REBOUND 2024: xGEO Numerical Integrator Analysis and Maneuver Detection

Benjamin L. Hanson
Ph.D. Student, Jacobs School of Engineering
Department of Mechanical and Aerospace Engineering
UC San Diego, La Jolla, CA

Dr. Aaron J. Rosengren
Assistant Professor, Jacobs School of Engineering
Department of Mechanical and Aerospace Engineering
UC San Diego, La Jolla, CA

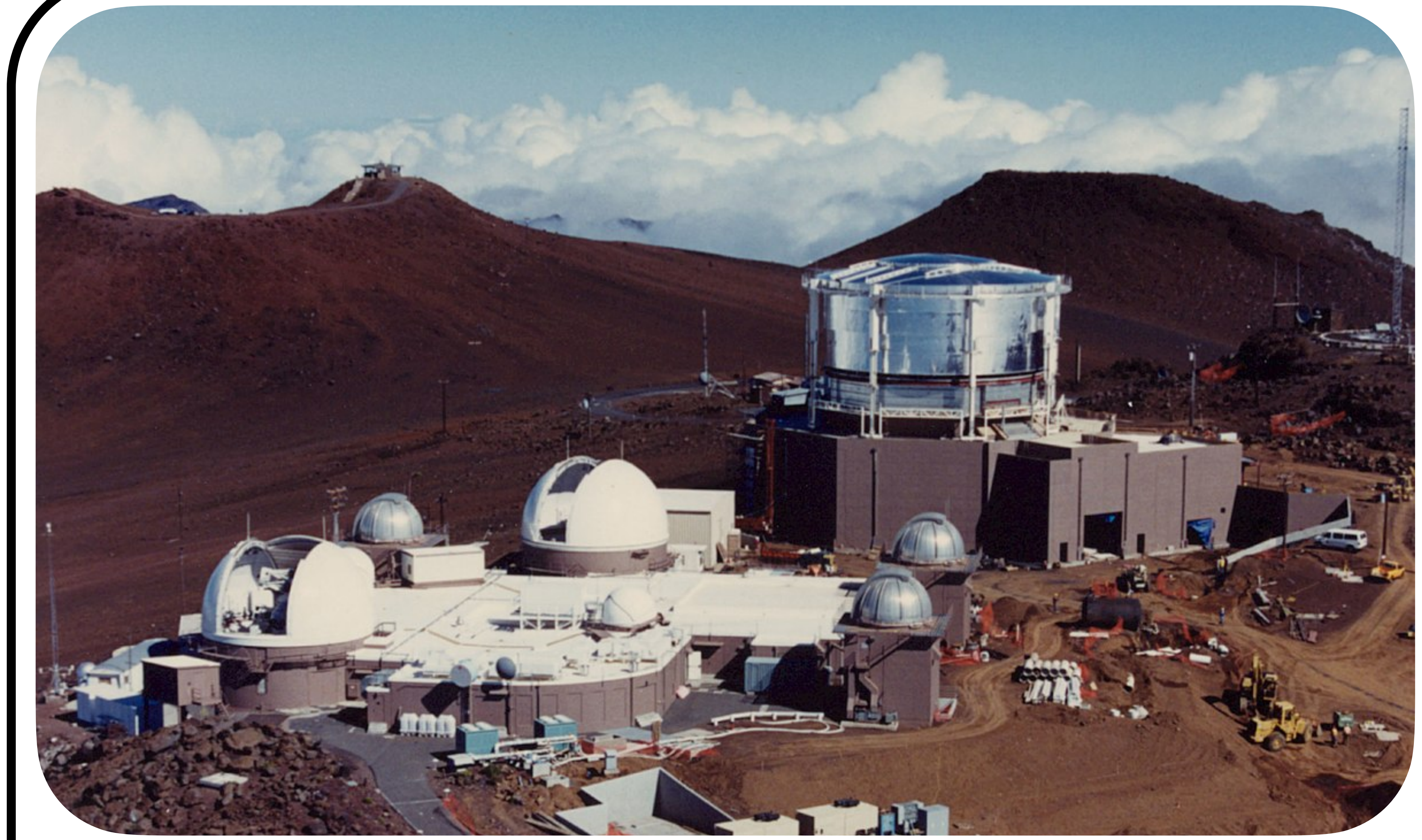
Capt. Zachary Funke
AMOS Research Engineer
15th Space Surveillance Squadron
USSF, Maui, HI

Motivation

Optical detection of suboptimal objects in suboptimal regimes

15th Space Surveillance Squadron (SPSS)

- Space domain awareness (SDA), space situational awareness (SSA), rendezvous proximity operations (RPOs), astronomy, spectroscopy, optimal trajectory control, near-Earth and **deep-space object detection**
- **Overarching objective:** Utilization of highly advanced tracking optics (including DoD's largest optical telescope) for tracking and imaging deep-space (possibly uncooperative) satellites



Mt. Haleakala, AEOS telescope (3.6 m aperture)

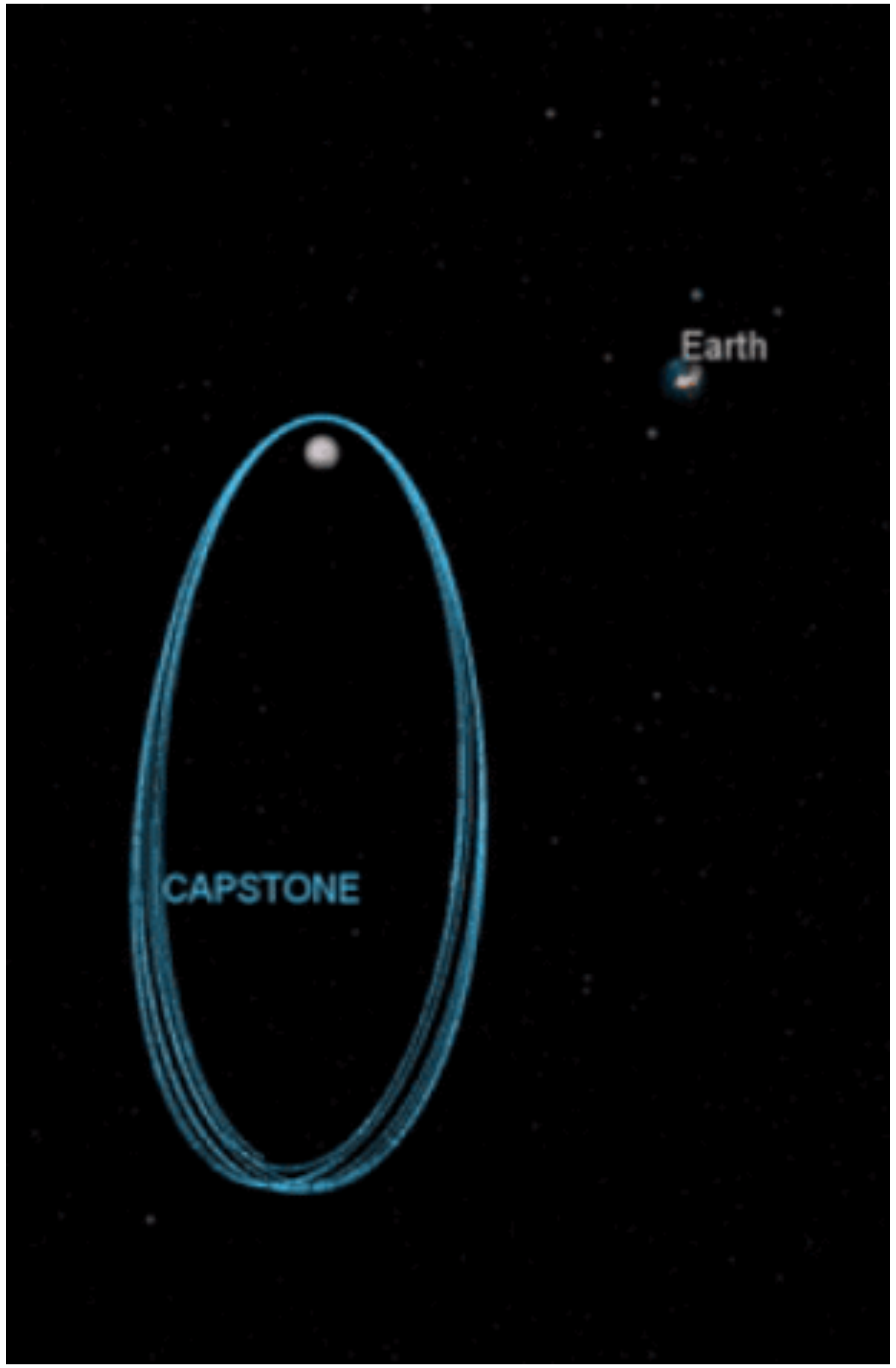
Suboptimal Objects

- Miniaturization of satellite technology (CubeSats) has increased the difficulty of tracking and imaging objects with smaller apparent magnitudes

Suboptimal Regimes

- xGEO objects are governed by dynamics that are less predictable than LEO or GEO objects
- Detection of lunar orbiters require telescopes to point closer to the Moon, decreasing signal-to-noise ratio and shortening viable observation periods

CAPSTONE



- 12U CubeSat traveling in a near-rectilinear halo orbit (NRHO) about the L_2 Earth-Moon libration point
- Launched 28 Jun. 2022, inserted into NRHO on 14 Nov. 2022
- Period of ~6.5 days, periselene altitude: ~1,500 km, aposelene altitude: ~70,000 km
- Operated by Advanced Space, ephermides available on JPL Horizons

Brute Force Pixel Stacking for Optical Detection of CAPSTONE

Brute Force Pixel Stacking for Optical Detection of CAPSTONE

Brute Force Pixel Stacking for Optical Detection of CAPSTONE

Fundamental Question: Are state-of-the-art numerical integrators accurate enough to be utilized by optical detection methods in the xGEO regime when the ephemeris is unavailable? If so, what is the limit of this accuracy with respect to the length of the propagation period?

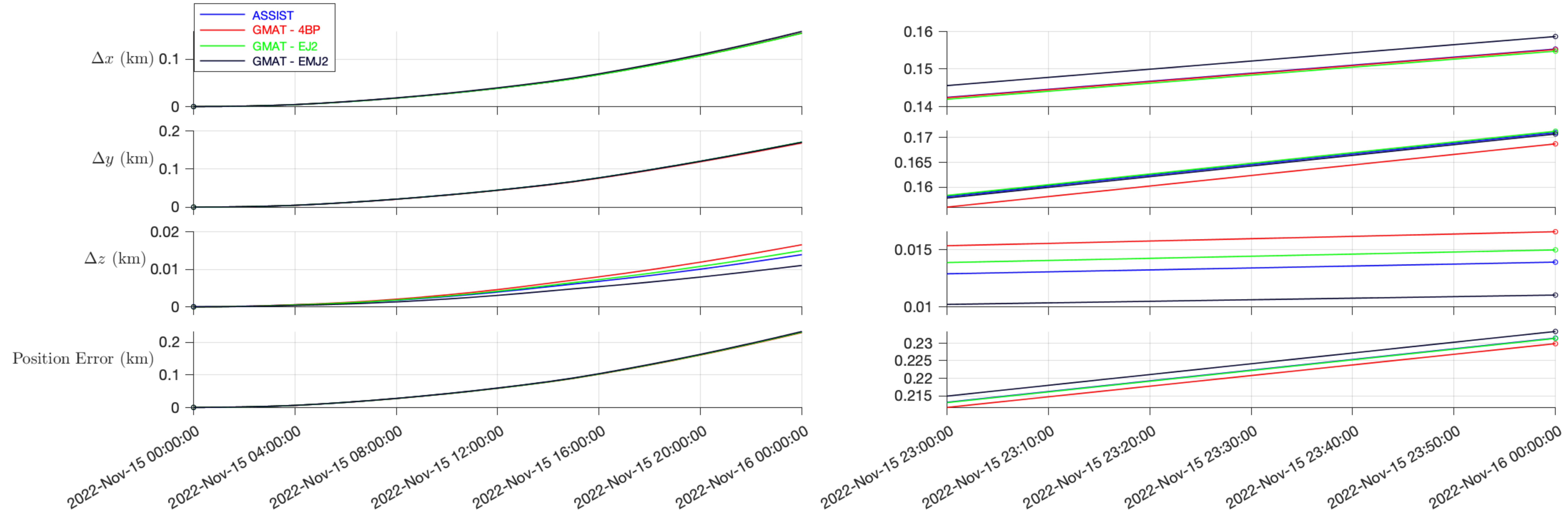
REBOUND 24

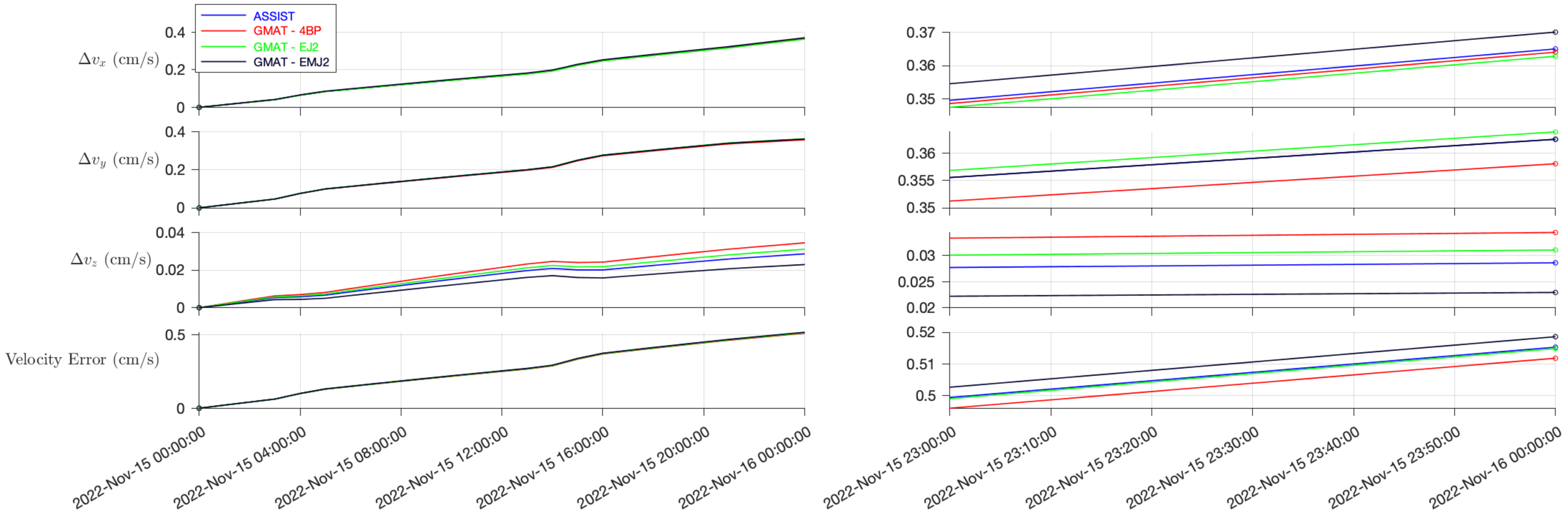
Numerical Integrator Analysis

Comparison of integration results to CAPSTONE ephemeris

Preliminary test: 24-hr propagation period

- Begin with initial conditions of CAPSTONE at an epoch (15 Nov 2022) provided by JPL Horizons
- Propagate using ASSIST/GMAT
  - ASSIST: Standard model
  - GMAT-4BP: Earth+Moon+Sun
  - GMAT-EJ2: All planets + Earth's J_2
  - GMAT-EMJ2: GMAT-EJ2 + Moon's J_2
- Compare propagated results with ephemeris at epochs





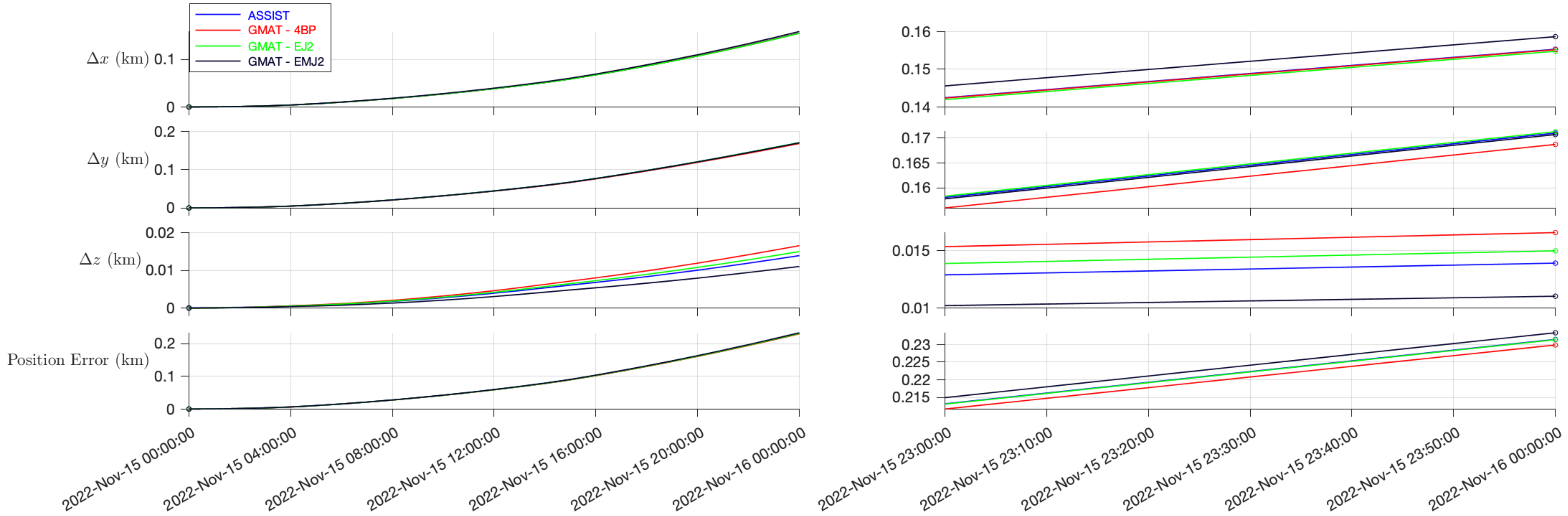
Numerical Integrator Analysis

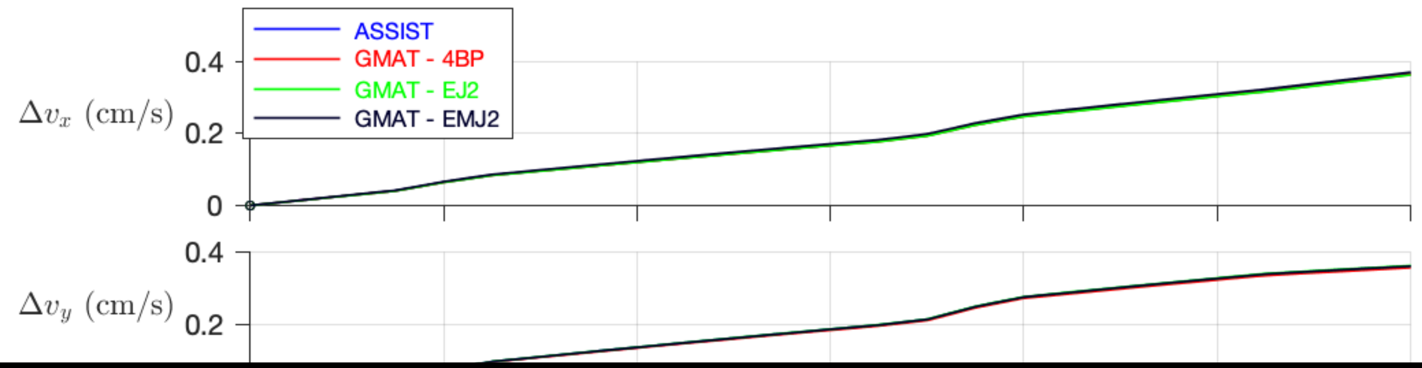
Comparison of integration results to CAPSTONE ephemeris

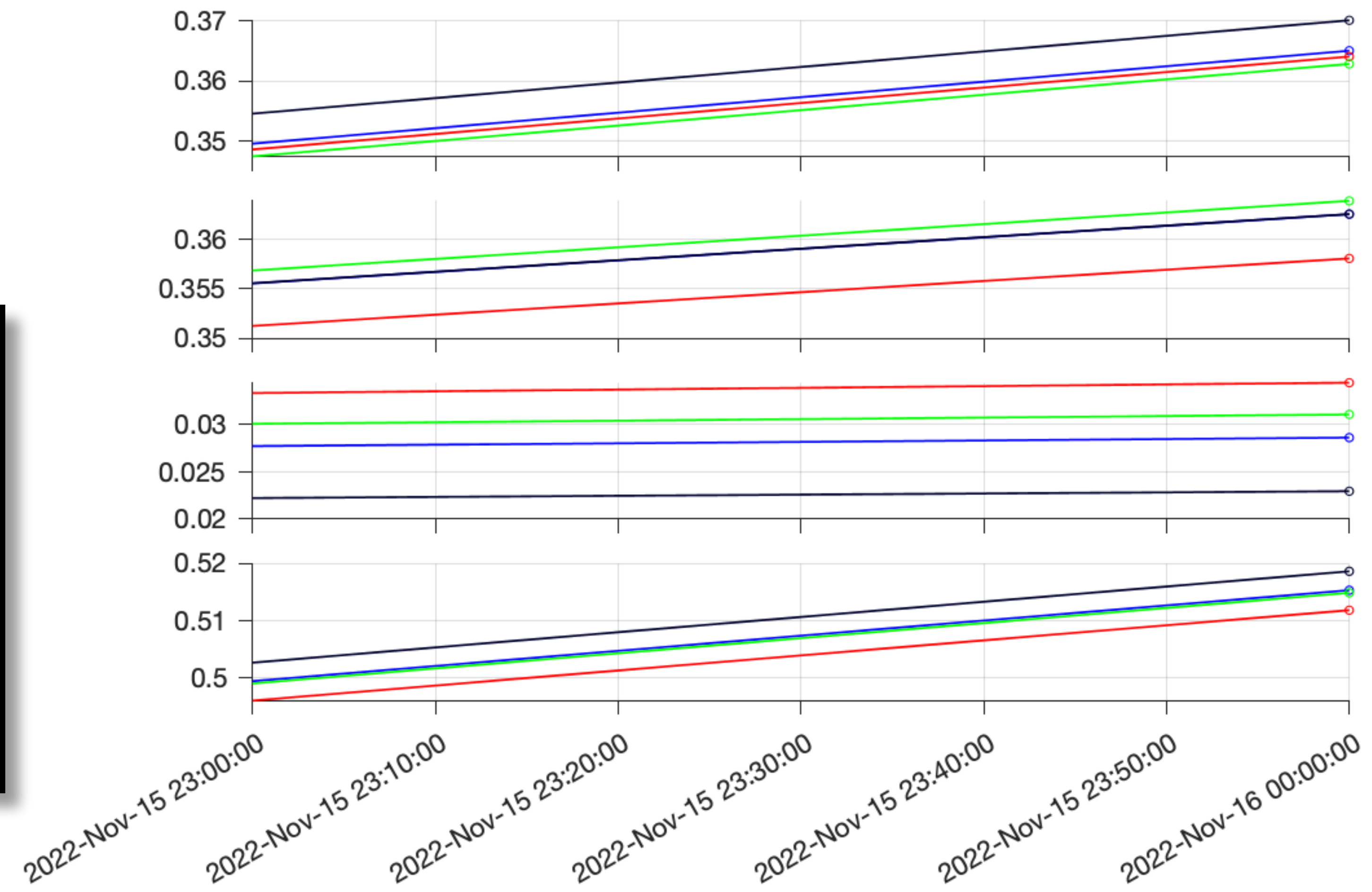
REBOUND 24

Preliminary test: 24-hr propagation period

- Begin with initial conditions of CAPSTONE at an epoch (15 Nov 2022) provided by JPL Horizons
- Propagate using ASSIST/GMAT
  - ASSIST: Standard model
  - GMAT-4BP: Earth+Moon+Sun
  - GMAT-EJ2: All planets + Earth's J_2
  - GMAT-EMJ2: GMAT-EJ2 + Moon's J_2
- Compare propagated results with ephemeris at epochs







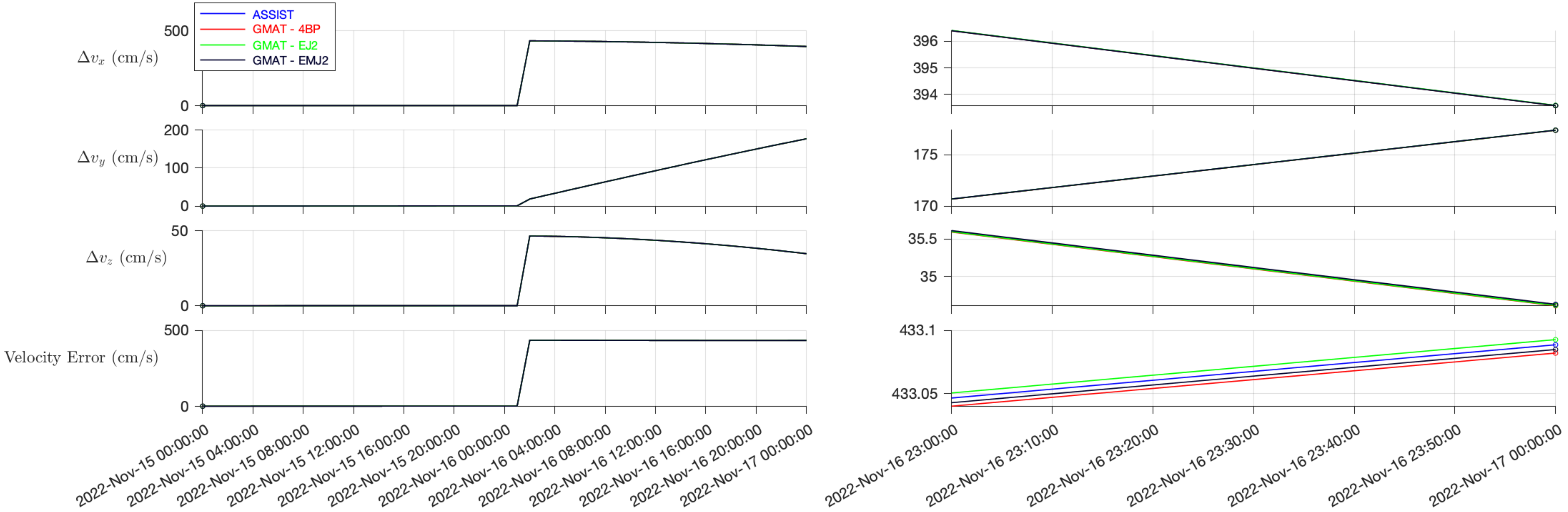
Model	ASSIST	GMAT-4BP	GMAT-EJ2	GMAT-EMJ2
Final Position Error (km)	0.22375	0.22222	0.22367	0.22557
Final Velocity Error (cm/s)	0.53015	0.52648	0.52956	0.53332

Maneuver Detection

Retrospective inspection of Cartesian residuals

- Numerical integrators only function as accurate approximations of the ephemeris during non-maneuvering periods
- CAPSTONE performs orbit maintenance maneuvers (OMMs) to maintain the NRHO
- Maneuvers (magnitude, direction, and epoch) are not explicitly stated in ephemeris repositories
- **Conclusion: ability to detect that a maneuver has occurred is a necessity for performing numerical integrator analysis**

Retrospective Inspection of Velocity Error

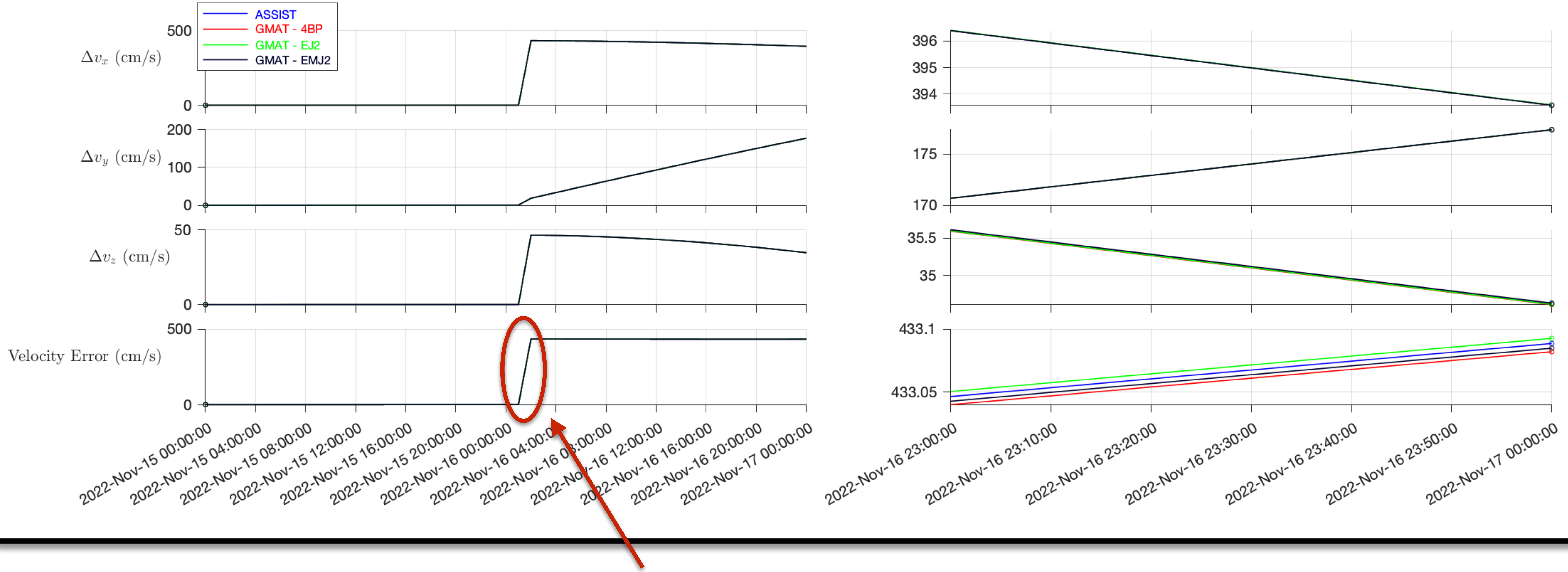


Maneuver Detection

Retrospective inspection of Cartesian residuals

- Numerical integrators only function as accurate approximations of the ephemeris during non-maneuvering periods
- CAPSTONE performs orbit maintenance maneuvers (OMMs) to maintain the NRHO
- Maneuvers (magnitude, direction, and epoch) are not explicitly stated in ephemeris repositories
- **Conclusion: ability to detect that a maneuver has occurred is a necessity for performing numerical integrator analysis**

Retrospective Inspection of Velocity Error



Instantaneous shift in velocity (indicative of a maneuver)

Maneuver Detection

Inspection over longer propagation window

REBOUND 24

- **Procedure**

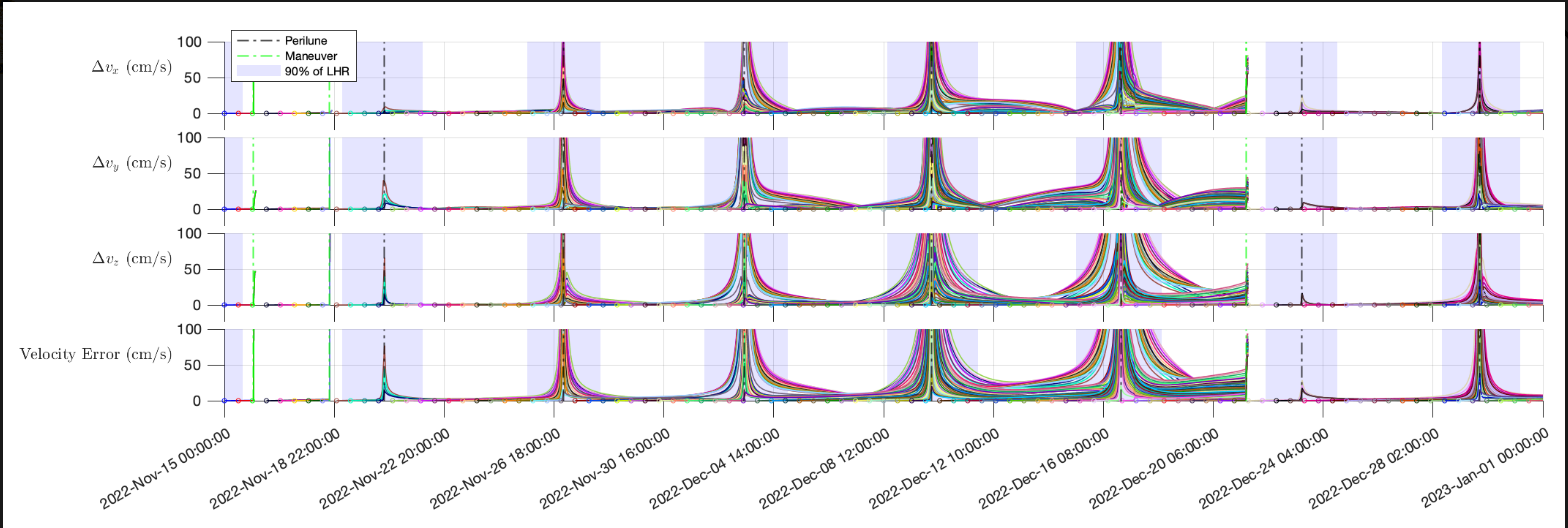
1. Determine a propagation window wherein retrospective maneuver detection will be applied
   - 15 Nov 2022 - 01 Jan 2023 (insertion into NRHO to EOY)
2. Initialize numerical integration simulations every n hours throughout the entire propagation window from ICs provided by ephemeris
   - $n = 12$ hours, ephemeris step size $= 1$ hour
3. Propagate simulations through window
4. Retrospectively analyze for each simulation where

$$\text{velocity residual error}(t + \Delta t) - \text{velocity residual error}(t) > \text{threshold value}$$

   - threshold value $= 5$ cm/s (per Advanced Space, maneuvers have magnitudes from 5 to 50 cm/s)

- **Considerations**
  - Large shifts in velocity between time steps are expected near periselene as velocity increases
  - Because of this, uncertainty of state estimation increases, thus Advanced Space has confirmed they do not perform OMMs “near periselene”
  - **Solution: develop “no-go” zone where maneuver triggers are ignored, Lunar Hill Region (LHR)**

$$r_{LHR} = a_{☾} \left(\frac{m_{☾}}{3\, m_{\oplus}} \right)^{1/3}$$



Complete Maneuver Detection Window - Velocity

Maneuver Table

Maneuver #	Maneuver Date (UTC)	# of Triggers	Trigger Rate
1	16 Nov. 2022 01:00:00	3	100%
2	18 Nov. 2022 18:00:00	5	100%
3	21 Dec. 2022 10:00:00	65	100%

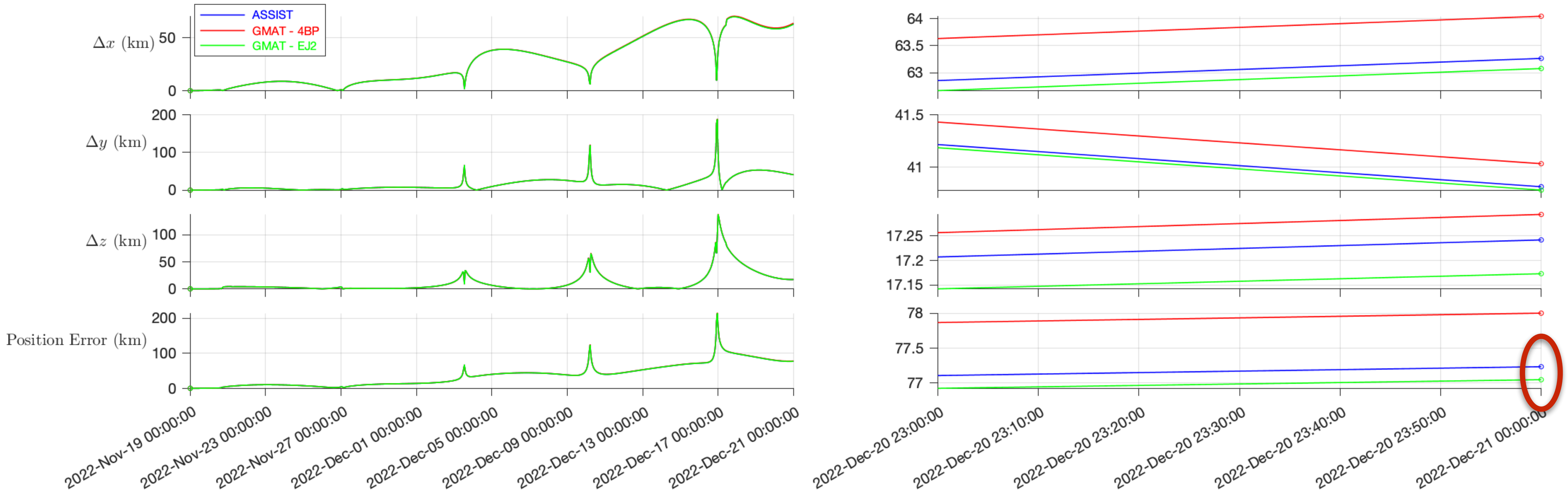
- Expected ~1 maneuver/week
- Maneuver threshold value may have been too high or no-go zone may be too large
- Carry-on with assumption that 19 Nov 2022 to 21 Dec 2022 is maneuver-free period

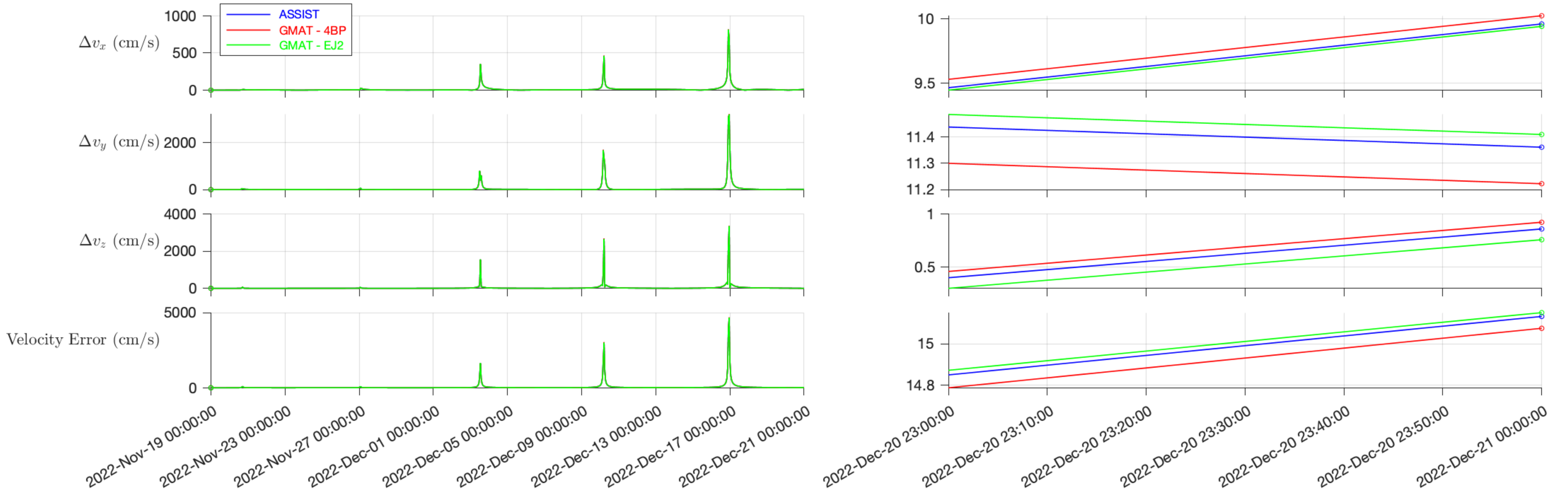
Numerical Integrator Analysis

Long term propagation period comparison

REBOUND 24

Propagation window: 19 Nov 2022 00:00:00 UTC - 21 Dec 2022 00:00:00 UTC (32 days)



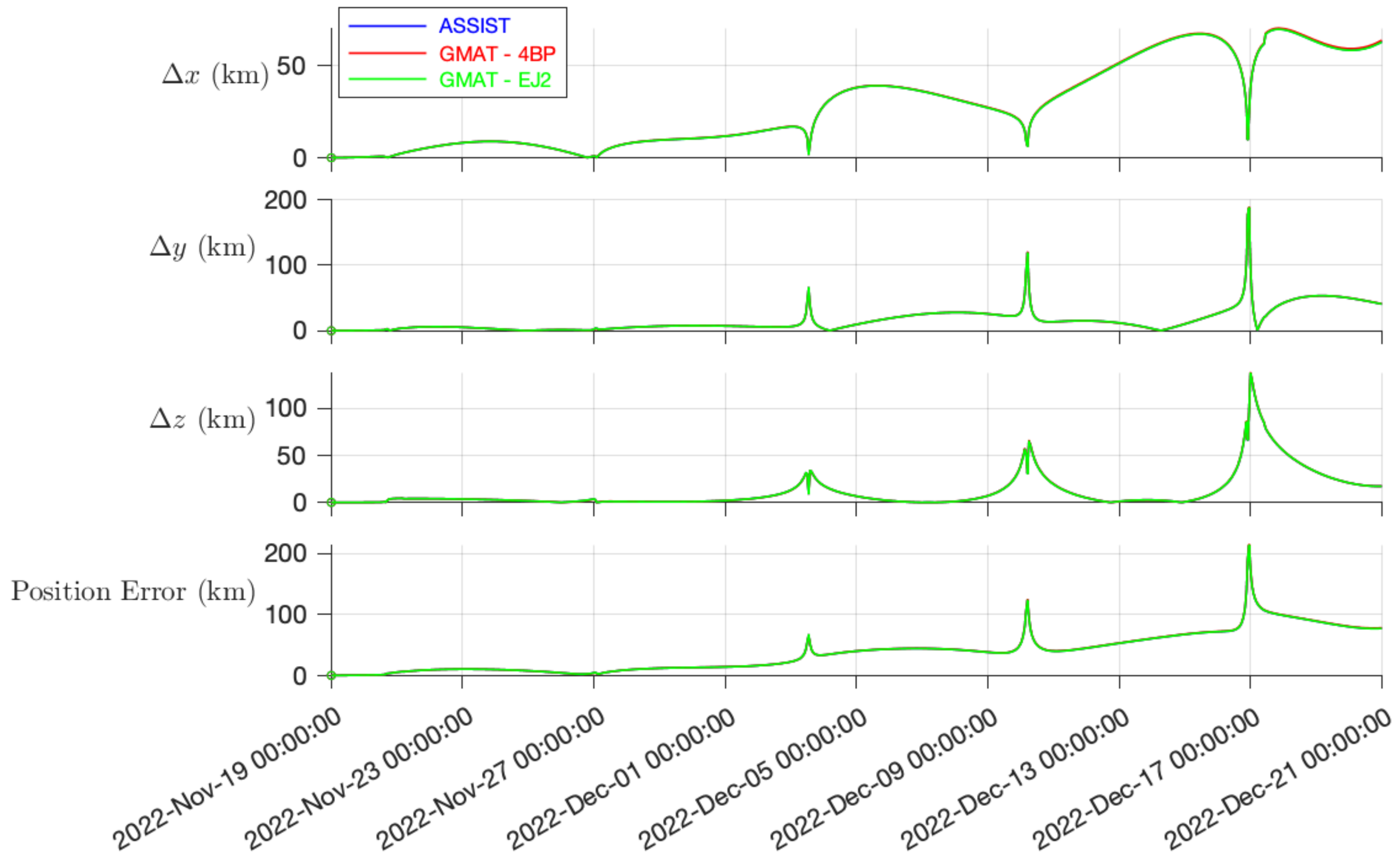


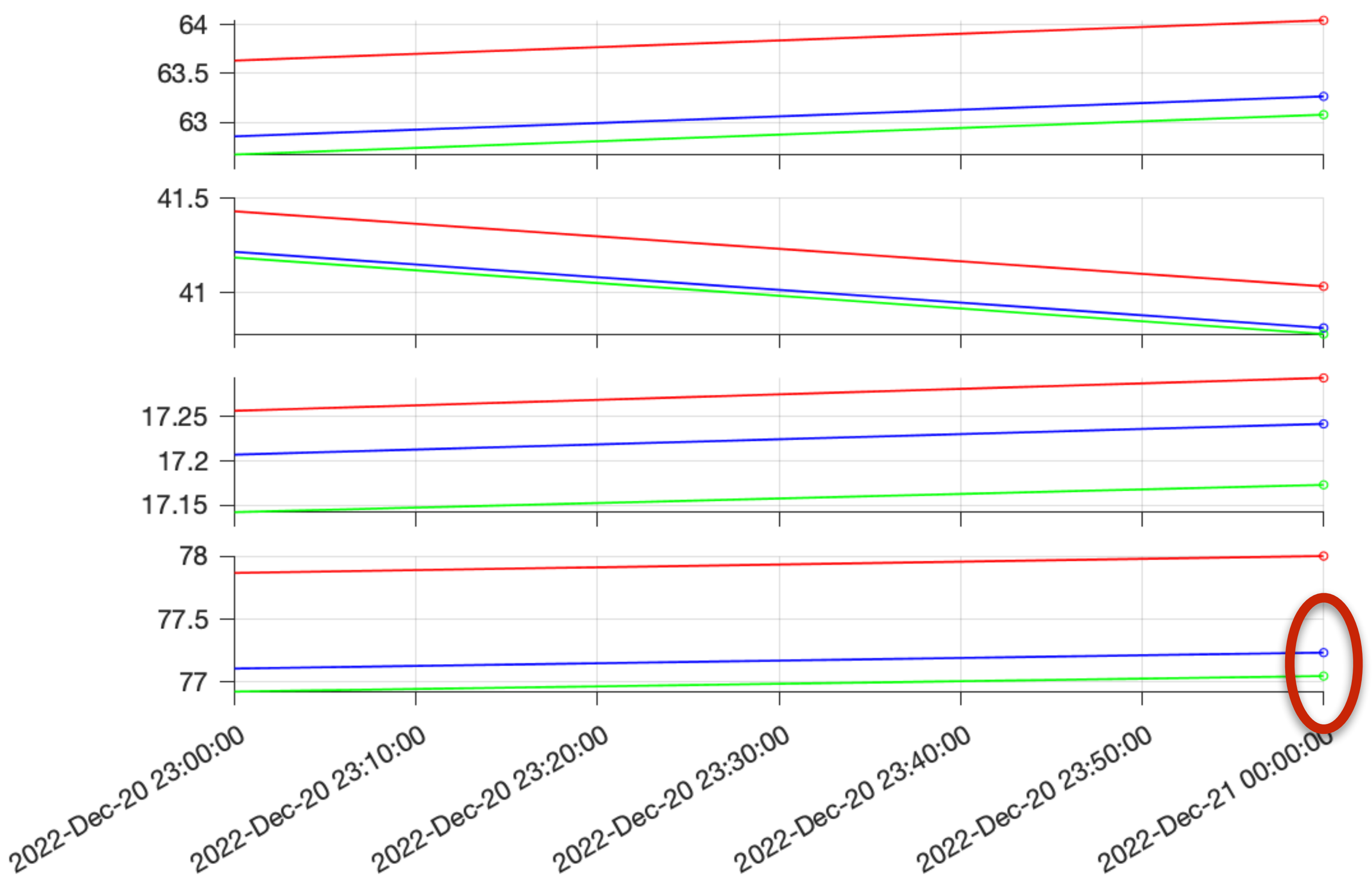
- ASSIST and GMAT-EJ2 are most accurate force models
- ASSIST includes J_2 of the Sun, as well as other perturbations from asteroids that are most likely not included in the orbit determination model

Numerical Integrator Analysis

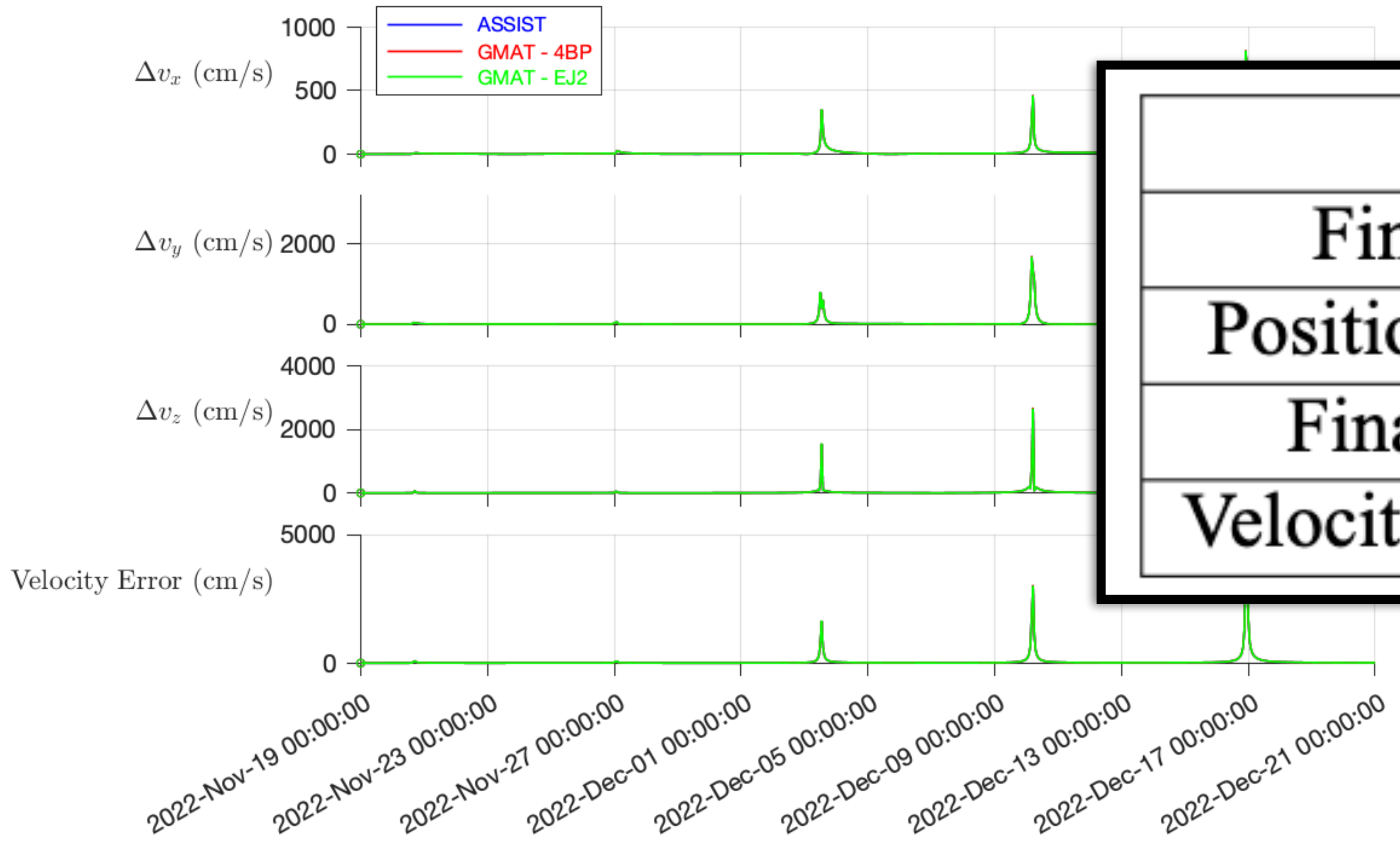
Long term propagation period comparison

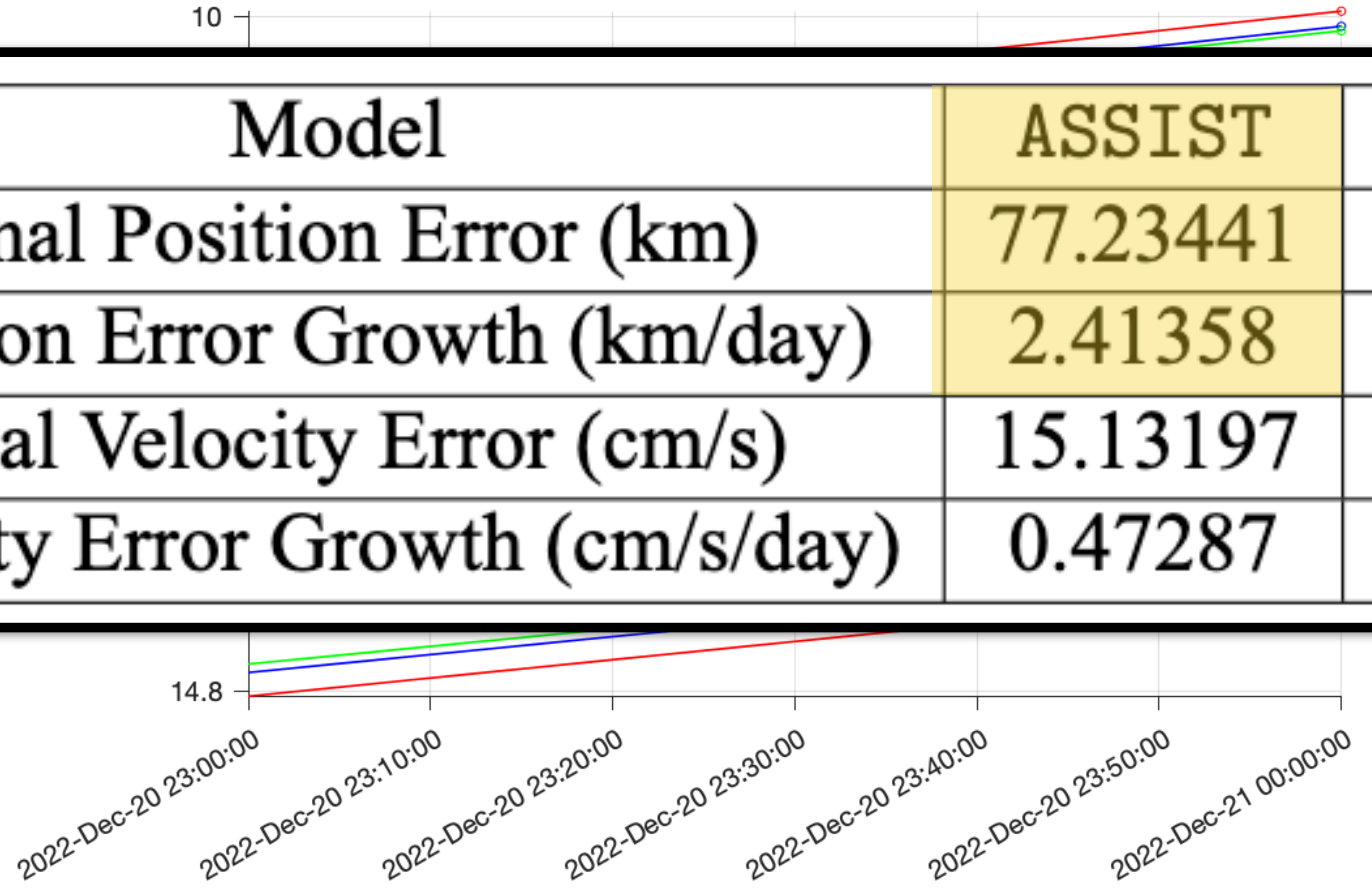
Propagation window: 19 Nov 2022 00:00:00 UTC - 21 Dec 2022 00:00:00 UTC (32 days)





- ASSIST and GMAT-EJ2 are most accurate force models
- ASSIST includes J_2 of the Sun, as well as other perturbations from asteroids that are most likely not included in the orbit determination model





Model	ASSIST	GMAT-4BP	GMAT-EJ2	GMAT-EMJ2
Final Position Error (km)	77.23441	77.99987	77.04892	159.56883
Position Error Growth (km/day)	2.41358	2.43750	2.40778	4.98653
Final Velocity Error (cm/s)	15.13197	15.07480	15.15035	32.59955
Velocity Error Growth (cm/s/day)	0.47287	0.47109	0.47345	1.01874

This investigation was supported by the AFRL/RD Summer Faculty Fellowship Program.

The authors would like to thank Patrick Miga and Bradley Cheetham from Advanced Space for their invaluable insight and contributions.

All code can be found at: https://github.com/bhanson10/CAPSTONE and https://github.com/bhanson10/TESS_IBEX_Spektr-R.

Thank you for your time. Questions?