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ORION EXPLORATION FLIGHT TEST-1 POST-FLIGHT NAVIGATION PERFORMANCE ASSESSMENT RELATIVE TO THE BEST ESTIMATED TRAJECTORY

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This paper details the post-flight navigation performance assessment of the Orion Exploration Flight Test-1 (EFT-1). Results of each flight phase are presented: Ground Align, Ascent, Orbit, and Entry Descent and Landing. This study examines the on-board Kalman Filter uncertainty along with state deviations relative to the Best Estimated Trajectory (BET). Overall the results show that the Orion Navigation System performed as well or better than expected. Specifically, the Global Positioning System (GPS) measurement availability was significantly better than anticipated at high altitudes. In addition, attitude estimation via processing GPS measurements along with Inertial Measurement Unit (IMU) data performed very well and maintained good attitude throughout the mission.

INTRODUCTION

On December 5th, 2014, NASA flew the Orion Exploration Flight Test-1 (EFT-1). This was the first test flight of the Orion MPCV Program - NASA's flagship program for exploration. The EFT-1 trajectory included two revolutions of the Earth with the second orbit being a high ellipse that brought the vehicle screaming back at speeds close to that of a lunar return. The high-speed entry was designed to test Orion's heat shield and Guidance, Navigation, and Control (GNC) design for future missions to the Moon and eventually Mars. Figure 1 provides a general overview of the EFT-1 trajectory and the flight-recorded altitude profile.

To satisfy performance requirements and maintain fault tolerance, the Orion EFT-1 was comprised of two Inertial Measurement Units (IMU), one Global Positioning System (GPS) receiver, two GPS antennas, and three Barometric Altimeters (BALT). There were also two self-checking-pare flight computers that each hosted duplicate versions of the GNC Flight Software (FSW). Each computer processed two navigation channels, one for each OIMU; and each navigation channel maintained an Inertial-only solution as well as a Kalman Filter solution. This paper analyzes the performance of the Kalman Filter solution relative to the Best Estimated Trajectory (BET) for all flight phases. The BET contains additional data such as ground tracking, launch vehicle state, day-of-flight winds, Global Reference Atmosphere Model (GRAM), ionosphere corrections, GPS precise ephemeris corrections, and other data editing and smoothing techniques.[1] Other Orion papers cover the design and tuning of the Kalman Filter.[2,3,4]

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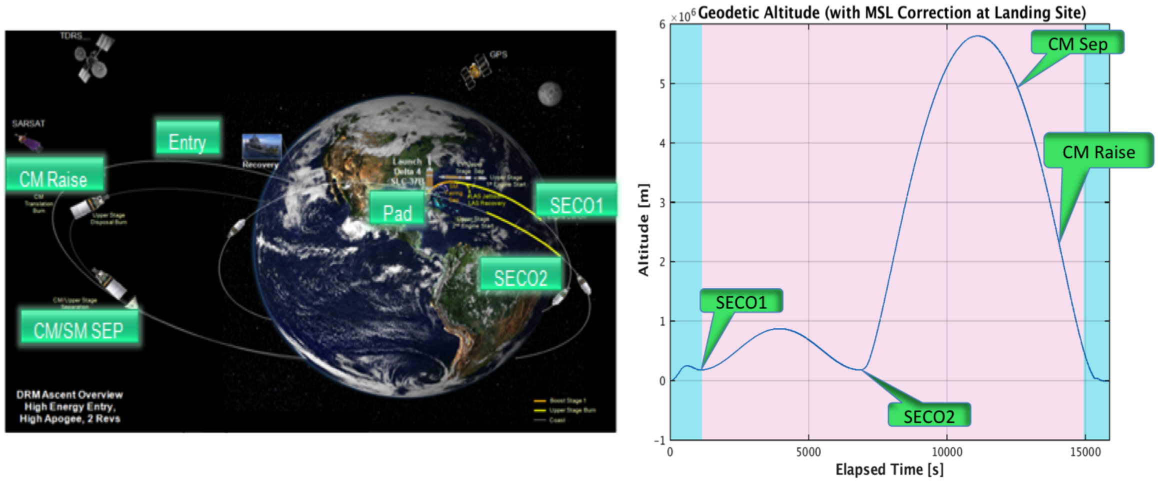

Figure 1. Orion EFT-1 Trajectory Overview and Flight Altitude Profile

It should be noted that at the time of the writing of this paper the BET was being updated with some additional GPS time corrections and more data editing. It was also determined that there were sufficient differences in the transformation from Inertial to Planet-Fixed coordinates (RNP) between the BET and the on-board values, to cause larger than expected deviations between the on-board solution and the BET. Unfortunately, the necessary data to compute the errors in the Planet-Fixed frame was not available in time for incorporation into this paper. Thus, the position and velocity differences between the FSW and BET are not representative of the relative uncertainties of the two solutions. It is assumed that once all these corrections are applied, the relative differences will be within expected limits.

FLIGHT PHASE PERFORMANCE

The operational envelope for navigation encompasses the entire mission, from ground alignment on the launch pad through ascent, orbit, and down through entry descent and landing. The following sections detail the Kalman Filter performance for all phases of flight. Only the position and velocity errors are computed relative to the BET data since there was no additional attitude knowledge to be processed post flight.

Ground Alignment

In order to determine the initial attitude of the vehicle, measurements from the IMU were used to compute first a "coarse" (or rough estimate), then a "fine" alignment. The Coarse Alignment was achieved through simple smoothing of the IMU rates and deltaVs, while Fine Alignment was accomplished with a Kalman Filter processing derived *Integrated Velocity* measurements. Since the vehicle was assumed to be motionless on the launch pad, the "integrated" planet-relative velocity should result in no change in position. Figures 2 - 4 show the Filter uncertainty during Fine Alignment. The BET position and velocity only started five minutes prior to launch and did not cover all of the Fine Align period. Errors relative to the BET in the last five minutes of Fine Align are pretty much equivalent to the errors at liftoff shown in the Ascent Section.

Figure 2 shows the position uncertainty growing slowly to a value that is bounded by dynamics of Earth rotation, IMU performance, and latitude. This error was well within the necessary performance for the EFT-1 mission. On-the-other-hand, the velocity uncertainty displayed in Figure 3, converges rapidly to approximately 0.05 m/s. This is just above the requirement of 0.04 m/s, but this is consistent with pre-flight simulations where no violations of the velocity error requirement were seen.

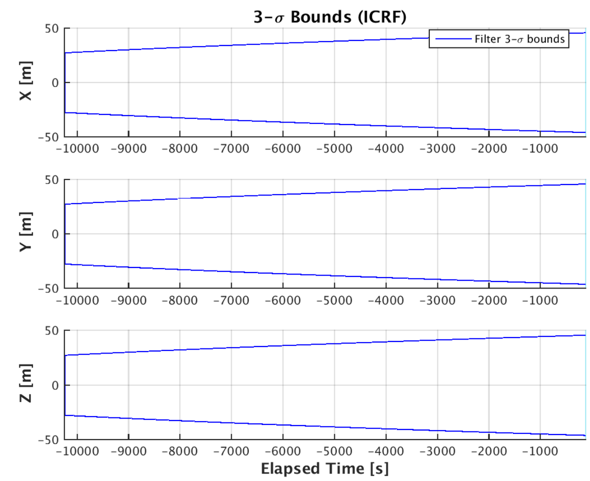

Figure 2. Ground Align Position Performance

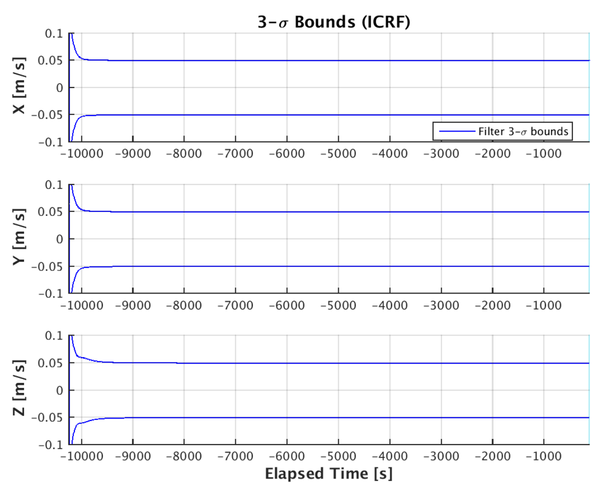

Figure 3. Ground Align Velocity Performance

Although the vehicle remained in Fine Alignment for nearly three hours, only forty minutes was required to converge the azimuth to within the required 0.2 deg as seen in Figure 4. The tilt uncertainty, also shown in Figure 4, converges much faster down to within the required 0.015 deg.

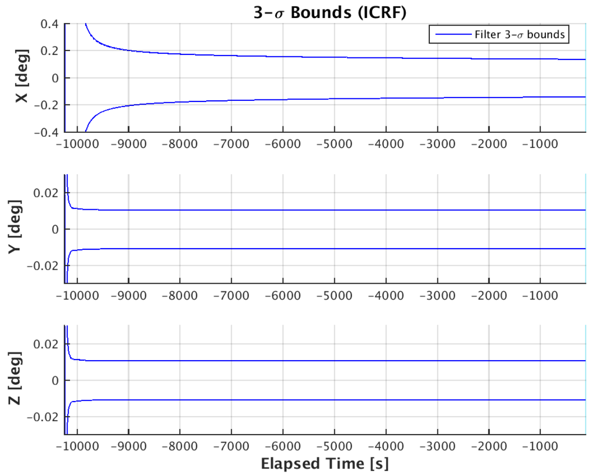

Figure 4. Ground Align Attitude Performance

Ascent

At liftoff minus two minutes (T-120s), the navigation state was propagated using IMU measurements. Once the Launch Abort System (LAS) (structure-only for EFT-1) and the Crew Module (CM) shroud was jettisoned, the GPS receiver antennas were exposed and started tracking satellites. At this point, Pseudo-range (PR) and Delta-range (DR) measurements were used in a Kalman Filter to estimate position, velocity, and attitude. Results in this section cover the Ascent phase from launch to orbit insertion.

The position errors and uncertainty shown in Figure 5 clearly clamp down as GPS processing begins around 450s. Figure 6 provides a "zoomed" view showing that the position uncertainty and error relative to the BET is well within the desired performance of 50 m. The errors are not within the 3-σ bounds due to the RNP errors mentioned earlier, but the errors are still within desired limits.

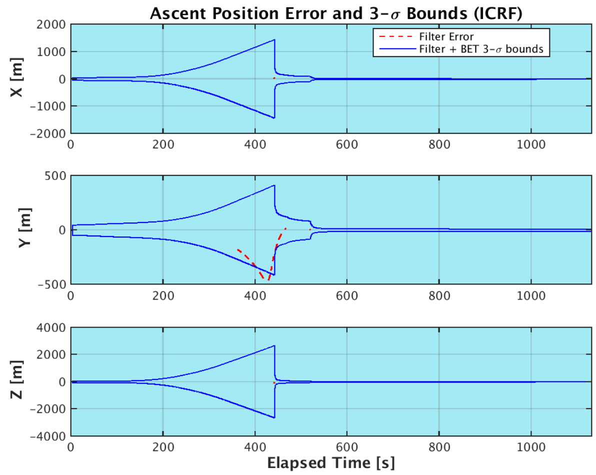

Figure 5. Ascent Position Performance

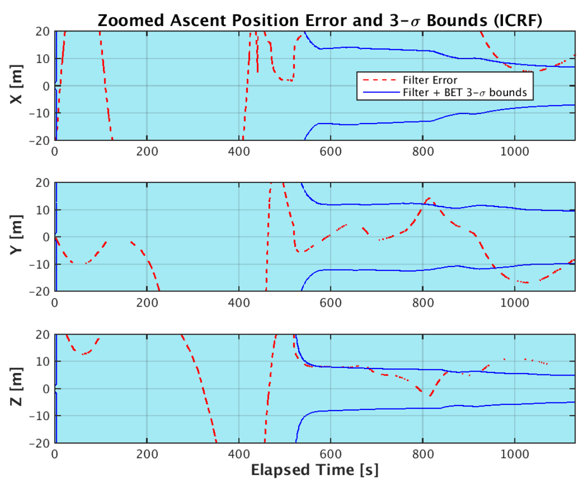

Figure 6. Zoomed Ascent Position Performance

Figures 7 and 8 show that the velocity errors and uncertainty behave very similarly to the position as GPS processing begins. As with position, the velocity errors are outside the 3-σ bounds, but they are within the desired performance limits of 0.5 m/s.

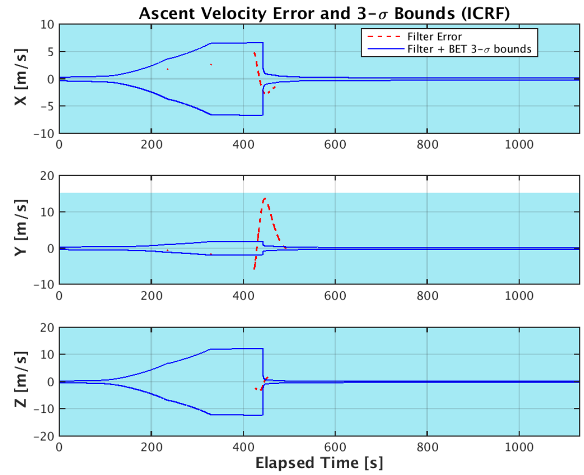

Figure 7. Ascent Velocity Performance

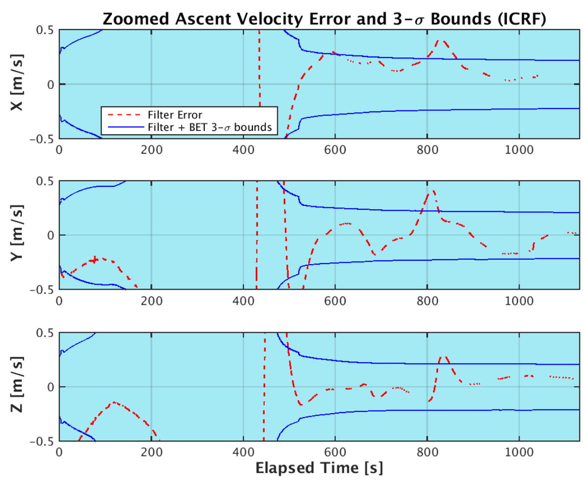

Figure 8. Zoomed Ascent Velocity Performance

Since the Kalman Filter included attitude and IMU error states, GPS measurement processing allowed the filter to very accurately determine attitude during Ascent. Figures 9 and 10 clearly show how the attitude uncertainty drops dramatically as GPS becomes available. The accuracy achieved was more than order of magnitude better than the overall mission requirement of 0.4 deg.

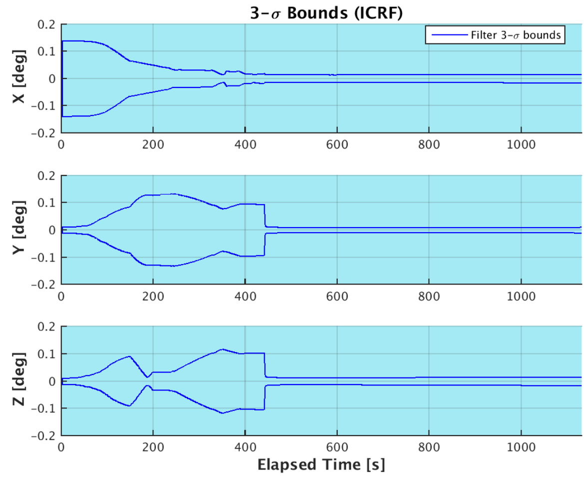

Figure 9. Ascent Attitude Performance

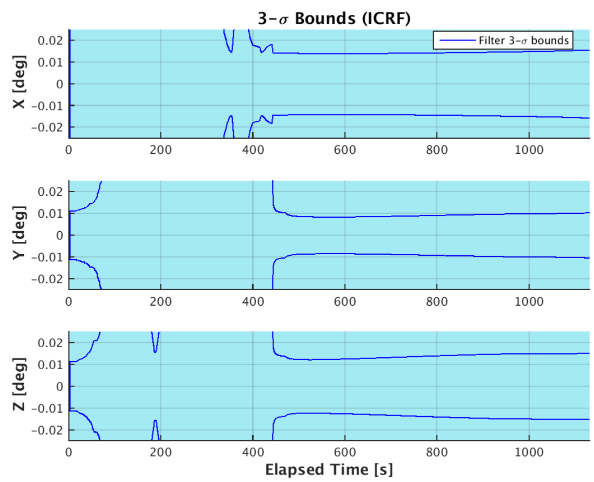

Figure 10. Zoomed Ascent Attitude Performance

Orbit

During orbital operations, the vehicle state continued to be propagated via gravitational modeling and IMU measurements, and updated with GPS Pseudo-range and Delta-range measurements when available. Since the EFT-1 mission was only about four and a half hours, a Star Tracker was not needed to maintain vehicle attitude (even without estimating the attitude in the Kalman Filter with GPS measurements). Future Orion missions, such as Exploration Mission 1 and 2 will include a Star Tracker for attitude determination while in orbit.

The on-orbit position uncertainty was very good and well within the 50 m requirement as seen in Figure 11. GPS measurements were available much higher than assumed during conservative pre-flight analysis. The GPS receiver tracked more than 4 satellites nearly the entire orbital phase with the exception of a small 5 minute window just shortly after reaching apogee (just under 6000 km altitude) of the second orbit. It was later determined that the outage would have been much shorter (a mere transient) if it were not for a software bug related to the GPSR clock bias estimate. Once again the errors relative to the BET were outside the bounds of the expected uncertainty but within the 50 m requirement. The only exception to this was during the 5-minute GPS blackout period, notable also in the uncertainty around 12000s.

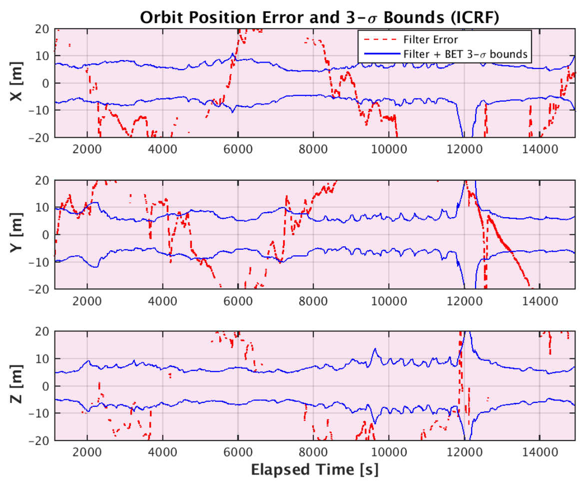

Figure 11. Orbit Position Performance

The on-orbit BET velocity uncertainty shown in Figure 12 was actually about three times larger than the on-board filter uncertainty in Figure 13 because the tool used to generate the BET could not process GPS Delta-range measurements. In fact, the on-board uncertainty would have been even smaller if it were not for the fact that the DR measurements were heavily de-weighted for EFT-1 as a precautionary measure. Thus, the relative uncertainty between the BET and the on-board solution was right at the requirement of 0.2 m/s. In this case the errors relative to the BET were outside the requirement limits, but it is anticipated that much of this error will be resolved with the previously mentioned BET updates and Planet-Fixed representation. Finally, there are two notable "bumps" in the uncertainty that align with the second Stage Engine Cutoff (SECO2) burn that raises the second orbit around 7000s and the GPS blackout period near apogee (around 12000s).

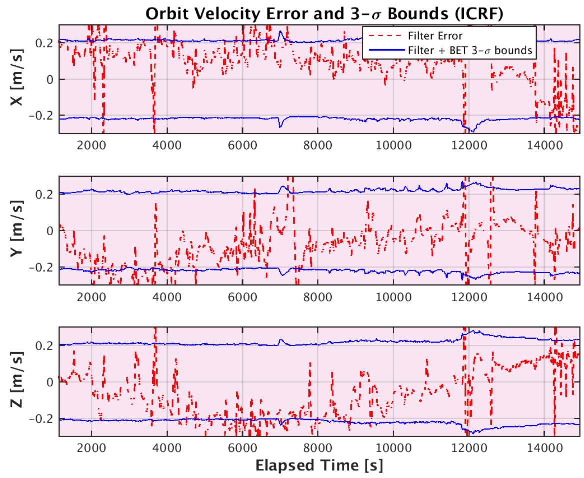

Figure 12. Orbit Velocity Performance

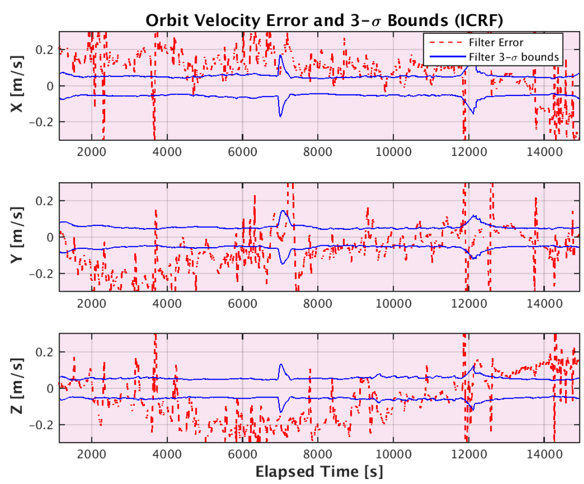

Figure 13. Orbit On-board Filter Velocity Uncertainty

The on-orbit attitude uncertainty was extremely good throughout the orbital phase. Figure 14 reveals that starting from around 0.02 deg, the per-axis error grew to a value bounded to just over 0.05 deg. It can also be seen that the SECO2 burn reduced the uncertainty as expected by generating non-conservative accelerations that allow the filter to observe the attitude errors. In turn, there was a minor increase starting a little before 12000s around CM separation from the Service Model (SM), and another small decrease during the CM raise burn around 14000s.

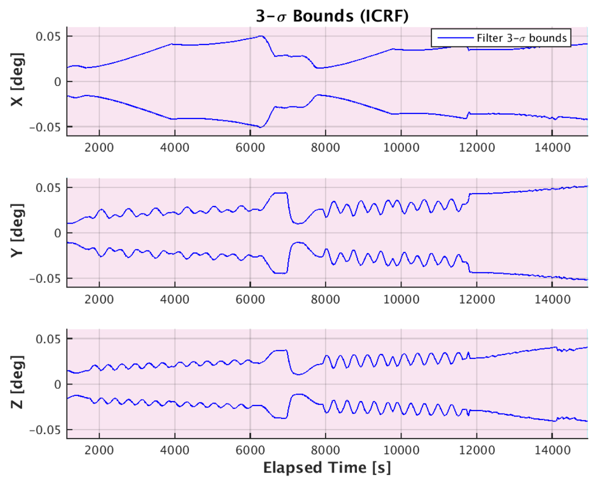

Figure 14. Orbit Attitude Performance

Entry

During entry the extreme heat generated as the vehicle screams through the atmosphere creates a plasma wake that is significant enough to attenuate communication and GPS signals. Thus, shortly after Entry Interface (EI), GPS measurements were not available, and stay unavailable for about 2-3 minutes. Is should be noted that the Entry plots in this section all start 5 minutes prior to EI.

While there were specific position, velocity, and attitude requirements at Entry Interface, only the attitude and altitude had requirements during the Entry phase. The position and velocity performance was bounded by IMU specifications, EI errors, and propagation method. As with Ascent, the desired performance during atmospheric flight while processing GPS measurements was 50 m for position, 0.5 m/s for velocity, and 0.4 deg for attitude.

As expected, the position errors and uncertainty grew quickly during the GPS blackout, but clamped down almost immediately when GPS measurements return. There was also a small increase in the uncertainty starting around 15600s that was due to high dynamics during parachute deploy. Figures 15 and 16 show that the position uncertainty was well behaved during GPS processing and within the desired performance of 50 m. The errors were outside the uncertainty bounds but generally within 50 m. As mentioned before, these errors should be reduced with BET and coordinate frame updates.

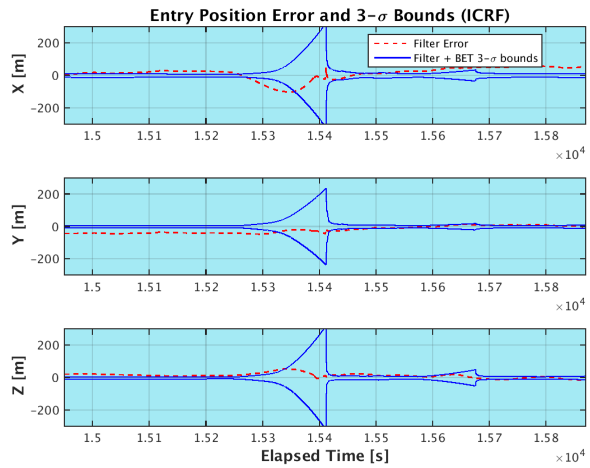

Figure 15. Entry Position Performance

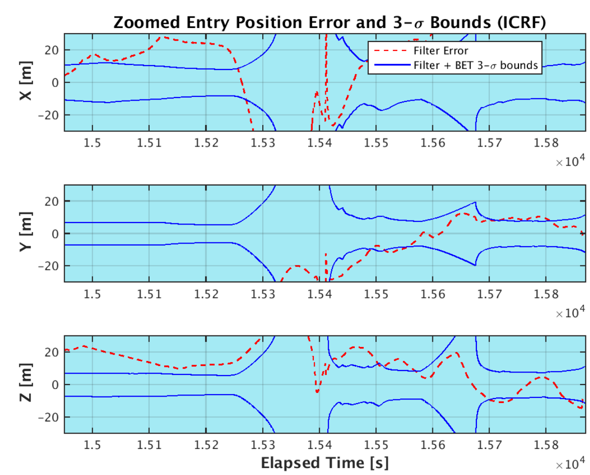

Figure 16. Zoomed Entry Position Performance

The velocity performance during Entry shown in Figures 17 and 18 was also very good. With the exception of GPS blackout and chute deploy, the uncertainty was within the desired 0.5 m/s limit. Again, the errors relative to BET were outside the uncertainty bounds, but BET updates are expected to reduce these errors within desired limits.

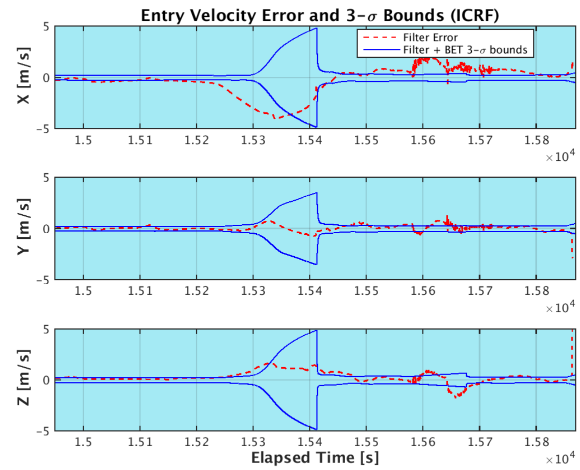

Figure 17. Entry Velocity Performance

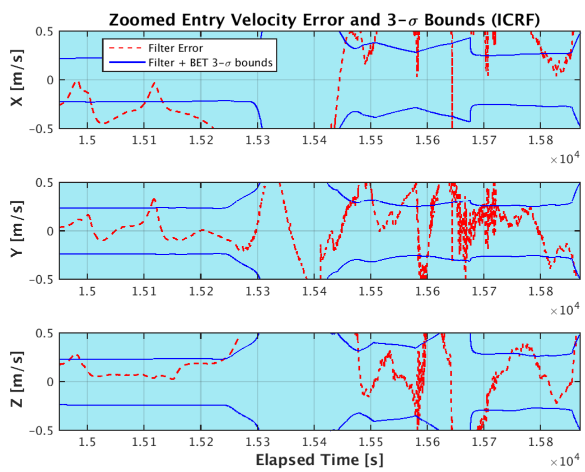

Figure 18. Zoomed Entry Velocity Performance

Since GPS signals are lost very quickly after EI, there is very little convergence of the attitude uncertainty until after GPS blackout around 15400s. Figure 19 reveals that the uncertainty is already very low around 0.05 deg at EI, but drops even further to less than 0.02 deg per axis once GPS processing returns and stays low until landing.

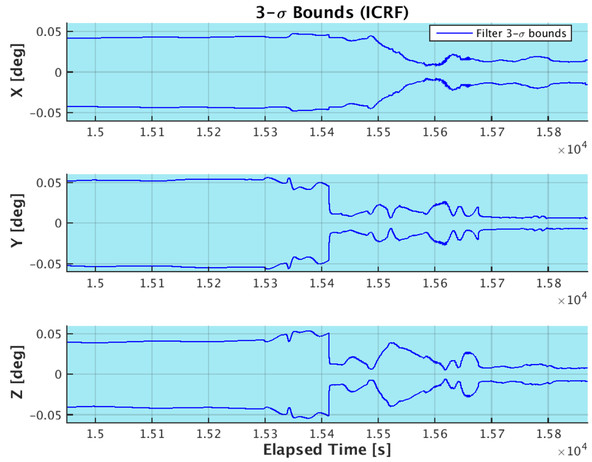

Figure 19. Entry Attitude Performance

CONCLUSION

Overall the Orion navigation system performed very well during it's first flight test. GPS acquisition and long-range tracking was better than expected, and the attitude estimation worked extremely well. This performance allowed the guidance system to hit the landing site target at chute deploy within less than one nautical mile, and helped the recovery forces capture realtime images of the descent and parachute deploy. The Orion EFT-1 flight was a great success.

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