

POST-FLIGHT ANALYSIS OF THE GUIDANCE, NAVIGATION AND CONTROL PERFORMANCE DURING ORION EXPLORATION FLIGHT TEST 1

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The first test flight of the Orion Multi-Purpose Crew Vehicle presented additional challenges for guidance, navigation and control as compared to a typical re-entry from the International Space Station or other Low Earth Orbit. An elevated re-entry velocity and steeper flight path angle were chosen to achieve aero-thermal flight test objectives. New IMU's, a GPS receiver, and baro altimeters were flight qualified to provide the redundant navigation needed for human space flight. The guidance and control systems must manage the vehicle lift vector in order to deliver the vehicle to a precision, coastal, water landing, while operating within aerodynamic load, reaction control system, and propellant constraints. Extensive pre-flight six degree-of-freedom analysis was performed that showed mission success for the nominal mission as well as in the presence of sensor and effector failures. Post-flight reconstruction analysis of the test flight is presented in this paper to show whether that all performance metrics were met and establish how well the pre-flight analysis predicted the in-flight performance.

INTRODUCTION

The Orion Multi-Purpose Crew Vehicle (MPCV) was successfully flown on an unmanned test flight on December 5, 2014. Orion is being developed by NASA with Lockheed Martin as prime contractor. The first Exploration Flight Test (EFT-1) demonstrated the Guidance, Navigation, and Control (GN&C) algorithms and flight dynamics of the Orion Crew Module (CM). Figure 1 shows the mission trajectory for EFT-1. The second of two orbits places the vehicle into a highly elliptical orbit that results in near lunar-return re-entry conditions that aero-thermally stress the capsule. This paper provides insight into the performance of the GN&C algorithms flown on EFT-1. The flight test objectives related to the GN&C subsystem include:

- Demonstrate performance of the Orion Inertial Measurement Units (OIMU)
- Demonstrate performance of the Global Positioning System (GPS) and the ability to re-acquire after the ionization-induced blackout

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- Demonstrate performance of the barometric altimeter
- Demonstrate attitude control and maneuvering using the Crew Module (CM) Reaction Control System (RCS) thrusters
- Demonstrate a translational burn
- Demonstrate guided entry
- Demonstrate deployment of the parachute system

The flight test was highly successful in achieving the flight test objectives defined for the mission.

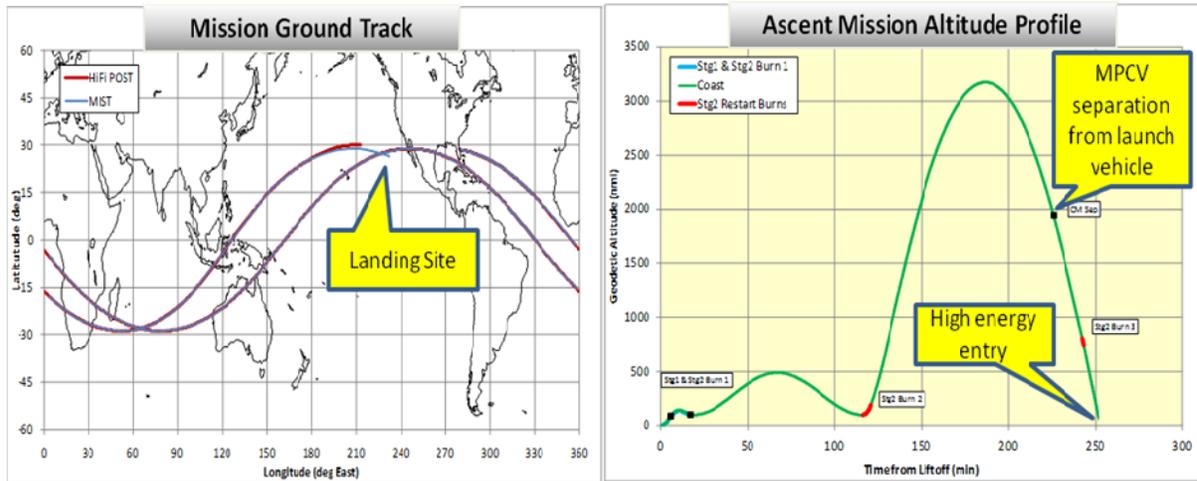


Figure 1. Orion EFT-1 Mission Trajectory.

PRE-LAUNCH AND ASCENT NAVIGATION

Orion must navigate in all mission phases so a ground alignment and sensor checkout were performed during pre-launch. Figure 2 below shows that after convergence the vehicle azimuth and tilt generally varied less than 0.01 degrees. The 0.015 degree shift in yaw tilt (3rd subplot) is attributed to launch vehicle tanking operation as a similar shift was also seen during the December 4th launch scrub. Figure 3 shows how the barometric altimeters compared with local pressure readings from the nearby Shuttle Weather Station. After accounting for the 236 ft altitude difference, known avionics errors, and the crew module purge pressure the barometric altimeter performance met expectations. The GPS receiver (GPSR) performance could not be evaluated on the pad since the GPS antennas were covered by Radio Frequency (RF) opaque Launch Abort System (LAS) shroud.

The green dashed line in the first subplot in Figure 4 shows that during ascent the GPSR began tracking satellites 11 seconds after the LAS jettison. The solid blue line in the same subplot shows the number of measurements actually passed to the navigation filter. This remained zero until 54 seconds aft LAS jettison when the GPS Position, Velocity, and Time (PVT) solution became valid after a full satellite ephemeris download. The second subplot in Figure 4 shows navigation filter solution quickly converged to the GPS state as the prefit pseudorange residuals went from a few hundred feet to less than 50 feet in less than 10 seconds. The slower changing residuals are generally indicative of a de-weighted low elevation satellite. Excellent attitude perfor-

mance was also demonstrated as a comparison of filtered and IMU-only states showed that the GPS measurements corrected less than 300 ft of position error and 0.004 degrees of attitude error.

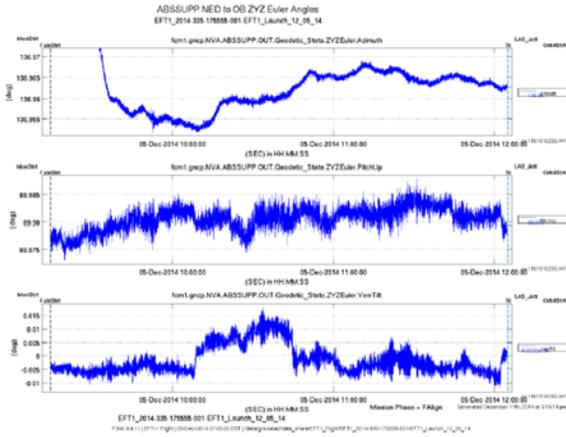


Figure 2. Ground Alignment Performance.

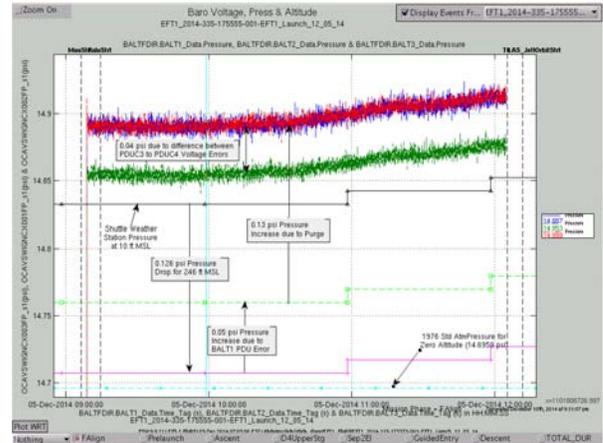


Figure 3. Baro Altimeter Ground Performance.

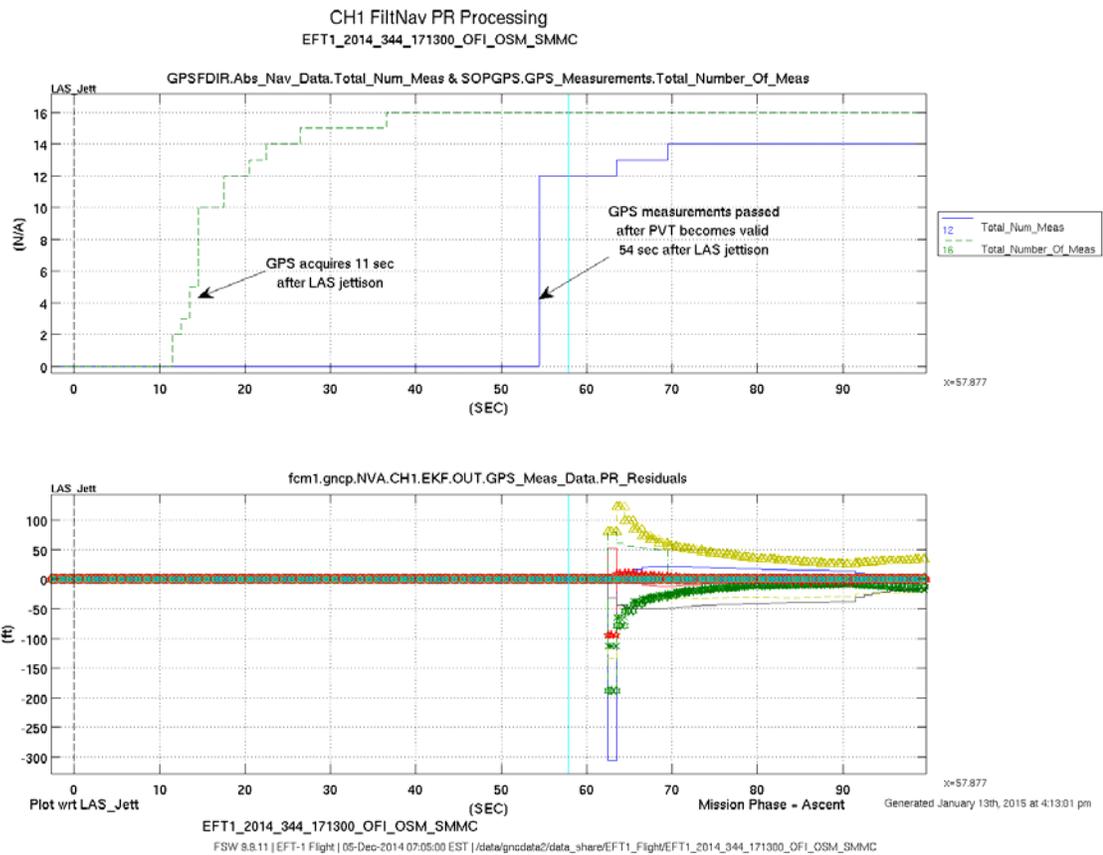


Figure 4. Ascent GPS & Navigation Filter Performance.

ORBIT NAVIGATION & ANTENNA POINTING

Figure 5 shows that GPS performance was much better than expected, especially at high altitudes, as the GPSR continued to track 8 to 12 satellites through the second apogee (0 to 5 satellites were expected due to conservative modeling of GPS satellite antenna gain patterns). The only time the number of satellites dropped below the five needed for navigation filter processing was near Crew Module (CM) separation from the launch vehicle upper stage when an attitude maneuver caused one of the antennas to point down. This measurement rich environment resulted in excellent navigation performance throughout the flight with position and velocity covariances generally staying below 50 ft and 0.3 ft/s (3σ), respectively, during orbital coasting flight (see figures 6 & 7). Clock bias and drift covariances also remained below 50 ft and 2.0 ft/s (3σ), respectively (see figures 8 & 9). All covariances exhibited nominal growth and reconvergence during the brief measurement outage near CM separation. A nominal growth and reconvergence near the second stage burn was also seen in the velocity covariance.

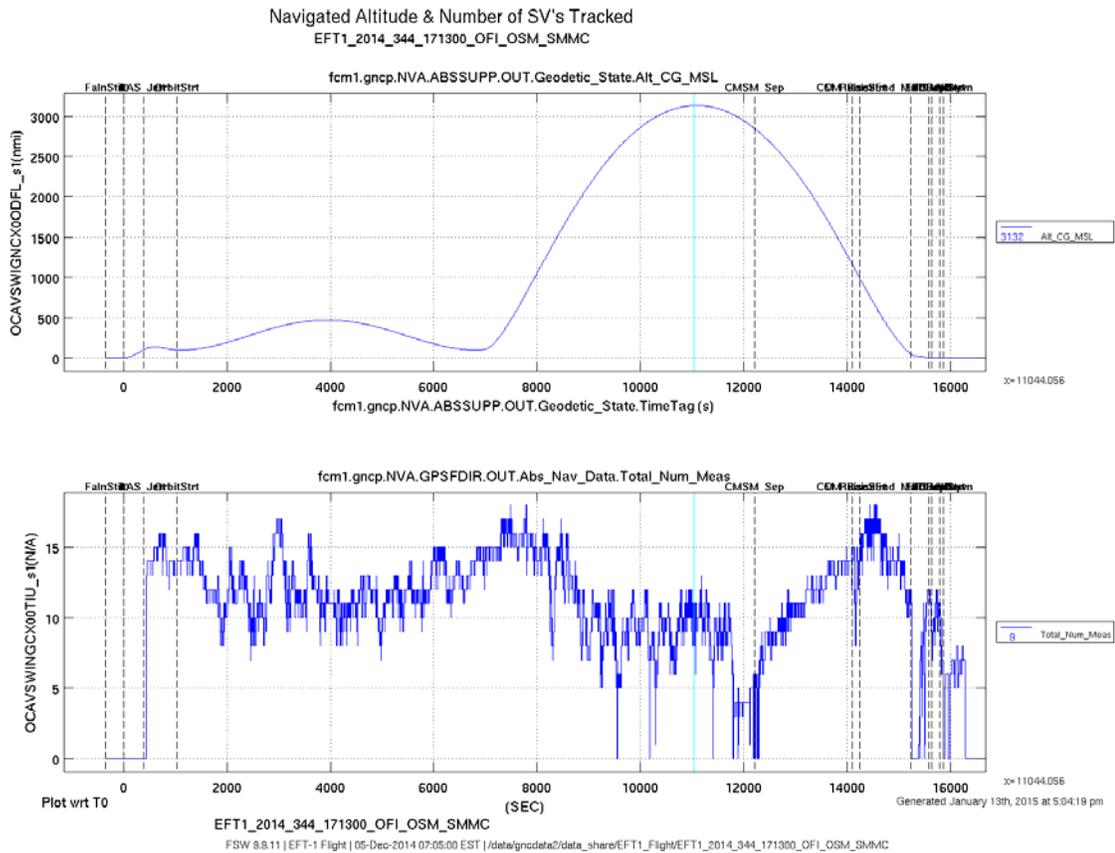


Figure 5. Number of GPS Satellites Tracked On-Orbit.

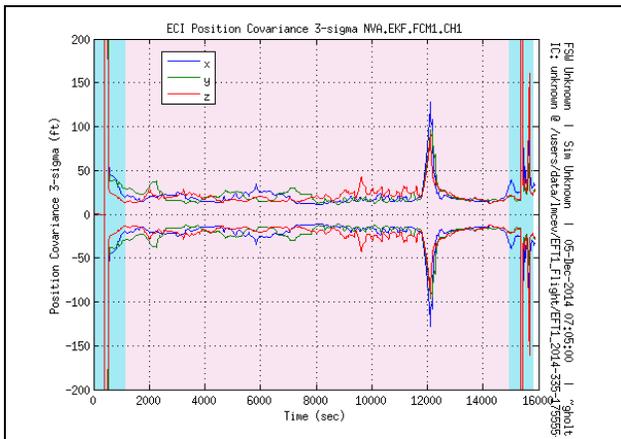


Figure 6. On-Orbit Position Covariance.

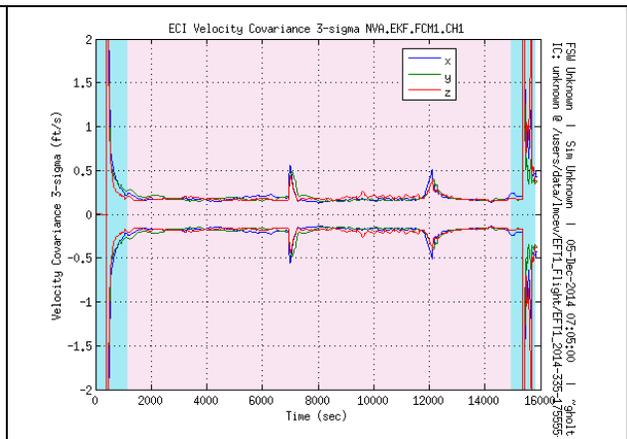


Figure 7. On-Orbit Velocity Covariance.

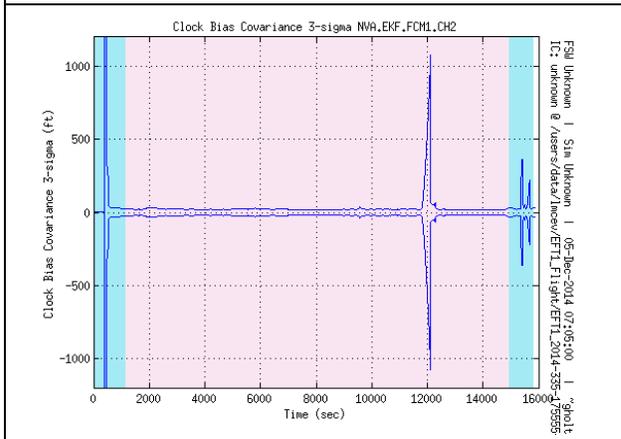


Figure 8. On-Orbit Clock Bias Covariance.

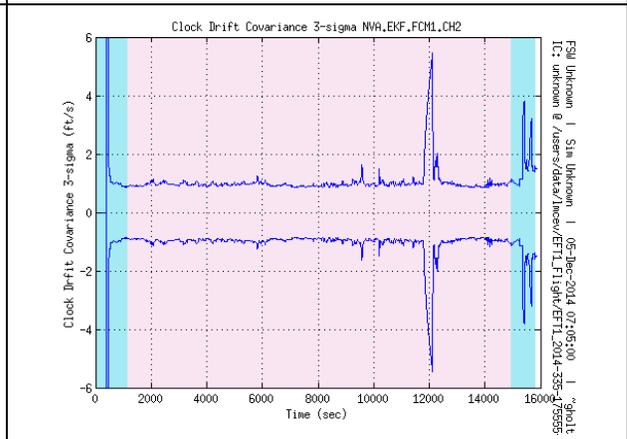


Figure 9. On-Orbit Clock Drift Covariance.

POST-SEPARATION CONTROL

The Orion vehicle takes over control of the capsule attitude after separation from the launch vehicle. Separation occurs 50 minutes prior to Entry Interface (EI). The concept of operations during this 50 minutes is straightforward. Flight control is in free drift for the first 10 seconds to avoid thruster firings while in near-proximity to the launch vehicle. Then the separation attitude [roll = 0 deg, pitch = 35 deg, yaw = 0 deg] is held for 30 minutes. A pitch maneuver to the atmospheric entry trim attitude [roll = 0 deg, pitch = 162 deg, yaw = 0 deg] is then performed. Shortly after the pitch maneuver, a demonstration trajectory correction burn was performed for 10 seconds. The yaw-right and yaw-left thrusters are fired simultaneously to produce a small delta-V to the trajectory. After the translational burn, the atmospheric trim attitude is held until aerocapture transitions the flight controller to atmospheric mode. Figure 10 shows the pitch attitude control performance for the full 50 minutes of the Exo-atmospheric segment. Figure 11 shows the vehicle body rates during the first 30 minutes of the Exo-atmospheric segment.

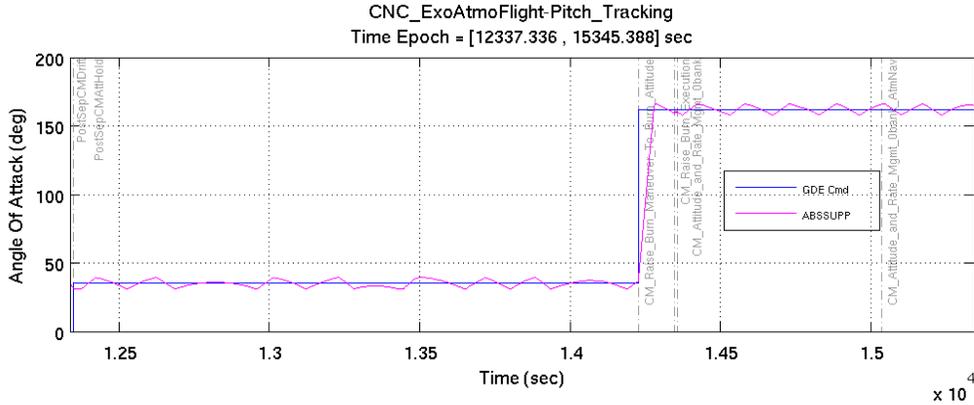


Figure 10. Orion EFT-1 Exo-atmospheric Pitch Attitude.

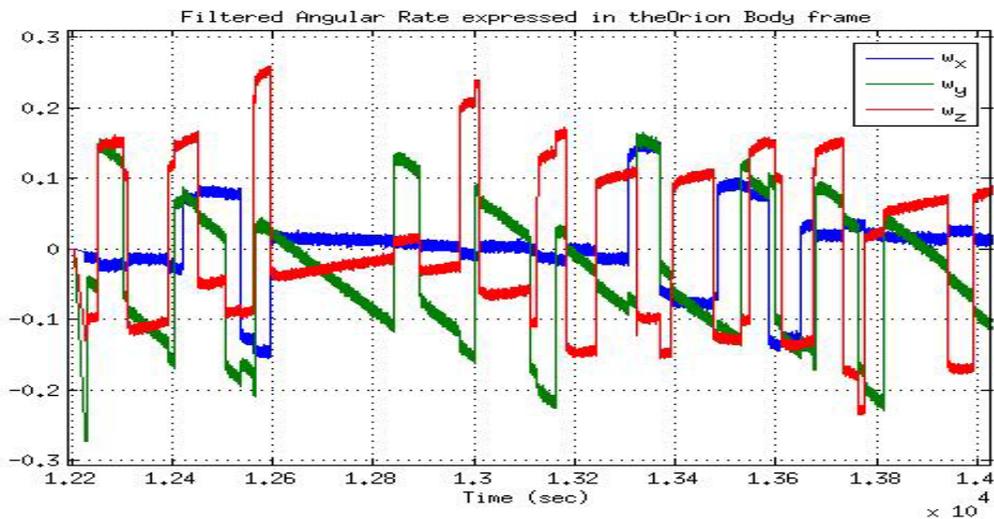


Figure 11. Orion EFT-1 Exo-atmospheric Body Rates.

The separation tip-off rates were very benign for EFT-1. The body rates after separation were [0.12, 0.265, 0.01] deg/sec. This was almost within the launch vehicle constraint to hold the attitude rates within 0.25 deg/sec prior to separation. The first capsule thruster firing to correct attitude did not occur until 6 seconds after the 10 second free drift period. During the coast phases, the flight controller performed well holding attitude within the effective deadbands of +/-4.5 deg. Most deadband thruster commands were minimum impulse firings, as expected. The pitch maneuver was clean. EFT-1 provide a good demonstration of the controller’s ability to perform a long translation burn while holding attitude. The yaw thrusters were “off-pulsed” based on attitude control commands, and pitch/roll attitude control thruster firings were performed during the burn.

The body rates plot shows an obvious slope to the pitch rate (and yaw rate to a lesser extent) between thruster firings. This disturbance is caused by the continuous venting of ammonia from the Active Thermal Control System (ATCS). Based on this slope, the estimated vent force was 32% of the force specified for Orion GN&C simulations. In pre-flight simulations, the pitch attitude always exhibited a single-sided deadbanding due to the persistent vent torque. Actual flight

performance exhibited double-sided pitch deadbanding as can be observed in the pitch attitude plot.

ENTRY GPS & BARO ALTIMETER PERFORMANCE

The GPS plasma induced RF blackout started EI +33 seconds at an altitude of 270 kft when the velocity was 28,000 ft/s (see Figure 12). Satellite reacquisition began two minutes later at EI+153 seconds at an altitude of 142 kft when the velocity had slowed to 12,000 ft/s. The navigation filter began accepting GPS measurements at EI+187 seconds at 135 kft. This provided 165 seconds and 111 kft of margin before the critical chute deployment events. The start of blackout was an excellent match with the nominal blackout model but the end of blackout was about 30 seconds later than predicted. IMU-only navigation performance during blackout was very good as less than 300 ft of GPS corrections were applied after blackout.

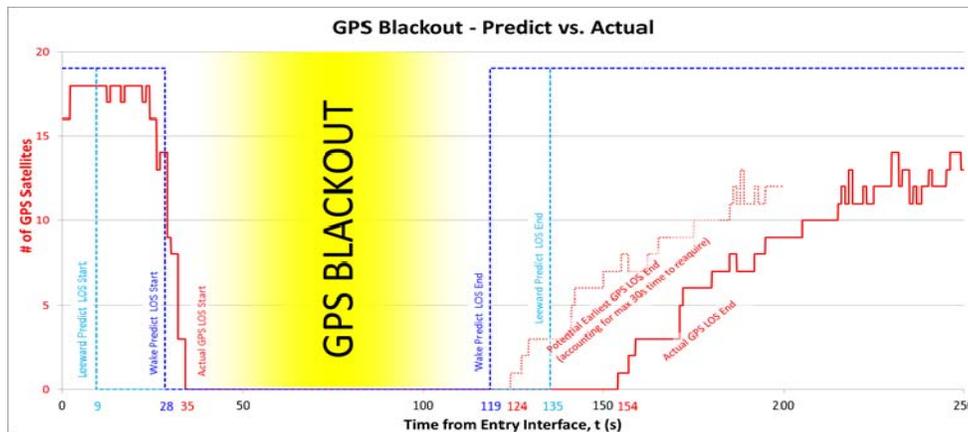


Figure 12. GPS Reacquisition After Blackout.

Figure 13 below shows the baro altimeters read about 40 kft higher than the filtered navigation altitude prior to 70 kft. A high baro altitude was expected prior to 70 kft due to aerodynamic wake effects, however, the wake effects started 50 to 100 seconds earlier than what was predicted by the aerodynamic models. Fortunately, these wake effects diminished as expected, validating the pressure gate that enables the baro altimeters near 70 kft. By the time the 24 kft drogue chute deployment altitude was reached, the baro altimeter was only 80 ft off from the filtered navigation altitude. After drogue deployment, the baro altimeters generally read 300 to 500 ft low due to known avionics errors and local barometric pressure differences from the 1976 standard atmosphere.

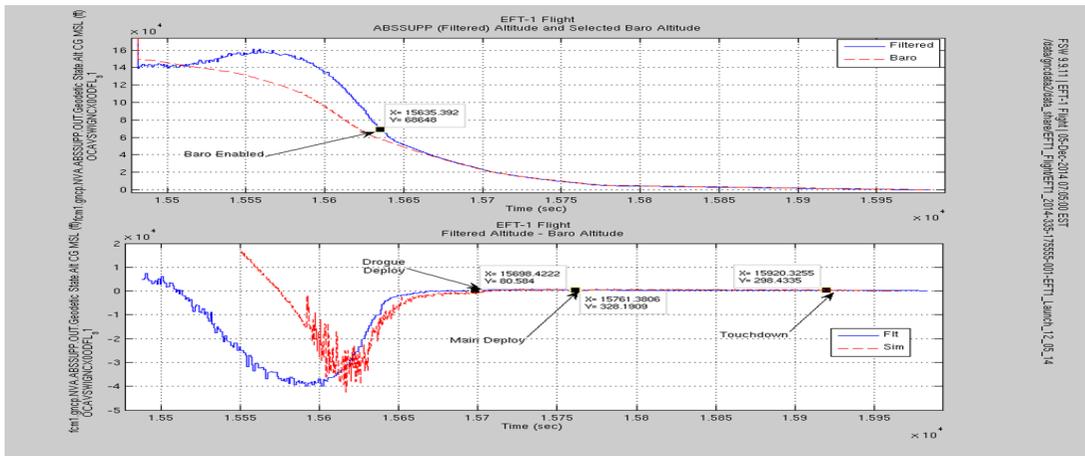


Figure 13. Barometric Altimeter Performance During Entry.

ENTRY GUIDANCE AND CONTROL PERFORMANCE

Once atmospheric entry is achieved at approximately 400,000 ft, the Orion precision guidance algorithm begins operation. The Orion capsule was designed with an offset center of gravity location along the Z body axis. This produces a fixed lift vector than can be pointed within an Earth-relative reference frame by controlling the vehicle bank angle. That vehicle angle of attack and angle of sideslip are effectively fixed due to the aerodynamic trim conditions; however, due to the symmetric shape of the capsule, the aerodynamic torque about the velocity vector (bank angle axis) is small enough to be controlled through the Reaction Control System (RCS) thrusters.

The Orion entry guidance algorithm is generally based on the Apollo algorithm where the downrange and crossrange guidance is decoupled. Longitudinal control is achieved by modulating the magnitude of the bank command where a 0 deg bank angle points the lift vector up, and a 180 deg bank command points the lift vector down. Lateral control is achieved through the adjusting the sign of the bank command through bank reversals (instantaneous change in sign of the command). The EFT-1 flight utilized four bank reversals which can be seen below in Figure 14. The solid lines in the figure are the EFT-1 flight data and the dashed lines represent the final pre-flight prediction, which showed an excellent match. The navigated bank angle is also shown which illustrates the lag between when a new bank angle is commanded and when it is achieved.

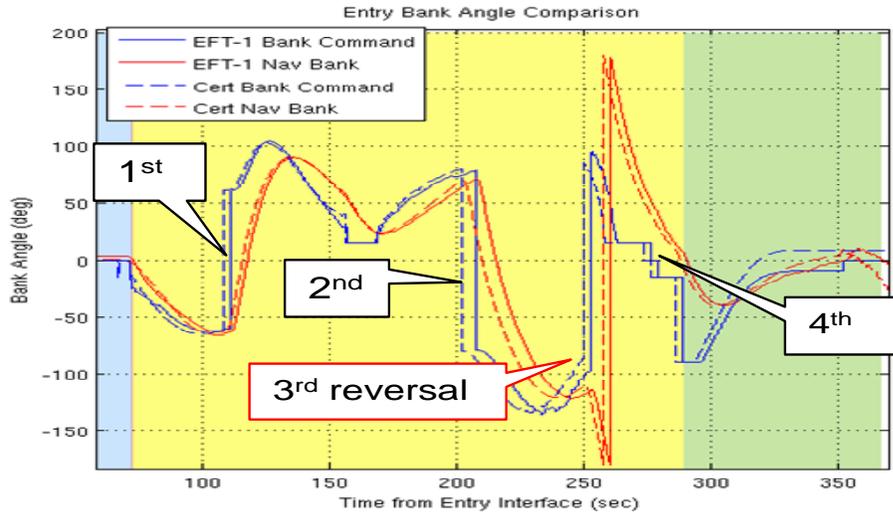


Figure 14. EFT-1 Entry Bank Angle.

The objective for landing accuracy for the EFT-1 mission was 10.8 nautical miles (nmi). As shown in Figure 15, the achieved accuracy at splashdown was 1.53 nmi. When the guidance software was terminated and parachutes deployed at 24,000 ft, the accuracy was 0.6 nmi; therefore, much of the miss distance was due to wind drift while under the parachutes. Earlier designs considered biasing the parachute deploy target to account for wind drift based on pre-flight balloon data; however, the EFT-1 mission did not require that level of accuracy.

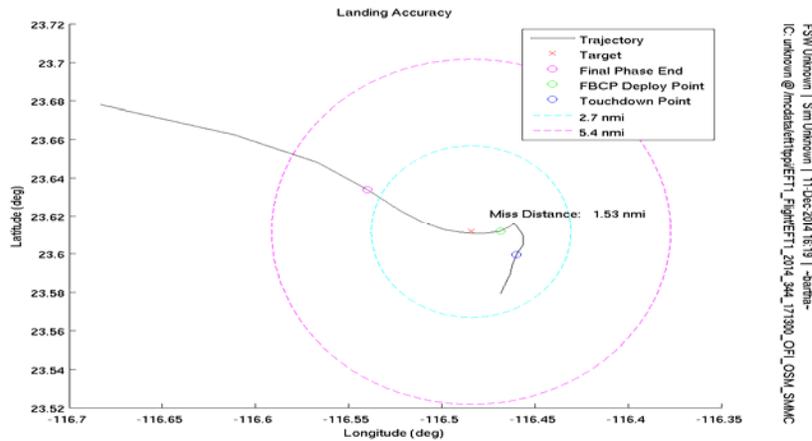


Figure 15. EFT-1 Landing Accuracy.

Aside from bank angle control, the main challenge for the control system during atmospheric entry is providing rate damping during the subsonic portion of flight and prior to parachute deployment. The capsule is aerodynamically unstable in this region and active control is needed to prevent the capsule from flipping apex-forward and from violating parachute deployment constraints. The plot in Figure 16 shows the pitch and yaw control errors with the inner (single jet firing) and outer (dual jet firing) deadbands shown. The aerodynamic environment was relatively benign during the EFT-1 flight and no dual jet firings were required for subsonic control.

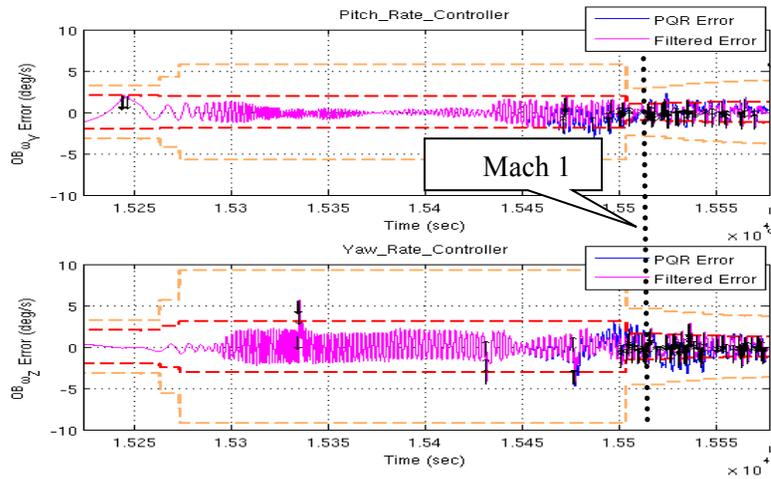


Figure 16. EFT-1 Atmospheric Pitch and Yaw Control.

Orion overall propellant usage was lower than predicted by pre-flight simulation. Total usage is estimated to have been 93 lbm compared to a mean pre-flight prediction of 119 lbm. This is $2\text{-}\sigma$ low compared to pre-flight statistics. Figure 17 show the time history of Orion propellant usage. Some reasons for lower propellant usage have been identified. The CM Separation tip-off rates were very low, the atmospheric wind perturbations were less than nominal simulation predictions, and the roll rates under parachutes were low compared to mean predicted roll rate. Aerodynamic modeling is also under investigation as a possible contributor to lower than expected propellant usage.

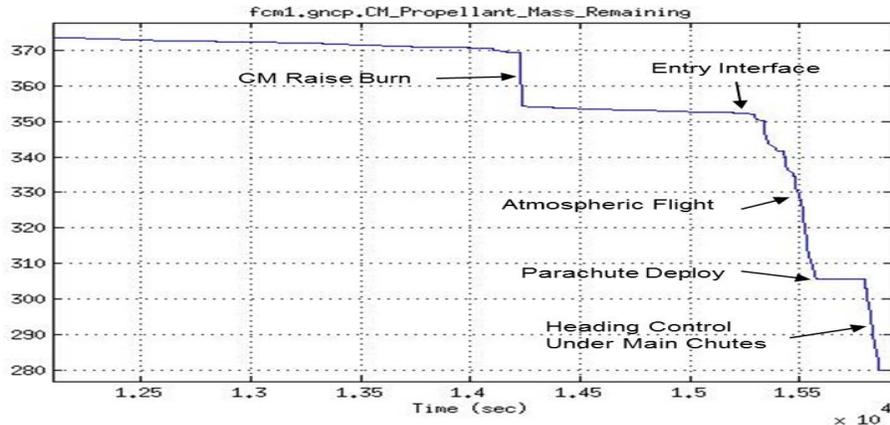


Figure 17. Orion EFT-1 Propellant Usage (lbm).

DESCENT & LANDING TRIGGERS

The Orion vehicle utilizes eleven parachutes along with two jettison events during the descent sequence. The EFT-1 test flight followed the nominal sequence of events shown below in Figure 18. The Forward Bay Cover (FBC) parachute deploy and Drogue parachute jettison events that are listed at the lowest row of the figure and shown in red are triggered by the Guidance systems. Each of these triggers begins a sequence of timed events executed by the Timeline and Vehicle Manager (TVM) software. The FBC parachute deploy trigger first initiates the FBC para-

chute mortar fire, then 1.4 seconds later initiates the FBC jettison thruster, and then 2.0 seconds later initiates the Drogue parachute mortar fire. The Drogue parachute jettison trigger initiates the Drogue parachute cutters then initiates the Pilot parachute mortar fire. The Pilot parachutes then automatically deploy the Main parachutes.

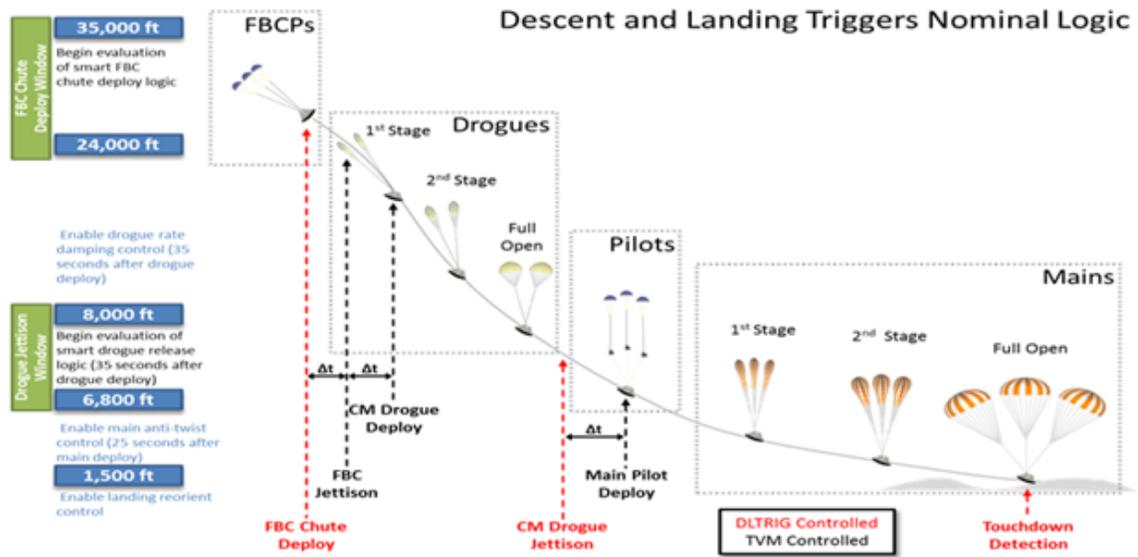


Figure 18. Orion EFT-1 Descent Sequence.

Forward Bay Cover Parachute Trigger

The trigger to deploy the FBC parachutes will nominally occur when the navigated altitude drops below 24,000 ft. Once the navigated altitude drops below 35,000 ft, a backup becomes active to monitor the Root Sum Squared (RSS) of the pitch and yaw body rates. If the RSS rate exceeds 20 deg/s, the FBC parachute trigger will be set early. This is in place so as to protect for excessive rate oscillation that can develop due to subsonic aerodynamic instabilities present in most re-entry capsule designs. As seen in the bottom subplot in Figure 19, the EFT-1 flight did not experience any rate build-up and the RSS pitch and yaw rate remained below 5 deg/s until parachutes were deployed at the altitude floor of 24,000 ft.

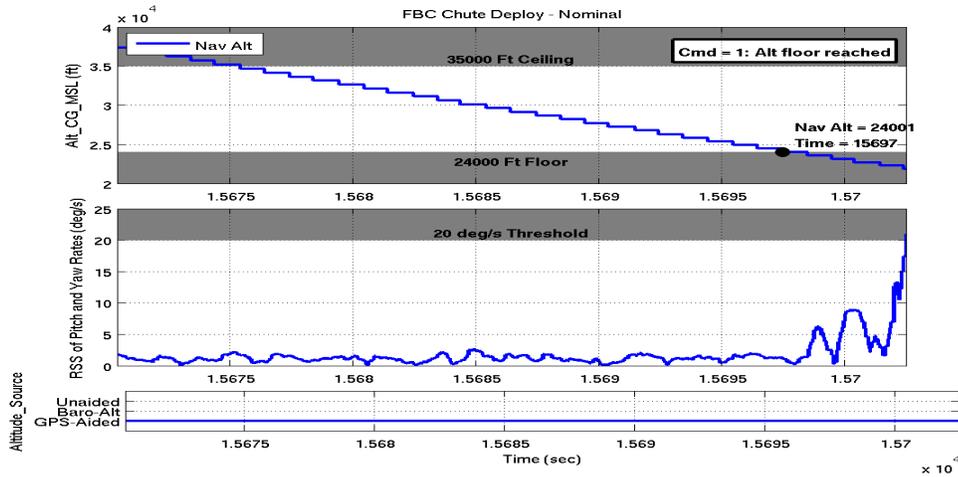


Figure 19. Orion EFT-1 FBC Parachute Deploy Trigger.

Drogue Parachute Jettison Trigger

After a 50 second ride on the Drogue parachutes, the risers are cut and the Main parachute deployment sequence is initiated. This event occurs within an altitude box from 8,000 ft to 6,800 ft. Once the vehicle is within this altitude box, the RSS of the pitch and yaw rate is monitored. The purpose is to release the Drogue parachutes while the rates are low and lessen the risk the vehicle will tumble during the brief un-controlled, free-flying period between Drogue parachute release and Main parachute deployment. The RSS of the pitch and yaw rate oscillates at roughly a 0.5 Hz frequency. The Smart Drogue Release algorithm tracks the peaks and troughs of this oscillation and sets the trigger when the oscillation is descending and 35% from the next trough. During the EFT-1 flight the algorithm performed well; it was able to detect all of the peaks/troughs of the oscillation and only mis-identified two or three false peaks. The Drogue parachutes were jettisoned at 7,960 ft which was during the first oscillation after the 8,000-6,800 ft altitude window opened. Performance of the Smart Drogue Release algorithm is shown below in Figure 20.

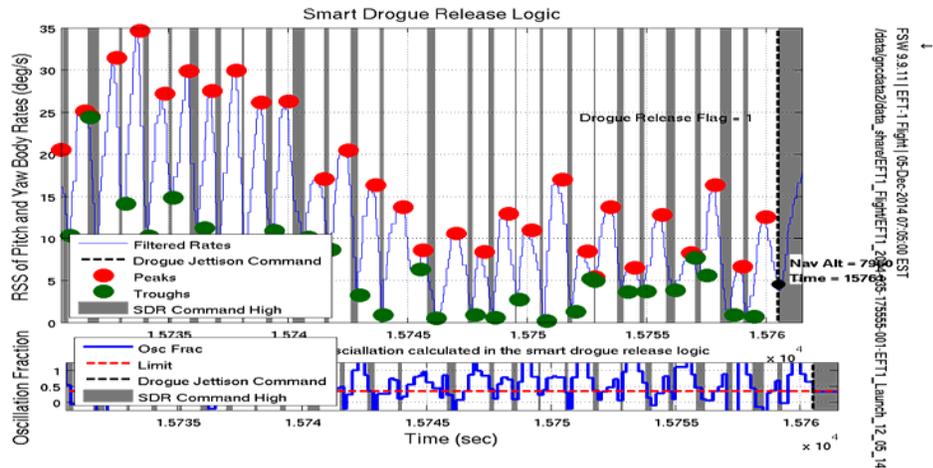


Figure 20. Orion EFT-1 Drogue Parachute Jettison Trigger.

Touchdown Heading Control

At an altitude of 1500 ft, the Orion attitude controller initiates touchdown heading control. At splashdown the Z-body frame oriented must be in the direction of the vehicle horizontal velocity. Under main parachutes, the horizontal velocity is determined primarily by the atmospheric wind speed and wind direction. The heading orientation is driven by a need to manage the landing impact loads that will be experienced by future human crewmembers. Figure 21 shows the EFT-1 touchdown heading control performance. The plot is a phase-plane of heading error vs. heading error rate and shows the heading control deadbands. The controller initiated with a heading error of 140 deg and a negative rate that was already reducing the heading error. The controller increased the heading rate to the maneuver rate and then successfully converged and held the desired heading until splashdown. The heading error at touchdown was less than 15 deg and achieved the needed accuracy. Note that all of the thruster firings were on the same side of the phase-plane indicating that a persistent parachute line twist torque was present in the system.

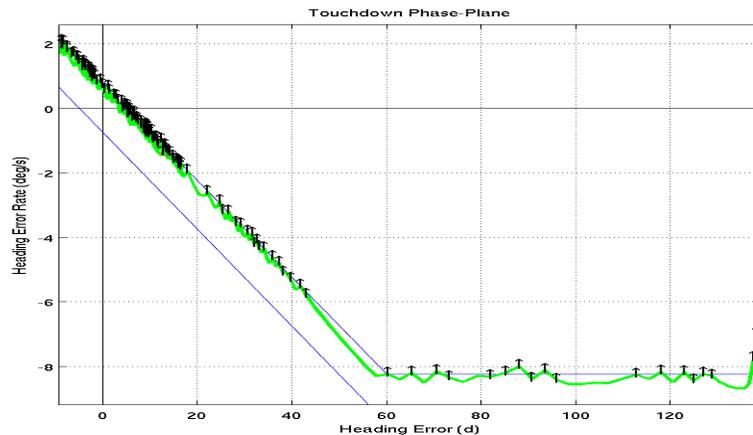


Figure 21. Orion EFT-1 Touchdown Heading Control Performance.

Touchdown Detection Trigger

The final descent trigger set by the guidance software is touchdown detection. Three critical events are dependent on an accurate detection of touchdown: the first is cessation of RCS commands so that no firings occur while submerged in the water, the second is the timed deployment of the airbags used to upright the vehicle in the event it settled in an apex-down orientation, and the third is the start of a timer that is used to cut the Main parachutes away from the vehicle. Acceleration thresholds are used to inhibit the RCS system and confirm touchdown. Care was taken to size the thresholds so that acceleration spikes due to off-nominal dis-reefing of the parachutes would not cause false triggers and premature jettison of the Main parachutes. The touchdown detection trigger was implemented using filtered 200 Hz acceleration data along with a persistence counter in order to counter the effect of noise on the OIMU acceleration signal. The resulting acceleration along with the threshold values used is shown in Figure 22. Note that after the persistence counter of 10 is met, the data in the plot goes stale.

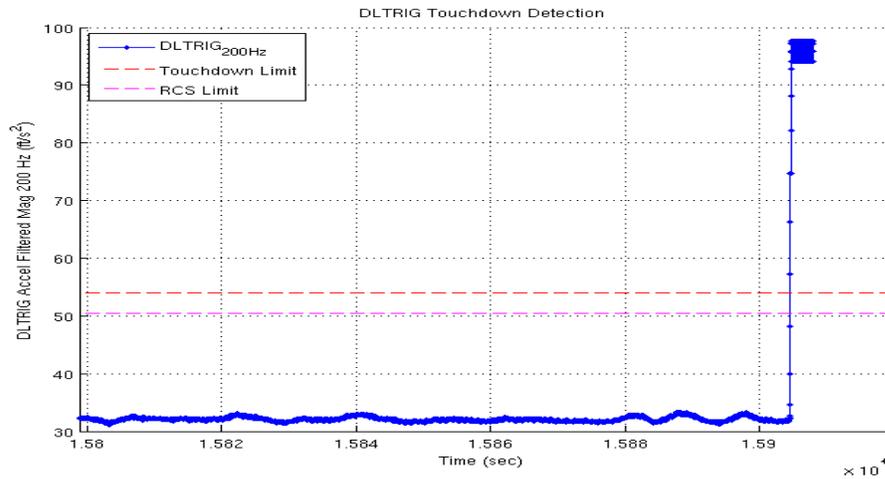


Figure 22. EFT-1 Touchdown Detection.

CONCLUSION

The EFT-1 flight test was an unqualified success in terms of GN&C performance with all GN&C flight test objectives achieved. Navigation performance, particularly in regards to the GPS, exceeded expectations, RCS control was excellent with propellant usage below the preflight mean, all parachutes were deployed at nominal conditions, and landing accuracy at guidance termination was less than 0.6 nmi. The EFT-1 flight test has put the Orion vehicle well on its way to the next test flight, Exploration Mission 1 (EM-1). The EM-1 mission will introduce several new capabilities not present on EFT-1 including abort and down-mode options, optical navigation, cislunar GN&C, solar array power generation, and skip re-entry. The data gathered during the EFT-1 flight will be critical for refining the vehicle design and simulation models that will be used for the EM-1 flight.

ACKNOWLEDGMENTS

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