Recovering Time and State for Small Satellites in Deep Space

Interplanetary Small Satellite Conference Presentation

Andrew Dahir
Dr. Scott Palo
Dr. Dan Kubitschek

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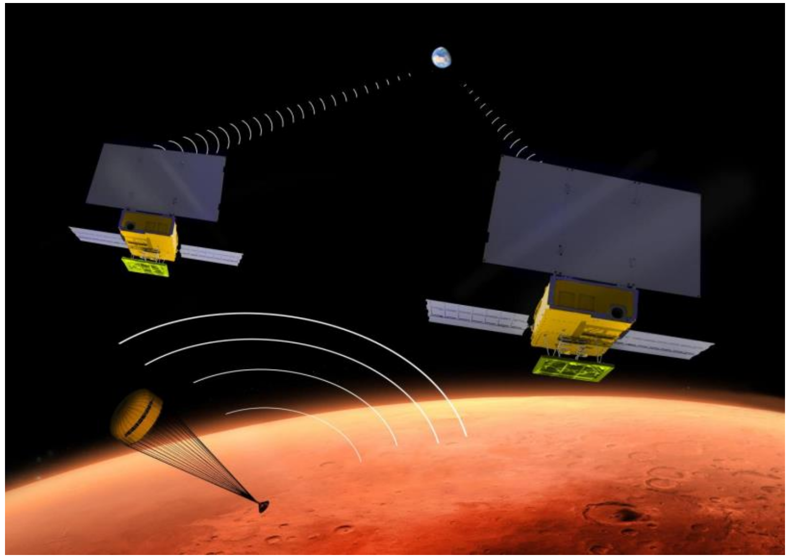
Overview of Problem

- To develop the architecture to demonstrate the complete, autonomous cold-start determination (Lost-In-Space) of time and state (Position and Velocity) for interplanetary autonomous optical navigation systems. (1)

Motivation

- Advancing autonomous navigation can ultimately reduce the cost of mission operations, including ground analysis. (2)
- Robustness and reduction in time-to-recovery of faulted systems (1)
- Reduced mission risk for both manned and unmanned spacecraft
- Helps enable small spacecraft missions for deep space



NASA MARCO Cubesats. Credit: NASA JPL

Overview of Problem

- Satellites primarily exist in two main locations, Earth orbiting, or in deep space.

Earth Orbiting

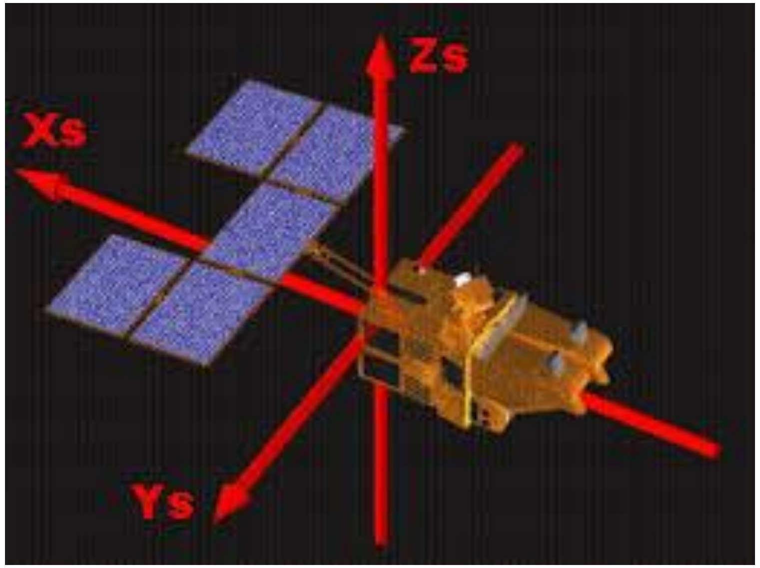
- GPS
- Ground Based Tracking

Deep Space

- Radiometric
- Optical Measurements

Lost in Space Problem

- There are two meanings when referring to the “Lost-In-Space” problem
  - Attitude
  - Orbit Determination



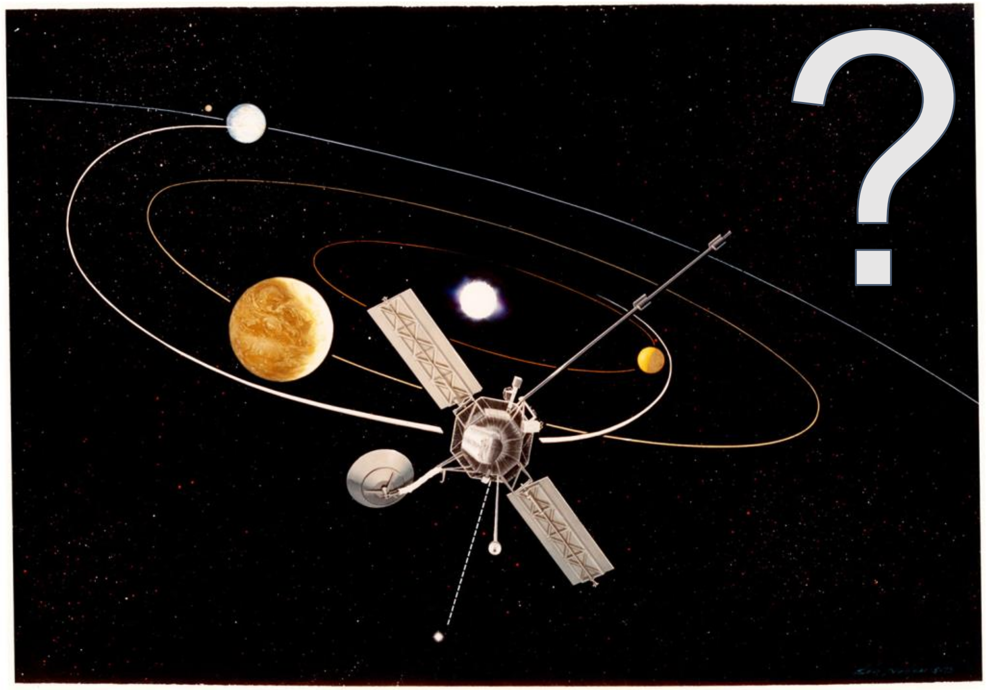
Lost in Space Problem

- Attitude “Lost-In-Space” problem
  - Solved via star trackers.

- Current furthest solution for Orbit Determination “Lost-in-Space” problem solves for position in a closed-form environment. (8)
  - Need Time, Position and Velocity (PVT)

Lost in Space Problem

- Processor Reboot
  - Watchdog Timer
  - Power loss
- Software Bug
- Initialization State
  - Rideshare
    - EM-1 Launch
- Memory Corruption
  - Single Event Upsets



Autonomous Navigation

- Autonomous Navigation is described by the following features, (3)
  a. Self-Contained
  b. Operating in Real Time
  c. Nonradiating (Not producing signals that aid in navigation, i.e. range/range rate between spacecraft)
  d. Not depending on outside operations
- When applied to a spacecraft you obtain a system that is considered autonomous when navigation is performed onboard an orbiting spacecraft in real time without ground support. (4)

Autonomous Navigation Background

AutoNav

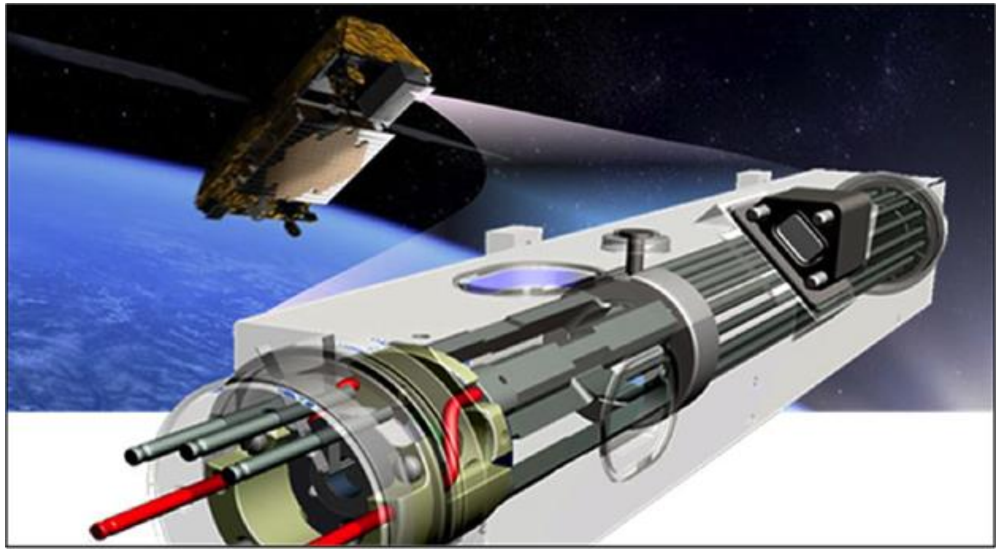
- Deep Space 1
- Deep Impact
- STARDUST

Deep-Space Positioning System (DPS)

- Deep Space Atomic Clock

OpNav

- In-Situ
    a. Voyager 1
    b. Voyager 2



(7)

Possible Sources

- Vast knowledge of autonomous navigation in existence

Degree of Autonomy	Sensor	Measurement
Autonomous	Horizon Sensor	Angles to Earth
Autonomous	Stellar Refraction	Angles to Earth
Autonomous	Magnetometer	Angles along Magnetic Field
Semi-Autonomous	Forward Link Doppler	Saclar to Ground Station
Semi-Autonomous	DIODE	Scalar to Ground Network
Semi-Autonomous	GPS Receiver	Spacecraft Position
Autonomous	Landmark Tracker	Angle to Known/Unknown Landmark
Autonomous	Space Sextant	Scalar to Moon
Autonomous	Sun Doppler	Angles to Sun
Autonomous	X-ray Pulsar Navigation	Scalar to Pulsar
Autonomous	Sun Sensor	Angles to Sun
Autonomous	Star Tracker	Angles to Star
Autonomous	Optical navigation	Angle to any Object

Unusable	Plausible	Useable

Constraints

1. Solution will be low Size Weight and Power (SWaP) and will be able to fit on a cubesat form factor
2. A star tracker will be used on the spacecraft, limit 7.5 magnitude
3. The spacecraft is solar powered
4. The spacecraft is located in deep space between 1 AU and 5 AU
5. The spacecraft is within ± 5° of the ecliptic

Solution - Find Jupiter

- Why?
  - Jupiter offers multiple targets by finding one object
  - Periods of Galilean Moons offer higher fidelity.
  - Jupiter is a bright object in the sky
  - Inner planets are harder to locate

- Time, Position, and Velocity?
  - Just position and velocity gives relative, not absolute
  - Communication schedules would be based on time

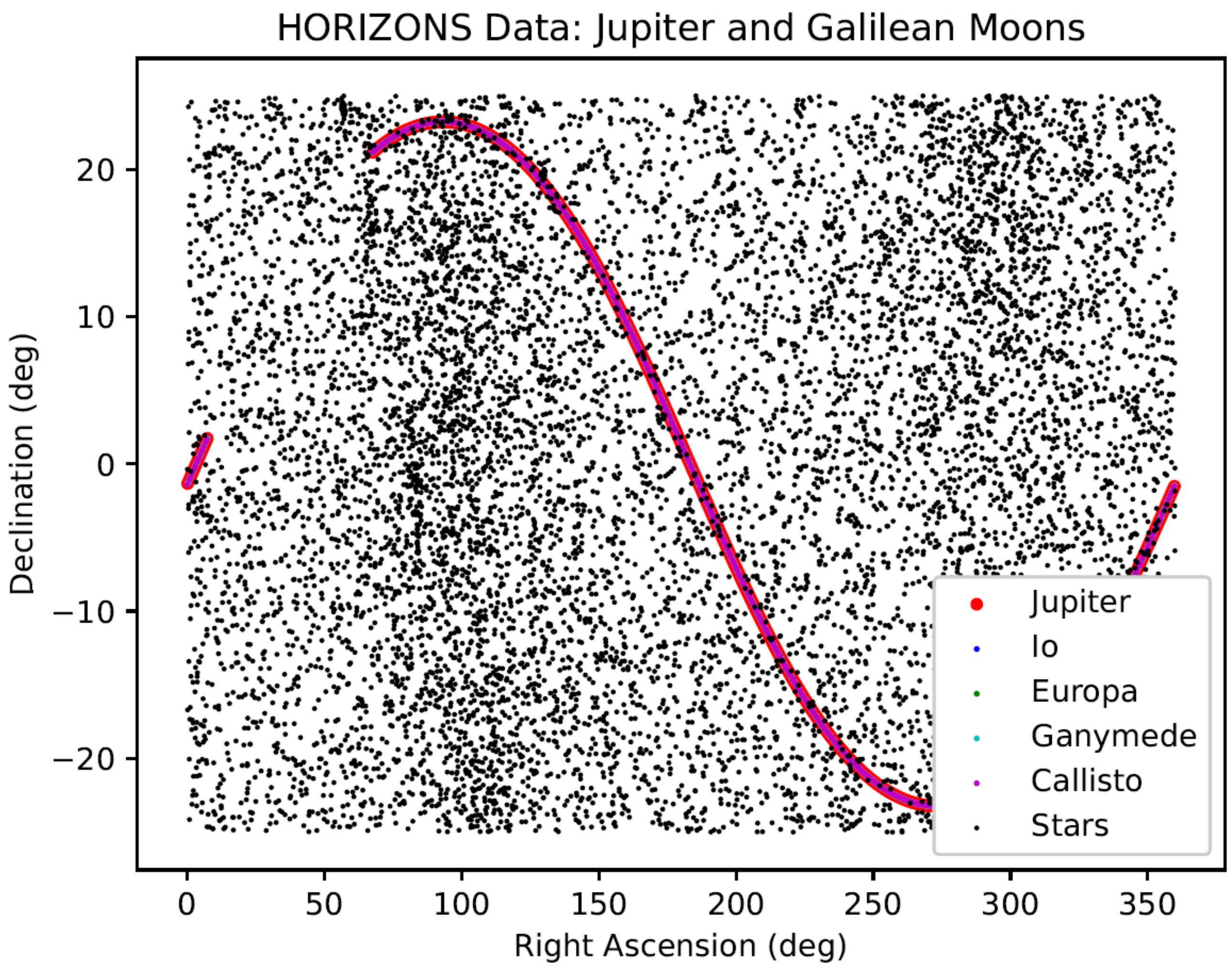
Lost-In-Space Concept of Operations

1. Determine attitude (star tracker)
2. Locate sun-line direction (fine sun sensor)
3. Obtain min/max distance from Sun
4. Estimate spacecraft distance from Jupiter
5. Compute search/scan angle to find Jupiter
6. Scan with star tracker, then image process
7. Detect Jupiter and estimate location
8. Stare at the Jovian system
9. Estimate Time, Position, and Velocity

Current Time Solution

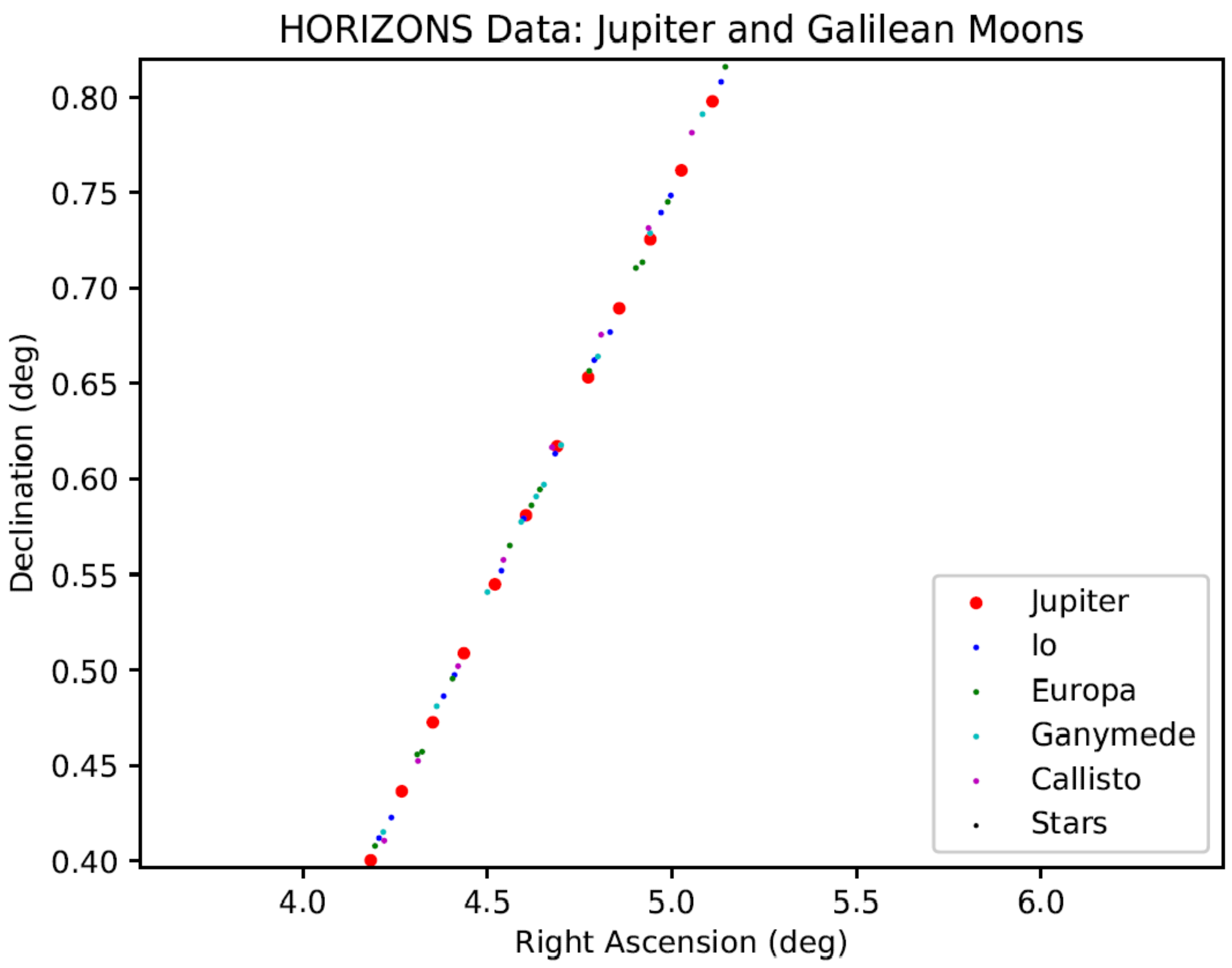
- HORIZONS Database used as Ephemeris
  - NASA JPL
- Located at Solar System Center
  - Non-Moving Satellite
- Jupiter Only
  - Nearest Neighbor Search
- Closest two used for higher fidelity search

- 5 day time step plotted



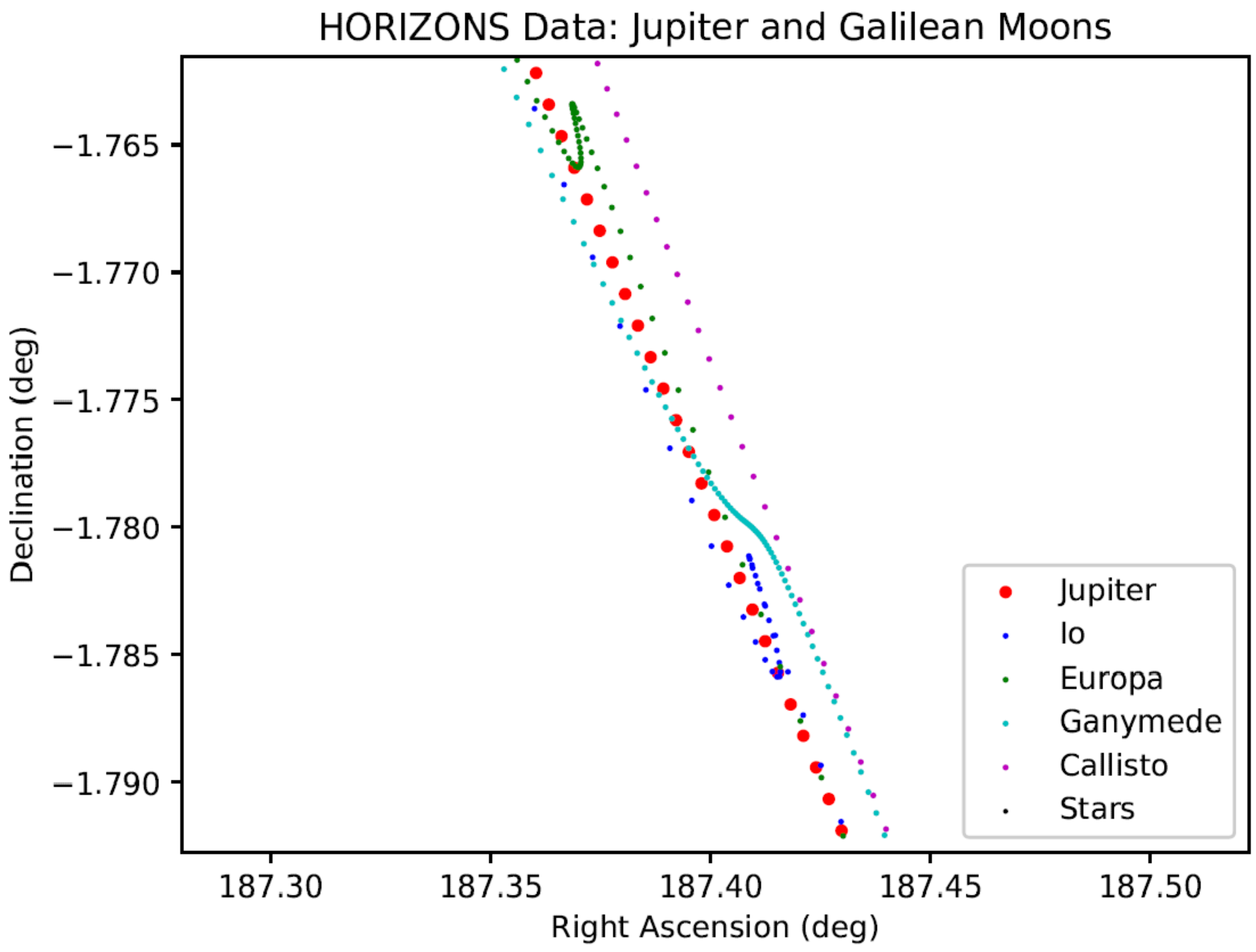
Best Ephemeris Time Solution

- 1 day time step plotted
- Closest two points taken to move to higher fidelity



Best Ephemeris Time Solution

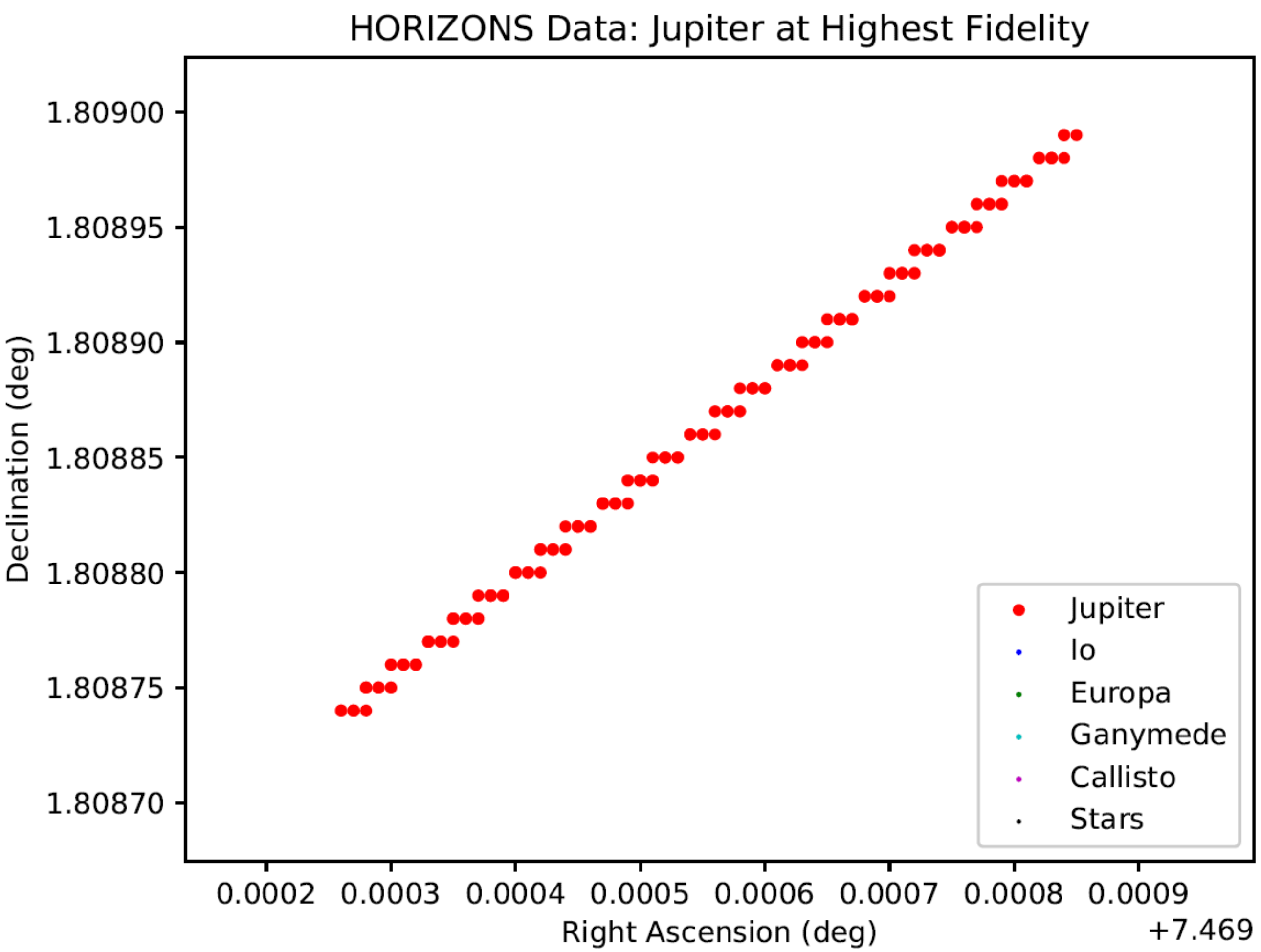
- 1 hour time step plotted
- Closest two points taken to move to higher fidelity



Best Ephemeris Time Solution

- Highest fidelity from astroquery python module.
  - 5 decimal places in RA/DEC

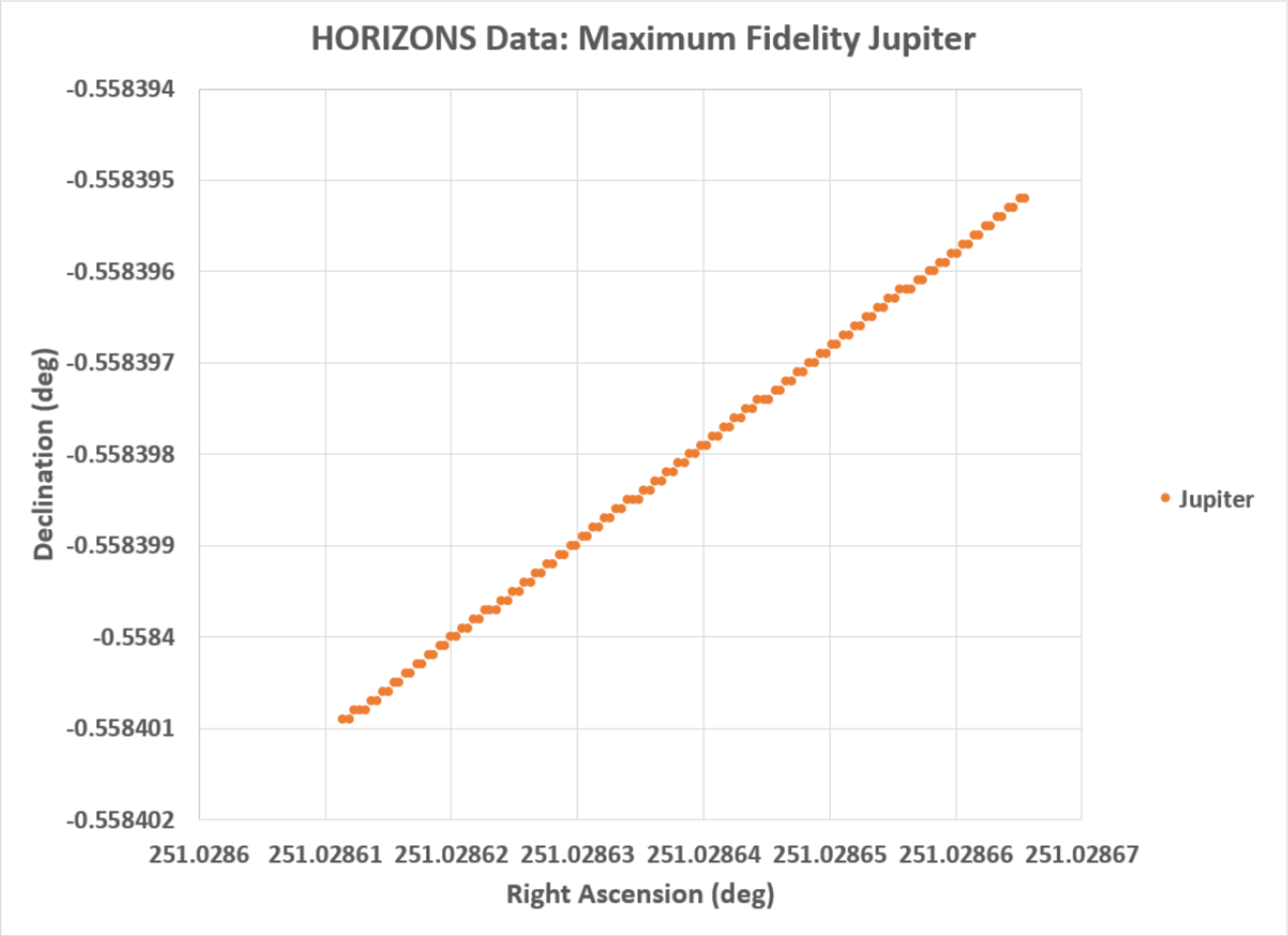
Corresponds to highest fidelity of 24 seconds.



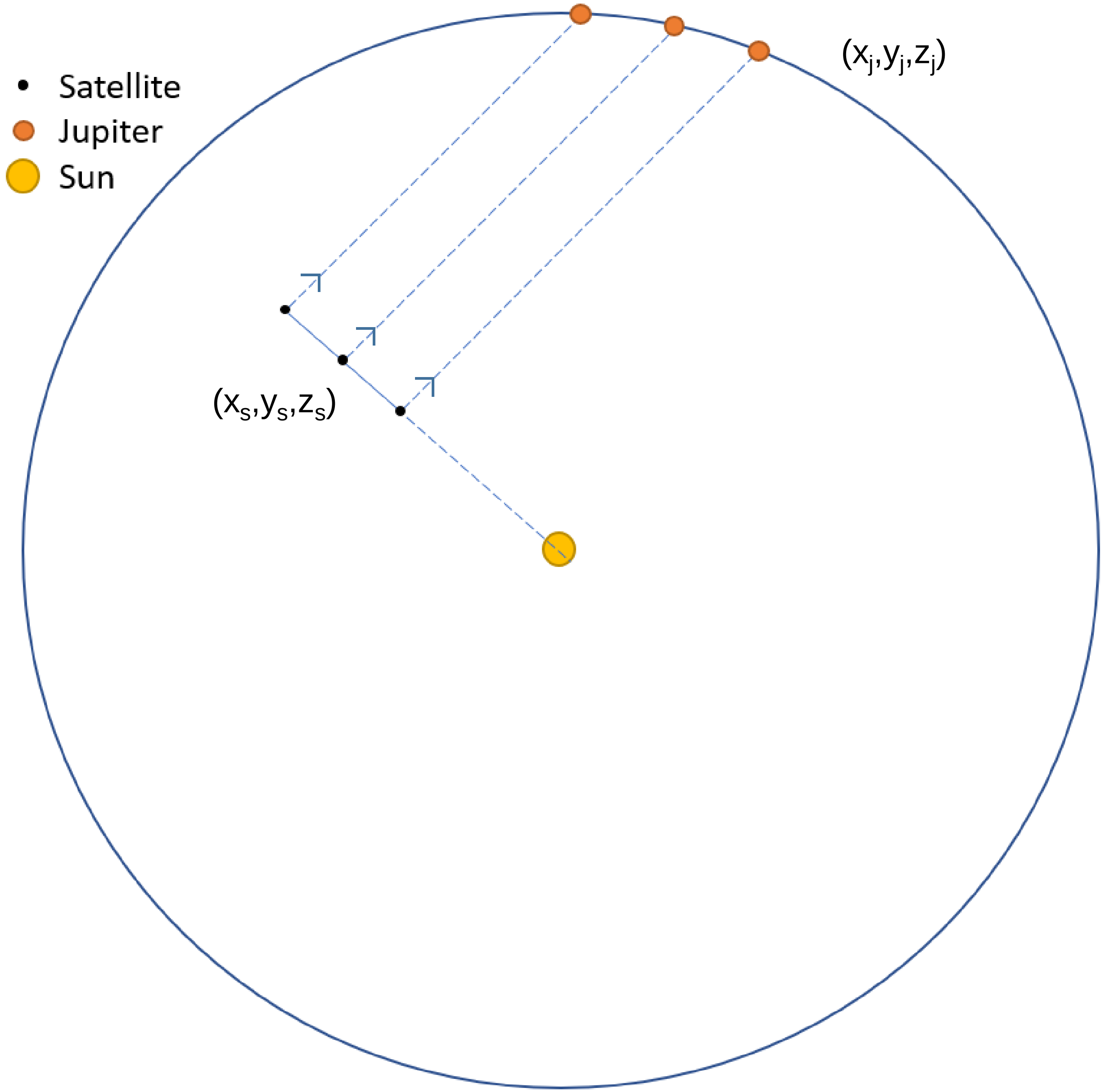
Best Ephemeris Time Solution

- Highest fidelity from HORIZONS database
  - 7 decimal places in RA/DEC

Corresponds to highest fidelity of 500 milliseconds.



Stationary Time Solution



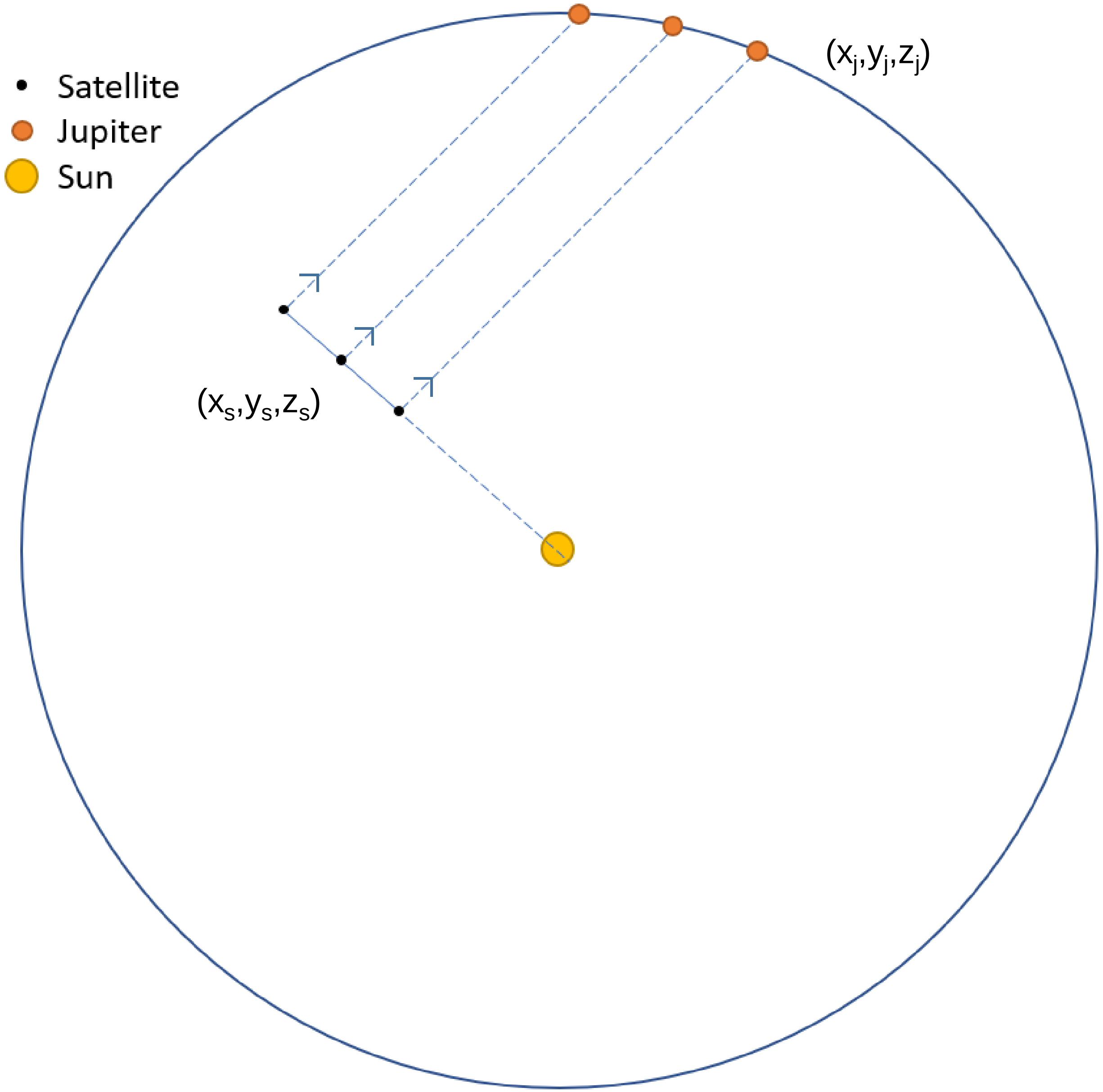
Once initial satellite position is calculated

1. Calculated satellite position difference from ephemeris truth data, (vector direction)
2. Compare to vector star tracker data (vector direction)
3. Match closest to get time
   a. Nearest Neighbor
4. Upper and Lower bound based on irradiance

Advanced Time Solution

Stationary Solution for Time

	.1% Error	1% Error	5% Error	10% Error
1 AU	1.5 hours	16 hours	74 hours	6 days
2 AU	3 hours	30 hours	6 days	11.4 days
3 AU	4.5 hours	42 hours	8.6 days	16.5 days
4 AU	5.5 hours	54 hours	11 days	21.2 days



Multi-Mission Optical Navigation Program (ONP)

- ONP
  - Used for Optical Navigation since Mariner 9
  - Developed by NASA JPL
    - Maintained by the Optical Navigation Group

- Three Main Programs
  - Trajectory Geometry Program (TGP) - Picture prediction tool
  - Optical Observables and Partials Generator (OOPG) - analyzes observations before the filtering process
  - Optical Data Analysis Program (ODAP) - Filtering tool

Algorithm Approach

- Batch Estimation
  - Initial time, position, and velocity.

State	Observations	Dynamics
Time	Jupiter Position	Spacecraft Attitude
Position	Jupiter Velocity	Spacecraft Velocity
Velocity	Io Position	
	Io Velocity	
	Europa Position	
	Europa Velocity	
	Ganymede Position	
	Ganymede Velocity	
	Callisto Position	
	Callisto Velocity	
	Star Tracker Vector	
	Sun Vector	

- Last saved state <24 Hours
- Start with perfect position and velocity knowledge and see how good we can resolve time.

$$a\ priori = \begin{bmatrix} \rho_\odot \\ \emptyset_\odot \end{bmatrix}$$

$$\downarrow$$

$$X = \begin{bmatrix} \vec{r} \\ \dot{\vec{r}} \\ \Delta t \end{bmatrix}$$

$$G(X) = \begin{bmatrix} J_{\vec{r}} \\ \vec{b} \end{bmatrix}$$

$\vec{r} = Position\ Vector$

$\dot{\vec{r}} = Velocity\ Vector$

$\Delta t = Time\ Difference$

$J_{\vec{r}} = Jupiter\ Position$

$\vec{b} = Star\ Tracker\ Quaternion$

$\rho_\odot = Sun\ Distance$

$\emptyset_\odot = Satellite - Sun\ angle$

Questions?

Sources

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