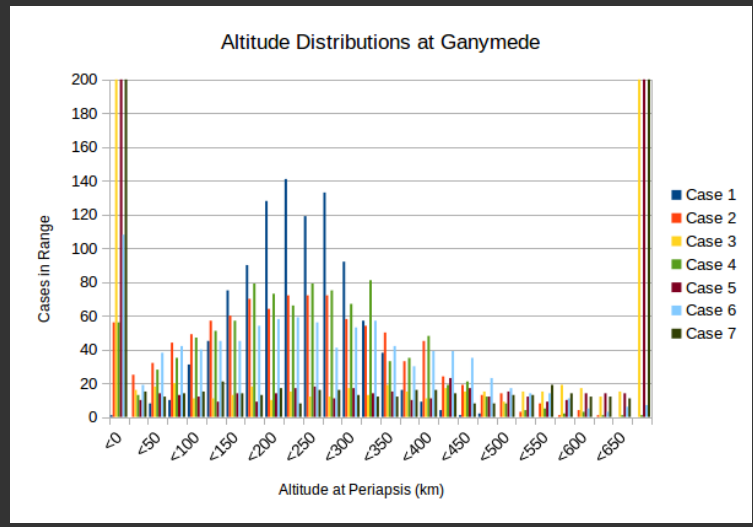
Coarse Runs

- 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

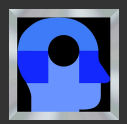
Paramat Notes

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



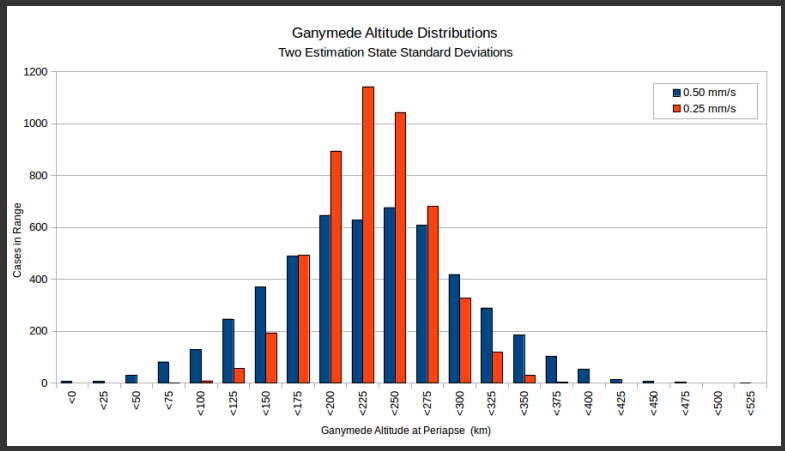
Final Nav Evaluation

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



Results: Case 1

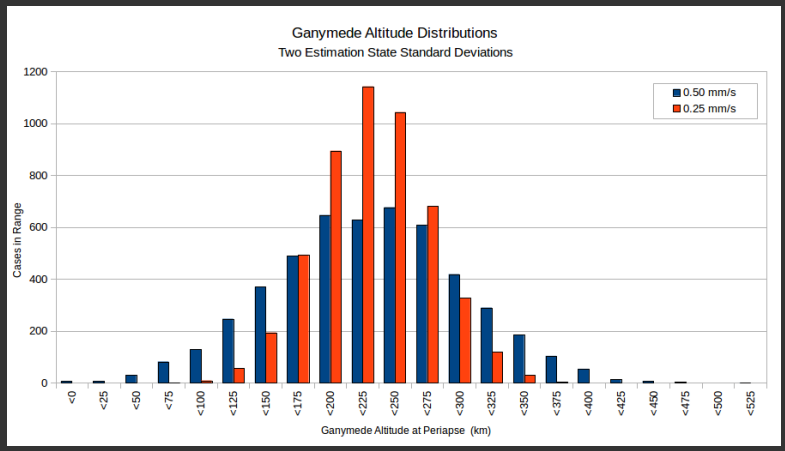
Event	Altitude	SDev	Min	Max
Calisto	55.7 km	0.144	55.1	56.2
Io	290.0 km	2.028	281.9	297.4
Jupiter	2.233 RJ	---	2.233	2.233
Ganymede	218.9 km	72.797	-44.4	510.4
Period	199.6 days	5.614	179.1	221.8



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

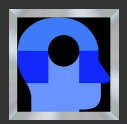
Results: Case 2

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

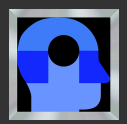
Combined Requirements



Maneuver + Navigation Run

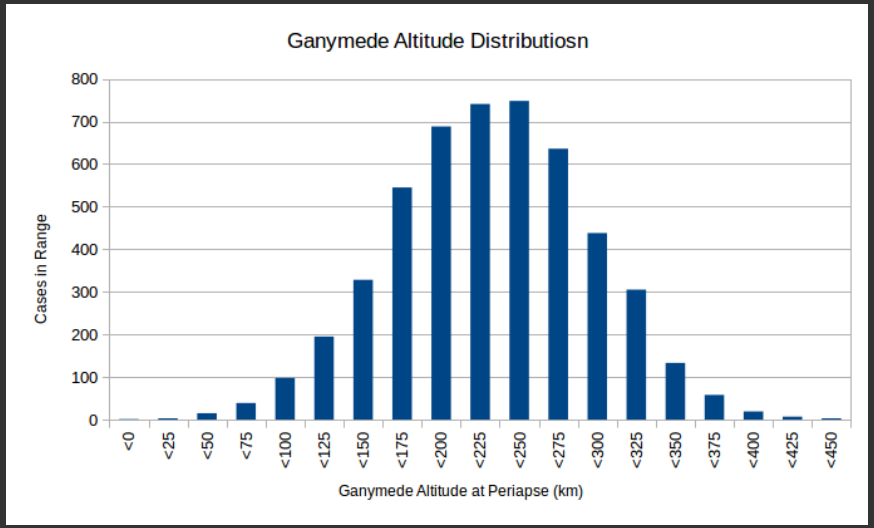
- Combine Best Navigation Case with Maneuver TSF
- Apply No TSF at Initial Maneuver
  - Rationale: Treat as Included in State Estimation Post-burn
- 5000 Iteration Run

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



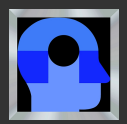
Results

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



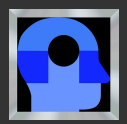
- 1 Impact at Ganymede out of 5000 iterations
- 3 Additional Cases Below 25 km

Conclusions



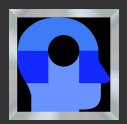
Conclusions

- 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