The First Solution to the Lost in Space Problem

SmallSat 2020

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MarCO

Launched May 5, 2018

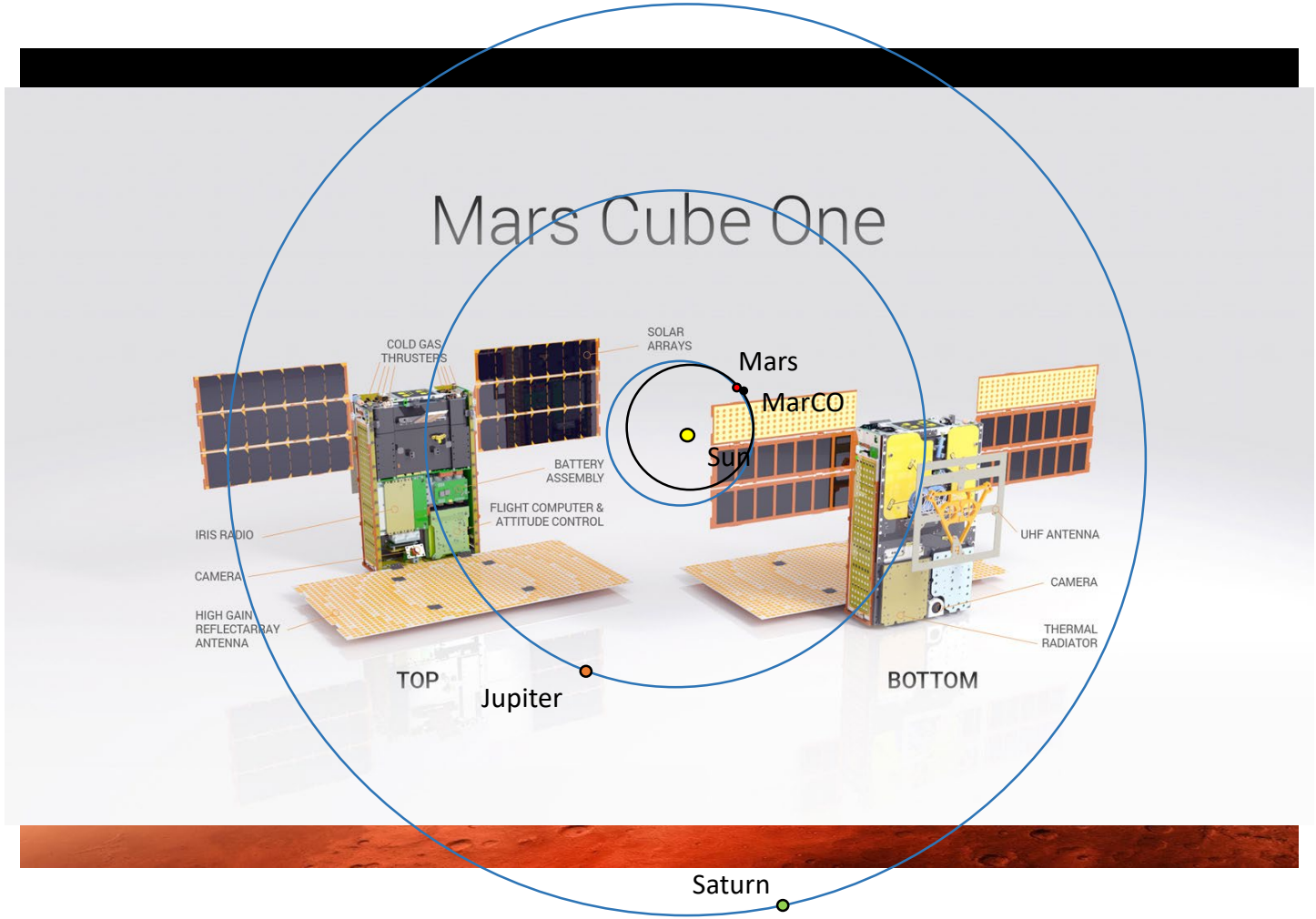
InSight Mission Relay

6U CubeSats

Lost
- December 29th 2018
- January 4th 2019

- Research aims to solve this problem

- Develop Architecture
  - Reduce risk
  - Reduce cost
  - Advance time to recovery
  - Enable small spacecraft



NASA MARCO CubeSat. Credit: NASA JPL

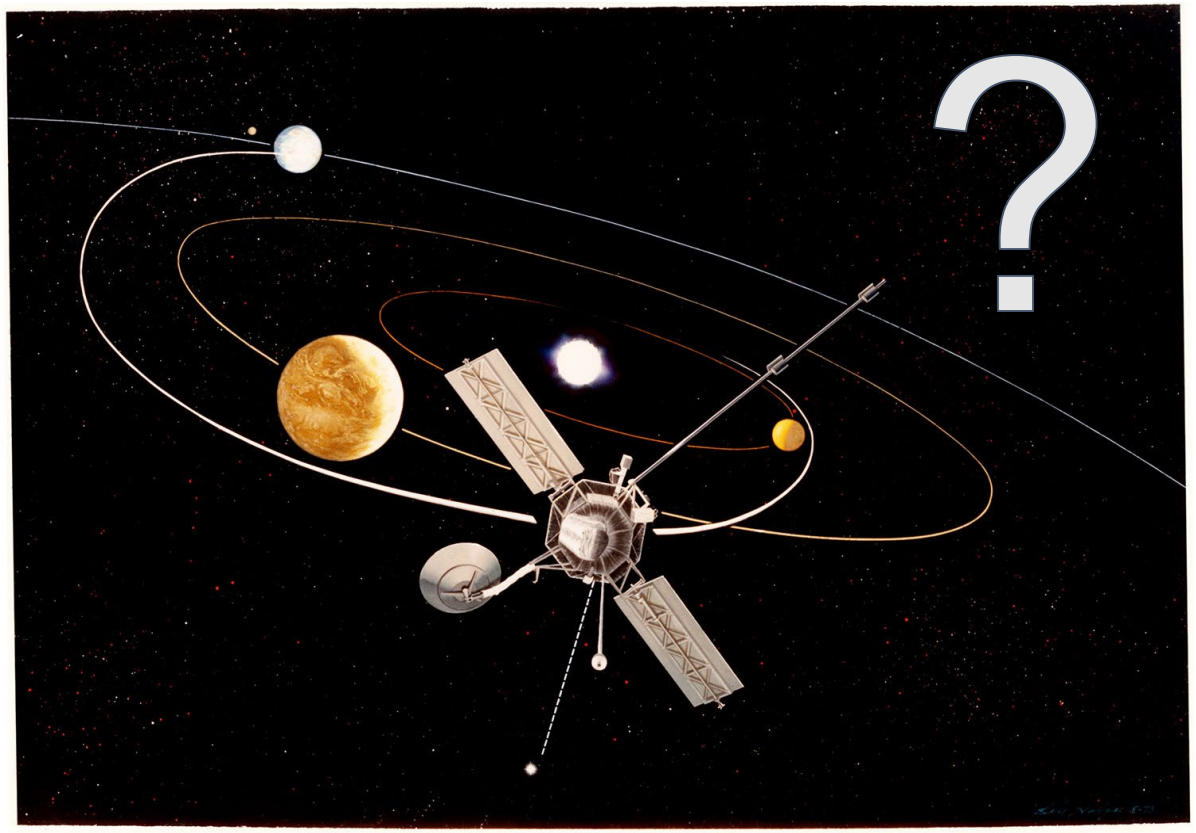
Lost in Space

- 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.
- Need Time, Position and Velocity (PVT)

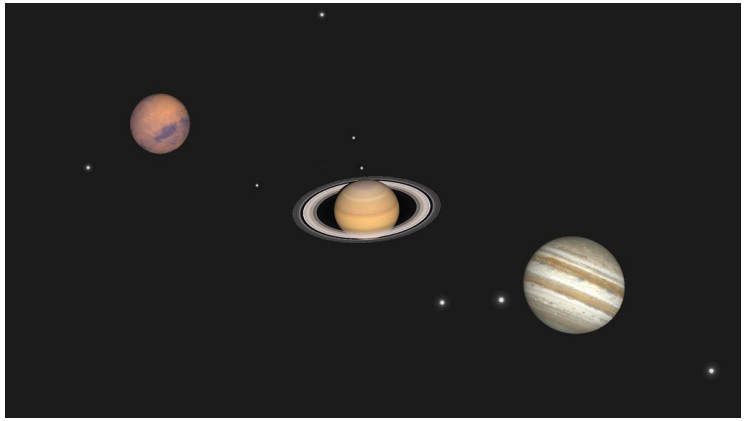
Lost in Space Problem

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



Solution

- Find Planets and Jovian Moons
  - Multiple targets increase the data available to create a solution.
  - When within 1-10 AU of Jupiter, Galilean moons can be used.



- Time, Position, and Velocity?
  - Just position and velocity gives relative, not absolute

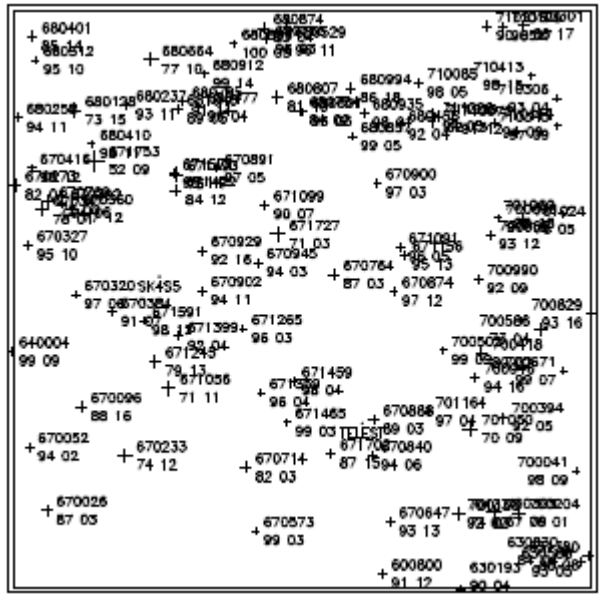
Lost-In-Space Concept of Operations Total Loss

1. Determine attitude (star tracker)
2. Locate sun-line direction (fine sun sensor)
3. Estimate distance from Sun
4. Find planetary objects
5. Scan with star tracker, then image process
6. Detect objects and estimate location from ephemeris
7. Image planetary systems
8. Initial estimate of Time, Position, and Velocity
9. Iterate
10. Detect and estimate the location of the Jovian moons
11. Final estimate of Time, Position, and Velocity

Multi-Mission Optical Navigation Program (ONP)

ONP

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

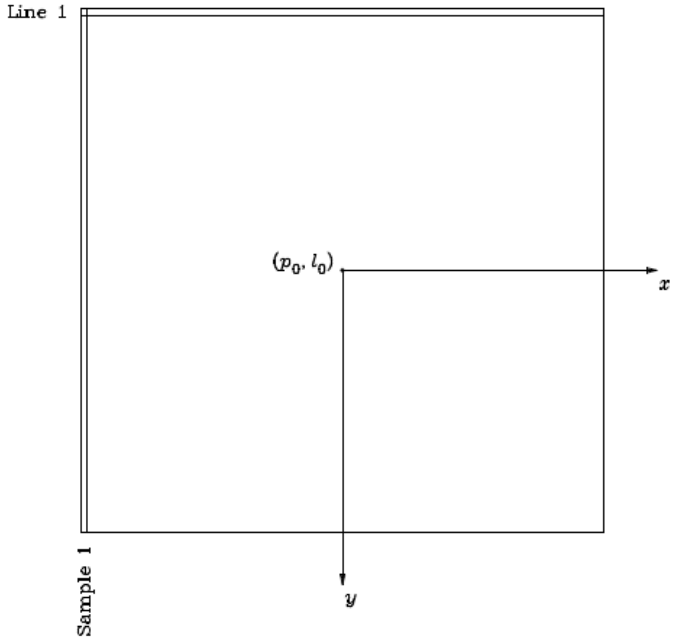


Three Main Programs

- 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

$$\begin{pmatrix} p \\ l \end{pmatrix} = \boldsymbol{K} \frac{f}{\rho_{t3}} \begin{pmatrix} \rho'_{t1} \\ \rho'_{t2} \end{pmatrix}$$



$$p_t\ l_t = Image\ Observable\ (Sample\ (pixel), Line)$$

$$f = focal\ length$$

$$K = K\ Matrix\ averaged\ to\ a\ single\ constant$$

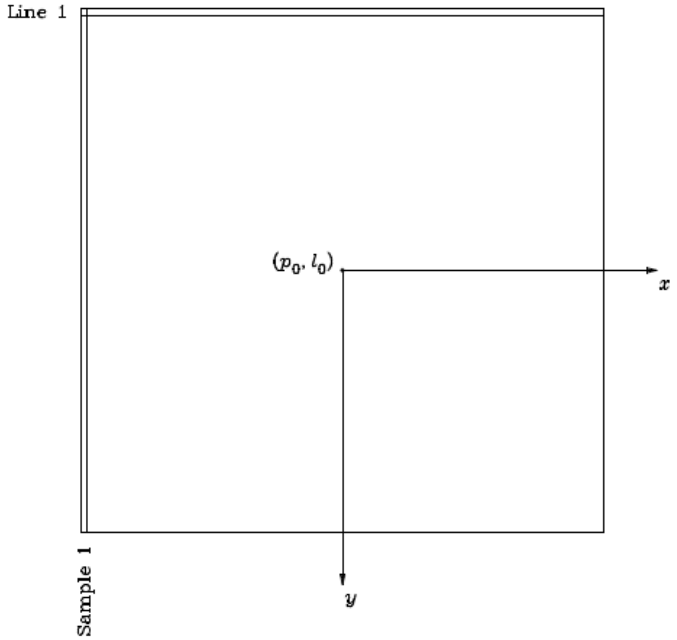
$$The\ K\ Matrix\ describes\ the\ physical\ layout\ of\ the\ pixels\ within\ the\ focal\ plane$$

$$\rho'_{t1}\ \rho'_{t2}\ \rho_{t3} = vector\ components\ of\ position\ difference\ between$$

$$planetary\ target\ and\ spacecraft$$

Algorithm Approach

$$\begin{pmatrix} \dot{p}_t \\ \dot{l}_t \end{pmatrix} = \boldsymbol{K}\left(\frac{f}{\rho_{t3}} \begin{pmatrix} \dot{\rho}'_{t1} \\ \dot{\rho}'_{t2} \end{pmatrix} - \frac{f}{\rho_{t3}^2} \begin{pmatrix} \rho'_{t1} \\ \rho'_{t2} \end{pmatrix} \dot{\rho_{t3}} \right)$$



$\dot{p}_t \;\; \dot{l}_t = Image\ Observable\ Derivative\ (Sample\ (pixel), Line)$

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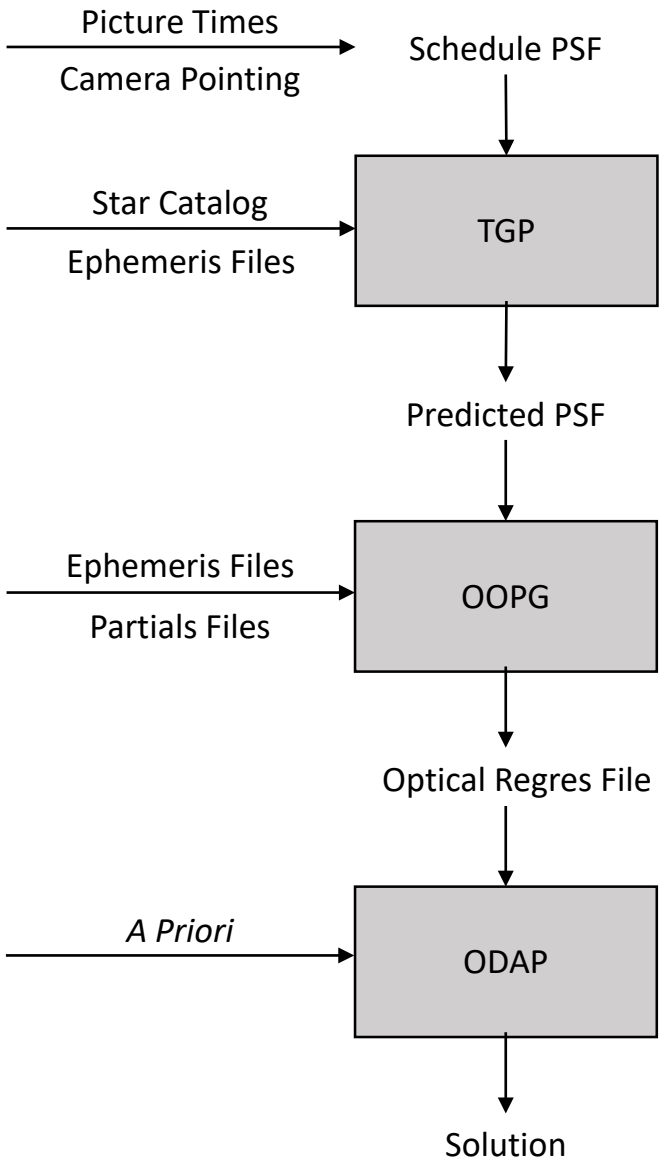
$The\ K\ Matrix\ describes\ the\ physical\ layout\ of\ the\ pixels\ within\ the\ focal\ plane$

$\dot{\rho}'_{t1} \;\; \dot{\rho}'_{t2} \;\; \dot{\rho}_{t3} = vector\ components\ of\ position\ differecnce\ time\ derivative\ between\ planetary\ target\ and\ spacecraft$

Software Functional Flow

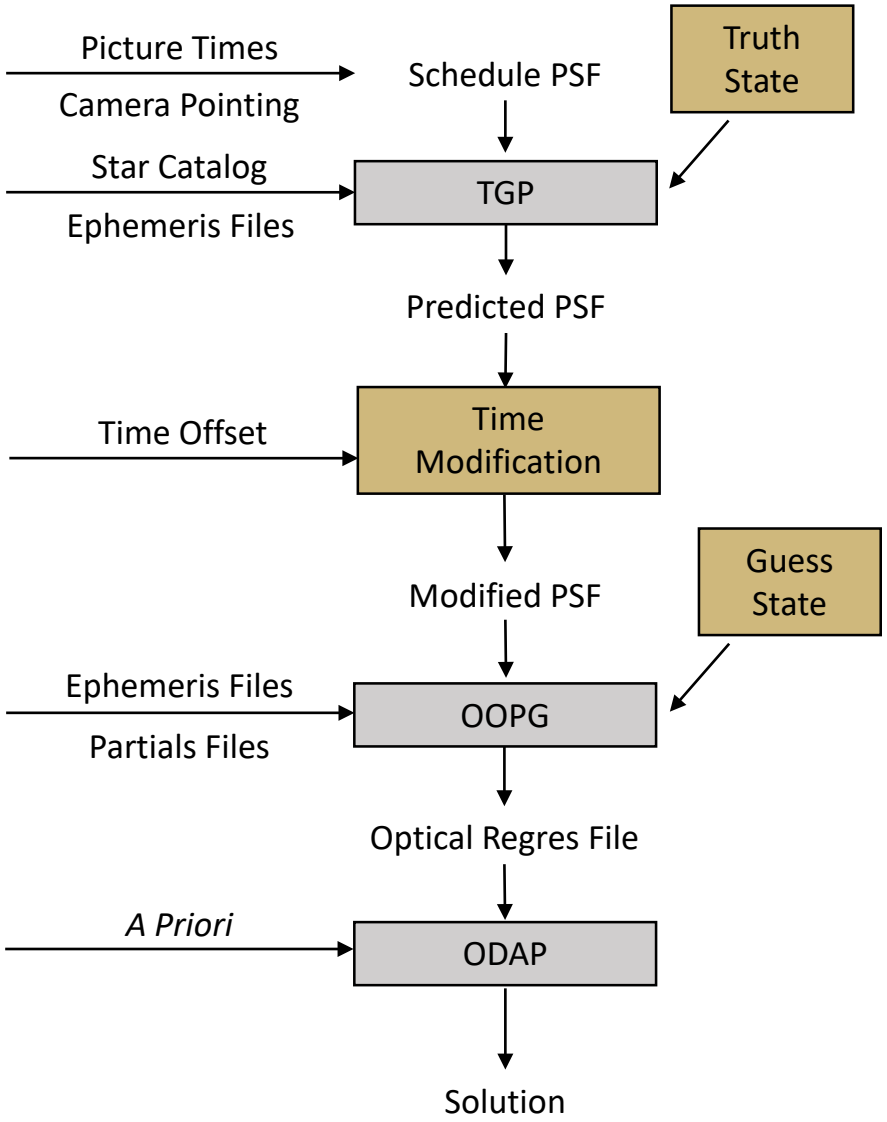


PSF - Picture Sequence File

Trajectory Geometry Program (TGP) - Picture prediction tool

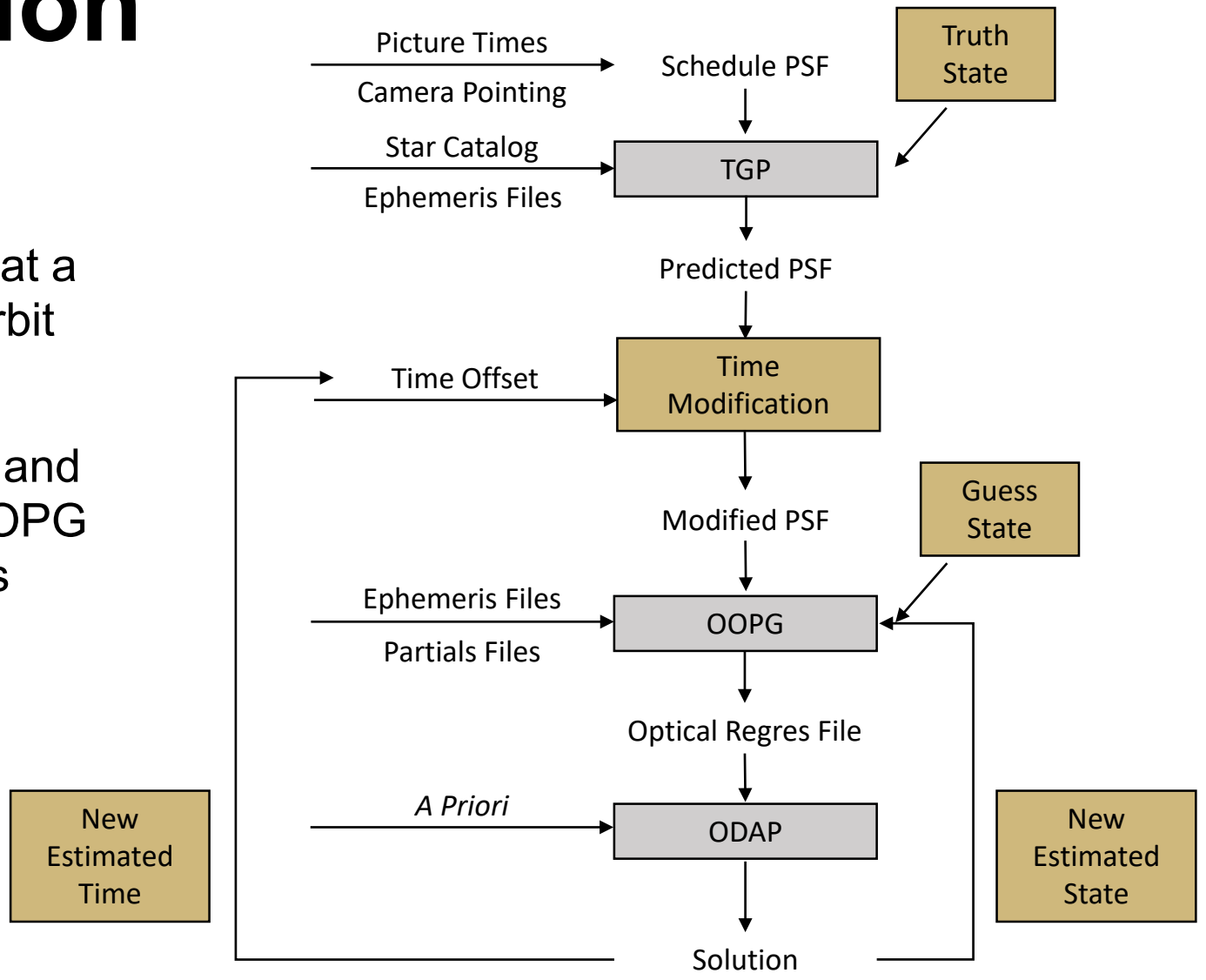
Optical Observables and Partials Generator (OOPG) - analyzes observations before the filtering process

Optical Data Analysis Program (ODAP) - Filtering tool



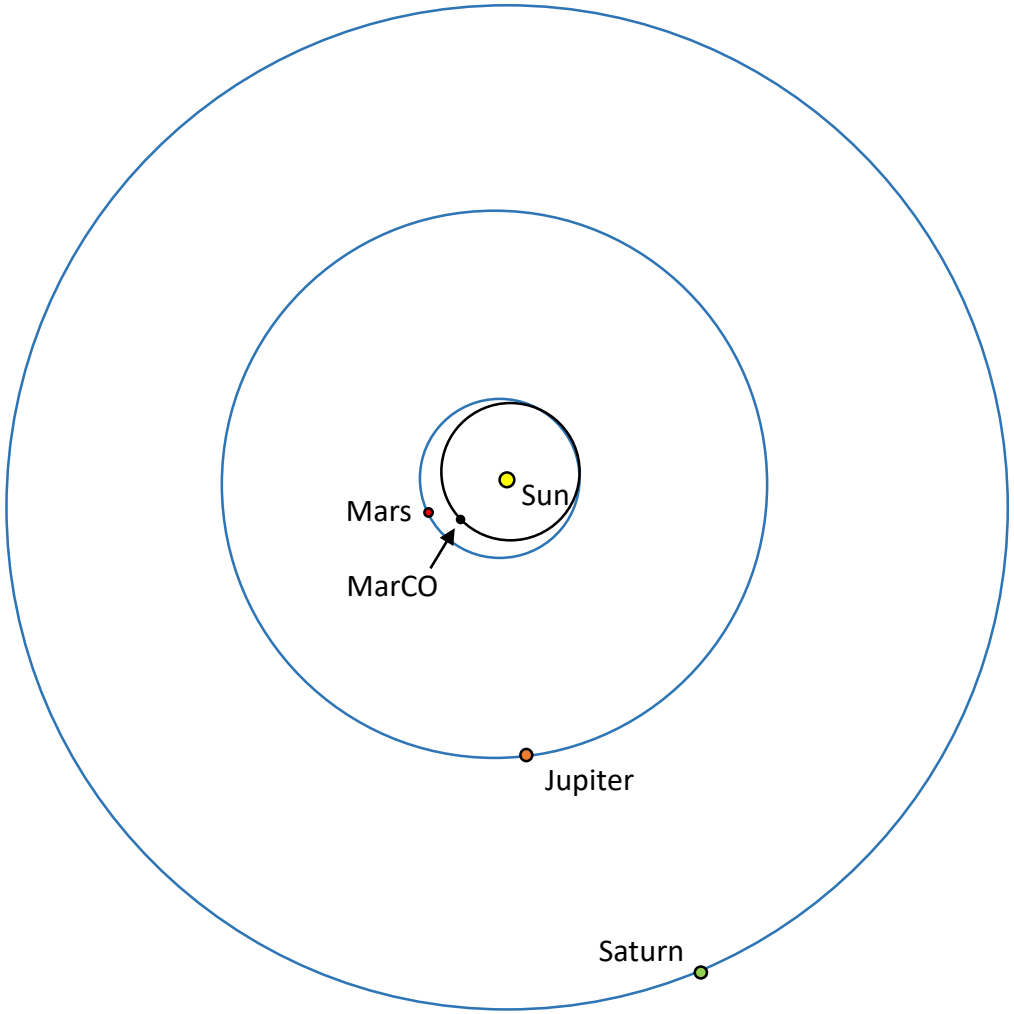
Results – Iteration

- Created a realistic scenario for what a spacecraft would experience on orbit
- Program written to take first t_{error} and re-modify PSF and run through OOPG and ODAP again and continue this process.



Results – Position and Velocity Solution

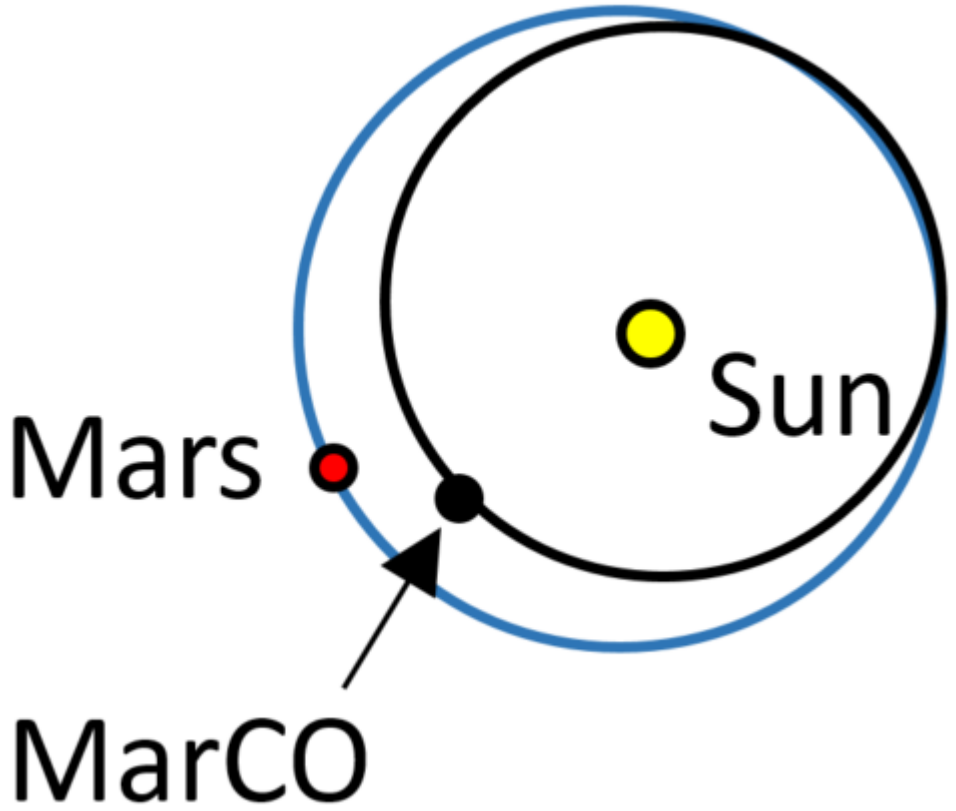
- Known trajectory from last known state
  - Along-Track Position and Velocity
  - Time solution = Position and Velocity Solution



December 6th 2019

Results – Position and Velocity Solution

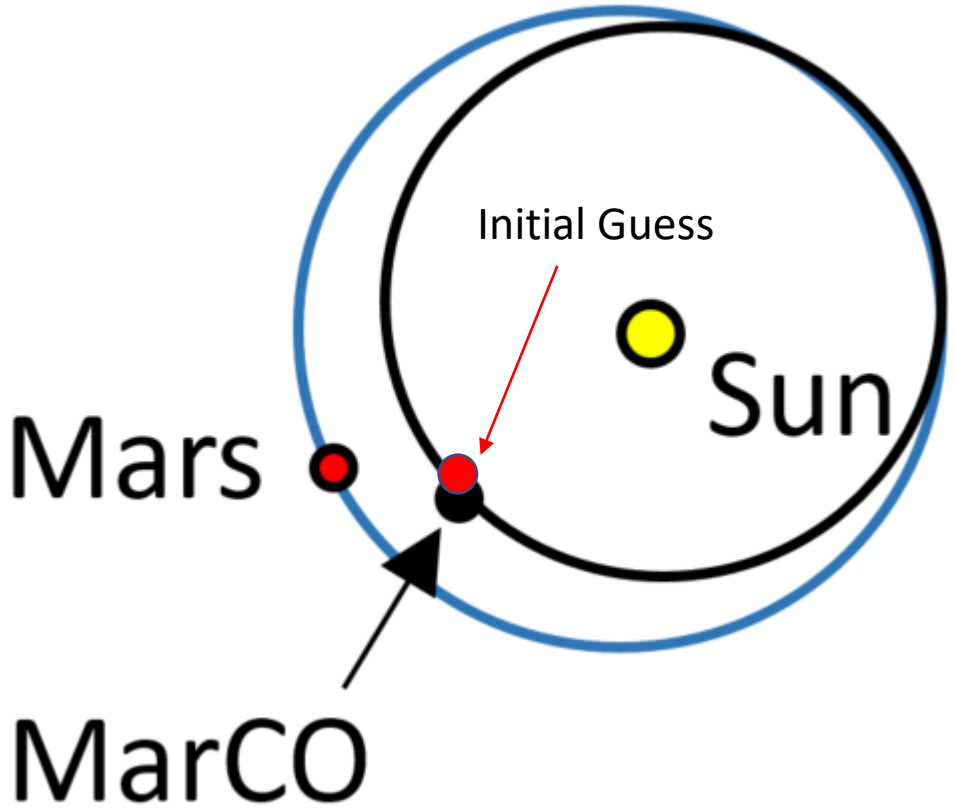
- Unknown previous state
  - Full Lost-In-Space Solution
- Obtain Initial Guess
  - Irradiance from Sun
    - Truth = 587 W/m^2
    - Guess = 603 W/m^2
  - Angles using Sun Sensors and Star Tracker
    - 1 Degrees off (Unrealistic)
  - Calculate New Position Vector
  - Time 1 week off
  - Simulated noise and 1/2 pixel error for realistic simulation.



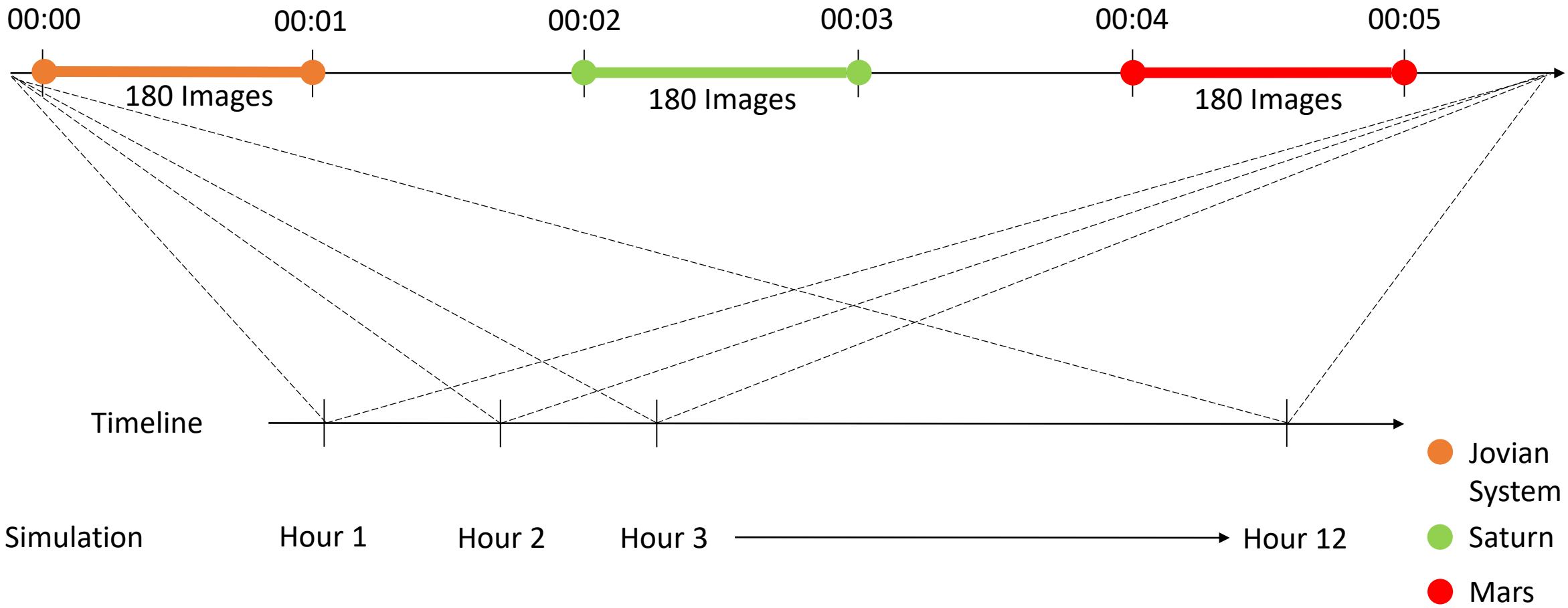
Results – Position and Velocity Solution

	TRUTH	INITIAL GUESS	
X	-1.428E+08	-1.406E+08	km
Y	-1.010E+08	-9.942E+08	km
Z	-4.195E+07	-4.130E+08	km
DX	20.18	0.00	km/s
DY	-18.47	0.00	km/s
DZ	-8.77	0.00	km/s
Time	Dec 06 2019	Nov 30 2019	

- 6 Batch Iterations Run
  - Galilean Moons Ganymede and Calisto added to filter on 5th iteration



Results – Simulation Setup



Results

- Dec 2019 Sim
- First runs using only planetary bodies
- Once sufficient threshold was met the Galilean moons were added.
  - Convergence was determined when time was less then uncertainty.
- Final t_{error} was <60 seconds when moons were added.

Iteration		1	2	3
Time Correction (s)		443835.57	-11287.45	77.84
Position (km)	X	-1.42691954970E+08	-1.4259926980E+08	-1.42814450180E+08
	Y	-1.0089876485E+08	-1.0122612274E+08	-1.0098396867E+08
	Z	-4.1912300973E+07	-4.2067210808E+07	-4.1953464246E+07
Velocity (km/s)	X	19.04786958	20.24033034	20.2043857
	Y	-21.42520649	-18.45377869	-18.47655598
	Z	-10.06617306	-8.73733542	-8.746710935

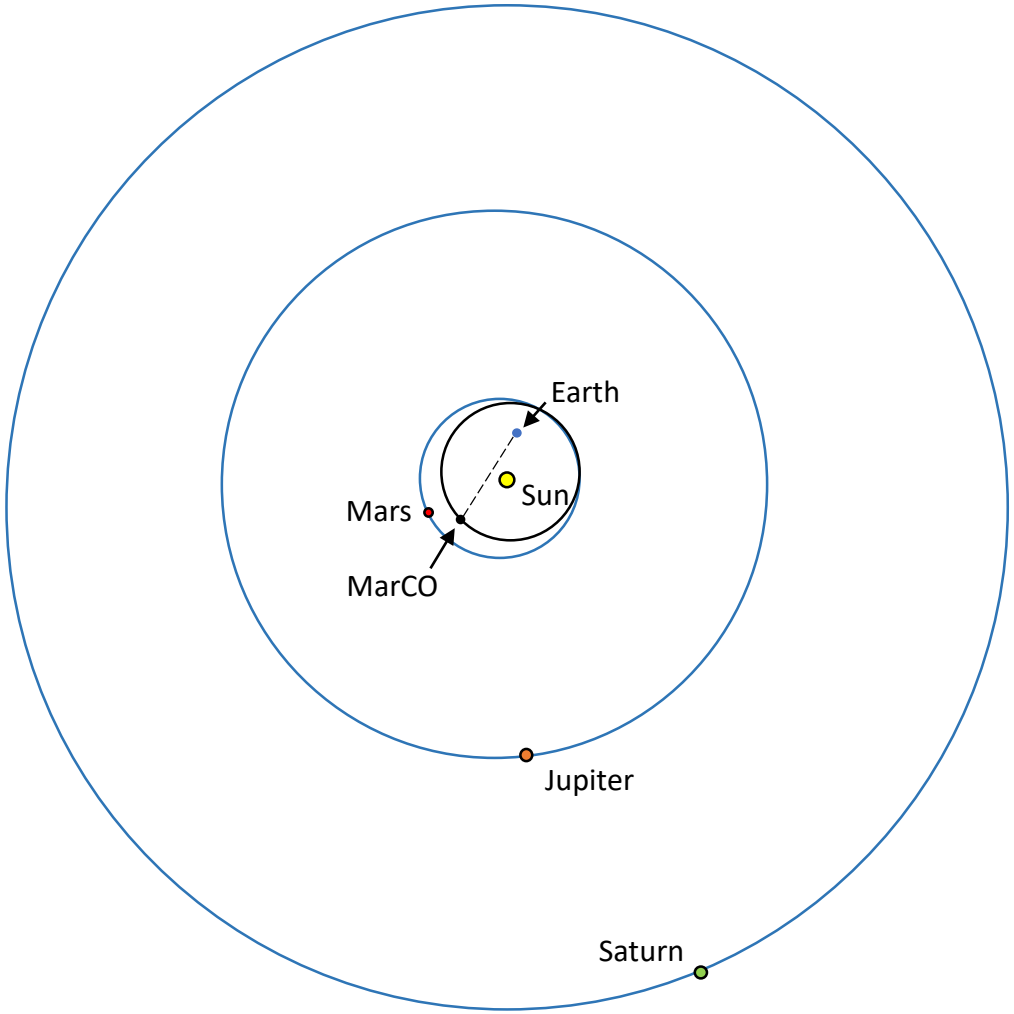
Iteration		4	5*	6
Time Correction (s)		77.87	-638.85	2.14
Position (km)	X	-1.42814467380E+08	-1.42815960850E+08	-1.42824513720E+08
	Y	-1.0098396016E+08	-1.0098172554E+08	-1.0097393611E+08
	Z	-4.1953465632E+07	-4.1952293459E+07	-4.1948605638E+07
Velocity (km/s)	X	20.20438576	20.20711006	20.20609717
	Y	-18.47655589	-18.47631556	-18.47736586
	Z	-8.746710944	-8.746662313	-8.747109303

*Galilean Moons Added

MarCO

	Truth State	Initial State	Final State	
X	-1.42823825380E+08	-1.42824513770E+08		km
Y	-1.00973667000E+08	-1.00973799738E+08		km
Z	-4.19482277781E+07	-4.19487058420E+07		km
DX	2.01854530013E+01	2.01854970720E+01		km/s
DY	-1.84723319180E+01	-1.84723688870E+01		km/s
DZ	-8.74699330982E+00	-8.74701090260E+00		km/s
Time	Dec 06 2019 00:00:00.00	Dec 06 2019 00:00:10.75		

Difference		Final Uncertainty	
688.33970	km	977.10	km
269.10965	km	280.87	km
377.85990	km	196.33	km
-20.64	m/s	7.85	m/s
5.03	m/s	2.17	m/s
0.12	m/s	1.58	m/s
10.75	s	59.26	s



December 6th 2019

Summary

- Lost-in-Space - Time, Position, and Velocity has been solved.
- Within a short 12 hour picture sequence, time was obtained down to 11 seconds.
- Will be implemented on future NASA missions
- Because a smallsat framework was initially used, the solution is instantly applicable to larger spacecraft.