Detection of Thermospheric Density Variations via Spacecraft Accelerations Observed Using the CASSIOPE GAP Instrument: Initial Investigations

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Introduction

As one of eight instruments of the Enhanced Polar Outflow Probe (e-POP) payload on the Canadian CAScade, Smallsat and IOnospheric Polar Explorer (CASSIOPE) small satellite (Figure 1), the GPS Attitude, Positioning, and Profiling experiment (GAP^2) can employ one or more of the four GAP-A dual-frequency GPS receivers and associated zenith-facing antennas (Figures 2 and 3) to provide high-resolution spatial positioning information, flight path velocity determination, and real-time, high-stability timing. Preliminary processing of raw GPS data acquired from the GAP-A GPS receivers using the University of New Brunswick's (UNB) CASSIOPE Atmospheric Profiling and Positioning Software (CAPPS) and International GNSS Service (IGS) precise products has produced sub-decimetre root-mean-square positions and correspondingly-accurate velocities for the CASSIOPE spacecraft. Spacecraft acceleration can also be determined by subsequent processing of the velocity estimates.

Figure 1: The Canadian CASSIOPE small satellite undergoing testing prior to its orbit injection via a SpaceX Falcon 9 rocket.

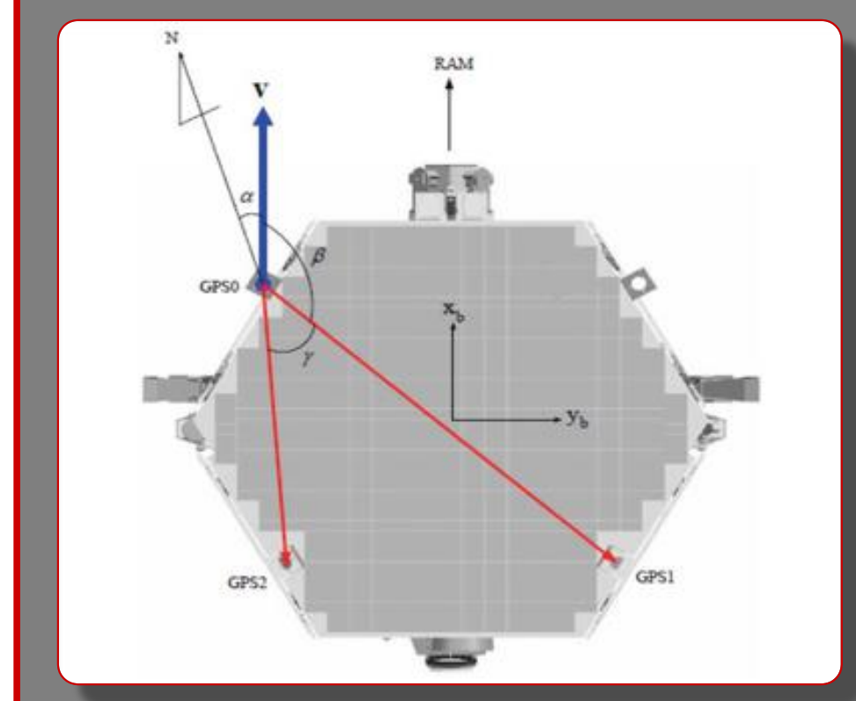


Figure 2: Configuration of the GAP-A antennas on the CASSIOPE satellite.

Figure 3: CASSIOPE's GAP GPS antennas under test prior to final installation on the satellite.

Methodology

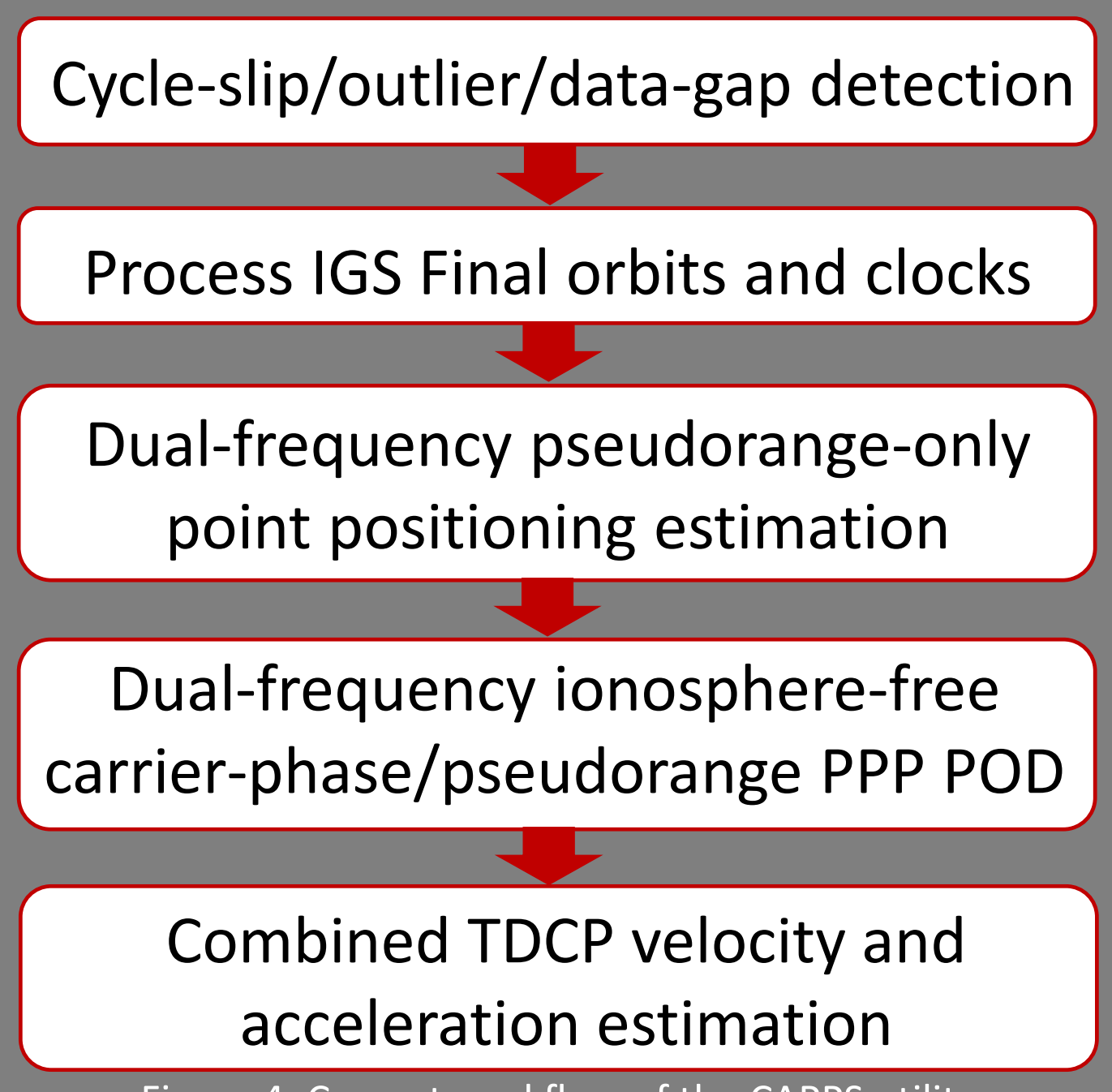
The CAPPS utility is a specially-designed low-Earth-orbit (LEO) processing engine capable of providing highly-accurate estimates of LEO spacecraft orbits as well as correspondingly-accurate spacecraft velocities and accelerations. The current software implementation utilizes the precise point positioning (PPP) technique using dual-frequency ionosphere-free GPS observables and IGS final orbit and clock products to perform a purely-kinematic approach to precise orbit determination (POD) at a sub-decimeter RMS level with future goals of achieving centimetre-level accuracies. Following the estimation of spacecraft position, time-differenced carrier-phase (TDCP) observables are used to determine spacecraft velocity and acceleration at a mm/s and mm/s^2 level, respectively (Serrano et al., 2004). Equations 1 and 2 illustrate the observables and observation equations used in CAPPS' velocity and acceleration estimation algorithms. Figure 4 summarizes CAPPS' current position, velocity, and acceleration estimation workflow.

$$D_{i_s} = \dot{\Phi}_k^j = \frac{\Phi_{k+\Delta t}^j - \Phi_{k-\Delta t}^j}{2\Delta t} \approx \frac{\boldsymbol{R}^s - \boldsymbol{R}_r}{\|\boldsymbol{R}^s - \boldsymbol{R}_r\|} \cdot (\boldsymbol{v}^s - \boldsymbol{v}_r) + \dot{B}_k + \varepsilon_k^j \quad (1)$$

$$\ddot{\Phi}_{k-\Delta t}^j = \frac{\dot{\Phi}_{k+\Delta t}^j - \dot{\Phi}_{k-\Delta t}^j}{2\Delta t} = \frac{\Phi_{k+2\Delta t}^j - 2\Phi_k^j + \Phi_{k-2\Delta t}^j}{4\Delta t^2}$$

$$\approx \frac{\boldsymbol{v}^s - \boldsymbol{v}_r}{\|\boldsymbol{v}^s - \boldsymbol{v}_r\|} \cdot (\boldsymbol{v}^s - \boldsymbol{v}_r) + \frac{\boldsymbol{R}^s - \boldsymbol{R}_r}{\|\boldsymbol{R}^s - \boldsymbol{R}_r\|} \cdot (\boldsymbol{a}^s - \boldsymbol{a}_r) + \ddot{B}_k + \varepsilon_k^j \quad (2)$$

where Φ_k^j = *Carrier − phase observable* Δt = *Time interval*
$\boldsymbol{v}^s$ = *GPS satellite velocity vector* $\boldsymbol{v}_r$ = *Receiver velocity vector*
$\boldsymbol{R}^s$ = *GPS satellite position vector* $\boldsymbol{R}_r$ = *Receiver position vector*
$\boldsymbol{a}^s$ = *GPS satellite acceleration vector* $\boldsymbol{a}_r$ = *Receiver acceleration vector*
$\dot{B}_k$ = *Receiver clock drift* $\ddot{B}_k$ = *Receiver clock acceleration*
ε_k^j = *Unmodeled errors*



Cycle-slip/outlier/data-gap detection

Process IGS Final orbits and clocks

Dual-frequency pseudorange-only point positioning estimation

Dual-frequency ionosphere-free carrier-phase/pseudorange PPP POD

Combined TDCP velocity and acceleration estimation

Figure 4: Current workflow of the CAPPS utility.

Initial Results

While the CAPPS utility remains a work in progress, initial processing results provide insight into the feasibility of the PPP POD algorithm as well as the achievable accuracies of its initial spacecraft position and velocity estimations. Unfortunately, a majority of the available GAP-A GPS observation data has random data gaps most likely attributed to a bottle-necking of high-volume receiver information. As seen in Figure 5, these data gaps necessitate regular resets of carrier-phase float ambiguity estimates and subsequent re-convergence of estimated parameters. A solution to avoid future data bottle-necking issues is currently being investigated with the assistance of the University of Calgary. Figure 6 illustrates the behavior of data gaps observed for CASSIOPE GAP-A receiver 1 on October 1, 2016.

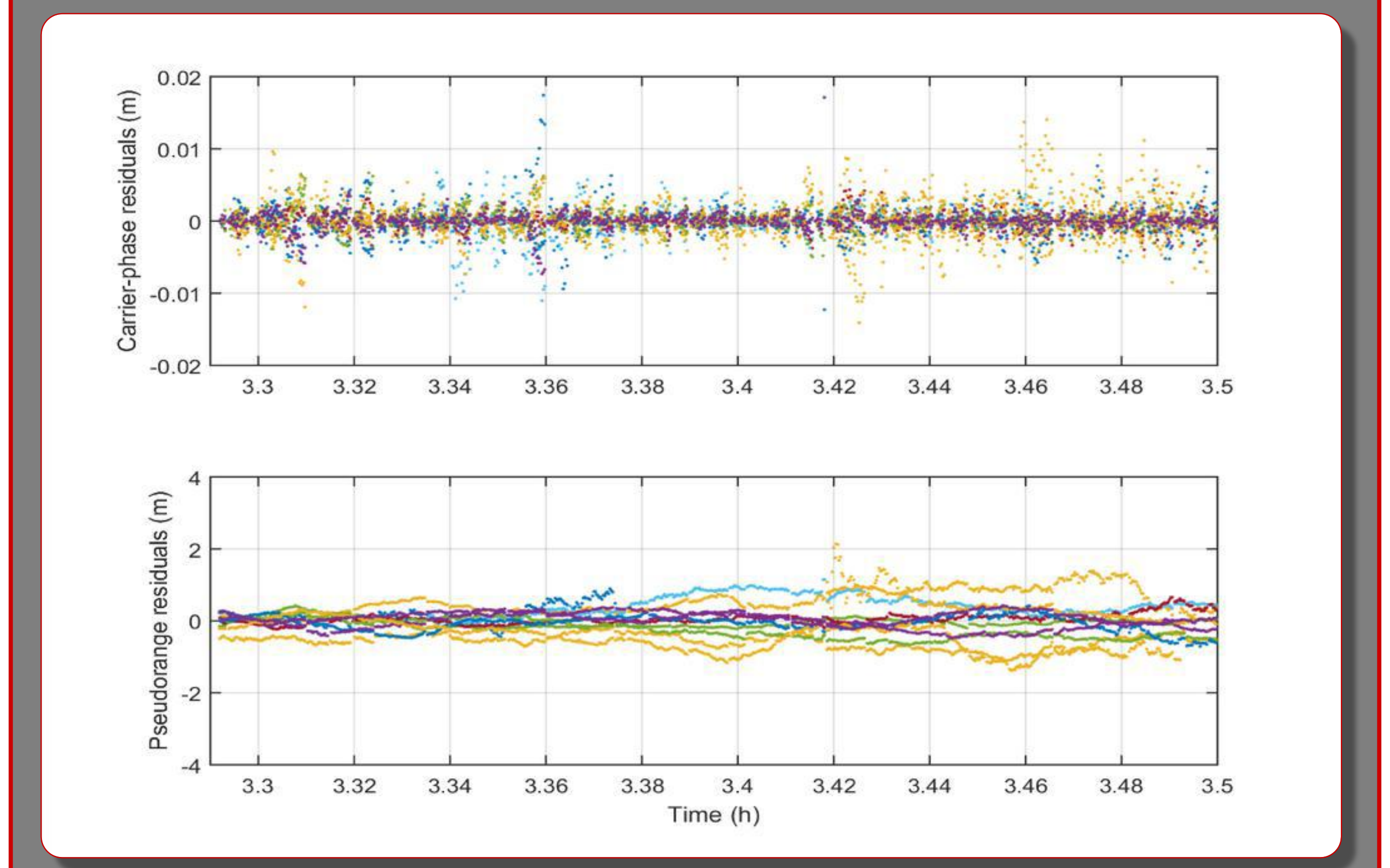


Figure 5: Carrier-phase and pseudorange residual estimates for CASSIOPE GAP-A receiver 1 on October 1, 2016. Discontinuities in the carrier-phase residuals represent epochs where float ambiguities have been reset due to the occurrence of random gaps in observation data.

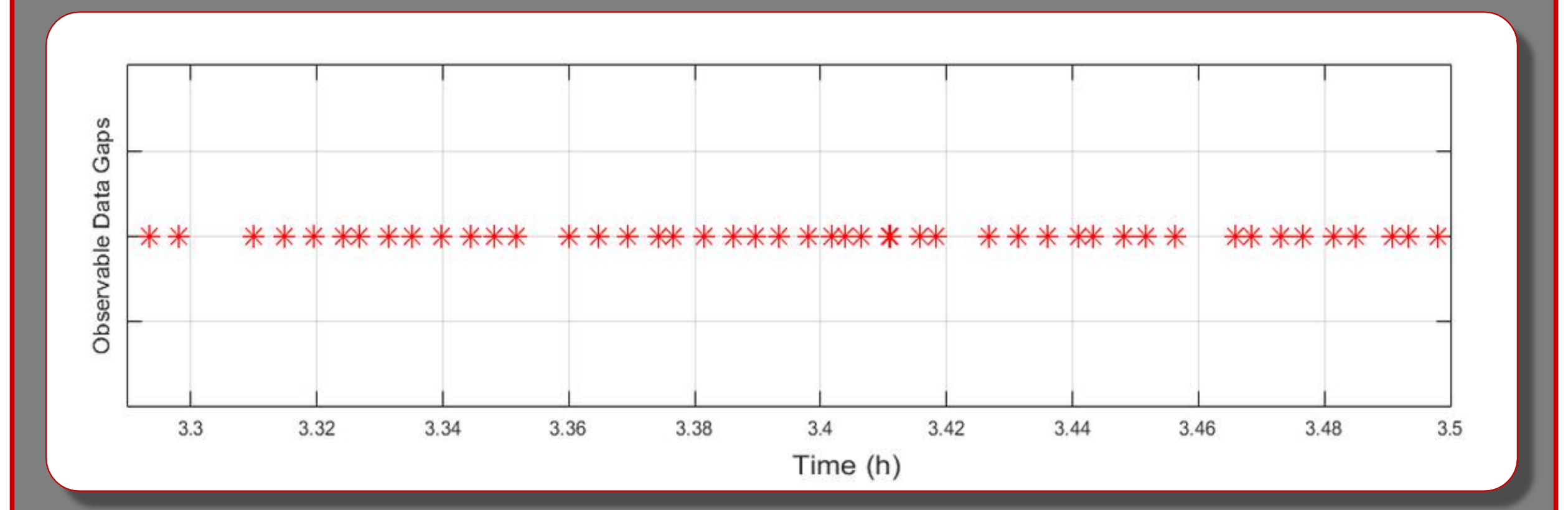


Figure 6: Observed gaps in observation data for CASSIOPE GAP-A receiver 1 on October 1, 2016. During the 10.5 minute observation session, GAP-A receiver 1 encountered 47 separate data gaps.

Despite the occurrence of these data gaps, preliminary results demonstrate the achievability of sub-decimeter RMS accuracies for CASSIOPE orbit determination. Figures 7 and 8 show 1-Hz spacecraft position estimates (represented in Keyhole Markup Language format using Google Earth) and associated position component standard deviations (1-sigma) for CASSIOPE GAP-A receiver 1 on May 5, 2017.

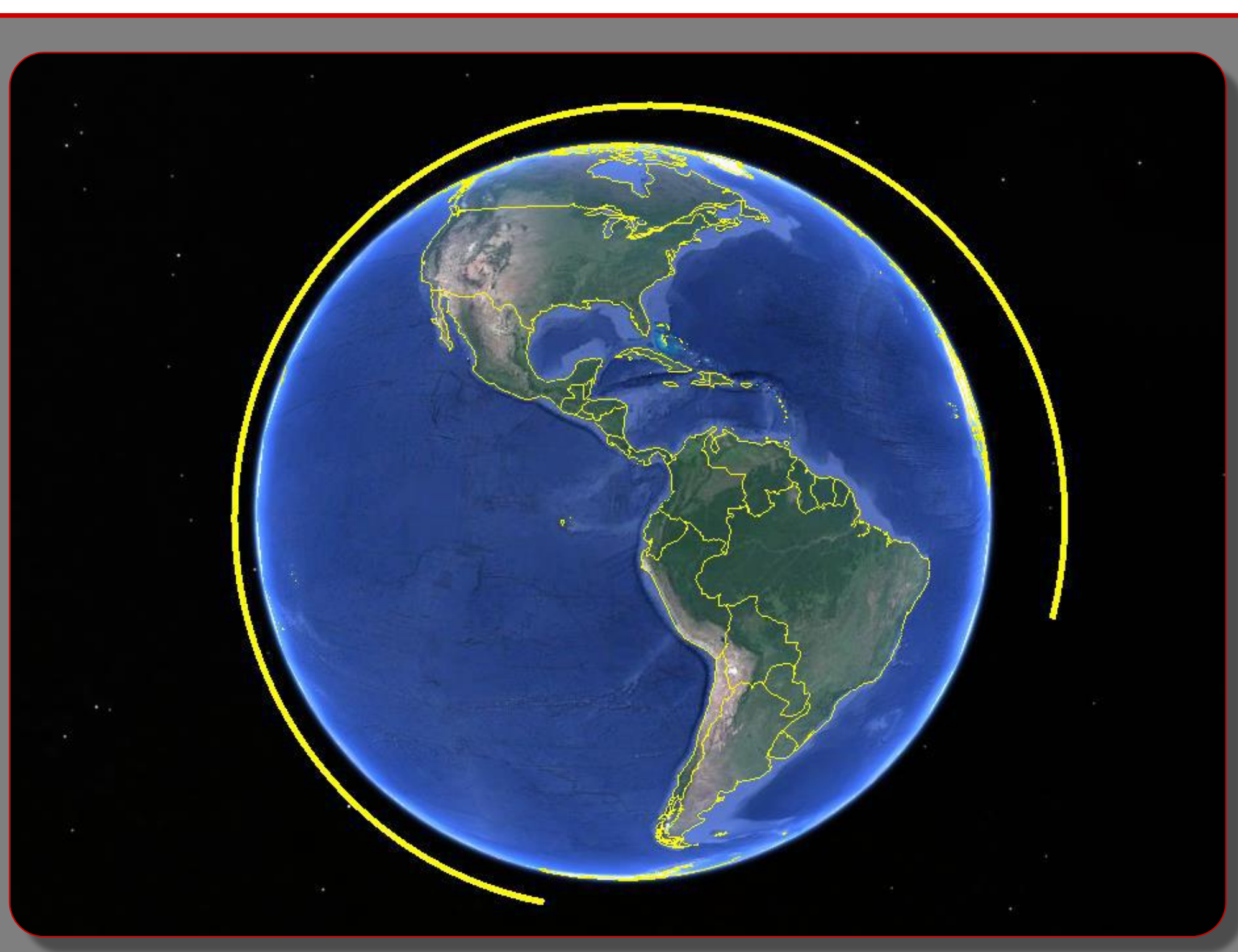


Figure 7: Estimated orbital positions of the CASSIOPE spacecraft via GPS observations from GAP-A receiver 1 on May 5, 2017.

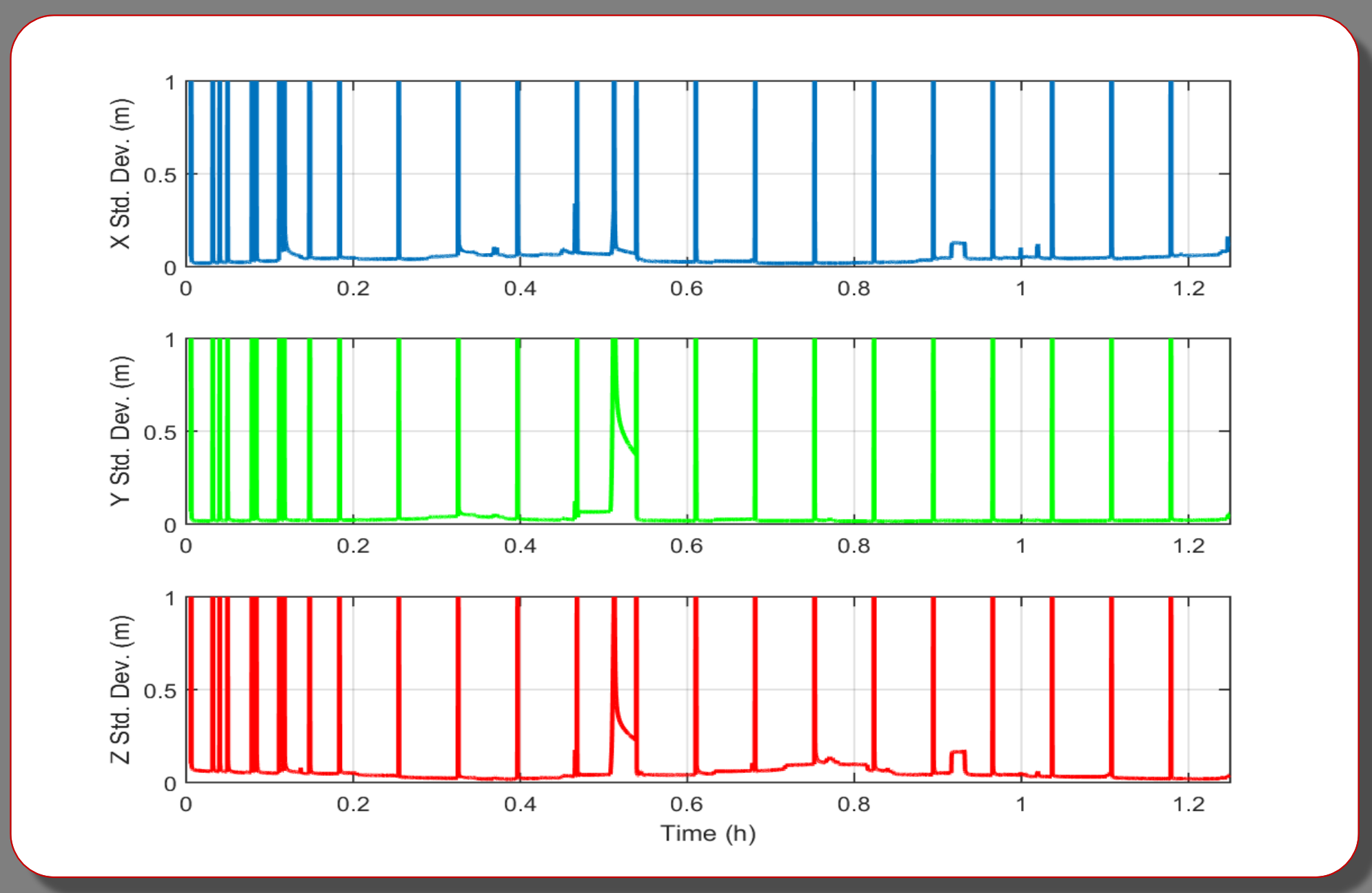


Figure 8: Position component standard deviation time series (1-sigma) for GAP-A receiver 1 on May 5, 2017. Large spikes in the time series represent epochs where data gaps occurred and ambiguity estimates were subsequently reset.

While CAPPS' time-differenced carrier-phase velocity estimation algorithm is still under development, initial estimations of spacecraft velocity at the decimeter-per-second level are available through the differencing of consecutive spacecraft positions. As seen in Figure 9, the CASSIOPE velocity time series varies from approximately 7.9 km/s at perigee to approximately 6.9 km/s at apogee. By again differencing these preliminary velocity determinations, correspondingly-accurate estimates of spacecraft acceleration can also be determined. Through careful discrimination of the forces causing the spacecraft to accelerate, variations in the density of the surrounding thermosphere can be determined.

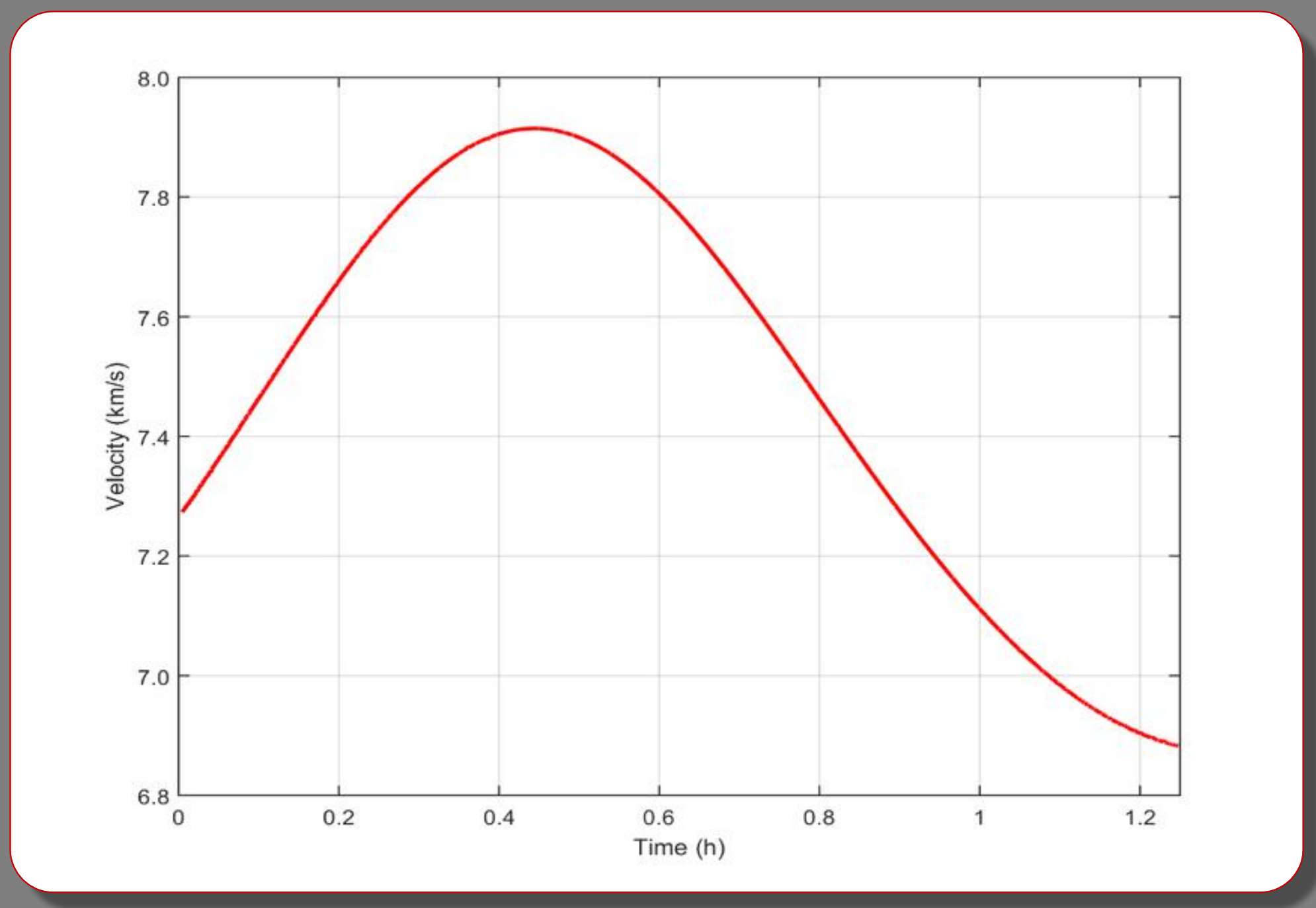


Figure 9: Estimated magnitude of spacecraft velocity for CASSIOPE GAP-A receiver 1 on May 5, 2017.

References

Serrano, L., Kim, D., Langley, R.B. (2004). A Single GPS Receiver as a Real-Time, Accurate Velocity and Acceleration Sensor. *Proceedings of the 17th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2004)*, Long Beach, CA, September 2004, pp. 2021-2034.

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